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

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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 750C 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.

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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.

Quantum Science and Technology Mini-Symposium
Room B110-112 - Session QS-MoA

Systems and Devices for Quantum Computing
Moderators: Ekta Bhatia, NY CREATES, **Dave Pappas**, Rigetti Computing

1:40pm **QS-MoA-1 Hole-Based, Atomic-Scale Quantum Devices in Silicon***, **Robert Butera**,* Laboratory for Physical Sciences **INVITED**

δ-doped Si provides a novel frontier to explore quasi-2D electronic transport of an extremely high concentration of carriers (> 10^{14} cm^{-2}) through a highly-disordered potential. These carriers can be further confined using atomic-precision advanced manufacturing (APAM) techniques to generate a variety of atomic-scale quantum devices [1]. Over the past two decades these techniques have been used to realize and characterize atomic-scale wires, single atom and single electron transistors, as well as single atom qubits based on P [2-5], the quintessential electron donor dopant for Si. In contrast, atomic-scale quantum devices have only recently begun to be explored with B [6, 7], the archetypal acceptor dopant in silicon.

Under standard conditions, a single B atom in Si has an associated hole that forms a promising single qubit platform on its own right [8], but with sufficiently high concentrations of B, Si has been shown to exhibit superconductivity [9]. Motivated by these intriguing possibilities, we developed an APAM-compatible process for B to ultimately explore single acceptor qubits and atomic-scale, superconducting Si devices. Here we discuss the fabrication and initial characterization of the resulting hole-based, atomic-scale quantum devices in which we observe weak anti-localization and universal conductance fluctuations in magnetotransport measurements, and demonstrate Coulomb oscillations in a single hole transistor.

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2:20pm **QS-MoA-3 Interface Loss Engineering for High Coherence Aluminium Qubits***, **Janka Biznarova**, J. Bylander,* Chalmers University of Technology, Gothenburg, Sweden

Superconducting qubits are current hot candidates for delivering on the promise of quantum computation. However, their implementation is not without challenges. Quantum information stored in a qubit has a finite lifetime before it loses coherence.For superconducting qubits to be able to sustain the fragile quantum information in a coherent state sufficiently long so that a meaningful number of logical gates can be executed, it is vital to examine the sources of decoherence and to eliminate them.In this work, we show how improvements in device fabrication can enableT1times of up to 500µs in aluminium-based transmon qubits.

The nature of the sources of coherence loss in quantum circuits is a topic of ongoing debate. In this work we investigate the parasitic two-level systems (TLS) that compete with our devices for photons, as well as uncover other losses that may limit performance once TLS loss has been mitigated.

This problem can be approached from two angles - through optimizing device geometry, and through surface engineering. Manipulating device geometry, we can quantify the relative effect each interface of the CPW resonator has on the total loss, and minimize the participation of the lossiest interfaces. With surface engineering, we can target a given interface in order to mitigate the specific type of loss it entails.

In this work, we design, fabricate and characterize resonators and qubits using aluminium on silicon in order to further investigate the nature of TLS. We vary the deposition conditions of the metal, as well as surface treatments, and draw conclusions for the participation of TLS loss to the total loss of the circuits at low temperatures.Varying the absolute size of the CPWs, as well as the ratio of the CPW center conductor to its gap to ground, we can get a more accurate picture of the various loss contributions. Once a fabrication recipe is optimized for a resonator proxy, the recipe is extended to qubit fabrication. We show that aluminium-based transmon qubits fabricated with the optimized recipe can reachT1values up to to 500µs, with meanT1values exceeding 200µs.

2:40pm **QS-MoA-4 Examine the Electrical Transport Properties of Superconducting Quantum Devices Based on PtSi***, **Tharanga Nanayakkara**, A. Bollinger, R. Li, M. Liu, C. Black,* Brookhaven National Laboratory

Quantum information systems have the potential to revolutionize many fields, including health, defense, and finance. Despite their vast potential, practical applications of quantum information systems face numerous challenges that must be addressed to fully realize their benefits. Fabricating nano-scaled superconducting qubits for quantum information systems is a highly challenging process. One of the primary remaining challenges is identifying suitable superconducting materials with sufficient coherence times in their qubits. Therefore, it is essential to investigate novel materials, such as platinum silicide (PtSi), to recognize their potential candidacy in quantum information science. PtSi is a transition metal silicide, formed by reacting silicon with platinum. PtSi finds extensive use in semiconductor microelectronics since its ability to create low resistance electrical contacts to silicon. Significantly, PtSi exhibits superconducting properties, and it is a potential material for integrating quantum computation with silicon technology.

In this study, Pt thin films were deposited onto silicon substrates using magnetron sputtering technique. Subsequently, the Pt on the silicon wafer was thermally annealed in a rapid thermal processor to form PtSi thin films, which were confirmed by X-ray diffraction measurements. We patterned PtSi thin films on Si substrate using electron-beam lithography to fabricate superconducting devices, including constriction type Josephson junctions (JJs), and Superconducting Quantum Interference Devices (SQUIDs). The fabrication process for constriction-type devices involves a single-step electron-beam lithography, which is simpler than the conventional tunneling junction fabrication process. After patterning the device structure onto the PtSi, a reactive ion etching technique was used to carve the device shape by selectively etching away the surrounding PtSi.

We performed low-temperature electrical transport measurements on constriction type JJs and SQUIDs to evaluate the material characteristics for high-quality superconducting quantum circuit fabrication. The parameters extracted from the PtSi devices, including critical temperature, normal-state resistance, coherence length, critical current density, and critical field values, will be comprehensively discussed in this work.

3:00pm **QS-MoA-5 Two Architectures for Superconducting Quantum Processors with Tunable Couplers*, Stefano Poletto,*** Rigetti Computing **INVITED**

Superconducting quantum processor units (QPUs) with 10s to 100s of physical qubits are now commercially available from multiple companies and institutions. However, to build and operate a high performance superconducting QPU several physics and engineering challenges must still be addressed.

In this talk, I will focus on the implementation of tunable qubit-qubit interactions as a promising alternative to fixed coupling schemes from both a scalability and performance point of view. I will present two types of floating tunable coupler architectures as well as two different methods to implement two-qubit gates. I show how floating tunable couplers allow increased physical separation between qubits; making it an ideal candidate for scalability. Additionally, the two-qubit parametric resonance gate can also help reduce the incoherent errors per operation by performing the gate at its maximum speed.
I will give a side-by-side comparison of the different architectures to highlight the benefits of the proposed approaches.

4:00pm **QS-MoA-8 Quantum Device Formation in Silicon via Ion Implantation*, Jeffrey McCallum,*** School of Physics, Australia **INVITED**

Spin qubits based on impurities such as phosphorus, P, in isotopically pure silicon ^{28}Si, have attractive attributes for development of quantum computing devices.[1] Very long coherence times can be achieved for donor-based qubits when the ^{29}Si atoms, that otherwise lead to decoherence, are removed from the active region of the device. Standard semiconductor-industry ion implantation techniques can be used to fabricate well-behaved donor qubits in Si. Exceptionally long coherence times greater than 30 s have been demonstrated for nuclear spin qubits. Conditional quantum operation of a pair of exchange coupled single P-donor spin qubits in an ion implanted ^{28}Si epi-layer device has also been recently demonstrated.[2] While many key achievements have been obtained for P donor qubits in Si, other donor qubit systems such as antimony, Sb, and bismuth, Bi, are also starting to be developed and have potential to offer new degrees of freedom and new qubit control functionalities. The crucial next stage is to develop suitable scale-up pathways that allow patterned arrays of donor qubits to be controllably coupled and that are robust against the inherent donor placement tolerances and material processing constraints that exist. Here, we will review progress on the fabrication and measurement of ion implanted donor-based qubits in silicon and discuss the pathway to deterministically implanted single donor arrays with inter-donor spacings suitable for available coupling protocols.

Silicon is also an attractive platform for the development of devices that contain both superconducting and semiconducting components on a single chip for emerging quantum technologies. Recently, we have investigated superconductivity in nanowire devices fabricated using an Al-Si exchange process in silicon-on-insulator wafers.[3] The Al-exchange-transformed material is conformal with predefined device patterns. Magneto-transport measurements on nanoring structures formed by this process exhibit periodic features in the differential resistance and in the critical current resulting from fluxoid quantization. The devices can be operated in temperature/magnetic-field regimes where some components of the device are in the superconducting state while others are in resistive states. The details of the Al-Si exchange process suggest that it could allow a range of new nanoscale superconducting-semiconducting device structures to be formed. Here, we will also briefly introduce our preliminary exploration of these superconducting nanowire devices and their promise for quantum technologies development.

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4:40pm **QS-MoA-10 Quantum Technology Manufacturing Roadmap v1.0*, Jonathan Felbinger,*** SRI International

This roadmap effort, led by SRI International and its team of industry, national lab and academic partners, will identify pre-competitive development work and supply chain gaps to support scaling up quantum technology and help maintain U.S. dominance in quantum-related fields, rather than focus on scientific discovery or a specific application.

Quantum information science and technology are rapidly advancing and have potential applications in computing, sensing, communications and security. The development of quantum technology and a U.S.-based quantum industry is a key strategic priority of the U.S. government. To achieve its full potential, novel materials, devices, structures and systems must be developed and manufactured. Though still emerging, the quantum industry is taking shape, products are beginning to emerge and companies are developing internal roadmaps for more complex systems, such as error-corrected quantum computers.

To support the development of technology critical to the quantum industry, SRI and its team of industry, national lab and academic partners propose to develop a technology roadmap focused on supply chain gaps and barriers to advanced manufacturing capability. SRI currently manages the Quantum Economic Development Consortium [https://quantumconsortium.org/] (QED-C), an industry-led consortium supported by the U.S. government and 170+ industry, academic and national lab members. The mission of QED-C is to enable and grow the U.S. quantum industry and supply chain. SRI proposes to leverage ties with QED-C members to establish a separate consortium to develop the roadmap that will guide development across the emerging industry and identify the necessary manufacturing technologies and capabilities. This new consortium will include QED-C members and non-QED-C members across the stakeholder spectrum.

5:00pm **QS-MoA-11 Cryogenic Properties of Discrete Electronic Components for Use in Quantum Measurement Circuits*, Nikki Ebadollahi,*** National Institute of Standards and Technology (NIST)/ University of Maryland, College Park*; P. Shrestha,* National Institute of Standards and Technology (NIST)*; D. Krymski,* University of Maryland, College Park*; Y. Hong, E. Rissanen, J. Pomeroy,* National Institute of Standards and Technology (NIST)

The changes in transistors, capacitors and resistors when they are cooled to cryogenic temperatures are measured to enable the design and fabrication of quantum control and readout circuits. Quantum devices, and eventual quantum computers, function at cryogenic temperatures, and achieving high efficiency requires that the classical and quantum components are positioned closely together within a circuit. Before discrete classical components can be integrated into basic auxiliary circuits for a quantum system, it is essential to understand the properties of these components at 4 K. While the cold temperatures yielded predictable changes for resistor properties, capacitors and transistors underwent significant and unpredictable changes. For the capacitors, the changes in capacitance were largely dependent on the material, dielectric constant, and surface area. The dielectric constant decreases as cryogenic temperatures are reached for some materials. For some capacitors, the capacitances decreased by a factor of 20 in response to the temperature drop. For the transistors, the threshold voltage, transconductance, and transfer curves all notably changed from room temperature to 4 K. Both the threshold voltage as well as the slope of the transfer curve increased significantly at 4 K compared to the behavior at room temperature. Due to the temperature-dependent characteristics of discrete electronic components, circuits must be designed with operating parameters suited for cryogenic temperatures in order to function.

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

SiC, Diamond and Related Materials for Quantum Information Sciences

Moderators: Erin Cleveland, U.S. Naval Research Laboratory, **Cheng Gong**, University of Maryland

8:40am **QS+EM-TuM-3 Topology, Superconductivity and Unconventional Quantum Criticality in Monolayer WTe2*, Sanfeng Wu,*** Princeton University **INVITED**

Quantum critical points associated with quantum phase transitions are highly intriguing states of matter; yet they are difficult to study. An example is the superconductor to insulator or metal transition in two dimensions (2D), a topic that has a long history in condensed matter research, but many problems remain unsolved. In this talk, I will discuss our recent experimental finding of a quantum critical point in monolayer tungsten ditelluride (WTe2), a unique 2D crystal in which topology, strong correlations and superconductivity all occur in a single material. We directly measure superconducting quantum fluctuations, whose behaviors are so anomalous that an unusual explanation beyond the conventional Landau-Ginzburg-Wilson paradigm is required.

9:20am **QS+EM-TuM-5 Robust Cavity Emitter Coupled System Based on Lifetime-Limited Emission in H-BN*, Sanchaya Pandit,*** Department of Mechanical and Material Engineering, University of Nebraska - Lincoln*; Y. Wang,* Department of Electrical and Computer Engineering, University of Nebraska - Lincoln

In the field of quantum information technology, it is essential to reach a strong coupling regime, where the coupled systems exhibit quantum coherent oscillations. The ability to control the interactions between the single photon emitter and the cavity mode allows for the manipulation of the photon's quantum state, which is crucial for many quantum applications. Quantum emitters based on defect centers in hexagonal boron nitride (h-BN) have emerged as prominent light sources for integrated quantum photonic applications. Especially, the defect centers with single photon emission around 635 nm have been demonstrated to exhibit lifetime-limited linewidth even at room temperature. This work explores the monolithic integration of this type of h-BN emitters with the whispering gallery mode (WGM) in the microdisk cavity. By optimizing the cavity design, strong coupling between the emitter and cavity has been predicted analytically. Furthermore, coherent manipulation of photon based on cavity-emitter detuning, and spatial position of emitter has been explored and visualized as vacuum Rabi splitting and Rabi oscillation through the Quantum toolbox in Python (Qutip) simulation. The robust cavity design and methodology developed will provide valuable guidelines for the realization of scalable and integrated quantum photonic circuits based on h-BN defect centers.

11:00am **QS+EM-TuM-10 Collective Excitations in Topological Materials*, Stephanie Law,*** Pennsylvania State University **INVITED**

Topological insulators (TIs) are materials that have a bulk band gap crossed by surface states with linear dispersion. These surface states are present at the physical boundaries of the material, and host two-dimensional, massless electrons that are spin-momentum locked. When they couple to a photon, these electrons form the basis of Dirac plasmon polaritons (DPPs) with resonances in the THz spectral range.

In this talk, I will first discuss our efforts to grow TI materials by molecular beam epitaxy (MBE). The TI materials of interest are Bi2Se3, BixSb1-x, and MnBi2Se4. These are all two-dimensional materials, meaning that they exhibit a layered structure with van der Waals (vdW) bonding between each layer. Due to the relativley weak interlayer bonding, these materials grow by van der Waals epitaxy, which has unique opportunities and challenges. I will show our results on growing these materials on passivated substrates (e.g. Al2O3) and unpassivated substrates (e.g. GaAs and Si).

I will then discuss our efforts to excite plasmonic excitations in these materials. The frequencies of the DPPs are predicted to depend both on the wavevector of the excitation as well as on the film thickness when the film is much thinner than the wavelength of light. In this regime, a DPP is excited on the top surface and on the bottom surface of the film simultaneously. These excitations couple, leading to an acoustic and an optical mode. By mapping this relationship, we have shown conclusively that we are able to excite DPPs in TI thin films. These resonances have mode indices of a few hundred, much higher than what is observed in traditional plasmonic systems, implying that light is strongly confined in these materials. We attribute the large mode index to the fact that we are exciting a coupled optical mode and that the bulk permittivity of the TI is also large. Unlike most materials, the large mode index does not lead to a decrease in lifetime. Instead, the lifetime of the mode determined by the full width at half maximum is a few hundred femtoseconds. We attribute this relatively long lifetime to the spin-momentum locking of the surface state electrons, which reduces their probability of scatting. We have also demonstrated coupling of the DPPs in the plane using a stripe array as well as coupling out of plane by growing a layered structure. Finally, we have created a multilayer structure comprising alternating layers of a TI and a normal insulator, leading to a Dirac hyperbolic metamaterial in the THz.

11:40am **QS+EM-TuM-12 Novel Particles in 2D Materials Detected with Quantum Interference and Raman.*, Kenneth Burch,*** Boston College **INVITED**

The pursuit of new quasi-particles is driven by the quest to uncover novel phases of matter, emergent phenomena. These may also serve as a foundation for future technological innovations. In this presentation, I will elaborate on our utilization of Raman spectroscopy to identify emergent particles in 2D materials. Firstly, I will delve into our endeavors to identify fractional spin excitations in RuCl3. Subsequently, I will highlight our recent breakthrough in discovering the Axial Higgs mode, which results from Quantum Geometry and a charge density wave. This discovery was facilitated by Raman's unique ability to detect the particle's symmetry and employ quantum interference to unveil its Axial properties.

Quantum Science and Technology Mini-Symposium
Room B110-112 - Session QS+SS-TuA

The Quantum Metrology Revolution

Moderators: Luxherta Buzi, IBM, **Petra Reinke**, University of Virginia

2:20pm **QS+SS-TuA-1** ***Quantum Sensing Enabled by Spin Qubits in Diamond*** ***, Fedor Jelezko,*** Institute of Quantum Optics, Ulm University, Germany **INVITED**

Synthetic diamond has recently emerged as a candidate material for a range of quantum-based applications including quantum information processing and quantum sensing. In this presentation we will show how single nitrogen-vacancy (NV) colour centres can be created with a few nanometers accuracy and coherent dipole-dipole coupling was employed to generate their entanglement. Single NV centers and clusters of entangled spins created close to the diamond surface can be employed as nanoscale sensors of electric and magnetic fields. We will show nanoscale NMR enabled by single NV centers and discuss sensitivity and spectral resolution limits of nanoscale NMR. We will also discuss applications of NV centres for hyperpolarization of nuclear spins and application of optical spin polarization in MRI.

3:00pm **QS+SS-TuA-3 Tunneling Andreev Reflection - New Quantitative Microscopy of Superconductors with Atomic Resolution***, W. Ko,* University of Tennessee Knoxville*; S. Song, J. Yan,* Oak Ridge National Laboratory*; C. Lane,* Los Alamos National Laboratory*; J. Lado,* Aalto University, Finland*;* ***Petro Maksymovych,*** Oak Ridge Natinal Laboratory

Andreev reflection is an established method to probe the existence of superconductivity, and, crucially, the symmetry of the superconducting order parameter. In its conventional implementation of the point contact Andreev reflection (PCAR), the technique relies on so-called directional contacts, which inject quasiparticles into superconductors with well-defined momentum. However, good momentum resolution requires a trade-off for essentially no spatial resolution, which has limited the applicability of PCAR to atomic-scale properties of superconductors, including inhomogeneities and interfaces.

In this talk, we will present our latest developments in Tunneling Andreev Reflection - a new experimental approach which we recently introduced to quantify Andreev reflection through atomic-scale tunnel junction [1]. Similar to PCAR, TAR exhibits direct sensitivity to the superconducting order parameter in both conventional and unconventional superconductors [2]. Recently, we used TAR to unambiguously confirm the sign-changing order parameter in paradigmatic FeSe, and further revealed suppression of superconductivity along the nematic twin boundaries above 1.2 K [2]. Locally suppressed superconductivity, in turn, explains the peculiar vortex templating effect exerted by twin boundaries - essentially causing recrystallization of the vortex glass phase [3]. However, due to atomic-spatial resolution TAR lacks momentum resolution - the opposite of PCAR. Therefore, the measurements, observables and their interpretation are fundamentally distinct from PCAR as well. We will discuss our present understanding of this technique, relevant methods of data analysis needed to reveal Andreev signal, and specific effects of band structure on TAR. These effects are crucially important for robust characterization of unconventional superconductivity, while also enabling TAR to complement tunneling spectroscopy and quasiparticle imaging in search for exotic quantum materials. Research sponsored by Division of Materials Science and Engineering, Basic Energy Sciences, Office of Science, US Department of Energy. SPM experiments were carried out as part of a user project at the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, a US Department of Energy Office of Science User Facility.

1. W. Ko, J. Lado, P. Maksymovych, *Nano Lett.*22 (2022) 4042.

2. W. Ko, S. Y. Song, J. Lado, P. Maksymovych, arXiv:2303.05301 [https://arxiv.org/abs/2303.05301] .

3. S. Y. Song, C. Hua, L. Bell, W. Ko, H. Fangohr, J. Yan, G. B. Halász, E. F. Dumitrescu, B. J. Lawrie, P. Maksymovych, *Nano Lett.*23(2023)2822.

3:20pm **QS+SS-TuA-4 Patterned-Stress-Induced Compositional Manipulation of Epitaxially Grown Semiconductors for Quantum Applications***,* ***Leonid Miroshnik,*** University of New Mexico*; B. Rummel,* Sandia National Laboratories*; M. Patriotis,* University of New Mexico*; A. Li, T. Sinno,* University of Pennsylvania*; M. Henry,* Sandia National Laboratories*; G. Balakrishnan, S. Han,* University of New Mexico

We have previously demonstrated compositional patterning of epitaxially grown compound semiconductors, using lithographically patterned nanoscale pillars as a mechanical press.[1-3] The elastically introduced strain from the press, at elevated temperatures, steers large atoms out of the compressed region of compound semiconductors (e.g., indium in InGaAs) to form quantum confined structures. This approach allows forming quantum structures at desired locations in an addressable manner. In this work, we describe a new approach to introduce a patterned stress field to semiconductor films, using Surface Acoustic Waves (SAW) generated by Interdigitated transducers (IDTs). We fabricate SAW devices on GaAs(100) substrate and demonstrate that we can image standing surface acoustic waves using 2D Raman spectroscopy as well as atomic force microscopy.[4] The magnitude of these waves, upon optimization of SAW devices[5], reaches greater than 5 nm, introducing 100s of MPa stress. We will share the stress characterization and optimization approach in this presentation and assess the likelihood of using the stress field to induce compositional patterning.

This material is based upon work supported by the National Science Foundation under Grant No. DMR-1809095

1. S. Ghosh, D. Kaiser, J. Bonilla, T. Sinno, and S. M. Han, "Stress-Directed Compositional Patterning of SiGe Substrates for Lateral Quantum Barrier Manipulation," *Applied Physics Letters***107,** 072106-1:5 (2015)

2. D. Kaiser, S. Ghosh, S. M. Han, and T. Sinno, "Modeling and simulation of compositional engineering in SiGe films using patterned stress fields," *Molecular Systems Design and Engineering***1,** 74-85 (2016)

3. D. Kaiser, S. Ghosh, S. M. Han, and T. Sinno, "Multiscale Modeling of Stress-Mediated Compostional Patterning in SiGe Substrates," *High Purity and High Mobility Semiconductors***75,** 129-141 (2016)

4. B. D. Rummel, L. Miroshnik, M. Patriotis, A. Li, T. R. Sinno, M. D. Henry, G. Balakrishnan, and S. M. Han, "Imaging of surface acoustic waves on GaAs using 2D confocal Raman microscopy and atomic force microscopy," *Applied Physics Letters***118,** 031602-1:6 (2021) https://doi.org/10.1063/5.0034572.

5. B. D. Rummel, L. Miroshnik, A. B. Li, G. D. Heilman, G. Balakrishnan, T. Sinno, and S. M. Han, "Exploring electromechanical utility of GaAs interdigitated transducers; using finite-elementmethod-based parametric analysis and experimental comparison," *Journal of Vacuum Science & Technology B***41,** 013203-1:8 (2023) https://doi.org/10.1116/6.0002169.

4:20pm **QS+SS-TuA-7 Atomic Tunneling Defects in Superconducting Quantum Circuits: Origins and Remedies***,* ***Jürgen Lisenfeld,*** Karlsruhe Institute of Technology (KIT), Germany **INVITED**

Parasitic two-level systems formed by defects in the materials of superconducting qubits are a major source of decoherence. I will review the defects' origins, and discuss possible ways to mitigate their detrimental impacts. A focus will be set on recent experiments in Karlsruhe, where we develop novel methods to in-situ control defect properties by applied mechanical strain and electric fields. E-field tuning of defects provides a possibility to mitigate energy loss of qubits due to resonant defects. It also allows us to identify the locations of defects in a given quantum circuit which helps to guide the way towards better qubit fabrication.

5:00pm **QS+SS-TuA-9 Mechanistic Investigations of Superconducting Film Growth: Substrate-Mediated Sn Diffusion on a Niobium Oxide***,* ***Sarah Willson,*** University of Chicago*; R. Farber,* University of Kansas*; S. Sibener,* University of Chicago

Niobium is the highest temperature elemental superconductor, making it the standard material for superconducting radiofrequency (SRF) cavities in next-generation linear accelerators. These facilities require cryogenic operating temperatures (< 4 K) to limit the formation of superconductivity-quenching hot spots in the near-surface region of the cavity. Widespread efforts are underway to increase the accelerating fields and reduce the cryogenic burden by improving SRF surfaces.

A promising solution is to coat the Nb SRF surface with a Nb_3Sn thin film *via* Sn vapor deposition. The higher critical temperature and critical field makes Nb_3Sn an ideal candidate for capping Nb surfaces. However, the persistence of defects, stoichiometric inhomogeneities, and excessive surface roughness in formed these Nb_3Sn films nucleate quenching sites – limiting the SRF performance.

As part of a widespread interdisciplinary effort to optimize SRF accelerating capabilities, this work aims to develop a comprehensive growth model for pristine Nb_3Sn films. We aim to understand the interplay between the underlying Nb oxide morphology, Sn coverage, and Nb deposition temperature on Sn wettability and Nb_3Sn growth mechanisms. Alloy films are grown on single crystal and polycrystalline Nb surfaces terminated with a diverse range of morphologies and analyzed using both *in situ* and *ex situ* techniques.

Characterization of initial Sn/Nb_xO_y phases provide insight towards the dynamic and reactive interface that templates Nb_3Sn films. Complementary experiments of Nb_3Sn films grown at higher Sn coverages further illustrate how the diverse underlying Nb oxide surface morphologies impact the quality, and ultimately the accelerating performance, of these SRF surfaces.

5:20pm **QS+SS-TuA-10 Revealing Pairing Symmetry of Superconductors by Tunneling Andreev Reflection***, **Wonhee Ko,*** University of Tennessee, Knoxville*; S. Song, J. Yan,* Oak Ridge National Laboratory*; J. Lado,* Aalto University, Finland*; P. Maksymovych,* Oak Ridge National Laboratory

Andreev reflection (AR) is an electronic transport process at the junction of a normal metal and a superconductor, where the electrons in the normal metal transform to the Cooper pairs by retroreflecting holes and conducts current across the junction. The process is highly sensitive to the superconducting order parameters and functions as a tool to directly probe the superconductivity. Based on AR, we developed a new technique, tunneling Andreev reflection (TAR), by applying AR to the tunnel junction in scanning tunneling microscope (STM) [1,2]. Specifically, we precisely tune the STM tip-sample distance to systematically study the AR as a function of the tunneling barrier height. Since the AR is a higher order tunneling process compared to the normal electron tunneling, the relative decay rate of the tunneling conductance increases inside the superconducting gap, whose specific shape depends on the nature of the superconductivity [3]. By comparing the decay rate spectra with the theoretical calculations, we identify the pairing symmetry of various kinds of superconductors, from conventional s-wave ones to the unconventional high-T_c ones such as iron-based or cuprate superconductors.

This research was performed at the Center for Nanophase Materials Sciences which is a DOE Office of Science User Facility.

[1] W. Ko, E. Dumitrescu, and P. Maksymovych, *Phys. Rev. Res.***3** 033248 (2021)

[2] W. Ko, J. L. Lado, and P. Maksymovych, *Nano Lett.***22** 4042 (2022)

[3] W. Ko, S. Y. Song, J. Yan, J. L. Lado, and P. Maksymovych, *arXiv:*2303.05301

5:40pm **QS+SS-TuA-11 Single-nm-Resolution Gate Fabrication for Top-Gated Quantum Dot Qubits***, J. Owen,* ***Joshua Ballard,*** *E. Fuchs, J. Randall,* Zyvex Labs*; F. Beaudoin,* Nanoacademic Technologies, Canada*; A. Sigillito,* U. Pennsylvania

Top gated semiconductor quantum dot qubits represent an attractive path to quantum computing. However, variations in the physical dimensions of the top gates create significant variations in the electrostatic confinement and therefore the energy levels in the qubit. The variation in gate dimensions complicates the design of multi qubit systems and the required tuning of the biases on the gates for multiple qubits is so complex that machine learning is employed.

Multiple modeling runs of a generic top gated multi-qubit system carried out with the spin-qubit computer-aided design tool QTCAD has found that a variation in the gate dimensions of ~2 nm causes a factor of 2 change in the tunneling rates, or a factor of 4 in the Exchange Interaction strength. This level of precision is not achievable using e-beam lithography where the proximity can cause an increase in the written feature width by 15 nm compared to the pattern.

We describe an alternative path which uses Atomic Precision Lithography[1] to create far more precise gates. Two methods to transfer the pattern into the gate structures are described; either saturate the patterns with dopant precursors to make dopant-based gate structures or growing area-selective etch mask material. The former will preserve the precision, but is less compatible with CMOS processes. Otherwise, area-selective atomic layer deposition and reactive ion etching can be used to make nanoimprint templates[2]. The accuracy of templates thus produced, and the precision of Jet and Flash Nanoimprint lithography will produce far more uniform top gates with a scalable manufacturing technique.

1. Bussmann, E.; Butera, R. E.; Owen, J. H. G.; Randall, J. N.; Rinaldi, S. M.; Baczewski, A. D.; Misra, S. Atomic – Precision Advanced Manufacturing for Si Quantum Computing. *MRS Bull.***2021**, *46*, 1–9.

2. Ballard, J.; McDonnell, S.; Dick, D.; Owen, J.; Mordi, G.; Azcatl, A.; Campbell, P.; Chabal, Y.; Randall, J.; Wallace, R., Patterned atomic layer deposition on scanning tunneling microscope constructed templates. *Technical Proceedings of the 2013 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2013* **2013,***2*, 481-484.

6:00pm **QS+SS-TuA-12 The Changing Role of National Metrology Institute with Quantum-Based Standards and the Nist on a Chip Program***, **Jay Hendricks**, B. Goldstein,* NIST

This oral presentation covers a bit of metrology history of how we got to where we are today and gives a forward-looking vision for the future of measurement science.The role of NIST as a National Metrology institute (NMI) is briefly described considering the world-wide redefinition of units that occurred on May 20th, 2019.The re-definition of units is now aligned with physical constants of nature and fundamental physics which opens new realization routes with quantum-based sensors and standards. The NIST on a Chip program (NOAC) is briefly introduced in this context.The re-definition of the SI units enables new ways to realize the units for the pascal and the kelvin.These quantum-based systems; however exciting, do raise new challenges and several important questions: Can these new realizations enable the size and scale of the realization to be miniaturized to the point where it can be imbedded into everyday products?What will be the role of metrology institutes in the is new ecosystem of metrology and measurement?What will be the NMI role for quality systems and measurement assurance for these new quantum-based systems? This talk will begin to explore these important philosophical questions.

Quantum Science and Technology Mini-Symposium
Room B110-112 - Session QS+VT-WeM

Vacuum Technology for Quantum Applications

Moderators: Ekta Bhatia, NY CREATES, **Freek Molkenboer**, TNO Science and Industry, the Netherlands

9:20am **QS+VT-WeM-5 Stand-Alone Vacuum Cells for Compact Ultracold Quantum Technologies***, **Oliver Burrow**, A. Arnold, P. Griffin, E. Riis,* University of Strathclyde, UK **INVITED**

Compact vacuum systems are key enabling components for cold atom technologies, facilitating extremely accurate sensing applications. There has been important progress toward a truly portable compact vacuum system; however, size, weight, and power consumption can be prohibitively large, optical access may be limited, and active pumping is often required. We have been developing centilitre-scale vacuum chambers with He-impermeable viewports and an integrated diffractive optic, enabling robust laser cooling with light from a single polarization-maintaining fibre. With these devices, a cold atom demonstrator based on the vacuum cell delivers 107 laser-cooled 87Rb atoms per second, using minimal electrical power.

Pressure measurements in these compact systems are made from cold-atom loading curves, and pressure evolution have been studied in a ceramic based vacuum chamber. With continuous Rb gas emission, active pumping yields a 10−7 mbar equilibrium pressure, and passive pumping stabilizes to 3×10−6 mbar with a 17 day time constant. With no Rb dispensing and only passive pumping, a ceramic based vacuum chamber has currently kept a similar pressure for more than 500 days. The passive-pumping vacuum lifetime is several years, which is estimated from short-term He throughput with many foreseeable improvements.

Progress is also reported, including new cell materials, mobile cold-atom demonstration and adaptation of the fabrication technique into a cold-atom gravimeter vacuum system. This technology enables wide-ranging mobilization of ultracold quantum metrology.

Oliver S. Burrow, Paul F. Osborn, Edward Boughton, Francesco Mirando, David P. Burt, Paul F. Griffin, Aidan S. Arnold, Erling Riis; Stand-alone vacuum cell for compact ultracold quantum technologies. Appl. Phys. Lett. 20 September 2021; 119 (12): 124002. https://doi.org/10.1063/5.0061010

11:00am **QS+VT-WeM-10 Hybrid Quantum-HPC Computing Clouds in Europe***, **Richard Versluis**,* TNO Science and Industry, the Netherlands **INVITED**

Quantum computing technology holds great promises for the long future but requires large investments in the near future as an enabler. Not only in terms of money and human resources such as talent, but also in infrastructure. This ranges from clean room infrastructure for QPU development, such as dedicated processing lines for quantum chip development to dedicated software and testing equipment for the screening and validation of quantum chips, to full stack system prototypes to demonstrate and validate crucial interfaces, but also to enable early adaptors to start implementing and exploring the potential of these new compute paradigms. Since a couple of years, some full stack demonstrators have been built, some in-house in a lab environment and some in an environment that is already a bit more market-orientated, such as a private cloud or a public cloud. Notably, some US companies like IBM, Google, Rigetti, IonQ and the Canadian company Dwave have set standards for online access to quantum computers. In Europe, the first publicly available cloud service for quantum computing, giving access to European quantum computers was Quantum Inspire, implemented by QuTech in The Netherlands. Since its launch in 2020, more online quantum computers have been launched in Europe, such as Quandela cloud.

With the necessity to get the most out of these early systems, hosting QPU's with still noisy and small numbers of qubits, a connection to HPC systems is crucial. It is anticipated that early advantage will be reached by combing classical and quantum algorithms, where the QPU could outperform an HC on some specific tasks, such as efficiency of the calculation in terms of wall clock time or energy used, the accuracy of the calculation, or simply by providing a different method of calculation that could not be done with a classical system. Integration of these, relatively immature systems, in an HPC workflow requires quite some effort. First of all, the language used to program quantum computers cannot be compared to high level classical programming languages like Python, C++, Rust etc. Secondly the integration of (runtime) compilers in the workflow is non-trivial. Hybrid classicll-quantum algorithms, therefore require systems that can handle multiple languages, compiler services. Thirdly, the workflow management is not-standard: where the integration of classical accelerators like GPU's is based on standard-predefined interfaces such as scrum, these workflow interfaces for QPUs have not been defined yet.

In this talk I will highlight the goals and some first results of European activities on the integration of HPC and Quantum Computers in European projects such as the EuroHPC projects, OpenSuperQ plus and Quantum Large Scale Integration.

11:40am **QS+VT-WeM-12 Design Considerations of an XHV System for an Ion Trap Quantum Computer***, **Paul Smith**, N. Burch, A. Chew, P. Jones, P. Lamb, E. Lucchetta, S. Lodge, P. Milner,* Edwards Ltd, UK*; D. Clement, T. Sinha,* Gamma Vacuum*; A. Abolghasemi, L. Earl, J. Randall,* Universal Quantum, UK

The design and configuration of an XHV system for an ion trap quantum computer is presented. A target operating pressure of 10^{-12} mbar has been identified to increase ion lifetime. Contributions to the residual gas load from leaks, permeation and outgassing will be evaluated as will the pumping strategies employed for each. The relative pumping performance of two combined NEG-IGP pumps will be reported. Other factors will be discussed including conductance optimization, limitations on component bakeout and NEG activation temperatures, vibrations, and shielding of magnetic fields and radiant heat loads.

12:00pm **QS+VT-WeM-13 Chances and Challenges: Aluminum Vacuum Components for Quantum Technology***, **Stefan Kiesel**, A. Trützschler, J. Hertel, K. Bergner,* VACOM Vakuum Komponenten & Messtechnik GmbH, Germany

Quantum technology currently experiences a huge push towards commercialization, since it promises a variety of attractive applications, including quantum sensors, quantum computers, and quantum clocks. Many of these systems require a vacuum to isolate quantum objects or devices from the surrounding environment and to create stable conditions. In addition, signal paths into the vacuum are necessary to manipulate quantum objects, facilitated by hermetically sealed electrical and optical feedthroughs. The most advanced modern systems are built up from large and expensive laboratory equipment. However, the needs of commercially usable applications drive the development of quantum systems towards transportable, durable, and standardized solutions. To meet these challenging demands, better materials, novel manufacturing technologies and innovative designs are issues of today's development projects. As an example, aluminum Con-Flat (CF) components offer the possibility of providing customized solutions with high geometrical accuracy, reduced weight, low outgassing rates as well as vanishing magnetic permeability. As a manufacturer of vacuum components, VACOM is actively collaborating in several publicly funded projects to promote the development of quantum technology. In this talk we show goals and results of these projects regarding the development of vacuum systems and vacuum components for quantum technology.

Thin Film Division
Room A105 - Session TF+QS-WeA
Thin Films for Space and Electronic Applications

Moderators: John Hennessy, Jet Propulsion Laboratory, **Richard Vanfleet**, Brigham Young University

2:20pm **TF+QS-WeA-1 From Space Thrusters to Exoplanets Research*****, Christine Charles****, R. Boswell, M. Davoodianidalik, J. Machacek, D. Tsifakis, M. Shadwell, H. Punzmann,* Australian National University, Australia*; K. Takahashi,* Tohoku University, Japan*; J. Lecomte, N. Suas-David, L. Rutkowski, E. Dudas, A. Benidar,* Université de Rennes, France*; S. Kassi,* Université de Grenoble-Alpes, France*; R. Georges,* Université de Rennes, France*; N. Smith, P. Tesch,* Oregon Physics **INVITED**

Thousands of nano and micro-satellites are expected to be launched over the next decade, many in constellations, and rideshare opportunities are increasing. The Space Plasma, Power and Propulsion (SP3) laboratory works on a range of projects dealing with fundamental physics in astrophysical plasmas (infrared spectroscopy of exoplanet atmosphere) as well as physics and engineering challenges related to space propulsion systems (geometric and plasma nozzles, the "Bogong" Naphthalene cold gas thrusters). The scalability in geometry and power of radiofrequency plasma devices has allowed the development of a range of electrodeless thrusters such as the low pressure (~1 mTorr) Helicon thruster and the higher pressure (~1 Torr) Pocket Rocket thruster. These have yet to be flown but have surprisingly been wonderful training platforms and opened doors to new areas of research. Expanding nearly collisionless plasmas (i.e. Helicon thrusters) can be used to investigate out-of-equilibrium thermodynamics via polytropic index studies both in the laboratory and in space. Expanding collisional plasmas (i.e. Pocket Rocket thruster) can be used to investigate plasma fluid flows in nozzle. As an example, the development of the Pocket Rocket thruster into a laminar nozzle capable of producing high vibrational temperatures for molecular gases, "Platypus", was carried out for implementation onto the SMAUG exoplanet research apparatus (Spectroscopy of Molecules Accelerated in Uniform Gas flows) which produces non-LTE (Local Thermodynamic Equilibrium) spectra of various molecules characterised using cavity ringdown spectroscopy yielding successful acquisition of absorption spectra in the infrared using naphthalene/argon plasmas. Naphthalene is also our propellant of choice for the cost-effective green and safe "Bogong" thruster, co-developed by Boswell Technologies and SP3, fully space qualified and deployed in Low Earth Orbit on the 4th of January 2023 by a Space X Falcon 9 rocket (Transporter-6 Mission, 300 kg Skykraft satellite stack).Similar radiofrequency plasma technologies are used for our various thruster concepts and for our focused ion beam (FIB) studies using the Hyperion source developed by Oregon Physics. The use of such FIB applies to materials characterisation, forensic studies and bio-medical applications. SP3 is collaborating with Oregon Physics to develop an O_3^- negative ion source. It is interesting that the mature ion gridded thruster technology (in operation on many commercial satellites including the deep space Bepi Colombo spacecraft on its way to Mercury) share technical similarities with focused ion beam sources.

3:00pm **TF+QS-WeA-3 Photodegradation of Self-Immolating Polymers as a Potential Solution to Optical Scattering*****, Alexandra Stapley****, S. McFarland, J. Vawdrey, K. Mitchell, W. Paxton, D. Allred,* Brigham Young University

Starshades and other optical devices that are sensitive to scattered light require dust mitigation techniques to provide low-scatter surfaces and edges. Poly(olefine) sulfones have been shown to photodegrade with the assistance of a photobase generator when exposed to deep UV light (254 nm) and heat (120°C). These may be applicable in minimizing dust on optical surfaces for space applications. Their behavior in vacuum was not investigated, however. We synthesized Poly(2-methyl 1-pentene) sulfone (PMPS) and Poly(1-hexene) sulfone (PHS) with and without a photobase generator. We studied the photodegradation (172 nm or 254 nm) of thin films in vacuum. Spectroscopic ellipsometry was used to quantify film thickness over time. The PMPS film with photobase generator fully degraded when exposed to 172 nm light in vacuum. A significant finding was that heat was not required to produce this result. PMPS film degradation without the photobase generator was slower and incomplete. The results of our PHS studies are also promising. This study shows that a PMPS film could potentially be used to protect optical surfaces until their deployment in space.

3:20pm **TF+QS-WeA-4 Enhancement of the Bifacial Absorber of Silver Antimony Sulfur Selenide Photovoltaic Devices*****, Sanghyun Lee,*** University of Kentucky*; M. McInerney,* Rose-Hulman Institute of Technology

Silver Antimony Sulfur Selenide, $AgSb(S_xSe_{1-x})_3$ thin-film solar cells have promising properties such as tunable bandgap (0.7 - 1.9 eV), good doping concentration (10^{16} cm^{-3}), and high absorption coefficient (>10^4 cm^{-1}). The efficiency of $AgSb(S_xSe_{1-x})_3$ thin-films with x=0.53, 0.58, and 0.61 has been studied with >2.77 %. Since Antimony Sulfur Selenide, $Sb(S_xSe_{1-x})_3$thin-films have shown good optical and electronic properties as an absorber layer, further optimization of thin-film absorber layers could be achieved by utilizing both $Sb(S_xSe_{1-x})_3$ and $AgSb(S_xSe_{1-x})_3$ thin-films for bifacial devices. Furthermore, substituting Ag in $Sb(S_xSe_{1-x})_3$ thin-films tends to increase the bandgap of the absorber layer by lowering the valence band based on studies of other thin-film absorber layers (CIGS, CZTSSe).

In this contribution, we have theoretically studied bifacial photovoltaic devices by combining thin-film absorbers of $AgSb(S_xSe_{1-x})_3$, $Sb(S_xSe_{1-x})_3$, and the combination of $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films from the electronic band structure perspective. To fully utilize the promising properties of both $Sb_2(S_xSe_{1-x})_3$ and $AgSb(S_xSe_{1-x})_3$ films, we investigated different compositions and concentrations of Sulfur and Selenium with proposed empirical equations for electron affinity and bandgap energy through modeling and simulations.

Four different structures of thin-film absorbers have been studied above Molybdenum metal thin-films. For both $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films, the electron affinity and bandgap energy increase as Sulfur (x) composition increases. However, the increased bandgap is not directly translated into improved solar cells efficiency due to the alignment of thin-film electronic structures. The best efficiency was achieved with 2 um $AgSb(S_{0.4}Se_{0.6})_3$ thin-film devices(18.4 %) at sulfur concentration, x = 0.4. However, once we combine two $AgSb(S_xSe_{1-x})_3$ and $Sb(S_xSe_{1-x})_3$ thin-films while keeping a total thickness, 2 um (1 um/1 um), an interface between $AgSb(S_{0.4}Se_{0.6})_3$/ $Sb_2(S_{0.4}Se_{0.6})_3$ and Molybdenum metal thin-films is preferably formed due to reduced effective Schottky hole barrier. If we assume the same amount of defect states at the interface, the improved effective Schottky hole barrier is 128 mV due to the favorable band alignment, which is approximate 4.3 times better than a $AgSb(S_{0.4}Se_{0.6})_3$ thin-film structure. With a bi-layer $AgSb(S_{0.4}Se_{0.6})_3/Sb_2(S_{0.4}Se_{0.6})_3$ thin-film absorber, we studied various doping concentrations impact on device efficiency based on the modified electronic band structure of each thin-film. The doping concentration of $AgSb(S_{0.4}Se_{0.6})_3$ thin-film mainly increases the photogenerated current while $Sb_2(S_{0.4}Se_{0.6})_3$ thin-film improves open circuit voltage.

4:20pm **TF+QS-WeA-7 Atomic Scale Processing and Surface Engineering to Maximize Microdevice Performance for Remote Sensing and Imaging Applications*****, Frank Greer,*** Jet Propulsion Laboratory (NASA/JPL) **INVITED**

Future UV, X-ray, infrared, and sub-millimeter telescopes and spectrometers have the potential to revolutionize our understanding of the formation and habitability of the modern universe, Earth, and other planetary bodies.[1-4] Star formation, dark energy, and the composition of the intergalactic medium are only some of the key scientific topics that can be addressed by UV astronomy and astrophysics. Sub-millimeter astronomy can probe the fine structure of the cosmic microwave background, giving glimpses into the early universe immediately following the Big Bang.[5] Remote observation in the infrared is critically important for the understanding of many aspects of Earth Science and Exoplanet atmospheres.

Unfortunately, harnessing the full potential of these missions is often constrained by performance of the available detectors and optical elements (the eyes of the instruments) that make the measurements and take the images. The limitations of these key components are frequently due to non-idealities in the materials and interfaces that are imbedded in or form these devices. Thus, the state-of-the art in materials science, thin films, and semiconductor processing can limit what we can know and learn because it constrains what we can "see". To improve our ability to "see" (by making new types of observations or observations with greater sensitivity), effort is required to improve the specialized materials that impact space-based instruments.

While bulk materials are important, many of the critical challenges in materials science for space applications occur at the nanoscale. Nanoscale coatings deposited by techniques such as atomic layer deposition (ALD) can be used in a variety of ways, including, but not limited to: anti-reflective coatings for UV detectors, passivation layers for infrared detectors, wiring layers in superconducting circuits, or superconducting sensing elements.Nanoscale surface engineering through atomic scale processes can substantially improve the optoelectronic properties of III-V sensors and optical elements such waveguides, especially in shorter wavelength ranges where surface roughness is particularly important.

This presentation will detail the fundamental materials science, surface engineering, and ALD/ALE approaches we have used in the fabrication of a variety of devices in multiple different wavelength ranges, demonstrating the boost in performance that is obtained with atomic level precision at key steps in the fabrication process.

[1]Barth, C. A. *Appl. Optics* 8, 1295, (1969).

[2]Hendrix, A. R., et al. *Icarus* 206, 608-617, (2010).

[3]Nicastro, F., et al. *Science* 319, 55-57, (2008).

[4]Martin, D. C. et al. *Nature* 448, 780-783, (2007).

[5]de Bernardis, P. et al. *Nature* 404, 955-959, (2000).

5:00pm **TF+QS-WeA-9 Advances in Plasma-Based Atomic Layer Processing of AlF_3 for the Passivation of FUV Mirrors***, **Virginia Wheeler**, D. Boris,* US Naval Research Laboratory*; L. Rodriguez de Marcos, J. del Hoyo,* NASA Goddard Space Flight Center*; N. Nepal, A. Lang, M. Sales, S. Walton,* US Naval Research Laboratory*; E. Wollack, M. Quijada,* NASA Goddard Space Flight Center

Efficient ultraviolet mirrors are essential components for UV astronomy. While aluminum mirrors with fluoride-based passivation layers are commonly used in this application space due to their proven stability and reliability, the optical performance is still insufficient for systems where several reflections are required. In previous work, we demonstrated the feasibility of a new, room temperature plasma process based on electron beam-generated plasma in a benign SF_6 environment to simultaneously remove the native oxide and form an AlF3 layer with tunable thickness [1]. This process has been used to demonstrate Al-mirrors with high FUV reflectivity ($R\approx90\%$ at $\lambda=121$nm), large area uniformity of the fluoride coating layer, low coating-induced polarization aberration, and improved durability. Plasma-enhanced atomic layer deposition (PEALD) is a known low temperature, highly conformal coating process which has previously been shown to produce AlF3 films [2], though little has been reported on their performance in FUV applications. In this work, we focus on optimizing PEALD AlF3 films and compare both the materials properties as well as the FUV performance with those produced through self-fluorination electron beam generated plasma process.

PEALD AlF3 films were deposited using trimethylaluminum and SF_6 plasma precursors in a Veeco Fiji G2 reactor equipped with a turbo pump and substrate biasing. This reactor has also been customized to include a similar planar electron beam generated plasma if required to etch the native oxide from substrates prior to deposition of AlF3 films. ALD windows were optimized using an *in situ* ellipsometer to monitor the growth rate directly on Al substrates and supplemented with post-deposition x-ray photoelectron spectroscopy and atomic force microscopy to elucidate process-structure-property relationships. Plasma diagnostics, including optical emission spectroscopy and Langmuir probe measurements, were also conducted on the reactor to correlate plasma properties, such as fluence and ion energy, to resulting film properties. Initial plasma characterization showed that there was high atomic fluorine present at the substrate surface using a 1:1 Ar/SF6 plasma at 10mTorr but that this concentration was slightly reduced from that measured within the remote ICP plasma. Additionally, it was found that the fluorine density within the plasma increases linearly with SF6 flow fraction and RF power but only subtle differences were seen with increasing pressure. The influence of these parameters on the AlF3/Al interface and FUV performance will also be discussed.

[1] L.V. Rodriguez de Marcos, et al. Opt. Mater. Express 11, 740-756 (2021)

[2] M.F.J. Vos, Appl. Phys. Lett. 111, 113105 (2017)

5:20pm **TF+QS-WeA-10 Thin Film Processes for UV Detector Technologies for Next Generation NASA Missions***, **Robin Rodríguez**, A. Jewell, J. Hennessy, M. Hoenk, T. Jones, S. Nikzad,* Jet Propulsion Laboratory (NASA/JPL)

Galileo was the first deep space mission to fly a silicon charge-coupled device (CCD) for imaging; since then, silicon-based photodetectors have been used for imaging and/or spectroscopy on nearly every NASA mission. JPL's Advanced Detectors and Nanomaterials Group utilizes thin-film processing and nanoscale interface engineering methods to fabricate advanced detector technologies with improved stability and sensitivity. Our research is largely focused on the use of molecular beam epitaxy (MBE) for band structure engineering and passivation of silicon-based photodetectors. Developments in recent years has been geared toward wafer-scale processing as well as improving the space worthiness of MBE-passivated detectors. We also use atomic layer deposition (ALD) processes to engineer new coatings for advanced optics or detectors, including the customization of detector response over a broad wavelength range. The performance objectives for our technologies are defined to meet the objectives of a variety of NASA research programs with the ultimate goal of flight instrument and mission infusion. This presentation will provide an overview of recent advances in detector optimization for ultraviolet (UV) imaging and spectroscopy applications.

5:40pm **TF+QS-WeA-11 Commercializing Nanowire LEDs***, **David Laleyan**, B. Le, G. Frolov,* NS Nanotech Canada*; M. Stevenson, S. Coe-Sullivan,* NS Nanotech

MicroLED display technology consists of many carefully arranged microscopic light-emitting diodes (LEDs) to directly create color pixels. MicroLED displays thus have the potential brightness, efficiency, and response time of inorganic LEDs, but suffer from the high cost of epitaxy, as well as the challenges of creating red, green, and blue emitters on a single material and substrate. Furthermore, conventional approaches of growing planar LEDs and then etching them into micron-scale devices cause a fundamental loss of efficiency, especially for the smallest devices. In this regard, nanowire-based LEDs for microLED applications have been of great interest and a topic of extensive research for over a decade. This is due to their unique ability to maintain high efficiencies as the LED size becomes quite small, even into the sub-micron regime, contrary to conventional thin-film LEDs. Another valuable benefit is the ability to form photonic crystal arrangements, such that the formation of a photonic bandgap leads to highly directional and narrow bandwidth emission. Most recently, reports have shown nanowire LEDs in the green with >25% external quantum efficiency (EQE) and red with >8% EQE, competitive with the best direct green and InGaN red LEDs ever fabricated – despite being sub-micron in size.

These structures were obtained by molecular beam epitaxy (MBE) using a selective area epitaxy (SAE) technique, where nanostructures can be controllably grown on a thin-film template. Novel development and engineering efforts are required for such nanowire LEDs to become commercially viable. This work presents a pathway towards the wafer-scale production of nanowire LEDs for displays. This talk will explain how breakthrough academic research can be made manufacturable by studying run-to-run variability, understanding the process windows, targeting yield-limiting steps, and ensuring process scalability. Focusing on the reproducibility and uniformity of nanowire growth by SAE is the first critical step toward the large-scale deployment of these highly efficient LED that are perfectly suited for the next generation of microLED displays.

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