MEMS and NEMS Technical Group
Room 302 - Session MN+AS+NS+QS+SE-MoM

Dynamics and Engineering of MEMS/NEMS

Moderators: Jürgen Brugger, EPFL, Switzerland, **Eva Weig**, University of Munich, Germany

9:00am **MN+AS+NS+QS+SE-MoM-3 MEMS-Based Surface Nanoengineering Using Thermal AFM Probes: 30 Years and Counting***,* ***Jürgen Brugger,*** École Polytechnique Fédérale de Lausanne, Switzerland **INVITED**

Soon after the first publication in 1985 of the atomic force microscope (AFM) attempts were made to extend AFM-based surface probing from microscopy to lithography [reviewed in 1]. The potential applications in writing and reading for data storagein the early years served as technology driver and showed remarkable performances [2]. One of the variants of AFM-based writing (and reading) operates a heated nano-tip to perform thermally induced phase changes of materials. The three-fold combination of nano-scale heat localization (30 nm scale), high temperature (~ 500 °C)and particularly fast heating/cooling cycles (10E-6 s) is unique and opens new opportunities for surface engineering and material conversion using heat.In the meantime, nano-tips and cantilevers were further perfected as nanotools to locally induce phase changes in materials for a wide range of exploratory studies. Today, thermal scanning probe lithography (t-SPL) has matured into turn-key systems that can be compared to some extend to electron beam lithography, but without the useof charged particles and without the need for development. The full grasp of potential applications in R&D and production is still growing as the technique is still emerging.

In this talk, we will give first some background how heated AFM probes were initially designed and fabricated that led to today's advanced thermo-mechanical probe design of micro-cantilevers and nano-tips. The paper will then review some main achievements up to date [3] and then present recent results on t-SPL utilized for 2D materials by our own work [4, 5], and will conclude with some outlook on further challenges in hot-tip nanoengineering.

References:

[1] R. Garcia, et al. Nature Nanotechnology (2014)

[2] H. J. Mamin et al. Applied Physics Letters (1992)

[3] S. T. Howell et al. Microsystems & Nanoengineering (2020)

[4] X. Liu et al. Advanced Materials (2020)

[5] X. Liu et al. Nano letters (2020)

10:40am **MN+AS+NS+QS+SE-MoM-8 Atomically-Thin MoS_2 Nanoelectromechanical Resonators***, R. Yang,* Shanghai Jiao Tong University, China*;* ***Jaesung Lee,*** University of Texas at El Paso **INVITED**

With the development of the Internet of Things (IoT), new sensors and signal processing elements that consume *near-zero* power to operate on resonance, have high tunability and small form factor are necessary.The ultralow mass and large resonance tunability make resonant 2D nanoelectromechanical systems (NEMS) suitable for ultrasensitive mass, force and biomolecular sensing, radio-frequency (RF) front end, and strain-tunable devices.Further, molybdenum disulfide (MoS_2) resonators only require picowatt level of power for sustaining the strong and stable resonance operations due to their ultralight weight.This opens an opportunity to explore new sensors and signal processing elements for IoT applications that really require near-zero power to operate on resonance, and at the same time, have wide dynamic ranges and tuning ranges. In this talk, we summarize our most recent advances in 2D MoS_2 NEMS resonators.

11:20am **MN+AS+NS+QS+SE-MoM-10 Can a Single Nanomechanical Mode Generate a Frequency Comb?***,* ***Eva Weig,*** Technical University of Munich, Germany **INVITED**

Doubly-clamped nanostring resonators excel as high Q nanomechanical systems enabling room temperature quality factors of several 100,000 in the 10 MHz eigenfrequency range. Dielectric transduction via electrically induced gradient fields provides an integrated control scheme while retaining the large mechanical quality factor [1]. Dielectrically controlled nanostrings are an ideal testbed to explore a variety of dynamical phenomena ranging from multimode coupling to coherent control [2]. Here I will focus on the nonlinear dynamics of a single, resonantly driven mode. The broken time reversal symmetry gives rise to the squeezing of the string's fluctuations. As a result of the high mechanical Q factor, the squeezing ratio is directly accessible from a spectral measurement [3]. It is encoded in the intensities of the two spectral peaks arising from the slow dynamics of the system in the rotating frame. For stronger driving, an onset of self-sustained oscillation is observed which leads to the generation of a nanomechanical frequency comb. The effect is a consequence of a resonantly induced negative effective friction force induced by the drive. This is the first observation of a frequency comb arising solely from a single mode and a single, resonant drive tone [4].

[1] Q. P. Unterreithmeier et al., Nature 458, 1001 (2009)

[2] T. Faust et al., Nature Physics 9, 485 (2013)

[3] J. Huber et al., Phys. Rev. X 10, 021066 (2020)

[4] J. Ochs et al., in preparation

Nanoscale Science and Technology Division
Room 304 - Session NS1+QS-MoM

Fabrication, Testing and Metrology of Quantum Devices and Systems

Moderator: Wonhee Ko, Oak Ridge Natinal Laboratory

8:20am **NS1+QS-MoM-1 Single Electrons on Solid Neon: A New Solid-State Qubit Platform with Ultralong Coherence***,* ***Xianjing Zhou,*** Pritzker School of Molecular Engineering, University of Chicago **INVITED**

Progress towards the realization of quantum computers requires persistent advances in their constituent building blocks—qubits. Novel qubit platforms that simultaneously embody long coherence, fast operation and large scalability offer compelling advantages in the construction of quantum computers and many other quantum information systems. Electrons, ubiquitous elementary particles of non-zero charge, spin and mass, have commonly been perceived as paradigmatic local quantum information carriers. Despite superior controllability and configurability, their practical performance as qubits through either motional or spin states depends critically on their material environment. In this talk, I will present our experimental realization of a new qubit platform based on isolated single electrons trapped on an ultraclean solid neon surface in vacuum. By integrating an electron trap in a circuit quantum electrodynamics architecture, we achieve strong coupling between the motional states of a single electron and a single microwave photon in an on-chip superconducting resonator [1]. Qubit gate operations and dispersive readout are successfully implemented. Our latest measurements show that both the relaxation time T_1 and coherence time T_2 have reached 0.100-millisecond scale [2]. The observed single-shot readout fidelity, without using a quantum-limited amplifier, is already 94.4%. Simultaneous strong coupling of two qubits with the microwave resonator is also demonstrated, as a first step toward two-qubit entangling gates for universal quantum computing. These results manifest that the electron-on-solid-neon (eNe) charge qubits have outperformed all the existing charge qubits to date and rivaled the state-of-the-art superconducting transmon qubits.

[1] X. Zhou … and D. Jin, "Single electrons on solid neon as a solid-state qubit platform", Nature 605, 46–50 (2022).

[2] X. Zhou … and D. Jin, "Electron charge qubits on solid neon with 0.1 millisecond coherence time", manuscript submitted (2022).

9:00am **NS1+QS-MoM-3 Ultra-thin TaN Damascene Nanowire Structures on 300 mm Si Wafers for Quantum Applications***,* ***Ekta Bhatia****, S. Kar, S. Olson, T. Vo, S. Schujman, J. Nalaskowski,* NY CREATES*; H. Frost,* SUNY Polytechnic Institute, Albany*; J. Mucci, B. Martinick, I. Wells, T. Murray, C. Johnson, V. Kaushik, S. Papa Rao,* NY CREATES

Tantalum nitride (TaN) is a material which has been used as a copper diffusion barrier in integrated circuits, along with many other applications ranging from corrosion-resistant coatings to superconducting quantum devices. Superconducting nanowire single photon detectors (SNSPDs) are critical for applications in photonic quantum computing, single-flux quantum logic circuits for qubit readout, and neuromorphic computing. TaN SNSPDs have been shown to extend the detection bandwidth to longer wavelengths, along with higher detection efficiency, enabling new applications in cosmology when fabricated into large scale arrays. TaN devices at 300 mm wafer scale can leverage the advances made by the semiconductor industry in process control, improving yield, pattern fidelity and wafer-to-wafer predictability of performance. Hence, the development of this process technology will enable large scale SNSPD arrays, and will also be useful for superconducting circuits for quantum applications.

Detailed studies of the influence of nitrogen content on the superconducting characteristics of TaN thin films are not widely available in the literature, particularly at 300 mm wafer scale. We report the development of ultra-thin reactive sputtered TaN films prepared with different Ta to N ratios on 300 mm scale. We fabricated damascene structures of TaN nanowires with widths varying from 100 to 3000 nm and thickness varying from 5 to 35 nm using 193 nm optical lithography and advanced chemical mechanical planarization.

We confirmed a sigmoidal dependence of TaN sheet resistance on Ta to N ratio, and a decrease in crystallite size (extracted from XRD measurements). The superconductor to insulator transition as a function of Ta to N ratio is reported. We will also discuss the influence of encapsulation of the superconducting wires with metallic TaN and copper. Cu encapsulation can improve contact resistance during measurement, and has implications for thermal conduction along the length of the superconducting nanowire. In contrast, adding an intervening layer of highly disordered metallic TaN between the superconducting TaN and Cu ensures minimal leakage of Cooper-pairs at TaN/Cu interface. We will report the variation of T_c and J_c of TaN nanowires as a function of film thickness, material characteristics, Ta to N ratio and encapsulation.The potential of ultra-thin TaN films at 300 mm scale will be discussed in the context of applications such as on-chip integration for readout of superconducting qubits, in quantum phase slip studies, and large focal-plane detector arrays for cosmology.

9:20am **NS1+QS-MoM-4 Direct Integration of Atomic Precision Devices into a MOS-Compatible Process***, **Jeffrey Ivie**, D. Campbell, A. Leenheer, C. Halsey, E. Anderson, S. Schmucker, D. Scrymgeour, X. Gao, W. Lepkowski, T. Lu, L. Tracy, S. Misra,* Sandia National Laboratories

Atomic precision advanced manufacturing (APAM) of electrical devices, fabricated using hydrogen depassivation lithography in a scanning tunneling microscope, offers a way to explore device physics with the ultimate degree of control. Almost all previous work has focused on exploring applications in quantum physics, particularly with a focus on qubits, using devices operating at cryogenic temperatures. While APAM may benefit applications in microelectronics, such as the strong doping of contacts in scaled transistors, the high temperature surface preparation of APAM generally makes it incompatible with modern metal-oxide semiconductor (MOS) process flows. To leverage significant past investments in CMOS manufacturing and enable a wider application space for APAM devices, demonstration of direct integration of APAM into existing MOS process flows is required.

To enable direct integration of APAM devices, we have established a natural insertion point for APAM processing between Front-end-of-line (FEOL) and Back-end-of-line (BEOL) steps on Sandia's 0.35-micron CMOS node. The insertion point allows for readily accessed device Si through gentle sputtering and thermal annealing, which has a sufficiently crystalline surface critical for APAM delta doping. Integration of the moderate temperature APAM processing step (<600 °C) between high temperature FEOL processing (1000 °C) and before low temperature BEOL processing (<400 °C) maintains the electrical characteristics of both the inserted APAM delta-doped material and the discrete transistors and integrated circuit components from FEOL. Furthermore, accelerated lifetime measurements of APAM wires demonstrate that patterned APAM material is more robust than standard metal features in modern CMOS devices. Establishing the capability of direct integration of APAM into a CMOS process flow opens the door to enhance CMOS transistors with APAM-based processing along with providing wider manufacturing interest. Similarly, implementation of novel APAM-based devices alongside CMOS circuits is a significant discovery platform for microelectronics, neuromorphic computing hardware, or hybrid quantum applications.

This work was supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories and was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

9:40am **NS1+QS-MoM-5 Low Thermal Budget PMOS in Low Temperature Epitaxial Silicon***, **Christopher Allemang**, D. Campbell, J. Ivie, T. Lu, S. Misra,* Sandia National Laboratories

Atomic precision advanced manufacturing (APAM) enables deposition of dopants in silicon (Si) with atomic precision and has been exploited to make donor-based qubits. However, understanding the electrical effects of the process tradeoffs in burying the dopants under an epitaxial Si capping layer grown at low temperatures has remained a challenge, both for qubits and for other microelectronics applications. This cap layer can be deposited at the lowest temperatures to limit the diffusion of dopants, or at modest temperatures to limit the density of point defects. Here, to evaluate the electrical quality of the Si cap, we explore using APAM materials and compatible processes for other microelectronic devices, namely p-type metal-oxide-semiconductor (PMOS) field-effect transistors.

The Si cap is unintentionally doped with aluminum during the growth process leading to a p-type material. To employ this p-type material for PMOS, we must have ohmic contacts and a way to gate the channel. Typical processes used for contacting and gating the channel, e.g. implants and thermal oxide, cannot be used here because they are high temperature processes. To maintain an APAM compatible thermal budget, we have developed ohmic contacts to the cap layer using platinum silicide formed at 400ºC and an atomic layer deposition Al_2O_3 gate oxide grown at 250ºC. These temperatures are also within the back-end-of-line thermal budget for Si CMOS, implying this process could be used to integrate an additional device layer on an existing chip.

The silicide contacts are qualified by fabricating Schottky diodes on n-type material and analyzing their current-voltage (*IV*) characteristics, while the gate oxide is qualified by measuring the capacitance-voltage characteristics of MOS capacitors. Further, these processes are combined to demonstrate PMOS transistor behavior in APAM material for the first time. The electrical transport in the cap layer is then qualified using *IV* measurements. While these results represent the initial qualification of electrical transport in the cap layer, further studies and analysis may reveal impacts to APAM quantum devices.

This work was partially funded by the Advanced Manufacturing Office project Big Energy Efficient Transistors, supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories, and performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525. The views expressed here do not necessarily represent the views of the DOE or the U.S. Government.

New Trends on Structural and Electronic Characterization of Materials, Interfaces, and Surfaces Using Synchrotron and FEL-Based Radiation Sources Focus Topic
Room 318 - Session LS1+2D+AS+EM+QS+SS-TuA

Operando Catalysis and Energy Systems

Moderator: Jyoti Katoch, Carnegie Mellon University

2:20pm **LS1+2D+AS+EM+QS+SS-TuA-1 In-situ/Real-time XPS Study of Electrochemical Reactions in All-solid-state Thin-film Lithium-Ion Batteries*, Takuya Masuda,*** National Institute for Materials Science, Japan **INVITED**

All-solid-state lithium-ion batteries (ASSLIBs) are one of the most promising next generation rechargeable batteries because of their very high safety and reliability. Understanding of the mechanism of electrochemical reactions and related physicochemical phenomena is very important for improving cell performances and durability. Application of ex-situ techniques to multiple samples disassembled from cells after certain charge/discharge cycles often results in misinterpretation due to the variation of samples and undesired side effects during sample transfer between battery test environment and characterization apparatus. Thus, various in-situ techniques which can be applied to the same position of the same sample kept at a certain charge/discharge state have been developed for hierarchical understanding of a series of electrochemical events interplaying with each other. X-ray photoelectron spectroscopy (XPS) is a powerful tool for analyzing the composition of reaction products, chemical state, and electronic structure of sample surfaces. By tuning the energy of incident x-rays, it also enables us to conduct the depth-resolved analysis of surfaces and interfaces including those buried with solid thin films. Recently, we developed an in-situ XPS apparatus equipped with a bias application system and a vacuum suitcase for sample transfer,[1] and applied it to the electrochemical lithiation/delithiation reactions of an amorphous Si thin film electrode sputter-deposited on a solid electrolyte sheet.[2] The chemical state of Si electrode changing during lithiation/delithiation processes was successfully tracked by sequential XPS measurements in the regions of Li 1s, C 1s, O 1s, and Si 2p. Not only lithium silicide (Li_xSi) which reversibly responds to the lithiation/delithiation but also irreversible species such as lithium oxides, lithium silicates and lithium carbonates were formed due to the lithiation of the Si electrode. Moreover, a rapid spectral change attributable to the phase transition of a crystalline Li_xSi to an amorphous phase was observed in the successive delithiation after preceding lithiation up to certain level. Based on the state of charge, Li content x in Li_xSi, and positions of XPS peaks, we summarized the lithiation/delithiation mechanism in Si electrodes. Further details will be presented.

[1] R. Endo, T. Ohnishi, K. Takada, T. Masuda, Journal of Physics Communications, 2021, 5, 015001.

[2] R. Endo, T. Ohnishi, K. Takada, and T. Masuda, J. Phys. Chem. Lett. 2020, 11, 6649−6654.

3:00pm **LS1+2D+AS+EM+QS+SS-TuA-3 Interaction of Molecular Nitrogen with Vanadium Oxide in the Absence and Presence of Water Vapor at Room Temperature: Near-Ambient Pressure XPS***, S. Nemsak,* Lawrence Berkeley National Laboratory*; **Kabirat Balogun**, P. Chukwunenye, T. Cundari, P. Bagus, J. Kelber,* Department of Chemistry, University of North Texas

Interactions of N_2 and H_2O at transition metal oxide surfaces are of fundamental interest for gaining insight into electrocatalytic nitrogen reduction reaction (NRR) mechanisms. N_2/H_2O interactions at the polycrystalline vanadium oxide/vapor interface were monitored at room temperature and N_2 partial pressures between 10^{-9} Torr and 10^{-1} Torr using Near-Ambient Pressure X-ray Photoelectron Spectroscopy (NAP-XPS). The oxide film was predominantly V(IV), with significant V(III) and V(V) components. Such films have been previously demonstrated to be NRR active at pH 7. There is little understanding, however, of the detailed nature of N_2-surface interactions. XPS measurements were acquired at room temperature in environments of both pure N_2 and equal pressures of N_2 and H_2O vapor, up to a N_2 partial pressure of 10^{-1} Torr. In the absence of H_2O, broad N 1s features were observed at binding energies of 401 eV and 398.7 eV with relative intensity ratios of ~ 3:1, respectively. These features remained upon subsequent pumpdown to 10^{-9} Torr, indicating that adsorbed nitrogen is stable at room temperature in the absence of equilibrium with gas phase N_2. In the presence of equal pressures of N_2 and H_2O vapor, the 401 eV N 1s feature was reduced in intensity by ~ 50% at 10^{-1} Torr N_2 partial pressure, with the feature at 398.7 eV binding energy barely observable. DFT calculations show that the above NAP-XPS data demonstrating stable N_2-surface binding in the absence of N_2 overpressure are consistent with N_2 binding at V(IV) or V(III) sites, but not at V(V) sites, and further show that N_2/H_2O binding is competitive. SCF-HF calculations suggest that the two N 1s XPS features correspond to "shake" and normal transitions at 401 eV and 398.7 eV, respectively, for N_2 bonded end-on to the surface. The shake feature involves a charge transfer from V 3d to N_2 pi* in addition to N 1s ionization. The difference in binding energies of the two features, ~ 2.3 eV, strongly suggests N_2 -V(III) binding. The data presented demonstrate the ability of NAP-XPS, in concert with theory, to provide atomic-level insight concerning interfacial reactions relevant to electrocatalysis.

Acknowledgement:

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3:20pm **LS1+2D+AS+EM+QS+SS-TuA-4 Catalysts Caught in the Act: an Operando Investigation of Copper during CO_2 Hydrogenation*, Elizabeth Jones,*** University of Oxford, UK

Amongst the foremost challenges in mitigating global warming are replacing fossil fuels with renewable alternatives, and storing/using carbon captured from CO2-emitting processes. Methanol production by CO2 hydrogenation promises a possible solution to both of these issues, particularly if H2 can be obtained through water electrolysis. When the resulting methanol is used as a fuel an equivalent amount of CO2 is released making it a “net-zero” fuel alternative. CO2 hydrogenation is performed industrially using a CO2/H2 mix at 200-300oC, 50-100 bar with a Cu-based catalyst, and the addition of CO is known to increase the methanol yield. However, mechanistic understand of this reaction and the role played by CO remains limited. Soft X-ray spectroscopies can provide details on the chemical state of copper to uncover the chemistry behind this reaction, however the typical requirement for measurement under high vacuum constrains how realistic these studies can be. There has been much recent development on improving operando techniques to enable heterogeneous catalytic reactions to be studied under realistic pressure conditions (E. S. Jones et al., in Ambient Pressure Spectroscopy in Complex Chemical Environments, 2021, ACS Symposium Series, vol. 1396, ch. 8, 175-218). A promising approach is to use an environmental cell which encloses the desired gas and separates it from the high vacuum environment, using an X-ray transparent window (R. S. Weatherup, J. Phys. Chem. Lett., 2016, 7, 1622-1627).

Using a custom-designed high pressure environmental cell we have studied model Cu catalysts using operando NEXAFS in total electron yield mode up to pressures of 1 bar and temperatures of 200oC. A thin Cu film was deposited onto a Si3N-4 membrane which acted to seal the high pressure gas within the cell and as a transparent window for incident X-rays. The aim of the study was to investigate how the Cu oxidation states varied when exposed to H2 and CO2 in different sequential order and how the introduction of CO can further influence the chemical state of Cu. It was found that H2 can provide a protective barrier to oxidation from CO2 when dosed first, however if H2 was added after CO2 it is unable to return the surface to its metallic state where CO is then required for reduction. This offers an insight into why CO plays an important role in the industrial production of methanol. Additionally, advances in sealing of the environmental cell enabled high pressures to be achieved at elevated temperatures, allowing this approach to be extended to more industrially-relevant conditions.

2D Materials Technical Group
Room 303 - Session 2D+EM+MI+NS+QS-WeM

2D Materials: Quantum and Symmetry-Protected States

Moderators: Thomas Michely, University of Cologne, Germany, **Frances Ross**, Massachusetts Institute of Technology

8:00am **2D+EM+MI+NS+QS-WeM-1 Semi-High Throughput Investigation of 2d Materials: Anomalous Quantum Confinement Effect and Spectral Properties***, **Francesca Tavazza**, K. Choudhary,* National Institute of Standard and Technology **INVITED**

Materials with van der Waals-bonding exhibit quantum confinement effect, in which the electronic bandgap of the three-dimensional (3D) form is lower than that of its two-dimensional (2D) counterpart. However, the possibility of an anomalous quantum confinement effect (AQCE) exists, where the bandgap trend is reversed. In this work, we computationally identify materials with AQCE. Using density functional theory (DFT), we compute ≈1000 OptB88vdW (semi-local functional), ≈50 HSE06 and ≈50 PBE0 (hybrid functional) bandgaps for bulk and their corresponding monolayers, in the JARVIS-DFT database. OptB88vdW identifies 65 AQCE materials, but the hybrid functionals only confirm such finding in 14 cases. Electronic structure analysis shows that AQCE is often characterized by the lowering of the conduction band in the monolayer and related changes in the p_z electronic orbital contribution. In addition to AQCE, the JARVIS-DFT contains IR and Raman spectra for many 2D materials. Properties of such spectra will be discussed as well.

8:40am **2D+EM+MI+NS+QS-WeM-3 Dry Patterning Chemically Sensitive Quantum Materials***, **Joseph Benigno**, Q. Zou, C. Cen, L. Li,* West Virginia University

Accurate, repeatable patterning of quantum material-based electronic devices is desirable for electrical transport measurements. However, the most common method, photolithography, can degrade, or even damage, chemically sensitive quantum materials during fabrication. Here we introduce a new dry-patterning method for device fabrication with lateral etching resolution down to ~30 µm. The new method utilizes a tabletop computer numerical control (CNC) router machine to gently etch patterns into thin films, leaving behind the desired device or devices on the substrate. We create Hall bars with conductive channel widths of 30, 60, and 120 µm from ~20 layer FeTe-capped superconducting single layer FeSe/SrTiO$_3$ systems. Transport measurements show the same zero resistance T_c of 10 K for the Van der Pauw (vdP) geometry and all Hall bar structures. However, the onset temperature T_{onset} is the largest at 28K for the vdP geometry, and decreases with the width of the Hall bar to 13K for the 60 µm device. Our method provides a new time-saving, cost-effective, and chemical-free strategy for fabrication of devices from quantum materials.

This research is supported by DOE DE-SC0021393.

9:00am **2D+EM+MI+NS+QS-WeM-4 Electron Transport and Charge Sensing in Strongly Coupled Quantum Dot Array in Silicon***, **Fan Fei**, J. Wyrick, P. Namboodiri, J. Fox,* NIST*; E. Khatami,* SJSU*; R. Silver,* NIST

Atomically precise donor-based quantum devices in silicon are fabricated using STM lithography, which has become a promising platform for solid state quantum computation and analog quantum simulation. Lattices of dopant-based quantum dots have unique advantages in simulating strongly correlated Fermionic systems of real atomic lattice sites because of their naturally occurring ion-cores which make them the Fermi-Hubbard sites in the Silicon Vacuum. Understanding electron transport and charge configuration in a smaller array is critical to using these arrays to simulate larger systems and explore various condensed matter physics phenomena such as superconductivity in the future. This talk will focus on the electron transport in the strongly coupled regime where the electrons delocalize across small N x N dot arrays. Numerical simulations for charge stability diagrams and transport properties show qualitatively agreement with our experiments. We apply rf reflectometry on a SLQD and use it as charge sensor for probing the electron configuration within the array.

9:20am **2D+EM+MI+NS+QS-WeM-5 Observation of the Layer Hall Effect in Topological Axion Antiferromagnet MnBi$_2$Te$_4$***, **Suyang Xu**,* Harvard University **INVITED**

While ferromagnets have been known and exploited for millennia, antiferromagnets were only discovered in the 1930s. The elusive nature indicates antiferromagnets' unique properties: At large scale, due to the absence of global magnetization, antiferromagnets may appear to behave like any non-magnetic material; At the microscopic level, however, the opposite alignment of spins forms a rich internal structure. In topological antiferromagnets, such an internal structure leads to a new possibility, where topology and Berry phase can acquire distinct spatial textures. We study this exciting possibility in an antiferromagnetic Axion insulator, even-layered MnBi$_2$Te$_4$ flakes. We report the observation of a new type of Hall effect, the layer Hall effect,where electrons from the top and bottom layers spontaneously deflect in opposite directions.

Reference:

A. Gao, et al.“Layer Hall effect in a 2D topological axion antiferromagnet.” *Nature* 595, 521 (2021).

11:00am **2D+EM+MI+NS+QS-WeM-10 Phonon Limited Mobility and Phonon Drag in h-BN Encapsulated Monolayer and AB-stacked Bilayer Graphene***, **Vasili Perebeinos**,* University at Buffalo

We report the electrical transport in h-BN encapsulated AB-stacked bilayer graphene theoretically and experimentally. Using the perturbation theory within the tight-binding model approach, we identify the dominant role of the shear phonon mode scattering on the carrier mobility in AB-stacked graphene bilayer at room temperature. The shear phonon mode is absent in free-standing monolayer graphene, which explains high mobilities in monolayer devices fabricated under similar conditions resulting in minimal Coulomb impurity scattering. At temperatures above 200K, the surface polar phonon scattering from the boron-nitride substrate contributes significantly to the experimental mobilities of 15,000 -20,000 cm^2/Vs at room temperature and carrier concentration n~10^{12} cm^2 reported here. A screened SPP potential for a dual gated bilayer and transferable tight-binding model allows us to predict mobility scaling with temperature and bandgap for both electrons and holes in agreement with the experiment Phys Rev. Lett. 128, 206602 (2022).

The resulting electron-SPP coupling is used to predict that, by exploiting the strong coupling of their electrons to surface polar phonons, van der Waals heterostructures can offer a suitable platform for phonon sensing, capable of resolving energy transfer at the single-phonon level. The geometry we consider is one in which a drag momentum is exerted on electrons in a graphene layer, by a single out-of-equilibrium phonon in a dielectric layer of hexagonal boron nitride, giving rise to a measurable induced voltage. Our numerical solution of the Boltzmann Transport Equation shows that this drag voltage can reach a level of a few hundred microvolts per phonon, well above experimental detection limits. Furthermore, we predict that drag voltage should be largely insensitive to the mobility of carriers in the graphene layer and increase the temperature up to at least 300 K, offering the potential of a versatile material platform for single-phonon sensing.

11:20am **2D+EM+MI+NS+QS-WeM-11 Exciton Physics at the Atomic Scale***, **Daniel Gunlycke**,* U.S. Naval Research Laboratory

Descriptions of excitons in pristine semiconducting crystals usually rely on the hydrogen model adopted for excitons. Owing to the weak screening in monolayer transition-metal dichalcogenides, however, the electron and hole separation in the strongest bound excitons is on the atomic scale, necessitating atomistic treatment. In this presentation, we present a minimalistic exciton model that accounts for the lattice and the spin-orbit and exchange interactions, thus making this model appropriate across the spectrum from Wannier to Frenkel excitons. Using this model, we show that the exciton lifetimes could be extended by transitioning the excitons into excitonic dark states. Longer exciton lifetimes could make these materials candidates for applications in energy management and quantum information processing.

11:40am **2D+EM+MI+NS+QS-WeM-12 Weyl Semimetals with Low-Symmetry Crystal Structure for Generating Out-of-Plane Oriented Spin Current***, **Simranjeet Singh**,* Carnegie Mellon University **INVITED**

Weyl semimetals (WSMs), such as WTe$_2$ and MoTe$_2$, host plethora of novel phenomena that are highly relevant for quantum spintronics, namely: Dirac type dispersion, strong spin-orbit coupling (SOC), Fermi arcs, and helical spin-momentum locked surface and bulk states. WSMsprovide a distinct opportunity to obtain highly efficient and unconventional charge to spin conversion owing to strong SOC, symmetry breaking, and these topology-based phenomena. On the other hand, spin-orbit torque (SOT) driven deterministic control of the magnetic state of a ferromagnet with perpendicular magnetic anisotropy is key to next generation spintronic applications including non-volatile, ultrafast, and energy efficient data storage devices. But field-free deterministic SOT switching of perpendicular magnetization remains a challenge because it requires an out-of-plane oriented spin current, which is not allowed in conventional spin source materials such as heavy metals and topological insulators due to the system's symmetry. The exploitation of low-crystal symmetries WTe_2 and $MoTe_2$ offers a unique approach to achieve SOTs with unconventional forms[1]. In this work, I will discuss our experiments to realize field-free deterministic magnetic switching of a perpendicularly polarized van der Waals magnet employing an out-of-plane spin current generated in layered WTe_2, which is a quantum material with low-symmetry crystal structure[2]. I will also discuss our experiments aimed at achieving field-free SOT switching of semiconducting and insulating FMs using spin current in WSMs. Our work establishes transition metal dichalcogenides, with lower symmetry crystal structure, as an appealing spin source material for future spin-orbit torque related magnetic memory technologies.

[1]. MacNeill, D. *et al.* Control of spin–orbit torques through crystal symmetry in WTe_2/ferromagnet bilayers. *Nature Physics***13**, 300-305, (2017).

[2]. Kao, I-H *et al.* Deterministic switching of a perpendicularly polarized magnet using unconventional spin–orbit torques in WTe_2. Nature Materials (2022). https://doi.org/10.1038/s41563-022-01275-5

Quantum Information Science Focus Topic
Room 302 - Session QS+EM+MN+NS-WeA

Systems and Devices for Quantum Information

Moderators: Megan Ivory, Sandia National Laboratories, **Dave Pappas**, Rigetti Computing

2:20pm **QS+EM+MN+NS-WeA-1 Photonics-Integrated Microfabricated Surface Traps for Trapped Ion Applications**, ***Megan Ivory**, W. Setzer, N. Karl, J. Schultz, J. Kwon, M. Revelle, R. Kay, M. Gehl, H. McGuinness,* Sandia National Laboratories **INVITED**

Some of the more advanced quantum systems for applications spanning clocks, sensors, and computers are based on the control and manipulation of atoms.While these atomic systems have led to promising results in laboratory systems, the transition of these devices from the laboratory to the field remains a challenge.Recently, advances in compact vacuum technology, microfabricated surface traps, and integrated photonics are paving the way toward deployable solutions.Here, I discuss ongoing efforts at Sandia National Laboratories to leverage microfabricated surface traps for low size, weight, and power (SWaP) deployable trapped-ion systems, and the unique systematics presented by these integration efforts.In particular, I present initial demonstrations of trapped ions utilizing multilayered waveguides for UV and visible/IR light and single photon avalanche detectors integrated with microfabricated surface traps.I also present characterization of heating rates and frequency shifts in these integrated devices, and an outlook for further reducing SWaP via compact vacuum systems.

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3:00pm **QS+EM+MN+NS-WeA-3 Toward Heterogeneous Quantum Networks: Interfacing Trapped Ion, Superconducting, and Integrated Photonic Qubits**, ***Kathy-Anne Soderberg**, A. Paul,* Air Force Research Laboratory*; N. Barton, A. Brownell,* Murray Associates*; D. Campbell,* Air Force Research Laboratory*; C. Craft,* Technergetics*; M. Fanto, D. Hucul,* Air Force Research Laboratory*; A. Klug,* Griffiss Institute*; M. LaHaye,* Air Force Research Laboratory*; M. Macalik,* Booz Allen Hamilton*; K. Scalzi,* Technergetics*; J. Schneeloch,* Air Force Research Laboratory*; M. Senatore,* Griffiss Institute*; E. Sheridan,* National Academies of Sciences, Engineering, and Medicine*; D. Sica,* Griffiss Institute*; A. Smith, Z. Smith, C. Tison,* Air Force Research Laboratory*; C. Woodford,* Griffiss Institute **INVITED**

Effective and efficient ways to connect disparate qubit technologies is an outstanding challenge in quantum information science. However, the ability to interface different qubit modalities will have far-reaching implications for quantum computing and quantum networking. Here we present plans and progress toward interfacing trapped ion, superconducting, and integrated photonic qubits for the purpose of entanglement distribution in a quantum network. We will also discuss how this work connects to the AFRL distributed quantum networking testbed.

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4:20pm **QS+EM+MN+NS-WeA-7 Superconductor/Semiconductor Heterostructures for Quantum Computing Applications**, ***Chris Palmstrøm**,* University of California, Santa Barbara **INVITED**

Superconductor/semiconductor heterostructures have potential for quantum computing applications. Coupling superconductivity to near surface quantum wells (QW) and nanowires of high spin-orbit semiconductors have allowed the observation of zero bias peaks, which can be a signature of, but not proof of, Majorana Zero Modes, a key ingredient for topological computing. These results of induced superconductivity pave the way for lithographically defined complex superconductor/semiconductor nanostructured networks necessary for quantum computation.

Our efforts have focused on developing high mobility of near surface quantum wells of the high spin-orbit semiconductors InAs, InSb and $InAs_ySb_{1-y}$. Rather than relying on post growth lithography and top down etching to form semiconductor nanostructures, we have investigated the development of shadow superconductor growth on atomic hydrogen cleaned MOVPE-grown vapor-liquid-solid InSb nanostructures and in-vacuum chemical and molecular beam epitaxy selective area grown InAs nanostructures. We have identified Sn as an alternative for Al for use as superconductor contacts to InSb vapor-liquid-solid nanowires, demonstrating a hard superconducting gap, with superconductivity persisting in magnetic field up to 4 Tesla. Further, a small island of Sn-InSb exhibits the two-electron charging effect, a clear indication of a supercurrent.

In more conventional superconductor qubits, a dramatic size reduction of the superconducting transmon devices is predicted by the development of merged element transmon devices based on superconductor/semiconductor/superconductor heterostructures. These superconductor/semiconductor/superconductor heterostructures also allow for selective control of conductance modes in planar lateral multi-terminal Josephson Junctions

In this presentation, progress in developing superconductor/semiconductor heterostructures for quantum computing applications will be presented. This will include progress in in-situ patterning and selective area growth, multi-terminal Josephson Junctions and the recent progress towards developing a Si fin based merged element transmon – the FinMET.

5:00pm **QS+EM+MN+NS-WeA-9 High Throughput Measurements of III-V Semiconductor Materials Stack of 2DEG-Based Tunable Couplers**, ***Nicholas Materise**,* Colorado School of Mines*; J. Pitten,* University of Colorado at Boulder*; W. Strictland,* New York University*; A. McFadden,* National Institute for Science and Technology (NIST)*; J. Shabani,* New York University*; E. Kapit,* Colorado School of Mines*; C. McRae,* University of Colorado at Boulder

Recent success in integrating cryogenic semiconductor classical systems with superconducting quantum systems promises to reduce the room temperature classical signal processing bottleneck. Incorporating semiconductor quantum devices with superconducting ones as tunable couplers and hybrid quantum systems requires quantitative estimates of the loss introduced by those devices. We report loss measurements of the III-V semiconductor stack used in 2DEG-based gatemon qubits and couplers using a superconducting microwave cavity. Extending the high throughput, low-cost substrate measurement method to thin films grown by molecular beam epitaxy, we can investigate surface roughness losses, bulk losses, and interface losses in a single microwave package. As with our previous measurements of substrates, we perform comparison studies with CPW resonators to validate our approach.

5:20pm **QS+EM+MN+NS-WeA-10 Strong Coupling between a Superconducting Microwave Resonator and Low-Damping Magnons Using Vanadium Tetracyanoethylene Thin Films**, *Q. Xu, H. Cheung,* Cornell University*; D. Cormode, H. Yusuf,* The Ohio State University*; Y. Shi,* University of Iowa*; M. Chilcote,* Cornell University*; M. Flatté,* University of Iowa*; E. Johnston-Halperin,* The Ohio State University*; **G. D. Fuchs**,* Cornell University **INVITED**

Hybrid quantum systems – in which excitations with distinct origin are hybridized through a resonant interaction – are attractive for quantum technologies because they enable tunability and the ability to combine desirable properties of each excitation. Here we study the hybrid excitation of a superconducting microwave resonator mode and a ferromagnetic resonance mode of vanadium tetracyanoethylene ($V[TCNE]_x$) thin films. Our work addresses a key challenge for hybrid superconducting resonator-magnon devices: the integration of a low damping thin-film material with microfabricated superconducting circuits. $V[TCNE]_x$ is a molecular-based ferrimagnet with exceptionally low magnetic damping – as low as 5×10^{-5} at room temperature. The ability to grow thin films of this material at low temperature via chemical vapor deposition and pattern it via lift-off processing enables the fabrication of integrated quantum magnon devices using this material. We couple a $V[TCNE]_x$ magnon mode to the mode of a thin-film Nb lumped-element LC resonator and demonstrate strong coupling, characterized by cooperativities in above 10^2. Characterization of this hybrid resonator-magnon system in both the frequency domain and the time domain reveals hybridization between resonator photons and magnons. This work demonstrates a pathway for scalable and integrated quantum magnonic technologies.

6:00pm **QS+EM+MN+NS-WeA-12 Role of Point Defect Disorder on the Extraordinary Magnetotransport Properties of Epitaxial Cd_3As_2**, ***Jocienne Nelson**, A. Rice, C. Brooks, I. Leahy, G. Teeter, M. van Schilfgaarde, S. Lany, B. Fluegel, M. Lee, K. Alberi,* NREL

Three-dimensional topological semimetals host extremely large electron mobilities and magnetoresistances making them promising for a wide range of applications including in optoelectronic devices, renewable energy, and quantum information. However, the extent to which disorder influences the properties of topological semimetals remains an open question and is relevant to both the understanding of topological states and the use of topological materials in practical applications. As a particular example, epilayers of the prototypical Dirac semimetal Cd3As2 exhibit high electron mobilities despite a having very high dislocation densities.[1,2]

Native point defects are inevitable in crystalline materials and introduce long and short-range disorder potentials that will impact carrier transport behavior. To understand their role in topological semimetals, we use molecular beam epitaxy to achieve unmatched and systematic control of point defect concentrations in Cd_3As_2. By reducing the concentration of scattering point defects, we increased the mobility from 5000 to 18,000 cm2/Vs and the magnetoresistance from 200% to 1000%. We find good agreement with the guiding center diffusion model, which indicates point defects are essential to the large linear magnetoresistance in topological semimetals.[3] However, the degree of linear magnetoresistance, is found to correlate inversely with measures of disorder. Our results demonstrate the importance of engineering high quality material with dilute concentrations of point defects to optimize the magnetoresistance properties in topological semimetals.[4]

[1] A.D. Rice, K. Park, E.T. Hughes, K. Mukherjee and K. Alberi, *Phys. Rev. Mater.*, **3**, 121201(R) (2019)

[1] M. Goyal, S. Salmani-Rezaie, T.N. Pardue, B. Guo, D.A. Kealhofer and S. Stemmer, *APL Mater.*, **8**, 051106 (2020)

[1] I.A. Leahy, Y.-P. Lin, P.E. Siegfried, A.C. Treglia, J.C.W. Song, R.M. Nandkishore and M. Lee*, PNAS*, **115**, 10570 (2018)

[1] J. N. Nelson, A. D. Rice, C. Brooks, I. A. Leahy, G. Teeter, M. Van Schilfgaarde, S. Lany, B. Fluegel, M. Lee, K. Alberi *arXiv:2206.10023* (2022).

Quantum Information Science Focus Topic
Room 302 - Session QS+AP+EM+MN+NS+SS-ThM

Systems and Devices for Quantum Computing

Moderators: Vivekananda Adiga, IBM, T.J. Watson Research Center, **Kathy-Anne Soderberg**, Air Force Research Laboratory

8:00am **QS+AP+EM+MN+NS+SS-ThM-1 Effects of Environmental Radioactivity on Superconducting Qubits***, L. Cardani, **Ambra Mariani**,* Istituto Nazionale di Fisica Nucleare, Italy **INVITED**

Environmental radioactivity was recently discovered as a potential limit for superconducting quantum bits.

We review recent works proving that ionizing radiation lowers the coherence of singe qubits and induces correlated errors in qubits arrays. We also present preliminary studies showing that operating qubits in a low-radioactivity environment improves their performance. These results fuelled the interest of several European and US groups in further investigating and mitigating radioactivity for next-generation quantum processors.

Using radioactivity measurements and simulations, we estimated the separate contribution of “far” radioactive sources (cosmic rays and laboratory radioactivity) and close materials contamination (chip holder, magnetic shield, …) on a typical chip, focussing on a qubit prototype developed within the SQMS center. We present such contributions and discuss the possibility of mitigating them in "standard" qubit laboratories or, eventually, in deep underground facilities.

8:40am **QS+AP+EM+MN+NS+SS-ThM-3 Dynamics of a Dispersively Coupled Transmon in the Presence of Noise from the Control Line***, **Antti Vaaranta**,* Bluefors Oy, Finland*; M. Cattaneo,* University of Helsinki, Italy*; R. Lake,* Bluefors Oy

In this talk we present theoretical results from a complete description of transmon qubit dynamics in the presence of noise introduced by an impedance-matched resistor (50 Ohm) that is embedded in the qubit control line, acting as a noise source [1]. We derive a model to calculate the qubit decoherence rate due to the noise emanating from this noise source [2]. The resistor is treated, using the Caldeira-Leggett model, as an infinite collection of harmonic LC-oscillators making it a bosonic bath [3]. To obtain the qubit time evolution affected by this remote bath, we start with the microscopic derivation of the Lindblad master equation using the dispersive Jaynes-Cummings Hamiltonian with added inductive coupling to the bath. To solve the resulting master equation, we transform it into a block diagonal form by exploiting its underlying symmetries following Ref. 4. The block diagonalization method reveals that the long time decoherence rate is given by the slowest decaying eigenmode of the Liouvillian superoperator. Moreover, when the readout resonator is in the equilibrium thermal state, the rate of exponential decoherence of the qubit is almost exactly exponential for all times with the predicted rate given by the slowest decaying eigenmode. We also study how the decoherence rate depends on the temperature of the noise source and explore the strong and weak dispersive coupling regimes. The model captures the often used dispersive strong limit approximation of the qubit decoherence rate being linearly proportional to the number of thermal photons in the readout resonator. However, in the dispersive weak limit we predict remarkably better decoherence rates. The model parameters are completely determined by the values of the circuit components, allowing for the exact study of the dynamics on the level of each individual circuit element.

[1] S. Simbierowicz et al., Rev. Sci. Instrum. 92, 034708 (2021).

[2] A. Vaaranta, Study of environmental effects on a dispersive transmon qubit, MSc thesis, Univ. of Helsinki, (2022).

[3] M. Cattaneo and G. Paraoanu, Adv. Quantum Technol. 2100054 (2021).

[4] M. Cattaneo et al., Phys. Rev. A 101, 042108 (2020).

9:00am **QS+AP+EM+MN+NS+SS-ThM-4 Accurate Microwave Characterization for Superconducting Quantum Technology***, **Slawomir Simbierowicz**,* Bluefors Oy, Finland

Recent breakthroughs in quantum technology have highlighted a need for methods for accurate characterization of cryogenic microwave devices at millikelvin temperatures. In this two-part talk, I will highlight recent progress on microwave measurements at the quantum device reference plane including: (1) system noise characterization of amplifier chains, and (2) calibrated S-parameters of qubit drive line components.In the first part, I will discuss an impedance-matched variable temperature noise source which can be installed in a coaxial line of a cryostat. Using the method of hot/cold source with many input noise temperature points, the system noise temperatures of qubit readout amplifier cascades can be determined. I present measurement results in terms of added noise in Kelvins or photons from a four-wave (4WM) mixing traveling wave parametric amplifier (TWPA) [1], a Josephson parametric amplifier [2], 3WM TWPA, and high electron mobility transistor amplifiers [1].In the second part of the talk, I will present measurements of the 1-port S-parameters of qubit drive line components using a data-based short-open-load calibration at a temperature of 30 mK [3]. The measurement enables us to model systematic errors in qubit state preparation due to non-idealities in qubit control lines such as impedance mismatch. We model the results using a master equation simulation of all XY gates performed on a single qubit. Our work directly addresses the gap between electrical engineering parameters of individual measurement components and performance of the quantum device itself.

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[2] Mustafa Bal et al., “Overlap junctions for superconducting quantum electronics and amplifiers”, Appl. Phys. Lett. **118**, 112601 (2021)

[3] Slawomir Simbierowicz, Volodymyr Y. Monarkha, Suren Singh, Nizar Messaoudi, Philip Krantz, and Russell E. Lake, "Microwave calibration of qubit drive line components at millikelvin temperatures", Appl. Phys. Lett. **120**, 054004 (2022)

9:20am **QS+AP+EM+MN+NS+SS-ThM-5 Improving Qubit Performance Through Engineering of the Substrate-Josephson Junction Interface***, **Cameron Kopas**, H. Cansizoglu, R. Cochrane, B. Ercan,* Rigetti Computing*; D. Goronzy, C. Torres-Castanedo,* Northwestern University*; J. Oh,* Ames Laboratory*; A. Murthy,* Fermi Lab*; E. Lachman,* Rigetti Computing*; A. Romanenko, A. Grassellino,* Fermi Lab*; M. Kramer, L. Zhou,* Ames Laboratory*; M. Bedzyk,* Northwestern University*; J. Mutus,* Rigetti Computing*; M. Hersam,* Northwestern University*; K. Yadavalli,* Rigetti Computing **INVITED**

The performance of a superconducting qubit is often limited by dissipation and two-level systems (TLS) losses. The dominant sources of these losses are believed to come from interfaces and surfaces, likely as a result of fabrication processes, materials, or atmospheric exposure. We show that certain chemical surface treatments can be used to modify the silicon surface before Josephson junction deposition, reducing the number of strongly-coupled TLS, and improving T1. While identifying specific microscopic sources for loss and TLS is still an open question, targeted characterization of test structures will show which physical changes correlate with performance improvements. We report chemical, structural, and low-temperature microwave characterization of superconducting qubits and films fabricated with different Si surface treatments.

11:00am **QS+AP+EM+MN+NS+SS-ThM-10 Design and Optimal Control of Superconducting Qubits to Achieve Quantum Speed Limits***, **Meenakshi Singh**,* Colorado School of Mines, USA **INVITED**

Fast two-qubit entangling gates are essential for quantum computers with finite coherence times. The finite interaction strength between qubits introduces a theoretical speed limit on the speed of these two-qubit entangling gates. This speed limit has been analytically found only for a two-qubit system under the assumption of negligible single qubit gate times. Here, we demonstrate such a speed limit experimentally using optimal control on two superconducting transmon qubits with a fixed capacitive coupling and finite single qubit gate times. Furthermore, we investigate the effect of additional couplings on the speed limit, both through introduction of an ancillary qubit as well as through utilization of higher transmon energy states. Finally, we discuss the generalization to many qubit systems where properly leveraging all available couplings can provide dramatic speedups.

11:40am **QS+AP+EM+MN+NS+SS-ThM-12 Atomic Scale Processing for Quantum Computing***, Harm Knoops,* Oxford Instruments Plasma Technology, Netherlands **INVITED**

With the increasing technological readiness of quantum technology (QT) the field has to start focussing on scalable fabrication methods for quantum bits (qubits) and quantum circuits. This contribution will focus on the enabling role atomic scale processing (ASP) methods such as atomic layer deposition (ALD) and atomic layer etching could play in scaling of QT. The main focus will relate to superconducting qubits and processing of superconducting nanolayers.

Superconducting nanolayers (metals, metal-nitrides) are required for various roles in QT including use in resonators, single-photon detectors, and interconnects.[1] The electrical contacts needed to control the qubits will require non-planar connectivity using superconducting interconnects.[2]Adequate routes for fabrication of planar superconducting layers exist, but for 3D interconnects or through-silicon vias (TSVs), the excellent conformality of ALD nanolayers could be essential. Although for resonators conformality is not a challenge, ALD's thickness control and uniformity should allow high-quality resonators with low spread in properties. For these superconducting nanolayers, metal-nitride compounds have been identified as particularly promising since they exhibit limited surface oxidation (compared to pure metals such as Nb), combined with relatively high critical temperature (T_c) for superconductivity (e.g., as compared to Al). Despite the challenges that the synthesis of high-quality nitrides pose, plasma ALD has demonstrated the capability to deposit high-quality nitrides (e.g., low O content, high electrical conductivity).[3] Furthermore, substrate-biased plasma-ALD offers unique opportunities to obtain and tune high-quality nitrides.[4] For removal of surface oxides or smoothing of resonator surfaces and interfaces, approaches combining ALD and ALE could be of interest.[5] Both ALD and ALE are envisaged to be key tools to allow scaling of these devices and advance the QT field.

References

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2. Kjaergaard et al., *Annu. Rev. Condens. Matter Phys.***11**, 369 (2020)
3. Knoops et al., *J. Vac. Sci. Technol. A***37**, 030902 (2019)
4. Faraz et al., *ACS Appl. Mater. Interfaces***10**, 13158 (2018)
5. Chittock et al, *Appl. Phys. Lett.* **117**, 162107 (2020)

Quantum Information Science Focus Topic
Room 302 - Session QS+EM+MN+NS-ThA

The Quantum Metrology Revolution

Moderator: Dave Pappas, Rigetti Computing

2:20pm **QS+EM+MN+NS-ThA-1 Magnetic Textures in Quantum Materials Revealed by SQUID-on-tip Microscopy*, Ella Lachman,*** Rigetti Computing **INVITED**

Quantum materials are rapidly emerging as the basis for possible novel computation devices. However, fully understanding the interplay between magnetic and electronic excitations prevents us from realizing their full potential. In my talk, I will present the nano-SQUID-on-tip device and the scanning microscope built around it. Originally built to study superconducting vortex dynamics, this microscope has unprecedented magnetic sensitivity and spatial resolution.

I will show how expanding the microscope's range and realizing the microscopic magnetic textures in quantum materials is crucial to the understanding of transport phenomena on the macro scale. This will be demonstrated with two examples from two different types of materials. First, I will show how scanning nanoSQUID-on-tip magnetic imaging of magnetically doped topological insulators reveals the underlying fragility of the Quantum Anomalous Hall effect at elevated temperatures. Then, I will show how with a combination of transport, magnetization, and magnetic imaging of the Weyl semimetal $Co_3Sn_2S_2$, we find that the dynamics of domain walls are responsible for the anomalous transport behavior in the material.

These examples show that better understanding of the microscopic magnetism in these systems reveal new phenomena and deepen our understanding of the interplay between magnetic textures and electronic properties.

3:00pm **QS+EM+MN+NS-ThA-3 Quantum-Based Measurements for Pressure and Vacuum and the NIST on a Chip Program*, Jay Hendricks,*** *B. Goldstein,* NIST

The world of pressure and vacuum measurements and standards is currently undergoing a revolution in both measurement traceability, “the fundamental philosophy behind a measurement chain back to primary units”, and measurement technology, the “how a measurement is made”.This keynote 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.The role of NIST as a National Metrology institute is described along with an explanation of how and why our world-wide standards changed on May 20th, 2019.The NIST on a Chip program (NOAC) is introduced which seeks to utilize fundamental physics and laws of nature to develop quantum-based sensors and standards that one day may be miniatured to the chip scale.The technical core of the lecture will be a deeper dive into new research on measurement methods for pressure, the Fixed Length Optical Cavity (FLOC) and for vacuum, the Cold Atom Vacuum Standard (CAVS).What is exciting about these new measurement approaches is that they are both primary (relying on fundamental physics), are quantum-based and use photons for the measurement readout which is key for taking advantage of the fast-growing field of photonics. The FLOC will enable the elimination of mercury barometers pressure standards worldwide and the CAVS will be first primary standard for making vacuum measurements below 1.3x10-5 Pa.

3:20pm **QS+EM+MN+NS-ThA-4 Materials and Devices for Efficient Quantum Memories and Sensors*, Lee Bassett,*** University of Pennsylvania **INVITED**

Certain point defects in semiconductors exhibit quantum-mechanical features comparable to isolated atoms or molecules, in a solid-state materials platform amenable to nanofabrication, heterointegration with other materials and classical devices, and large-scale system engineering. Well-known quantum point defects such as the diamond nitrogen-vacancy center are leading candidates as robust quantum memories, versatile quantum sensors, and efficient light-matter interfaces. Meanwhile it is increasingly clear that alternative materials and defect systems offer potential advantages and new capabilities for quantum science [1]. However, millions of potential defects exist, and their identification is often tedious and challenging. This talk will introduce the opportunities and challenges of identifying point defects, including several new approaches to efficiently predict, characterize, and engineer their properties for quantum science and technology.

[1] L. C. Bassett, A. Alkauskas, A. L. Exarhos, and K.-M. C. Fu, "Quantum defects by design" Nanophotonics 8, 1867 (2019).

Funding: We acknowledge support from the NSF (DMR-1922278 and DMR-2019444).

Quantum Information Science Focus Topic
Room Ballroom A - Session QS-ThP
Quantum Information Science Poster Session

QS-ThP-2 Creating, Controlling, and Characterizing Quantum Emission in Hexagonal Boron Nitride*, **Annemarie Exarhos,*** Lafayette College*; D. Hopper, R. Patel, R. Grote,* University of Pennsylvania*; A. Alkauskas,* Center for Physical Sciences and Technology, Lithuania*; M. Doherty,* Australian National University, Australia*; L. Bassett,* University of Pennsylvania

Optically addressable spins associated with localized defects in wide-bandgap semiconductors are the basis for rapidly expanding quantum technologies in nanoscale sensing and quantum information processing. Most research has focused on three-dimensional host materials such as diamond and silicon carbide, but more recent reports of single-photon emission – also known as quantum emission - from van der Waals materials has led to an increasingly active area of research focused on these systems. Within the family of two-dimensional materials, hexagonal boron nitride (hBN) has emerged as a robust host for bright, stable, room-temperature quantum emitters. However, many questions persist regarding the chemical and electronic structure of the defects responsible for emission as well as the potential role of spin-related effects. Significantly complicating the identification is the heterogeneity of optical characteristics observed for these quantum emitters.

Our studies focus on identifying and characterizing the optical and magnetic properties of quantum emitters in suspended hBN films in ambient conditions, via confocal fluorescence microscopy. Some qualitative similarities in optical dipole orientation, spectral shape, and emission statistics are evident among quantum emitters in hBN, even for large variations in emission energy, though some emitters exhibit significantly different behavior, suggesting that quantum emission in hBN may result from chemically different types of defects, different charge states of the same defect, or as the result of strong local perturbations [1]. Significantly, a small percentage of observed quantum emitters exhibit strongly anisotropic photoluminescence modulation in response to an applied magnetic field at room temperature [2]. The magnetic-field-induced modulation is consistent with an electronic model featuring a spin-dependent inter-system crossing between triplet and singlet manifolds, suggesting that these defects host optically addressable spin states. This discovery represents a critical step towards the realization of spin-based quantum technologies using van der Waals heterostructures. More broadly, the experimental considerations and techniques involved in this work provide a roadmap for the future experimental identification of quantum emitters in other wide-bandgap structures, paving the way for the discovery of quantum emitters with varying properties in a variety of hosts for use in future quantum technologies.

[1] Exarhos et al., ACS Nano 11, 3328 (2017).

[2] Exarhos et al., Nature Communications 10, 222 (2019).

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