Thursday Afternoon, January 19, 2023

AVS Quantum Science Workshop
Room Redondo - Session AQS-ThA1

AVS Quantum Science Workshop: NV Sensors for Quantum Sensing

Moderator: Andrew Yeats, Naval Research Laboratory

1:55pm **AQS-ThA1-1 AQS Workshop Welcome and Opening Remarks***,*

2:00pm **AQS-ThA1-2 Quantum Sensing with NV Centers***,* ***Erika Janitz****, C. Degen,* ETH Zürich, Switzerland **INVITED**

The electronic spins of single atomic defects in diamond can serve as magnetic sensors with exquisite sensitivity and nanoscale spatial resolution. One such defect -- the nitrogen-vacancy (NV) center -- is particularly well-suited as it retains excellent spin coherence under a variety of experimental (including ambient) conditions with efficient mechanisms for optical spin initialization and readout. A primary focus of our group has been to optimize the sensing capability of near-surface (<10-nm-deep) NV centers for the development of a nanoscale-NMR platform aimed at structural determination of single molecules. I will discuss recent progress toward this goal, including diamond fabrication and surface treatments designed to improve detection sensitivity while simultaneously enabling highly generalizable molecular surface functionalization [1]. Currently, we are extending these techniques toward detecting conformational changes in biomolecules bound to the diamond surface. In parallel to NMR studies, our group has developed a scanning NV platform for imaging magnetic samples with ~50 nm spatial resolution at a wide range of temperatures (~350 mK [2] – room temperature). I will present recent results from this initiative, including images of nanoscale currents in graphene [3], antiferromagnetic materials [4], and superconductivity in nanostructures [2]. Finally, I will conclude with an outlook on extending this diamond-based sensing toolbox to study electric fields as well as opportunities for utilizing alternative diamond defects.

[1] Abendroth *et al*., Nano Letters **22,** (2022).

[2] Scheidegger *et al.,* Applied Physics Letters **120**, (2022).

[3] Palm *et al.,* PRApplied **17**, (2022).

[4] Huxter *et al.,* Nature Communications **13,** (2022).

2:40pm **AQS-ThA1-10 Diamond Quantum Sensors: Sensitivity Frontier***, V. Acosta,* ***Yaser Silani****,* University of New Mexico **INVITED**

Color centers in wide-bandgap semiconductors have emerged as a leading platform in the field of quantum sensing, broadly defined as the use of qubits to measure environmental parameters. In my lab at the University of New Mexico, we are using Nitrogen-Vacancy (NV) spin qubits in diamond to image magnetic phenomena in condensed-matter and biological systems over a broad range of length scales.

At the nanometer scale, we build super-resolution diamond magnetic microscopes to image, for example, super paramagnetic iron oxide nanoparticles used as bio-tags. At the micrometer scale, we embed diamond quantum sensors inside microfluidic chips to perform nuclear magnetic resonance spectroscopy at the length scale of single cells. At the millimeter scale, we use magnetic flux concentrators to detect femtotesla-level magnetic fields and perform nuclear quadrupole resonance of powders, with potential applications in chemical analysis, navigation, and the search for new elementary particles.

I will provide an overview of the field, discuss recent results and ongoing challenges, and outline future directions.

AVS Quantum Science Workshop
Room Redondo - Session AQS-ThA2

AVS Quantum Science Workshop: Color Centers for Quantum Sensing

Moderator: Tongcang Li, Purdue University

3:50pm **AQS-ThA2-24 Engineering Diamond for Quantum Sensing***,* ***Jennifer M. Schloss****, J. Mallek, D. deQuilettes, E. Price, L. Pham, J. Barry, M. Steinecker, D. Phillips, D. Braje,* Massachusetts Institute of Technology Lincoln Laboratory **INVITED**

Diamond hosts a wide array of color centers, several of which demonstrate outstanding optical and spin properties. Among these defects, the nitrogen vacancy center in its negatively charged state (NV-) has emerged as a promising emitter for quantum sensing, owing to its unique combination of characteristics including: (1) robust operation over wide-ranging conditions; (2) optical and microwave control of the NV- quantum states without need for narrow-band lasers or cryogens, and (3) capability for vector magnetic field sensing and high-resolution imaging.

Harnessing the potential of these centers requires tailoring their density and charge state distribution as well as the surrounding environment. Plasma enhanced chemical vapor deposition (PECVD) has become a key enabling technology for this optimization. NVdense layers of engineered material may be created through in-situ doping into highcrystalline-quality diamond lattice. Tailored material is fashioned through a combination of PECVD growth together with post-growth processing such as electron irradiation and high temperature annealing.

We will show how diamond is optimized for quantum sensors through a supervised machine-learning based feedback approach. Through highlighting some recent optimized diamonds, we will demonstrate how critical properties such as N-doping density and strain differ for bulk magnetometry [1, 2] and magnetic imagers.

[1] E. Eisenach et al. Nature Communications 12 1357 (2021)

[2] S. Alsid et al. arXiv:2206.15440 (2022)

+ Author for correspondence: Jennifer.Schloss@ll.mit.edu

4:30pm **AQS-ThA2-32 Quantum Diamond Sensors — Best of Both Worlds***,* ***Ron Walsworth****,* University of Maryland **INVITED**

The nitrogen–vacancy (NV) quantum defect in diamond is a leading modality for magnetic, electrical, temperature, and pressure sensing and imaging with high spatial resolution and wide field-of-view under ambient and extreme conditions. This quantum sensing technology has diverse applications across the physical and life sciences — from probing magnetic materials to biomedical diagnostics. I will provide an overview of quantum diamond sensors and their many applications, with a focus on the enabling material properties and future challenges for improved performance.

5:10pm **AQS-ThA2-40 Spin-Carrying Quantum Centers in Wide-Band Gap Semiconductors as Magnetometry Sensors for Space Applications***,* ***Hannes Kraus****, A. Gottscholl, C. Cochrane,* Jet Propulsion Laboratory **INVITED**

There are various forms of magnetometers currently in development and each significantly vary in terms of their size, cost, complexity, and performance. However, only a small subset of them can be used in the remote and harsh environment of space due to the heavy requirements levied on the instrument prior to flight. These space bound magnetometers should be reliable, simple, and robust. With over 60 years of development heritage, Fluxgate and optically pumped atomic gas-based magnetometers are the most commonly used instruments for missions in space.

However, recent trends in spaceflight towards smaller and cheaper spacecraft (e.g. CubeSats) necessitate also downscaling size and complexity of scientific instruments. Here, solid-state quantum effect-based magnetometer instruments enter the spotlight. The wide band-gap nature of materials like silicon carbide (SiC), diamond or hexagonal boron nitride (hBN) allows application in harsh environments, while sub-gap defects carrying spins, which can be addressed optically and electrically, contribute magnetic field sensitivity through magnetic resonance response.

The *SiCMAG* electrically detected magnetometer sensor leverages an increased spindependent recombination (SDR) current furnished through sub-gap silicon vacancy (VSi) defects in SiC. Quantum singlet-multiplet mixing effects close to zero field make those devices sensitive to minuscule modulation of the magnetic field around zero. Under electron paramagnetic resonance (EPR) conditions under a bias field, the sensor becomes an EPR spectrometer, allowing detection of electron-nuclear hyperfine interaction (HFI), and thus enabling an in-situ absolute magnetic field calibration to the physically constant HFI.

Current sensitivities of unoptimized sensors reach the order of 1μT/√Hz. The *OPuS-MAGNM* optically pumped solid state quantum magnetometer operates on a similar approach, with addressing and readout of the magnetically sensitive quantum centers happening through optical excitation and detection. Lab-scale instruments using diamond NV centers have already shown sensitivities below 100pT/√Hz. We show progress building an integrated sensor using the SiC VSi center, and an outlook on how this sensor is easily adaptable to the other mentioned quantum solid state material systems, i.e. diamond NV centers and hBN.

Friday Morning, January 20, 2023

AVS Quantum Science Workshop
Room Redondo - Session AQS-FrM1

AVS Quantum Science Workshop: Superconducting Quantum Computing

Moderator: Hannes Kraus, Jet Propulsion Laboratory

8:45am **AQS-FrM1-1 Laser-Annealing Josephson Junctions to Achieve Scaled-Up High-Performance SuperconductingQuantum Processors***, **Jared Hertzberg**,* IBM Research **INVITED**

As we increase the scale of superconducting quantum-computing circuits, we face challenges in maintaining high-fidelity quantum gates across the device. Fixed-frequency tansmons offer excellent coherence, noise stability and simplicity of operation, making them an ideal qubit platform for large-scale circuits. However, established fabrication methods cannot set the frequencies of such qubits with precision better than about 2%. High two-qubit gate fidelities require precise control of the relative qubit frequencies. To quantify the precision needed, we define "frequency collisions" in a cross-resonance gate architecture, and show statistically that 2% frequency precision is insufficient to evade such collisions. To overcome this challenge, we introduce a 'heavy hexagon' lattice of qubits along with selective laser-anneal to tune the qubits into desired frequency patterns. This anneal procedure offers a nearly tenfold improvement in qubit frequency precision. In 28-qubit and 65-qubit processors, we demonstrate no measurable effect of this tuning on qubit coherence, and median two-qubit gate fidelity of 98.7%. We discuss the application of these techniques to the current generation of processors at 100-qubit scale, as well as prospects for further scaling. Precise control of qubit frequencies will be essential to increasing quantum volume and to achieving quantum advantage, at the 1000 qubit scale and beyond.

References:

[1] Zhang, E. J. et al. High-Performance Superconducting Quantum Processors via Laser Annealing of Transmon Qubits. *Science Advances* **2022**, *8* (19), eabi6690.

[2] Hertzberg, J. B. et al. Laser-Annealing Josephson Junctions for Yielding Scaled-up Superconducting Quantum Processors. *npj Quantum Inf* **2021**, *7* (1), 1–8.

[3] Chamberland, C. et al. Topological and Subsystem Codes on Low-Degree Graphs with Flag Qubits. *Phys. Rev. X* **2020**, *10* (1), 011022.

9:25am **AQS-FrM1-9 Progress Towards Merged-Element Transmons***, **David Pappas**, E. Lachman, J. Mutus,* Rigetti Computing*; C. Palmstrom,* University of California Santa Barbara **INVITED**

Transmons have become the dominant type of qubit used for superconducting quantum computing. This is primarily due to their relative charge insensitivity and well defined anharmonicity. However, significant technical challenges are presented in the areas of frequency allocation and loss. These challenges can be traced back to the use of amorphous, ultra-thin tunnel junctions used to generate the non-linear inductance. These challenges can be mitigated by actively trimming the junction normal resistance and using a quasi-lumped element approach, with very small junctions in parallel with a large shunt capacitor. However, it is clear that improvement of the frequency spreads will still likely be limited by fluctuations in the superconducting Josephson inductance and reductions of the size of the devices (typically on the order of 100's of um^2) will be limited by the shunt capacitors. In addition, the appearance of spurious two-level systems in the amorphous material is still an issue. In this talk we will discuss the concept and implementations of the merged-element transmon (MET). The design goals and demonstrated optimization for low-loss will be presented, along with the new proposal for addressing the frequency allocation problem and achieving sub-um devices using single-crystal, fin-based tunneling technology.

AVS Quantum Science Workshop
Room Redondo - Session AQS-FrM2

AVS Quantum Science Workshop: Novel Materials for Quantum Computing

Moderator: Ron Walsworth, University of Maryland

10:35am **AQS-FrM2-23 A Neutral Atom Quantum Processor Supporting Long Coherence Times***, **Kristen Pudenz**,* Atom Computing **INVITED**

Atom Computing is creating a quantum processing platform based on nuclear spin qubits. The system makes use of optical tweezers to assemble and individually manipulate a two-dimensional register of neutral strontium atoms. We demonstrate the robustness of these systems by characterizing their coherence times. While other systems have shown impressive coherence times through some combination of shielding, careful trapping, global operations, and dynamical decoupling,we achieve comparable coherence times while individually driving multiple qubits in parallel. The talk will also explore progress on a 100 qubit hardware platform and the potential of the technology to create scalable quantum computing solutions.

11:15am **AQS-FrM2-31 Scalable Integrated Quantumdotnetworks and Nanophotonic Neuromorphic 'Brain-Inspired' Computing***, J. Grim, A. Bracker, J. Hart,* Naval Research Laboratory*; S. Carter,* Laboratory of Physical Sciences*; C. Kim,* Naval Research Laboratory*; M. Kim,* Jacobs*; I. Welland, K. Tran, I. Vurgaftman, T. Reinecke, **Andrew Yeats**,* Naval Research Laboratory **INVITED**

I will show progress from our quantum optics team toward creatingscalable integrated semiconductor quantum dot (QD) networks. This work is motivated by the prospects of photonic quantum computing, simulation, communication, and sensing. We use InAs QDsthat are embedded in GaAs photonic crystal membranes thatcan host electron/hole spin qubitsand can be connected with 'flying qubit' single photons. Although QDs have become very advanced with numerous demonstrations ofhighphoton indistinguishability, quantum transistors, and spin-spin entanglement, these efforts have been limited to one, and at most, two QDs (a limitation shared by all solid-state single photon sources). Our team has recently made a breakthrough with a technique that enablesscalable tuning of QDs into resonance. We have leveraged this technique to perform a demonstration of an entangled, superradiant state from multiple QDscoupled tothe same photonic crystalwaveguide1. We have also used this technique to realize collective scatteringof laser light from two QDs, and have observed an enhanced optical nonlinearity at the few-photon level2.I will also present our workin the area ofneuromorphics ('brain-inspired' computing), where we aim to use the nonlinear dynamics ofnetworks ofnanolasers for low size, weight, and power machine learning.

1.Grim, J. Q. *et al.*Scalable in operando strain tuning in nanophotonic waveguides enabling three-quantum-dot superradiance. *NatureMater.***18**, 963–969 (2019).

2.Grim, J. Q. *et al.*Scattering laser light from two resonant quantum dots in a photonic crystal waveguide. *Phys. Rev. B***106**, L081403 (2022).

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AVS Quantum Science Workshop
Room Redondo - Session AQS-FrA1

AVS Quantum Science Workshop: Topological Quantum Materials

Moderator: Erika Janitz, ETH Zürich

2:00pm **AQS-FrA1-1 Topological Materials, a New Quantum State of Matter*, Luis A. Jauregui,*** University of California Irvine **INVITED**

Topological order and materials have been at the center of attention in condensed matter physics and engineering. Topological materials, a new quantum state of matter, are a family of quantum materials with boundary states whose physical properties are robust against disorder. Therefore, there have been few examples of a topological phase transition realized experimentally, and even fewer cases of an in-situ tuning of the topological phase. I will discuss our results and methods to apply uniaxial strain in topological van der Waals quantum materials and how it influences its electrical properties. Our results point towards a topological phase transition of the system tuned by in situ uniaxial strain. By measuring the electrical properties of high-quality thin topological heterostructures, we observe that the non-zero Berry curvature enables an anomalous Hall effect in our samples and its influence can be tuned by the carrier density, temperature, and magnetic field. Our results could pave the way towards creating and controlling topological phases of matter by strain and heterostructure engineering in quantum materials at the same time they would enable the creation of novel quantum electronic devices.

2:40pm **AQS-FrA1-9 Probing Topologically Protected Quantum States with Scanning Tunneling Microscopy*, An-Ping Li,*** Center for Nanophase Materials Sciences, Oak Ridge National Laboratory **INVITED**

Topological quantum materials are a promising platform to investigate the interplay of dimension, symmetry, magnetism, and topology. In this talk, I will present a few examples to illustrate how scanning tunneling microscopy (STM) and 4-probe STM can be used to assess a variety of quantum states in topological magnet $MnBi_2Te_4$ (MBT). First, using Sb substitutions at Bi sites, we are able to tune the Fermi level of $MnBi_{2-x}Sb_xTe_4$ so that the bulk carrier density is minimized to allow for access to the surface states. A surface band gap has been revealed around the Dirac point inside the bulk band gap [1]. In situ transport spectroscopy using our unique 4-probe STM has confirmed the surface nature of the carriers at the Fermi level through the exhibition of 100 % surface-dominant conductance [2]. The surface band gap is found to be topologically protected and robust against magnetic field up to 9 T [1]. Second, the exchange is shown to vary widely across the surface due to the chemical disorder, which reconciles the conflicting reports on the existence of such a gap in the literature. By mapping the local density of states in the topological surface state, we are able to pinpoint nanoscale fluctuations in the local surface gap and doping level and disentangle the roles of the individual types of defects on the electronic properties of the compound [3]. Third, by employing $MnBi_2Te_4$ films with varying film thickness, we can systematically study thickness-dependent electronic properties as well as edge states as the film changes layer thickness. The band inversion is observed as the film thickness increases continuously from one to six septuple layers. The inverted band gaps oscillate with thickness, indicative of alternating QAH and axion insulator phases as corroborated by extensive theoretical calculations. At step edges, we observe localized electronic states, in agreement with axion insulator and QAH edge states, respectively, indicating topological phase transitions across the steps [4]. These results highlight the role of nanoscale control over novel quantum states, reinforcing the necessity of local probing techniques in understanding quantum materials.

[1] W. Ko et al, Phys. Rev. B 102, 115402 (2020).

[2] W. Ko et al, Phys. Rev. Lett. 121, 176801 (2018).

[3] F. Lüpke et al, arXiv:2208.13374.

[4] F. Lüpke et al, Phys. Rev. B 105, 035423 (2022).

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

AVS Quantum Science Workshop
Room Redondo - Session AQS-FrA2

AVS Quantum Science Workshop: 2D Materials for Quantum Sensing

Moderator: Chip Eddy, Jr., ONR Global

3:50pm **AQS-FrA2-23 Artificial Graphene Nanoribbons with Tailored Topological States*, Nathan P. Guisinger,*** Argonne National Laboratory **INVITED**

Low-dimensional materials functioning at the nanoscale are a critical component for a variety of current and future technologies.From the optimization of light harvesting solar technologies to novel electronic and magnetic device architectures, key physical phenomena are occurring at the nanometer and atomic length-scales and predominately at interfaces.In this presentation, I will discuss low-dimensional material research occurring in the Quantum and Energy Materials (QEM) group at the Center for Nanoscale Materials.Specifically, the synthesis of artificial graphene nanoribbons by positioning carbon monoxide molecules on a copper surface to confine its surface state electrons into artificial atoms positioned to emulate the low-energy electronic structure of graphene derivatives.We demonstrate that the dimensionality of artificial graphene can be reduced to one dimension with proper “edge” passivation, with the emergence of an effectively-gapped one-dimensional nanoribbon structure. Remarkably, these one-dimensional structures show evidence of topological effects analogous to graphene nanoribbons. Guided by first-principles calculations, we spatially explore robust, zero-dimensional topological states by altering the topological invariants of quasi-one-dimensional artificial graphene nanostructures. The robustness and flexibility of our platform allows us to toggle the topological invariants between trivial and non-trivial on the same nanostructure.Our atomic synthesis gives access to nanoribbon geometries beyond the current reach of synthetic chemistry, and thus provides an ideal platform for the design and study of novel topological and quantum states of matter.

4:30pm **AQS-FrA2-31 Quantum Sensing and Nuclear Spin Control with Spin Defects in a 2D Material*, Tongcang Li,*** Purdue University **INVITED**

Spin defects in solids such as diamond have broad applications in quantum sensing and quantum networking. The recent discovery of spin defects in hexagonal boron nitride (hBN), a van der Waals (vdW) layered material, provides new opportunities for these applications. Thanks to its layered structure, hBN can be easily exfoliated and integrated with other materials and nanostructures. Spin qubits in hBN nanosheets will be particularly suitable for probing two-dimensional (2D) quantum materials at atomic and nanoscales. Recently, we created boron vacancy spin defects in hBN with femtosecond laser writing and ion implantation, demonstrated high-contrast plasmon-enhanced spin defects in hBN for quantum sensing [*Nano Letters* 21, 7708 (2021)], and investigated their excited-state spin resonance. In addition, we achieved optical polarization and coherent control of nuclear spins in hBN at room temperature [*Nature Materials* 21, 1024 (2022)]. Our work opens new avenues for manipulation of nuclear spins in vdW materials for quantum information science and technology.

5:10pm **AQS-FrA2-39 AQS Workshop Closing Remarks*,***

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