Tuesday Afternoon, November 7, 2023

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.

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