Quantum Science and Technology Mini-Symposium
Room 123 - Session QS-TuA

Advances in Quantum Dots and Dynamic Effects in Josephson Junctions

Moderators: Sisira Kanhirathingal, Rigetti Computing, **Ekta Bhatia**, NY CREATES

2:15pm **QS-TuA-1 Toward Robust Spin-Optical Interfaces in Molecular Spin Qubits***, **Leah Weiss**, G. Smith,* University of Chicago*; R. Murphy, B. Golesorkhi, J. Long,* University of California at Berkeley*; D. Awschalom,* University of Chicago **INVITED**

Efficient spin-optical interfaces play a key role in quantum technologies ranging from generation of multi-qubit entangled states to remote nanoscale quantum sensing. This interface can be designed from the bottom up in organometallic molecules to enable optical initialization and read out of ground-state molecular spins [1], providing a synthetic analog of solid-state spin qubits. We have shown that by changing the atomic structure of either the molecule or its local environment, the spin and optical properties of this class of qubits can be chemically modified [2,3]. Building on these demonstrations, we report the development of molecular ground-state spin qubits with robust spin-optical coupling. We utilize the observed spin-photon interface to demonstrate all-optical detection of ground-state spin properties in molecular ensembles. These results open avenues for the tailored design of molecular qubits for targeted sensing applications requiring efficient coupling of spins with photons.

[1] S. L. Bayliss,et al., Science. **370**, 6522 (2020).

[2] D. W. Laorenza, et al. JACS. **143**, 50 (2021).

[3] S. L. Bayliss, et al. Phys. Rev. X. **12,** 3 (2022).

2:45pm **QS-TuA-3 Development of a Flip-Chip Induced Quantum Dot Device with Semiconductor Materials***, **Giovanni Franco-Rivera**, J. Marbey, M. Dryer, R. Butera,* Laboratory for Physical Sciences

The ability of the semiconducting industry to manufacture advanced technology devices is expected to speed up the development of quantum computing. Confining few electrons in silicon-based heterostructures via lithographically-designed, gated on-chip quantum dots (QD) enables the manipulation of the spin degree of freedom for quantum information processing. Some of the appealing features of the QD spin qubits are their long coherent properties [1] achievable by solid-state all-electrical control readout [2] leading to recent demonstrations of high fidelity multiqubit operations [3]. However, performance of current state-of-the art QD qubits is typically limited by the fundamental properties of the underlying materials. Moreover, the exploration of new quantum materials as potential hosts of spin qubits is often overlooked due to the complications resulting from developing an overwhelming fabrication process. We propose an alternative method based on a flip-chip geometry allowing a QD to be induced on an arbitrary material of interest. The control chip, separated from the host material by ~100nm, contains all the necessary circuit elements for gating and readout of the QD structure. A vacuum gap separates the control and host chips via an engineered mesa recess and bonding pads. We will present the efforts on the integrated flip-chip design based on a control silicon chip and a host Ge/SiGe heterostructure target chip. Lastly, fabrication efforts and device screening measurements for on-chip Ge/SiGe QD structures are presented enabling future comparison of the device performance between on-chip and flip-chip architectures.[1] J. T. Muhonen et al., Nature Nanotech. 9, 986-991 (2014).[2] P. Harvey-Collard et al., Phys. Rev. X 8, 021046 (2018).[3] A. R. Mills et al., Sci. Adv.8, eabn5130 (2022).

3:00pm **QS-TuA-4 Nanoscale Spatial Control of Colloidal Quantum Dots and Rods Using DNA for Next-Generation Quantum Devices***, X. Luo, C. Chen, **Mark Bathe**,* MIT

Advances in photonic quantum technologies require precise control over quantum emitters at sub-10 nanometer scales for quantum computing and sensing applications. Conventional top-down fabrication methods face limitations in resolution and scalability on this front. In contrast, scalable bottom-up approaches utilizing DNA self-assembly offer unprecedented control over colloidal quantum materials at the nanoscale, such as quantum dots (QDs) and rods (QRs). We program and manipulate QDs and QRs using DNA nanostructures as templates, towards their scalable and precise incorporation into quantum photonic devices. DNA nanotechnology has emerged with unparalleled versatility and accuracy in creating complex, programmable architectures at the nano- to micro- scale (1, 2). Using versatile 3D wireframe DNA templates of customized geometry and chimeric single-stranded DNA (ssDNA) wrapping, we developed a general strategy to program ssDNA valences on QD surfaces (3). This valence-geocoding approach enabled the fabrication of QD energy transfer circuits (3). Using a rigid, planar wireframe DNA origami template, we arranged aligned QRs into 2D arrays on surfaces with nanoscale precision (4). We developed an ultrafast dehydration-assisted method to conjugate a dense layer of ssDNA onto QDs/QRs directly from organic solvent to facilitate their precise and stable assembly to 2D DNA template lattices up to a micron in size (4). To integrate DNA templated QDs/QRs into chip-based photonic devices, we further employed electron beam lithography (EBL) to guide the deterministic patterning of precisely positioned and oriented DNA templates on silicon chips, which were then used to template QDs and QRs with nanoscale accuracy. Scalable production of DNA templates using biologically produced DNA molecules (5) and its application in quantum photonics aligns with initiatives promoting biomanufacturing innovation for a sustainable bioeconomy (6). Combining the strengths of top-down lithography methods and bottom-up DNA self-assembly holds the potential of a scalable, parallel and environmentally benign nanofabrication framework that accurately patterns single colloidal quantum emitters over 2D surfaces on the wafer-scale.

1. Bathe, M. and Rothemund, P. (2017). MRS Bulletin, 42: 882.
2. Knappe, G.A., et al. (2023). Nature Reviews Materials, 8: 123.
3. Chen, C., et al., (2022). Nature Communications, 13: 4935.
4. Chen, C., et al., (2023). Science Advances, 32: eadh8508.
5. Shepherd TR, et al., Scientific Reports. 2019;9(1):6121.

3:15pm **QS-TuA-5 Characterization of epitaxially grown Al-Ge/SiGe quantum wells for voltage-controlled Josephson junctions***, **Joshua Thompson**,* Laboratory for Physical Sciences*; S. Davari,* University of Arkansas*; C. Gaspe, K. Sardashti,* Laboratory for Physical Sciences*; H. Churchill,* University of Arkansas*; C. Richardson,* Laboratory for Physical Sciences

Strained germanium quantum wells host heavy holes with high mobility and low effective mass, which combined with highly transparent epitaxial aluminum creates a promising platform for voltage-controlled superconductor-semiconductor devices that are compatible with standard Si fabrication methods. This talk will discuss the characterization of undoped germanium quantum wells in a SiGe heterostructure grown by molecular beam epitaxy and the fabrication of planar Josephson junctions. By applying an electrostatic gate, the induced two-dimensional hole gas was observed to have a carrier mobility > $2x10^4$ cm^2/Vs with a density < $1x10^{12}$ cm^{-2}. Using an etch process, 50-100 nm Josephson junctions where fabricated on a tall mesa structure and characterized by measuring I_CR_N and the supercurrent dependance on applied gated voltage and magnetic field.

4:00pm **QS-TuA-8 Developing a Novel Approach to Extract the Current-Phase Relation of Josephson Junctions with On-Wafer Microwave Probing and Calibration Techniques***, **Elyse McEntee Wei**,* Colorado School of Mines*; P. Dresselhaus, A. Fox, D. Williams, C. Long,* National Institute of Standards and Technology, Boulder*; S. Eley,* University of Washington

We are developing a novel approach to characterize the current-phase relation (CPR) of Josephson junctions using on-wafer microwave probing and calibration techniques. Josephson junctions are the integral component in superconducting quantum circuits and exhibit a supercurrent that is modulated by a function of the phase difference between the order parameters of the superconducting electrodes, known as the CPR. Typically, the CPR is assumed to be sinusoidal. However, skewing has been observed in junctions with various barrier compositions such as normal metals, ferromagnetic materials, InAs nanowires, and graphene. This skewing can significantly affect the output of devices such as timing in single-flux quantum circuits used for digital logic, as well as the harmonic power in pulsed junction arrays used in voltage standards. The CPR is commonly measured using specialized superconducting quantum interference device (SQUID) circuitry. However SQUIDs are very sensitive to flux noise and can easily couple to nearby circuit components, limiting the ability of the SQUID circuit to measure the CPR. Our approach employs a homebuilt cryogenic probe station for measurements of Josephson junction arrays embedded in superconducting coplanar waveguides. It then involves extracting the Josephson inductance from Josephson transmission lines as a function of bias current using scattering-parameters calibrated with an on-wafer multiline Thru-Reflect-Line calibration to reconstruct the CPR. Here, we apply this approach to studying the CPR in niobium-doped amorphous silicon Josephson junction arrays, in which preliminary data shows evidence of skewing and higher order harmonics. Upon validation, this novel approach would offer broadband, low noise measurements of the CPR, providing critical design information for circuits that are based on Josephson junctions.

4:15pm **QS-TuA-9 Aging effects after Alternating Bias Assisted Annealing of Josephson Junctions***, **David P. Pappas**, X. Wang, J. Howard, E. Sete,* Rigetti Computing*; G. Stiehl,* rice University*; S. Poletto, X. Wu, M. Field, N. Sharac, C. Eckberg, H. Cansizoglu, J. Mutus, K. Yadavalli, A. Bestwick,* Rigetti Computing

New avenues of trimming the resistance of Josephson junctions promise to allow for precise frequency allocation. This can be expected to significantly improve the yield and fidelity of chips and measurements, respectively. In this talk we will discuss the stability of the junction normal resistance over a wide range of time scales.

4:30pm **QS-TuA-10 Evaluating Radiation Impact on Transmon Qubits Using a Fast Decay Protocol in Above and Underground Laboratories***, **Tanay Roy**,* Fermi Lab

Superconducting qubits can be sensitive to sudden energy deposits caused by ambient radioactivity and cosmic rays. Previous studies have focused on understanding possible correlated effects over time and distance due to this radiation. In this study, for the first time, we directly compare the response of a transmon qubit measured initially at the SQMS above-ground facility (Fermilab, Illinois, USA) and then at the deep underground Gran Sasso Laboratory (INFN-LNGS, Italy). We observe the same average qubit lifetime of roughly 80 microseconds at both facilities. We then apply a fast decay detection protocol and investigate the time structure and relative rates of triggered events due to radiation versus intrinsic noise, comparing the above and underground performance of several high-coherence qubits. Using gamma sources of variable intensity we calibrate the response of the qubit to different levels of radiation in an environment with minimal background radiation. Results indicate that qubits respond to a strong gamma source, and it is possible to detect particle impacts. However, we do not observe a difference in radiation-induced-like events when comparing the above and underground results for niobium-based transmon qubits with sapphire substrates. We conclude that the majority of these events are not radiation-related and are attributed to other noise sources, which by far dominate single-qubit errors in modern transmon qubits.

[1] Dominicis, Roy et al. arXiv:2405.18355

4:45pm **QS-TuA-11 Quantum Enhanced Josephson Junction Field-Effect Transistors for Logic Applications***, **W. Pan**, A. Muhowski, W. Martinez, C. Sovinec, J. Mendez, D. Mamaluy,* Sandia National Laboratories

Josephson junction field-effect transistors (JJFET, Fig. 1a) have recently emerged as a promising candidate for low-energy, power-efficient microelectronics applications. JJFETs are particularly useful for low power consumption applications as they are operated with, in the superconducting regime, zero voltage drop across its source and drain. For JJFETs to perform logic operations, the gain-factor (a_R) value must be larger than 1. Here a_R = dIc/d(Vg–Vt) x πΔ/Ic, Δ is the superconducting gap, Vg the gate bias voltage, Vt the threshold voltage. Ic ~ exp(-L/ξ_c) is the critical supercurrent, where L is the channel length and ξ_c the carrier coherence length. In a conventional JJFET, ξc ~ (Vg–Vt)0.5 (Fig. 1b), and thus dIc/d(Vg–Vt) is small (Fig. 1c). This translates to a requirement of superconducting transition temperature of ~ 400K for a_R larger than 1, far exceeding any recorded critical temperatures. As such, it is impossible to use conventional JJFETs for logic operations.

Here, we propose a novel type of JJFET based on quantum phase transition, such as the excitonic insulator (EI) transition in an InAs/GaSb type-II heterostructure, for low-energy, power-efficient logic applications. The nature of the collective phenomenon in the EI quantum phase transition can provide a sharp transition of the supercurrent states (e.g., ξ_c ~ (Vg–Vt)5 and dIc/d(Vg–Vt) very large, as shown in Figs. 1b and 1c, respectively) which will enable a_R larger than 1 with an easy-to-achieve superconducting transition temperature, e.g., ~ 40K.

In this talk, we will present some preliminary results demonstrating that indeed the gain factor in these quantum enhanced JJFETs can be greatly improved, thus making them a promising candidate for logic applications. Fig. 2a shows a JJFET made of a zero-gap InAs/GaSb heterostructure with tantalum (Ta) as the source and drain electrodes. The superconducting critical current in the JJFET is zero when Vg-Vt ≤ 0.23V, but sharply jumps to a finite value at Vg-Vt = 0.24V and then increases slowly as Vg-Vt continues to increase (Fig. 2b). The gain factor is calculated to be ~ 0.06. Though still less than 1, it is already more than 50 times larger than that recently reported in a conventional JJFET made of InAs quantum wells. With further optimization, a sharper excitonic insulator transition can be achieved. Together with a higher superconducting transition temperature, a large gain factor can be expected.

5:00pm **QS-TuA-12 Revealing Signatures of Unconventional Superconductivity in Tunneling Andreev Spectroscopy***, **Petro Maksymovych**, S. Song,* Oak Ridge National Laboratory*; C. Lane,* Los Alamos National Laboratory*; J. Wang,* Oak Ridge National Laboratory*; W. Ko,* University of Tennessee Knoxville*; J. Lado,* Aalto University, Finland

Understanding order parameter symmetry in superconductors continues to be a frontier topic in condensed matter, particularly with the recent surge of new superconducting materials and their prospective applications in quantum information processing. Recently we introduced a new technique to detect Andreev reflection across the tunneling gap - dubbed Tunneling Andreev Reflection (TAR) [1] - which essentially measures the probability of injecting Cooper pairs with atomic-scale contacts. When combined with scanning tunneling microscopy (STM), this method can achieve true atomic-scale imaging of the superconducting state and extend the ability of STM to probe pairing symmetry, magnetism, and topological properties by analogy with Andreev measurements in devices and heterostructures. For example, 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].

To achieve atomic-scale resolution, TAR makes a necessary trade-off in the loss of momentum resolution. It is one of the main differences between TAR and the more traditional, point contact method to measure Andreev reflection, and one the requires a fundamental rethinking of the origins of specific tunneling Andreev spectra. In this talk, based on detailed tight-binding modeling of model Hamiltonians with support from model experiments, we will reveal the basic mechanisms by which TAR spectra connect to the properties of the superconductor. Remarkably, the key ingredients of these spectra can all be rationalized by considering four contributing phenomena: (1) competition between Andreev and single electron tunneling in any given junction; (2) electronic changes of the conductance spectra as a function of increasing coupling strength; (3) energy-dependence of Andreev tunneling, particularly for sign-changing and nodal order parameters; (4) specific details of the band structure. Therefore, tunneling Andreev spectra will in general reflect both intrinsic properties of the superconductor as well as those of the tunneling transport - providing a wealth of information to characterize complicated materials and dramatically expanding the ability of tunneling spectroscopy to search for exotic quantum materials. Research sponsored by Division of Materials Science and Engineering, Basic Energy Sciences, Office of Science, US DOE. SPM experiments were carried at the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, a US DOE User Facility.

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