Tuesday Evening, January 21, 2025

PCSI
Room Keahou I - Session PCSI-TuE

Rump Session: Quantum Computation Materials and Devices and Panel Discussion
Moderator: Christopher Palmstrøm, University of California, Santa Barbara

7:00pm **PCSI-TuE-1 Challenges & Opportunities for Developing Superconducting Quantum Information Systems***, Raymond Simmonds,* National Institute of Standards and Technology, Boulder

Developing large-scale quantum information processors has become a major industrial goal over the last few years. Of the many quantum systems available to tackle this difficult task, superconducting circuits have shown impressive results thus far and appear to be posed to scale up rapidly. In fact, systems with over 1,000 superconducting qubits have already been built and operated. [1] Although scaling the number of qubits as well as the infrastructure to control and measure them is an outstanding challenge, it seems that individual qubit coherence still must improve in order to lower the overhead required to successfully perform quantum error correction, vital for quantum computations. About 20 years ago [2], two-level system defects were found to reside in qubit Josephson junctions: "We report spectroscopic data that show a level splitting characteristic of coupling between a two-state qubit and a two-level system. ...Although two-level systems are known to exist in amorphous materials, the sensitivity of our Josephson qubit at the quantum level has allowed us to uncover individual two-level microwave resonators hidden within a 40-yearold technology. ...We predict that improvements in the coherence of all Josephson qubits will require materials research directed at redistributing, reducing, or removing these resonator states." Since that time, coherence has improved tremendously, but two-level system defects not only in the tunnel junction but residing at all material interfaces continue to pose a significant challenge.

In this presentation, I will provide a basic introduction to superconducting qubits, their fabrication, measurement, and coupled operations. Then, I will focus on some of the difficulties associated with developing superconducting circuits for large scale quantum information processors. Specifically, I will provide a historical overview of early measurements that showed the influence of individual two-level system point defects on qubit operations. In addition, distributions of these defects on surfaces can also work collectively to degrade the coherence of quantum circuits. Even with these defects present, enormous progress has been made thus far in developing quantum information processors. Tackling the remaining materials science challenges associated with fabricating superconducting quantum circuits could lead to a new understanding of creating clean material systems or finding ways to engineer microwave two-level defects as coherent qubits.

7:30pm **PCSI-TuE-7 Spin-Orbit Qubits with Holes in Silicon and Germanium***, Dominik Zumbuhl,* University of Basel, Switzerland **INVITED**

Semiconductor spin qubits are leading candidates for full-scale quantum computation due to their compatibility with industrial nanofabrication and their advantageous quantum properties. Holes spins can be coherently manipulated with all-electrical control due to the spin-orbit interaction (SOI) without requiring micromagnets, but this also opens the door for decoherence by charge noise. Across a broad range of qubits, a pervasive trade-off becomes obvious: increased speed seems only possible at the cost of qubit coherence. This qubit speed-coherence dilemma is posing a fundamental challenge for quantum computation.

In this talk, I will present recent progress on building spin-orbit qubits with holes in Ge/Si core/shell nanowires and Si fin FETs with emphasis on the material challenges at the surfaces and interfaces. Employing machine learning, we have demonstrated fully autonomous tuning of a qubit from grounded gates to operational qubit [1]. The physics of the hole spins is highly interesting and non-trivial, starting with pronounced anisotropies of the g-factor reflecting the heavy-hole light-hole mixing in the strongly confined quasi-1D geometry, leading to a new type of SOI taking place fully in the valence band – the direct Rashba SOI. The two-hole exchange is also highly anisotropic [2], opening the door for fast high fidelity gate operation.

Finally, we demonstrate how the qubit speed and coherence can be maximized together at the same time, thus boosting the Q-factor by over an order of magnitude [3]. Here, this is made possible by heavy-hole light-hole mixing providing a maximum of the spin-orbit strength at finite electrical field. This maximum leads to a minimum in g-factor, decoupling charge fluctuations and enhancing coherence exactly where the drive speed becomes maximal. This proof-of-concept experiment resolves the speed-coherence trade-off and shows a new way forward for fast *and* coherent quantum computing with Si and Ge.

This work was supported by the NCCR SPIN [https://nccr-spin.ch/], the Swiss National quantum computation program of the Swiss NSF, the Swiss Nanoscience Institute (SNI), the Georg H. Endress Foundation, and the EU H2020 European Microkelvin Platform EMP, TOPSQUAD and QUSTEC.

[1] Fully autonomous tuning of a spin qubit, J. Schuff, M. J. Carballido, et al., arXiv:2402.03931.

[2] Anisotropic exchange interaction in a fin field-effect transistor, S. Geyer, B. Hetényi, et al., Nature Physics 20, 1152 (2024).

[3] Compromise-free scaling of qubit speed and coherence, M. J. Carballido et al., arXiv:2402.07313.

8:00pm **PCSI-TuE-13 The Critical Role of Interfaces in Si/SiGe Quantum Dot Qubits: Valley Splitting and Radiation Impacts***, Mark Eriksson,* University of Wisconsin-Madison **INVITED**

Interfaces and other atomic-scale materials features are critical to the operation, properties, and robustness of Si/SiGe quantum dot qubits. In this talk I discuss two important examples.First, the atomic-scale structure of the quantum well in Si/SiGe heterostructures plays the dominant role in determining the valley splitting.This splitting, which arises from a coupling between the two z-valleys in the silicon band structure, determines the energy gap that protects spin-up and spin-down qubit states.If the valley splitting is small, the qubits fail.While the interface between the quantum well and the upper quantum well barrier by itself does cause some valley splitting, recent results demonstrate a new method: silicon quantum wells containing short wavelength oscillations in the concentration of added germanium atoms can significantly increase the valley splitting.Second, there are deeper, buried defect layers that in principle can trap charges induced by external radiation.I will discuss recent experiments that imitate such radiation impacts in Si/SiGe quantum devices using fiber optic illumination on the back of the wafer to deposit energy and induce bursts of electron-hole pairs deep in the bulk of the wafer. We find that some of the generated charge – mostly negative charge (electrons) – migrates to the top region of the wafer and shifts the offset charge of quantum dot qubits. We are able to identify abrupt jumps in the offset charge that appear to arise from trapping of individual electrons. Based on the magnitude of the jumps in the offset charge, the charge trapping occurs within a few hundred nanometers of the qubit. Importantly, the device can be very stable both before and right after the single-charge trapping, as we demonstrate by turning off the optical illumination as soon as a charge jump is observed.

8:30pm **PCSI-TuE-19 Panel Discussion***,*

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