PCSI
Room Canyon/Sugarloaf - Session PCSI-2MoA
Dopants in Semiconductors

Moderator: John Robertson, University of Cambridge

4:20pm **PCSI-2MoA-29 Control of Spin-Orbit Coupling in Single Acceptor States in Silicon*, Sven Rogge,*** University of New South Wales, Australia **INVITED**

Spins in silicon are suitable candidates for scalable quantum information devices, because of their long coherence times and inherent compatibility with current CMOS processing techniques. While quantum information devices in donor-based systems have been shown to be promising [1], the small dipole moment of donor spins make interaction of multiple qubits challenging to implement. The presence of spin-orbit coupling in acceptors however, could allow for fast quantum-gate manipulations [2] and effective long-range inter-qubit coupling [3]. Recent acceptor qubit proposals [4] suggest the possibility of maintaining the dipole moment between the spin-orbit states, without suffering from short coherence times.

In the first part of the presentation we show that long coherence times can be achieved for acceptor spins in bulk isotopically purified strained ^{28}Si. By coupling the bulk ^{28}Si crystal to a superconducting coplanar waveguide (CPW) resonator, we measured a coherence time (T2) of 0.7 ms for the acceptor spin ensemble in bulk ^{28}Si crystal under strain, in contrast to 0.04 ms for the same crystal without externally applied strain. The coherence time for the strained 28Si crystal was extended to 8.5 ms with the Carr-Purcell-Meiboom-Gill (CPMG) sequence [5]. This value for this coherence time is over 4 orders of magnitude higher than previously found in boron-doped silicon devices [6] and demonstrates the potential of boron-based acceptor spins in silicon as a candidate for scalable, electrically-driven qubits with long coherence times.

In the second part of the talk we focus on addressing single acceptors [7]. In general, J = 3/2 systems are much less studied than S = 1/2 electrons, and spin readout had not yet been demonstrated for acceptors in silicon. We present acceptor hole spin dynamics by dispersive readout of single-hole tunneling between two coupled acceptors in a nanowire transistor [8]. We identify mJ = ±1/2 and mJ = ±3/2 levels, and we use a magnetic field to overcome the initial heavy-light hole splitting and to tune the J = 3/2 energy spectrum. We find regimes of spin-like (+3/2 to −3/2) and charge-like (±1/2 to ±3/2) relaxations, separated by a regime of enhanced relaxation induced by mixing of light and heavy holes. The demonstrated control over the energy level ordering and hybridization are new tools in the J = 3/2 system that are crucial to optimize single-atom spin lifetime and electrical coupling.

5:00pm **PCSI-2MoA-37 UPGRADED: Low-Temperature Epitaxial Silicon Growth and Confinement of Delta Doped Si:P Nanostructures*, Scott Schmucker*,** *E Anderson, J Lucero, E Bussmann, P Lu, A Katzenmeyer, T Luk, T Beechem, L Tracy, T Lu, A Grine, D Ward, D Campbell, P Gamache, M Gunter, S Misra,* Sandia National Laboratories

Atomically precise placement of phosphorus dopants using scanning tunneling microscopy-based hydrogen depassivation lithography (Figure 1) on silicon (Si:P) has implications for both high-performance digital electronics and quantum devices. Devices are fabricated by dissociative chemisorption of donor precursor molecules into patterned reactive areas in a hydrogen resist. A silicon capping layer, needed to encapsulate the device, is deposited at temperatures low enough to prevent dopant movement, but high enough to minimize defect generation.

Here, we explore the origin and influence of atomic defects in both the dopant layer and Si overgrowth, techniques available for characterization of these defects, and the relationship between surface passivation and device fidelity. Using a combination of optical spectroscopy, electrical transport, and transmission electron microscopy (TEM) (Figure 2), we relate P confinement and defect density in Si epitaxy to parameters of the fabrication process, surface chemistry, and the electronic characteristics of the resulting devices.

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. Sandia National Laboratories is managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy under contract DE-NA-0003525. The views expressed do not necessary represent the views of the U.S. DOE or the United States Government.

5:20pm **PCSI-2MoA-41 The Electronic Bandstructure of Atomically Sharp Dopant Structures in Silicon*, Justin Wells,*** Norwegian University of Science and Technology, Norway **INVITED**

Recently, it has become possible to control the placement of dopants in silicon with atomic precision, and this has given rise to a plethora of atomic scale and quantum proto-devices [1-3]. In this talk, I will present our ongoing work on understanding the electronic bandstructure of these dopant profiles in silicon.

Angle Resolved Photo-Electron Spectroscopy (ARPES) is the method of choice for observing the bandstructure, however observing the bandstructure of buried structures is extremely challenging. We have demonstrated that it is nonetheless possible to use ARPES to measure the bandstructure of dopant structures which have been created several nm beneath the surface [4]. It is also possible to see electron-phonon and electron-impurity interactions [5], quantum confinement of both the valence band and conduction band [6] and more. I will present these findings together with an overview of the current in understanding and controlling the electronic structure of dopant assemblies in semiconductors.

[1] Weber *et al.,* Science 335, 64 (2012)

[2] Zwanenburg *et al.*, Rev. Mod. Phys. 85:961 (2013).

[3] Watson *et al.*, Nature 555, 633 EP (2018)

[4] Miwa *et al*., Phys. Rev. Lett. 110:136801 (2013)

[5] Mazzola *et al.,* Appl. Phys. Lett. 104: 173108 (2014)

[6] Mazzola *et al.*, Phys. Rev. Lett. 120:046403 (2018)

Author Index

Bold page numbers indicate presenter