SAND2019-3861C

ECS 236 abstract

Session D01 (Semiconductors, Dielectrics, and Metals for Nanoelectronics)

"Gate-defined quantum dots in Ge/SiGe quantum wells as a platform for spin qubits"

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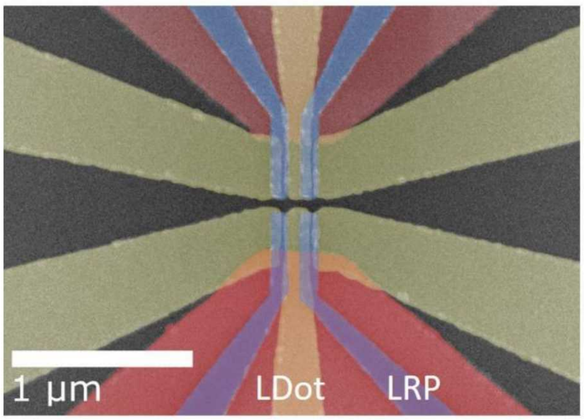

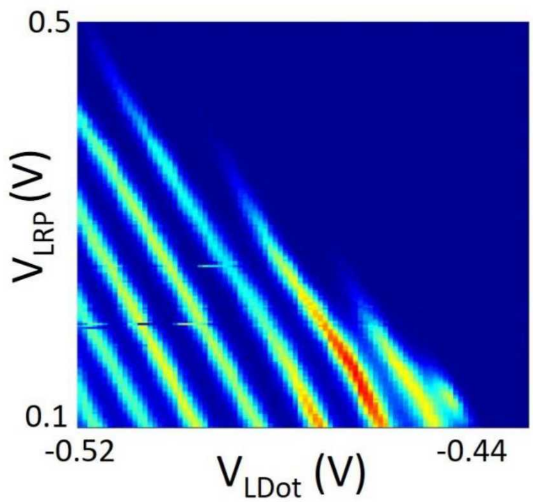

In the field of semiconductor quantum dot spin qubits, there is growing interest in leveraging the unique properties of hole-carrier systems and their intrinsically strong spin-orbit coupling to engineer novel spin qubits. In contrast to the weak spin-orbit interaction found in Si, strong spin-orbit coupling in Ge may allow purely electrical spin control using the electric field component of a microwave drive signal applied to a confinement gate, without the need for additional components such as microwave stripline antennas or micromagnets. A crucial aspect in the search for alternative semiconductor qubit host materials is the need to maintain the advantages of existing platforms such as Si: low disorder, long coherence times, extensibility, and semiconductor foundry compatibility.

Recent advances in semiconductor heterostructure growth have made available high quality, undoped Ge/SiGe quantum wells that can serve as hosts for hole spin qubits. These quantum wells consist of a pure strained Ge layer flanked by Ge-rich SiGe layers above and below, grown by reduced pressure chemical vapor deposition. Isotopic enrichment is possible if required. The heavy hole charge carriers are characterized by a small effective mass m* ~ 0.08m0 (about 2.4x lighter than for electrons in Si), high mobility mu >~1E5 cm^2/Vs, and highly anisotropic g-factors. The small effective mass should allow relatively large and easily-coupled quantum dots. The next-nearest light hole band is theoretically predicted to be on the order of ~ 100 meV below the heavy hole band. The p-orbital character of the hole wavefunction may provide an advantage in minimizing contact hyperfine interactions with nonzero-spin lattice nuclei. There is both theoretical and experimental evidence of a cubic Rashba-type spin-orbit interaction in this material, whose large strength is manifest as a spin-orbit length on the order of 1 micrometer. An additional advantage over Si is that the two-dimensional band structure of Ge quantum wells does not feature valley states, which can present difficulties for qubit operations.

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Here, we will describe our ongoing efforts to prepare spin qubits in this platform, including development of gated device architectures, device tuning protocols, and charge-sensing capabilities. Initial work focused on single-layer gate layouts, in which lithographically-defined single and double quantum dots were demonstrated at dilution refrigerator temperatures. Charging energies of ~ 1.7 meV were observed. These devices featured a broad and shallow potential landscape, and only a small number of holes could be confined to a quantum dot. Although adjacent quantum dots could be coupled to one another, this coupling was not easily tuned using this gate design. These limitations in the confinement and control of quantum dots motivated the subsequent adoption of multilayer gate-stack architectures, similar to what has been demonstrated in Si. Our three-layer devices feature gate electrodes designed for accumulation of holes, local depletion to form quantum dots, and selective isolation/screening of electric fields. Device structures feature Ti/Pt gates, ALD oxide dielectrics, and implanted ohmic contacts. Symmetrically constructed devices comprise two gated channels for quantum dot confinement, one to be used as the quantum dot under study and the other operated as a local charge sensor. By monitoring the conductance of the charge sensor as the quantum dot is tuned, we can remotely determine the dot’s occupation number, in principle down to the last hole. Iterative cycles of device fabrication and measurement, combined with numerical modeling, have allowed continuous improvements to the device design. Early three-layer device designs suffered from poor isolation between the upper and lower mirror-symmetric device channels. Numerical modeling showed (and measurements have confirmed) that an additional isolation gate could allow improved autonomy of the two channels while maintaining their electrostatic coupling needed for charge sensing. Ongoing, simulation-informed work to fine-tune the device geometry, as well as efforts toward a qubit demonstration, will be discussed.

This work was funded, in part, by the Laboratory Directed Research and Development Program and performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the US Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the US Department of Energy’s National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in this article do not necessarily represent the views of the US Department of Energy or the United States Government. The work at NTU was supported by the Ministry of Science and Technology (107-2622-8-002-018-).