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Spin Qubits Using Holes in Strained Germanium Quantum Well Heterostructures

Dwight Luhman

Sandia National Labs

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Outline

- Project Overview
- Recent activities
  - Fabrication Challenges
  - Hardware upgrades
  - Modeling of spin orbit coupling in Ge dots
- Outlook

Project Overview

Goal: Demonstrate and study hole spin qubits in strained Ge/SiGe Heterostructures

Motivation: Holes in Ge/SiGe provide a compelling alternate approach to spin based qubits. They maintain many of the advantages of silicon without valley splitting.

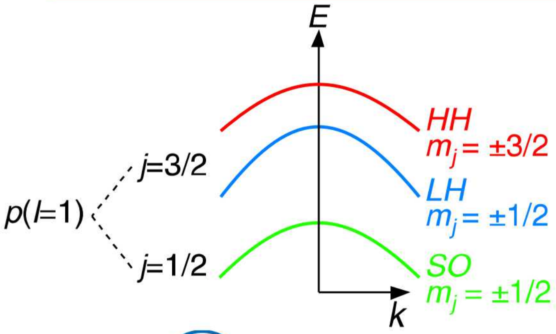
Team:
Dwight Luhman (PI)
Tzu-Ming Lu
Will Hardy
Mitchell Brickson

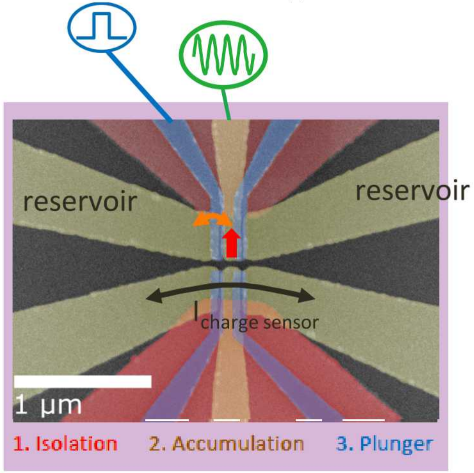
Near Term Goals:
Stable Quantum Dots in Ge/SiGe
Single Spin Readout
Spin Rotations
Better understanding of SOC in Ge dots

Basic Idea

- Single Hole confined to lateral quantum dot in Ge heterostrucutre
- Spin Qubit States: $m_j = \underline{+}3/2$
- Qubit readout and initialization through energy selective tunneling to reservoir
- Qubit Control through microwaves applied to gate
- Occupancy detected through nearby charge sensor
- Strong spin orbit coupling (SOC) is important. Form is ~k^3 in 2DHG.

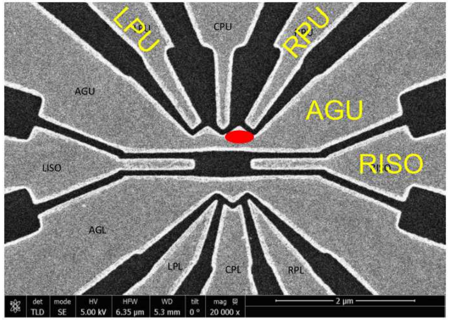
Single valence band of heavy holes with $m_j = \underline{+}3/2$

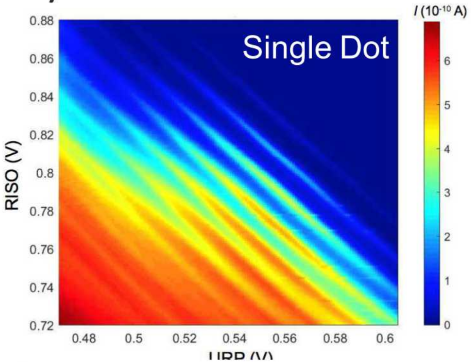


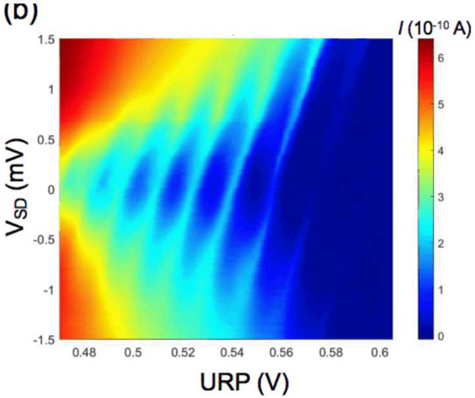


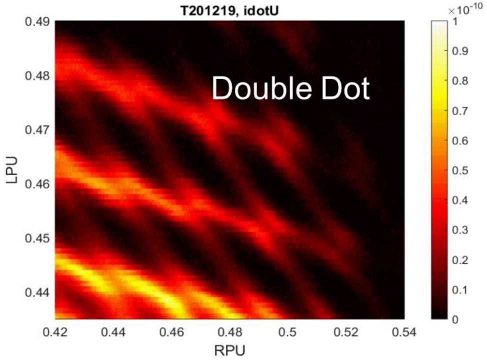
Summary of Previous Results

Lithographic Dot in Single Layer Devices:

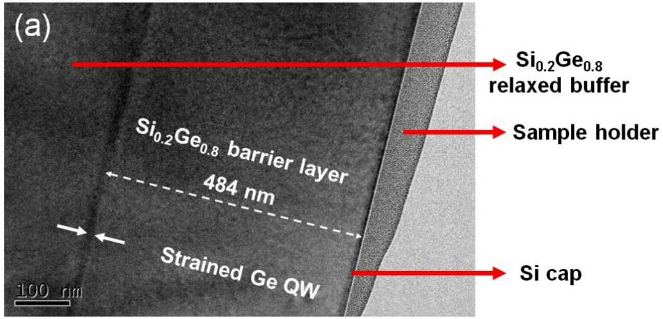


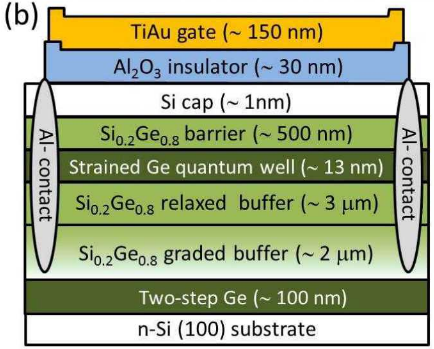






Undoped Strained Germanium Quantum Well Heterostructures

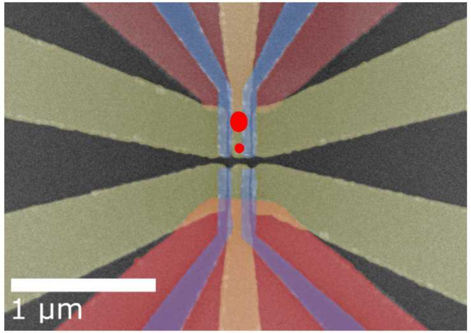


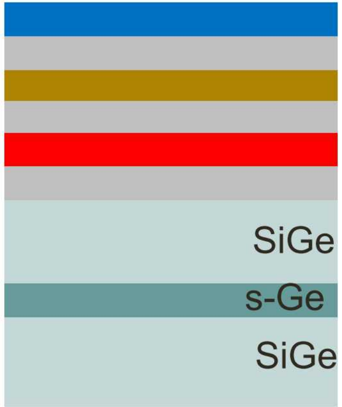


Summary of Previous Results

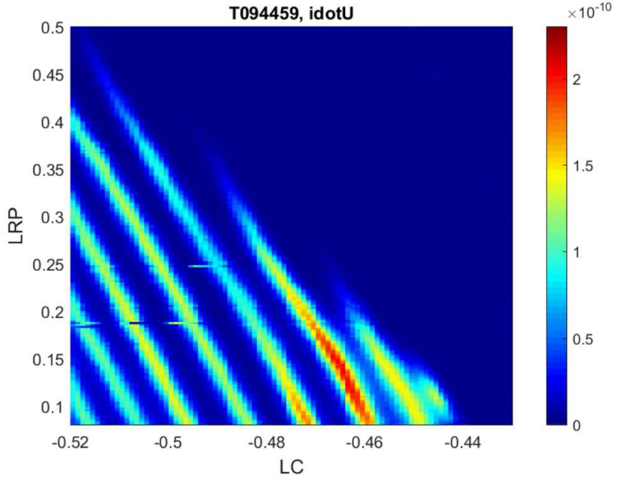
Lithographic Dot in Three Metal Layer Devices:

E-beam lithography
ALD oxide
Ti/Pt gates





3. Barrier gates
ALD oxide
2. Accumulation gates
ALD oxide
1. Isolation gates
ALD oxide



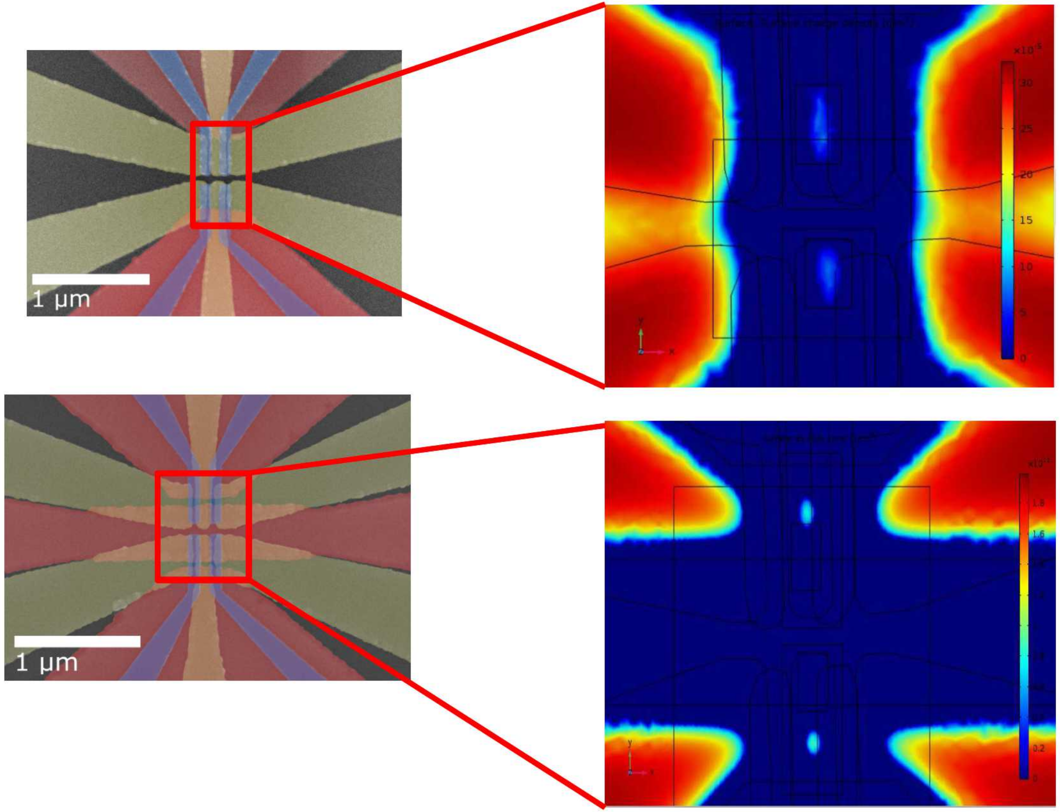
Large aspect ratio of quantum dot was likely causing multiple isolated dots

Nanostructure Yield: 2/8

Device Redesign

Original Design

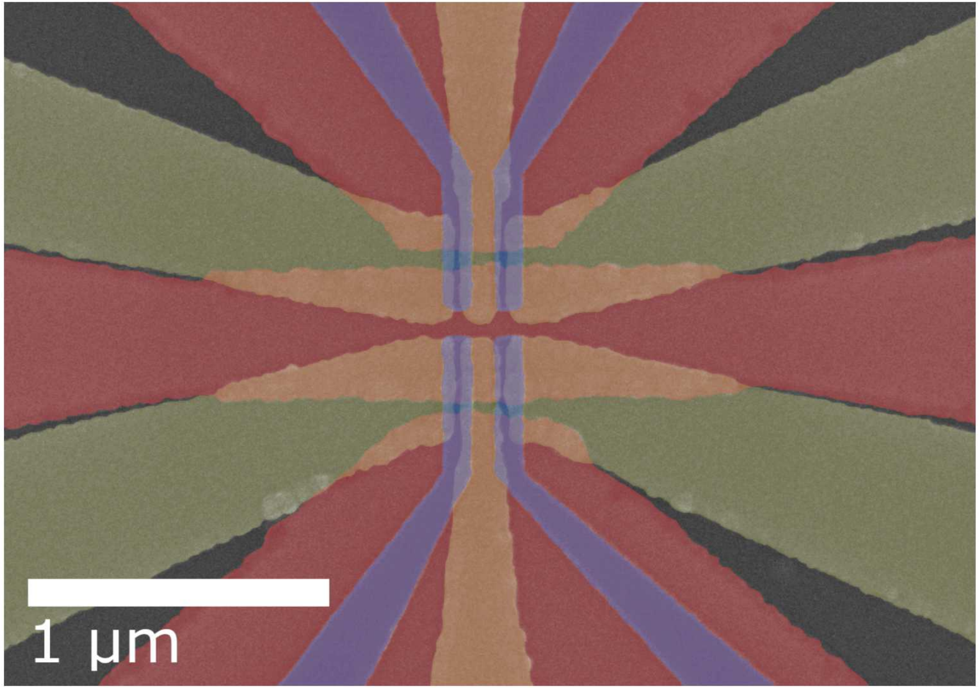
New Design



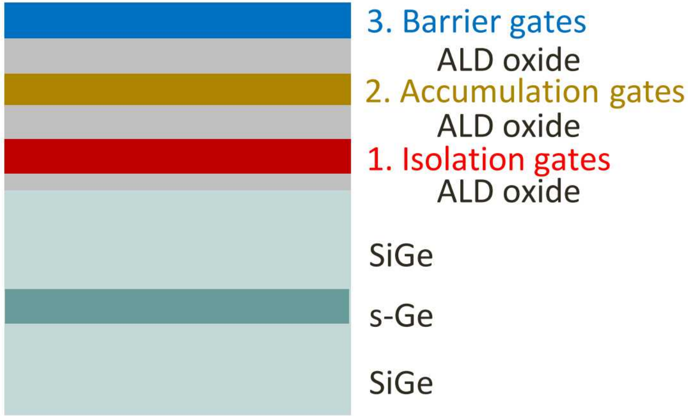
COMSOL calculations by M. Brickson

Central gate isolates 2DHGs between upper and lower dots and creates better confinement for each dot

New 3-layer device design



Add horizontal isolation gate



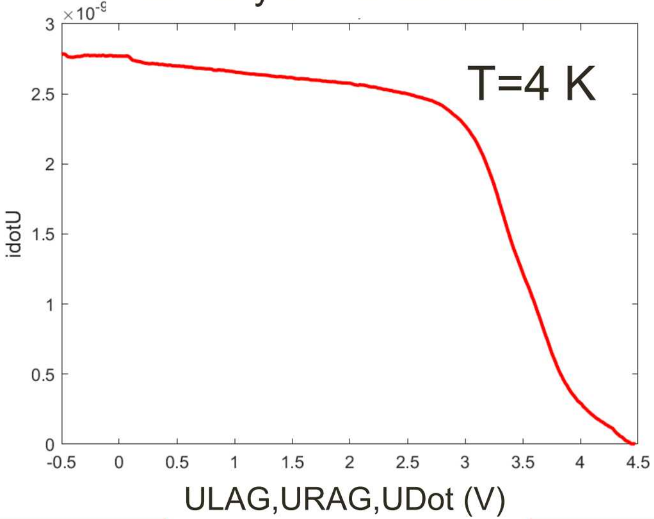
ALD Oxide=24 nm Al_2O_3 + 1 nm HfO_2
Metal = 2 nm Ti + 18 nm Pt

Device Challenges

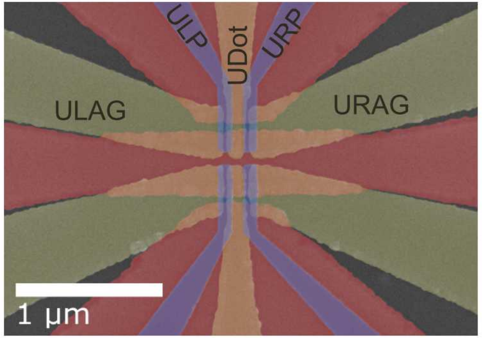
First batch of new devices had low yield

- Gate leakage
- Normally on
- Unstable
- No usable nanostructures: 0/8

Normally-on nanostructure



Lithography had good yield

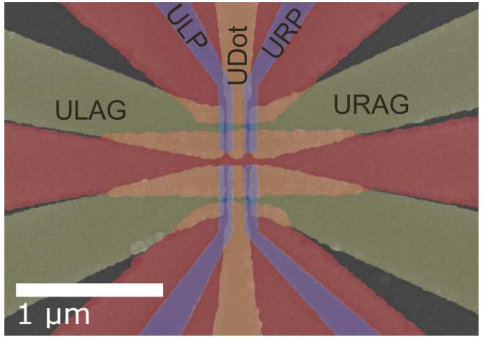


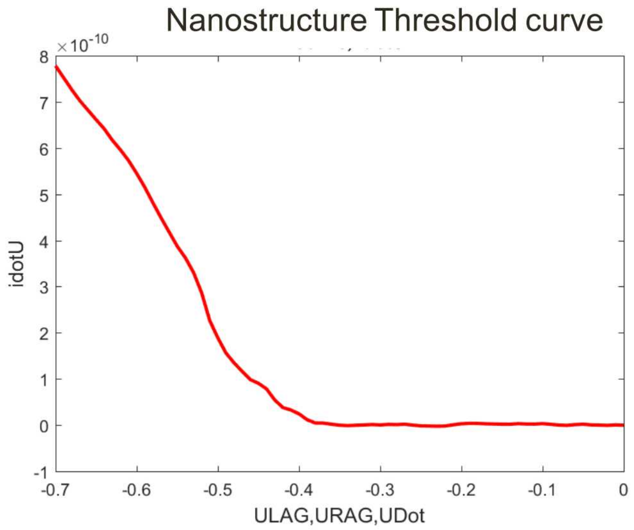
Something changed between fab runs

- Suspect ALD machine

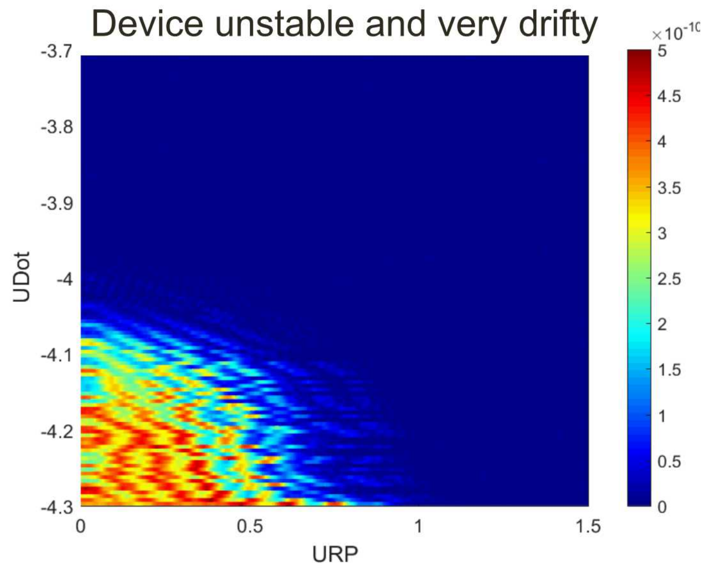
Device Challenges

- Clean ALD Machine
- Fabricate new set of devices
- Nanostructures Yield: 1/8





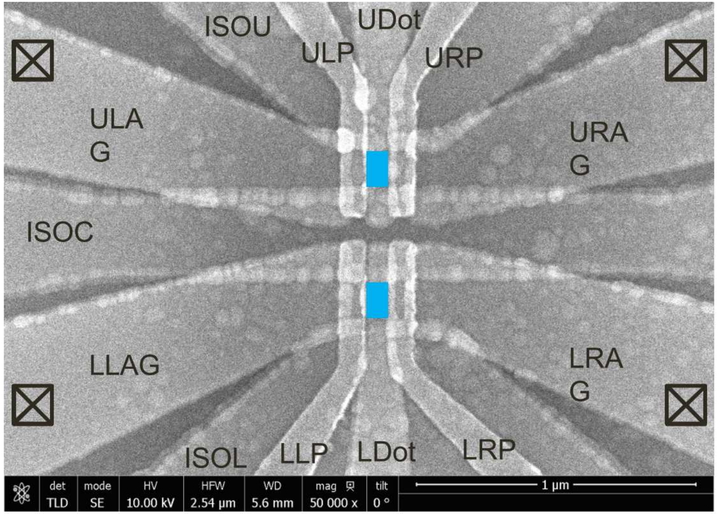
T=40 mK

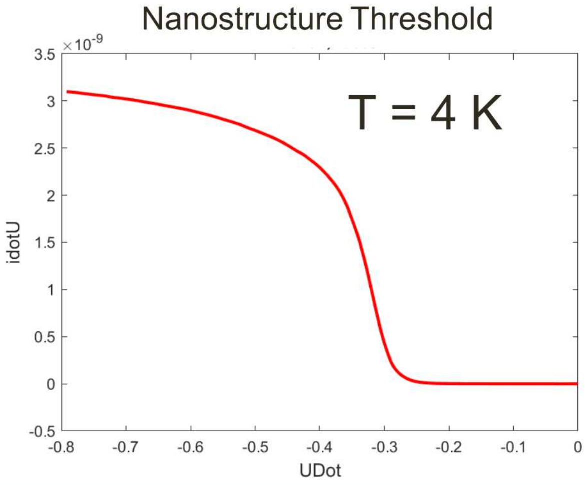


Device Challenges

Continued to work on EBL
Quantum dot is now about 130 x 80 nm

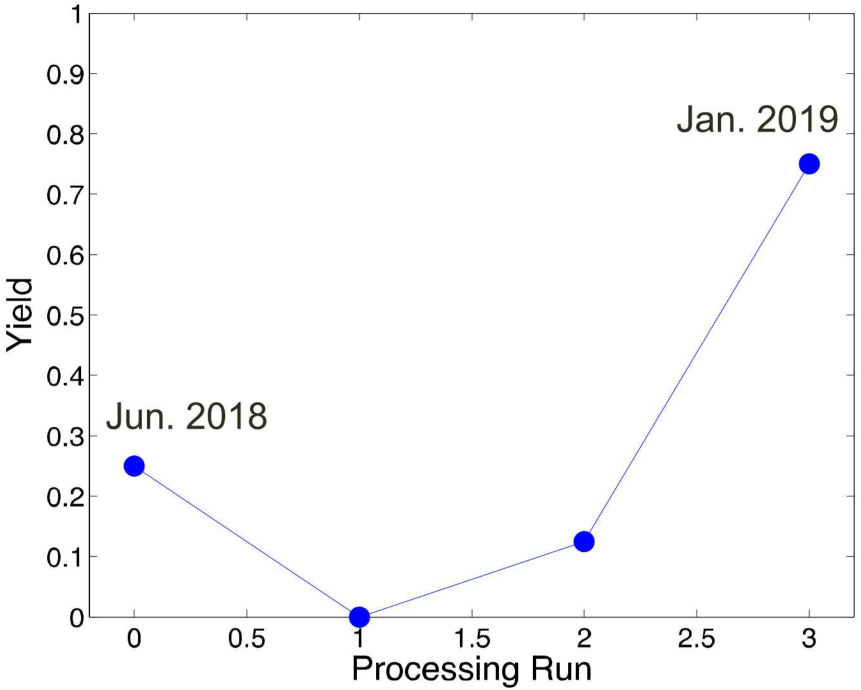
- Implement Forming Gas anneal after every oxide layer
  - 400^0 C for 30 minutes
- Fabricate new set of devices
- Nanostructures: 6/8





Devices look good at T=4 K.
Cooling down in dilution refrigerator now.

Device Challenges Summary

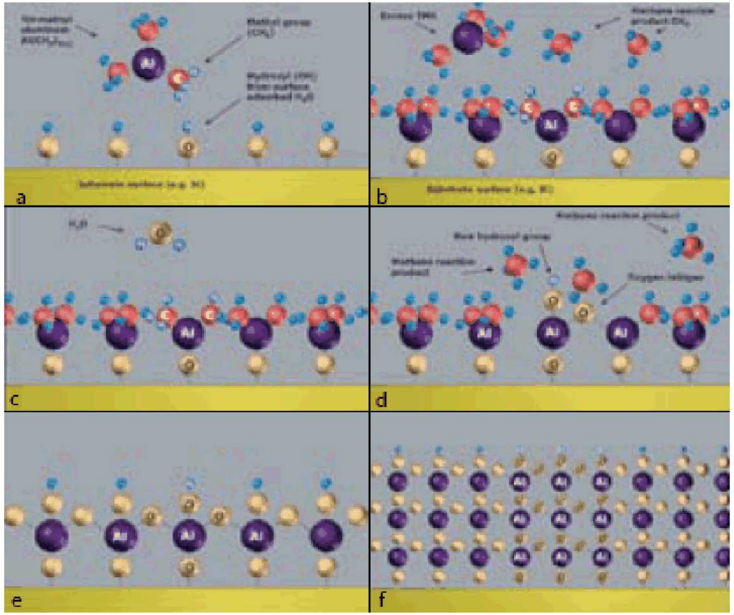


- We experienced an abrupt, unexpected fabrication issue in August 2018
- The issue seems to be related to contamination in the ALD machine (next slide)
- A combination of cleaning the tool and forming gas anneals appears to have improved the issue---new device in fridge now
- Improved yield

Atomic Layer Deposition (ALD)

<u>ALD Steps</u>

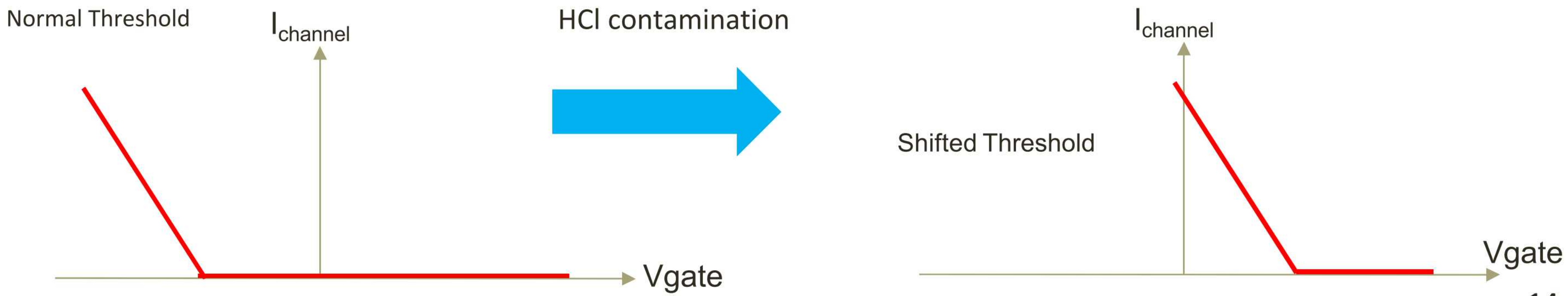
1. Chemisorption of a precursor molecule (H_2O and trimethyl-aluminum for Al_2O_3)
2. Dissociation into ions on the surface
3. Diffusion of ions on the surface and association into a molecule
4. Desorption of the volatile molecule (CH_4)



D. Monsma and J. Becker, Material Matters 1, 5 (2006)

Best Guess for the cause of device challenges

- Machine is a general purpose tool at the Center for Integrated Technology (CINT)
- Users have introduced $TiCl_4$ in the chamber for TiO_2 growth.
- Metal chloride molecules form as a byproduct
- Chlorine molecules react with H_2O to form HCl, which acts as an additional precursor
- During Al_2O_3 growth, residual HCl strongly bonds with Al and C as the oxide grows
- Incorporation of Cl ions may shift thresholds and form poor oxide
- Forming gas passivates these ions and densifies the oxide



Plan for future devices:

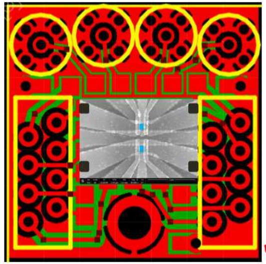
- Immediate
  - Use CINT ALD + Forming gas anneal
- 2-4 Months
  - Test a different ALD machine at Sandia
  - System dedicated to Al_2O_3
  - Oxide quality needs to assessed
- Long term
  - Acquire and install new ALD machine
  - Machine dedicated to sensitive electronic devices
  - Limited to metal organic precursors
  - Access control

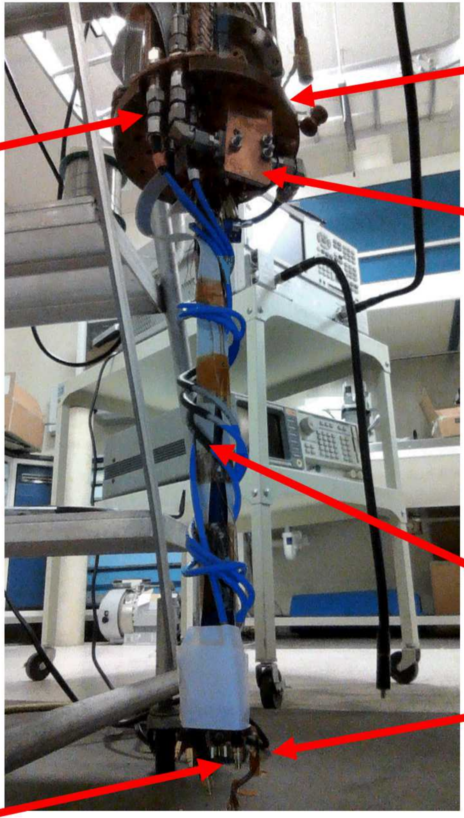
Hardware Improvements

- High Speed lines into dilution refrigerator
  - Qubit pulsing gates
  - Micro-wave line for qubit rotations
- Simple packaging solution for high speed control

0 dB microstrip attenuators

Sample PCB





Mixing chamber

Bias tee

Blue coaxial cables from mixing chamber to sample board

Mini-SMP connectors to circuit board

Modeling SOC in Ge QDs

Goal: Develop device-level models to guide & interpret experiments

- Challenges
  - The form of the SOC Hamiltonian remains ambiguous in Ge quantum dots
  - No existing software for device-level modeling with SOC
- Our trajectory
  - Use Rabi oscillation frequency as a connection to experiment
  - Calibrate expectations with a simple model
  - Enhance device-level modeling tools to accommodate SOC physics
  - Use tools to explore various SOC models (e.g., linear vs. cubic)
  - Integrate more physical details into our theory

Modeling by M. Brickson

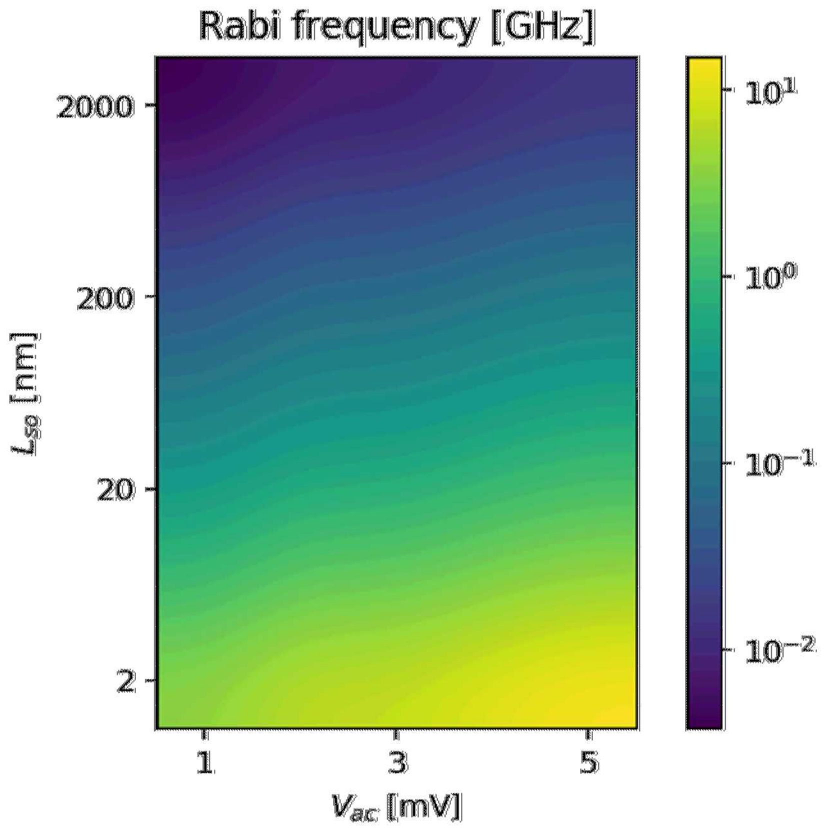
Simple Model

Calibrate expectati

- Sandia experiments sug range for spin-orbit len
- Electrostatic calculatior gate-dot coupling

$$f_R = \frac{\nu \Delta x}{L_{so}}$$

- Rabi frequencies $\mathcal{O}(10$ may be possible in SNL

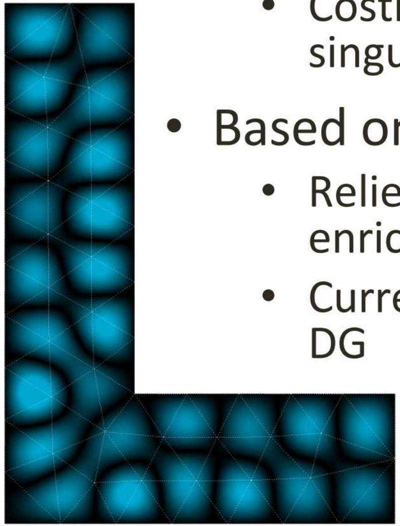


Laconic software package

Andrew Baczewski

PDE-solver designed for accurate solutions of quantum models

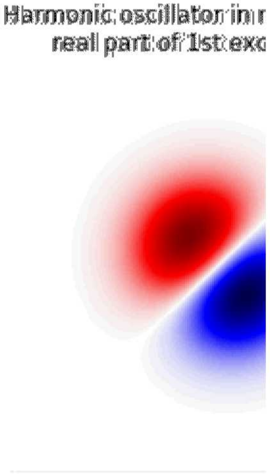
- High accuracy needed for multi-scale device models
  - Energy resolution across multiple orders of magnitude
  - Costly to accurately describe behavior near material barriers or Coulomb singularities, while accounting for realistic device electrostatics
- Based on a Discontinuous Galerkin (DG) framework
  - Relies on a mesh-based description Basis function space can be locally enriched to capture difficult physics
  - Current version implements effective mass theory using interior penalty DG

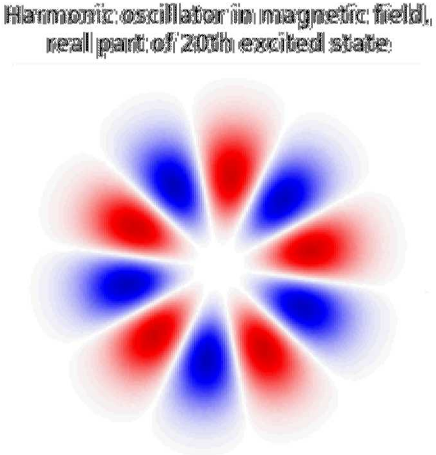


Additions to Laconic modeling software

- Laconic was updated to include:
  - Magnetic vector potential
    $\boldsymbol{A} \cdot \nabla + \nabla \cdot \boldsymbol{A}$
  - Zeeman term
  - Free particle SOC operator
    $\boldsymbol{\sigma} \cdot \boldsymbol{p} \times \nabla V$
  - Momentum operator
- Computes QD eigenstates subject to realistic electrostatic → direct evaluation of Rabi frequencies

Test with Harmonic oscillator potential





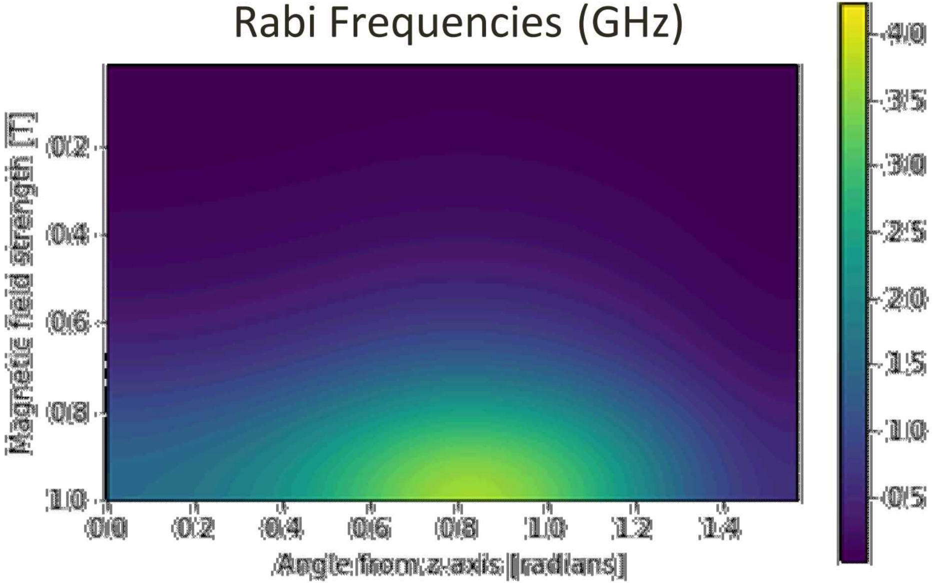
Linear SOC

- SOC Hamiltonian
  $\hat{H} = i\alpha(\hat{\sigma}_+\hat{p}_- - \hat{\sigma}_-\hat{p}_+)$
- f_R monotonically increases with magnetic field
- f_R peaks with B-field oriented halfway between z- and xy-plane
- Need to compare to cubic SOC

Initial Results:

- Confinement by 20 nm QW along z-axis
- Assume SHO potential in xy-plane
- Value of α from literature; 1 mV drive

Rabi Frequencies (GHz)

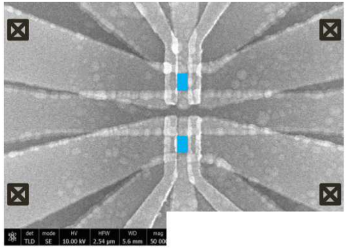


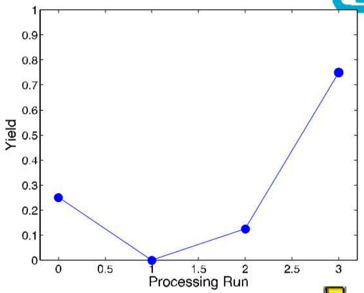
Ongoing and future modeling work

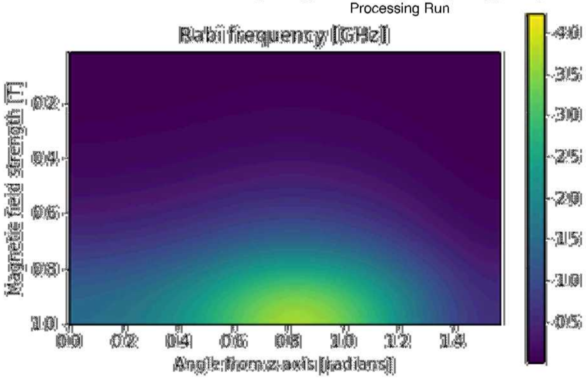
- Implementation of cubic SOC model
- Incorporate more microscopic details
  - QW band structure as a function of material conditions (effective masses)
  - Multi-band effective mass theory (light and heavy hole)
  - Static and dynamic noise sources
- Understand and optimize single-qubit gate fidelities
- Model two-qubit gate

Progress and Outlook

- Overcame major device fabrication hurdles
  - Better understanding of fab process
  - Significant increase in yield
  - Improved EBL
  - Improved Device Design
- Hardware Upgrades
  - Dilution Refrigerator ready for qubit measurements
- Modeling
  - Significant advances to capturing the SOC physics in Ge dots







Demonstrate Quantum Dot → Single Hole Occupation (In Progress) → Spin Readout & Initialization (In Progress) → Qubit Control (EDSR) → Qubit Characterization

Acknowledgements

Modeling:

- Leon Maurer
- Toby Jacobson
- Andrew Baczewski
- Jonathan Moussa

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- C.-Y. Liu
- C.-T. Chou

This work 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 a multi-mission laboratory 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's National Nuclear Security Administration under contract DE-NA-0003525

Backup Slides

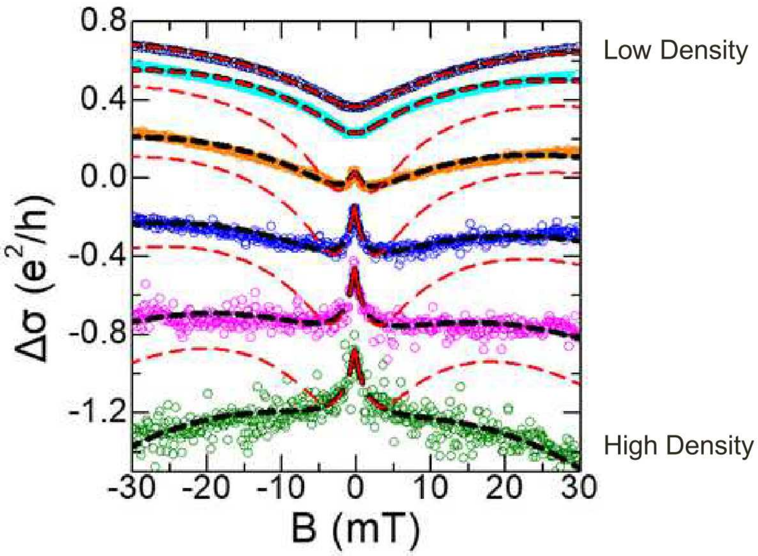
Hole spins in Ge/SiGe provide a compelling alternative to electron spin qubits

- Absence of nearly degenerate states (i.e. valley states)
- Low Disorder (heterostructure similar to Si/SiGe)
- Enhanced Quantum Dot-Quantum Dot coupling due to a small effective mass
- Natural way to electrically control the spin (strong spin-orbit coupling) without additional components, such as micro-magnets
- Ge and Si have spin free isotopes and can be enriched.
- Potential for weaker hyperfine coupling because p-type wavefunctions vanish at the nucleus.
- Compatible with silicon processing techniques
- Can leverage designs and techniques already developed for semiconductor qubits.
- Challenge: Charge Noise

2DHG Properties

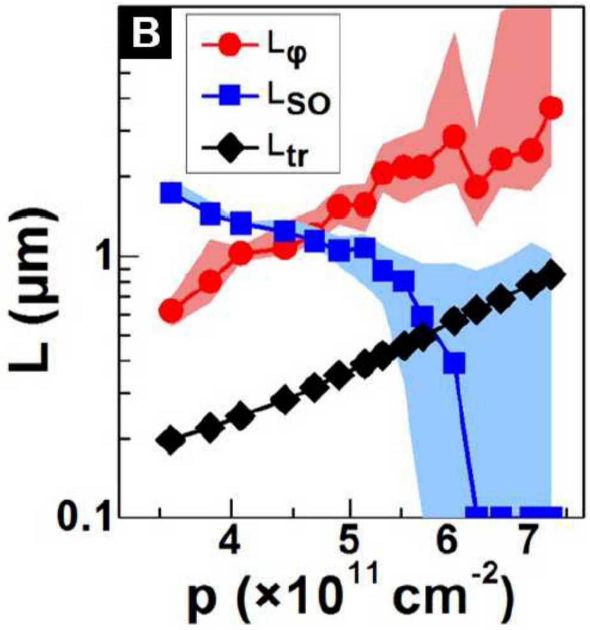
Strong Spin-Orbit Coupling

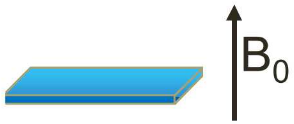
Weak antilocalization peak emerges with increasing density



- - - Linear Rashba Spin Orbit Coupling

- - - k^3-Rashba Spin Orbit Coupling





Chou et al. arxiv 1807.01400 (2018)