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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
- New Device Design
- Fabrication Challenges
- Charge Sensing
- Device Level Modeling for Holes in Ge
- 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.

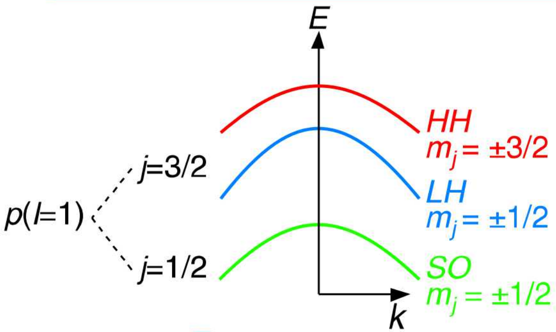
Team:
Dwight Luhman (PI)
Tzu-Ming Lu
Will Hardy (now staff)
Mitchell Brickson

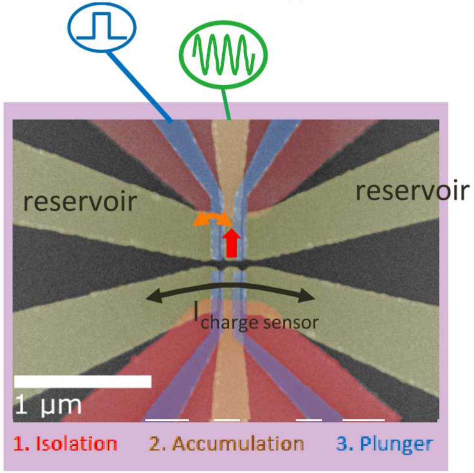
Near Term Goals:
Single Spin Readout
Spin Rotations
Better understanding of SOC in Ge dots

Basic Idea

Single valence band of heavy holes with $m_j=\pm3/2$

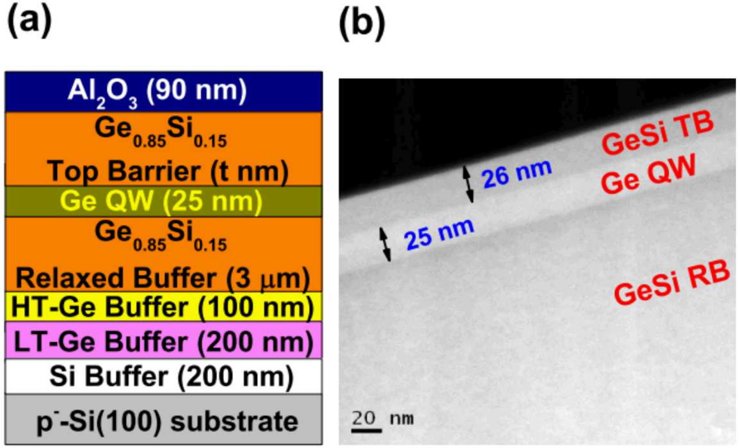
- Single Hole confined to lateral quantum dot in Ge heterostrucutre
- Spin Qubit States: $m_j=\pm3/2$
- Qubit readout and initialization through energy selective tunneling to reservoir
- Qubit Control through microwaves applied to gate
- Occupancy detected through nearby charge sensor
- Strong spin orbit coupling (SOC) is important. Form is ~k^3 in 2DHG.





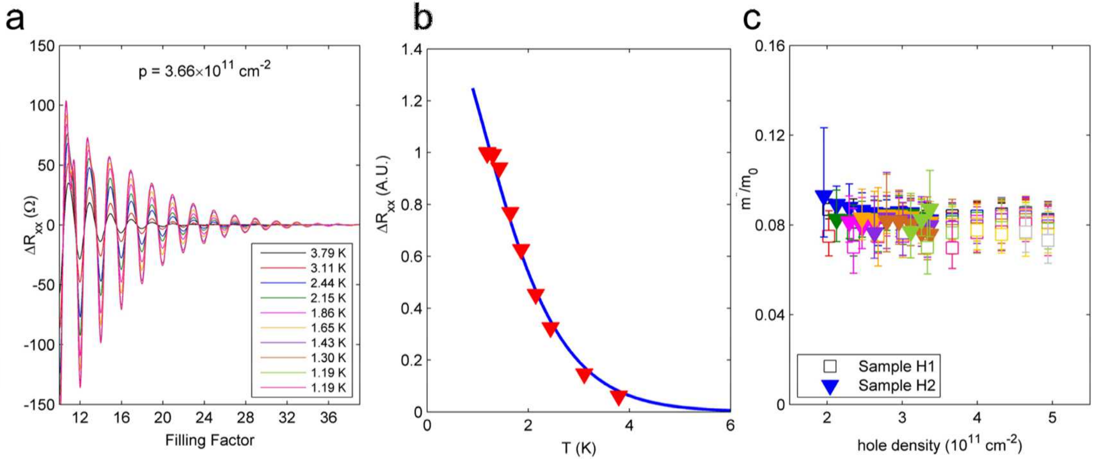
Ge/SiGe quantum wells

Undoped Heterostructures
Clean epitaxial interface



Su, *et al. Phys. Rev. Mater.* (2017)

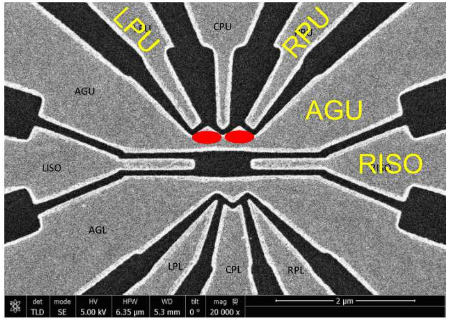
Small effective mass, $m^* \sim 0.08\ m_0$

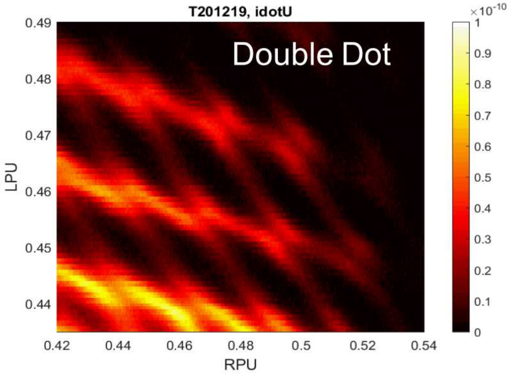


Hardy *et al., Nanotechnology* (2019)

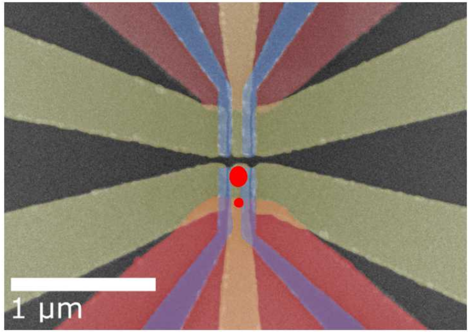
Summary of Previous Results

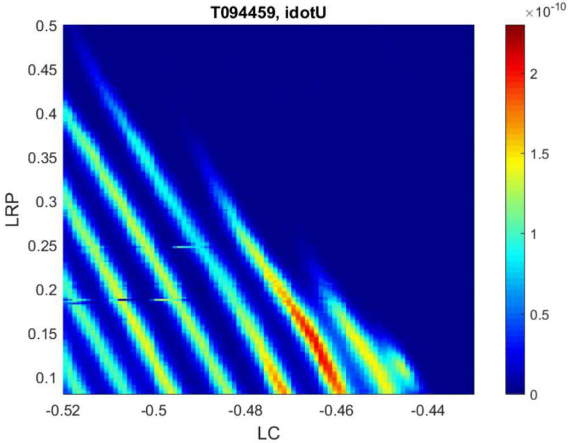
Single Layer Design:





Three-Metal Design





Good Coulomb Blockade

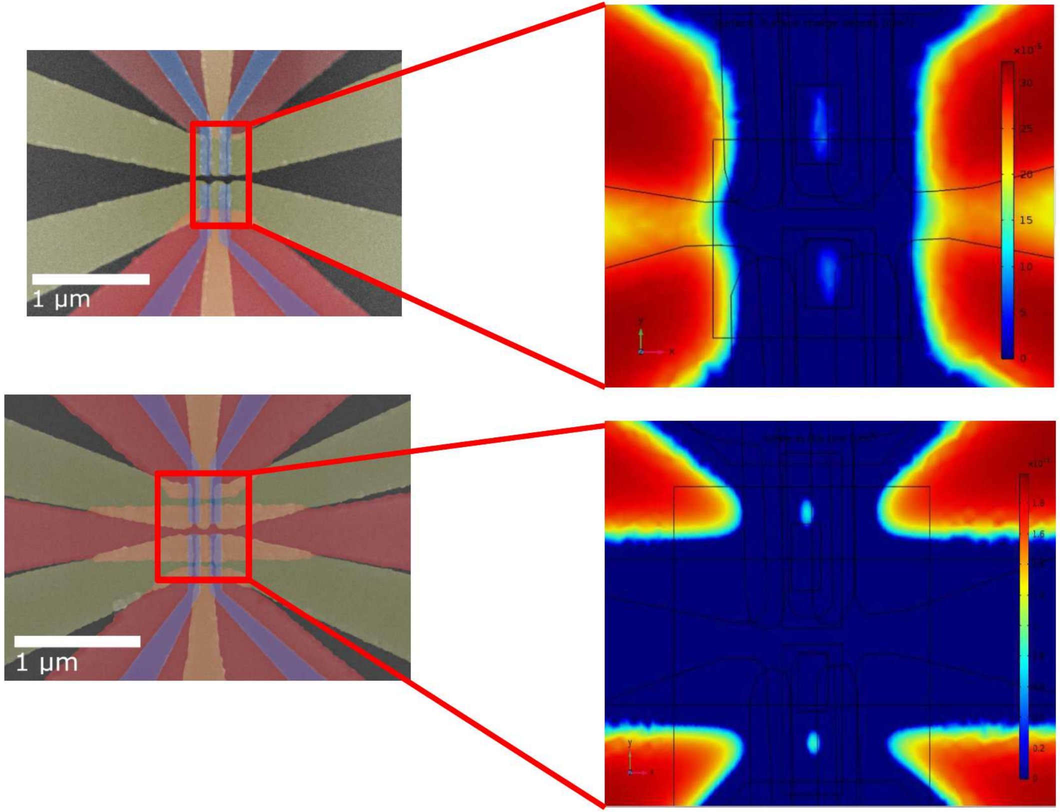
Upper and lower dots merge when both activated

Large aspect ratio of dot design causes multiple dots to be formed under a single gate

Device Redesign

Original Design

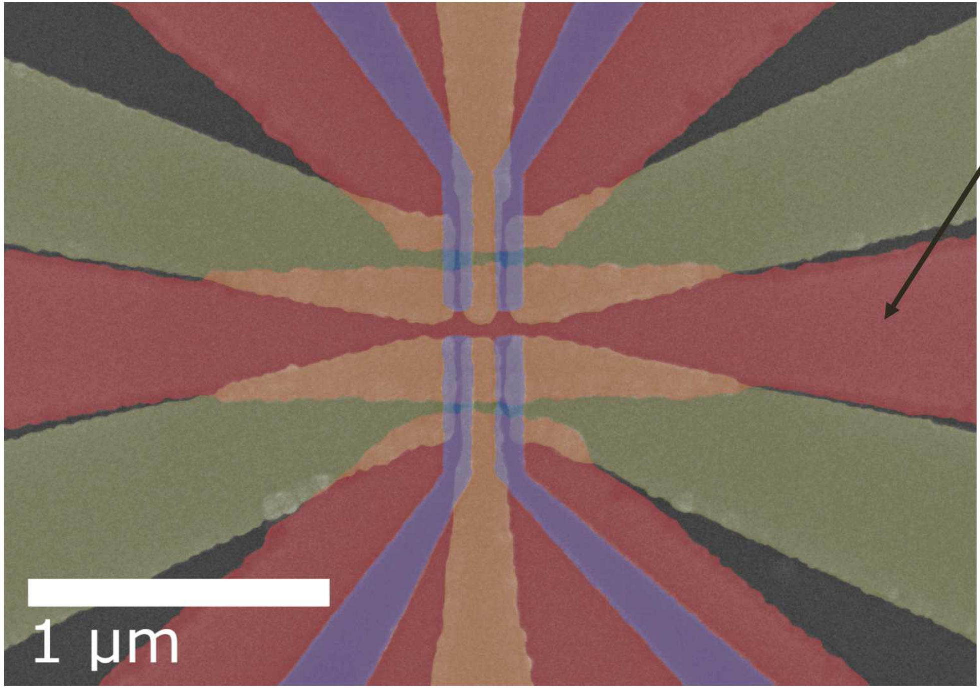
New Design



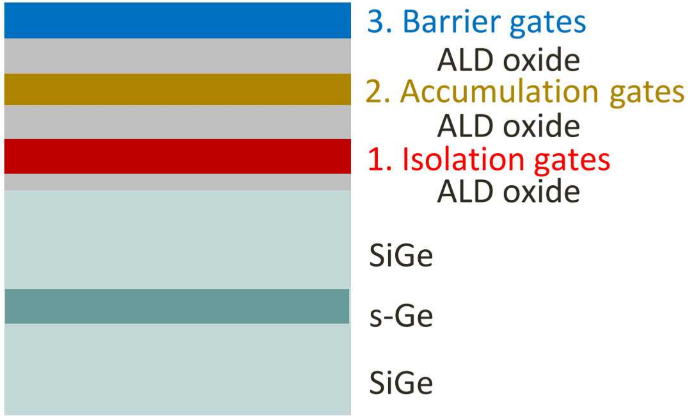
COMSOL calculations by M. Brickson

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

New 3-layer device design



Includes horizontal isolation gate



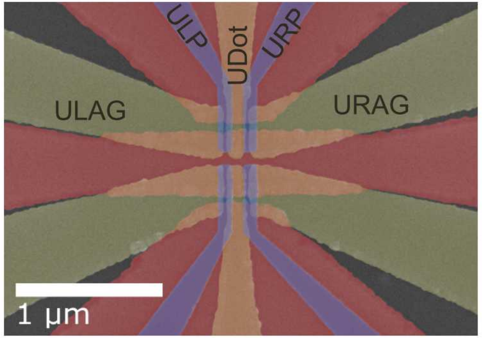
ALD Oxide=24 nm Al_2O_3 + 1 nm HfO_2

Metal = 2 nm Ti + 18 nm Pt

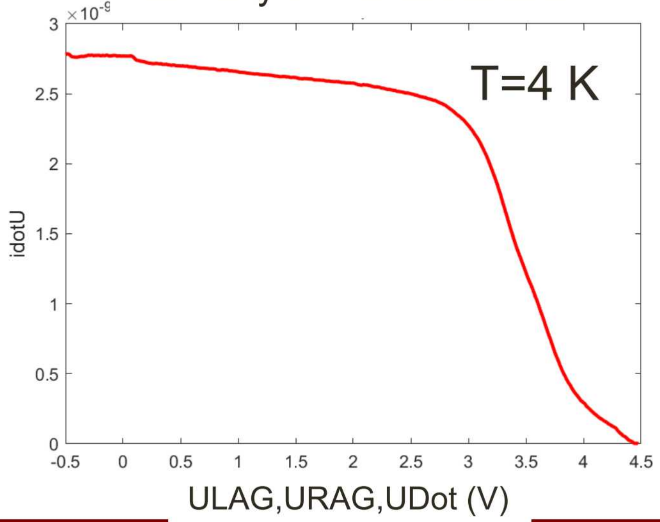
Device Challenges

Lithography had good yield

First batch of new devices had low yield
- Gate leakage
- Normally on
- Unstable
- No usable nanostructures: 0/8

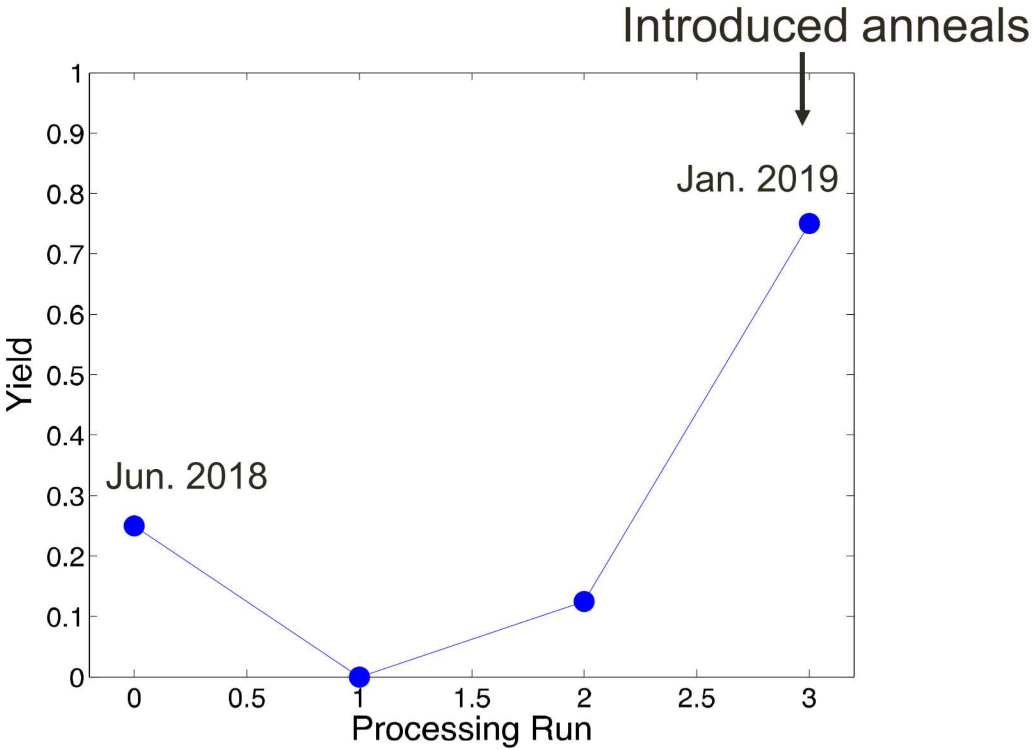


Normally-on nanostructure



Something changed between fab runs

Improved Device Yield



- We experienced an abrupt, unexpected fabrication issue in August 2018
- The issue seems to be related to contamination of $TiCl_4$ in the ALD machine
- A combination of cleaning the tool and forming gas anneals (400^0 C for 30 minutes) after every oxide layer improved the issue

New ALD Tool

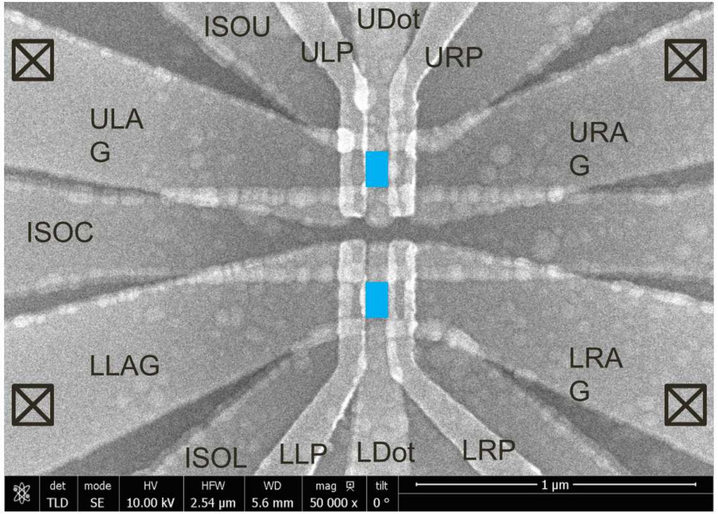
Longer term solution

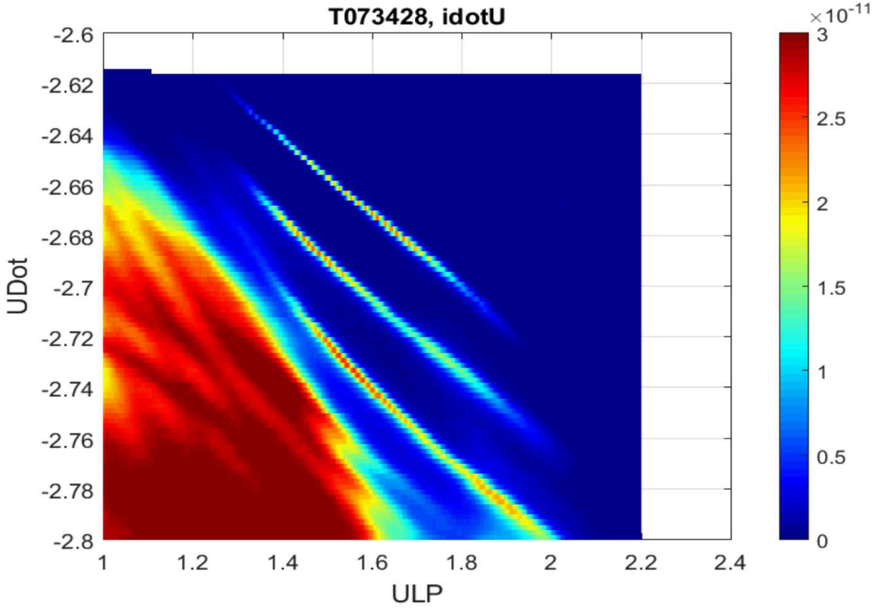
New dedicated ALD tool for Si-based quantum devices

- Veeco Savannah G2
- Al_2O_3 and HfO_2 availalbe
- Controlled access to maintain cleanliness
- Status
  - Tool installed and qualified
    - 0.93 A/cycle
    - 1.6% variation across 6” wafer
  - Awaiting final administrative approval (expected soon)

Successful Three Layer Devices

Quantum dot size is ~ 130 x 80 nm

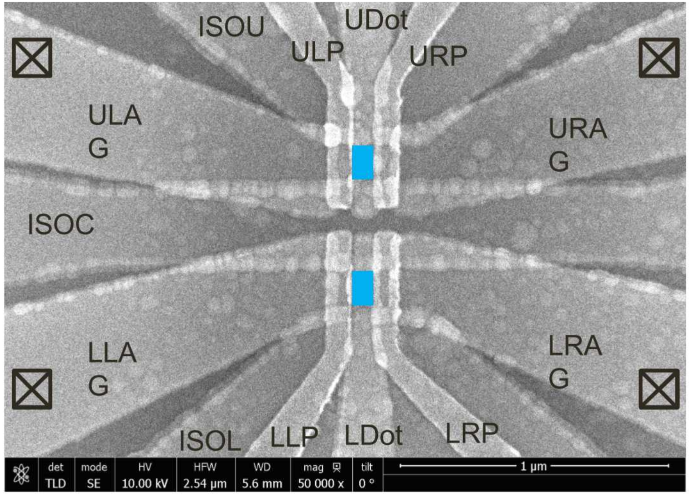


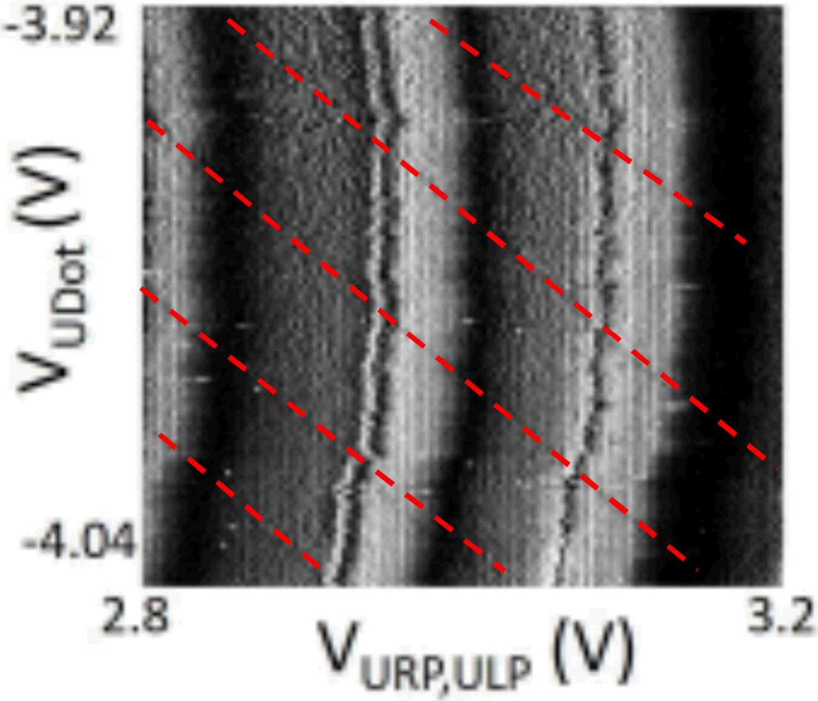


Regular Coulomb blockade observed in multiple devices

W. Hardy

Charge Sensing



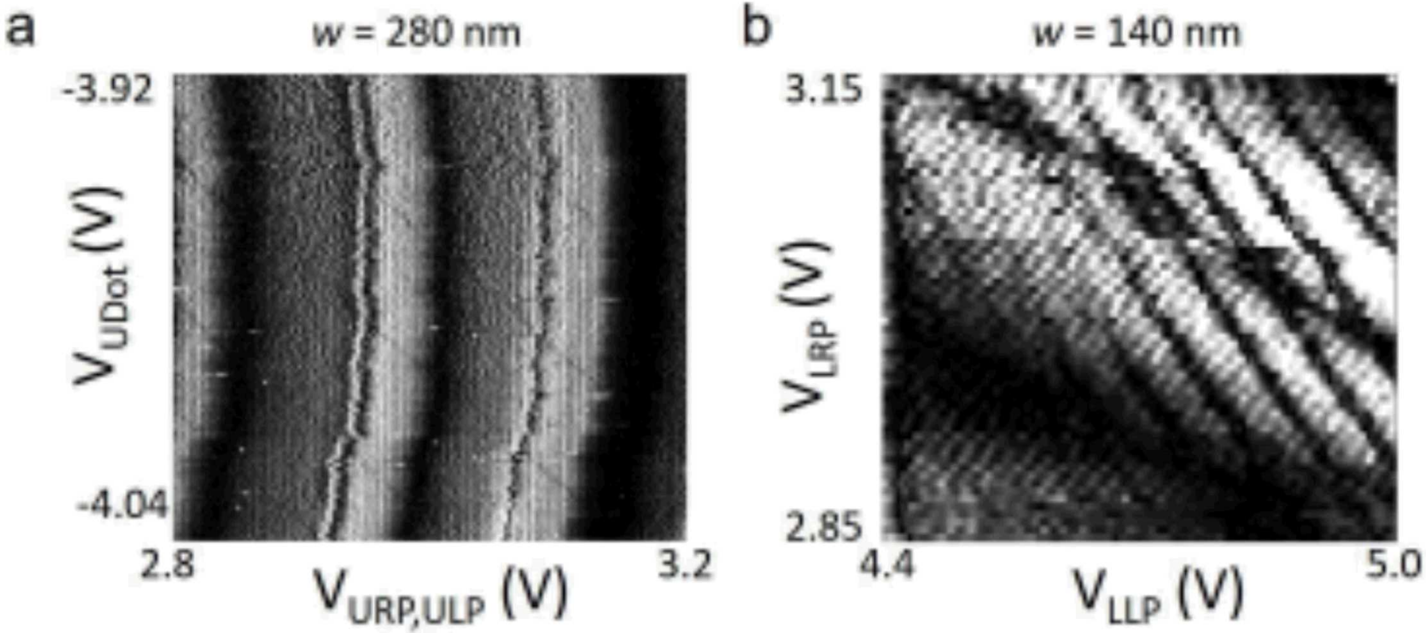


- New design allows charge sensing
- Charge sensed signal is very weak

W. Hardy

Improved Charge Sensing

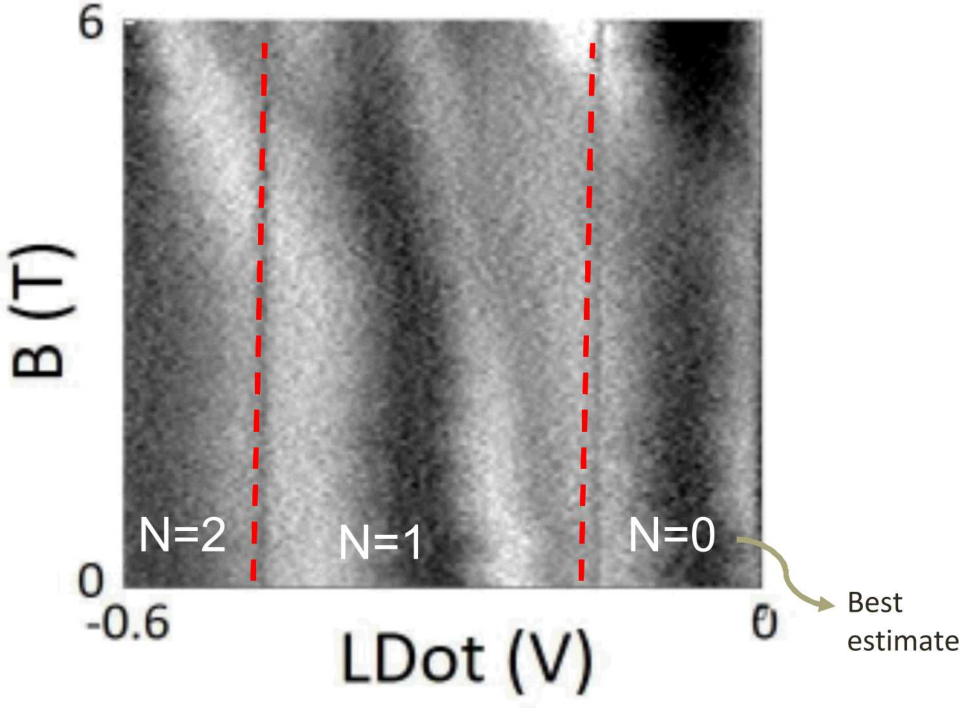
- Reduce center gate from *w*=280 nm to 140 nm in width
- 150% increase in charge sensed signal



W. Hardy

Magnetospectroscopy

- Tune to the low electron regime
- Observe charge transition lines versus magnetic field
- Slope of the lines gives an estimate of the g-factor (field in-plane)
- $g_{||}$~0.3 (rough estimate), consistent with Delft result* for a quantum dot



*Hendrickx et al., Nature Comm. 9, 2835 (2018)

Modeling SOC in Ge QDs

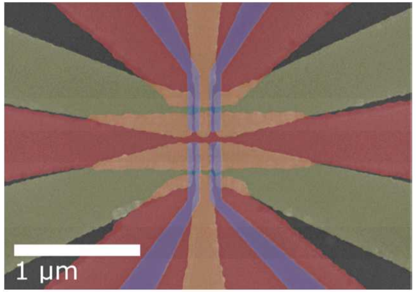
Overall Goal: Develop accurate device-level models of SOC coupling in quantum dots to guide & interpret qubit experiments

Near Term Goal: Understand the magnetic field angular dependence of the Rabi frequency in Ge quantum dots

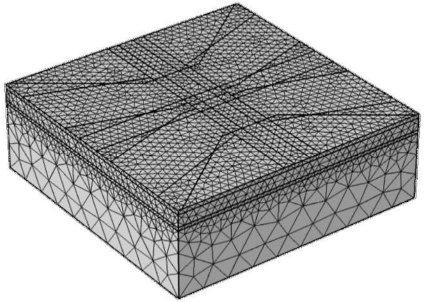
M. Brickson

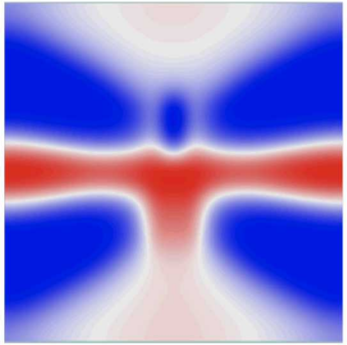
Modeling Sequence

Real Device

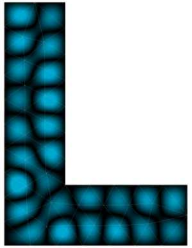


Electrostatic Potential in COMSOL





Laconic (Andrew Baczewski)



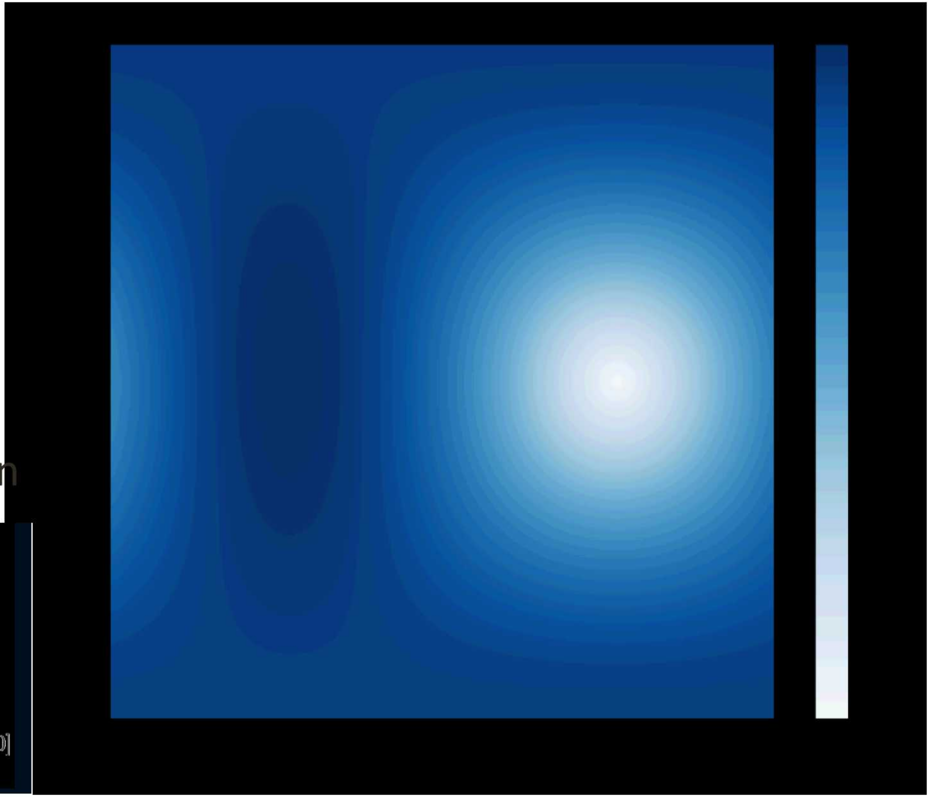
- Mesh based solver for multi-scale quantum models
- Locally enriched to capture difficult physics

Single Band Model

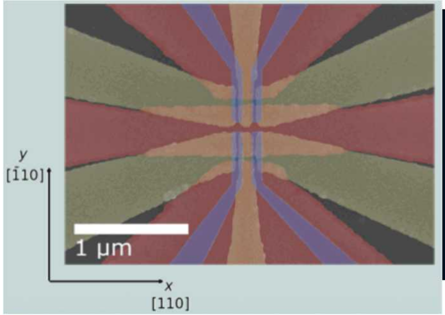
Simple angular dependence

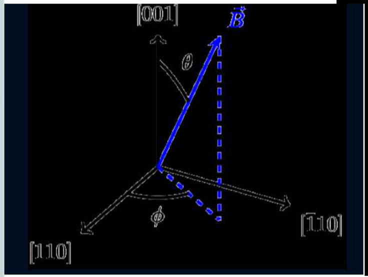
Capabilities added to Laconic

- Magnetic Fields (vector potential)
- Zeeman Splitting
- Momentum Operator
- Spin Orbit Coupling



V_{AC} along the y $[\bar{1}10]$ direction





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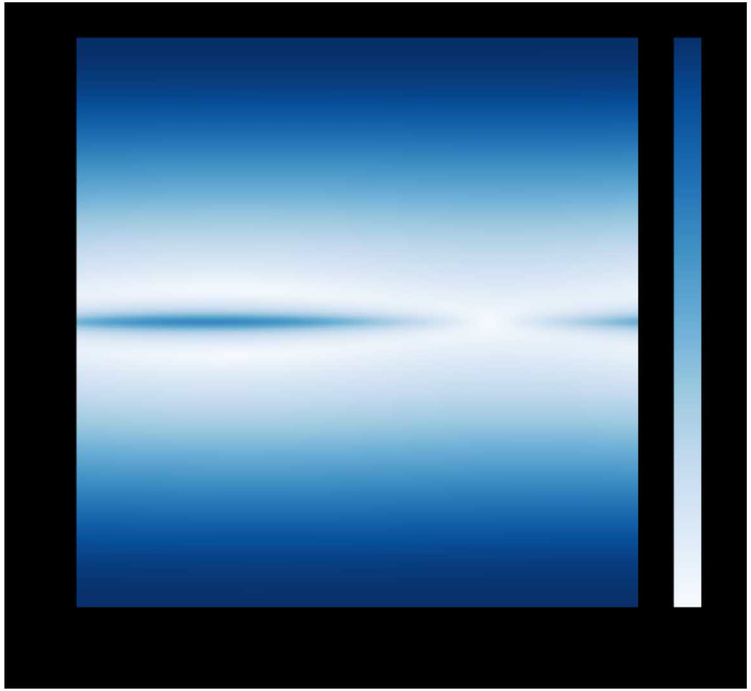
Multi Band Model

- Luttinger Hamiltonian to describe light and heavy hole mixing
- Expand in effective mass envelope function basis
- Ground and excited states are a combination of heavy hole and light hole terms
- Complex behavior from the Luttinger Hamiltonian
    - Natural spin quantization along confinement direction competes with Zeeman splitting
    - Near degeneracy in heavy hole term near $\theta=\pi/2$ causes a spike in frequency

Predicted Rabi frequency for our design



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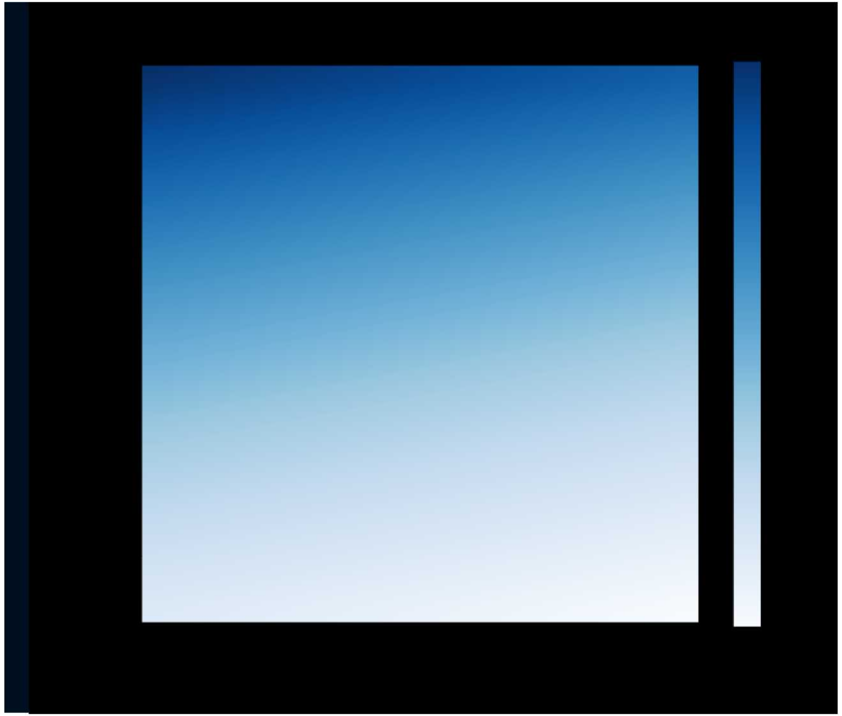
Dependence on Dot Shape

- Increasing the size of the quantum dot in the y direction leads to a larger Rabi frequency due to a larger dipole

- Increasing the size of the quantum dot in the x direction leads to a modestly smaller Rabi frequency due to a decrease in extent of k-space



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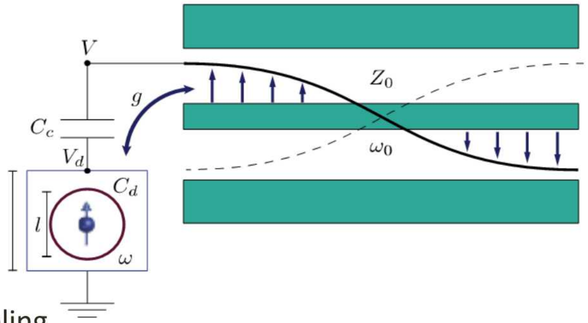
Spin photon interaction

Understand the spin-photon interaction in Ge holes in low photon limit

- Perpendicular magnetic field
- Cubic SOC as perturbation
- Quantized photon Interaction



g=20
f=4.5 GHz
B=5 mT

Charge Photon Coupling

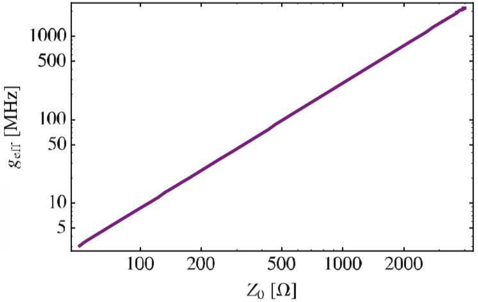
$$g_0 \equiv \frac{elv}{2s}\omega_0\sqrt{\frac{Z_0}{\pi\hbar}}$$

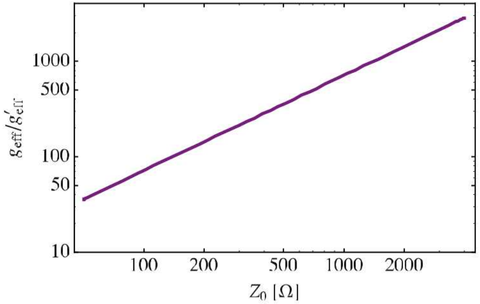
$$H_{\text{so}} = i\hbar\omega_{\text{so}}l^3\left(k_-^3\sigma_+ - k_+^3\sigma_-\right)$$

$$g_{\text{eff}} = \left|\left\langle \widetilde{0,0,\Uparrow;3}\right| H_{\text{int,eff}} \left|\widetilde{0,0,\Downarrow;0}\right\rangle\right| \approx \frac{3\sqrt{6}g_0^3\eta}{4\Omega^2}\left|\tilde{\Lambda}_+ + \tilde{\Lambda}_-\right|$$

$$H'_{\text{so}} = -i\hbar\omega'_{\text{so}}l^3\left(k_+k_-k_+\sigma_+ - k_-k_+k_-\sigma_-\right)$$

$$g'_{\text{eff}} = \left|\left\langle \widetilde{0,0,\Uparrow;1}\right| H_{\text{int}} \left|\widetilde{0,0,\Downarrow;0}\right\rangle\right| \approx 4g_0\eta'\tilde{\Lambda}'$$

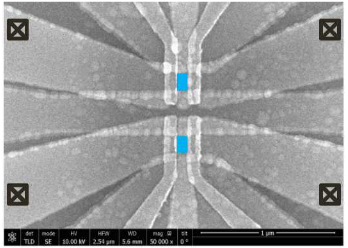


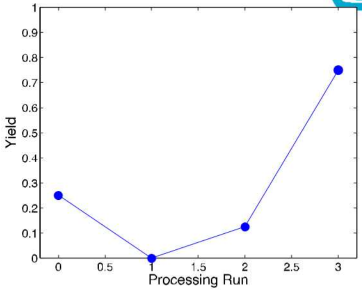


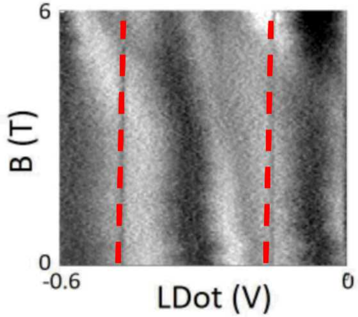
Complementary internally funded work

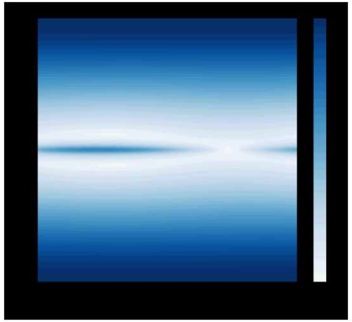
Progress and Outlook

- Improved Device Design
- Overcame major device fabrication hurdles
- Successful Quantum Dots
    - Charge Sensing
    - Single Hole Occupancy
    - Magnetospectroscopy
- Modeling
    - Multiband model for realistic quantum dots









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

Acknowledgements

Modeling:
- Leon Maurer
- Toby Jacobson
- Andrew Baczewski

Center for Integrated Nanotechnologies:
- Tom Harris
- Mike Lilly

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- Jiun-Yun Li
- C.-Y. Liu
- C.-T. Chou

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Backup Slides

Venitucci and Niquet model

- Particle in a box with a static E-field along y-direction
- Calculate Rabi frequency as a function of B-field direction

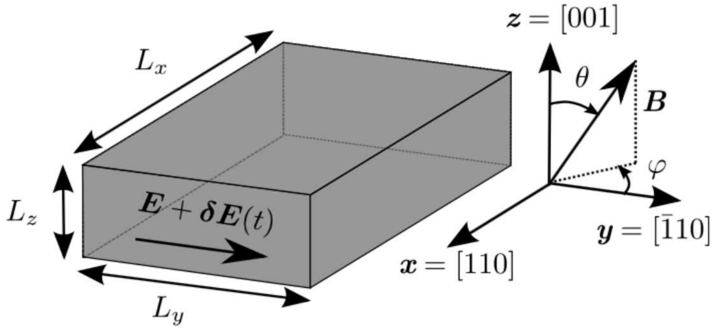
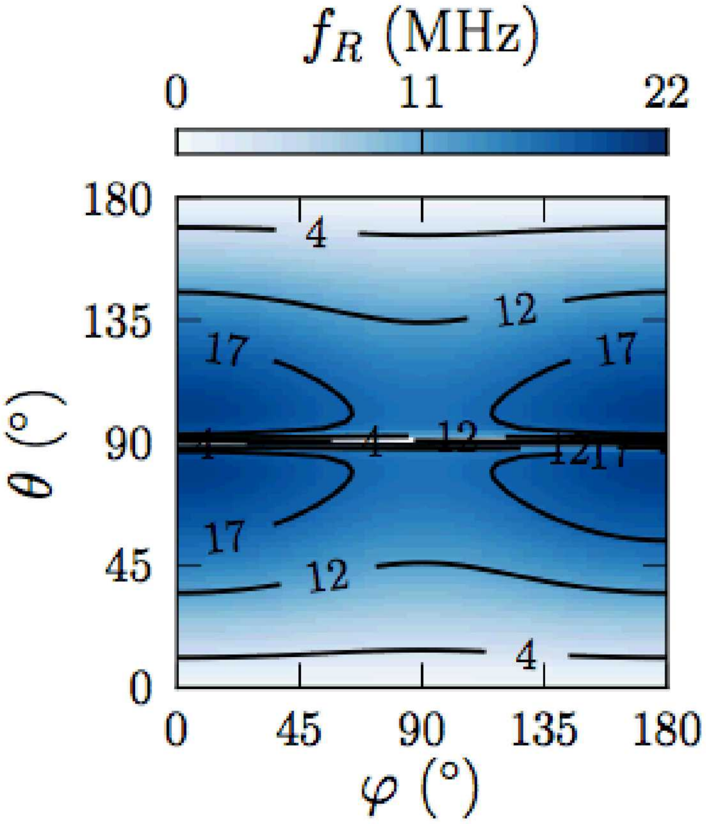


FIG. 1. The model system. A rectangular box with sides L_x, L_y and L_z is subjected to a static magnetic field $\boldsymbol{B}$, a static electric field $\boldsymbol{E} = E_0\boldsymbol{y}$ and a radio-frequency electric field modulation $\delta\boldsymbol{E}(t) = E_{\mathrm{ac}}\sin(2\pi f_L t + \phi)\boldsymbol{y}$. The orientation of $\boldsymbol{B}$ is characterized by the polar angle θ and the azimuthal angle φ.

Venitucci and Niquet, arXiv:1901.09563

Venitucci and Niquet results



Approximate eigenstates of the Luttinger Hamiltonian:

$$|g\rangle \approx \alpha_g|+3/2\rangle + \beta_g|-1/2\rangle,$$
$$|e\rangle \approx \alpha_e|-3/2\rangle + \beta_e|+1/2\rangle.$$

The dipole drive is diagonal in spin. Thus if we have a magnetic field along z, which also doesn't further mix spins, we have no Rabi oscillations.

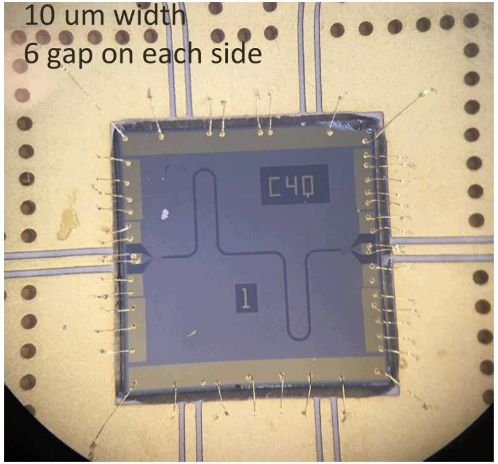
The Rabi frequency increases mostly as the magnetic field drifts away from z, until it comes to the xy-plane. With $B_z = 0$, eigenstates are like

$$|g\rangle = \frac{1}{\sqrt{2}}(|+3/2\rangle + e^{i\alpha}\,|-3/2\rangle)$$

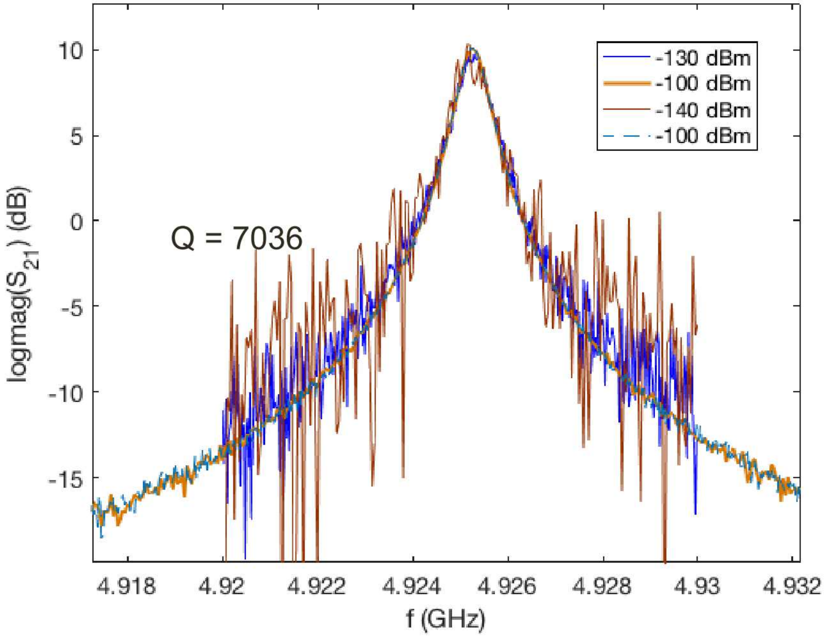
with too large of a level spacing between LH and HH to mix better

Nb 50 Ohm CPW sample from Star Cryo

Metal patterned on 25 nm Al_2O_3, similar to what we expect to use for quantum dots



6 pF coupling capacitors



- High quality superconducting films can be obtained from Star Cryo
- High Q resonators are possible on our quantum dot oxide

NbTiN summary

T=4 K

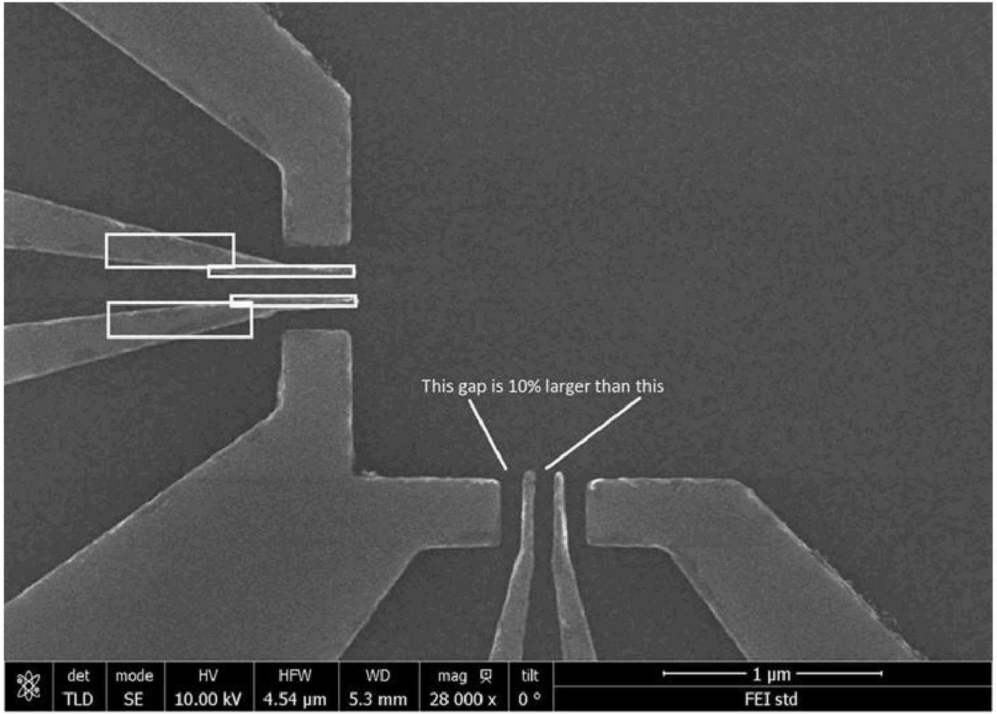
From AppCad

Sample	fp1	fwhm	Q	Z non SC	F design	fm/fd	Z m
5 um line	4.699 GHz	1.76 MHz	2670	94.3 Ohms	5.321 GHz	.883	105
3 um line	3.5428 GHz	1.26 MHz	2806	106.6	5.400	.656	163
2 um line	1.963 GHz	281 KHz	6981	117.4	5.506	.3565	322
1 um line	not measured yet			139.0	5.8		

$$\left(\frac{Z_g}{Z_m}\right)^2 = \frac{L_g}{L_g + L_k} = 1 - \alpha$$

$$\alpha = \frac{L_k}{L_k + L_g}$$

$$\alpha = 1 - \left(\frac{f_m}{f_g}\right)^2$$


This gap is 10% larger than this
det
TLD
mode
SE
HV
10.00 kV
HFW
4.54 μm
WD
5.3 mm
mag
28 000 x
tilt
0 °
1 μm
FEI std

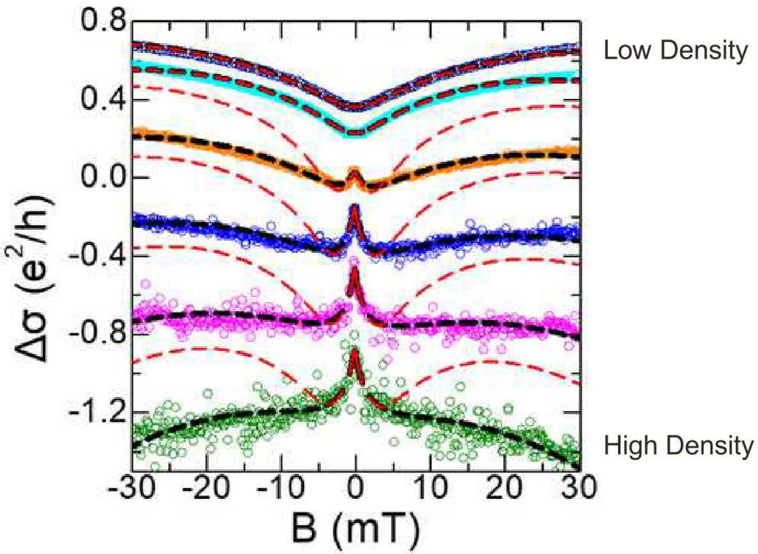
Hole spins in Ge/SiGe provide a compelling alternative to electron spin qubits

- 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

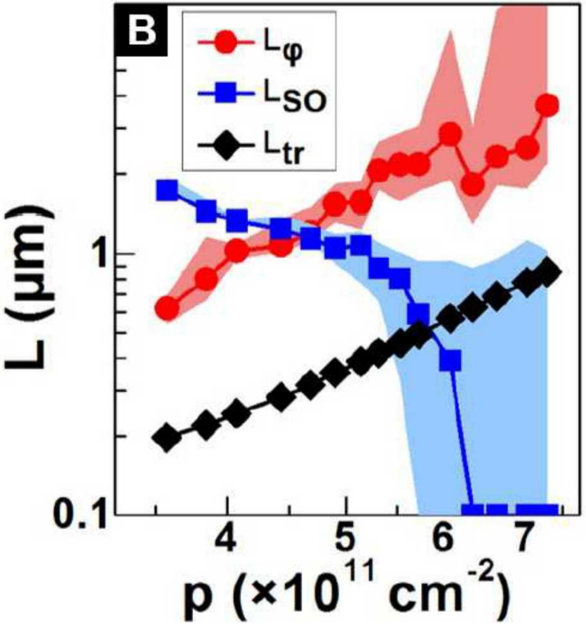
Strong Spin-Orbit Coupling

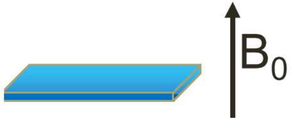
Weak antilocalization peak emerges with increasing density



- - - Linear Rashba Spin Orbit Coupling

- - - k^3-Rashba Spin Orbit Coupling





Chou et al. *Nanoscale* 10.44 (2018)