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Hole spins in Ge/SiGe heterostructures

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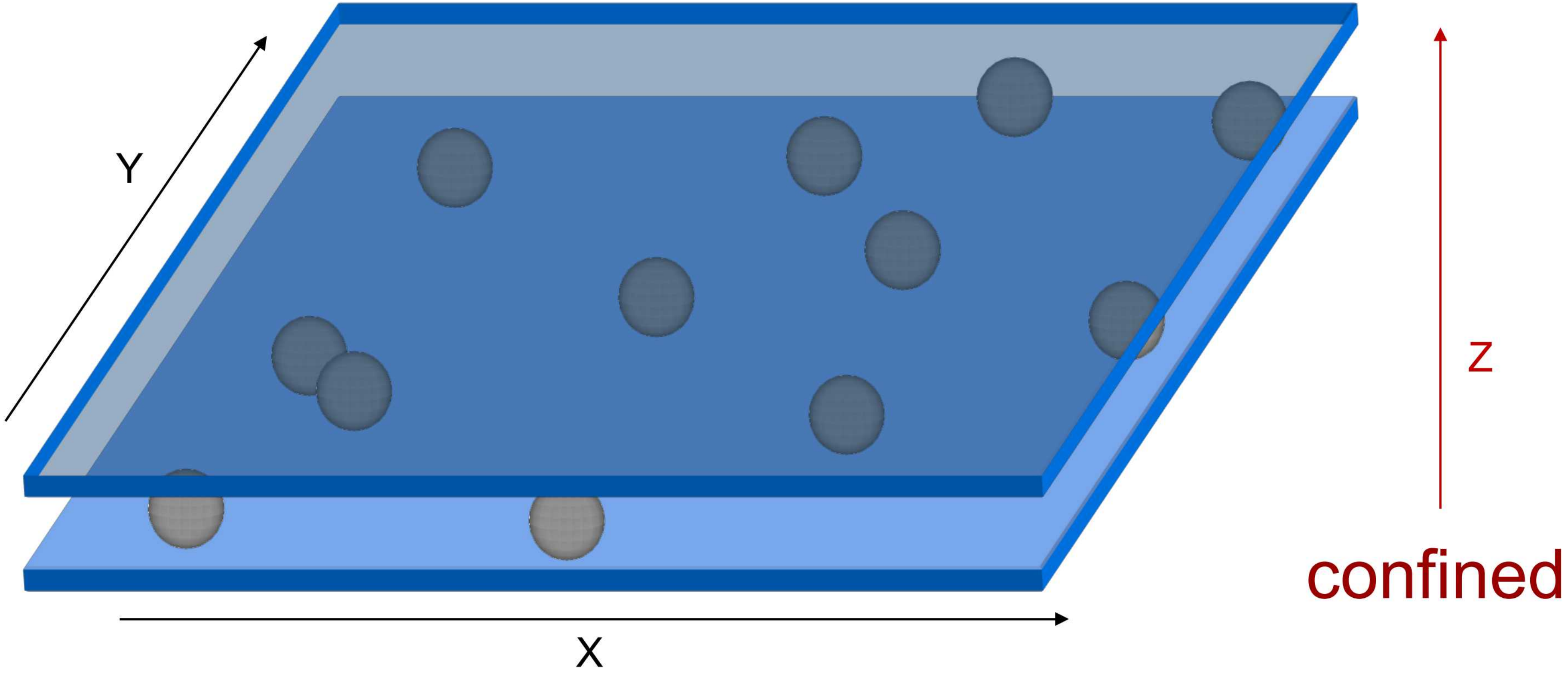
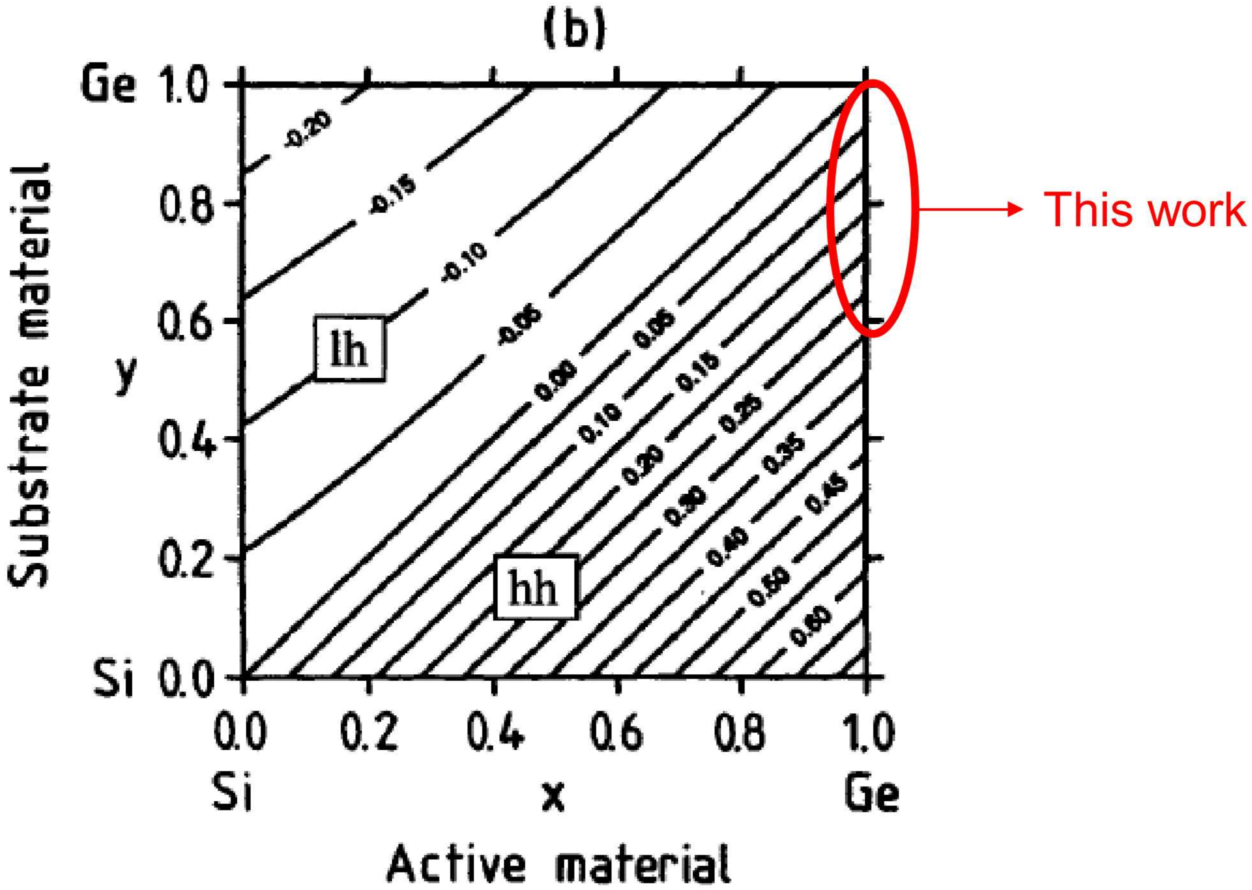
Outline

- Holes in Ge/SiGe heterostructures
  - Physical properties
  - Quantum Hall ferromagnetic transition
  - Spin qubits in Ge/SiGe

2D holes



Band alignment of SiGe heterostructures

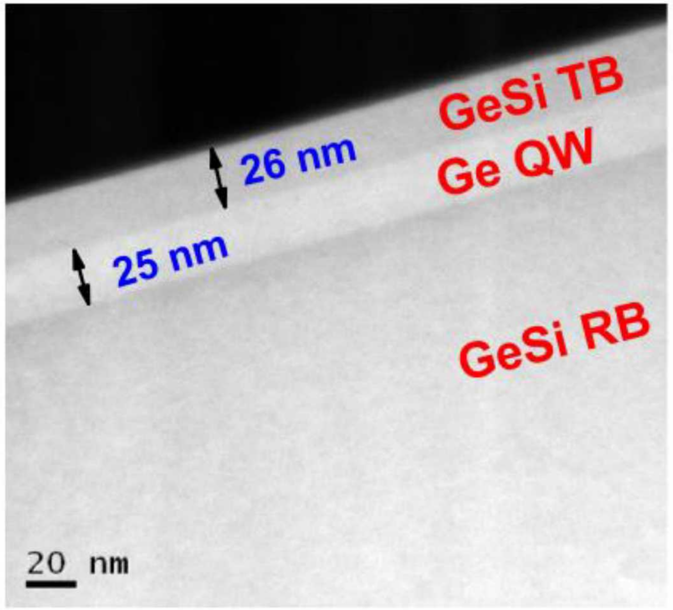


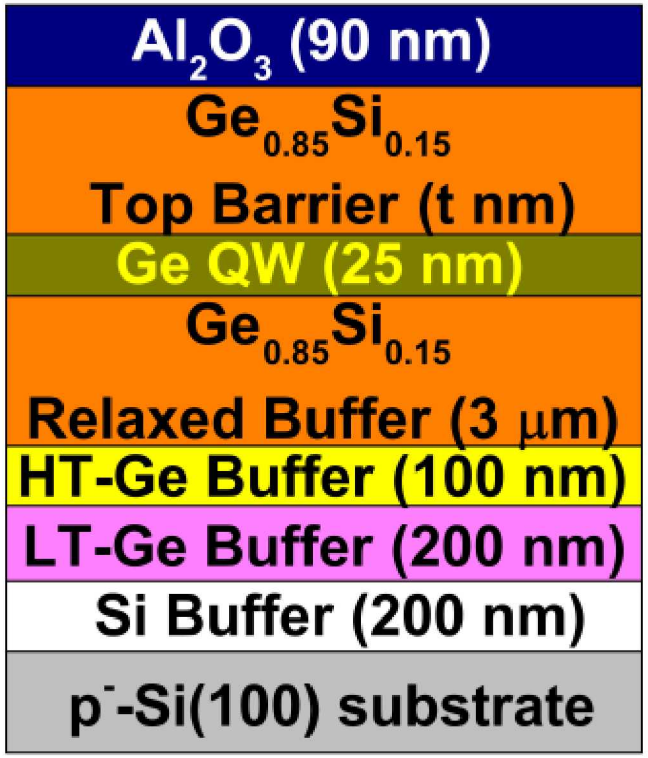
Valance band

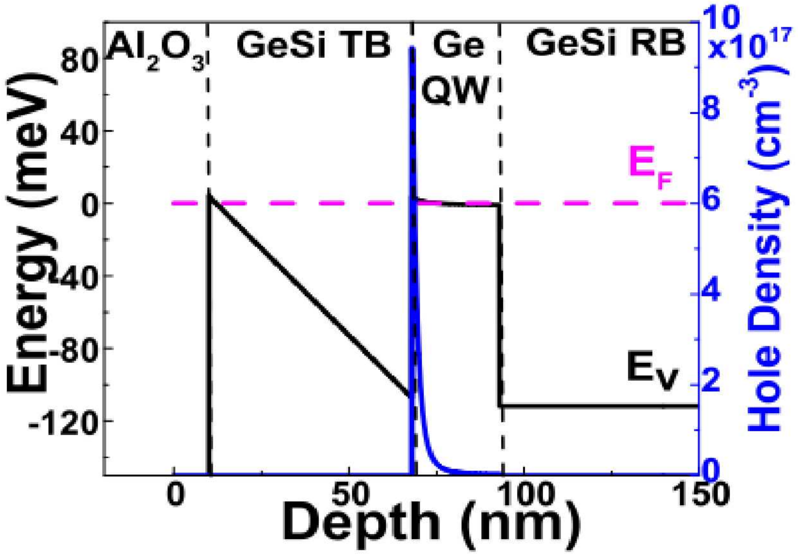
2D holes in Ge quantum wells

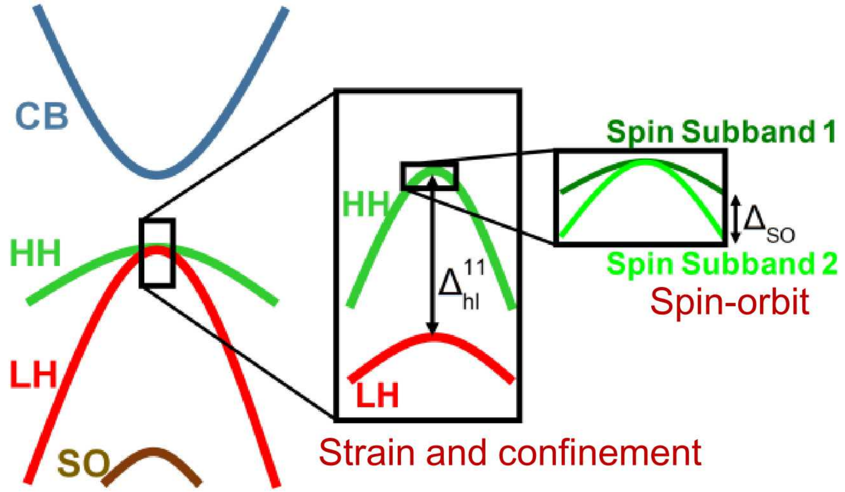
Properties of Silicon Germanium and SiGe: Carbon. Edited by: Kasper, Erich; Lyutovich, Klara (2000)

Undoped Ge/SiGe heterostructure field-effect transistors









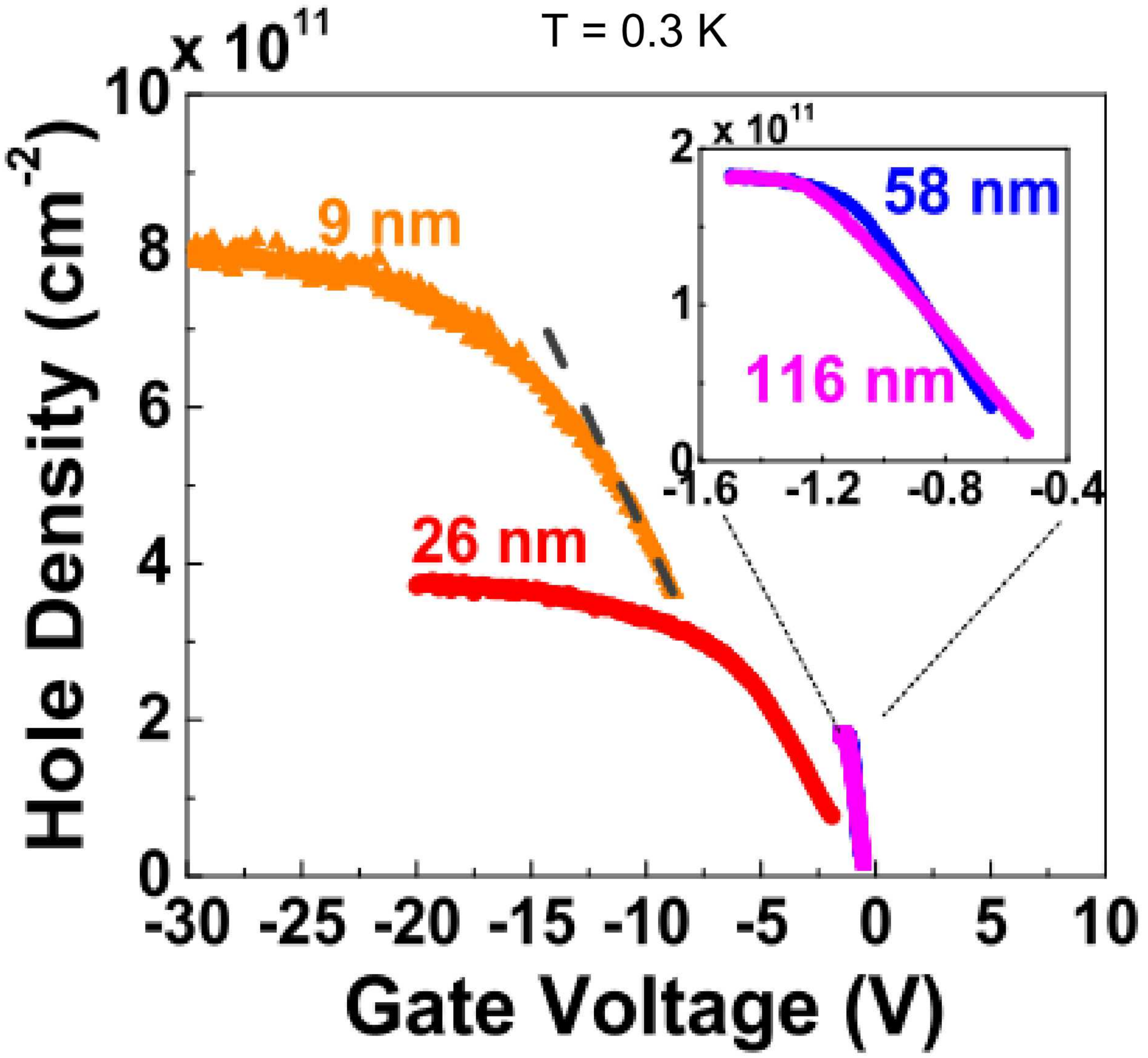
Laroche, Appl. Phys. Lett. 108, 233504 (2016)
Su, Phys. Rev. Mater. 1, 044601 (2017)

Device operation – 2D hole density

- The 2D hole density saturates.

- Shallow channels
  - High saturation densities, depth dependent.
  - Small slopes (capacitances)

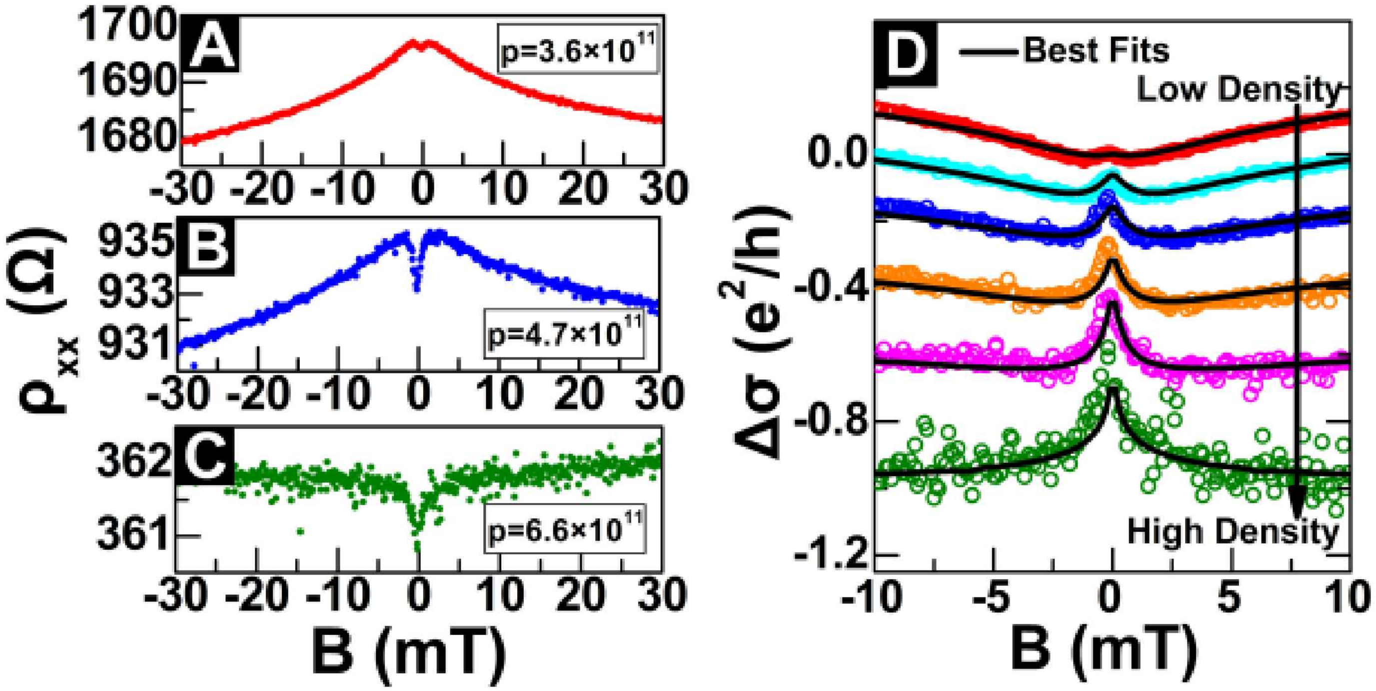
- Deep channels
  - Low saturation densities, depth independent.
  - Large slopes (capacitances)



Su, Phys. Rev. Mater. 1, 044601 (2017)

Physical properties – spin-orbit coupling

- Low densities
  - ➢ Weak localization only
- Intermediate densities
  - ➢ Weak anti-localization on top of weak localization only
- High densities
  - ➢ Weak anti-localization only

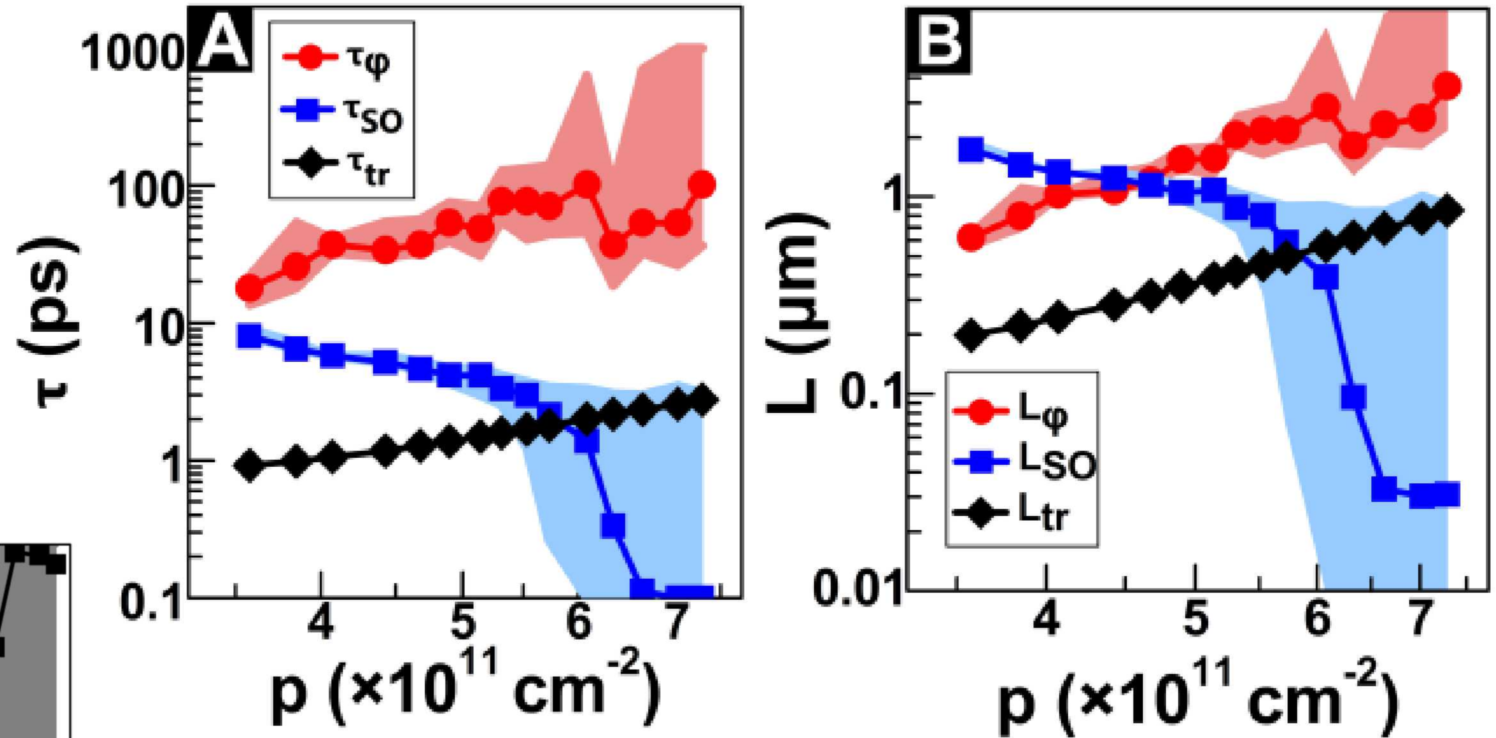


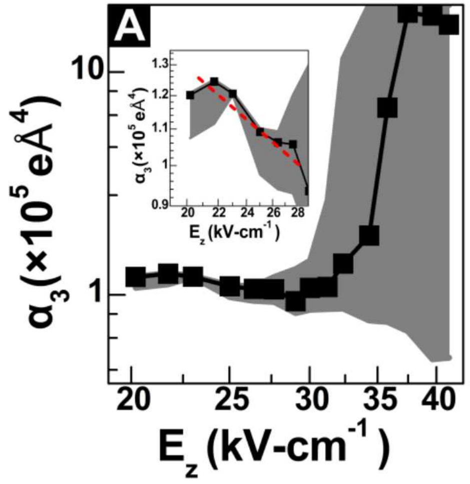
Cubic Rashba: ~(sin3θ,-cos3θ)

Chou, Nanoscale 10, 20559 (2018)

Physical properties – spin-orbit coupling

- Spin-orbit length decreases with density and can be as short as 0.1 um (< mean free path), while the phase coherence length can be a few microns long (>mean free path)
- This means the hole spin can rotate at a high yet controlled rate, maintain its phase coherence, and suffer no scattering.

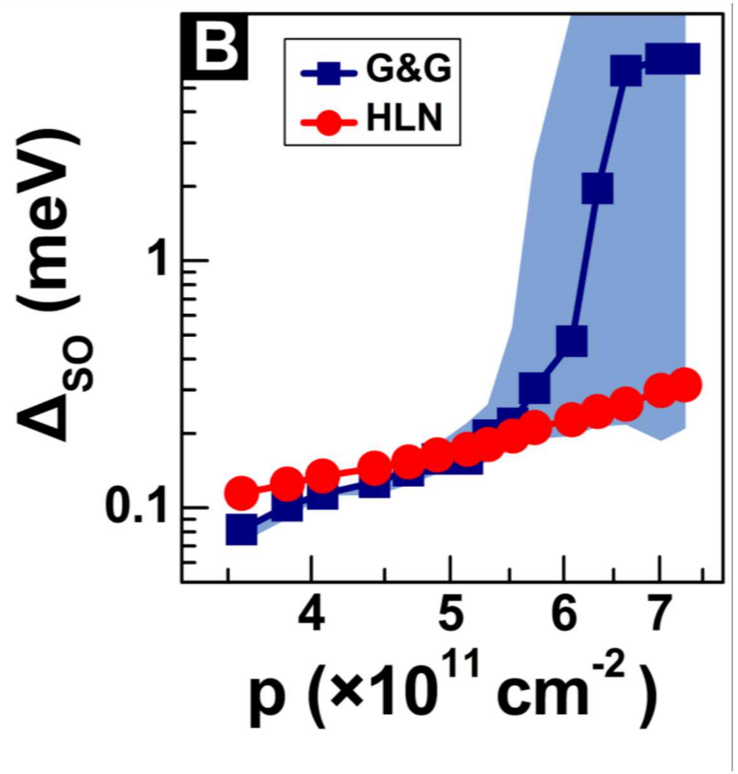




Chou, Nanoscale 10, 20559 (2018)

Physical properties – weak antilocalization beyond diffusive regime

- Conventional theories for weak (anti)localization are only valid in the diffusive regime at low magnetic fields.
- Our data lie outside this regime.
- Numerical methods and code for HPC available with paper.
-



Chou, Nanoscale 10, 20559 (2018)

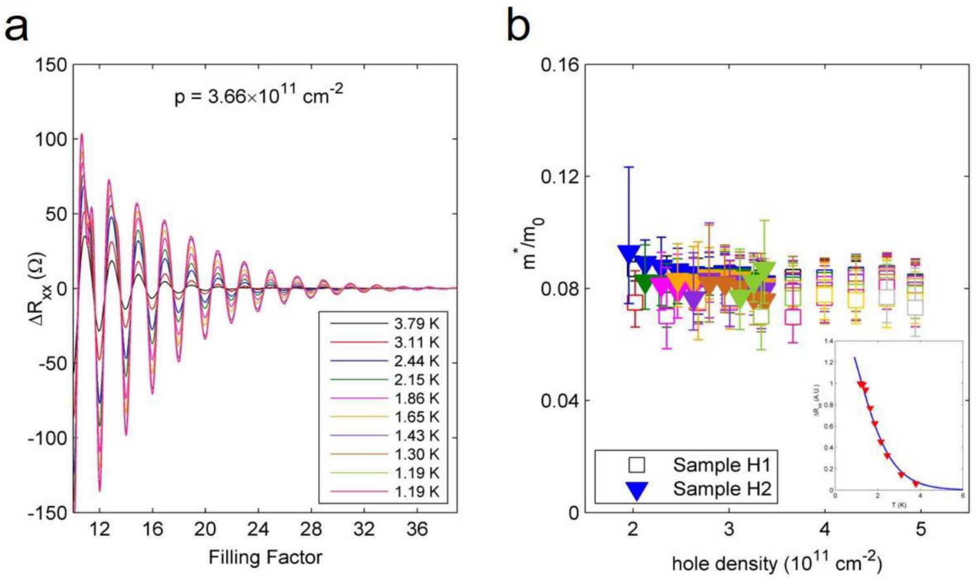
Physical properties – effective mass

- ~ 0.08 m_0.
- ~ density independent.

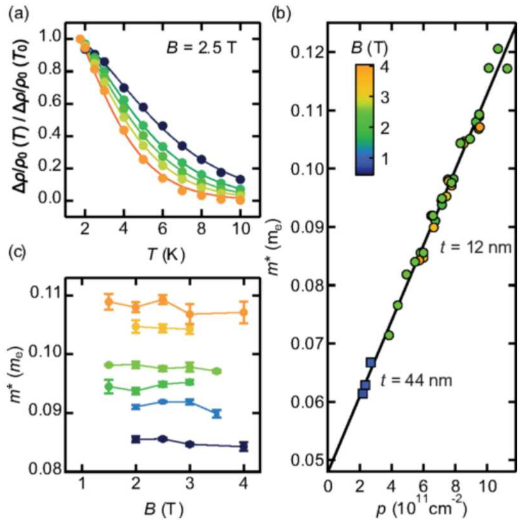
- This mass is small compared to the mass of electrons in Si (0.19), the mass of holes in GaAs (0.2-0.4), and is comparable to the mass of electrons in GaAs (0.07).

- Smaller mass
  => more extended wave functions
  => easier gate controls for nanostructures

  => larger orbital gaps
  => can use higher T cryostats



Hardy *et al.*, *Nanotechnology*, 30, 215202 (2019)

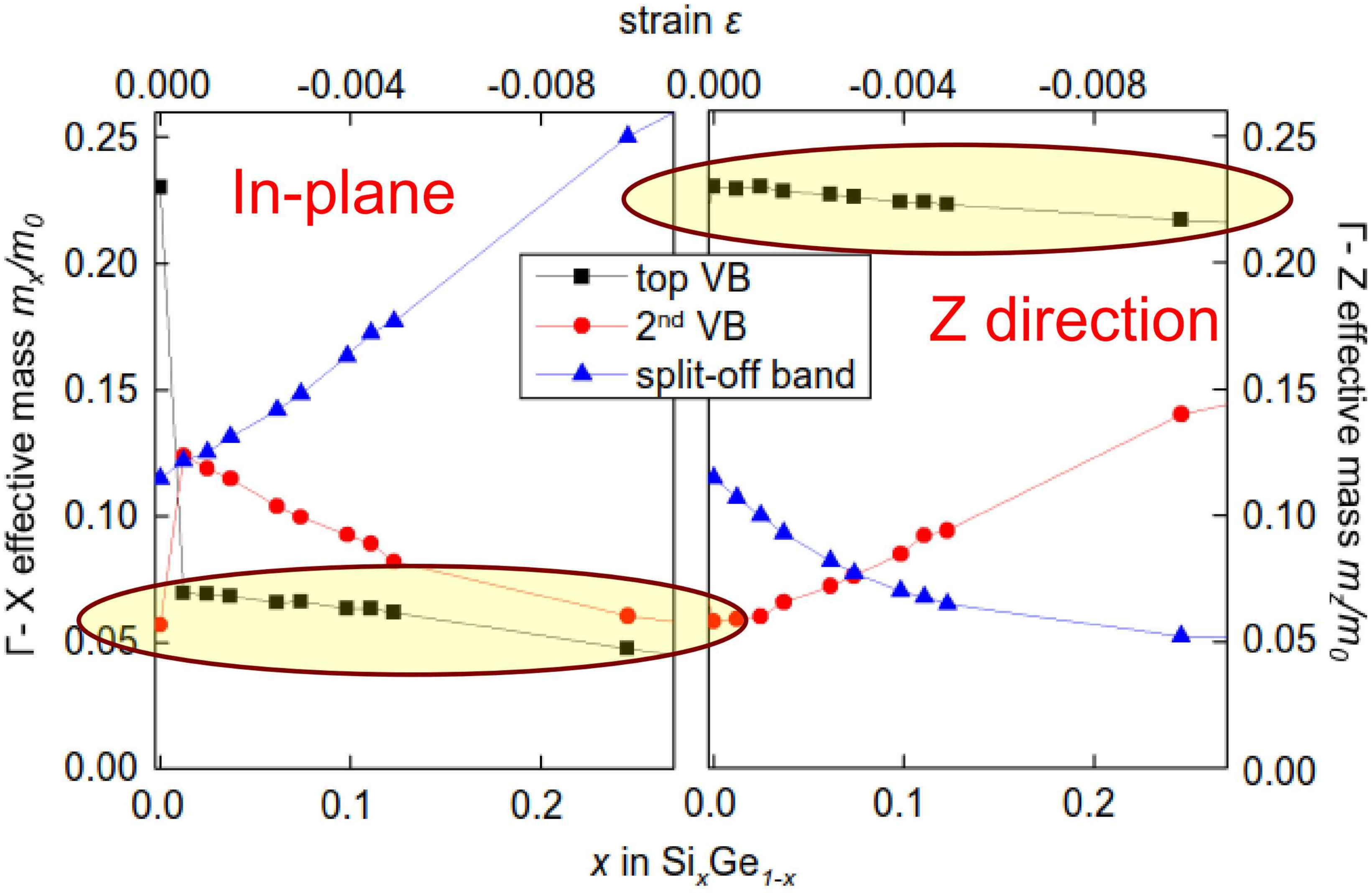


Lodari *et al.*, PRB, 100, 041304(R) (2019)

- Delft results
  - ~ 0.06-0.12 m_0.
  - ~ density dependent.

Physical properties – effective mass

Theory



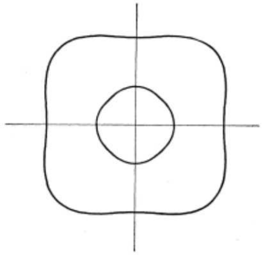


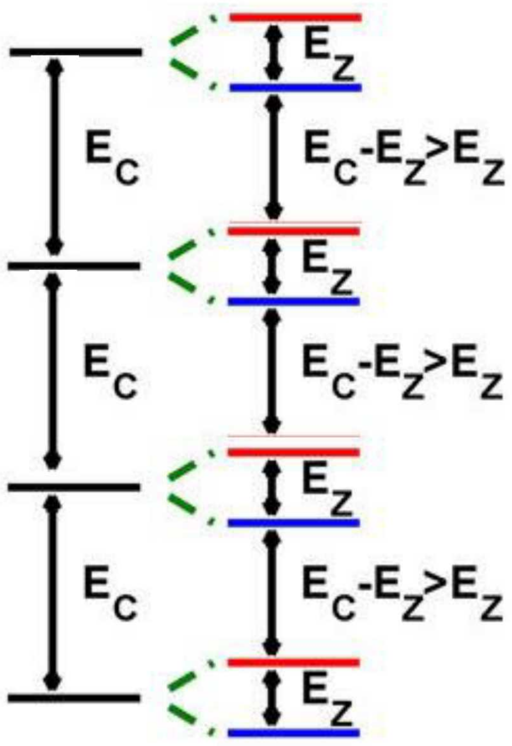
FIG. 8. Figures of constant energy in the (100) plane of k-space for the two fluted energy surfaces which are degenerate at the valence band edge; constants as for germanium.

Dresselhaus PR 98, 368

Terrazos arXiv:1803.10320v1

The quantum Hall effect

In a perpendicular magnetic field, the spectrum of a 2D gas is a series of Landau levels:



Ec is cyclotron gap: $heB/(2\pi m^*)$

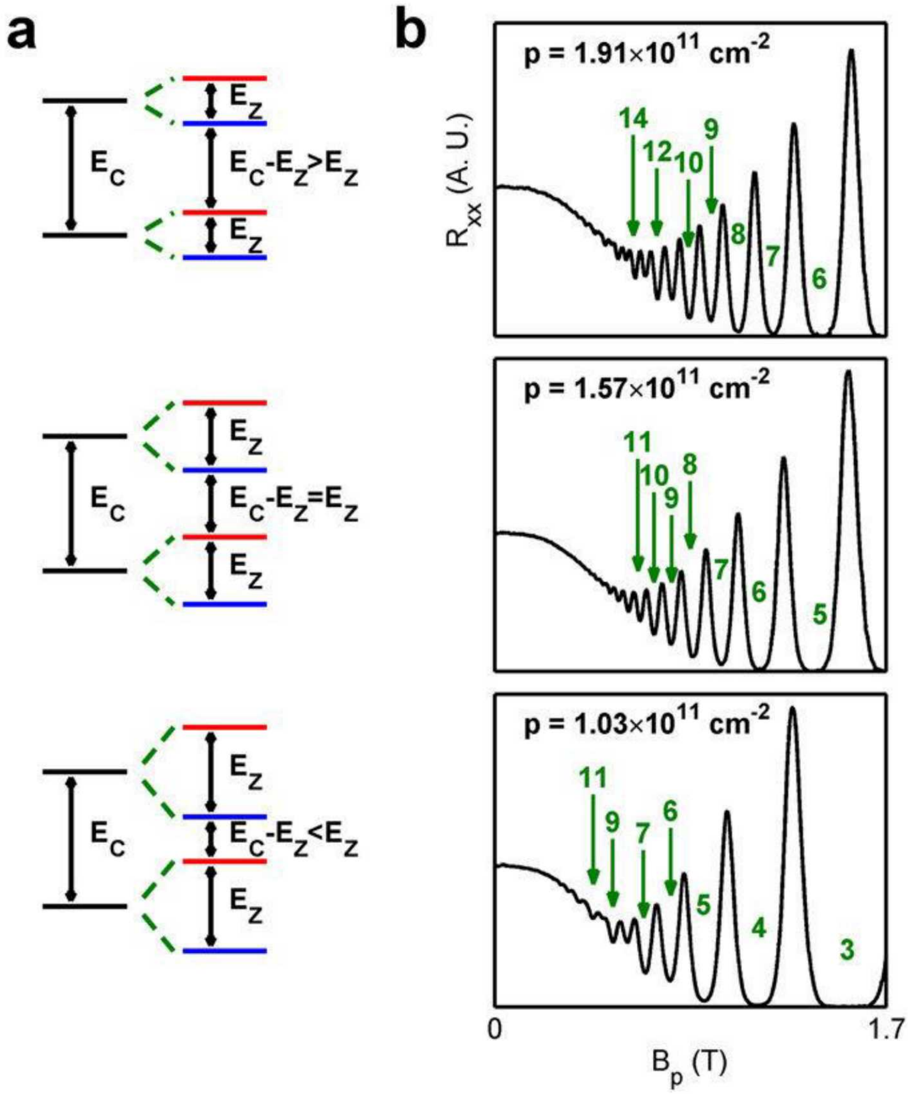
Ez is Zeeman gap: $g^*\mu B$

m^* and g^* are material parameters.

Landau level degeneracy (# electrons / area):
eB/h

Lu, Scientific Reports 7, 2468 (2017)

Quantum Hall ferromagnetic transition



In most cases, Ec >> Ez

⇒ Strong even states, weak odd states

If Ec ~ 2Ez

⇒ Strength of even states ~ strength of odd states

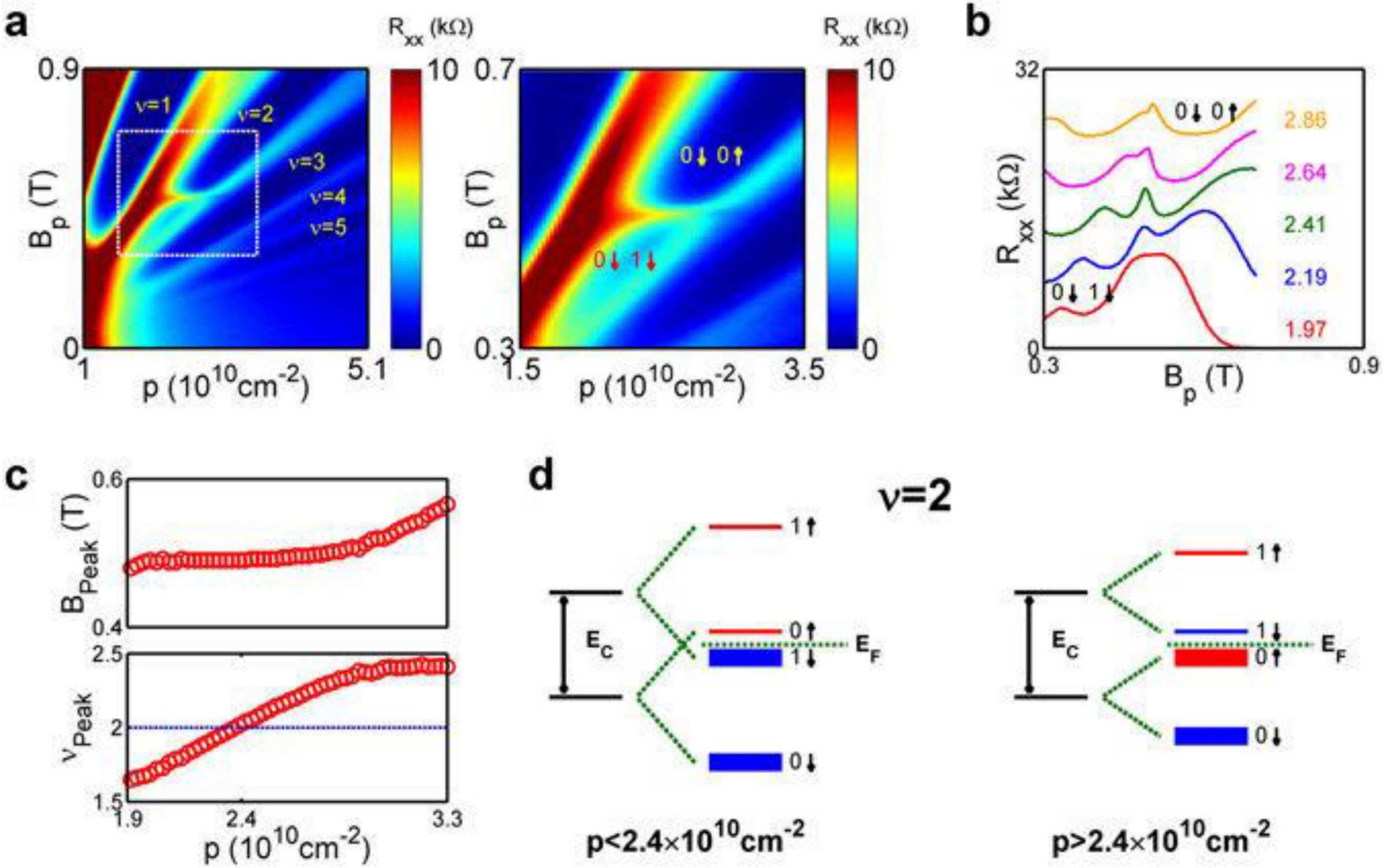
If Ec < 2Ez

⇒ Strong odd states, weak even states

Ez/Ec increases with decreasing density.

Lu, Scientific Reports 7, 2468 (2017)

Quantum Hall ferromagnetic transition



A spin transition (unpolarized <-> polarized) at ν=2 occurs at p~2.4x10^{10} cm^{-2}.

This transition marks the point where Ec~Ez

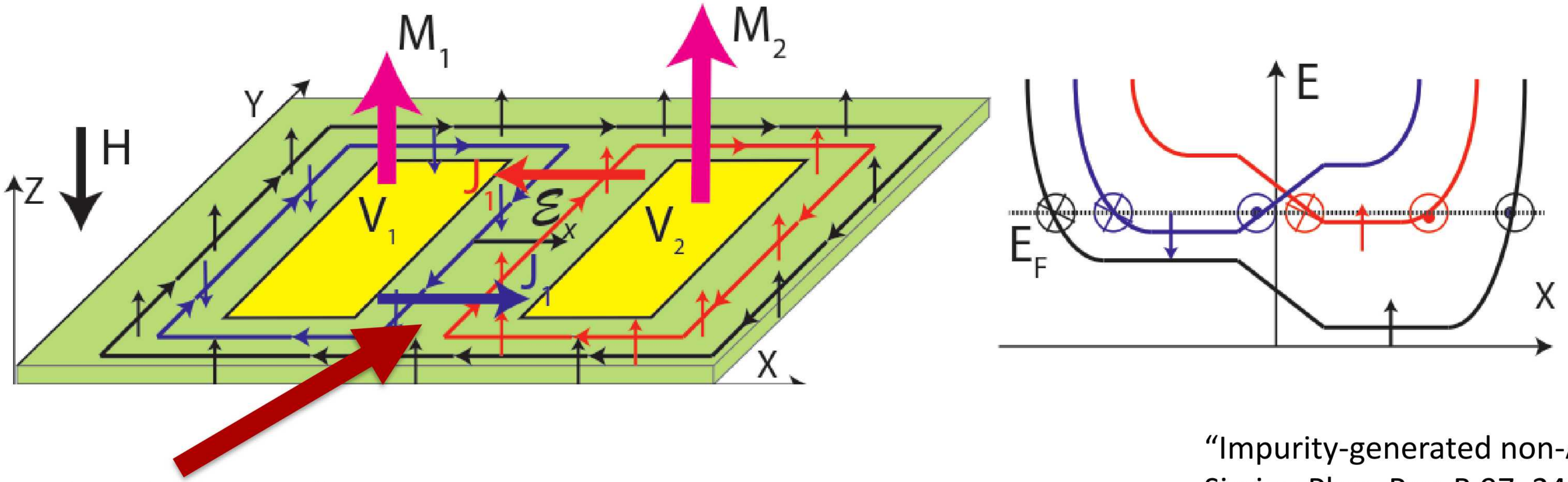
$heB/(2\pi m^*) = g^*\mu B$

$\Rightarrow m^*g^* = 2$

Lu, Scientific Reports 7, 2468 (2017)

Quantum Hall ferromagnetic transition

- Local gating to create counter-propagating edge states with opposite spins
- Depending on the strength of the effective spin-orbit coupling, topological superconductivity and Majorana modes can emerge.
- Bc ~ 0.5T -> very friendly for superconductivity.



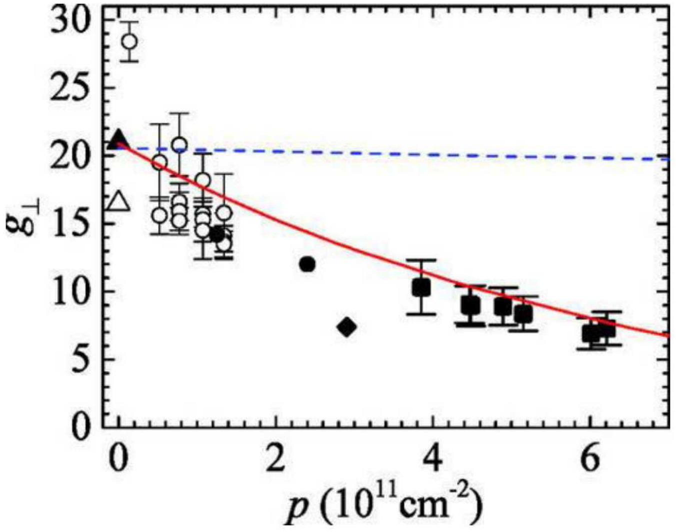
Helical domain wall

"Impurity-generated non-Abelions"
Simion Phys. Rev. B 97, 245107 (2018)

Physical properties – g factor

- ~ 5 – 30
- ~ density dependent.

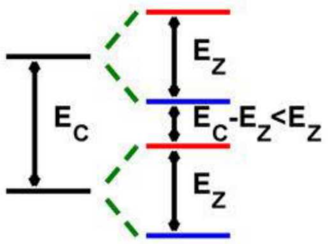
- The g factor is large compared to the g factor of electrons in Si (~2) and the g factor of electrons in GaAs (~0.44).

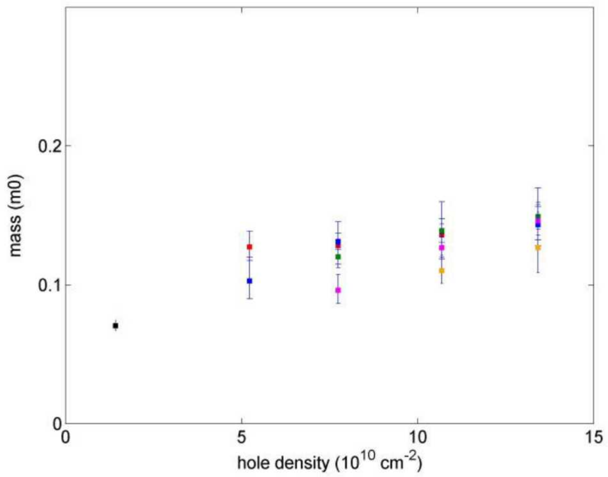


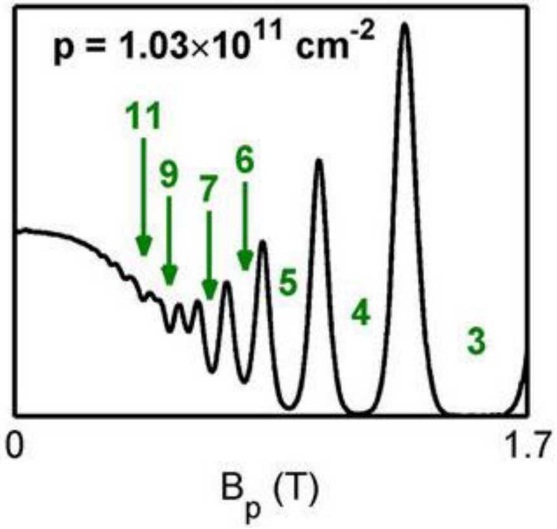
6x6 k.p

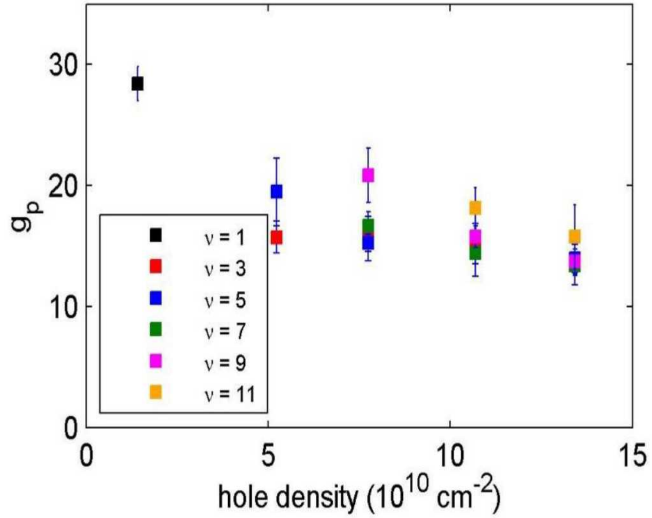
Drichko J. Appl. Phys. 123, 165703 (2018)

P<1.6 x 10^{11} cm^{-2}
0.5 Ec < Ez < Ec









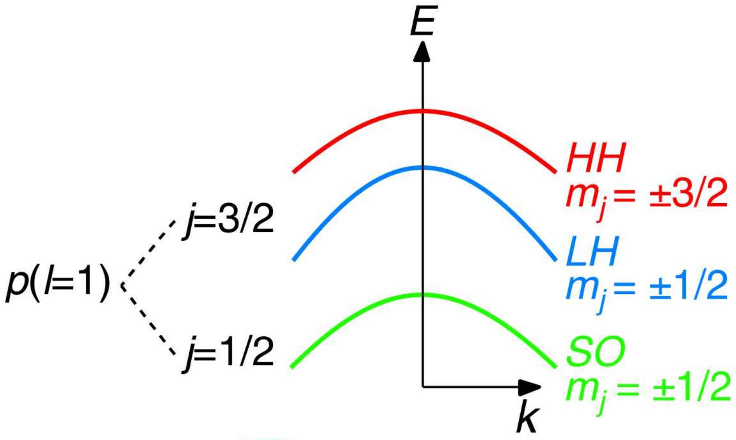
Lu, Appl. Phys. Lett. 111, 102108 (2017)

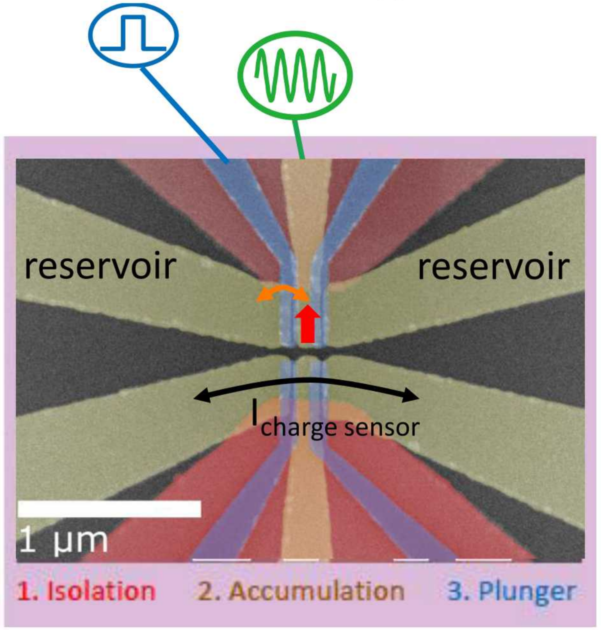
Approach

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

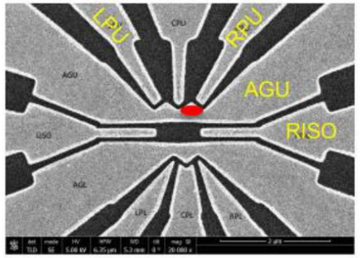
- Single hole confined to lateral quantum dot in Ge heterostructure (small mass)
- Spin qubit states: $m_j=\underline{+}3/2$ (no valley splitting)
- EDSR qubit control through microwaves applied to gates (strong SOC)
- Qubit readout and initialization through energy selective tunneling to reservoir
- Occupancy detected through nearby charge sensor

- P-orbital nature -> suppressed hyperfine.
- Enrichment is possible.

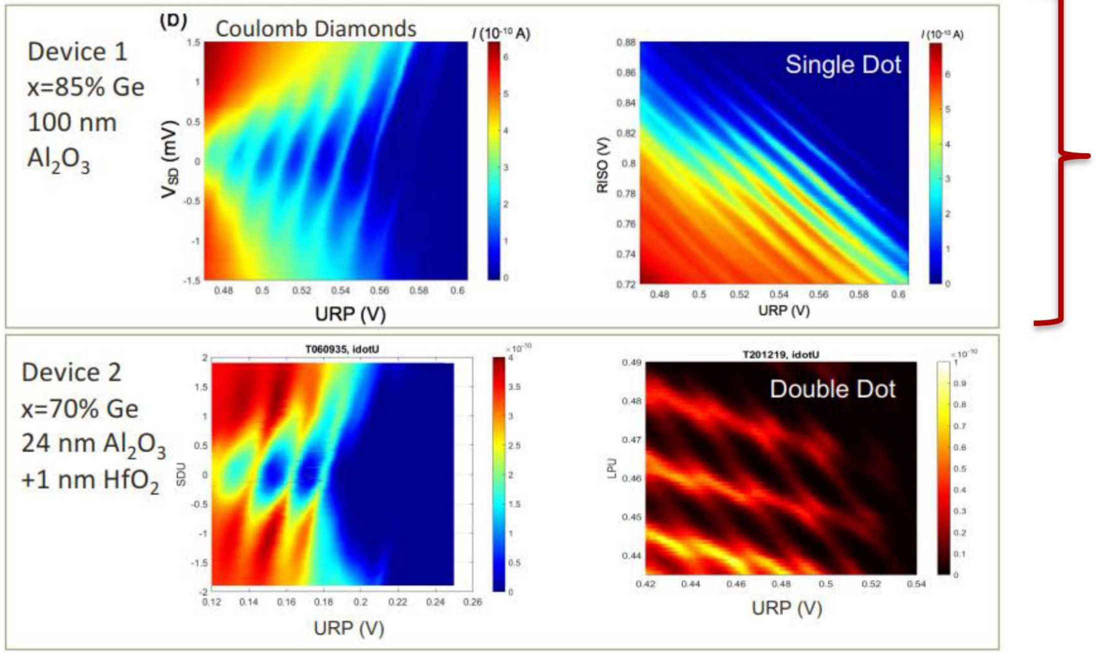


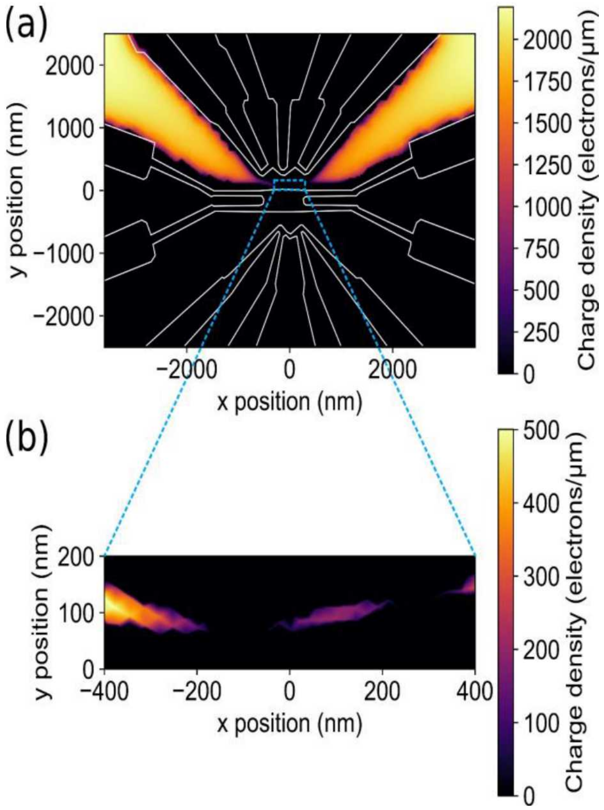


Spin qubits in Ge/SiGe



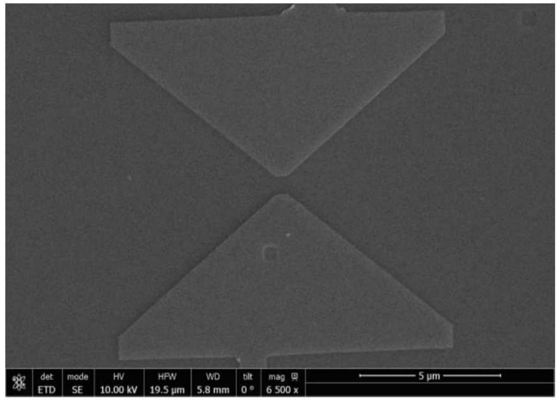
Single Layer Devices can be tuned to low-hole regime in transport



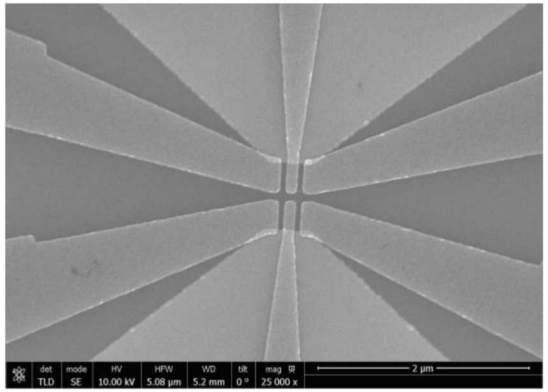


Hardy *et al.*, *Nanotechnology*, 30, 215202 (2019)

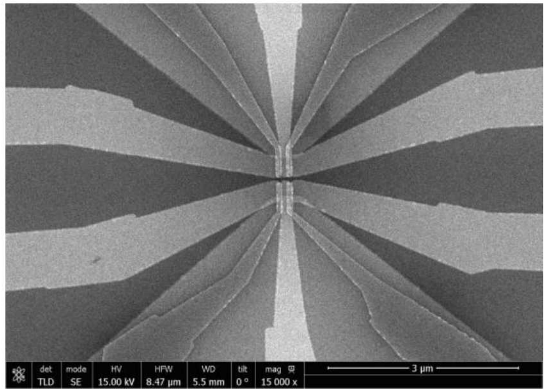
3-layer device fabrication



1: isolation gates

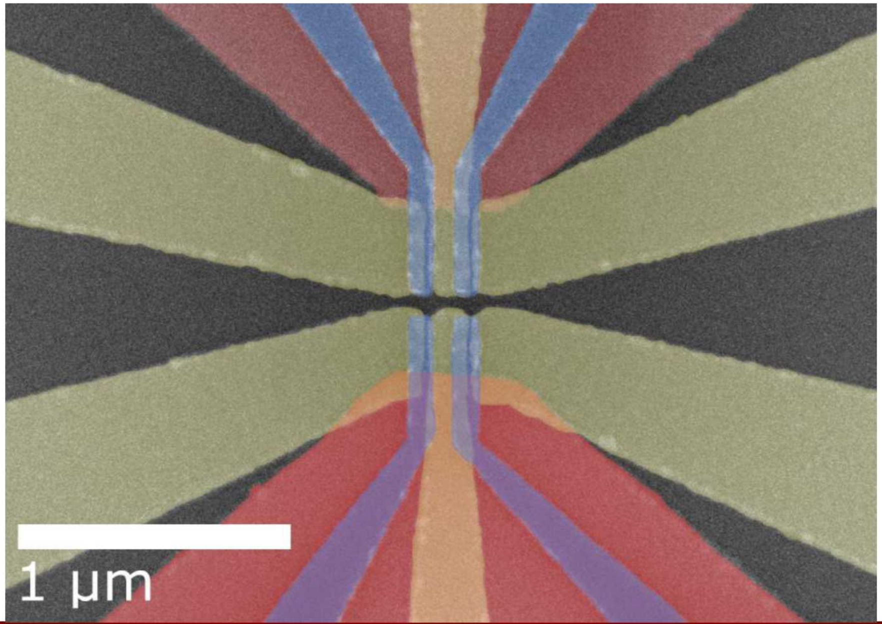


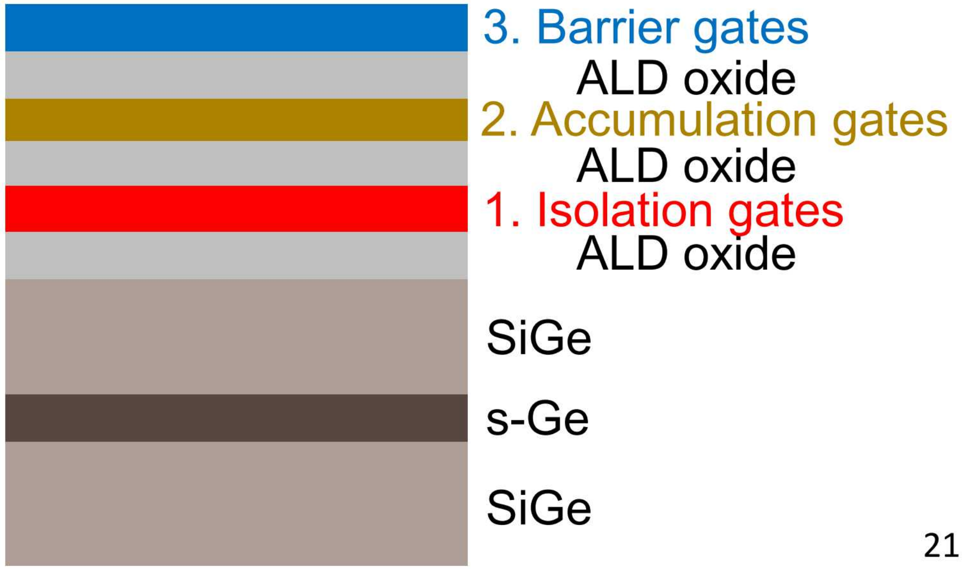
2: accumulation gates



3: barrier gates

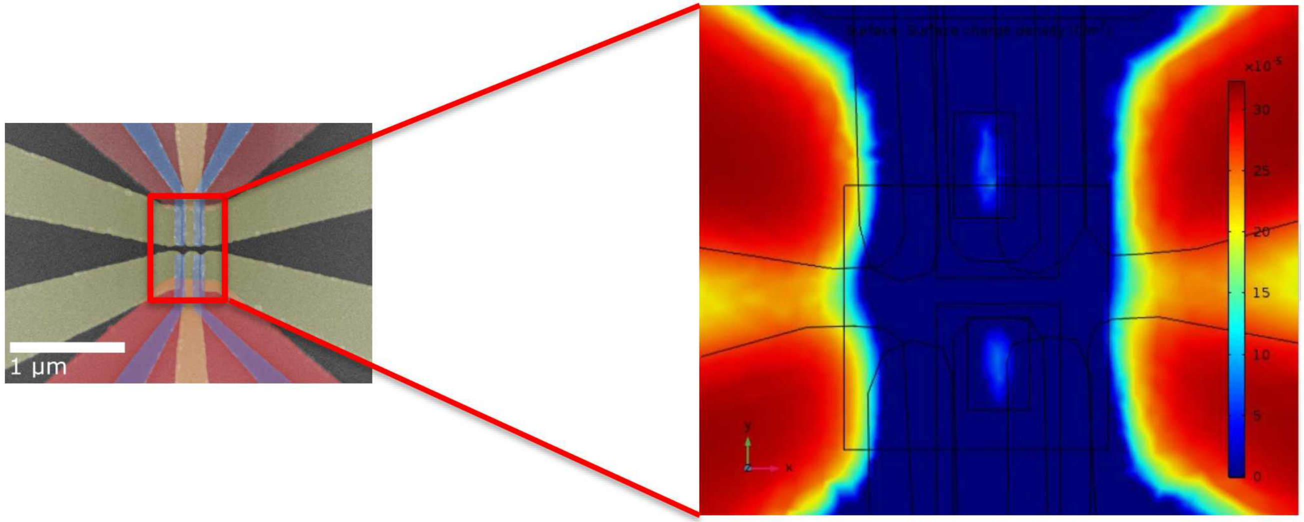
E-beam lithography
ALD Al_2O_3 oxide
Ti/Pt gates



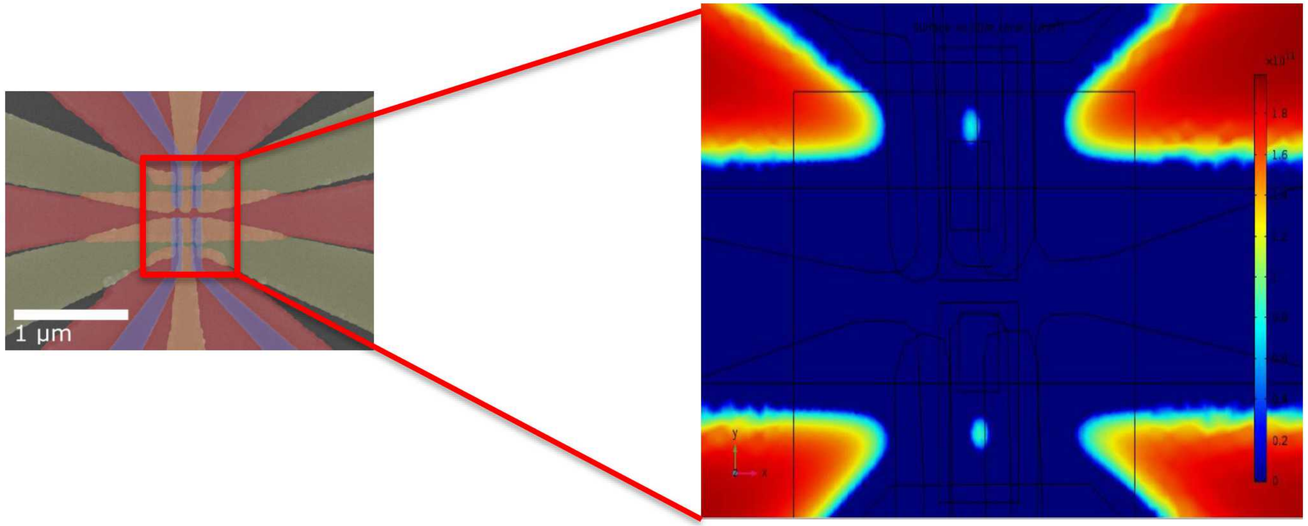


3-layer device modeling: surface charge density

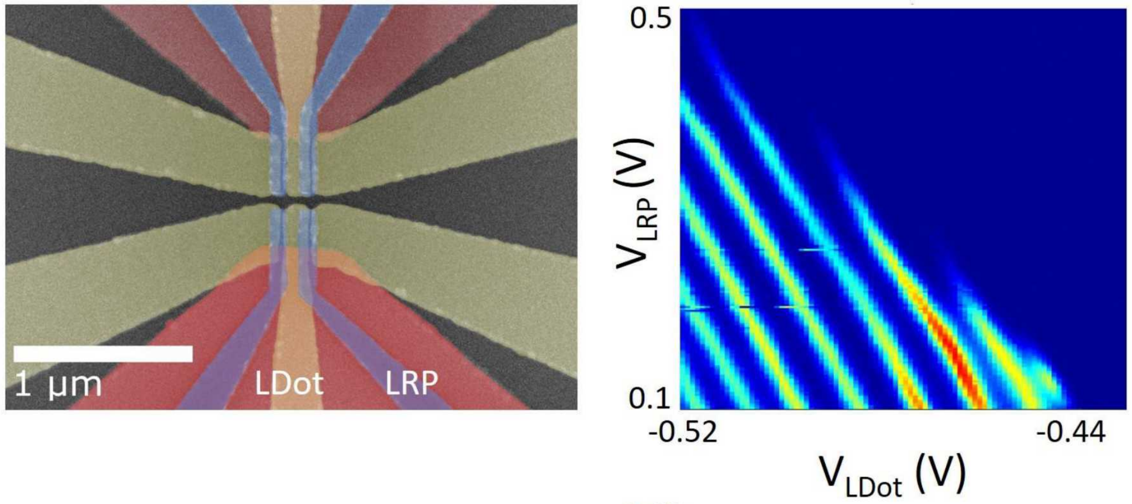
Without horizontal isolation gate: reservoirs merge



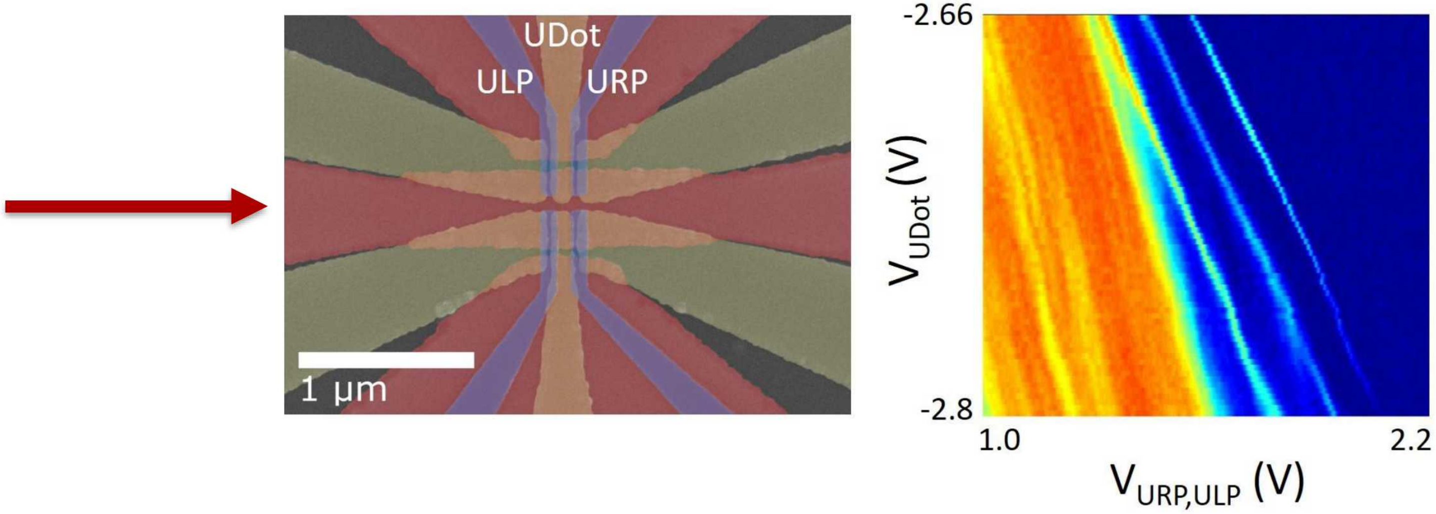
Add horizontal isolation gate: reservoirs separated



Improved Coulomb blockade by adding center isolation gate



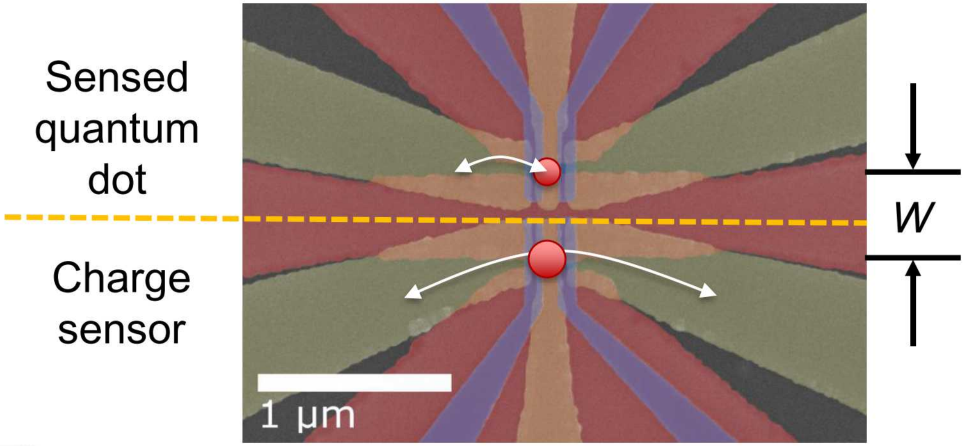
Without horizontal isolation gate

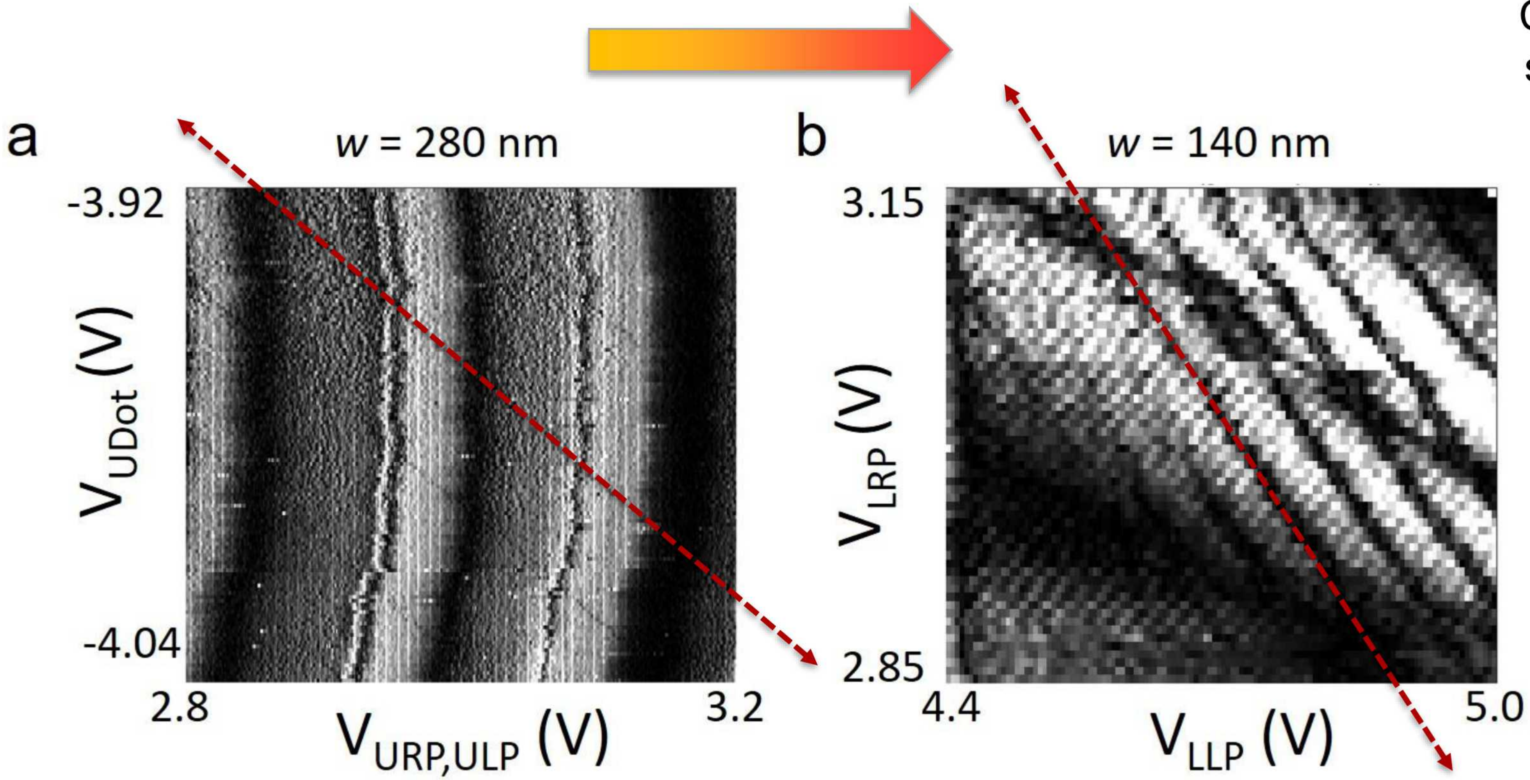


With horizontal isolation gate

Charge sensing: Comparison of isolation gate widths

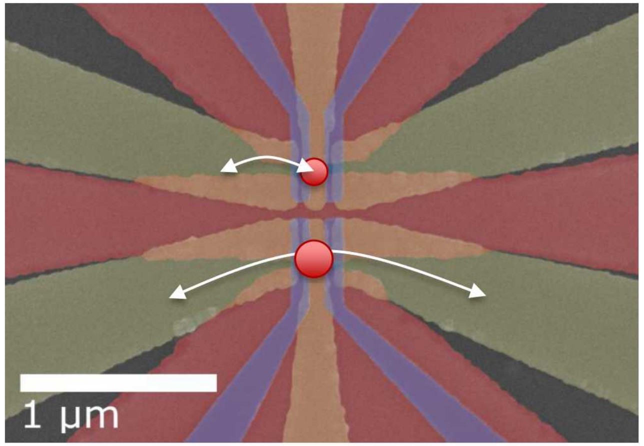
150% improvement in charge sensing signal when *w* is reduced by 2x

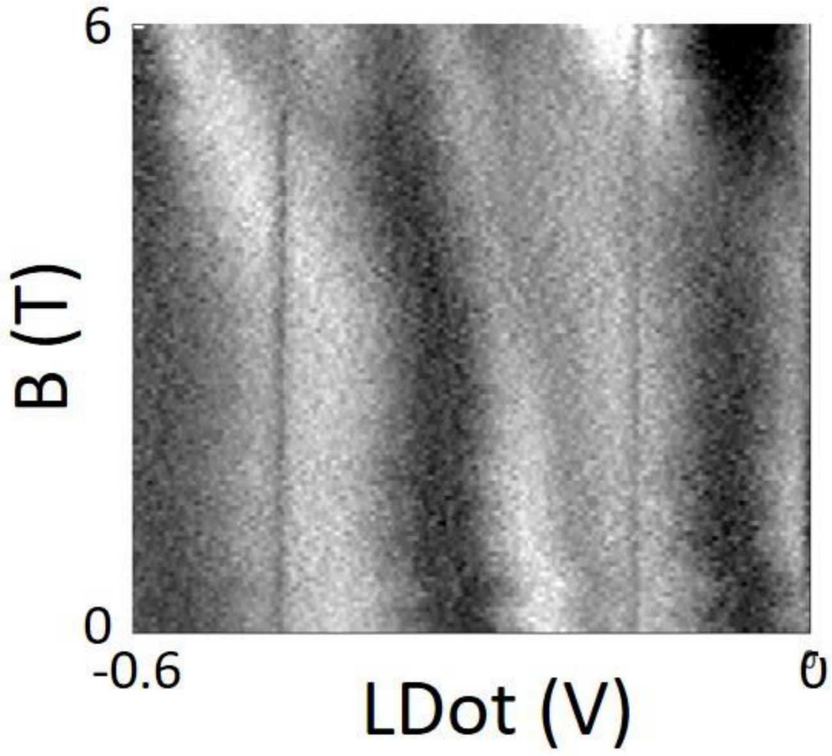




Parallel diagonal lines are sensed charge transitions

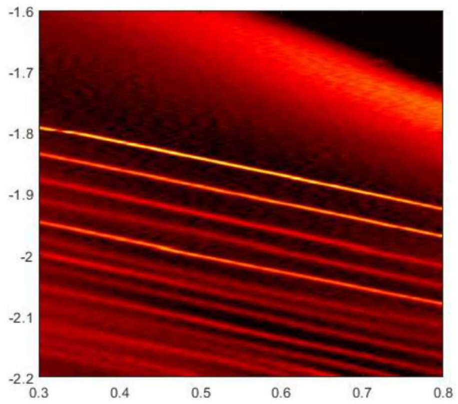
In-plane B field

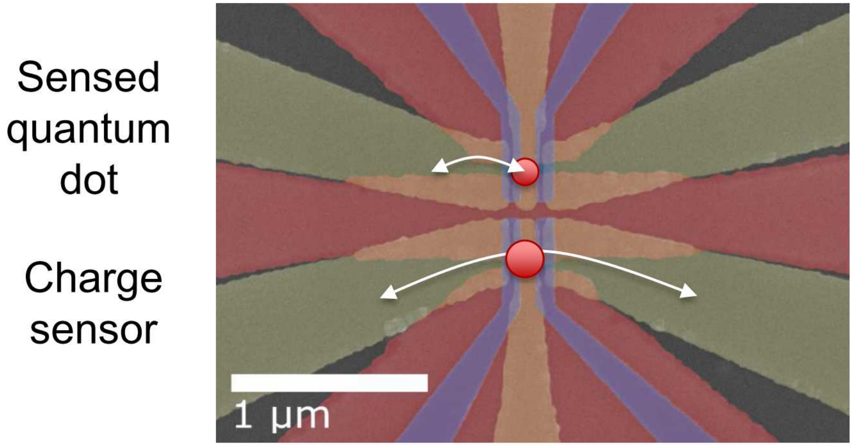


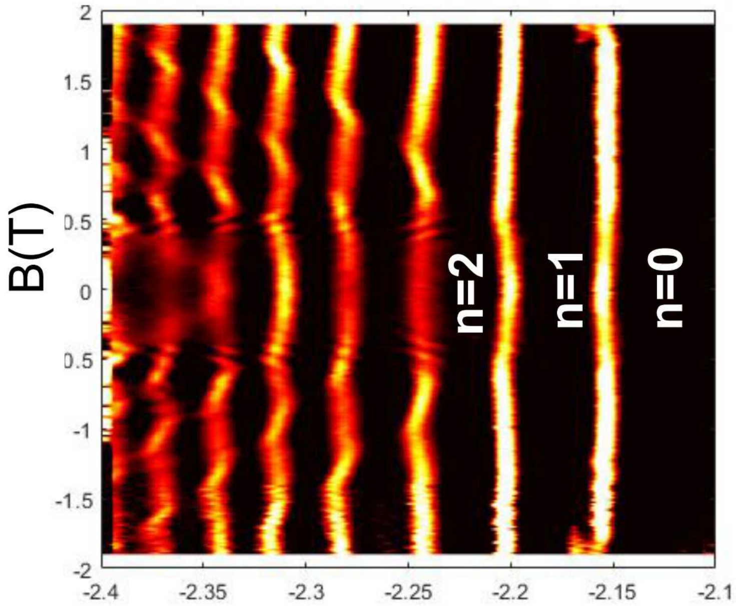


- Charge sensed lines appear insensitive to in-plane B-field
    - $g_{in\text{-}plane}$ is very small (estimate < 0.5)

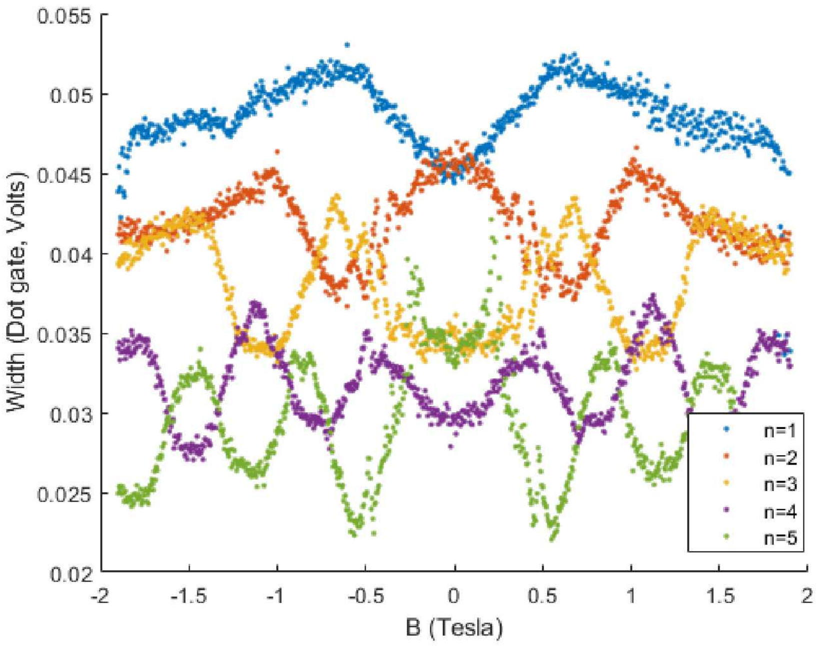
Perpendicular B field







Perpendicular B field



- $g_{perpendicular}$: ~15 (based on N=1)
  ~18 (based on N=2)
- Consistent with estimates from transport measurement on 2DHGs.

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., single-band vs. multi-band)
  - Integrate more physical details into our theory

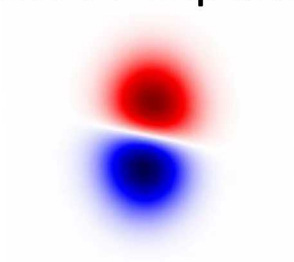
Luttinger Hamiltonian for SOC modeling

- Include externally applied potential and (spin-3/2) Zeeman term

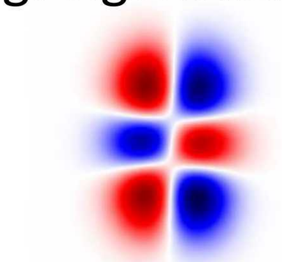
$$\hat{H}_Z = \kappa\mu_B \begin{bmatrix} 3B_z & \sqrt{3}B_- & 0 & 0 \\ \sqrt{3}B_+ & B_z & 2B_- & 0 \\ 0 & 2B_+ & -B_z & \sqrt{3}B_- \\ 0 & 0 & \sqrt{3}B_+ & -3B_z \end{bmatrix}; \quad B_+ = B_x \pm iB_y$$

- Select a basis in which to expand $\hat{H}_{LK}$, e.g. eigenstates of the potential

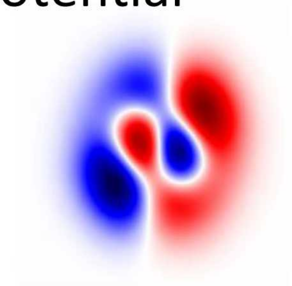
$|\psi_0\rangle$



$|\psi_1\rangle$



$|\psi_5\rangle$

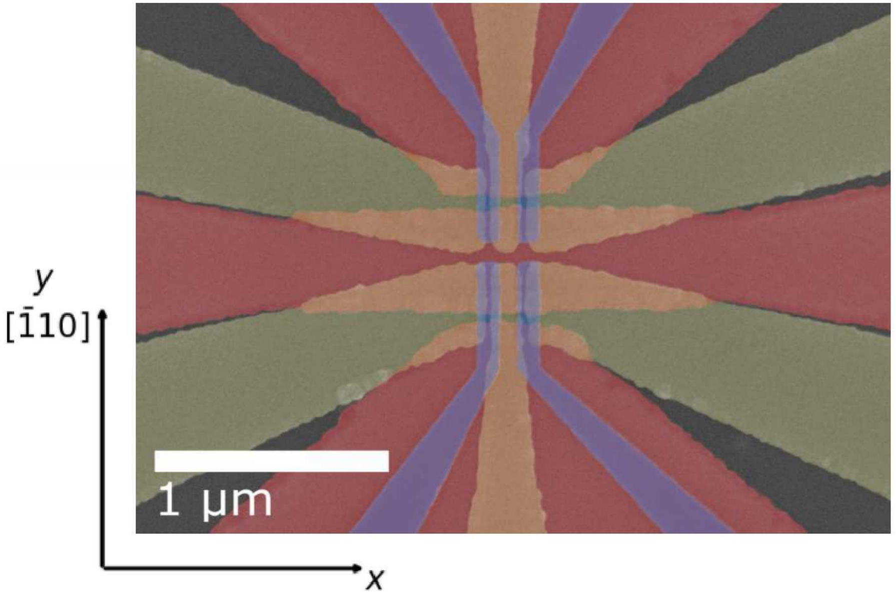


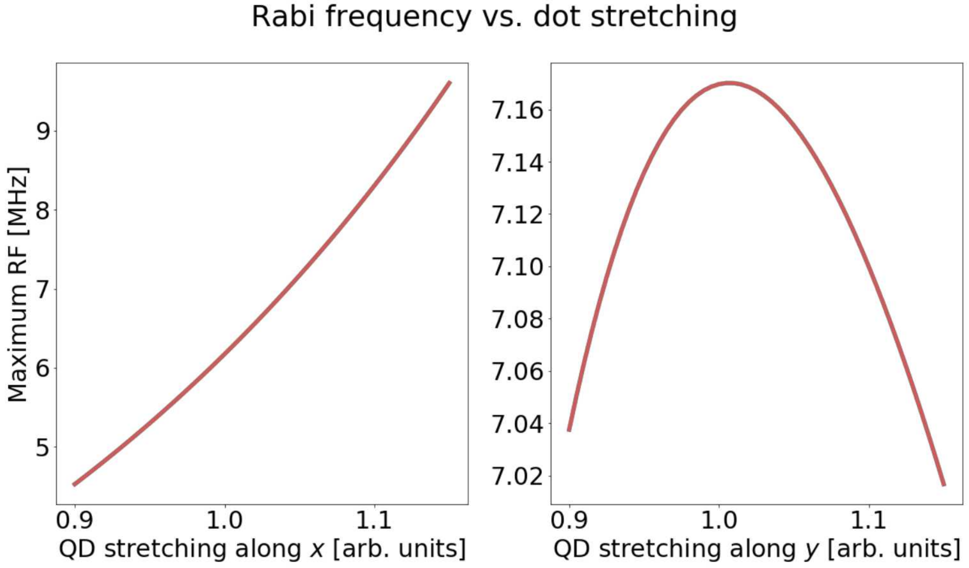
$|\psi_{10}\rangle$

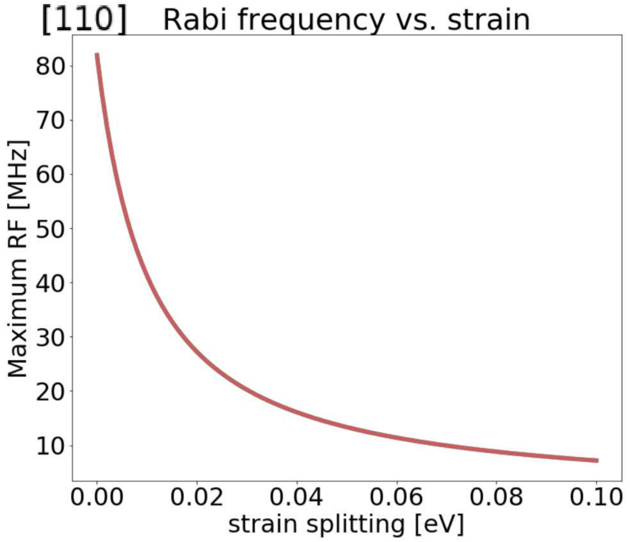
- Calculate ground state $|g\rangle$ and first excited state $|e\rangle$
- Rabi frequency:

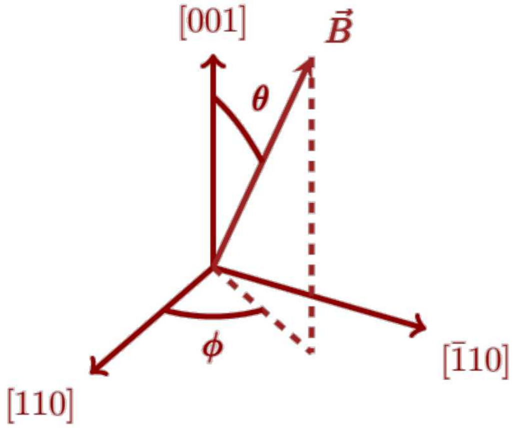
$$f_R \propto \langle e|\hat{D}|g\rangle$$

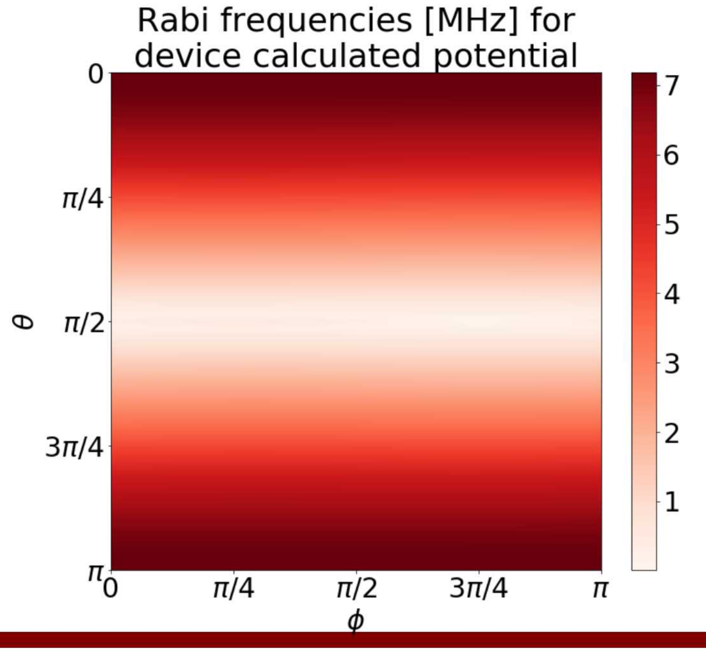
Results!


1 μm
y
[1̄10]
x
[110]


Rabi frequency vs. dot stretching
Maximum RF [MHz]
QD stretching along x [arb. units]
QD stretching along y [arb. units]


Rabi frequency vs. strain
Maximum RF [MHz]
strain splitting [eV]


[001]
B
θ
ϕ
[110]
[1̄10]


Rabi frequencies [MHz] for
device calculated potential
θ
ϕ

Summary

- Induced 2D holes in Ge/SiGe heterostructure field effect transistors demonstrated.
- Physical properties (mass, g factor, spin-orbit coupling strength) characterized.
- Gate controlled quantum Hall ferromagnetic transition observed at low densities. Potential platform for topological superconductivity.
- Development of spin qubits in Ge/SiGe