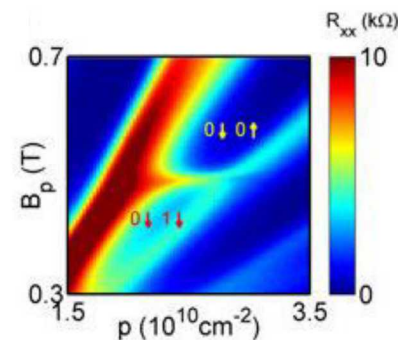
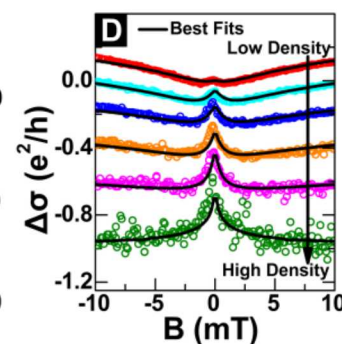
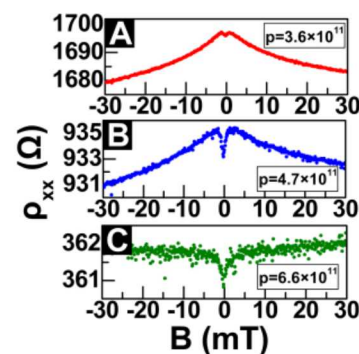
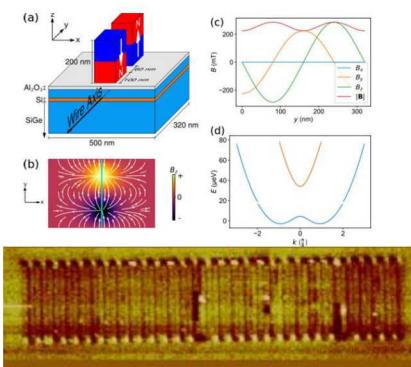




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SAND2019-12411PE

SiGe-based quantum electronic devices



Tzu-Ming Lu

Department of Quantum Phenomena,
Sandia National Laboratories, New Mexico
Center for Integrated Nanotechnologies,
Sandia National Laboratories, New Mexico



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BIG SCIENCE AT THE NANOSCALE

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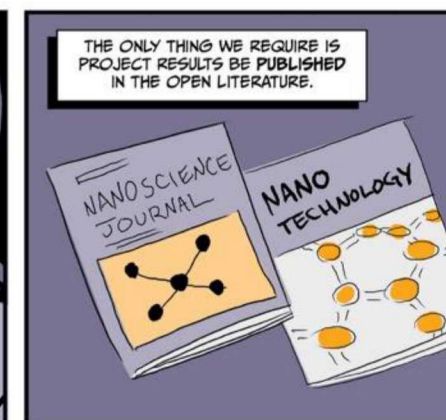
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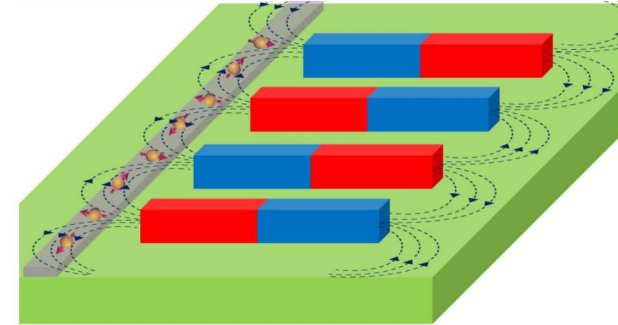
Acknowledgements

- Sandia National Laboratories: M. P. Lilly, D. Laroche, L. A. Tracy, C. T. Harris, N. T. Jacobson, J. Moussa, A. D. Baczewski, D. R. Luhman, W. Hardy, J. Gamble, and L. N. Maurer.
- Los Alamos National Laboratory: Serena Eley
- National Taiwan University: C. W. Liu, J.-Y. Li, C.-H. Lee, S.-H. Huang, Y. Chuang, Y.-H. Su, C.-T. Chou
- NHMFL

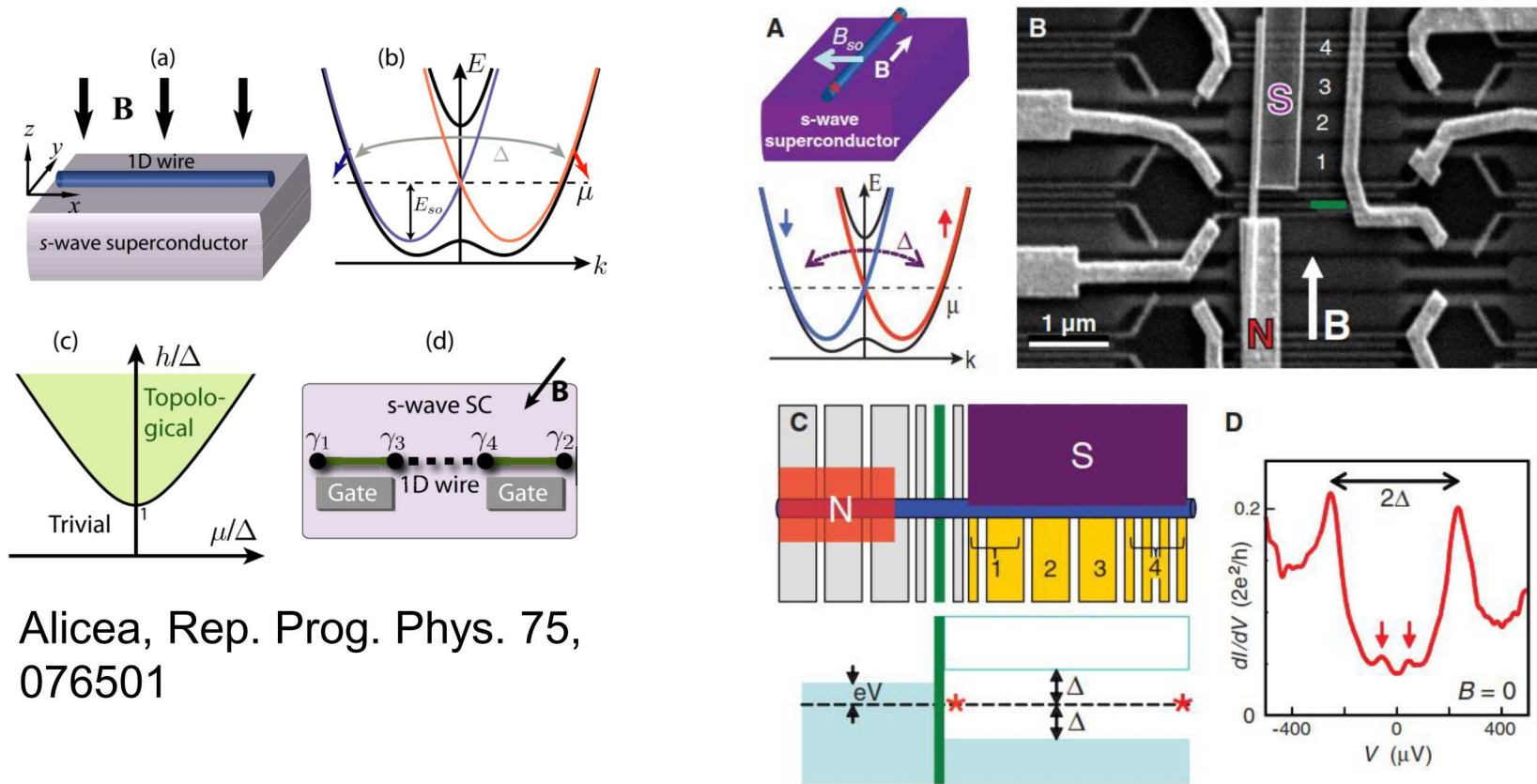
This work at Sandia National Laboratories has been supported by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy (DOE) and the Laboratory Directed Research and Development Program. This work was performed, in part, at the Center for Integrated 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. The views expressed in this presentation do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Outline

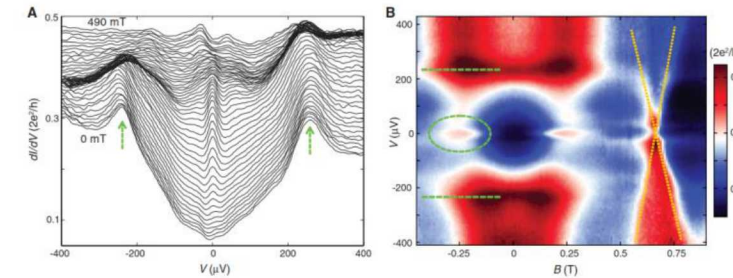
- Artificial spin-orbit coupling in Si/SiGe
 - Theory/modeling
 - Nano-magnet arrays
- Holes in Ge/SiGe
 - Physical properties
 - Quantum Hall ferromagnetic transition
 - Spin qubits in Ge/SiGe



Majorana fermions in spin-orbit coupled nanowire topological superconductors



Alicea, Rep. Prog. Phys. 75, 076501



Mourik, Science 336, 1003

Strong spin-orbit coupling is required -> InAs, InSb
Can we do this in silicon?

1D spin orbit coupling

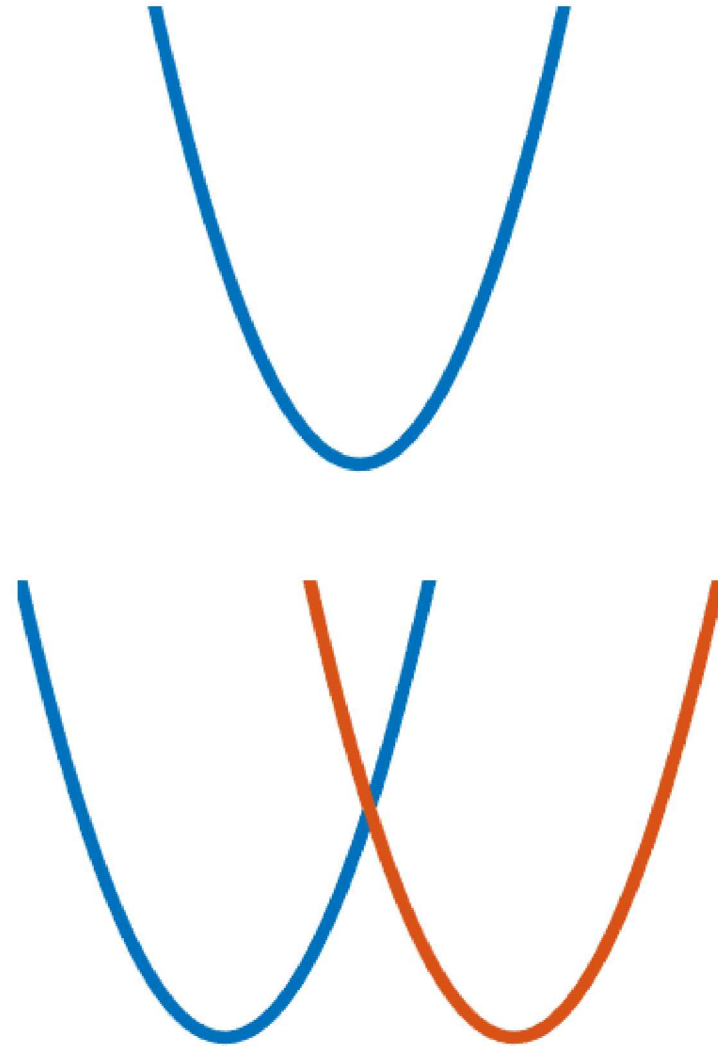
- 1D E- k_x dispersion **without** SOC:

$$E \sim \frac{\hbar^2 k_x^2}{2m}$$

- 1D E- k_x dispersion **with** SOC:

- $B_{SO} \sim k_x \times E_z$ (along y)

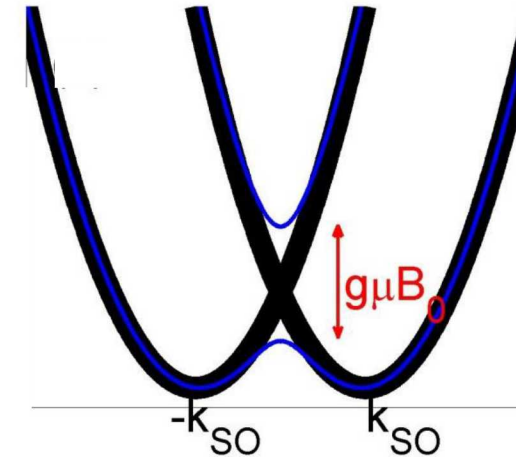
$$E \sim \frac{\hbar^2 k_x^2}{2m} + a k_x E_z S \sim \frac{\hbar^2 (k_x \pm k_{SO})^2}{2m}$$



1D spin orbit coupling

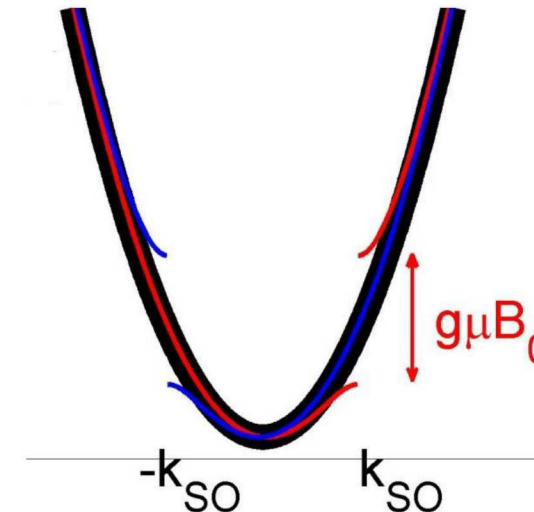
- 1D $E-k_x$ dispersion **with** SOC with **B_0 along z** :

Gap near $k=0$
(blue curves)

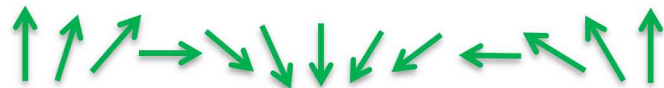


- Canonical transformation of the above case:

Spin selective gaps near $\pm k_{SO}$
(blue and red curves)

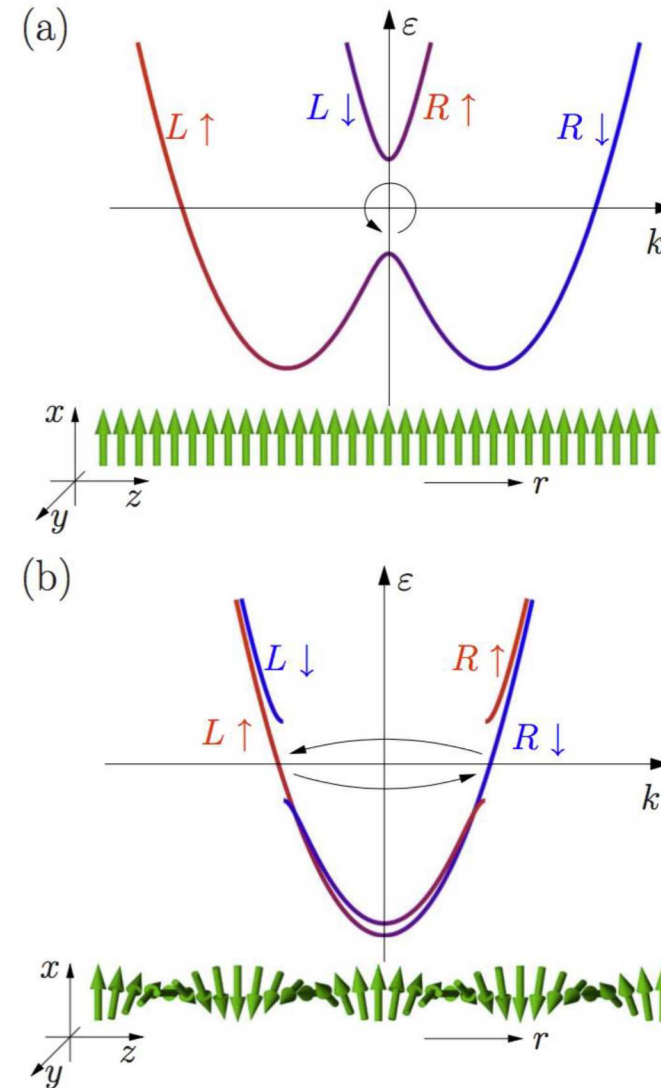


Effective magnetic field



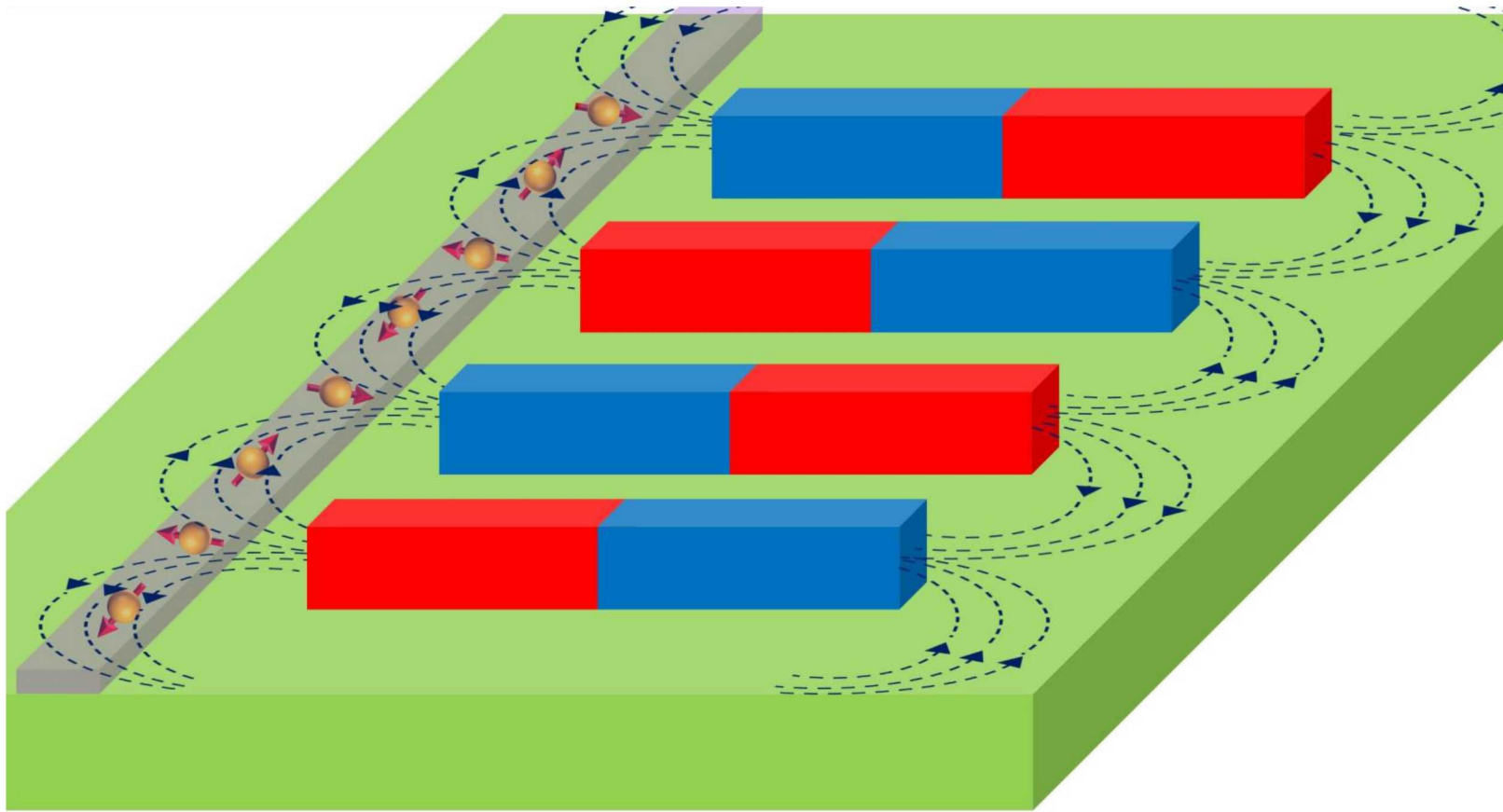
Engineer the SOC using nano-magnets

- Magnets that produce a spatially rotating magnetic field can have the same effect as intrinsic SOC (plus an external bias magnetic field)
- Designer material!
- We want to use Si/SiGe, because of the high mobility (and therefore long mean free path and phase coherence length)



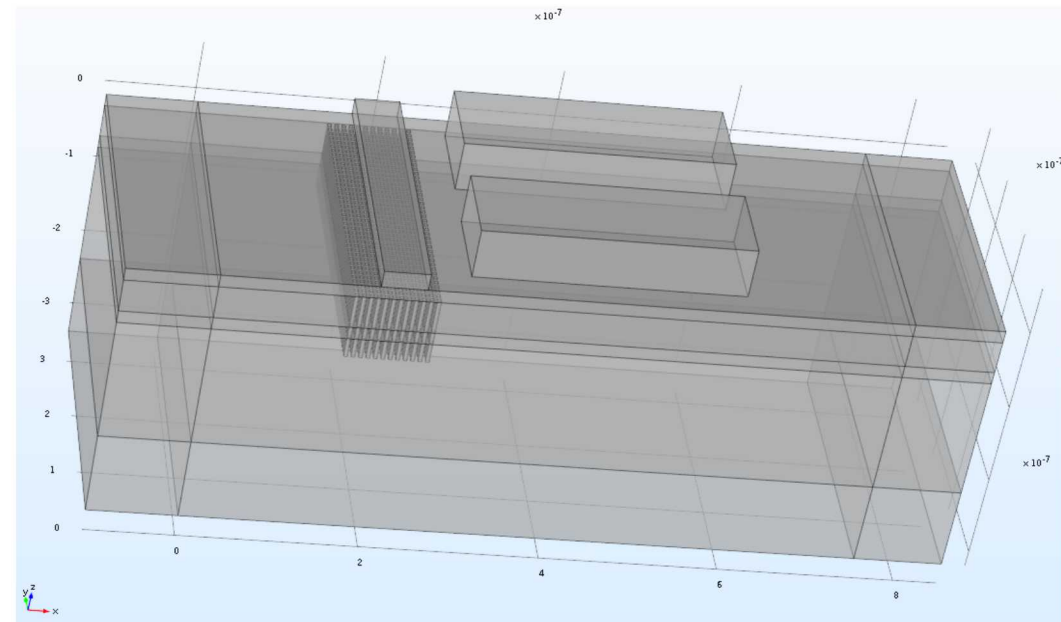
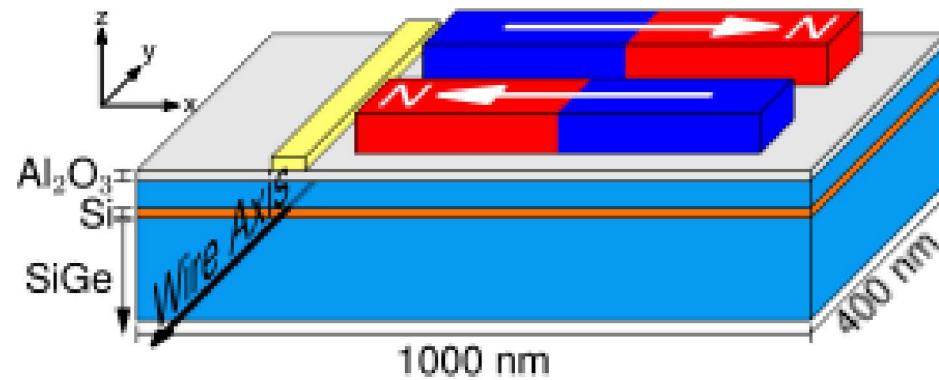
B Braunecker et al., *PRB* **82**, 45127 (2010)

1D, spatially rotating magnetic field from nano-magnet arrays



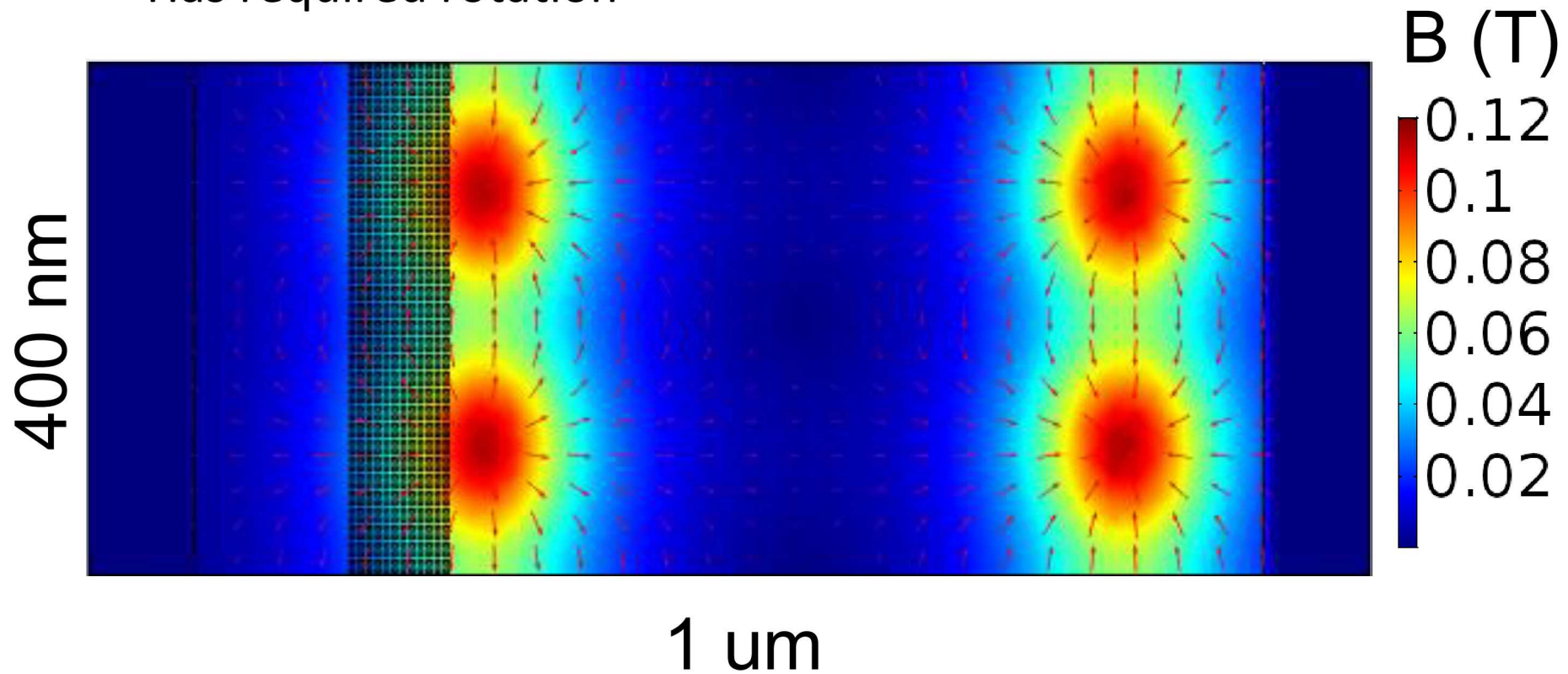
Magnetostatics I

- Layout and calculate magnetic fields with COMSOL
- Planar design example



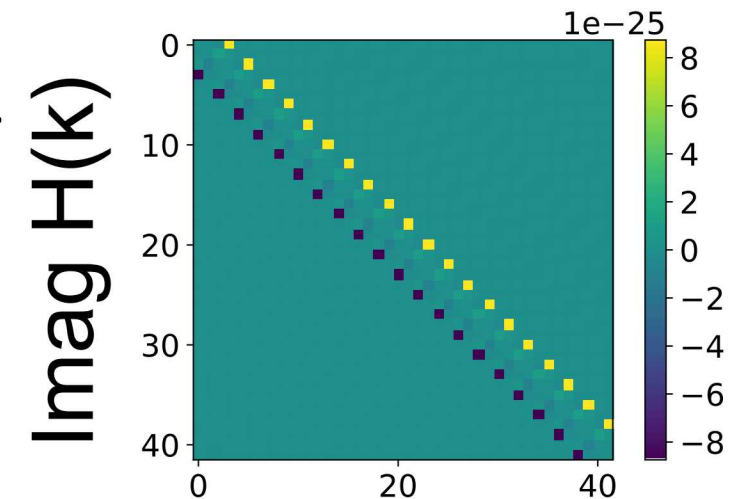
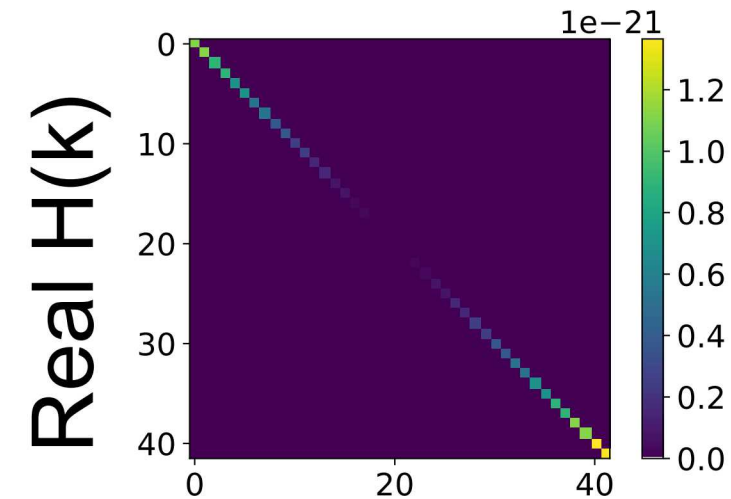
Magnetostatics II

- Magnetic field in 2DEG plane
- Has required rotation



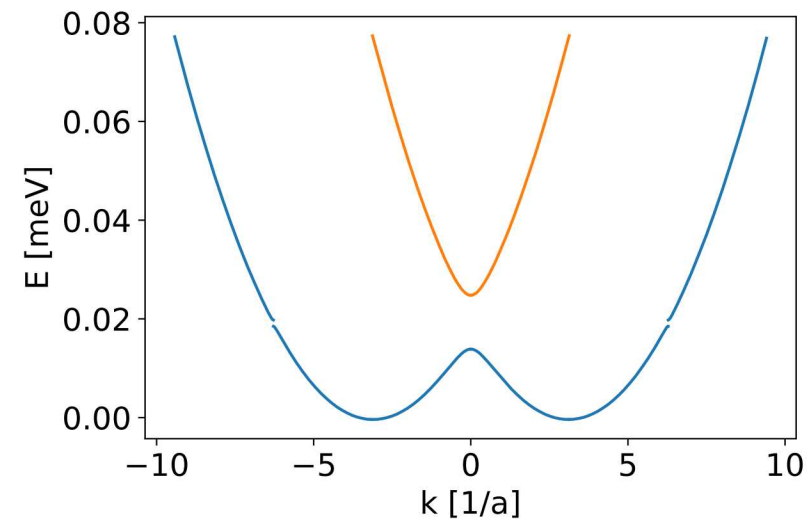
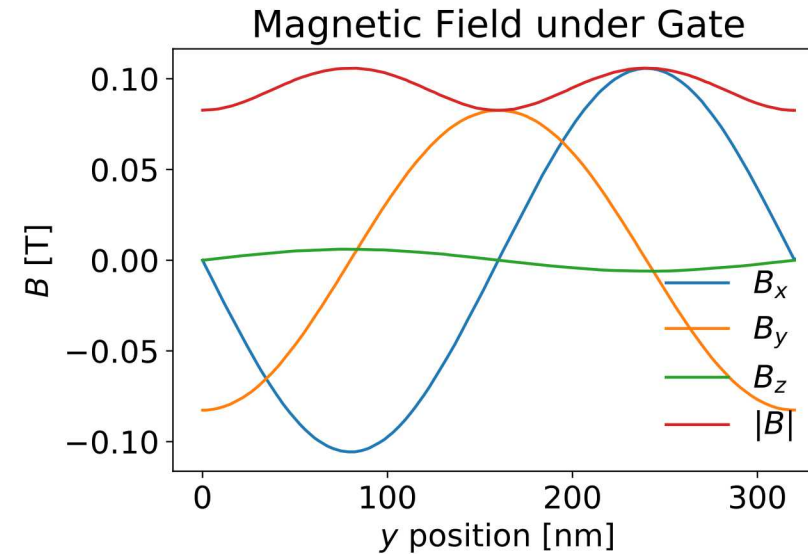
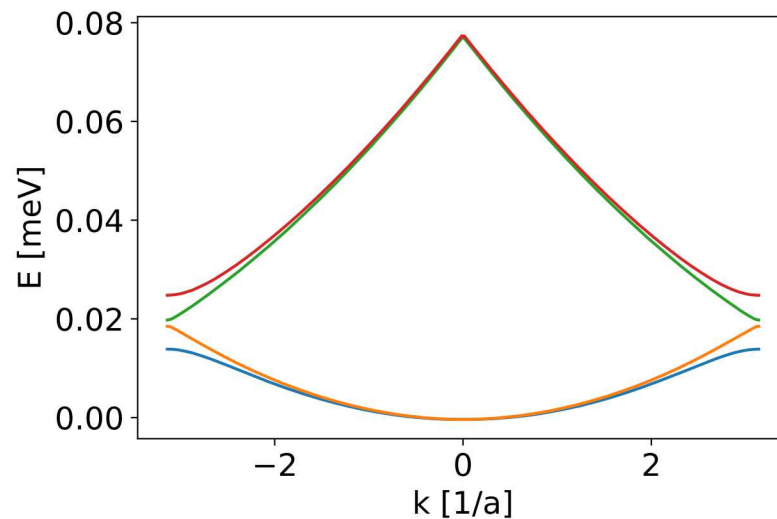
Band Structure Calculations

- Kp-like method
- $\psi(x) = e^{ikx}u(x)$
- $V(x) = \frac{1}{2}g\mu_B\vec{B}(x) \cdot \vec{\sigma}$
- Write V and u as Fourier series
 - $V(x) = \sum_g c_g e^{igx}$
 - $u(x) = \sum_q c_q e^{iqx}$
- Infinite set of linear equations, one for each band
$$Ed_q = \frac{\hbar^2}{2m}(q+k)^2 + \sum_g c_g d_{q-g}$$
- Solve with a decent number of bands

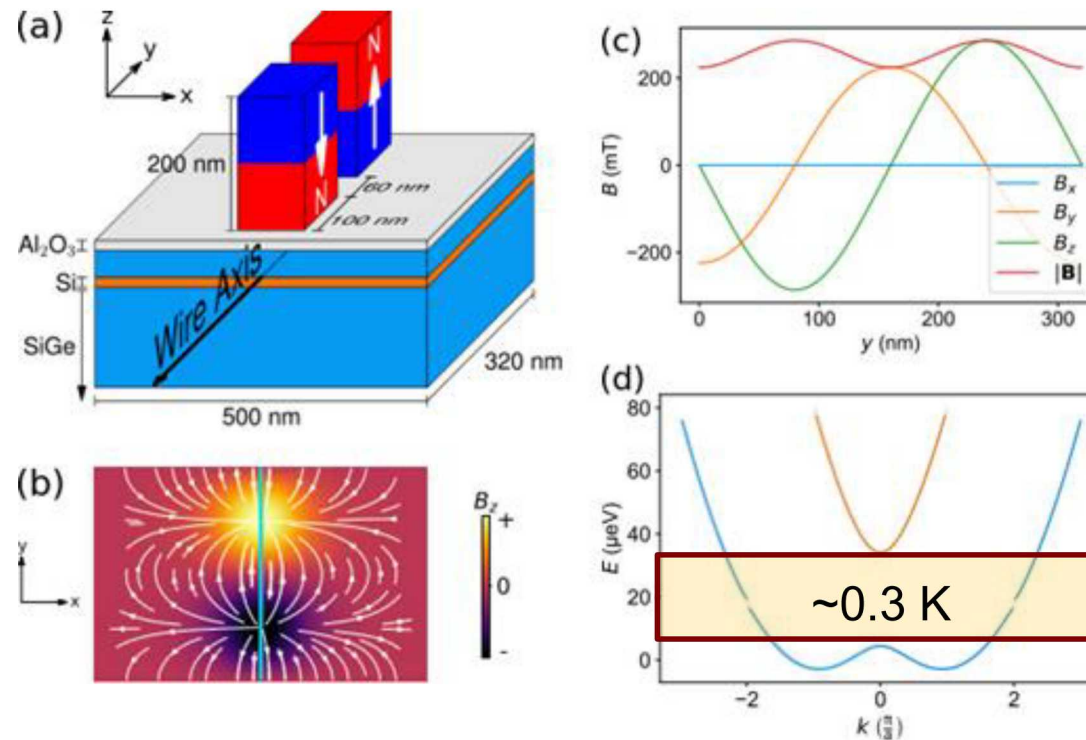
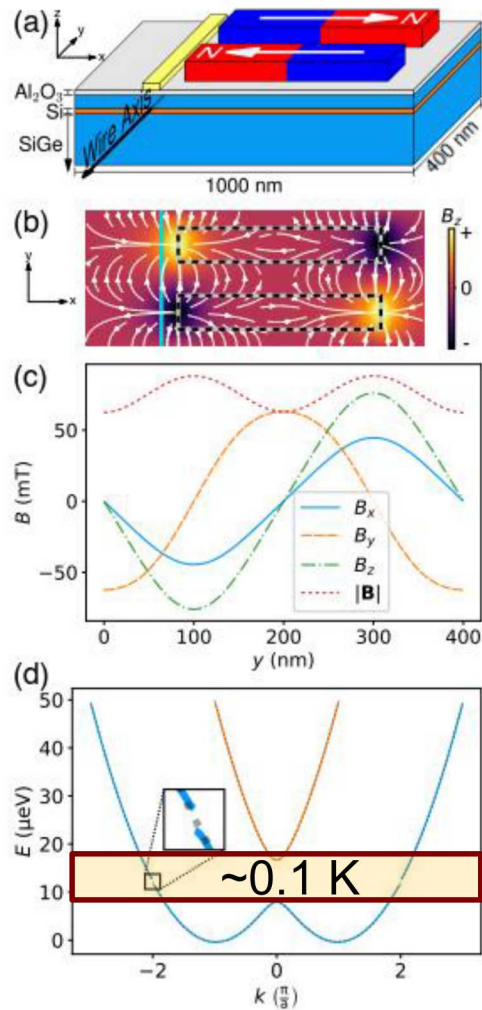


Example Results

- Trenched design with 2 T magnets
- Gap of 0.01 meV (0.13 K)
- Could be measurable experimentally
- Working to optimize

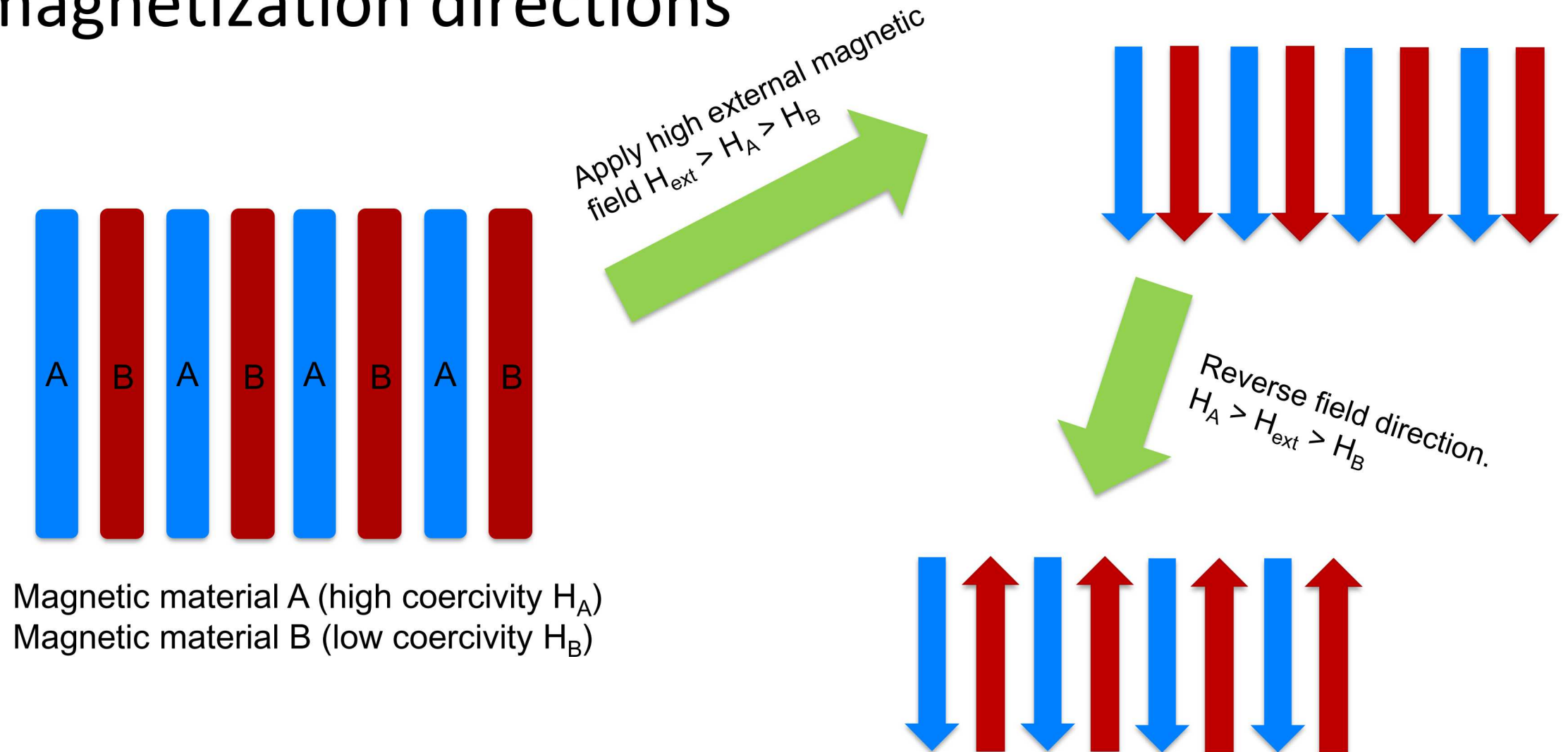


Effective spin-orbit gaps in Si/SiGe



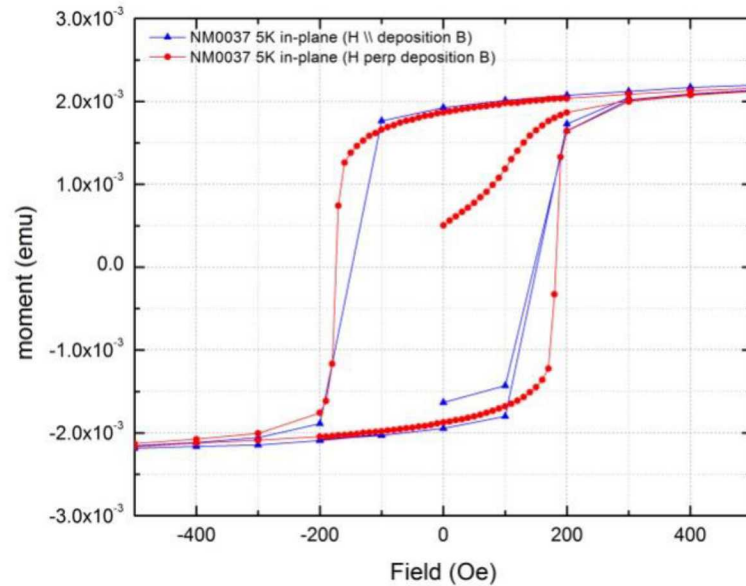
The effective spin-orbit gaps are experimentally accessible using dilution refrigerators.

Realizing nano-magnet arrays with alternating magnetization directions

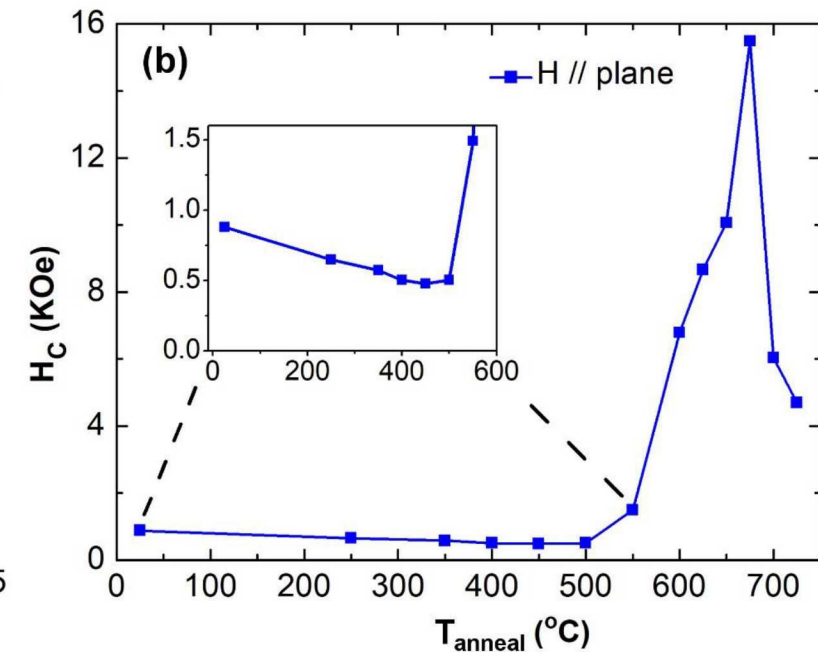
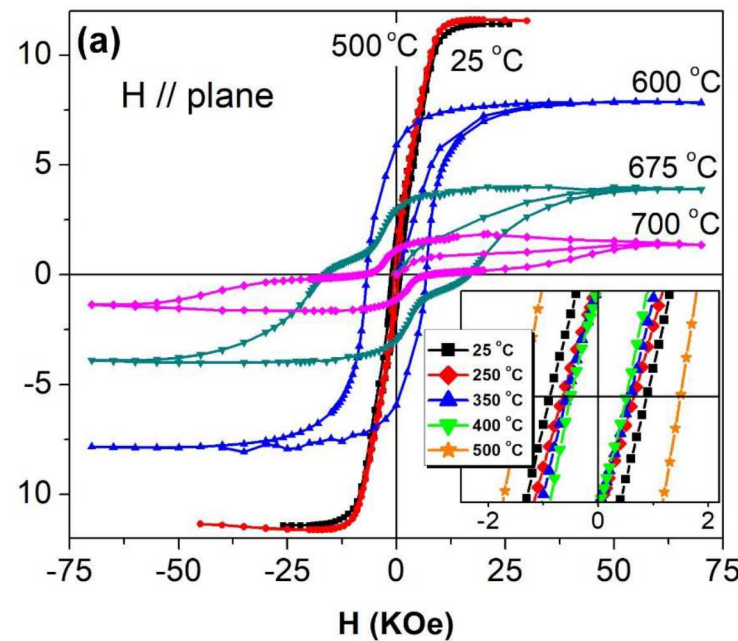


Magnetic materials with high coercivity contrast

Low-coercivity (200 Oe) as-deposited Co films

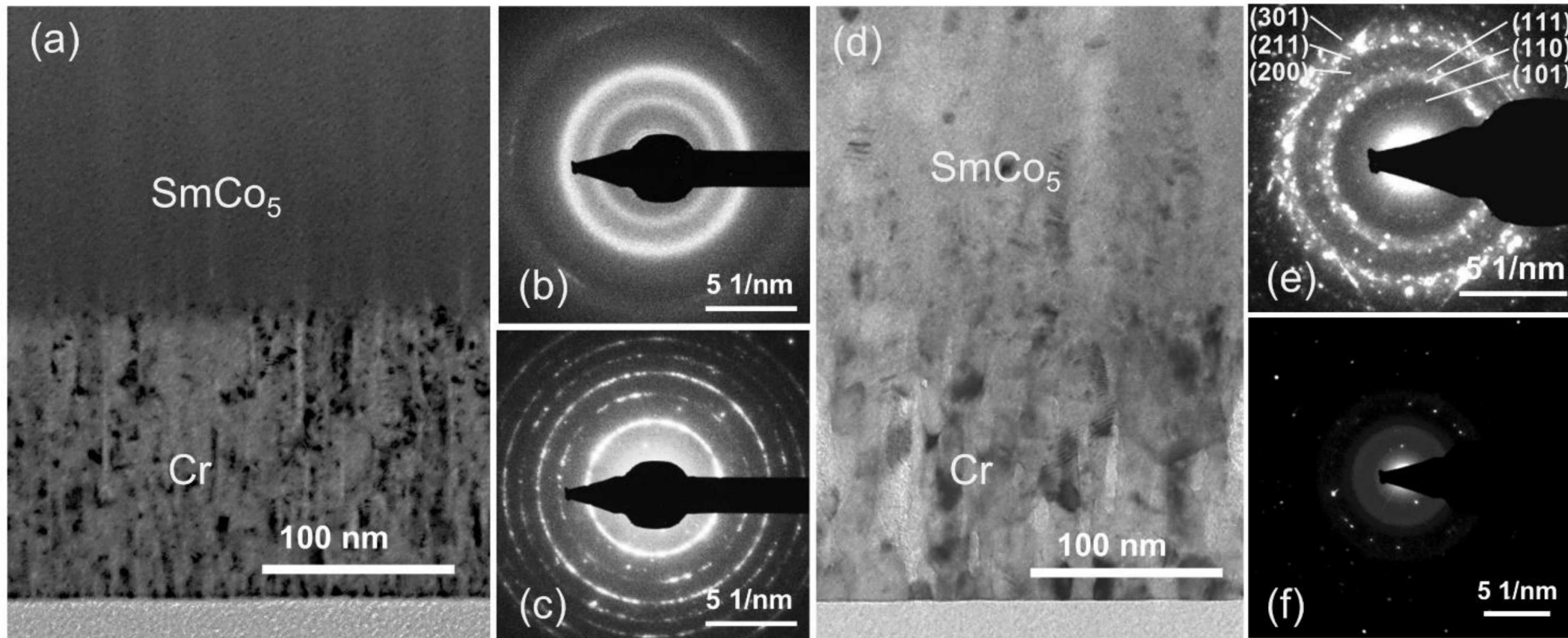


High-coercivity (~ 10000 Oe) SmCo_5 films obtained after post-deposition annealing

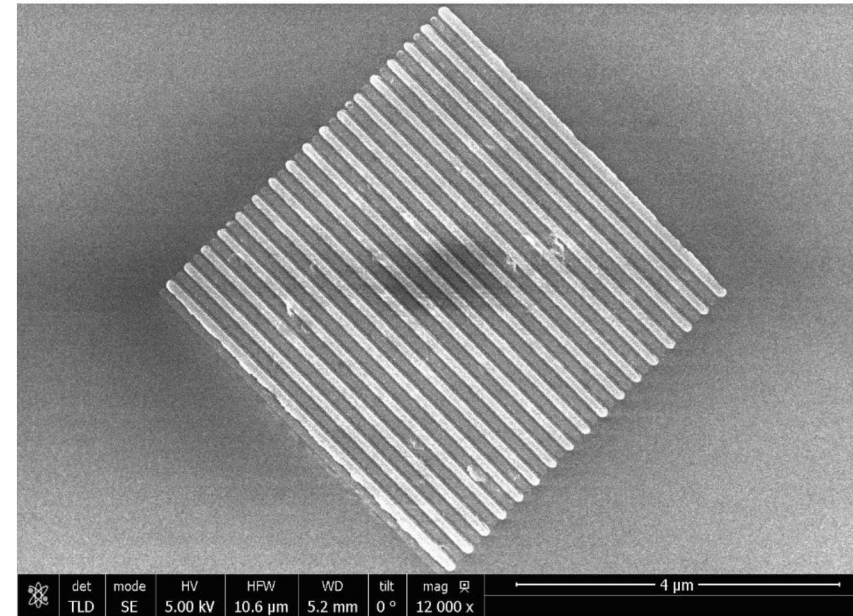
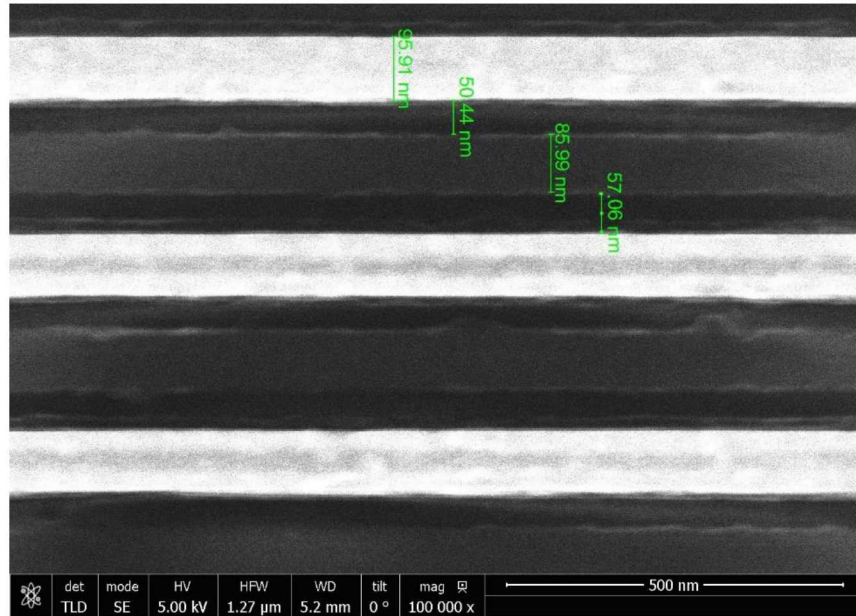


Magnetic materials with high coercivity contrast Sandia National Laboratories

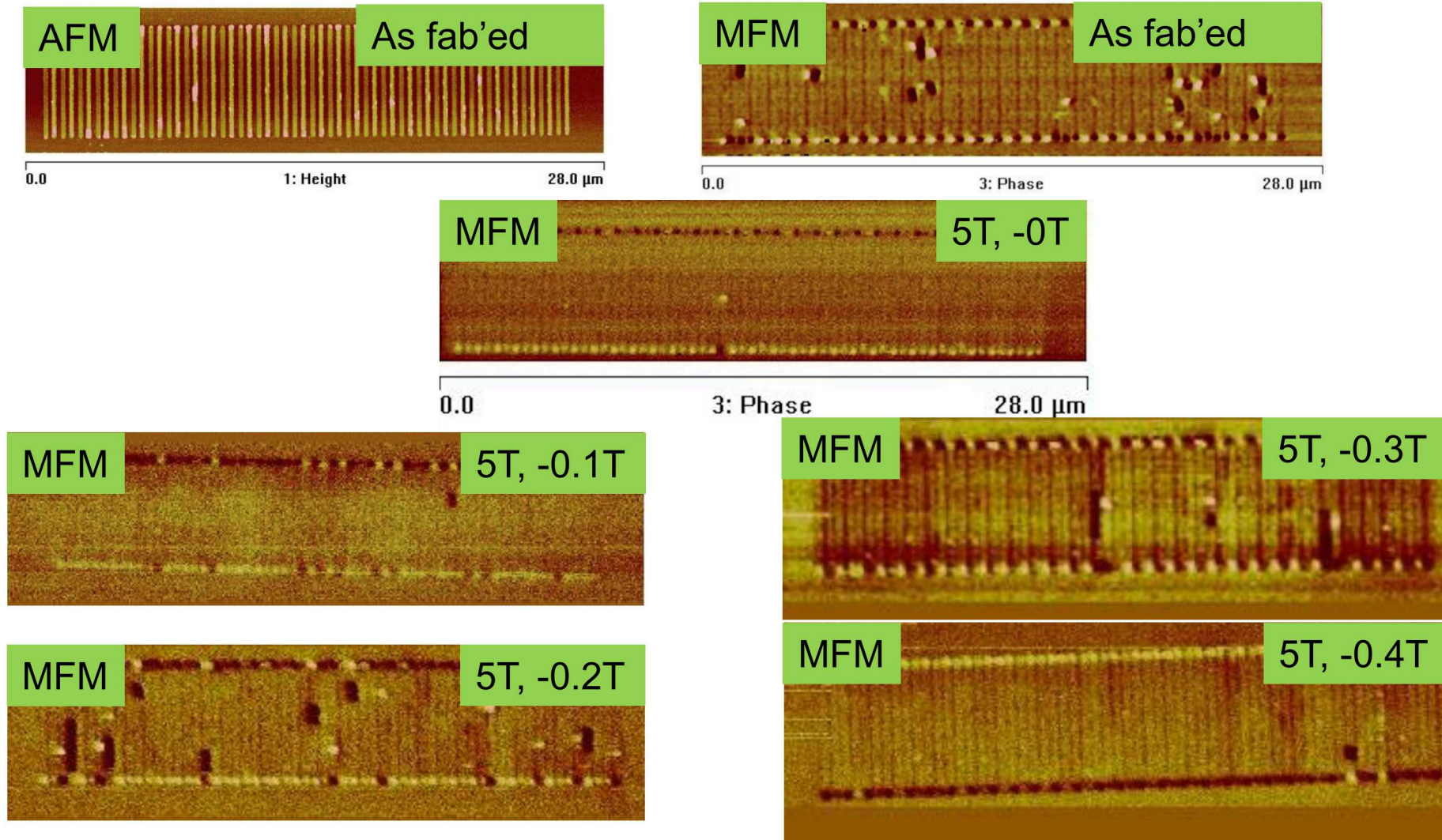
Crystallization of SmCo_5 leads to high coercivity.



Interdigitated nanomagnet arrays



Programming nanomagnets with external B field



Summary

- Nanomagnet arrays with alternating magnetization directions demonstrated. Artificial spin-orbit gaps can in principle be engineered in materials with weak spin-orbit coupling, such as silicon.
- Nanoscale magnetic field synthesis achieved by using nanomagnets with coercivity contrast and an external magnetic field for programming. This may find applications in other areas, such as MRI, nanoparticle manipulation.

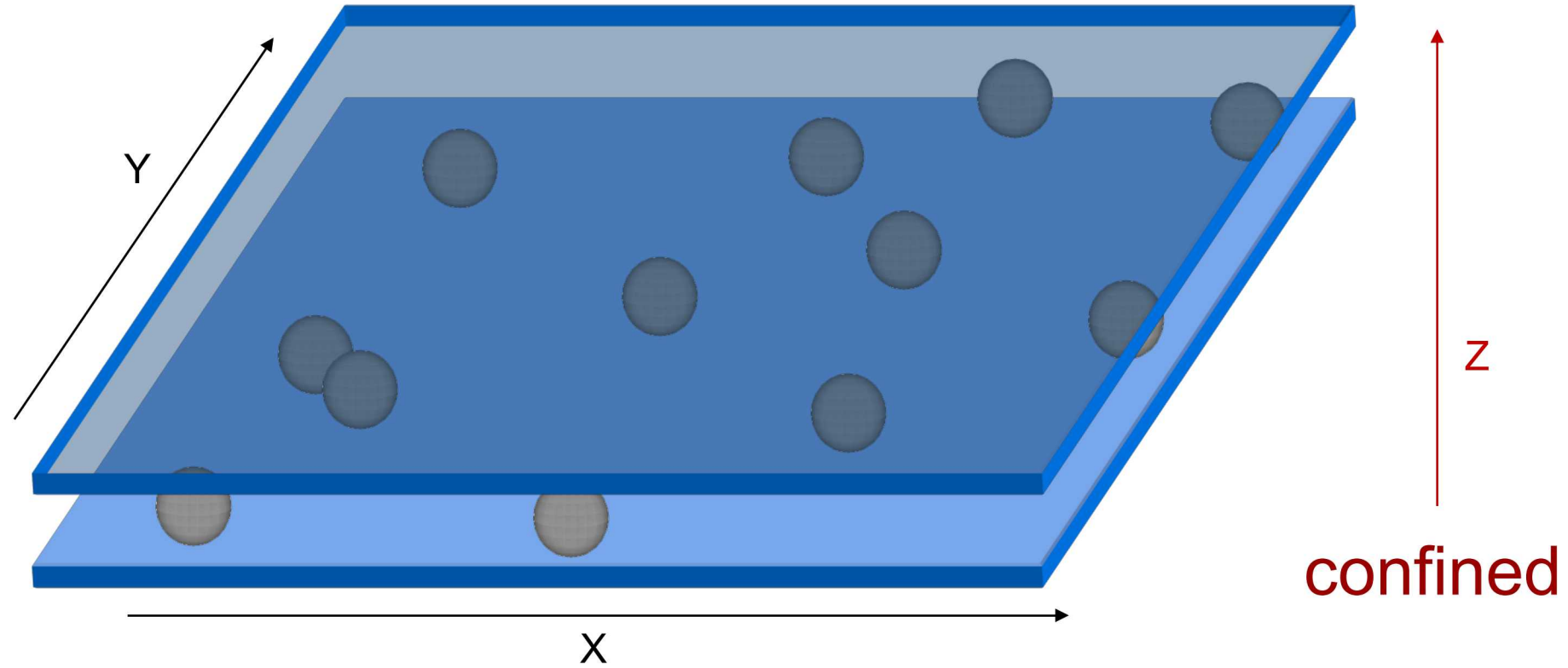
Questions to be answered

- Defects in the nanomagnets.
- Effects of geometry and interactions between nanomagnets.
 - Larger coercivity in Co nanomagnets than in Co films.
 - Smaller coercivity in SmCo_5 nanomagnets than in SmCo_5 films.

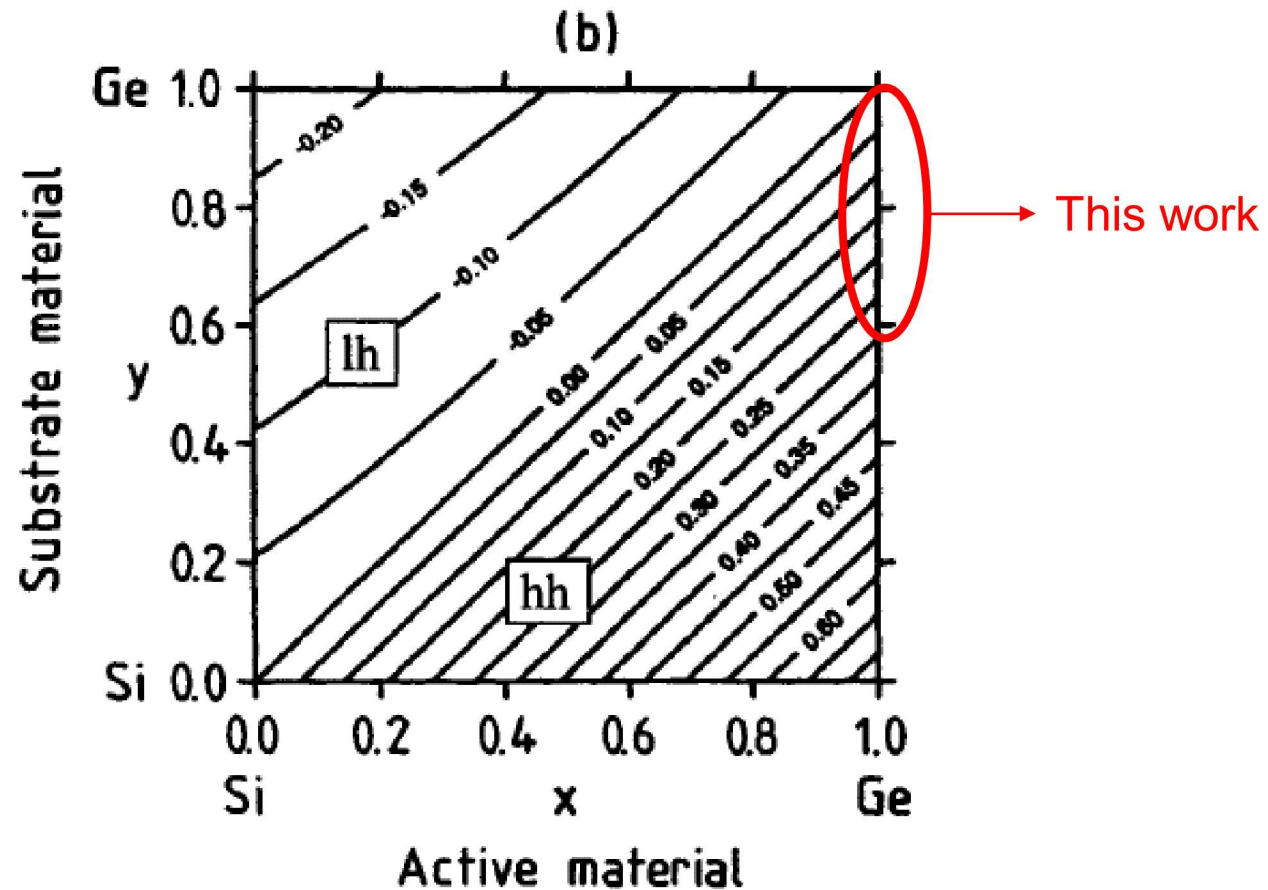
Outline

- Artificial spin-orbit coupling in Si/SiGe
 - Theory/modeling
 - Nano-magnet arrays
- Holes in Ge/SiGe
 - Physical properties
 - Quantum Hall ferromagnetic transition
 - Spin qubits in Ge/SiGe

2D holes

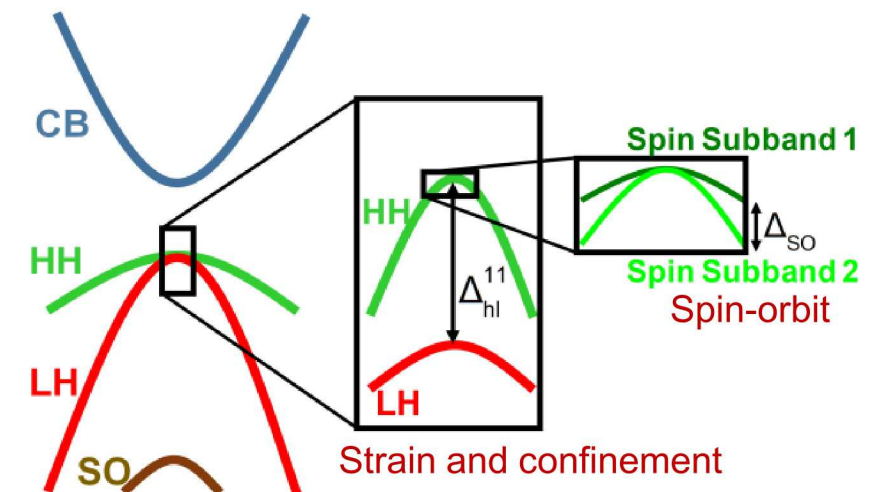
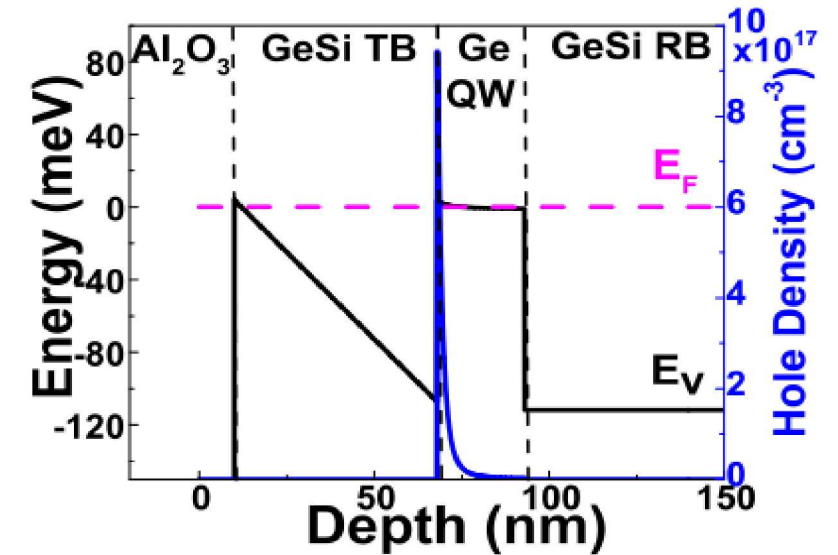
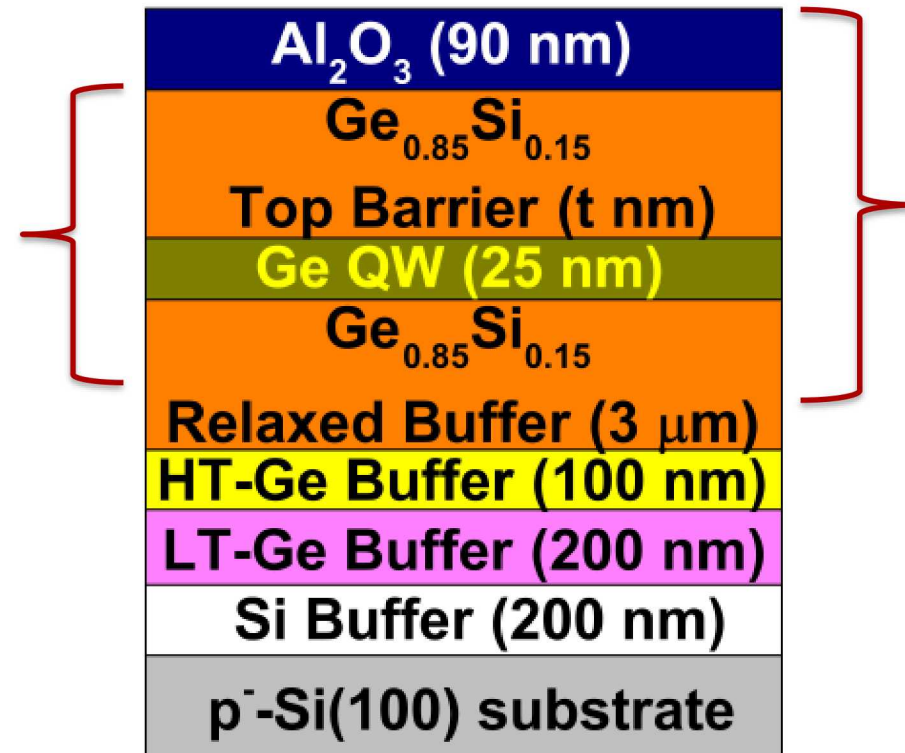
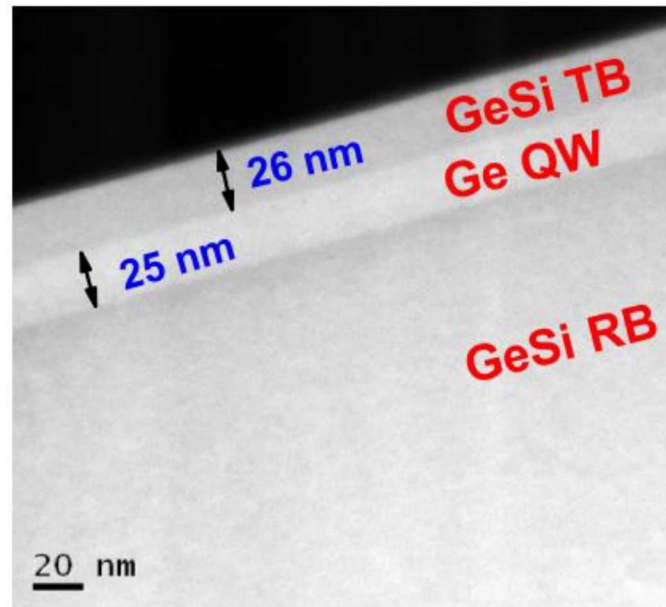


Band alignment of SiGe heterostructures



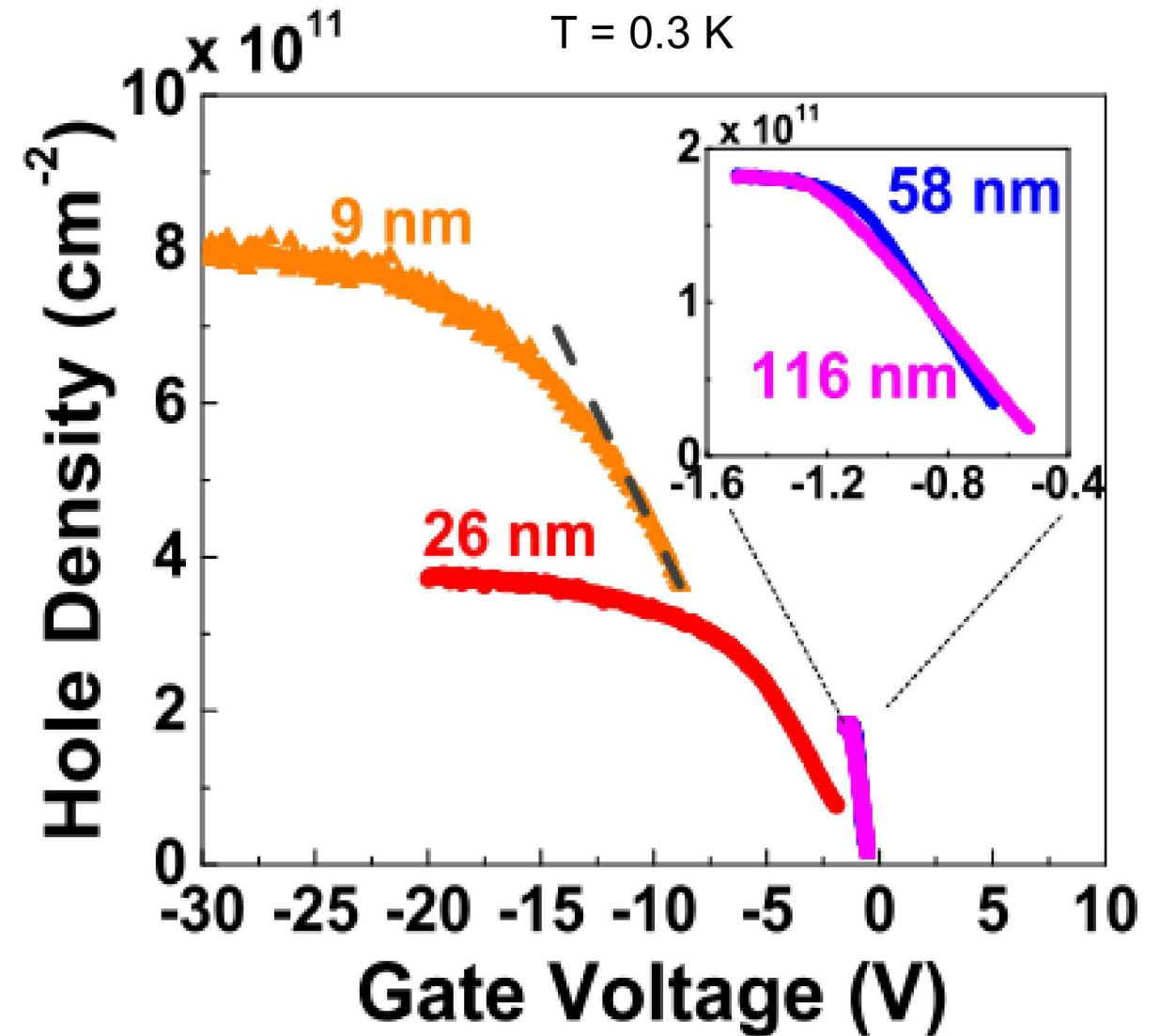
Valance band
2D holes in Ge quantum wells

Undoped Ge/SiGe heterostructure field-effect transistors

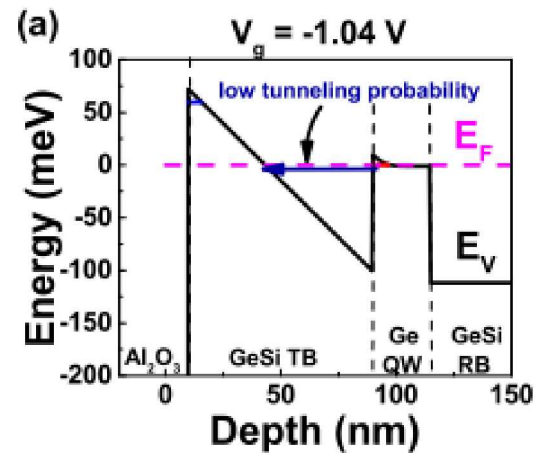


Device operation – 2D hole density

- 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)



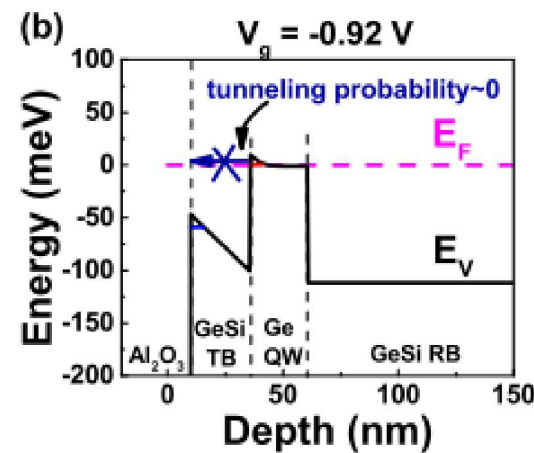
Device operation – 2D hole density



Deep channels

The tunnel rate is limited by triangular barrier (set by Si%) and is depth independent.

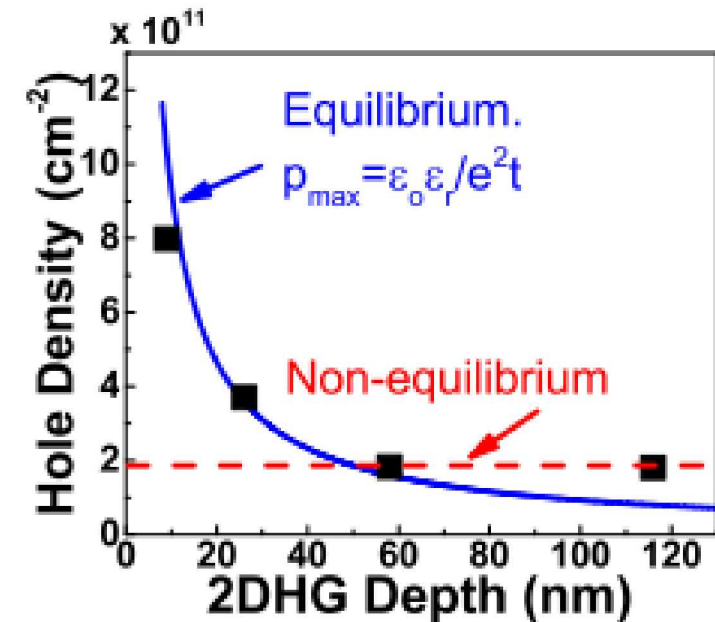
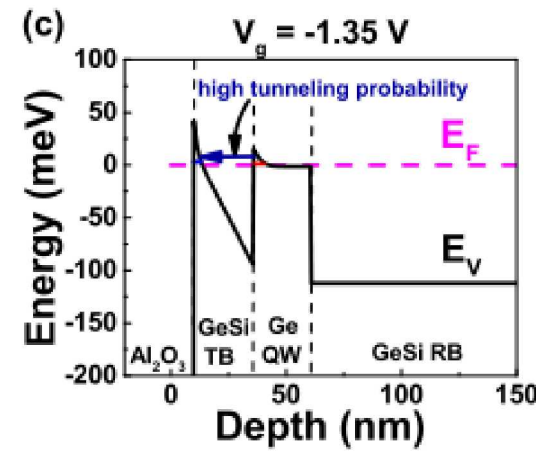
The tunnel rate can be so low that the density only slowly decreases and never reaches equilibrium at low temperatures!



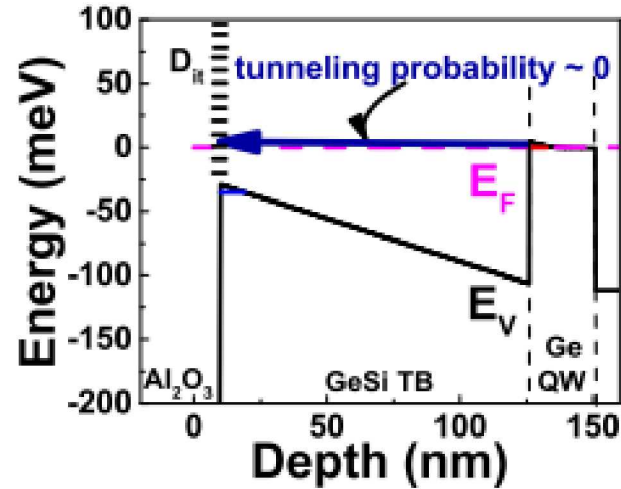
Shallow channels

The tunneling rate is high (compared to experiment time scales).

The density probed by the Hall effect approaches the equilibrium case.



Device operation – 2D hole density

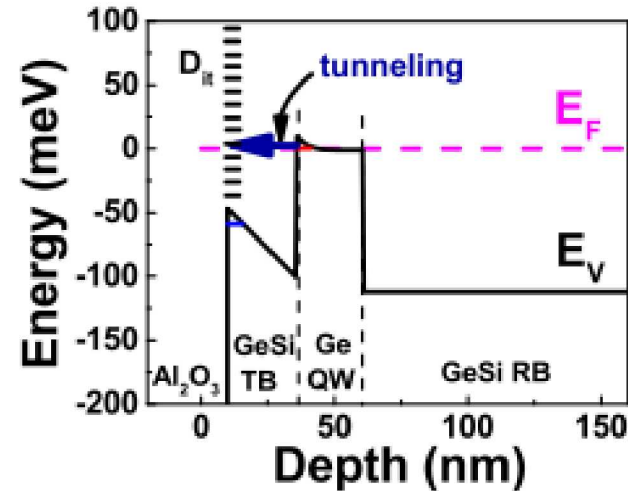


Deep channels

The tunnel rate is low.

The traps at the oxide/GeSi interface do not (need to) get filled.

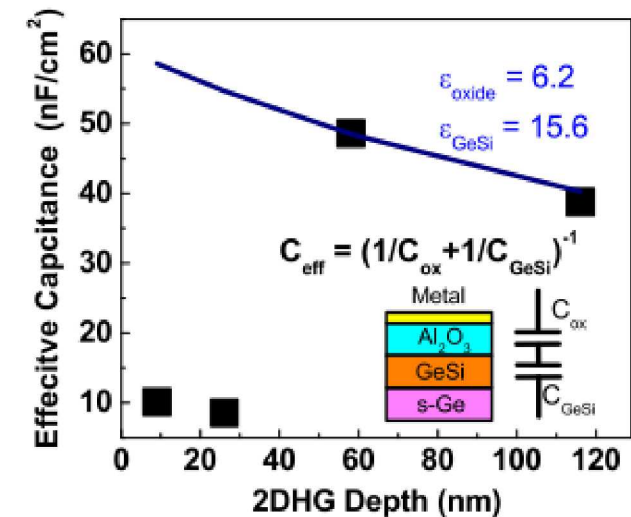
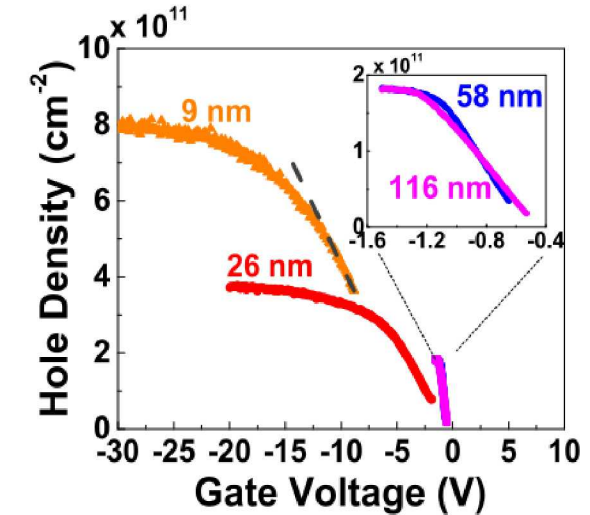
$$C_{\text{eff}} \sim C_{\text{geometric}}$$



Shallow channels

The tunnel rate is high.

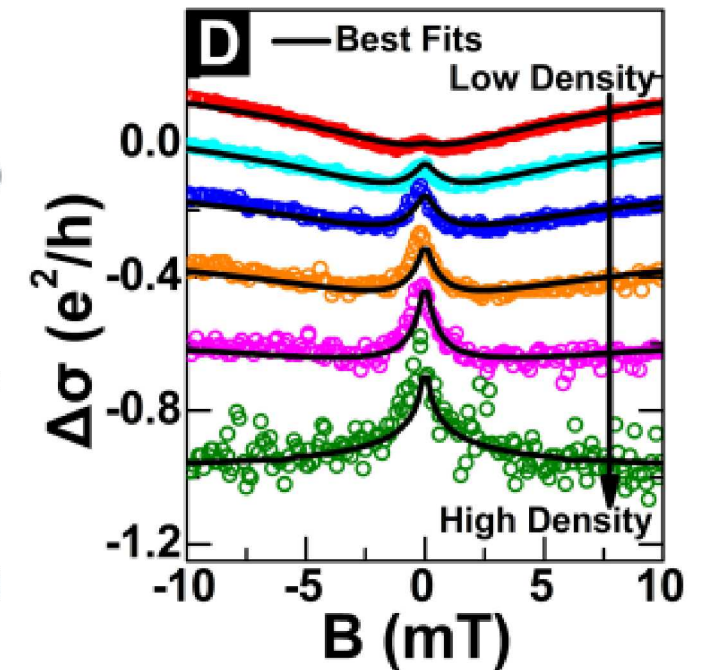
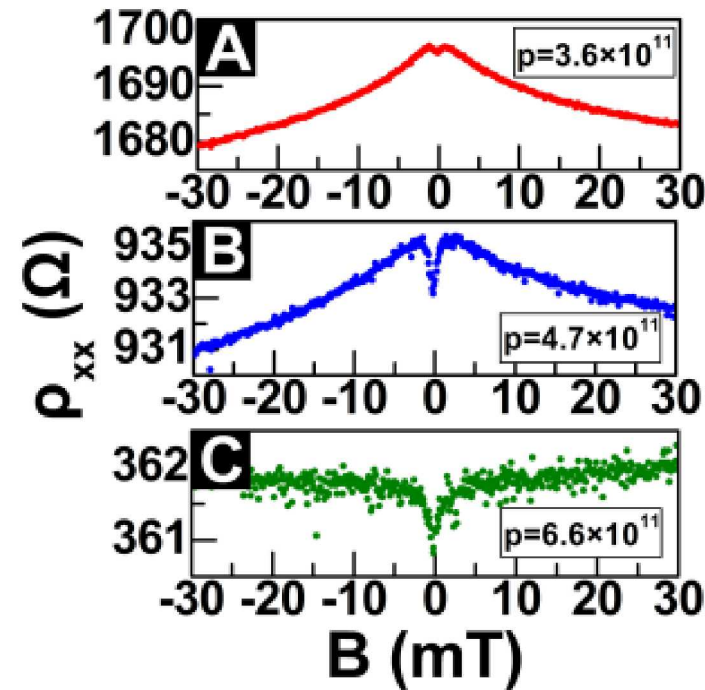
The traps at the oxide/GeSi interface need to be filled before the Fermi level can move.



Physical properties – spin-orbit coupling

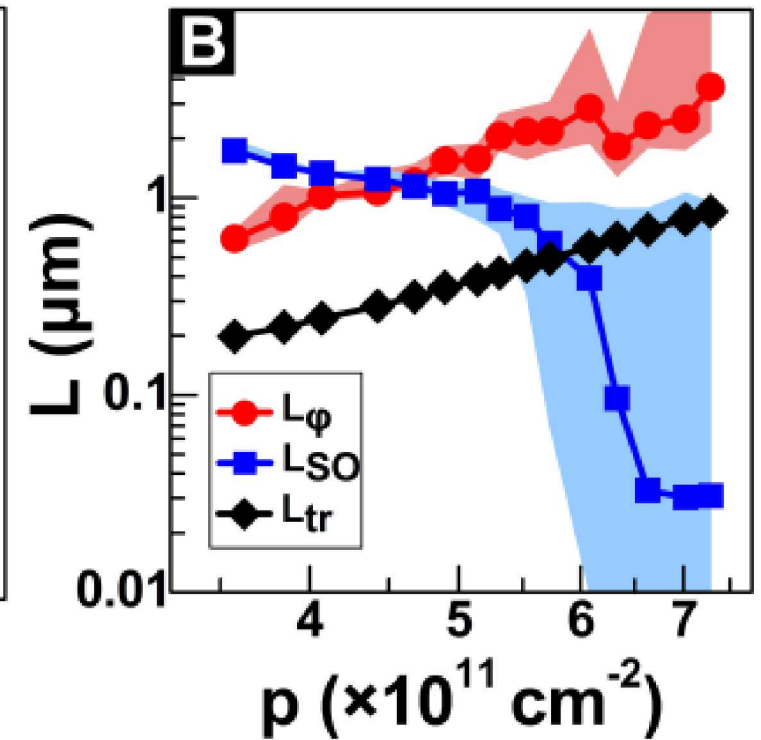
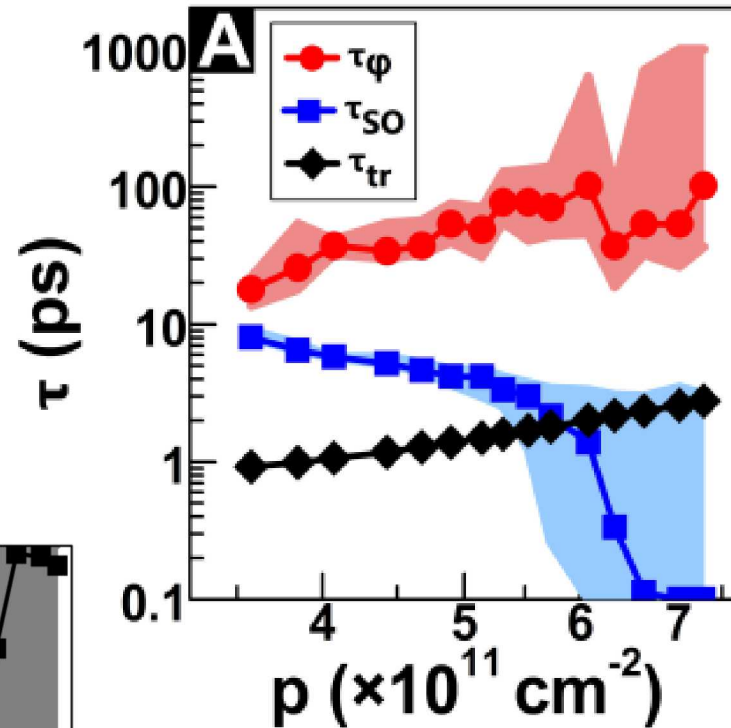
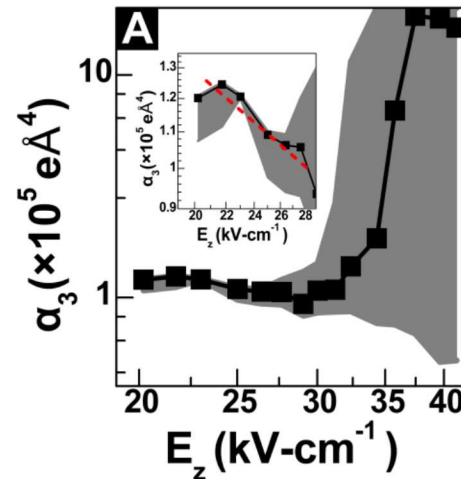
- Low densities
 - Weak localization only
- Intermediate densities
 - Weak anti-localization on top of weak localization only
- High densities
 - Weak anti-localization only

Cubic Rashba: $\sim(\sin 3\theta, -\cos 3\theta)$



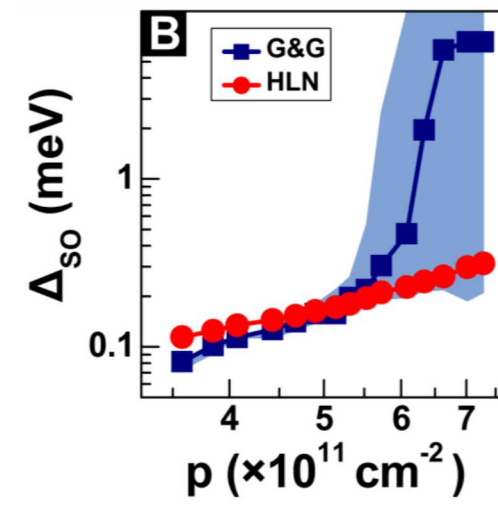
Physical properties – spin-orbit coupling

- Spin-orbit length decreases with density and can be as short as 0.1 μm ($<$ 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.



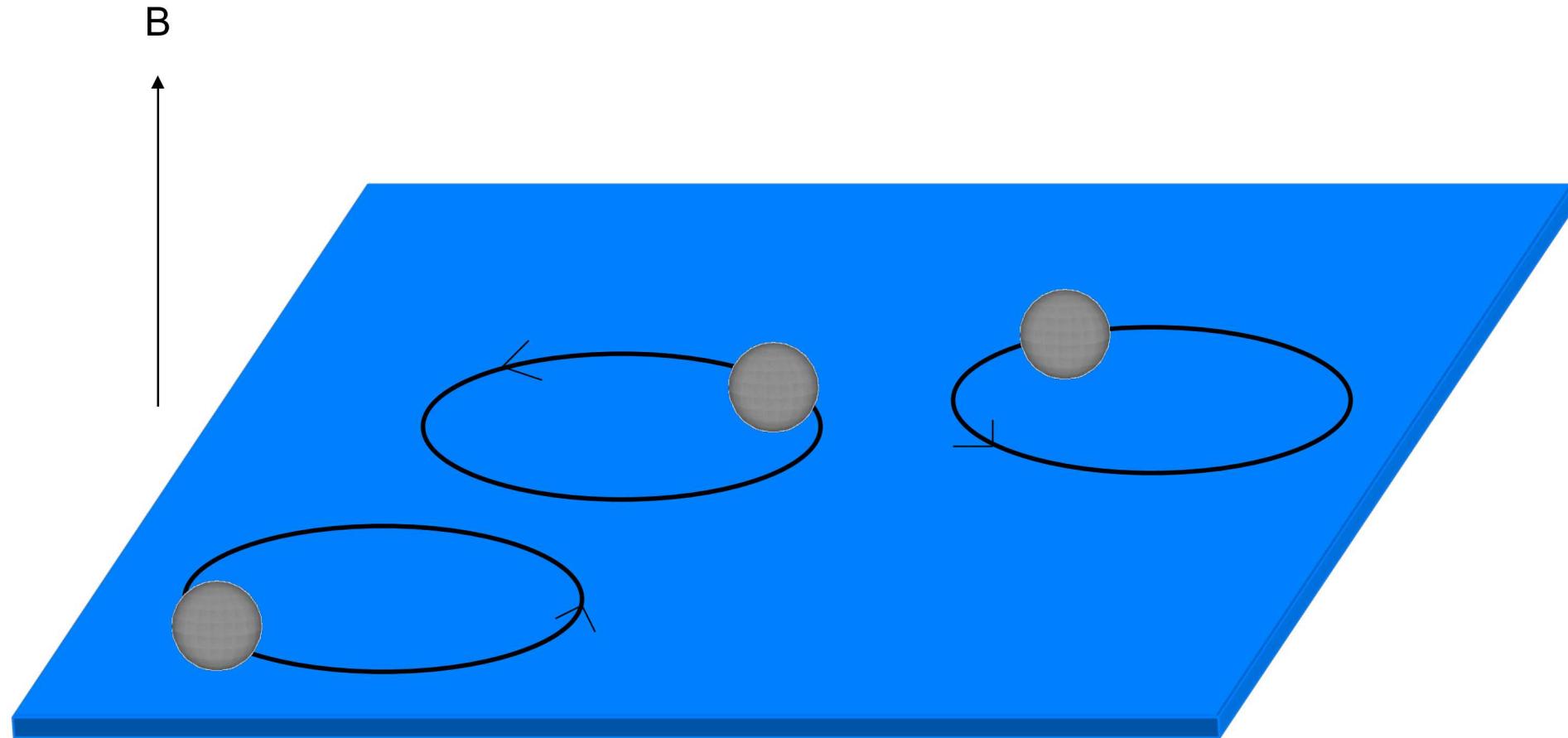
Physical properties – weak antilocalization beyond diffusive regime

- 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)

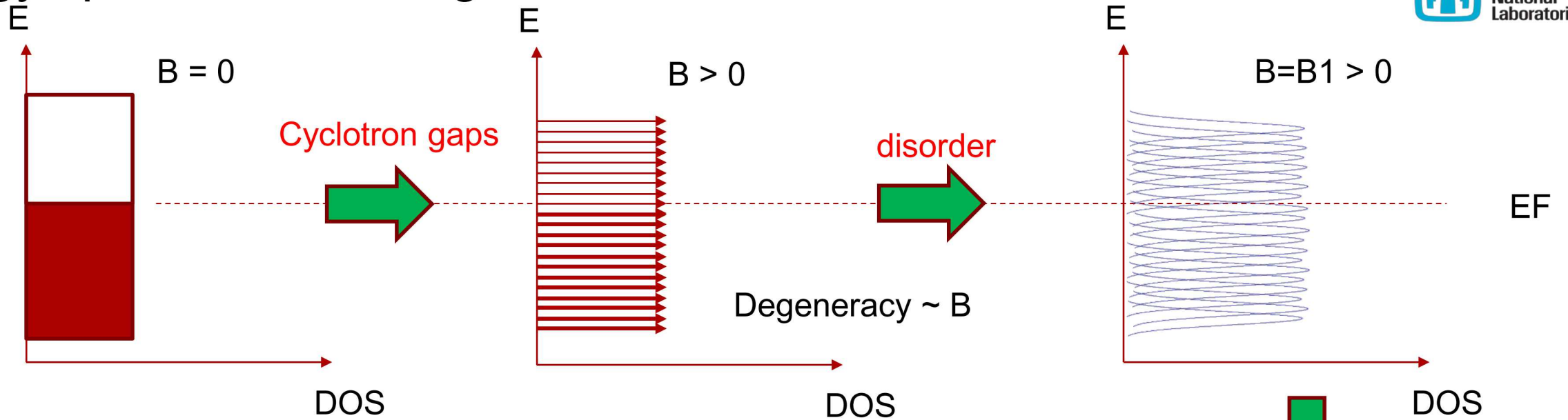
In a perpendicular magnetic field...



Cyclotron motion, $E_c = \hbar e B_{\text{perp}} / m^*$

Spin splitting, gap $E_z = g \mu B$

Energy spectrum in a magnetic field



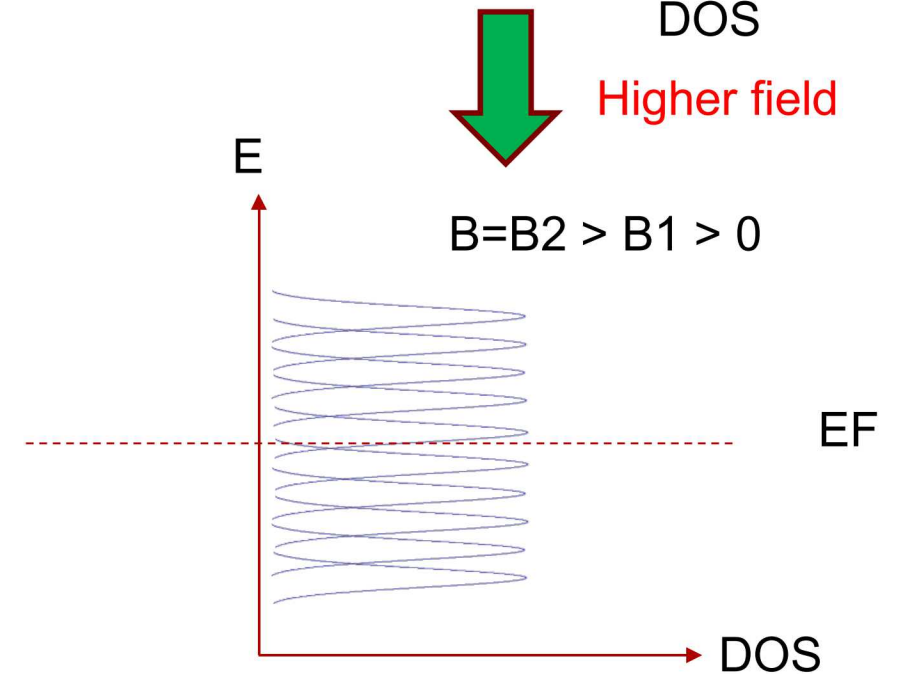
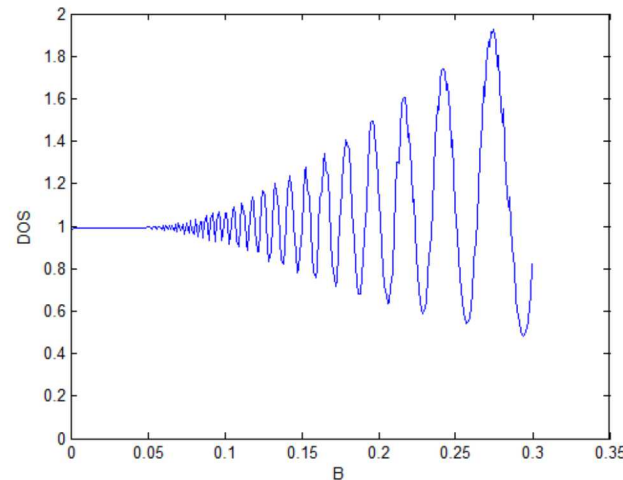
$$\frac{\Delta \rho}{\rho_0} \sim D(X) \frac{\Delta \text{DOS}}{\text{DOS}_0}$$

$$D(X) = X / \sinh X$$

$$X = 2\pi kT / EC$$

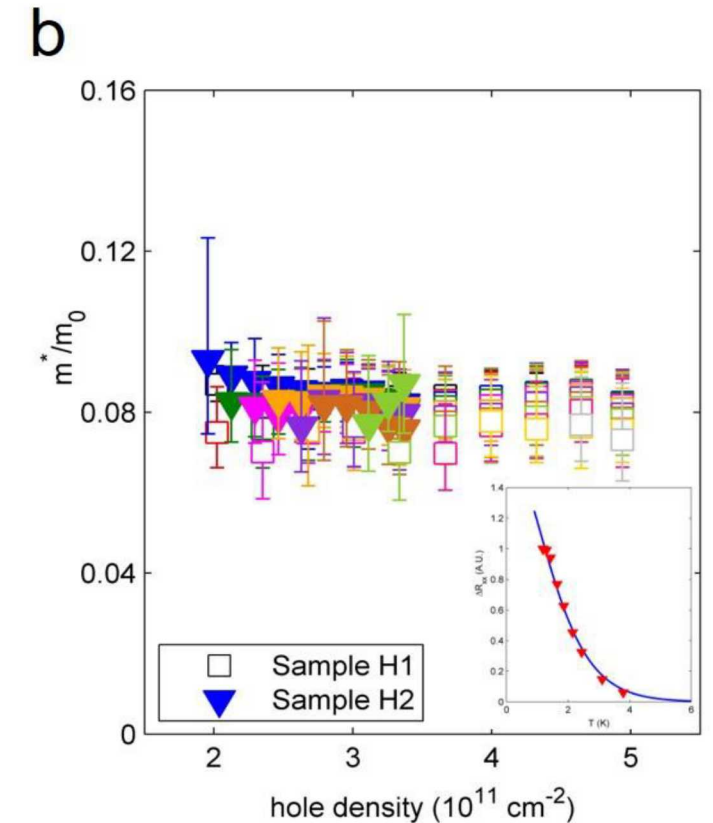
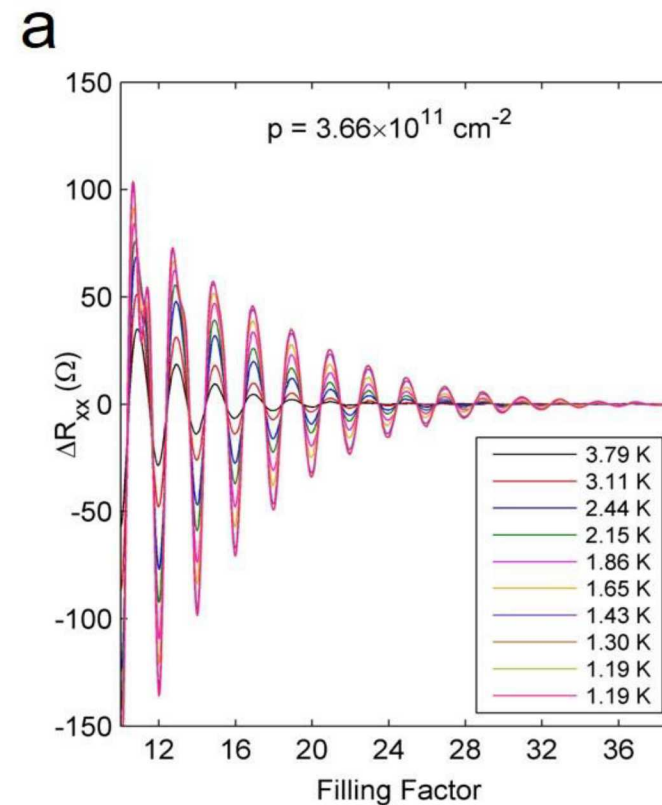
Temperature dependence
 $\Leftrightarrow$ cyclotron gap

DOS at Fermi energy at a fixed density



Physical properties – effective mass

- $\sim 0.08 m_0$.
- $\sim$ 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



Physical properties – effective mass

Theory

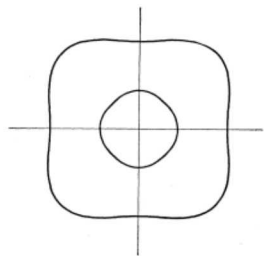
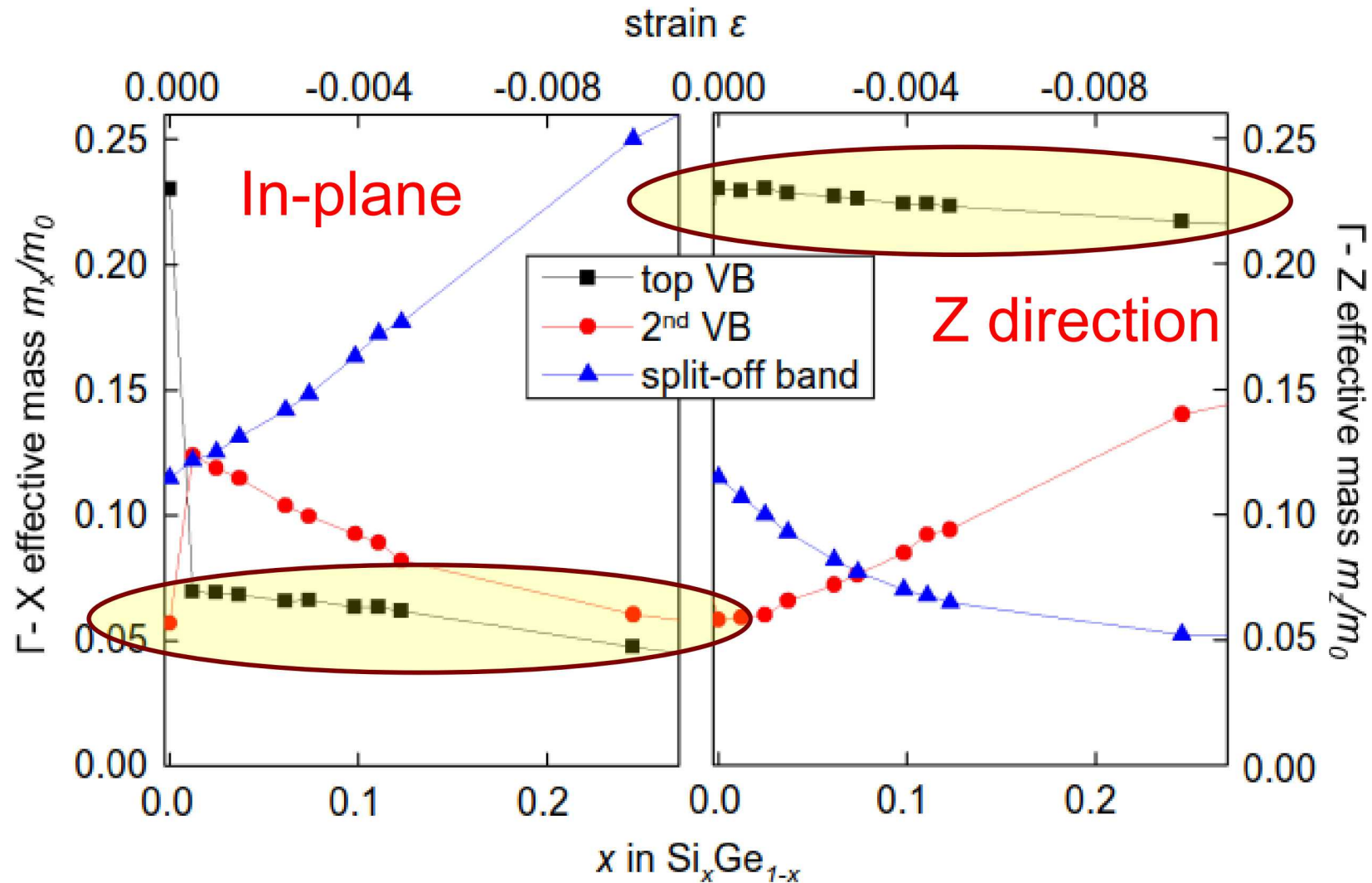
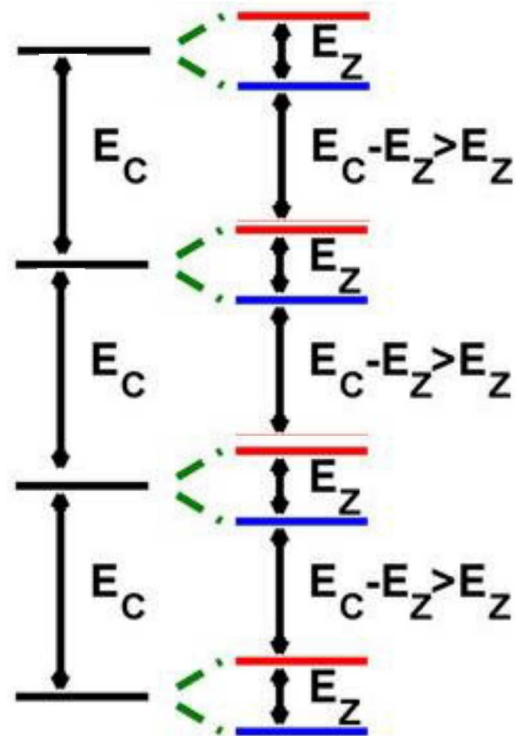


FIG. 8. Figures of constant energy in the (100) plane of k -space for the two fluted energy surfaces which are degenerate at the valence band edge; constants as for germanium.

The quantum Hall effect

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



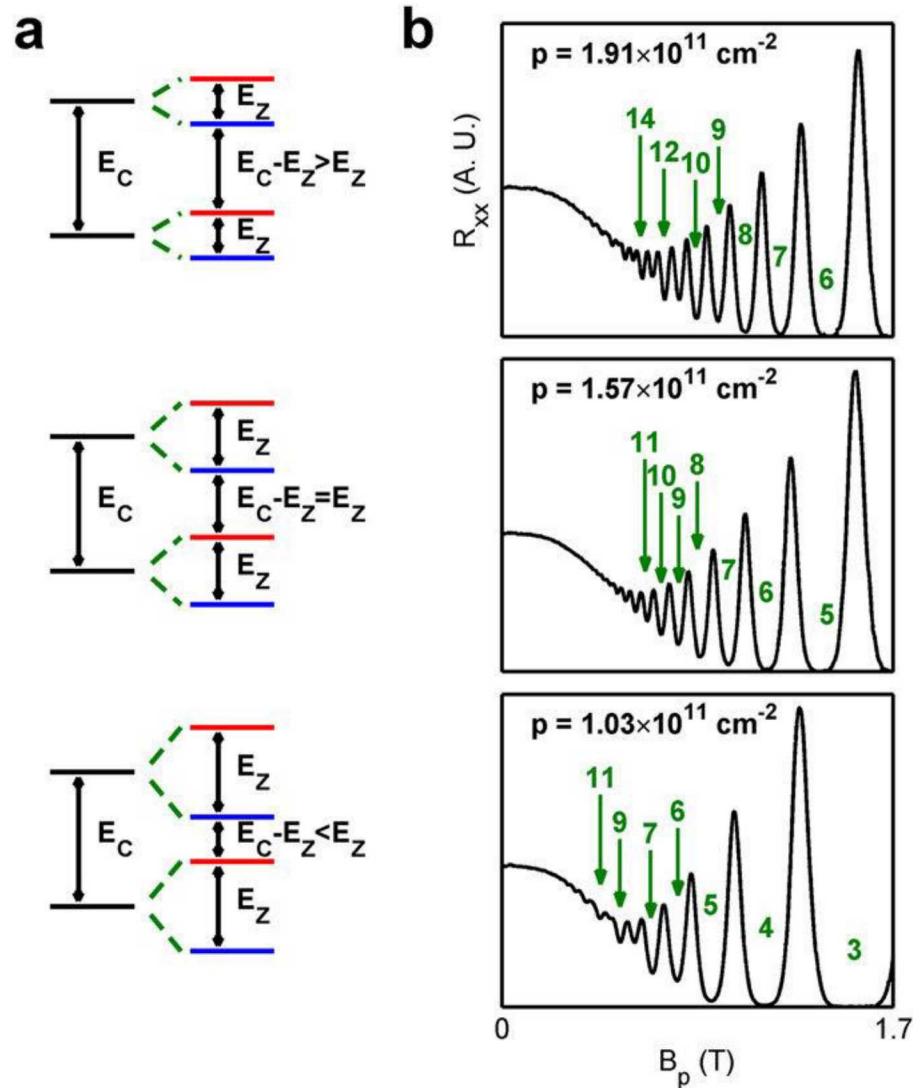
E_C is cyclotron gap: $\hbar e B / (2\pi m^*)$

E_Z is Zeeman gap: $g^* \mu_B$

m^* and g^* are material parameters.

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

Quantum Hall ferromagnetic transition



In most cases, $E_c \gg E_z$

$\Rightarrow$ Strong even states, weak odd states

If $E_c \sim 2E_z$

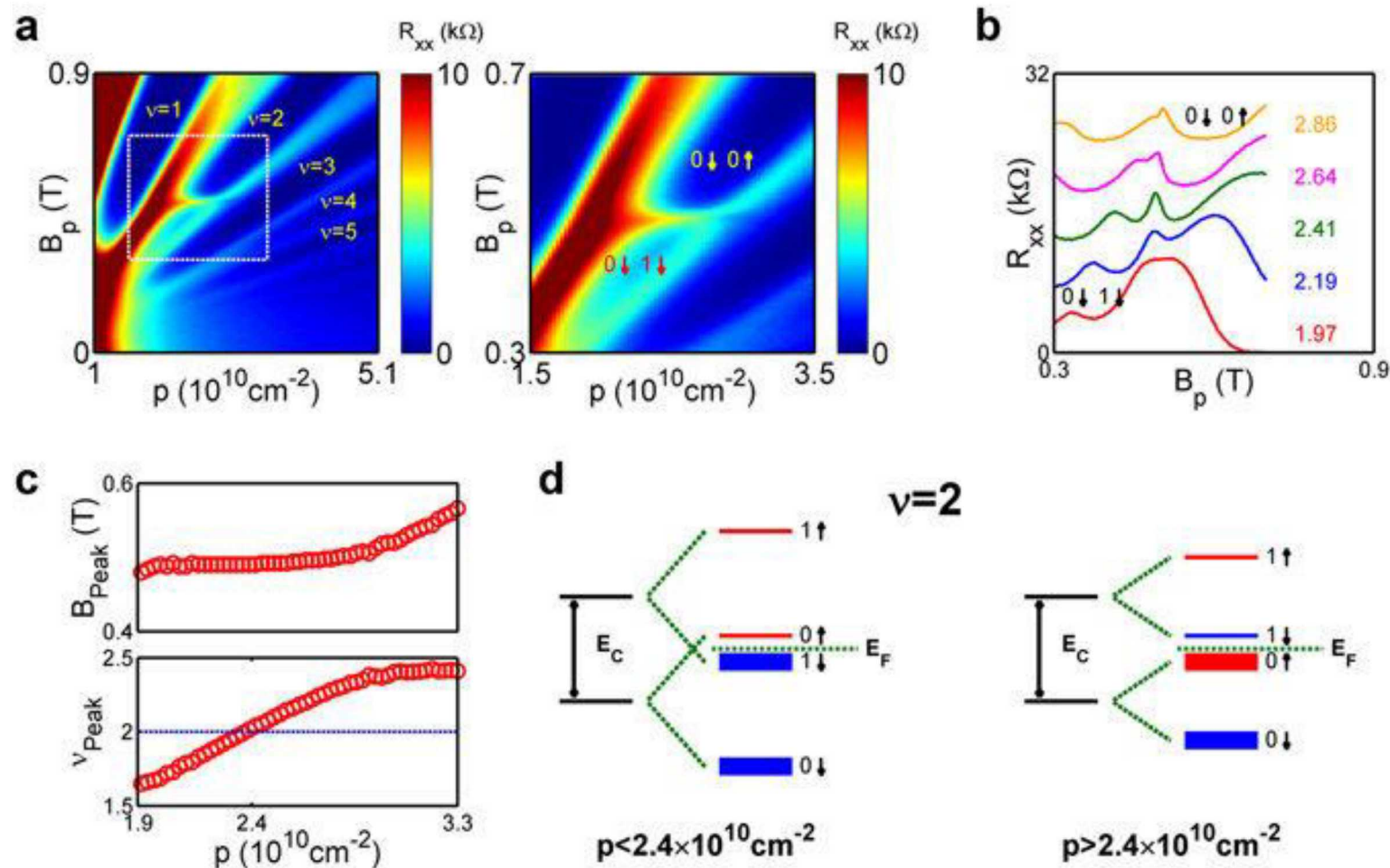
$\Rightarrow$ Strength of even states $\sim$ strength of odd states

If $E_c < 2E_z$

$\Rightarrow$ Strong odd states, weak even states

E_z/E_c increases with decreasing density.

Quantum Hall ferromagnetic transition



A spin transition (unpolarized $\leftrightarrow$ polarized) at $\nu=2$ occurs at $p \sim 2.4 \times 10^{10}$ cm $^{-2}$.

This transition marks the point where $E_c \sim E_z$

$$\frac{\hbar e B}{(2\pi m^*)} = g^* \mu_B$$

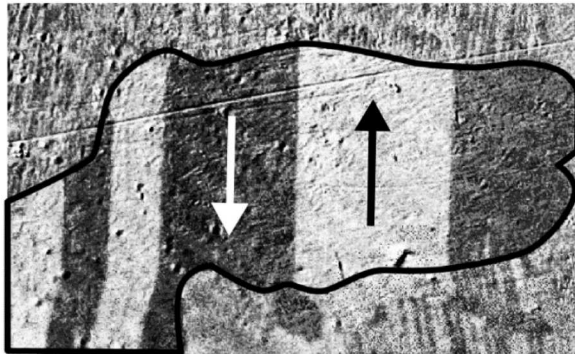
$$\Rightarrow m^* g^* = 2$$

Quantum Hall ferromagnetic transition

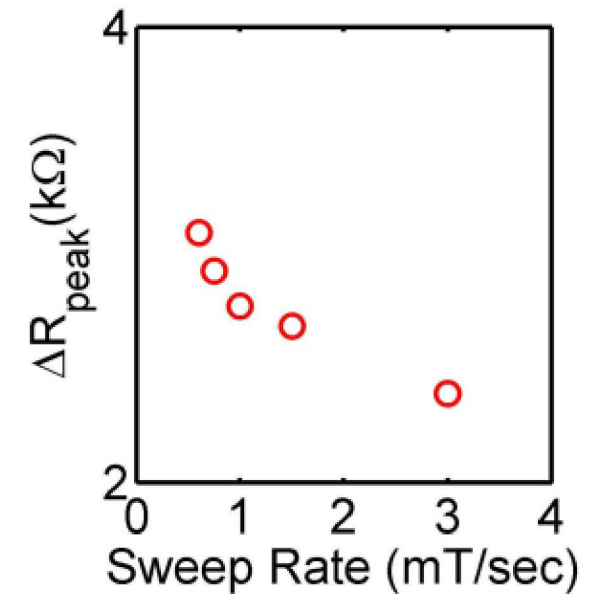
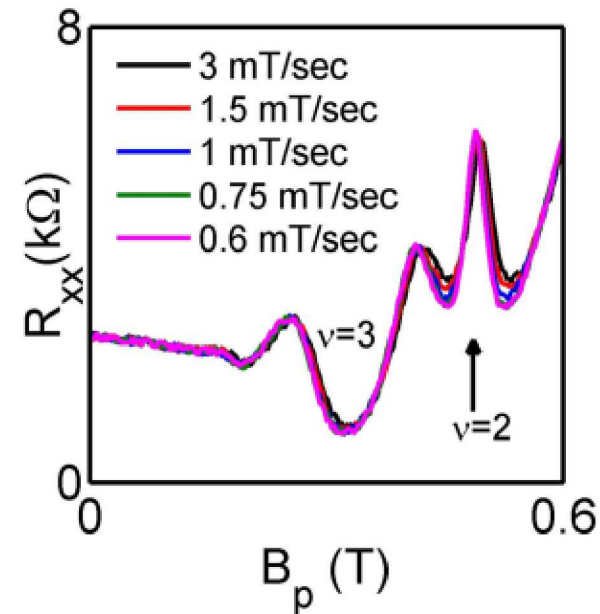
The physical picture of the system at the transition:

micro-domains of different spin configurations. Away from the transition, one spin configuration is preferred. Domains move and merge to minimize surface energy.

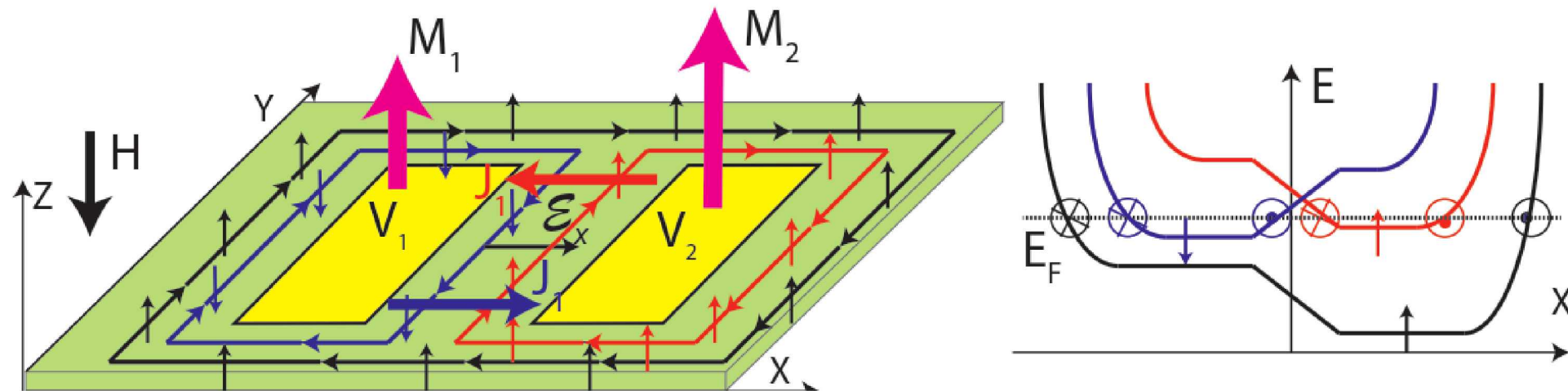
Evidence of micro-domains is found in the time dependence.



by S. Zurek, E. Magnetica, [CC-BY-3.0](https://creativecommons.org/licenses/by/3.0/)



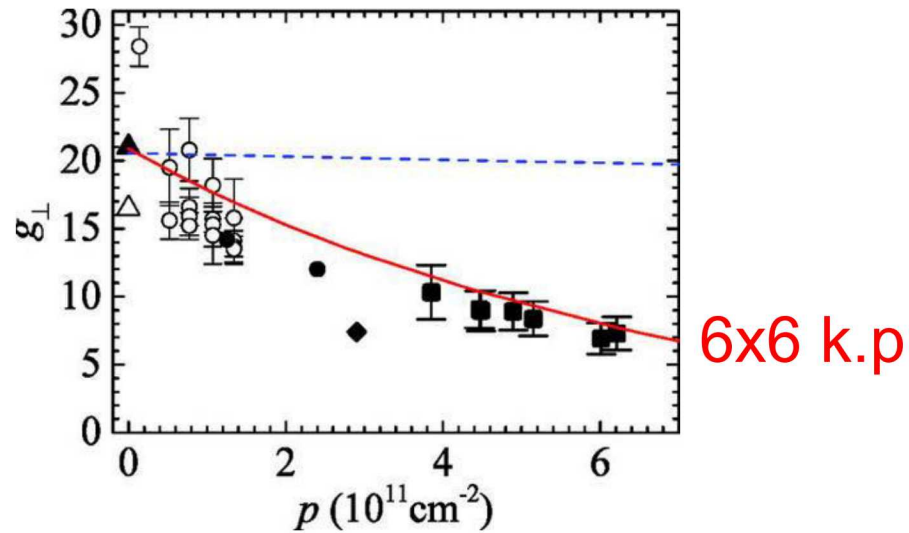
Local gating to create counter-propagating edge states with opposite spins



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

Physical properties – g factor

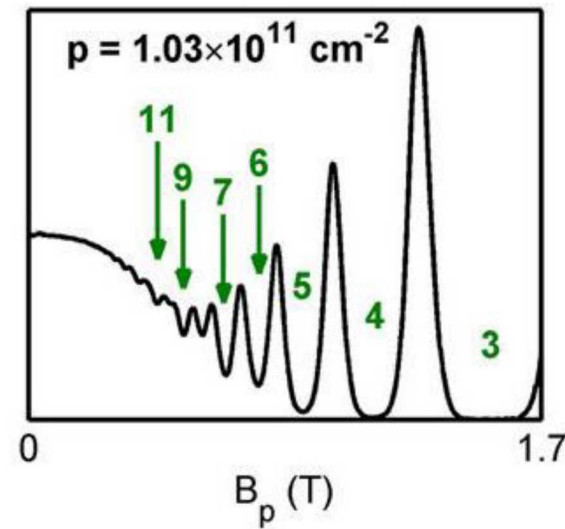
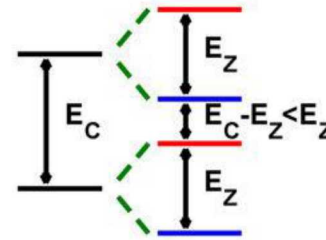
- $\sim 5 - 30$
- $\sim$ density dependent.
- The g factor is large compared to the g factor of electrons in Si (~ 2) and the g factor of electrons in GaAs (~ 0.44).



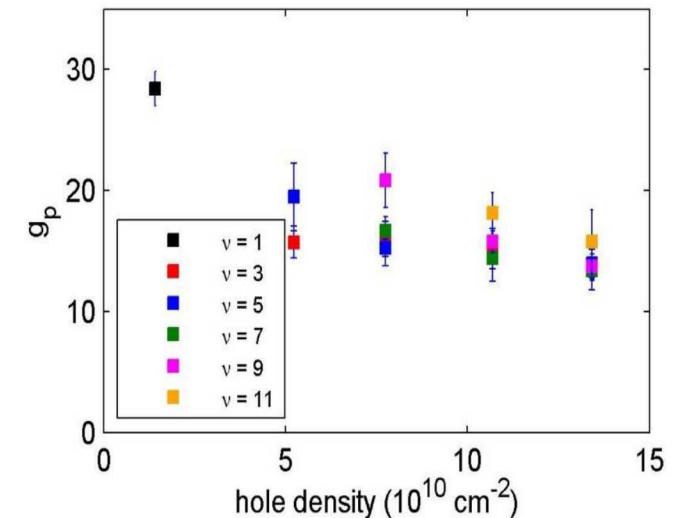
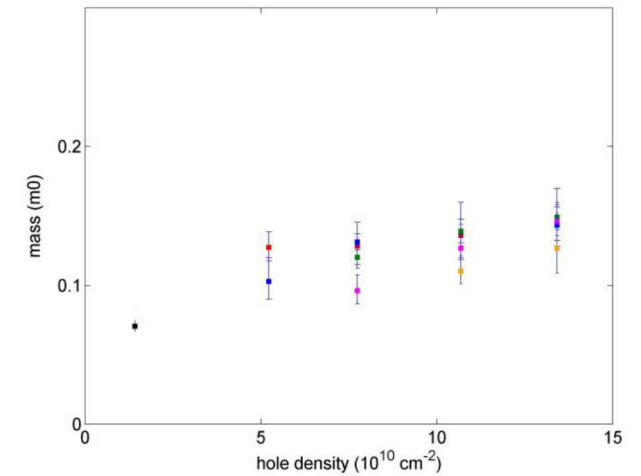
Drichko J. Appl. Phys. 123, 165703 (2018)

$$P < 1.6 \times 10^{11} \text{ cm}^{-2}$$

$$0.5 E_c < E_z < E_c$$



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



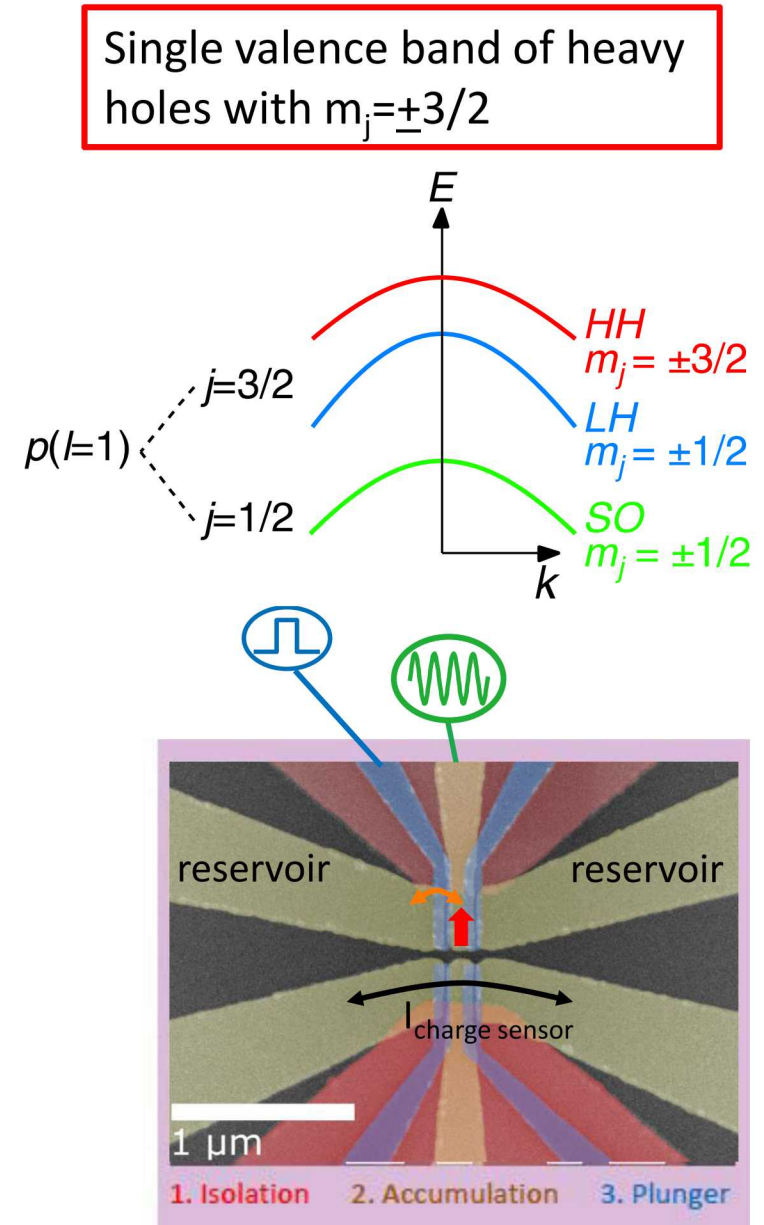
Project overview

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

- Common material platforms for spin qubits: GaAs, Si/SiGe, Si-MOS
- Challenges of these materials
 - GaAs: lattice nuclear spins severely limit coherence times
 - Si: valley splitting
 - Si-MOS: disordered interface
- Holes in Ge/SiGe provide a compelling alternate approach to spin based qubits. They maintain many of the advantages of silicon without valley splitting.

Approach

- Single hole confined to lateral quantum dot in Ge heterostructure
- Spin qubit states: $m_j = \pm 3/2$
- 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 $\sim k^3$ in 2DHG.



Ge/SiGe quantum well heterostructures

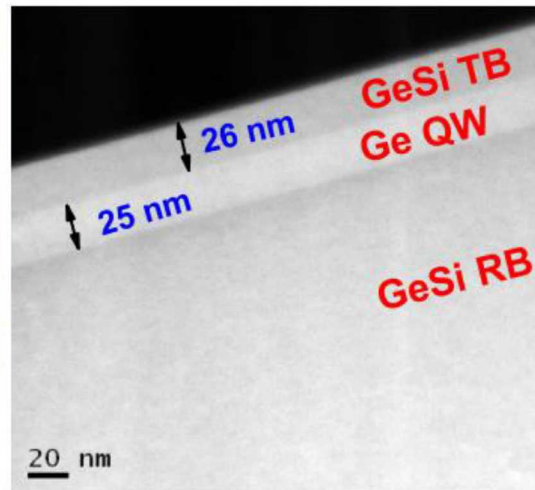
RP-CVD growth
Clean epitaxial interface

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

(a)

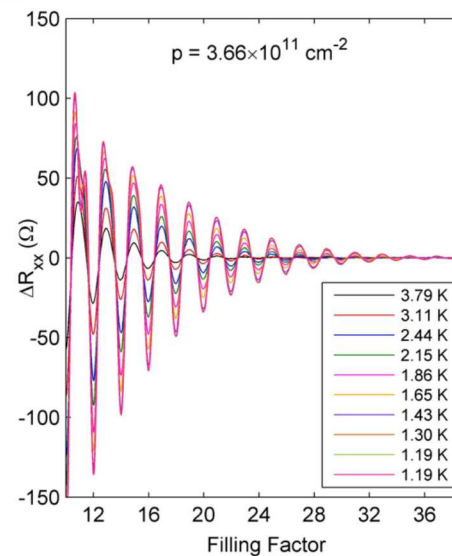


(b)

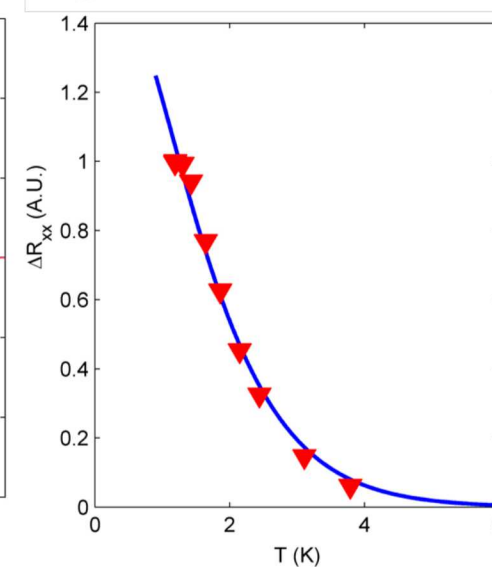


Su, et al. *Phys. Rev. Mater.* (2017)

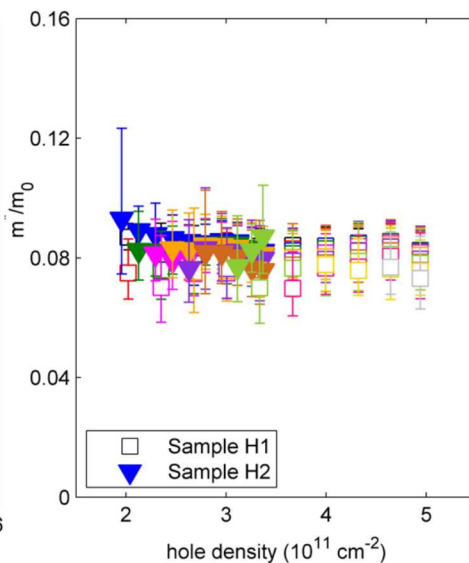
a



b



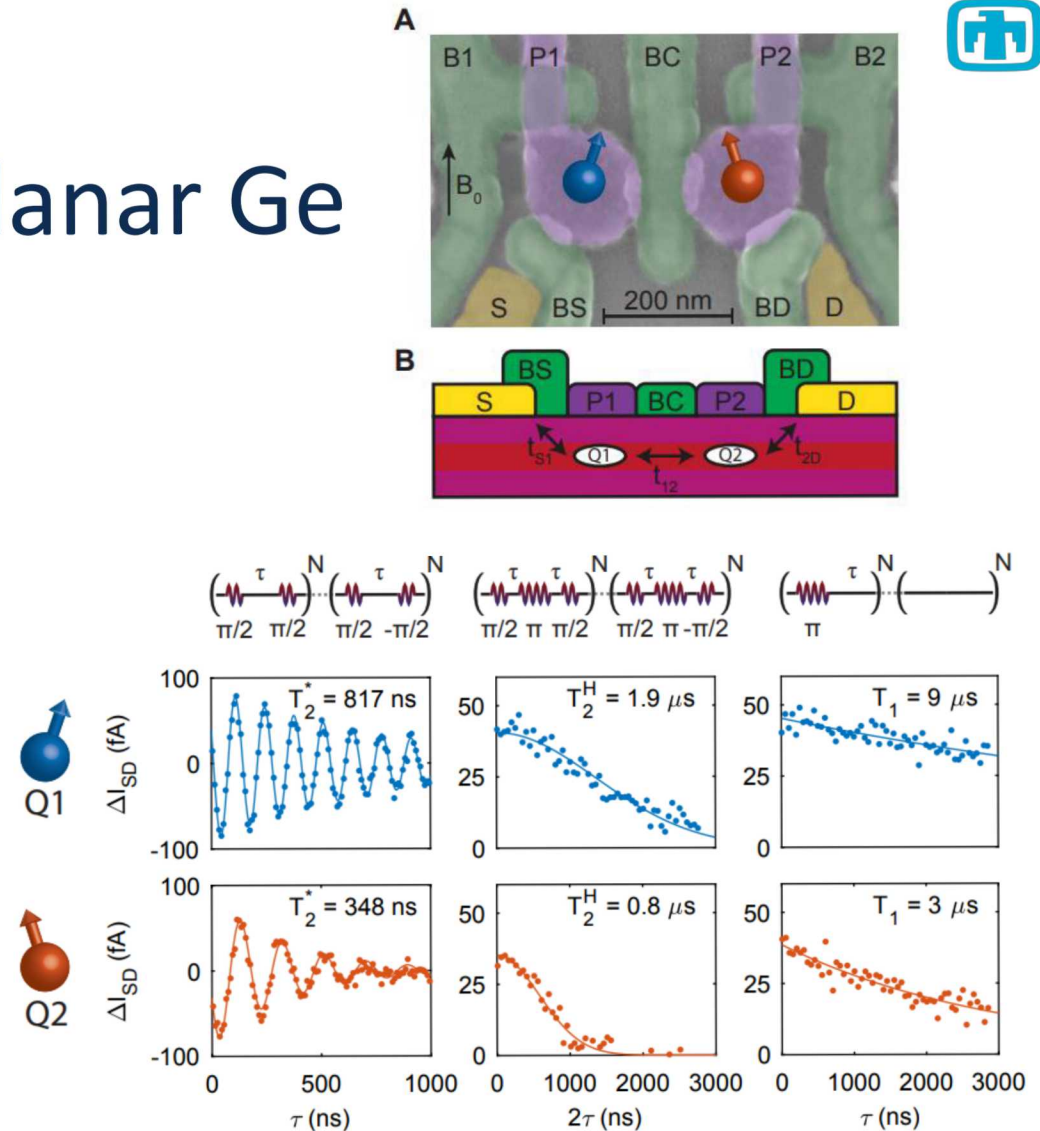
c



Hardy et al., *Nanotechnology* (2019)

Recent literature result: Multi-hole spin qubits in planar Ge

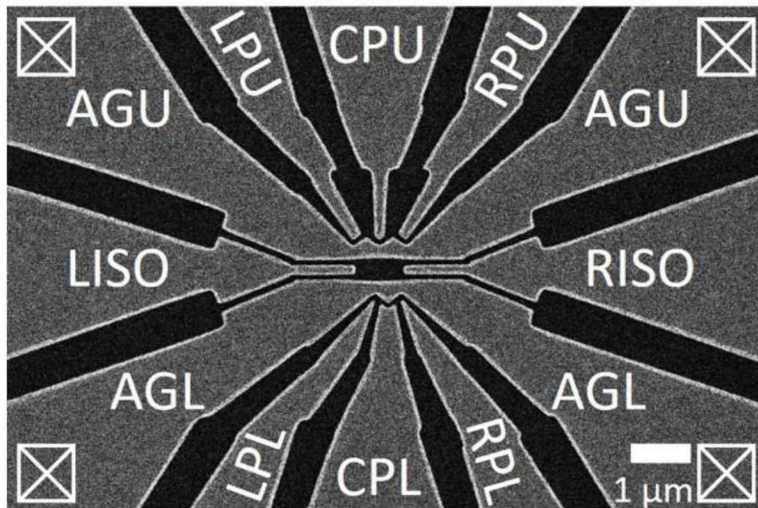
- Single and two-qubit gates have been measured in transport in multi-hole Ge/SiGe quantum dots
- T_2^* coherence times are long (hundreds of ns)
- Encouraging as we look toward single-hole spin qubits



Hendrickx, *et al.* arXiv 2019

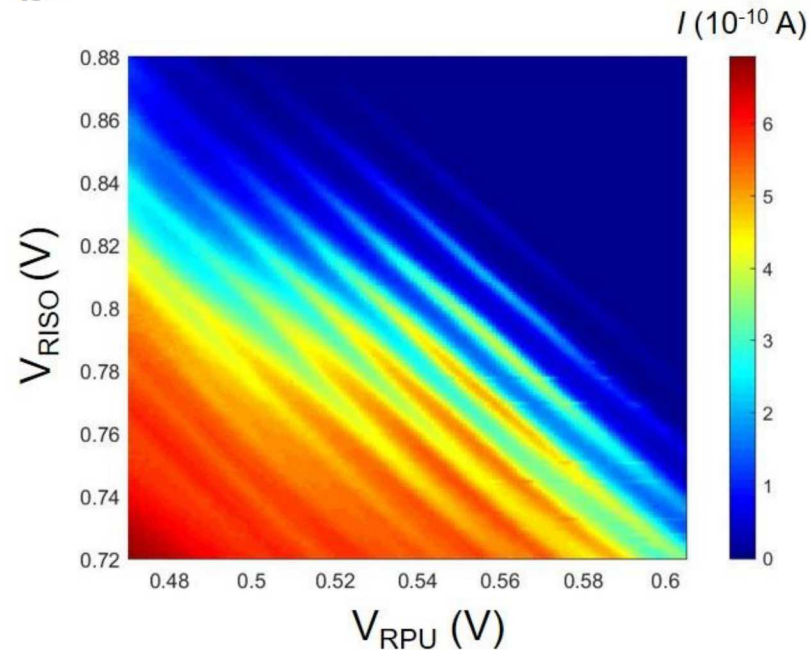
Single layer devices host quantum dots

a Single layer device



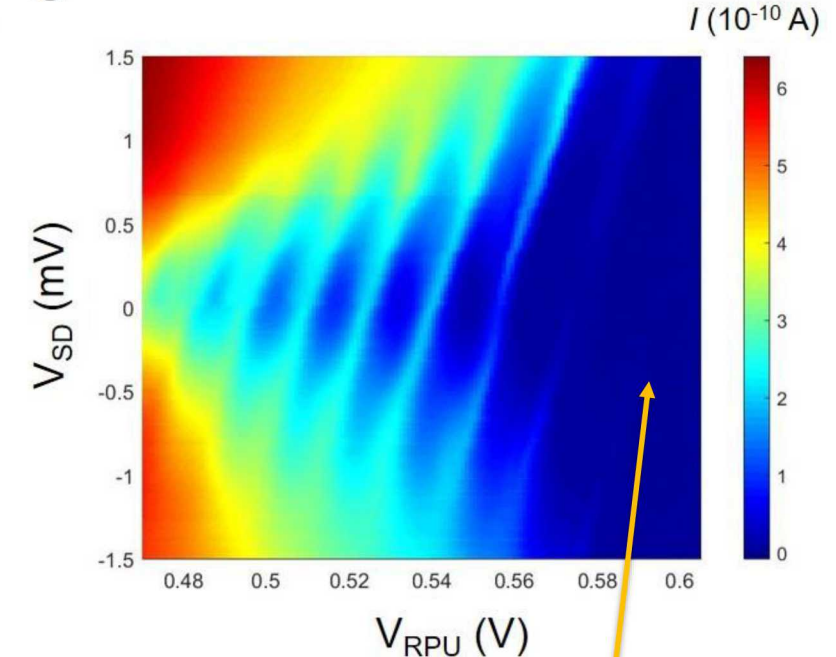
Measure in dilution refrigerator
 $T \sim 30$ mK

b Coulomb oscillations



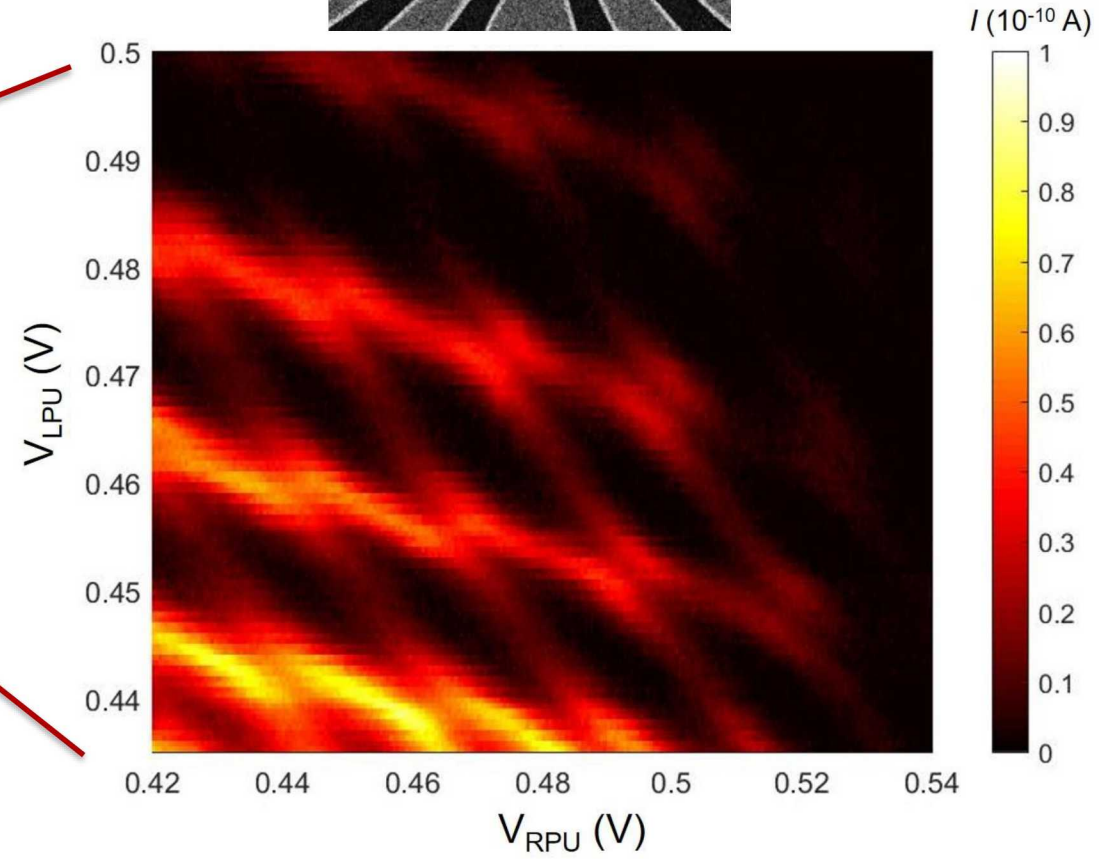
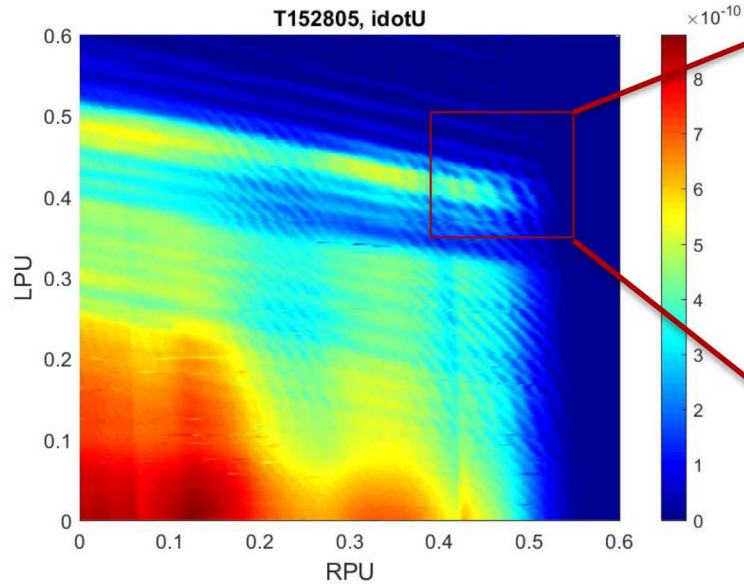
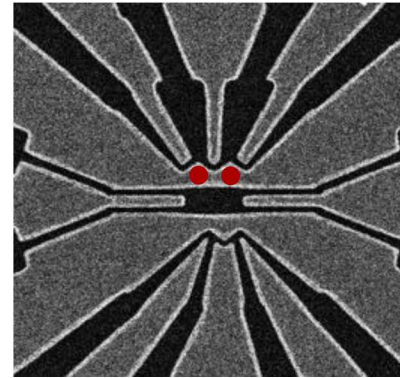
Lines are broadened
Confinement is not tight enough

c Coulomb diamonds



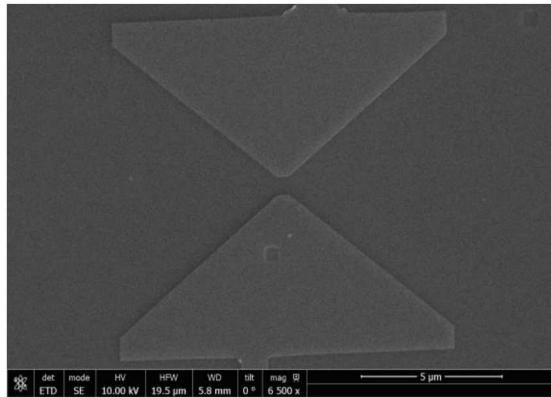
Few-hole regime

Double quantum dot

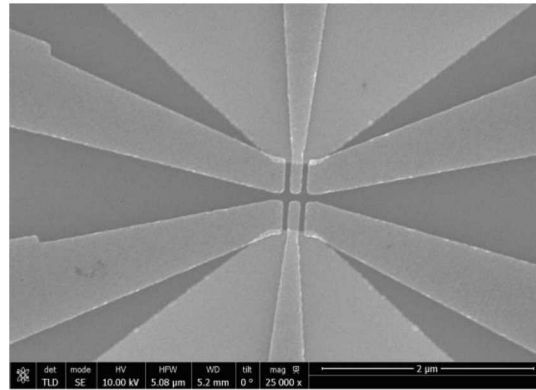


- Difficult tuning of dot-dot coupling using center plunger gate
- Need more orthogonal control

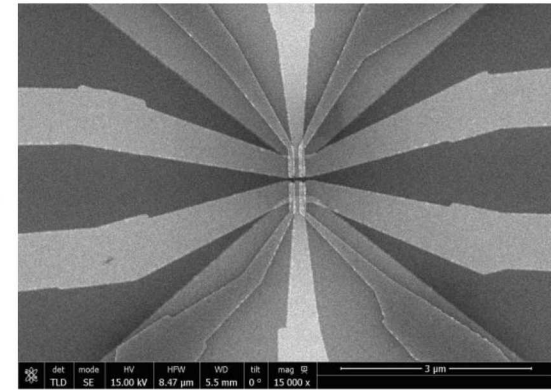
3-layer device fabrication



1: isolation gates

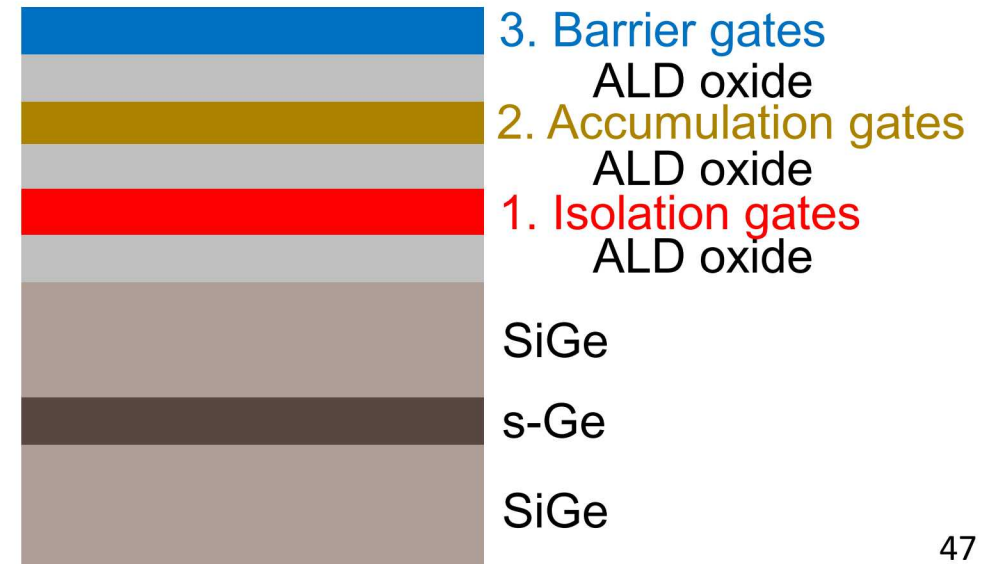
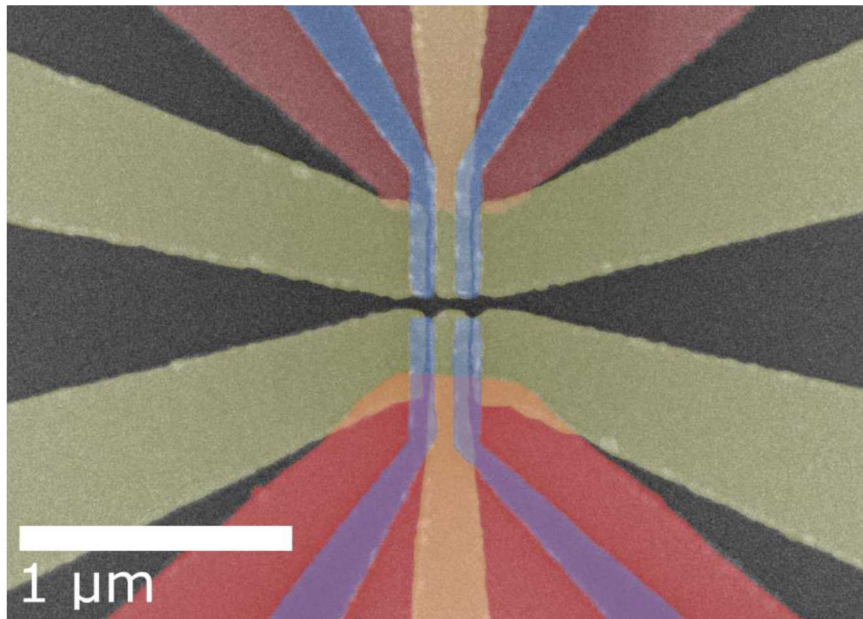


2: accumulation gates



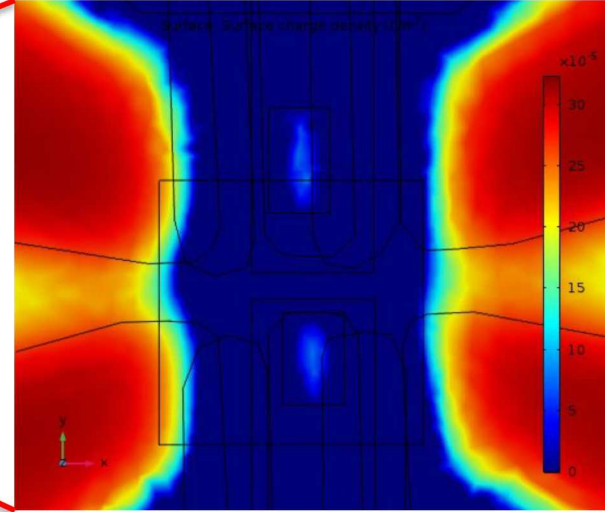
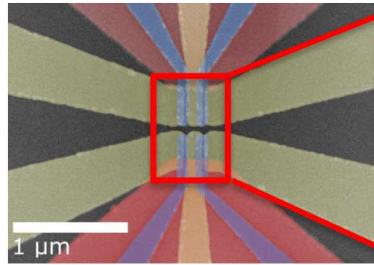
3: barrier gates

E-beam lithography
ALD Al_2O_3 oxide
Ti/Pt gates

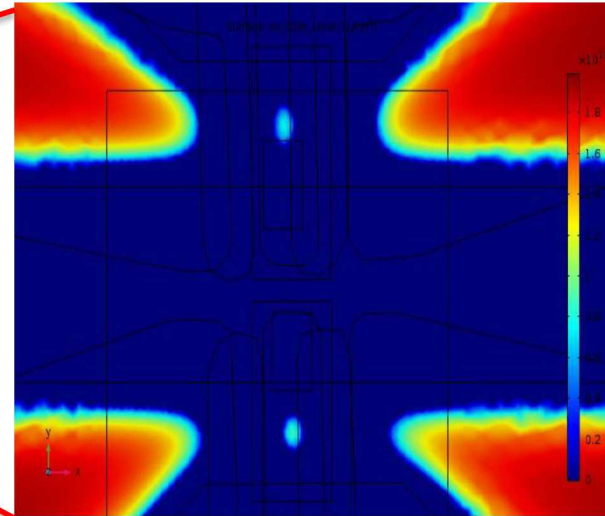
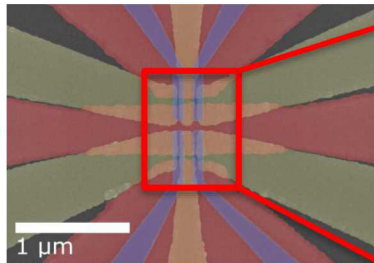


3-layer device modeling: surface charge density

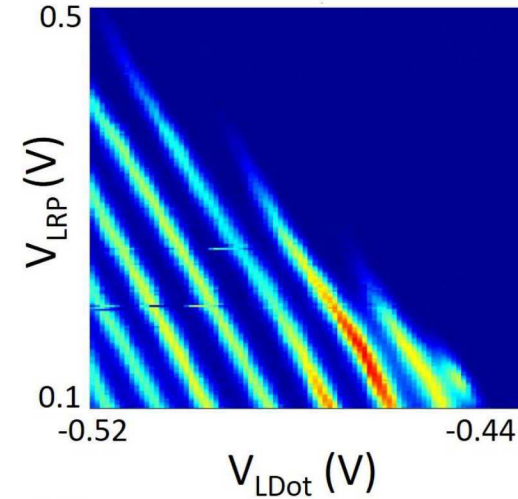
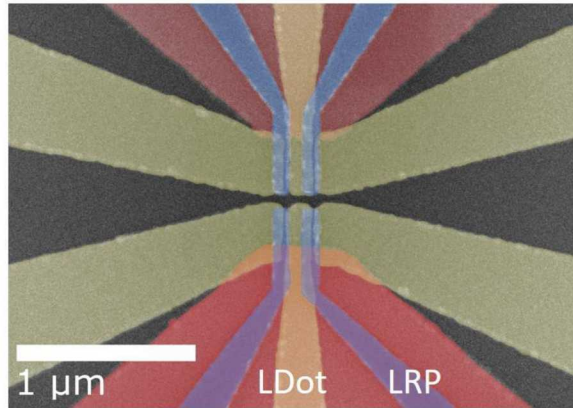
Without horizontal isolation gate:
reservoirs merge



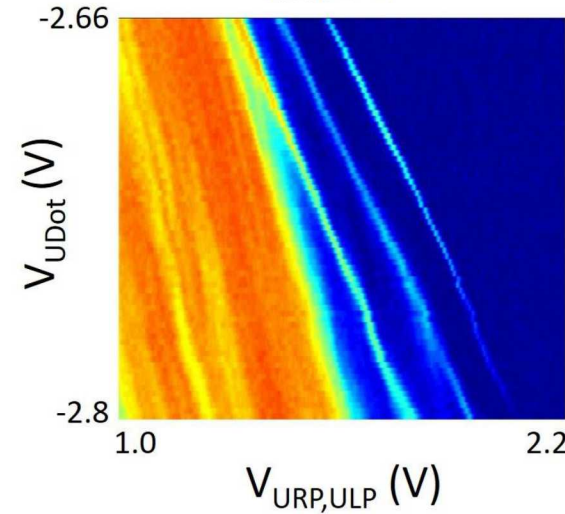
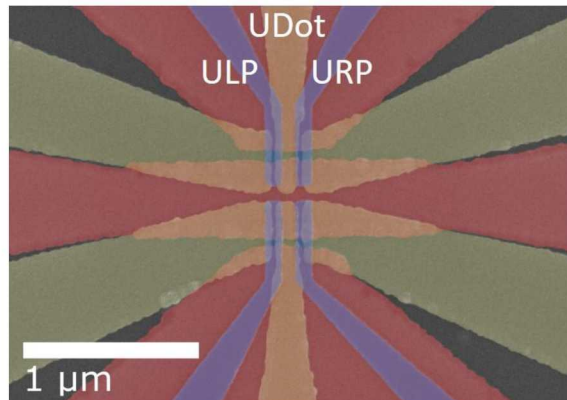
Add horizontal isolation gate:  reservoirs separated



Improved Coulomb blockade by adding center isolation gate



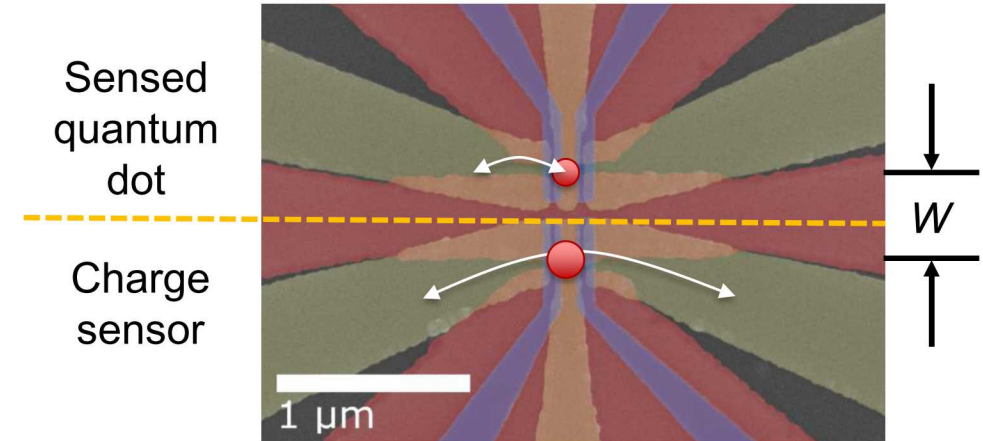
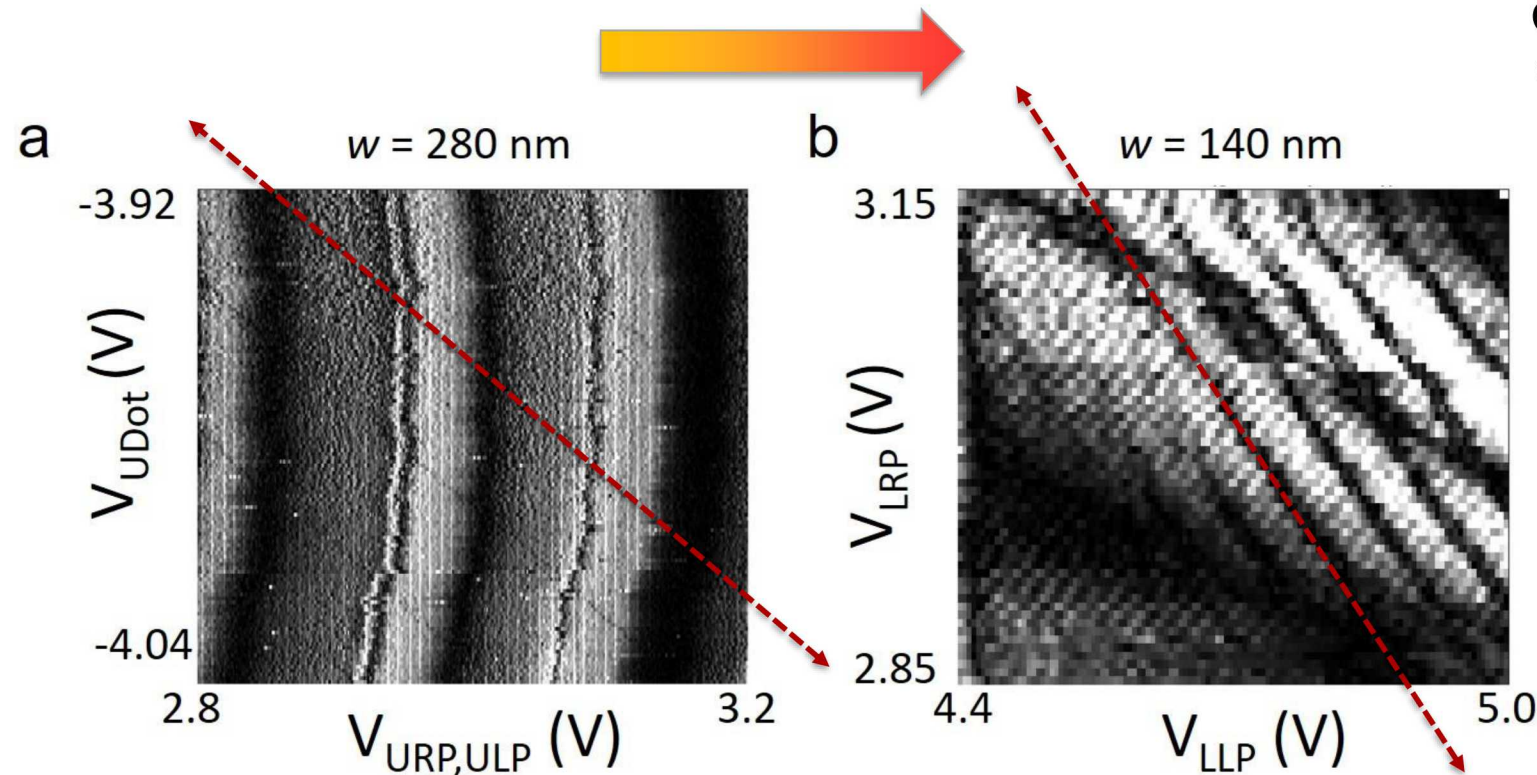
Without horizontal
isolation gate



With horizontal
isolation gate

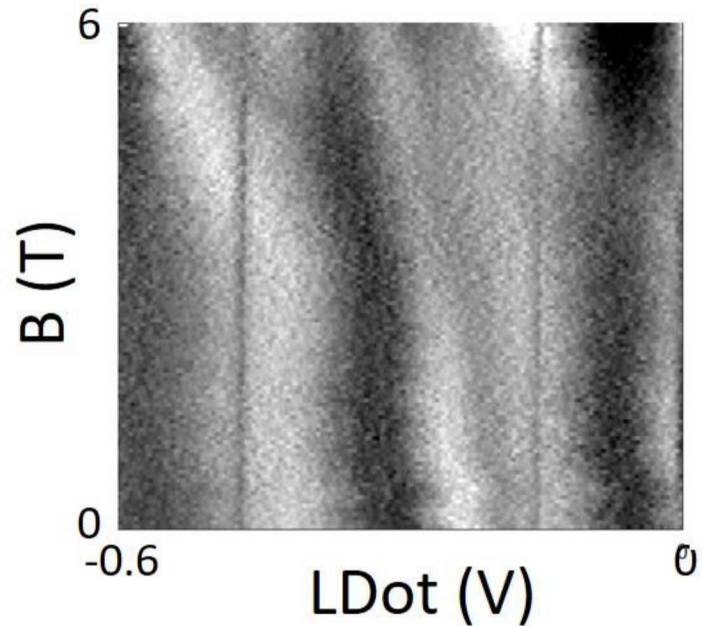
Charge sensing: Comparison of isolation gate widths

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



Parallel diagonal lines are sensed charge transitions

In-plane g-factor



- Charge sensed lines appear insensitive to in-plane B-field
 - $g_{\text{in-plane}}$ is very small
- Next experiment: apply B out-of-plane
- g-factor anisotropy is expected
[Lu et al. 2017, Sammak et al. 2019]

Summary

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