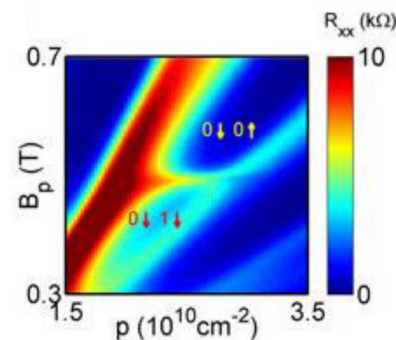
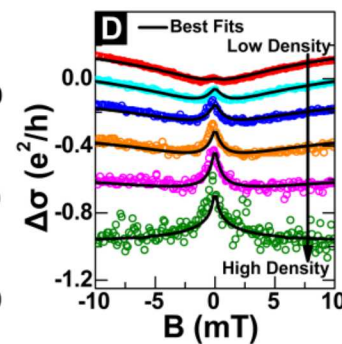
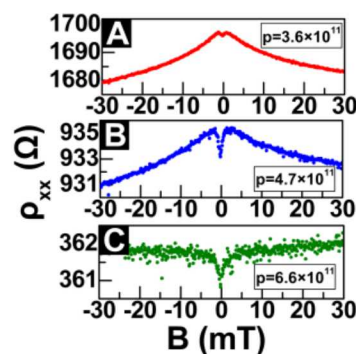
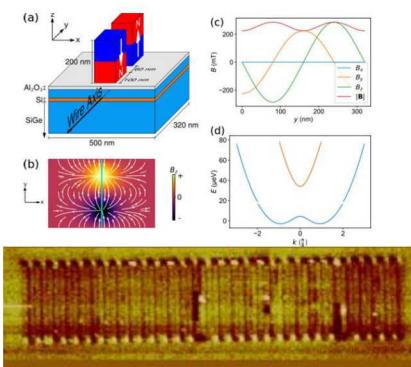




Sandia
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SAND2019-5530PE

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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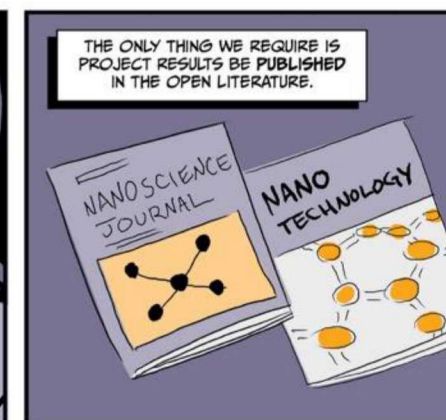
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Acknowledgements

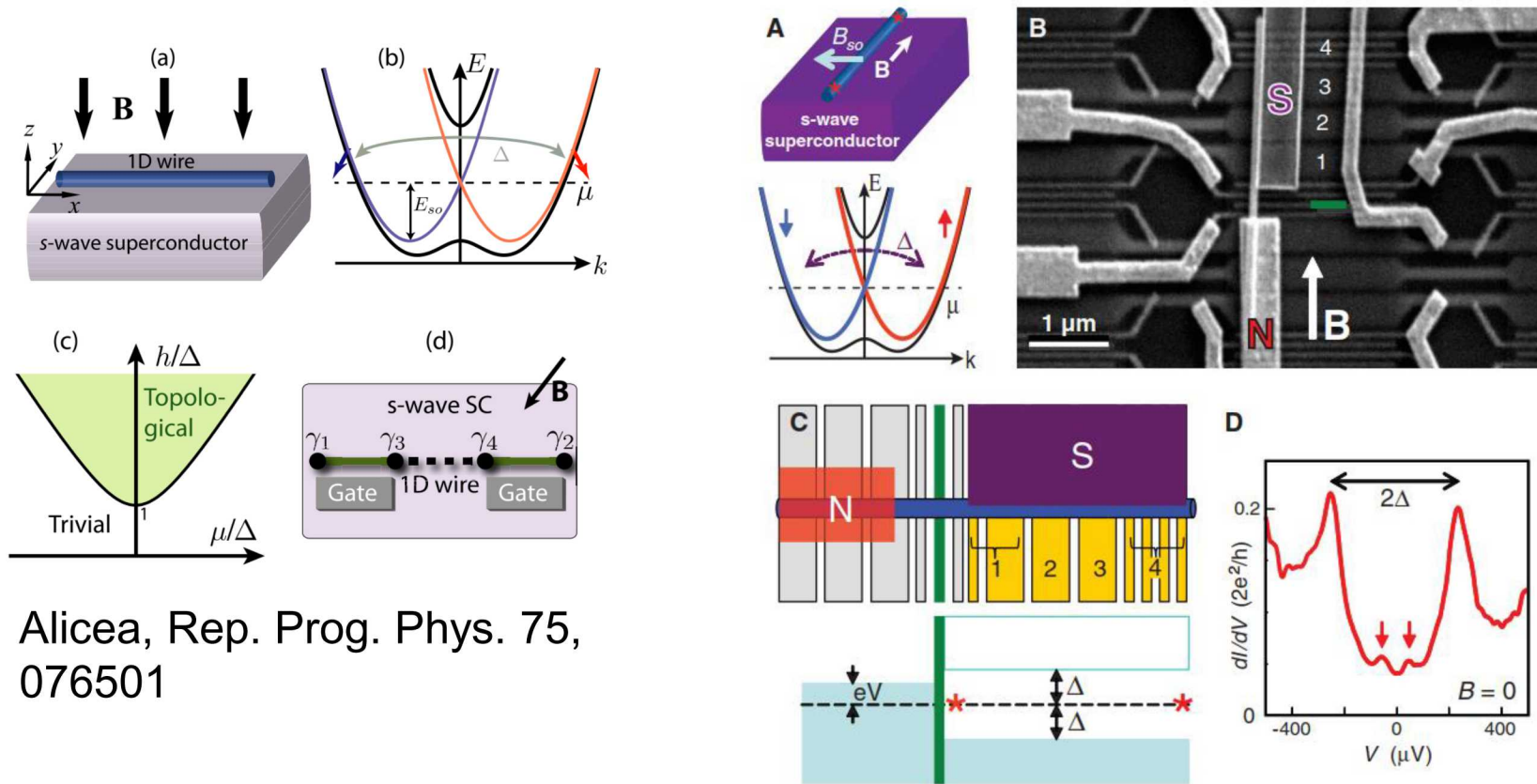
- Sandia National Laboratories: M. P. Lilly, D. Laroche, L. A. Tracy, C. T. Harris, N. T. Jacobson, J. Moussa, A. D. Baczewski, D. R. Luhman, W. Hardy, J. Gamble, and L. N. Maurer.
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- National Taiwan University: C. W. Liu, J.-Y. Li, C.-H. Lee, S.-H.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

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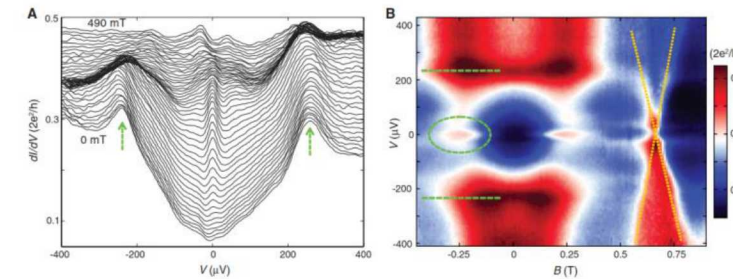
Outline

- 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



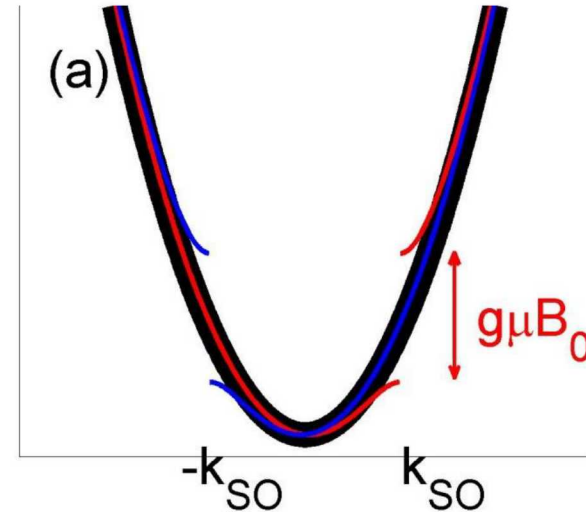
Mourik, Science 336, 1003

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:

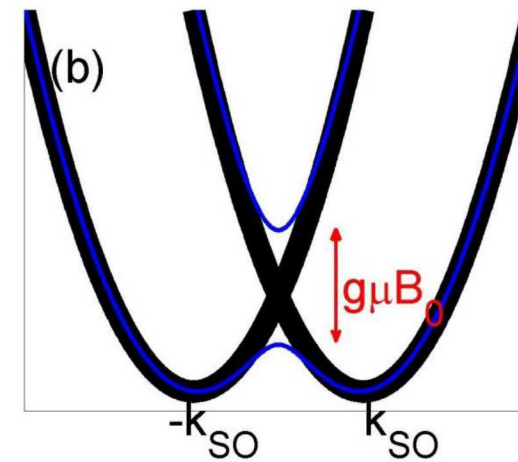
$$E \sim \frac{\hbar^2 k_x^2}{2m} \quad (\text{black in a}) \quad (\text{free electrons})$$



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

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

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

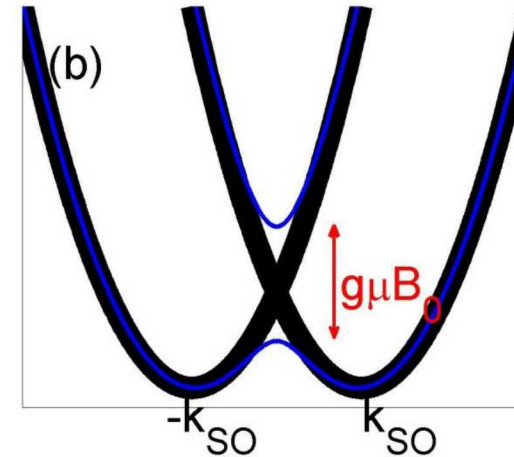


(black in b) (shifted free electron dispersion)

1D spin orbit coupling

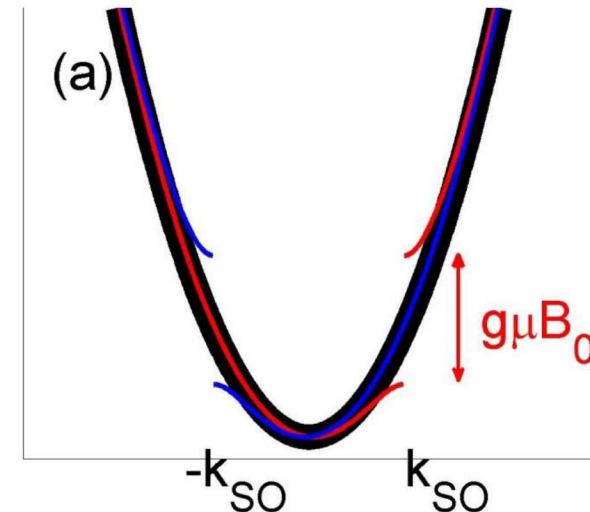
- 1D $E-k_x$ dispersion **with** SOC with B_0 along z :

Gap near $k=0$
(blue curves)

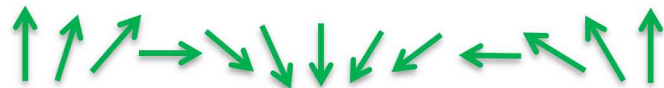


- Canonical transformation of the above case:

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

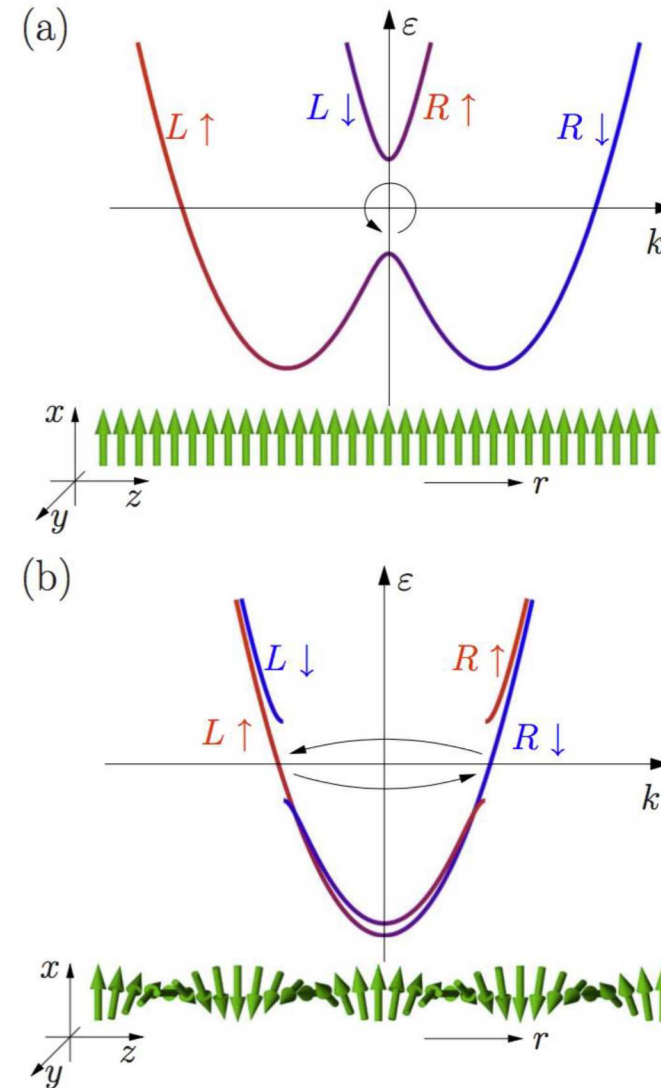


Effective magnetic field



Engineer the SOC using nano-magnets

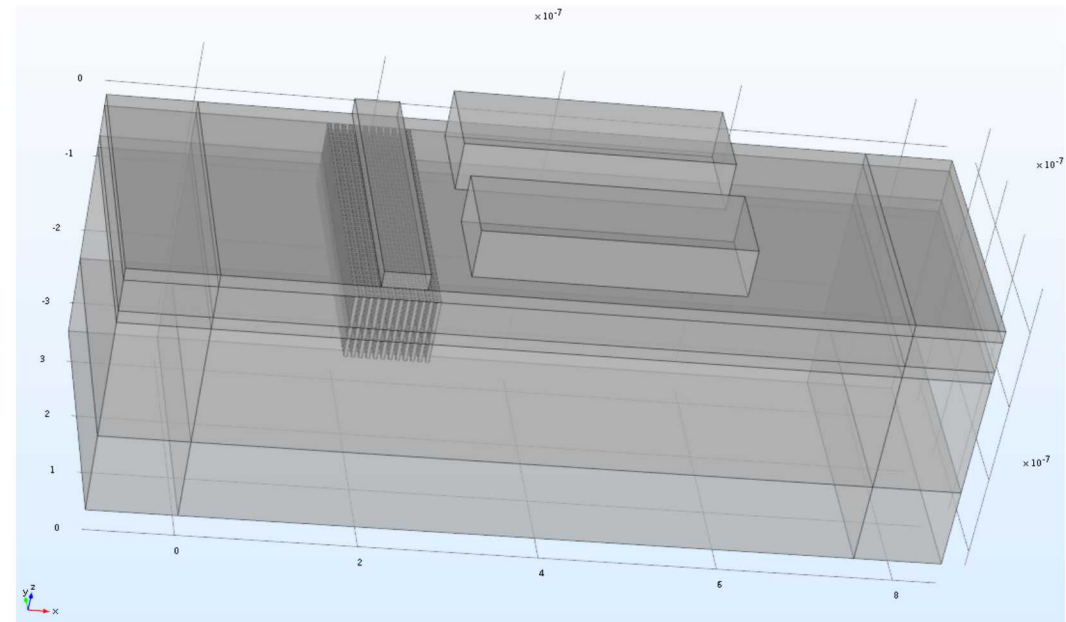
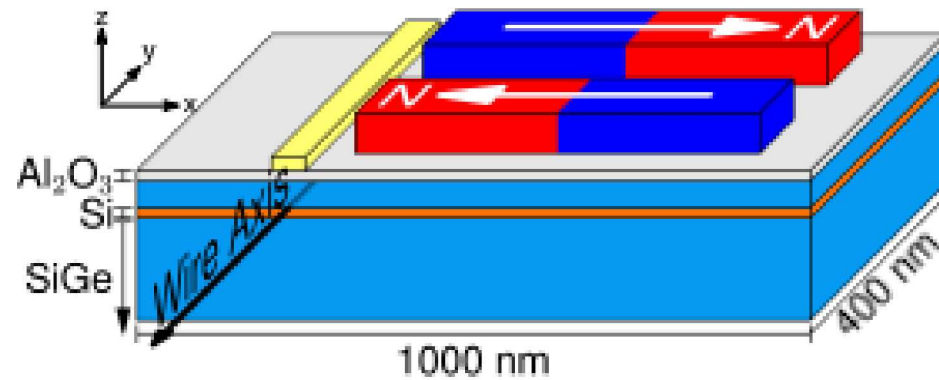
- Magnets that produce a spatially rotating magnetic field can have the same effect as intrinsic SOC (plus an external bias magnetic field)
- Designer material!
- We want to use Si/SiGe, because of the high mobility (and therefore long mean free path and phase coherence length)



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

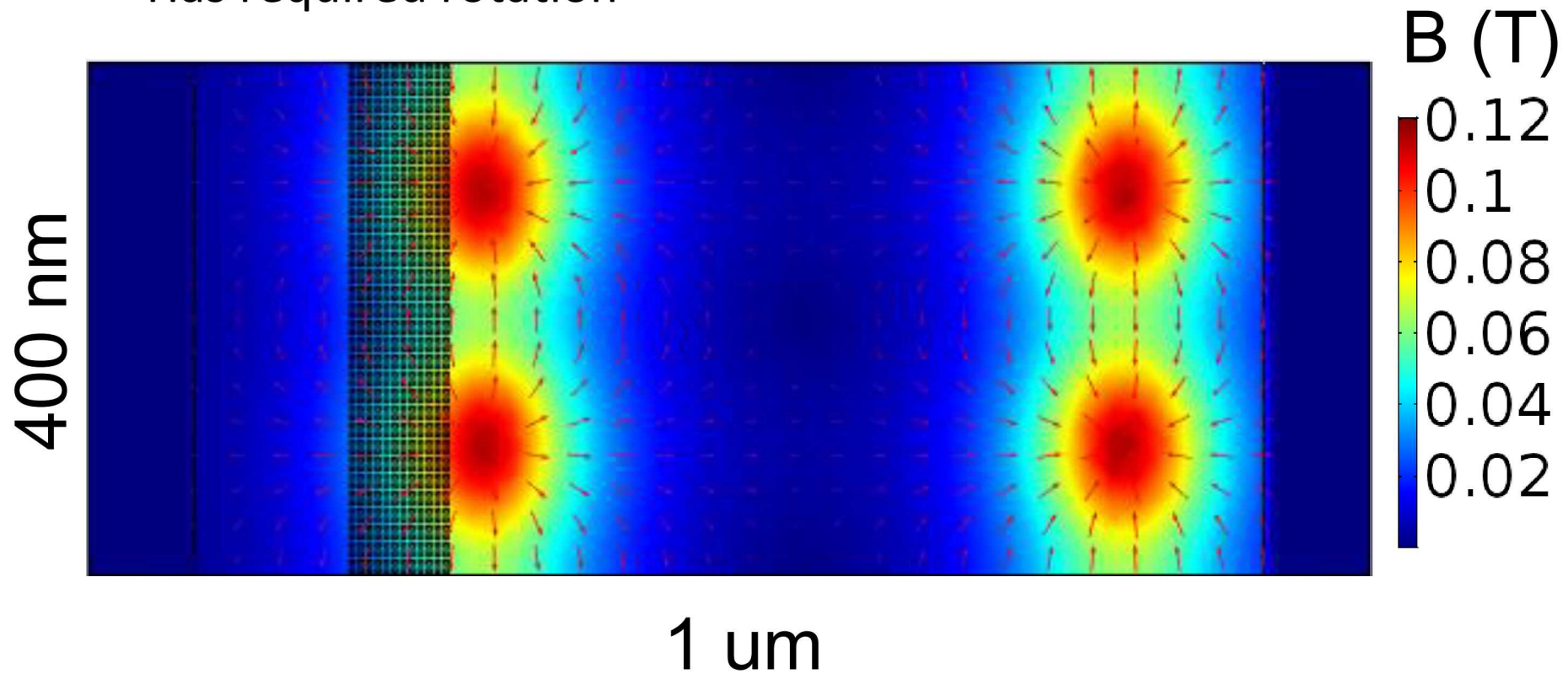
Magnetostatics I

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



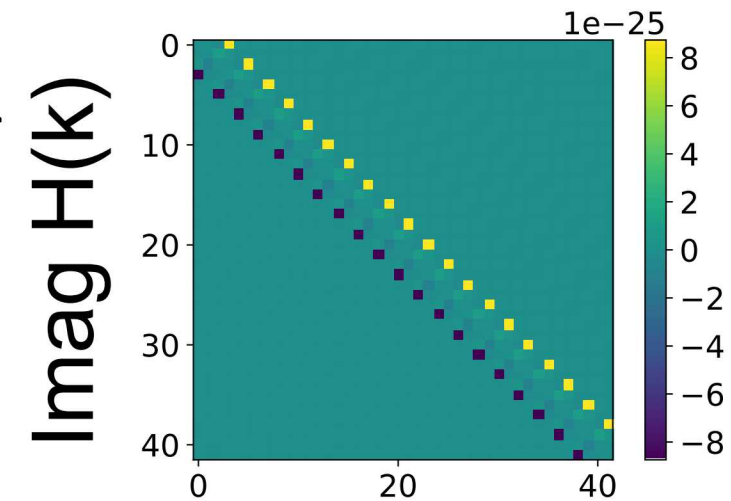
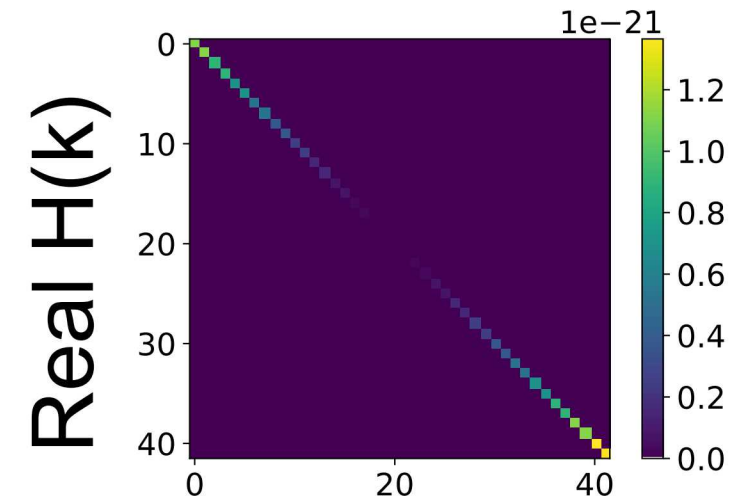
Magnetostatics II

- Magnetic field in 2DEG plane
- Has required rotation



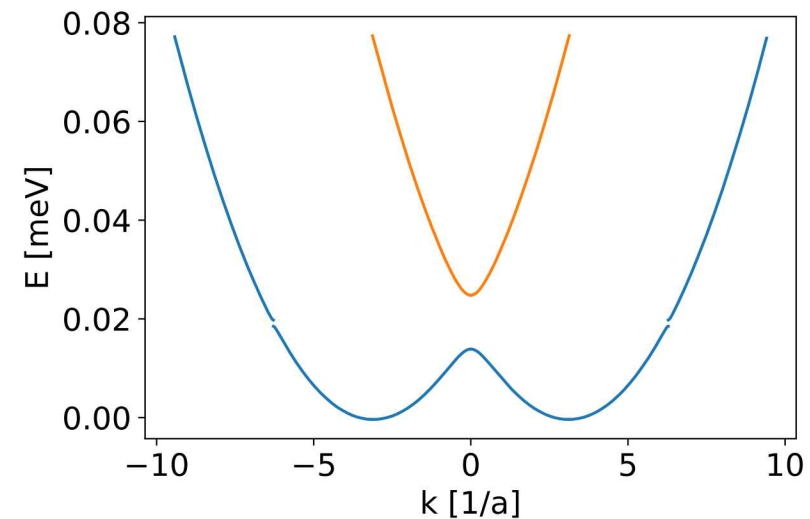
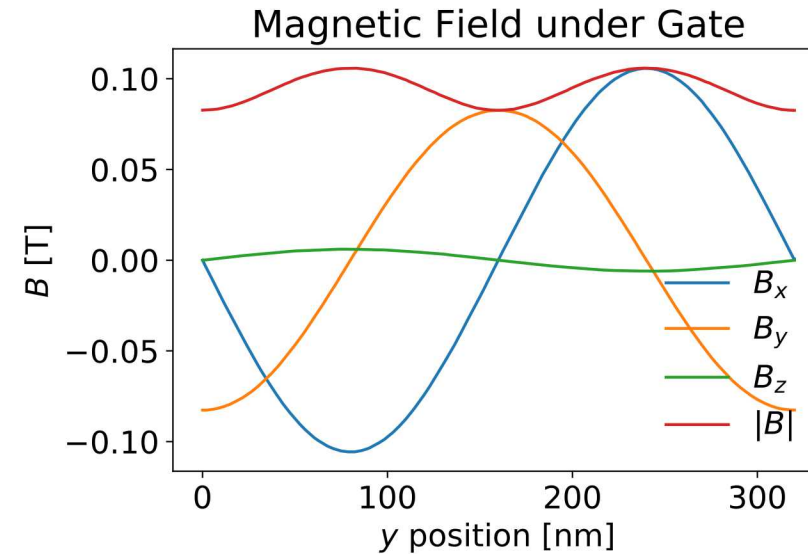
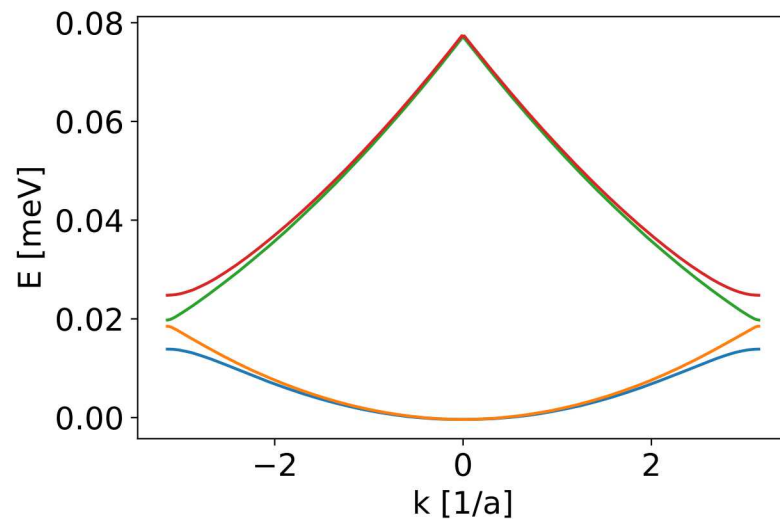
Band Structure Calculations

- 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

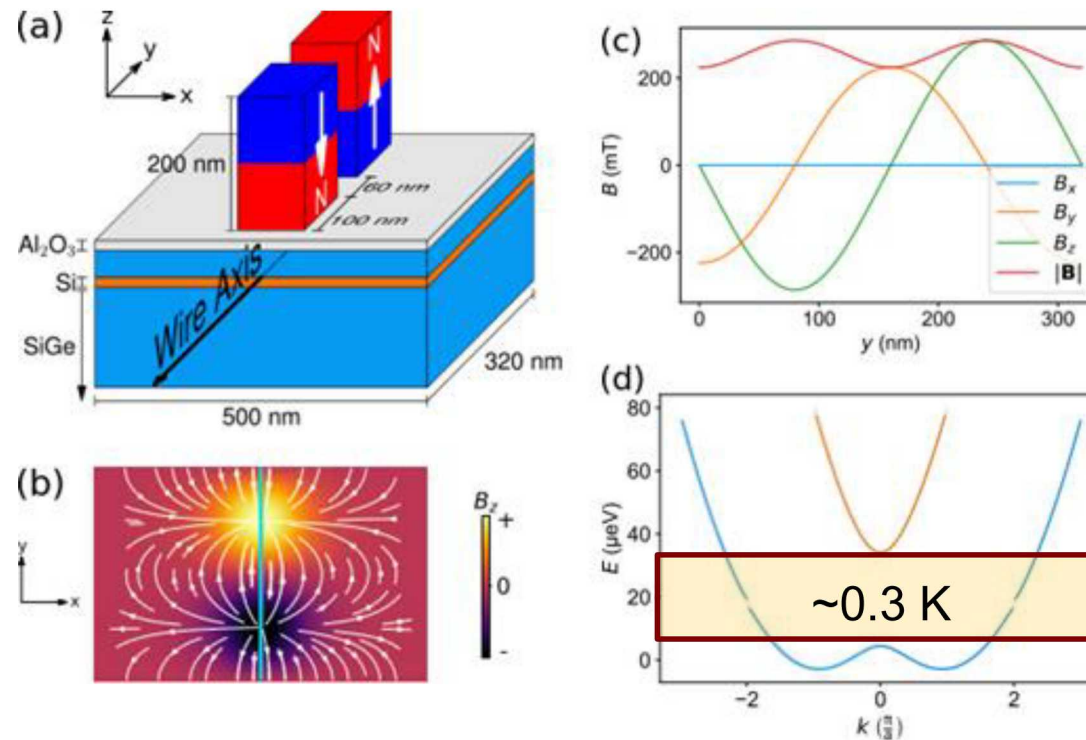
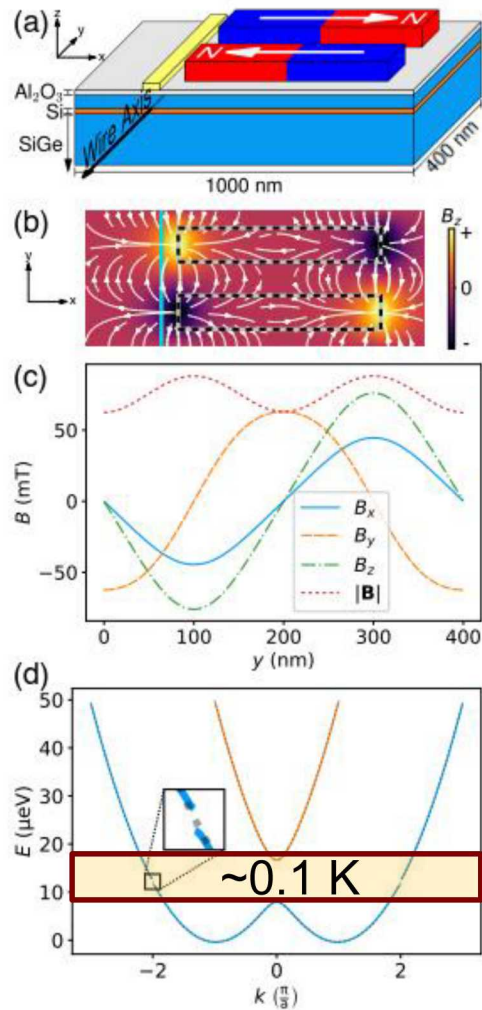


Example Results

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

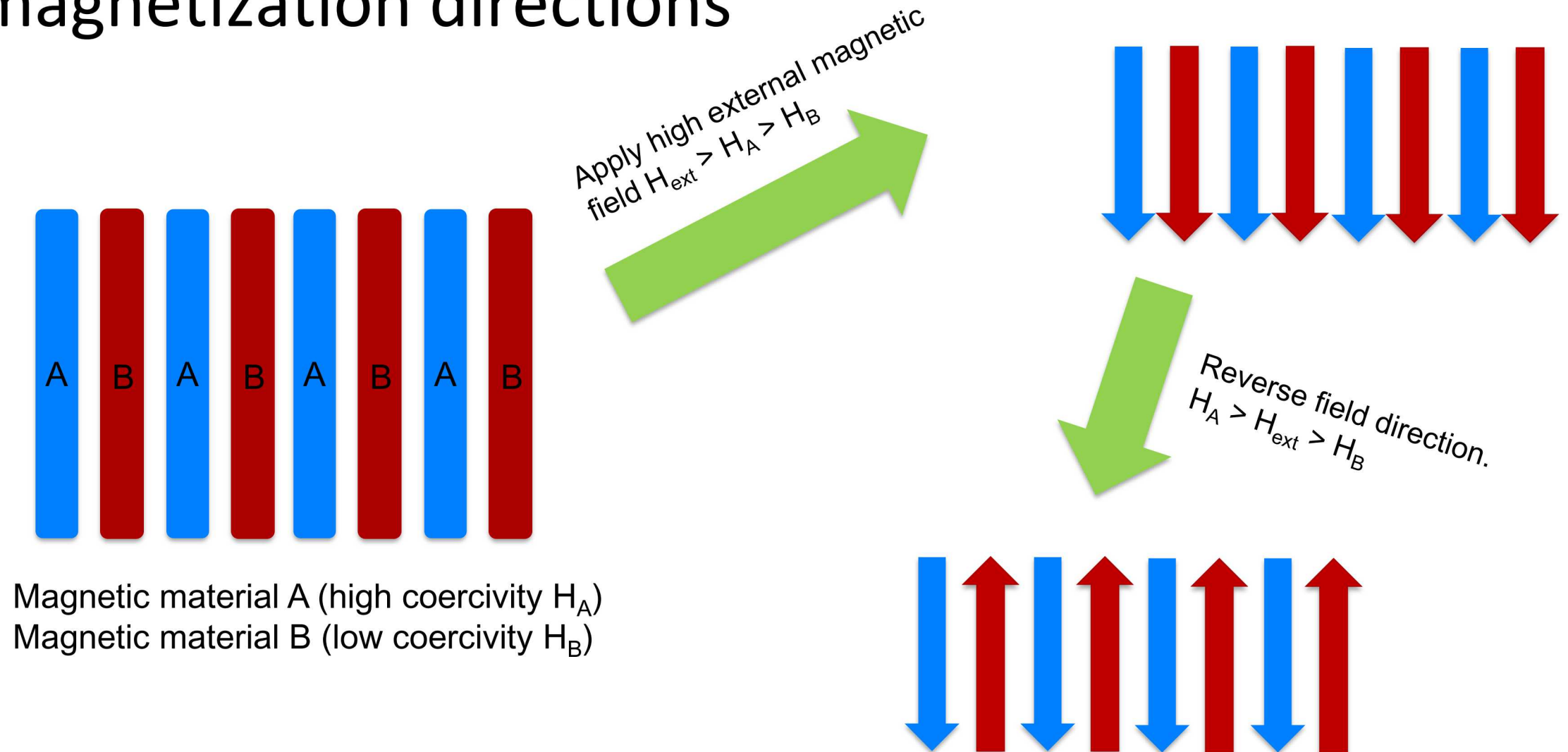


Effective spin-orbit gaps in Si/SiGe



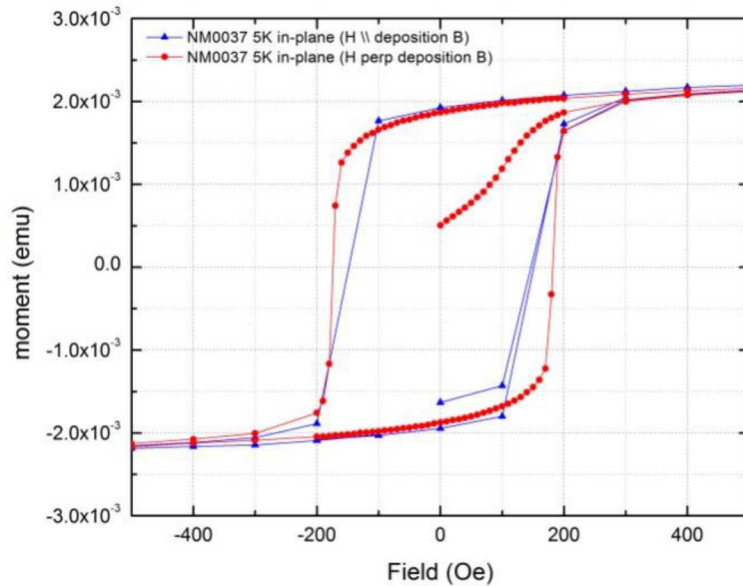
The effective spin-orbit gaps are experimentally accessible using dilution refrigerators.

Realizing nano-magnet arrays with alternating magnetization directions

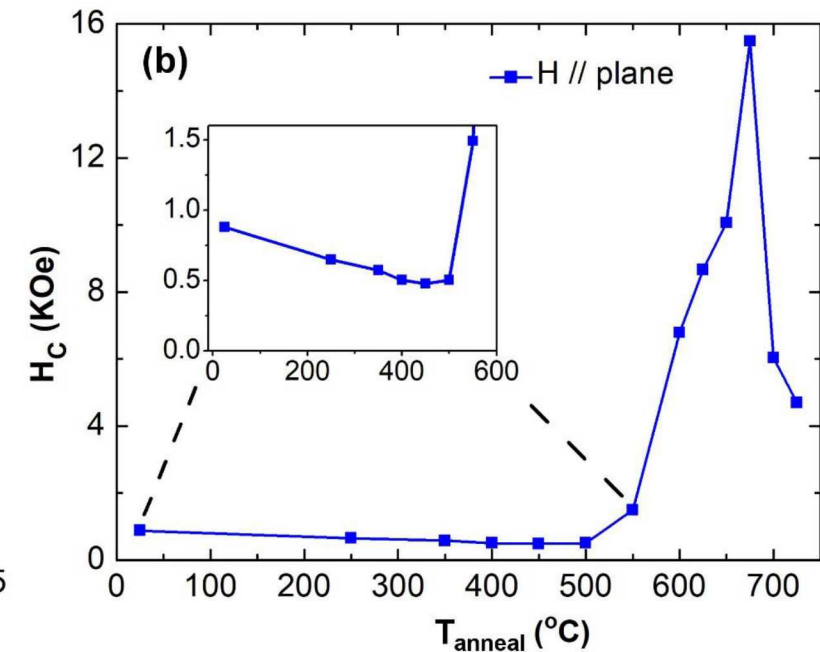
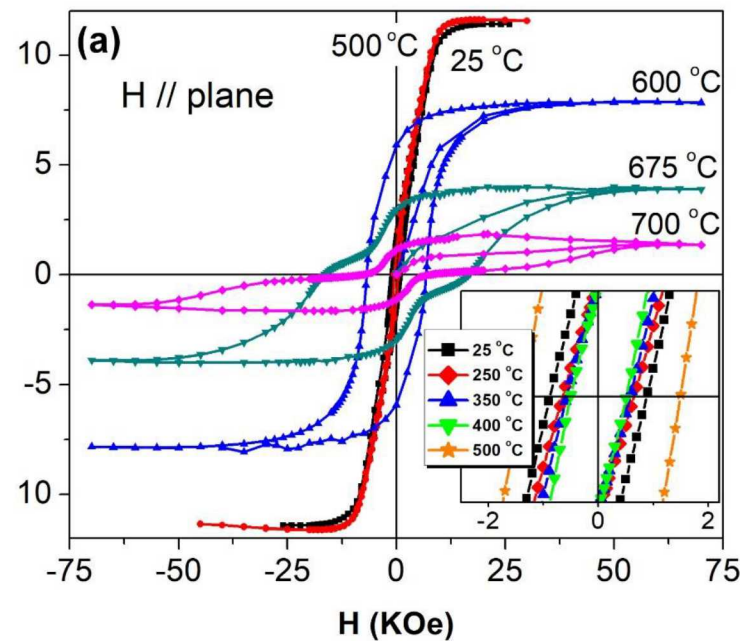


Magnetic materials with high coercivity contrast

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

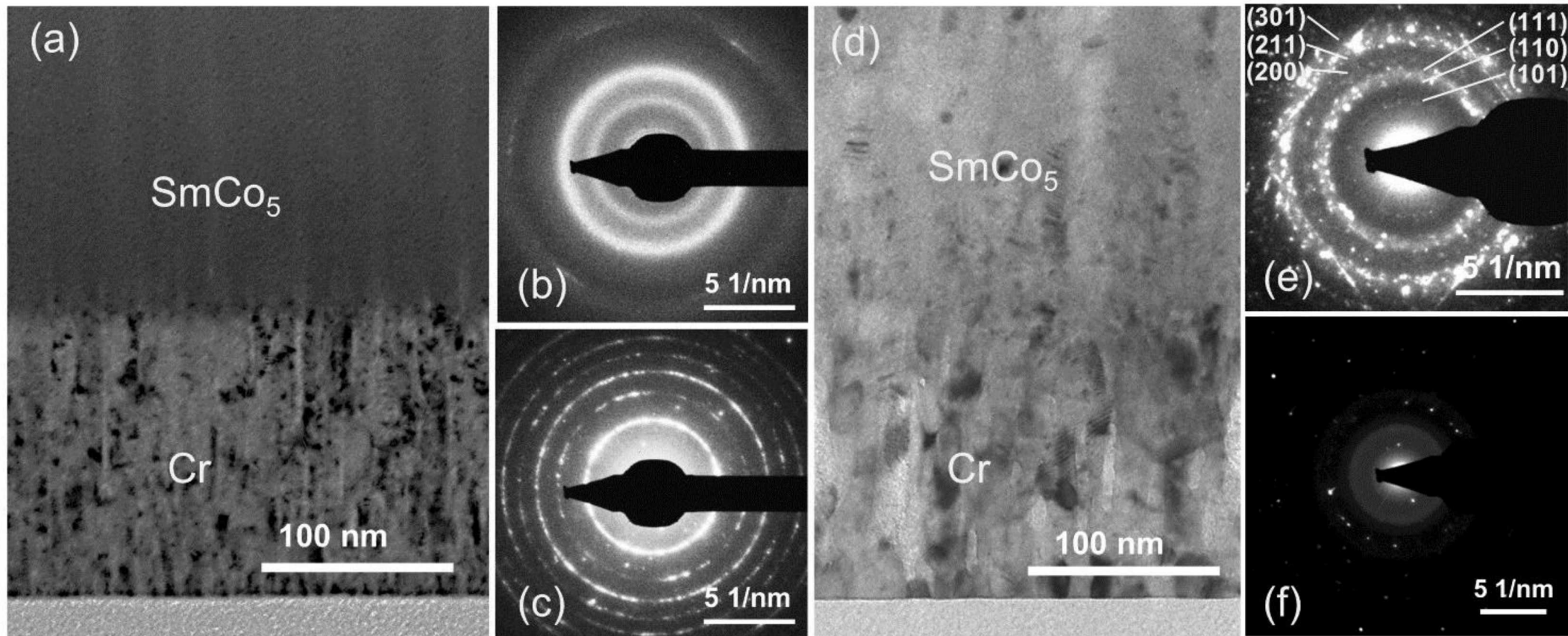


High-coercivity (~ 10000 Oe) SmCo_5 films obtained after post-deposition annealing

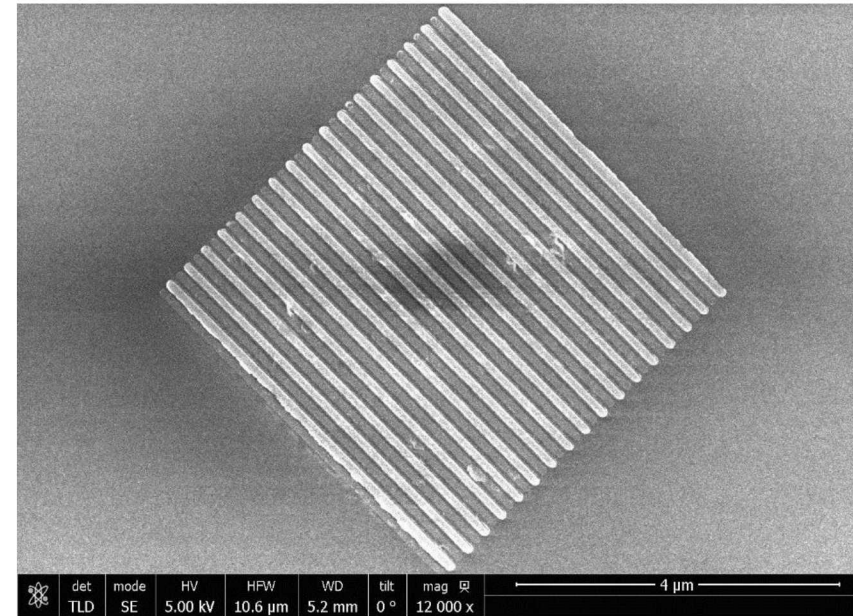
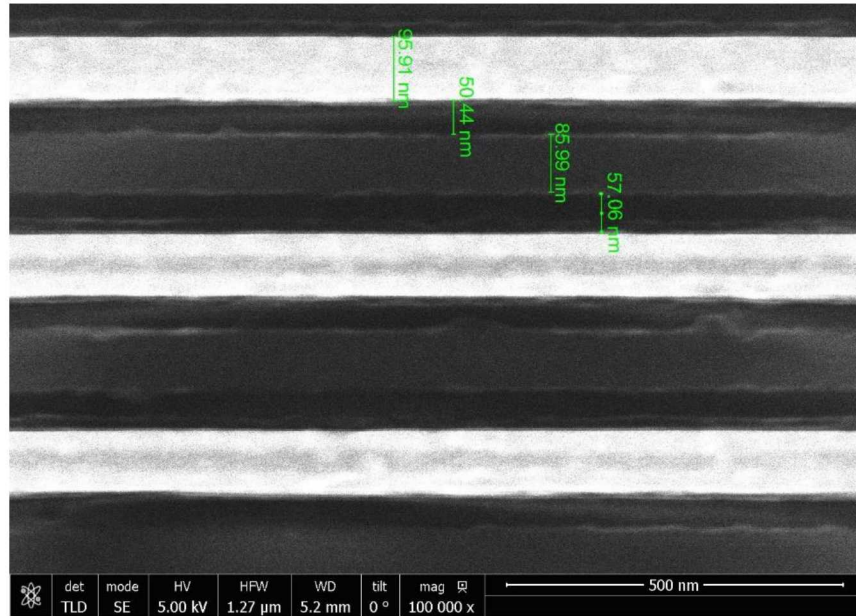


Magnetic materials with high coercivity contrast Sandia National Laboratories

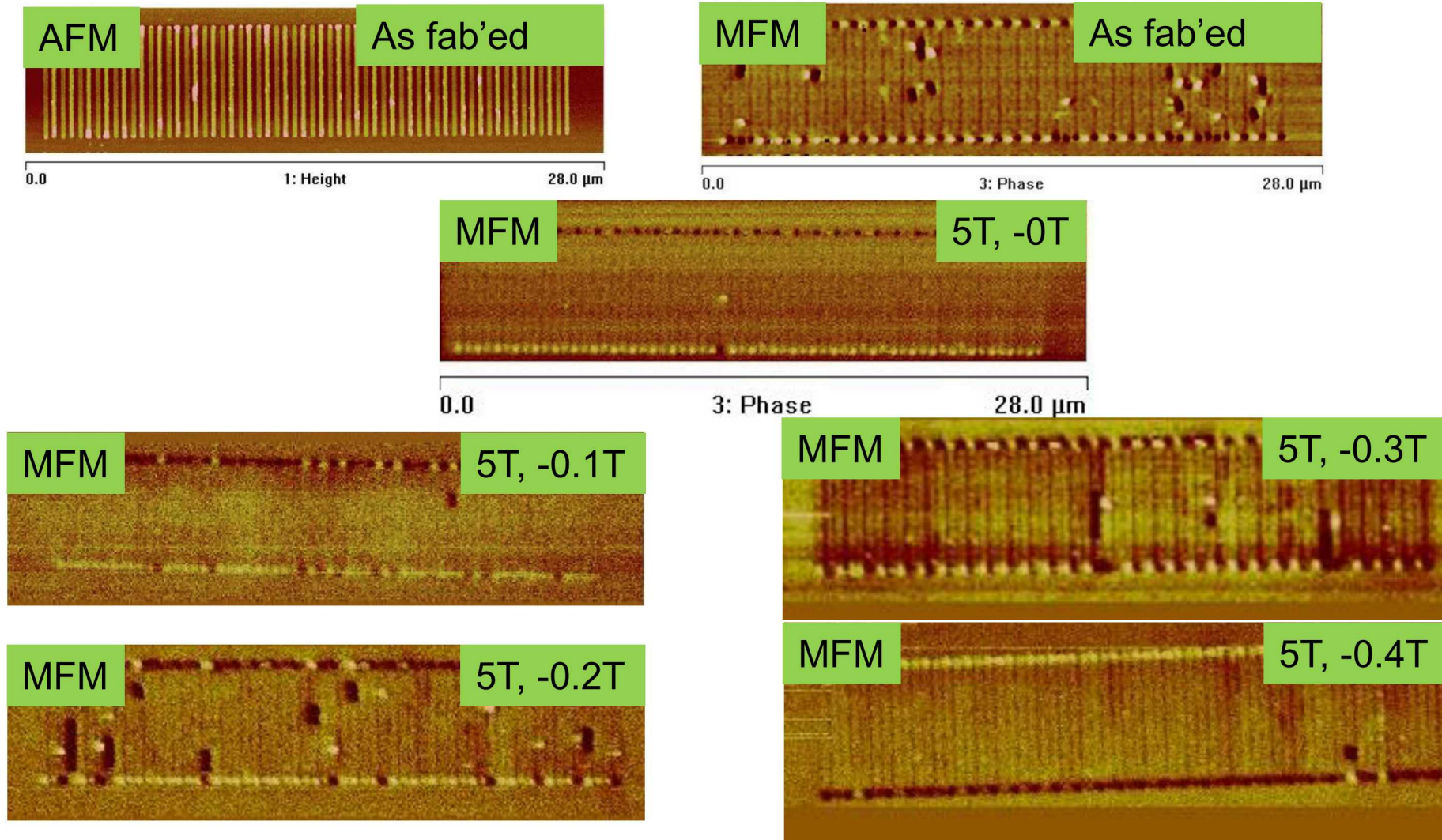
Crystallization of SmCo_5 leads to high coercivity.



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.

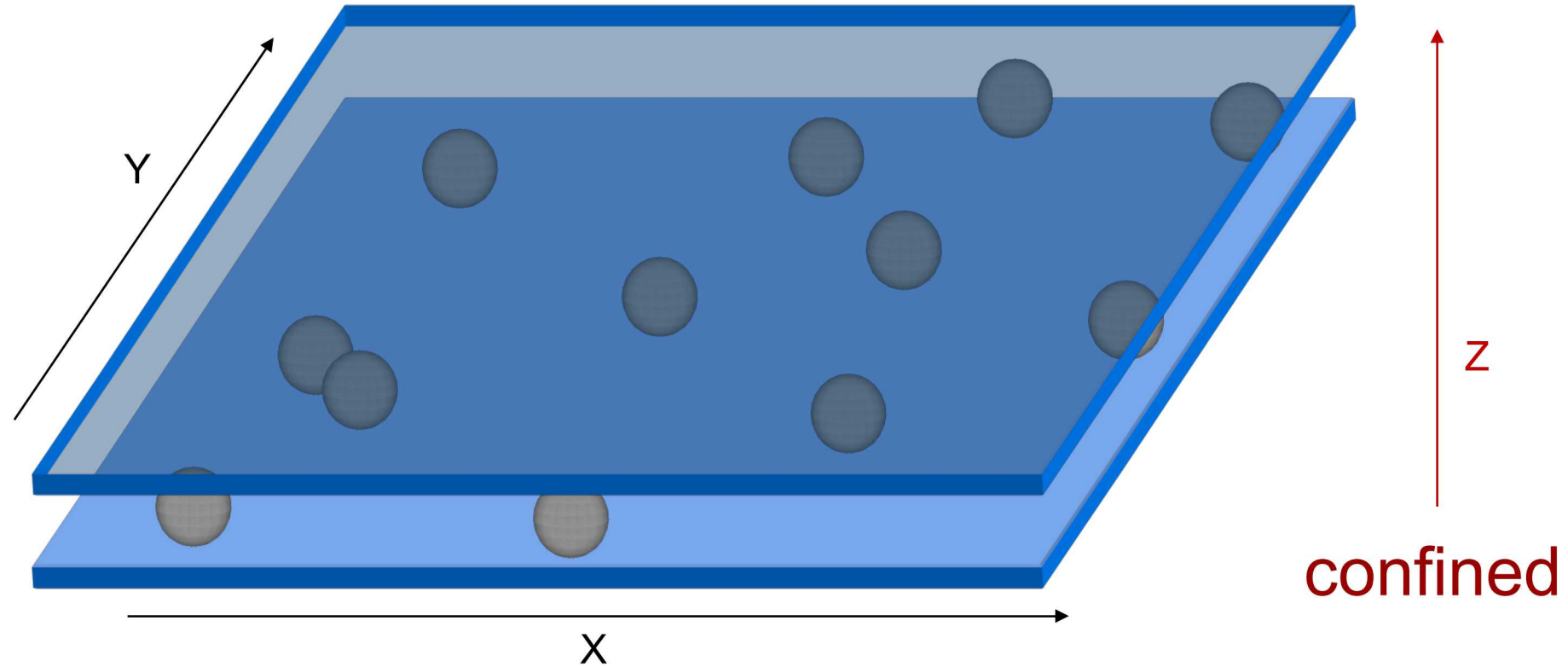
Questions to be answered

- 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.

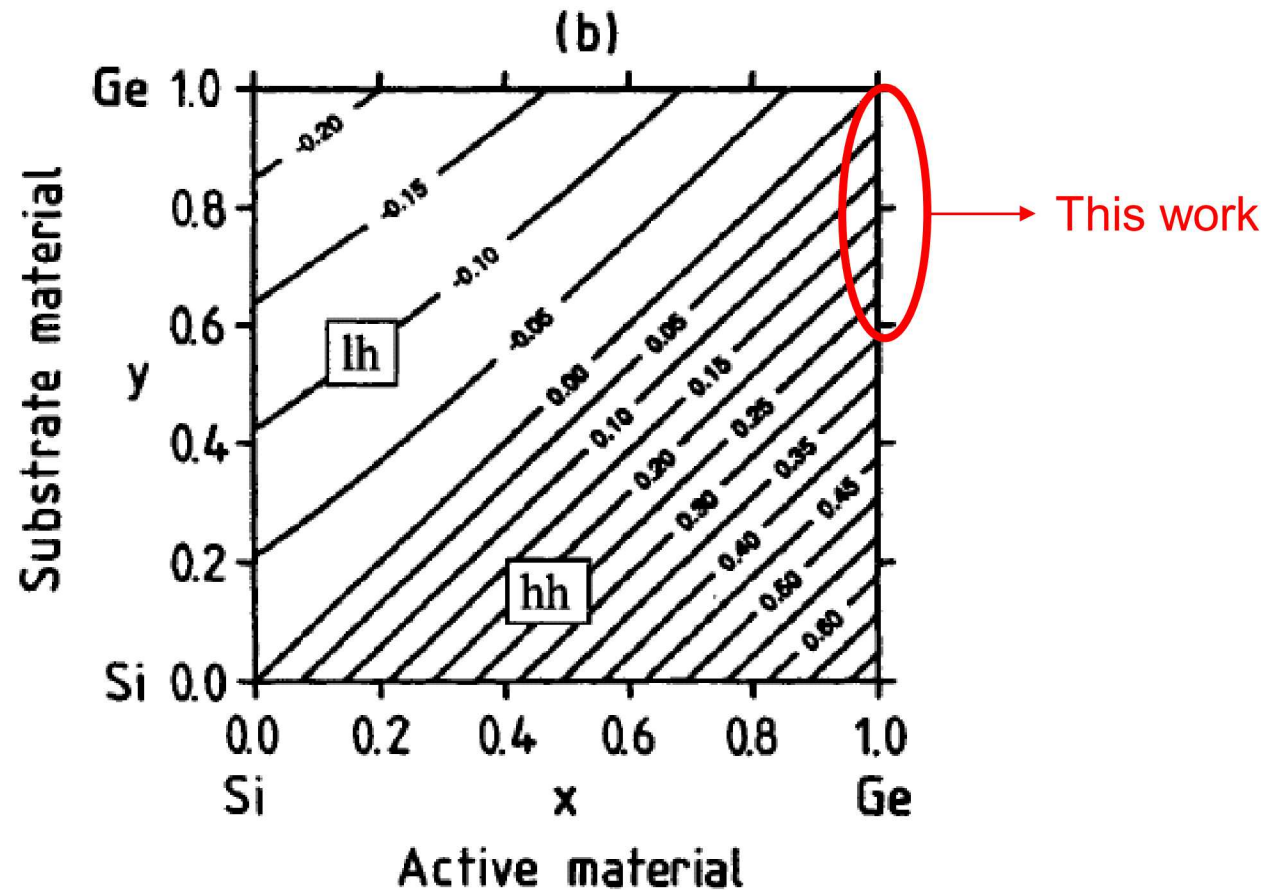
Outline

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

2D holes

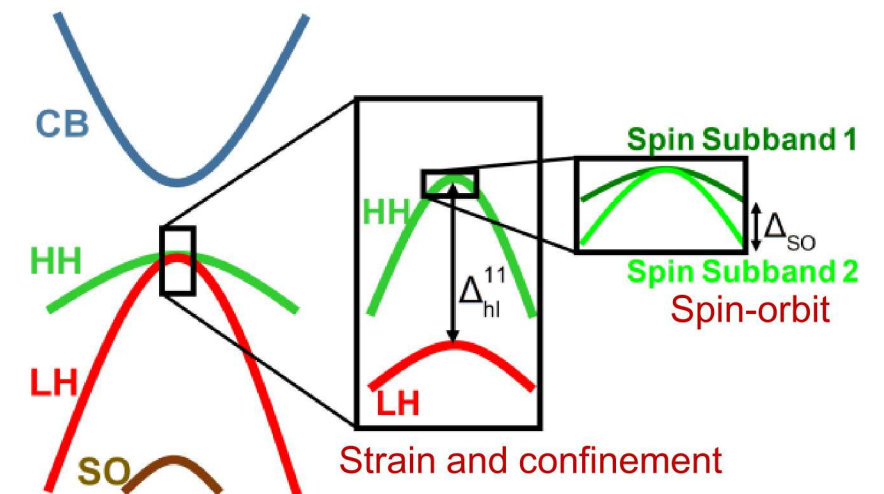
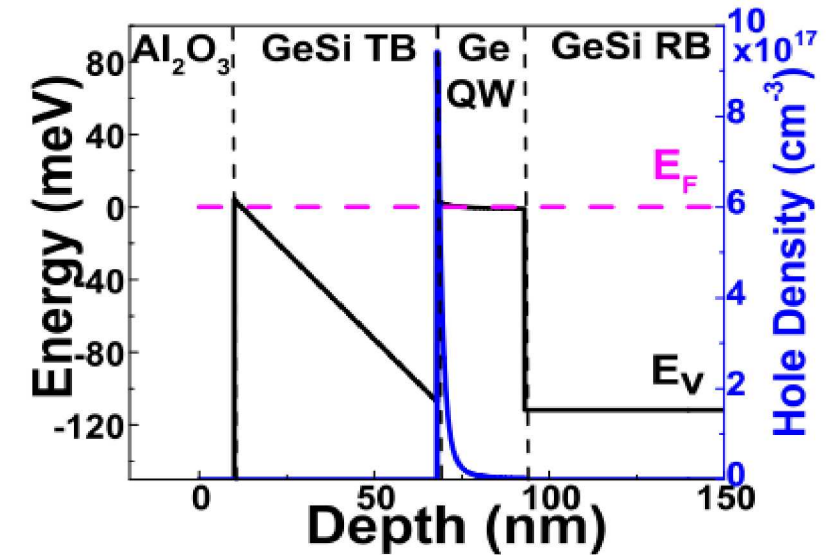
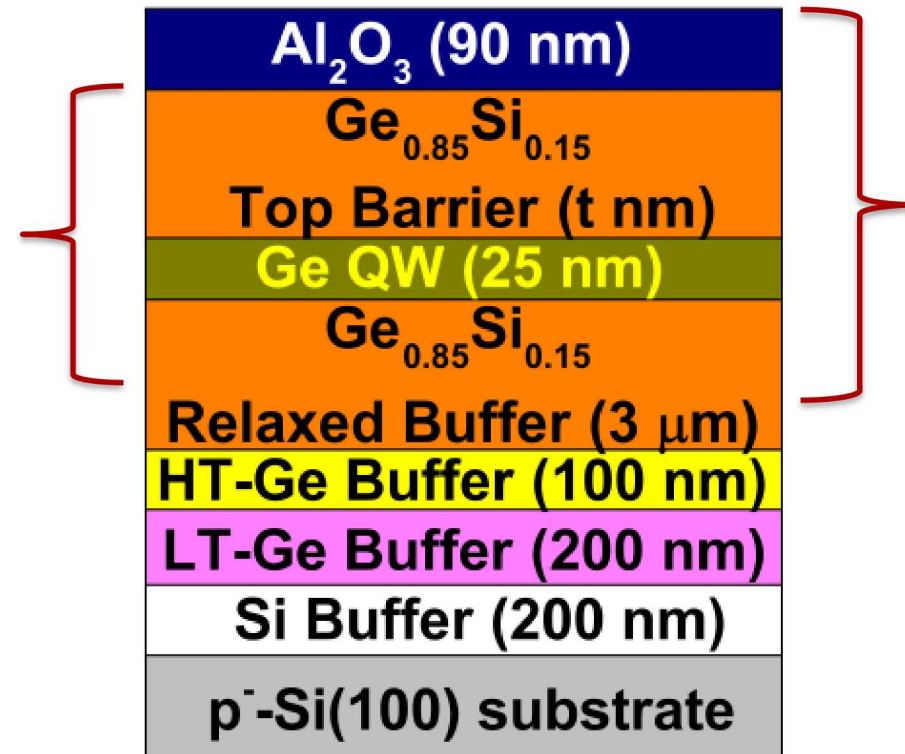
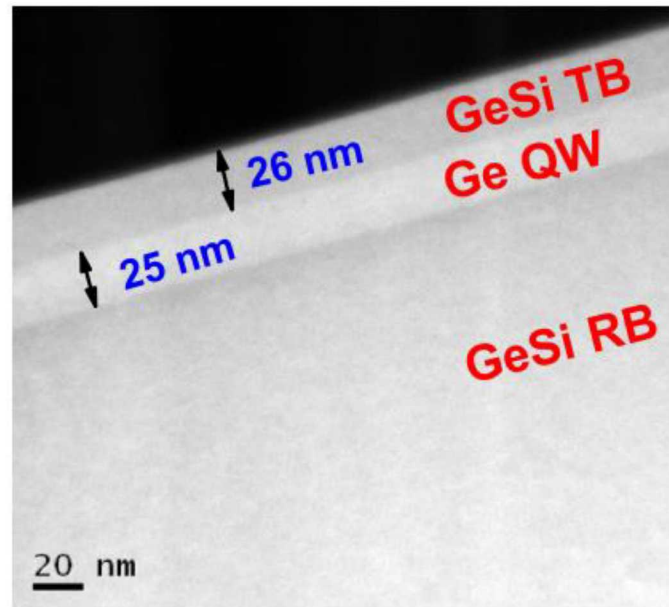


Band alignment of SiGe heterostructures



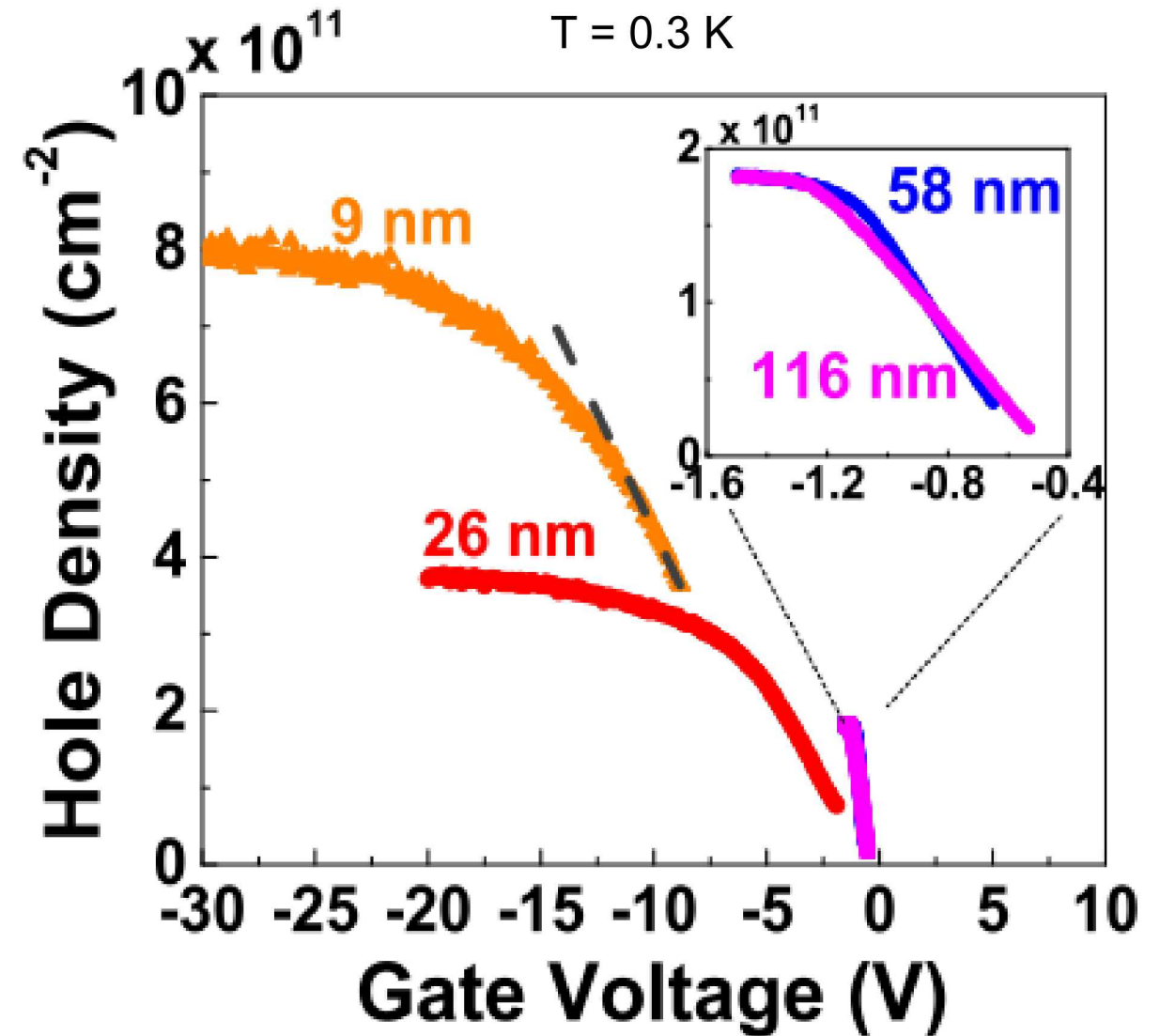
Valance band
2D holes in Ge quantum wells

Undoped Ge/SiGe heterostructure field-effect transistors

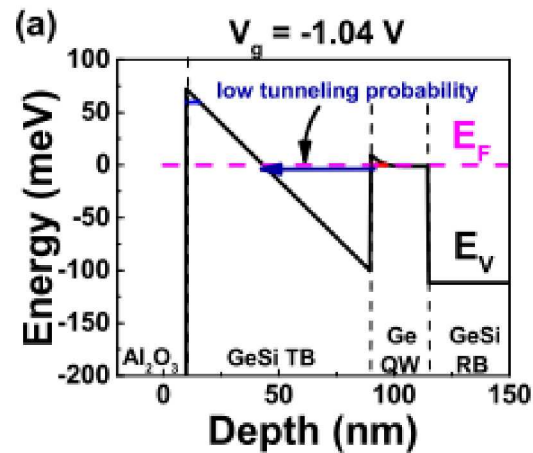


Device operation – 2D hole density

- 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)



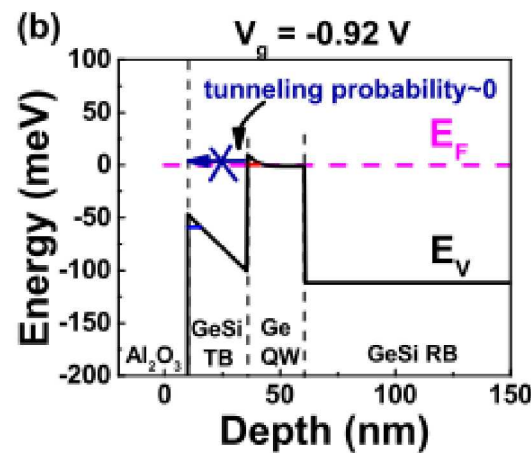
Device operation – 2D hole density



Deep channels

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

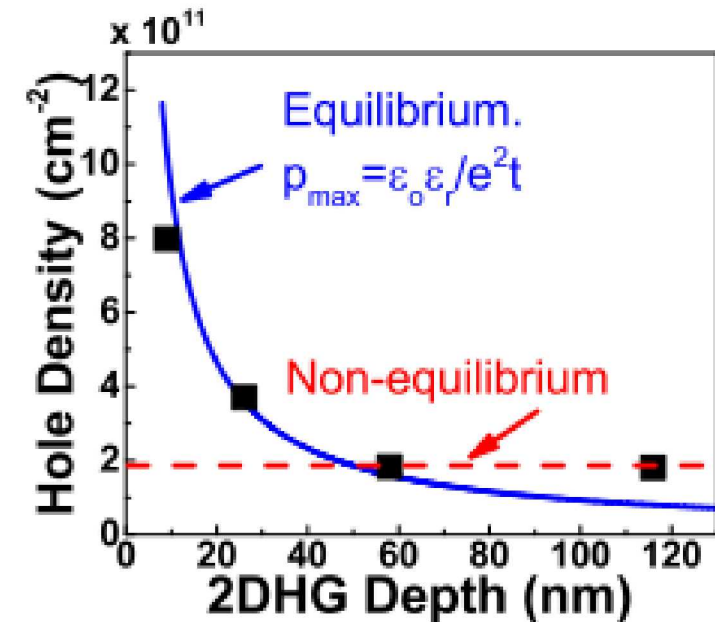
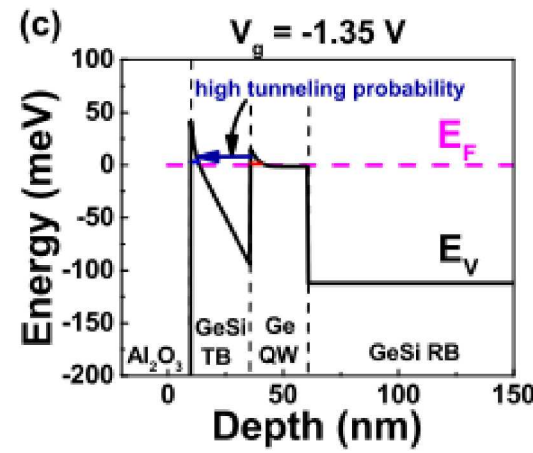
The tunnel rate can be so low that the density only slowly decreases and never reaches equilibrium at low temperatures!



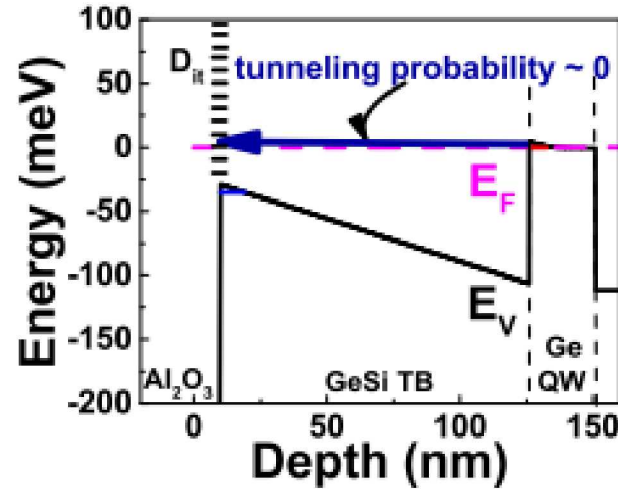
Shallow channels

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

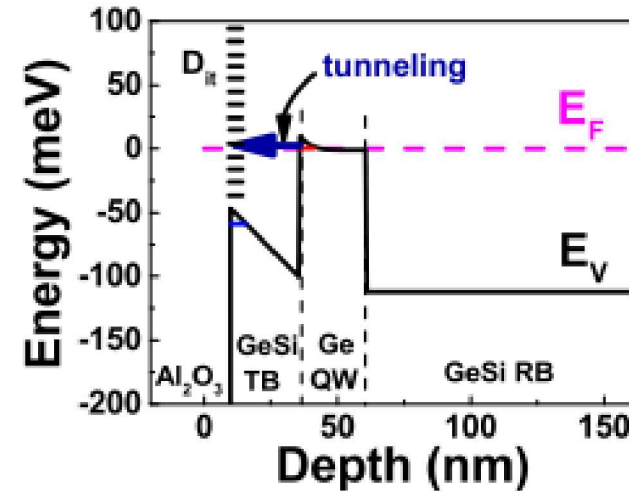


Deep channels

The tunnel rate is low.

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

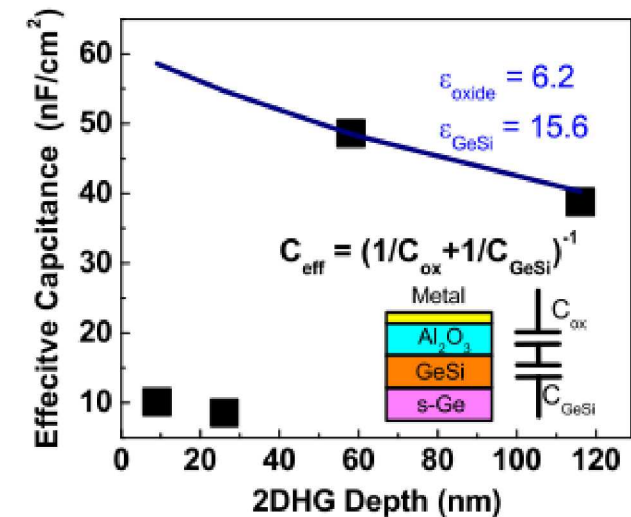
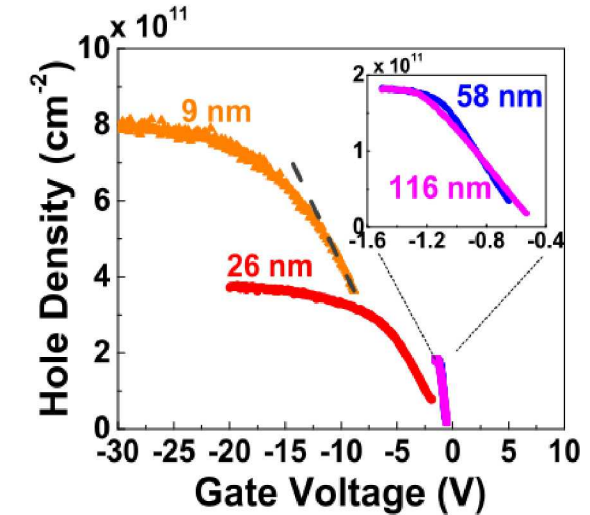
$$C_{\text{eff}} \sim C_{\text{geometric}}$$



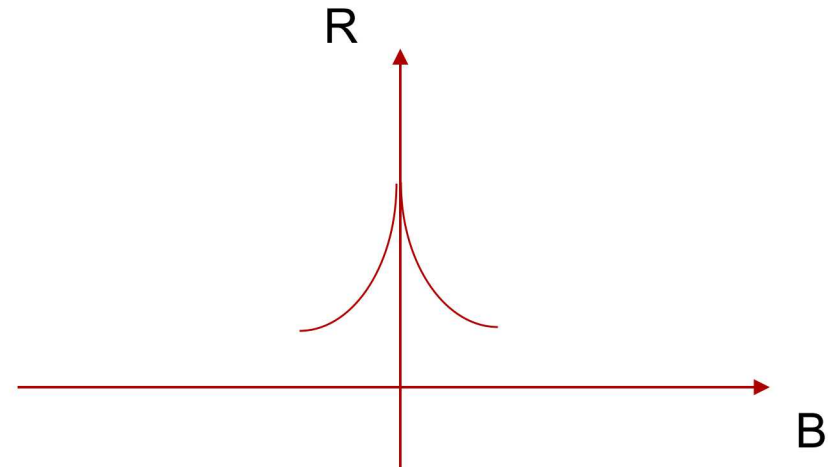
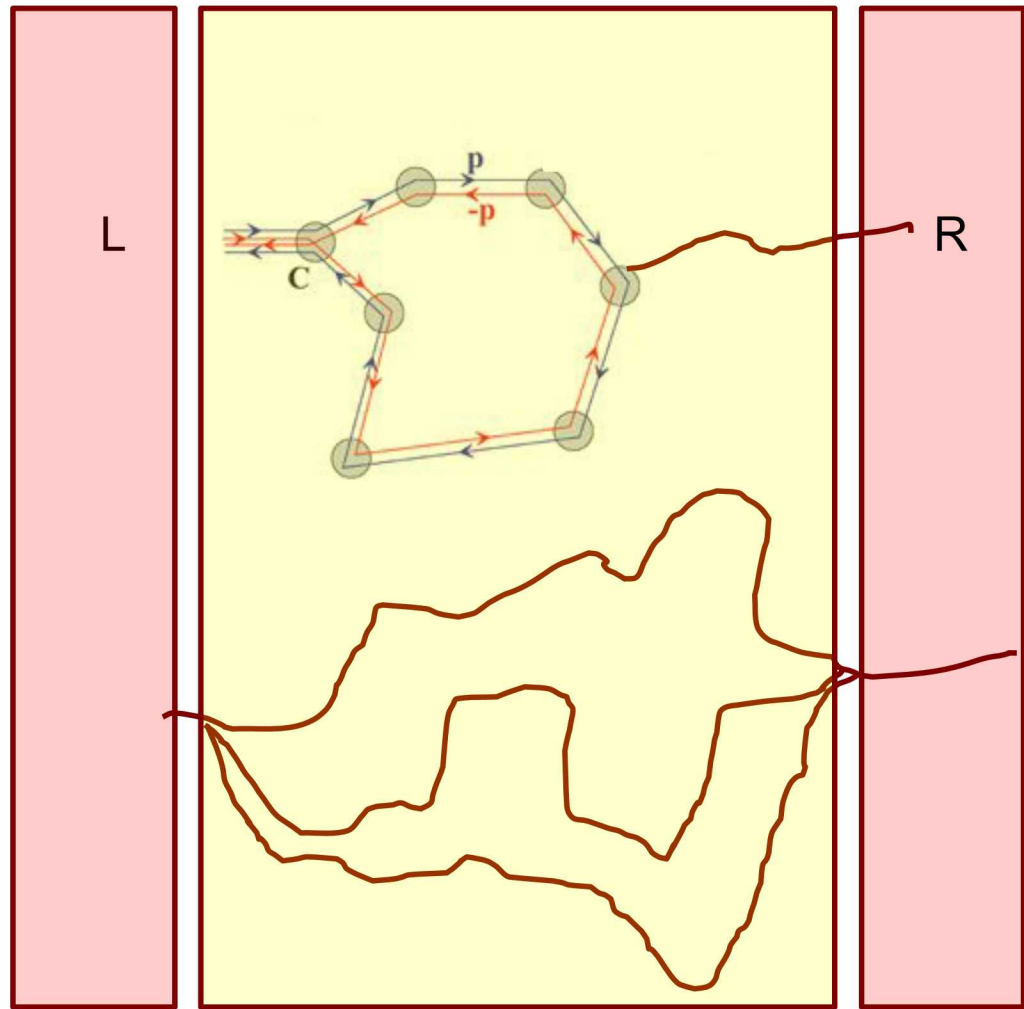
Shallow channels

The tunnel rate is high.

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

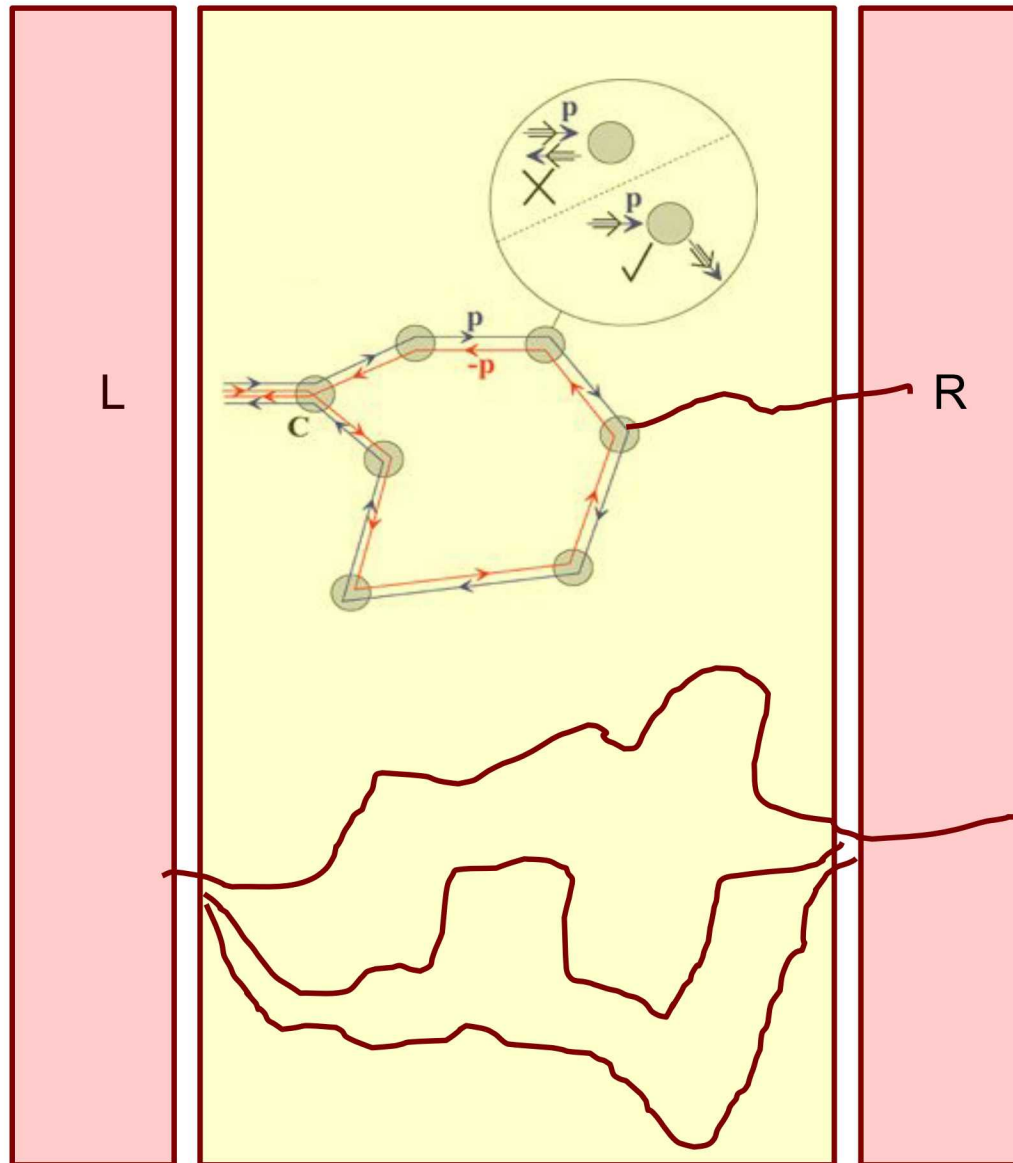


Weak localization (no spin-orbit coupling)

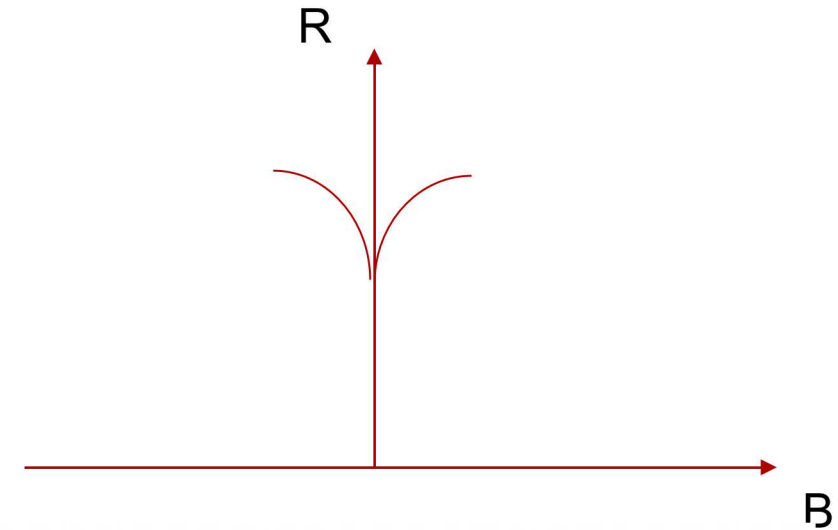


Adapted from McCann Physics 2, 98

Weak anti-localization (spin-orbit coupling)



Spin and momentum are locked together.
Back scattering is suppressed.



$$\Delta\sigma(B) - \Delta\sigma(0) = \frac{e^2}{2\pi^2\hbar} \left\{ \psi\left(\frac{1}{2} + \frac{H_\varphi}{B} + \frac{H_{SO}}{B}\right) + \frac{1}{2} \psi\left(\frac{1}{2} + \frac{H_\varphi}{B} + \frac{2H_{SO}}{B}\right) - \frac{1}{2} \psi\left(\frac{1}{2} + \frac{H_\varphi}{B}\right) - \ln \frac{H_\varphi + H_{SO}}{B} - \frac{1}{2} \ln \frac{H_\varphi + 2H_{SO}}{B} + \frac{1}{2} \ln \frac{H_\varphi}{B} \right\}$$

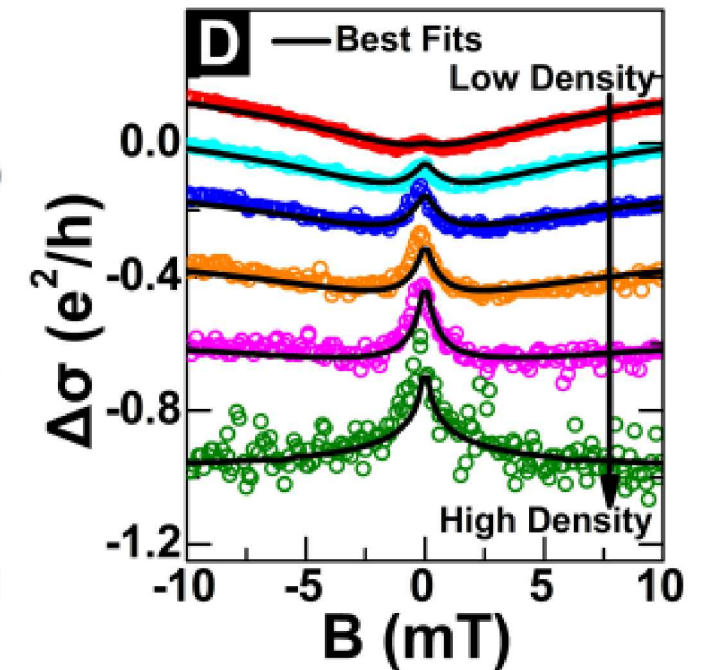
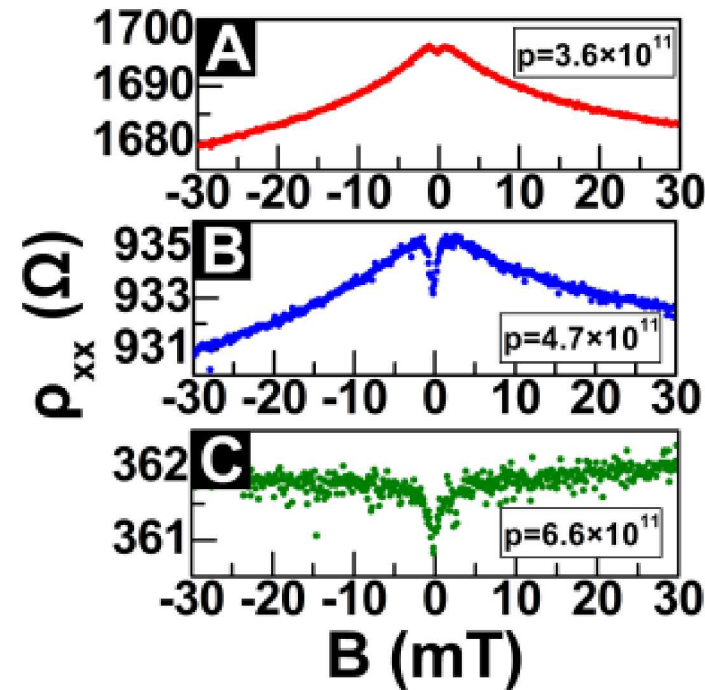
Hikami Prog. Theor. Phys. 63, 707

Adapted from McCann Physics 2, 98

Physical properties – spin-orbit coupling

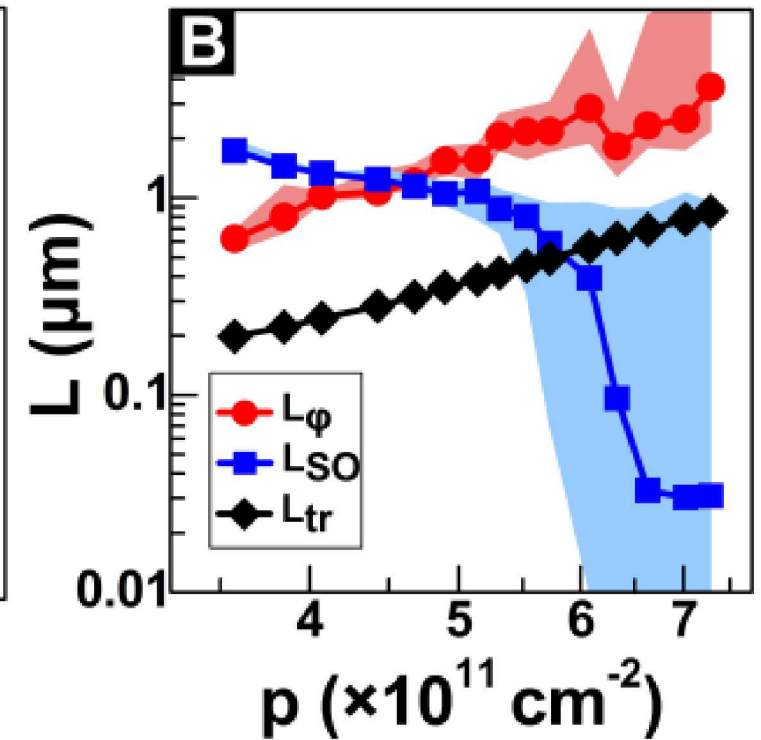
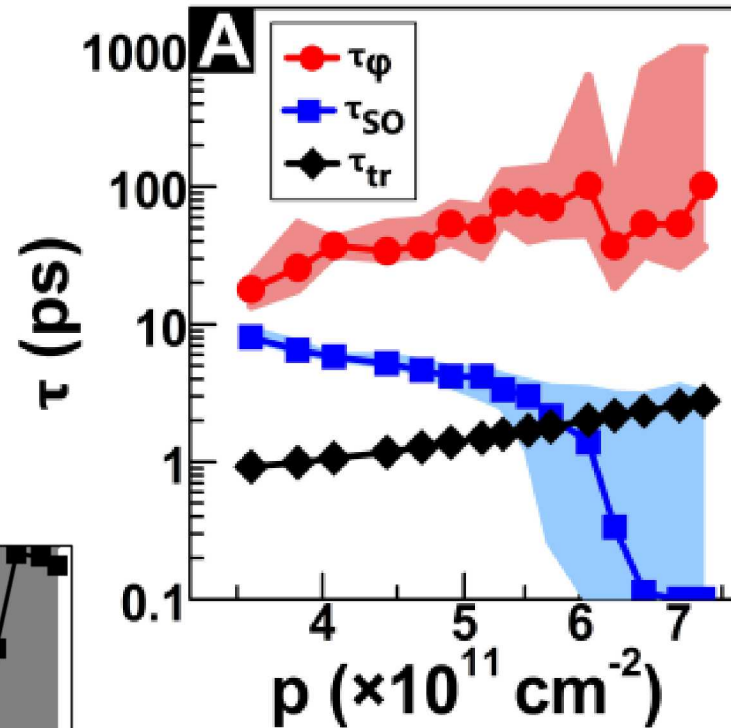
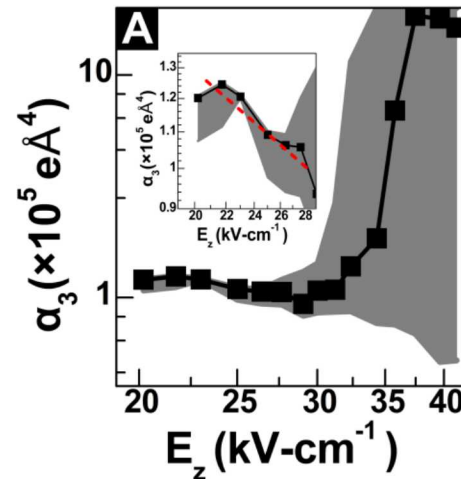
- Low densities
 - Weak localization only
- Intermediate densities
 - Weak anti-localization on top of weak localization only
- High densities
 - Weak anti-localization only

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



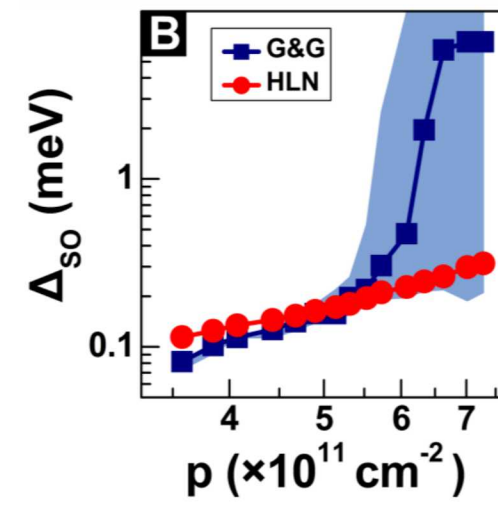
Physical properties – spin-orbit coupling

- 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.



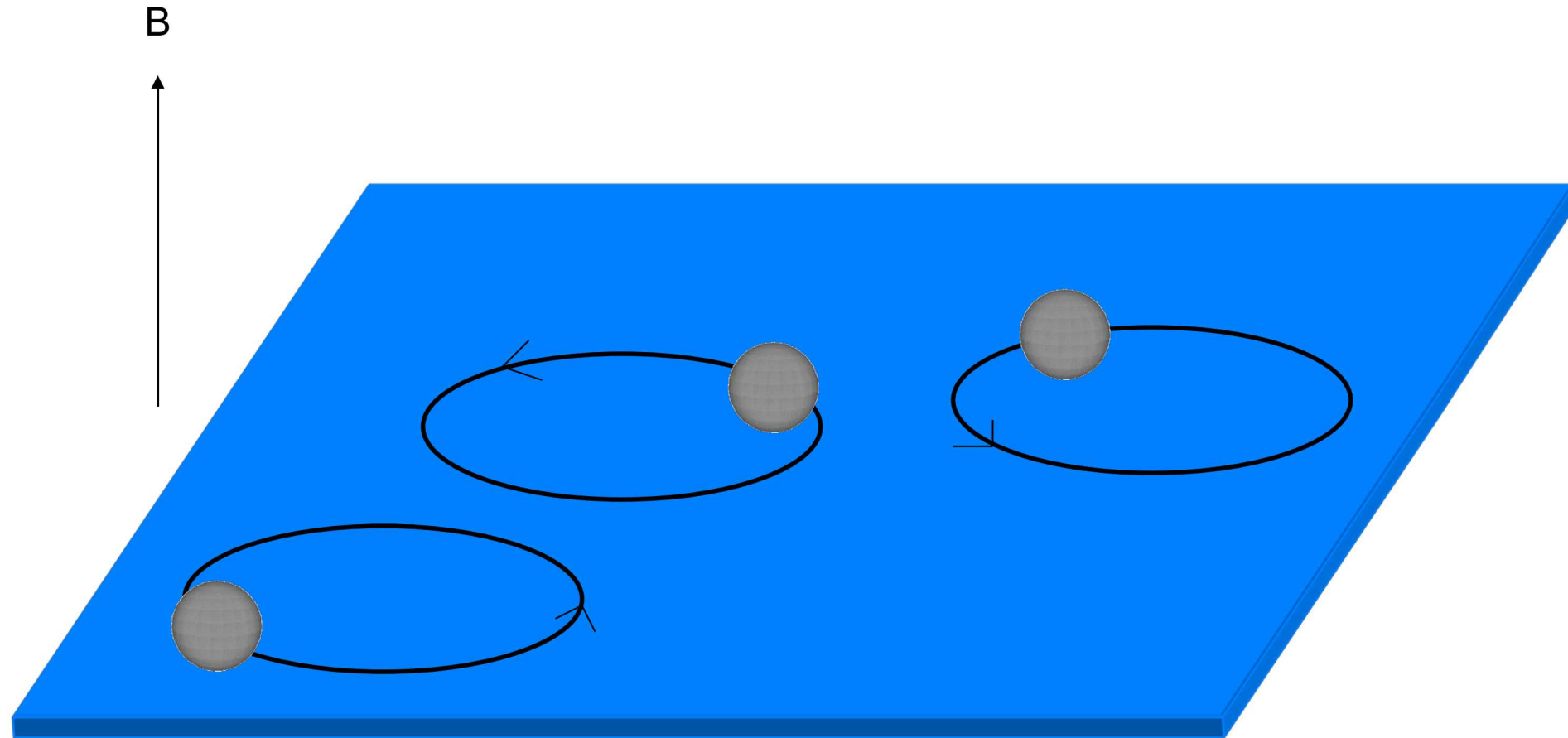
Physical properties – weak antilocalization beyond diffusive regime

- 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)

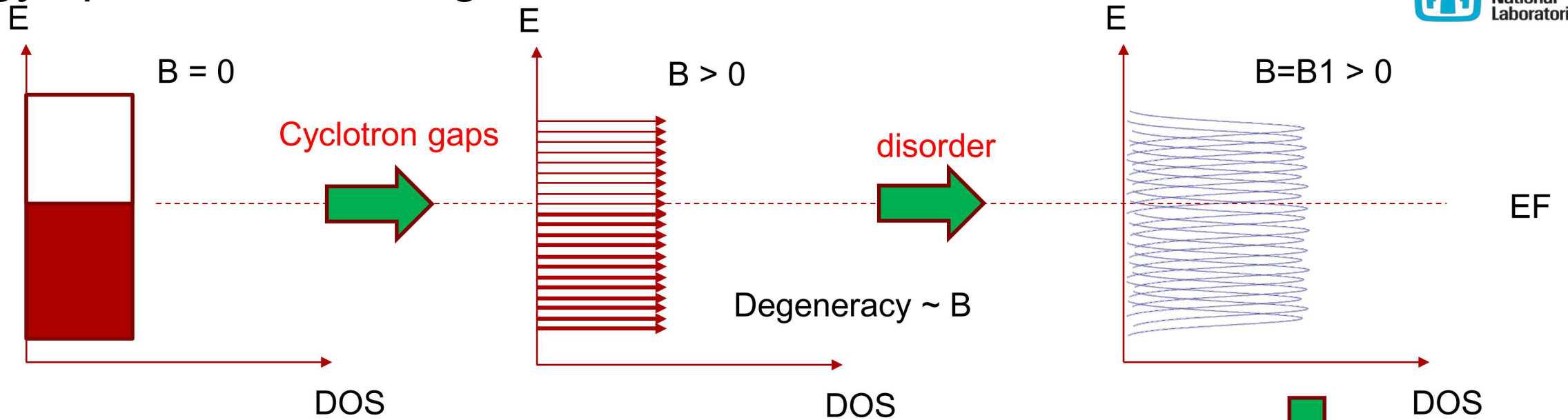
In a perpendicular magnetic field...



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

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

Energy spectrum in a magnetic field



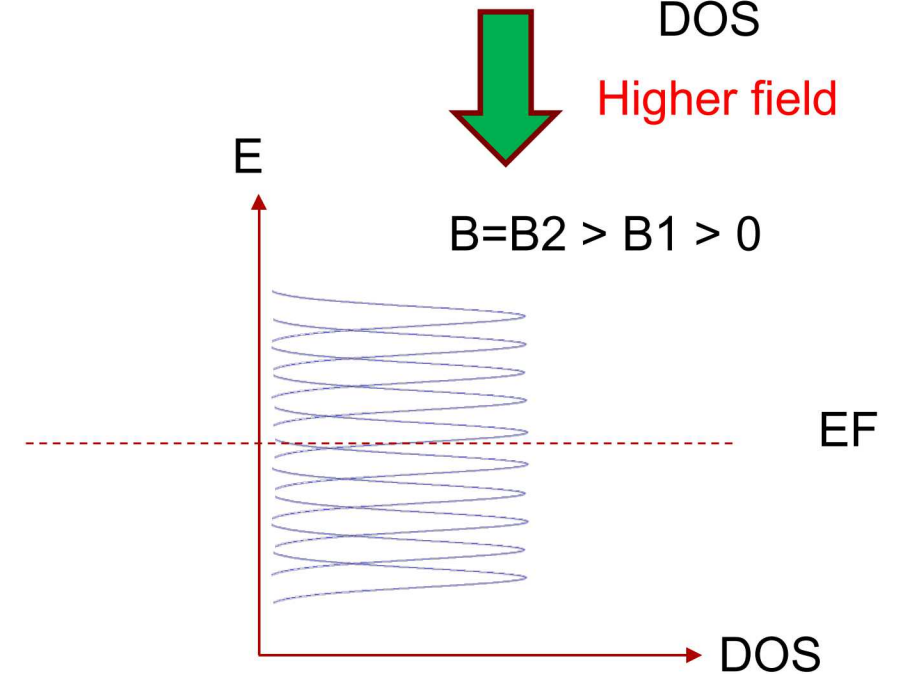
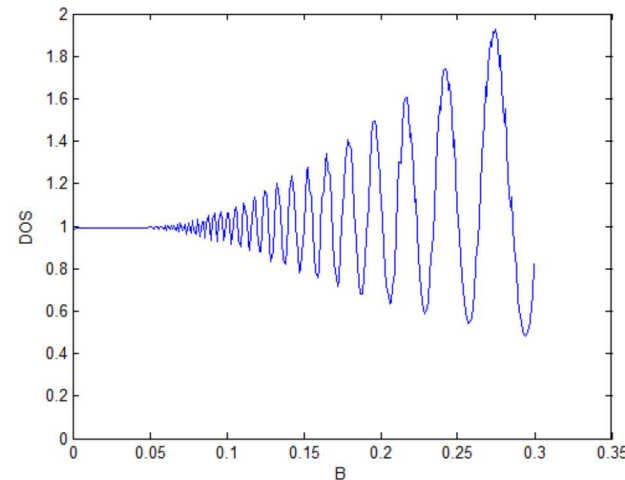
$$\frac{\Delta \rho}{\rho_0} \sim D(X) \frac{\Delta \text{DOS}}{\text{DOS}_0}$$

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

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

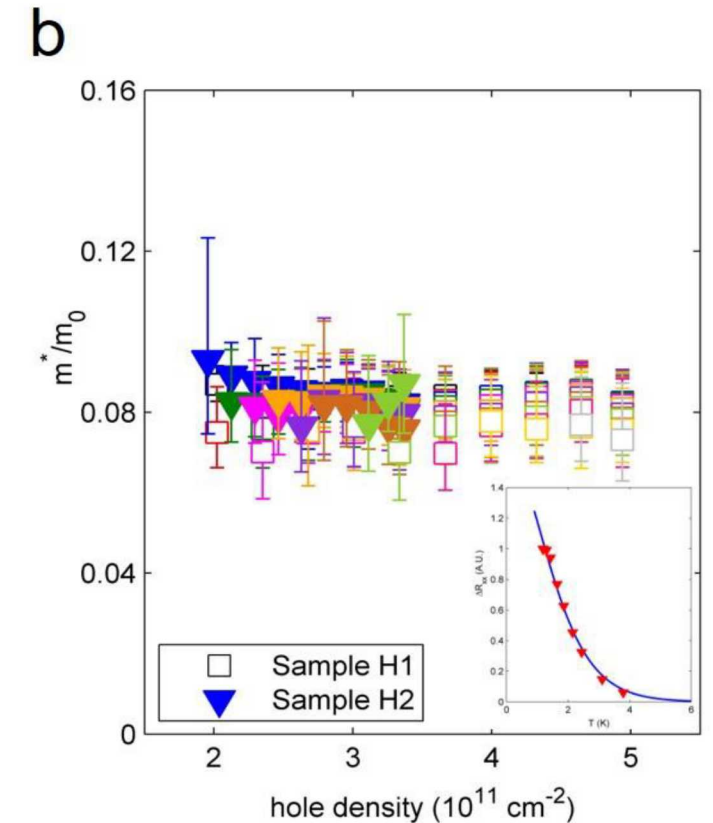
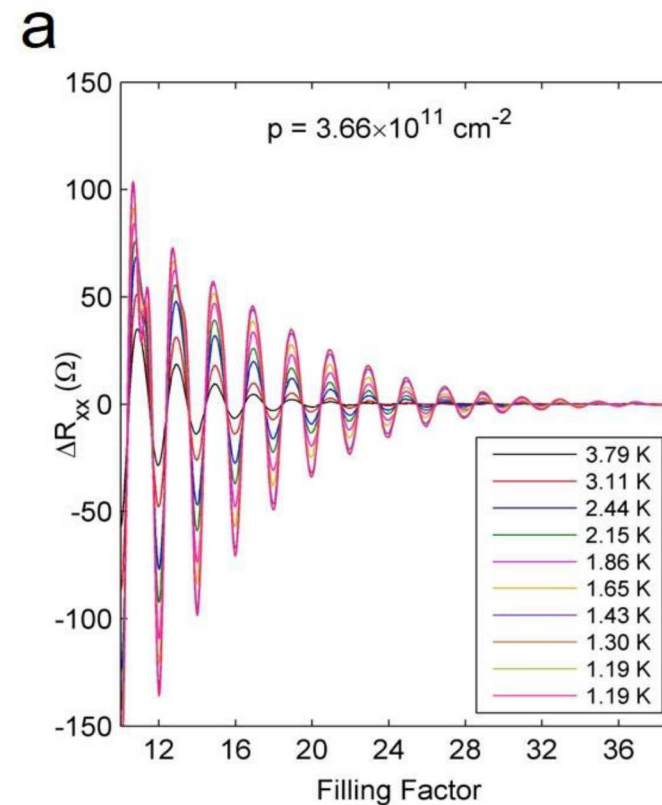
Temperature dependence
 $\Leftrightarrow$ cyclotron gap

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

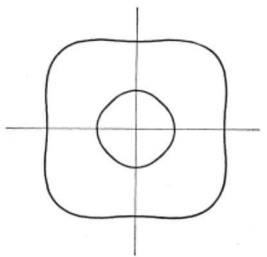
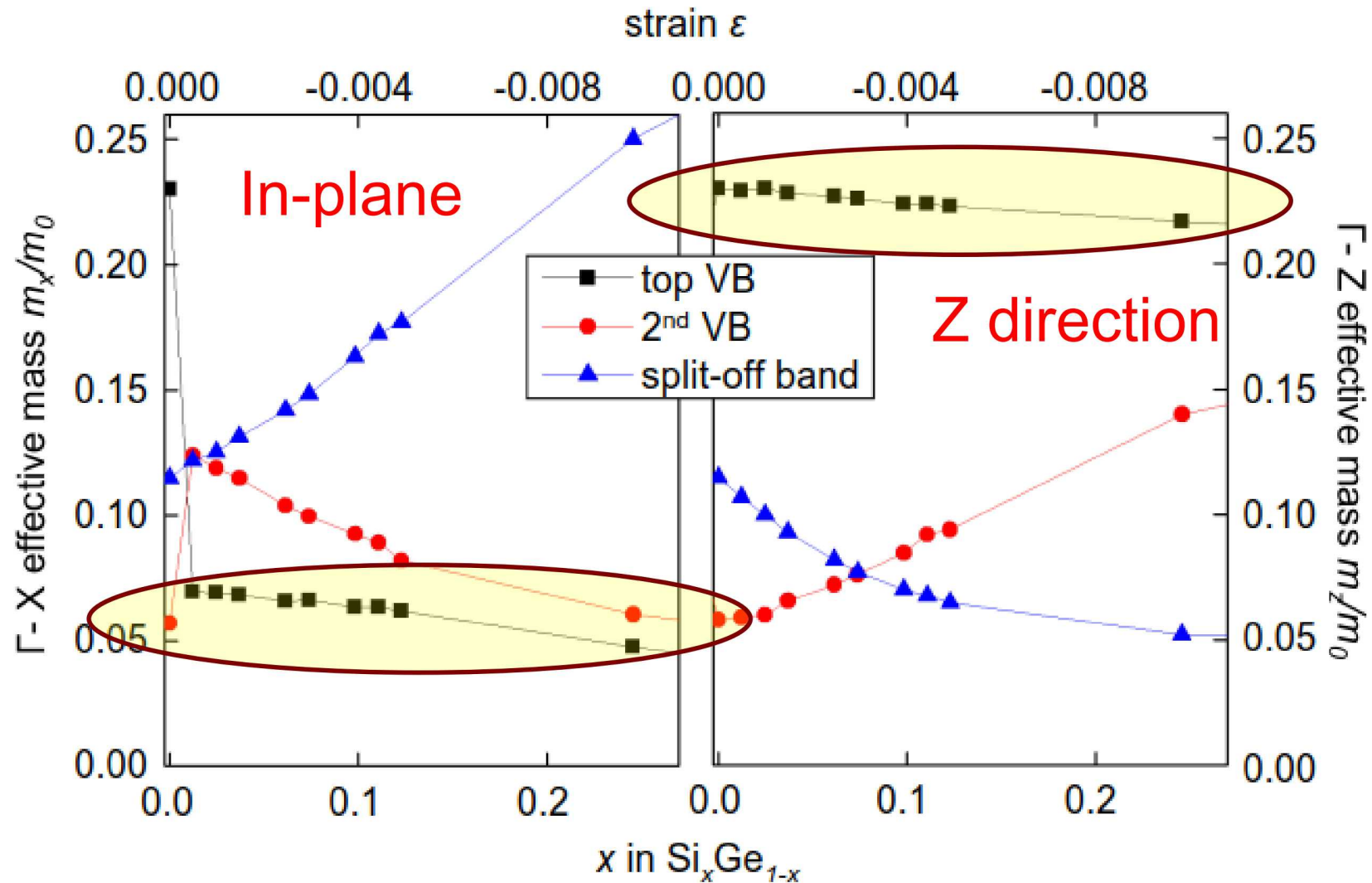
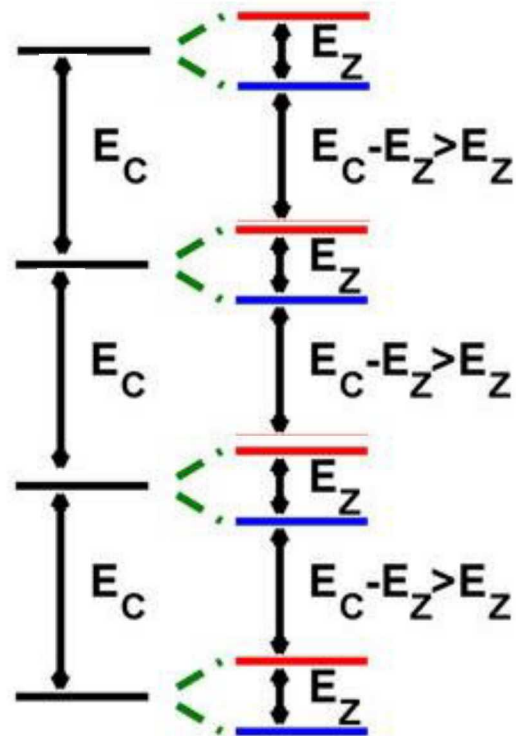


FIG. 8. Figures of constant energy in the (100) plane of k -space for the two fluted energy surfaces which are degenerate at the valence band edge; constants as for germanium.

The quantum Hall effect

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



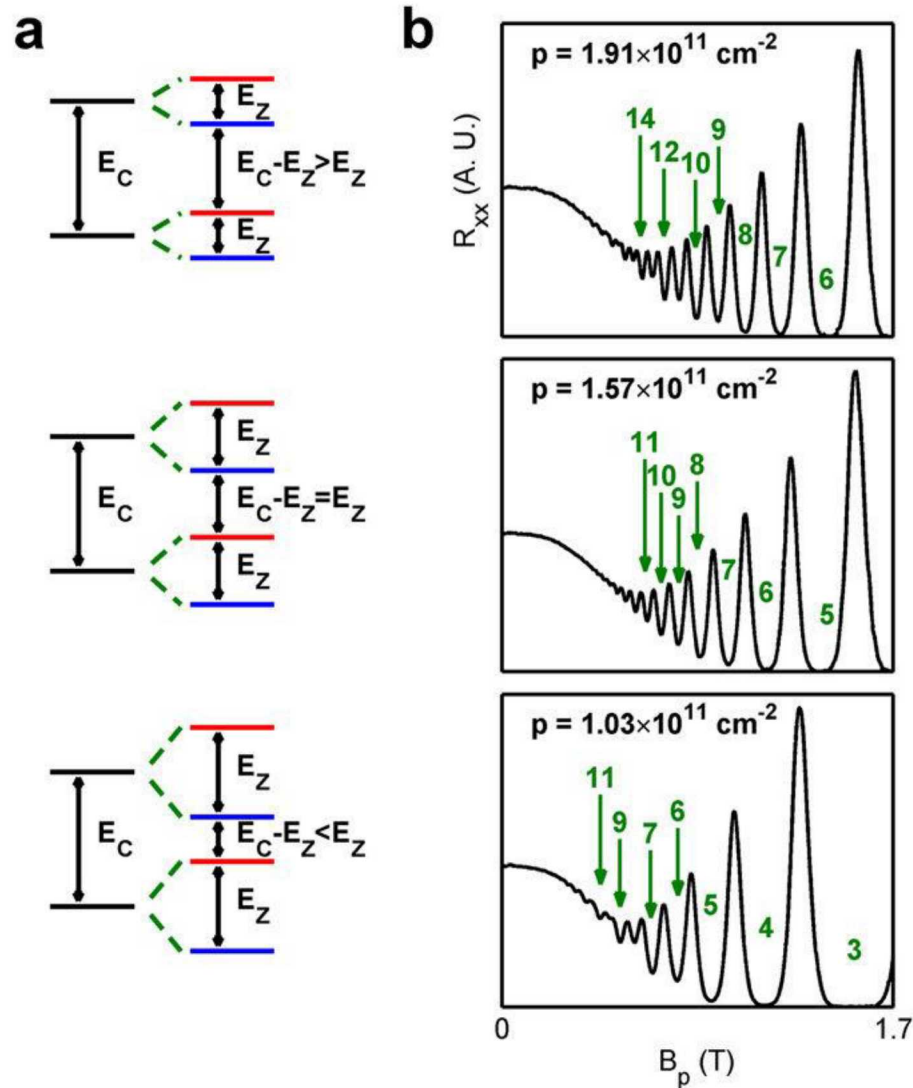
E_C is cyclotron gap: $\hbar e B / (2\pi m^*)$

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 $E_c \sim 2E_z$

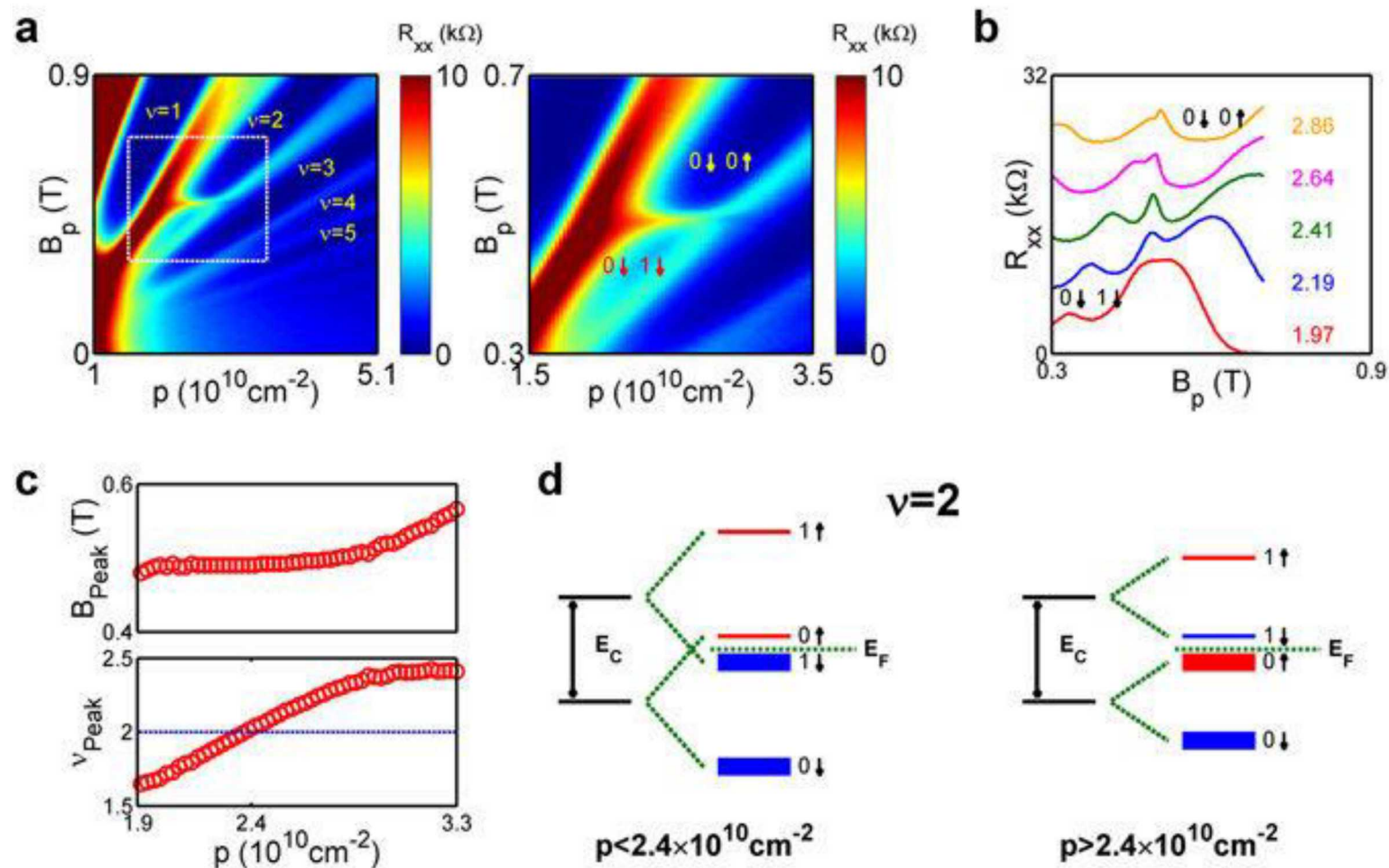
$\Rightarrow$ Strength of even states $\sim$ strength of odd states

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 $E_C \sim E_z$

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

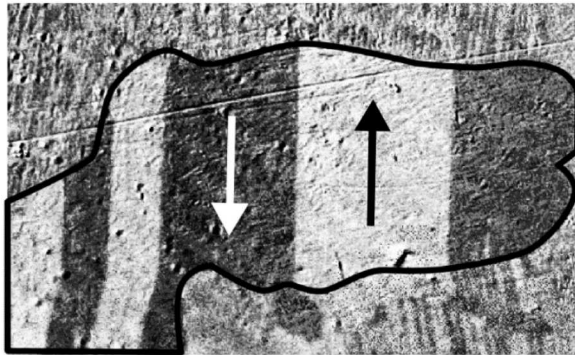
$$\Rightarrow m^* g^* = 2$$

Quantum Hall ferromagnetic transition

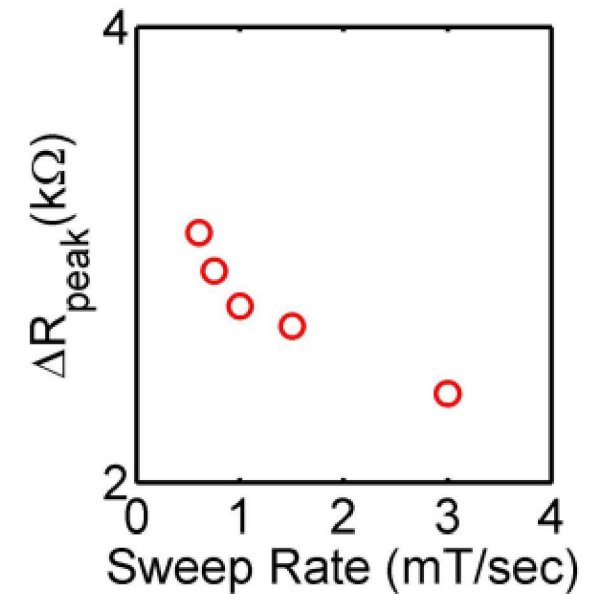
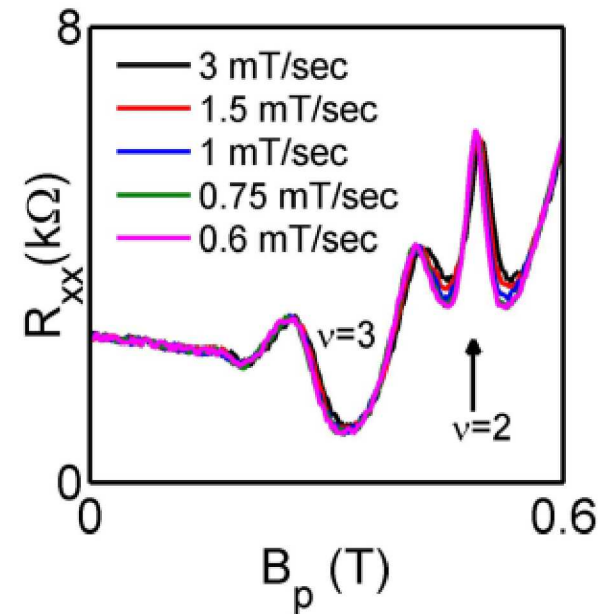
The physical picture of the system at the transition:

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

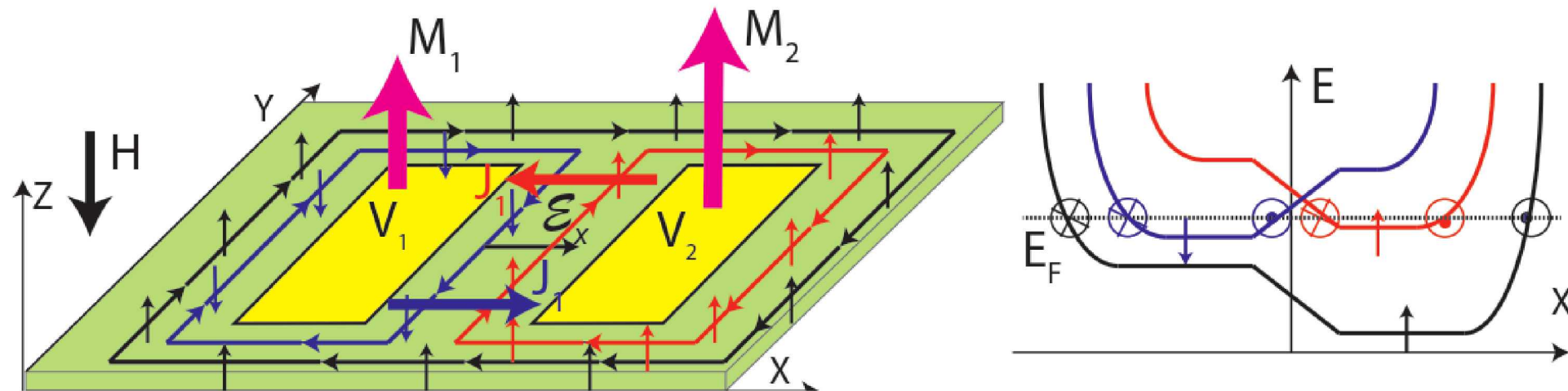
Evidence of micro-domains is found in the time dependence.



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



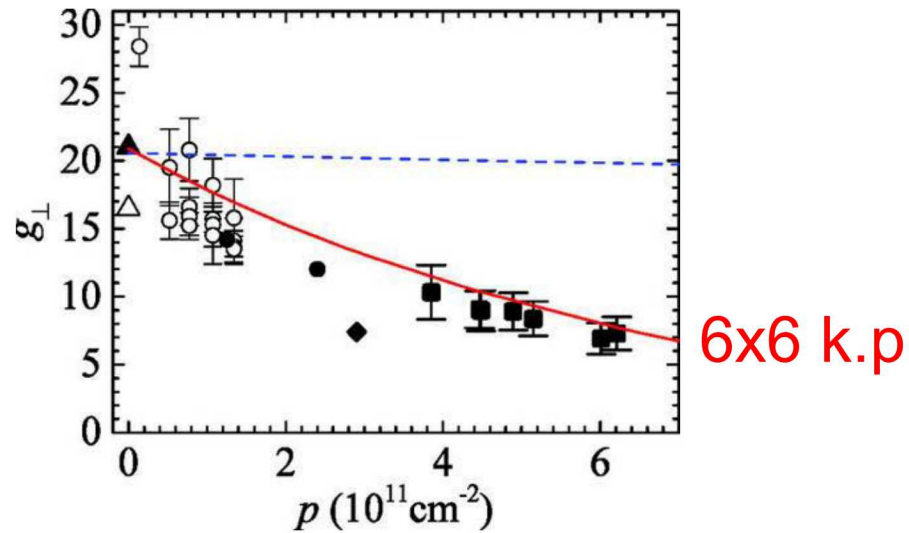
Local gating to create counter-propagating edge states with opposite spins



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

Physical properties – g factor

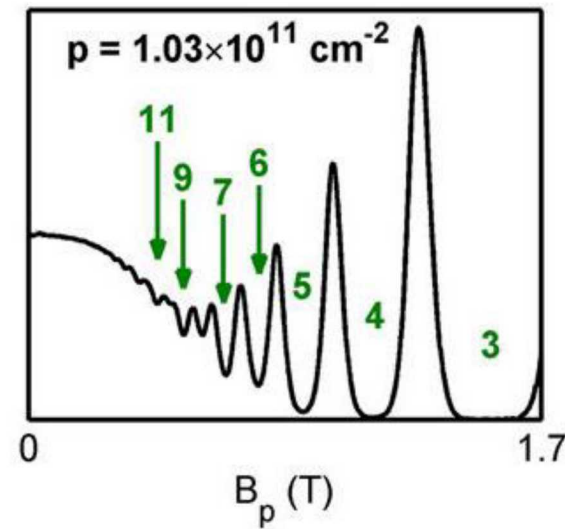
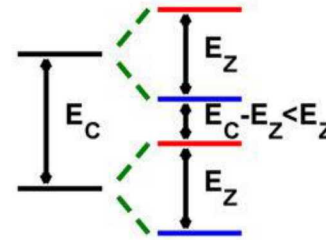
- $\sim 5 - 30$
- $\sim$ density dependent.
- The g factor is large compared to the g factor of electrons in Si (~ 2) and the g factor of electrons in GaAs (~ 0.44).



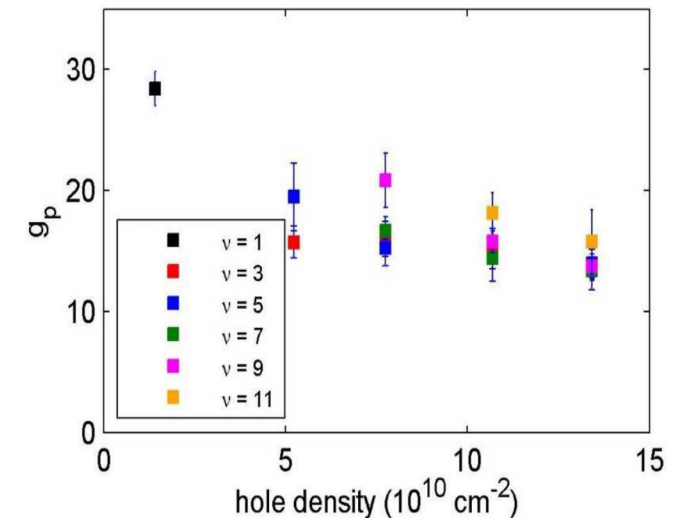
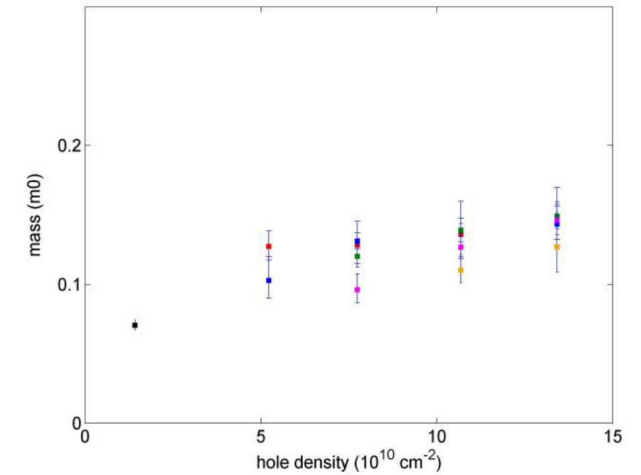
Drichko J. Appl. Phys. 123, 165703 (2018)

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

$$0.5 E_c < E_z < E_c$$



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

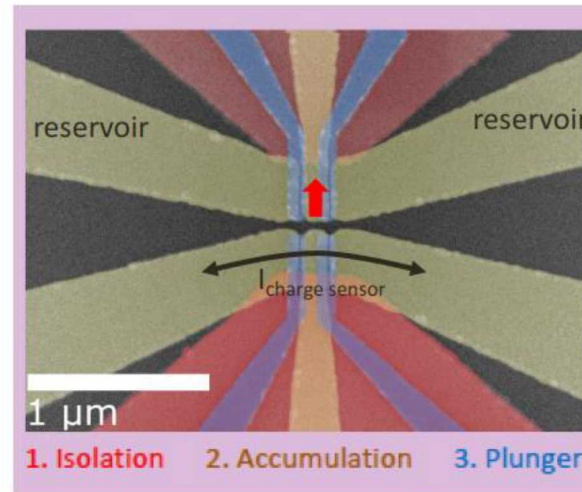


Implications for Quantum Dots

- Low Disorder
 - Help Dot-Dot Coupling
- Small Effective Mass
 - Help Dot-Dot coupling
 - Easier Lithography
- Anisotropic g-factor
 - Large g-factor allows operation at smaller magnetic fields
 - Dot-to-Dot variation is possible
- Strong Spin-Orbit-Coupling
 - Natural mechanism for qubit control
 - Introduces additional noise channel

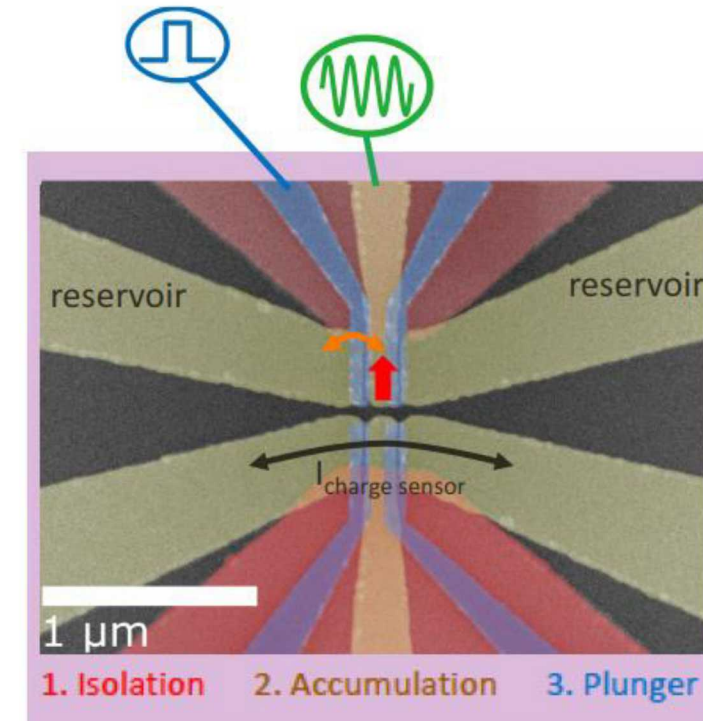
The effect of confinement on these properties remains largely unexplored

Surface electrodes used to laterally confine hole

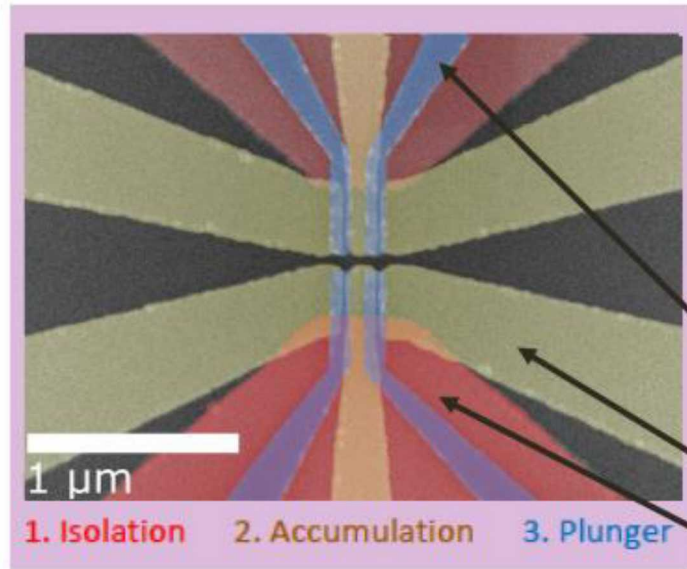


Spin qubits in Ge/SiGe

- Single Hole confined to lateral quantum dot
- 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



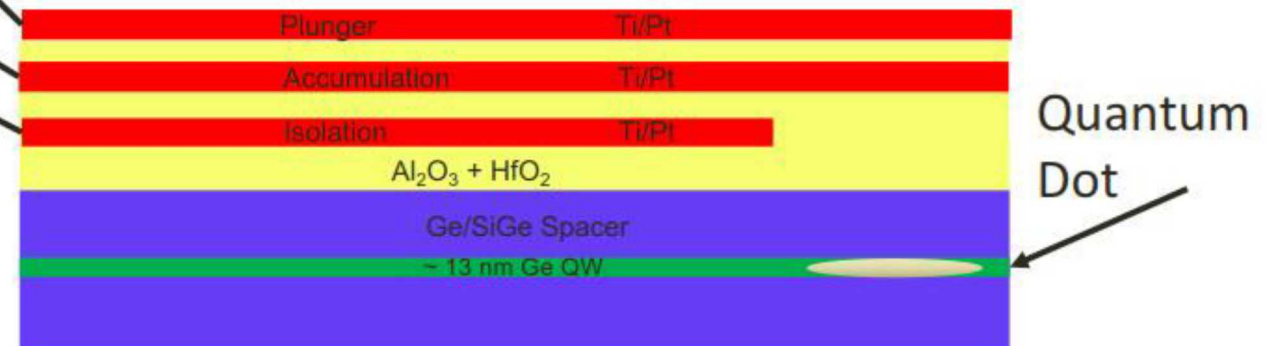
Spin qubits in Ge/SiGe



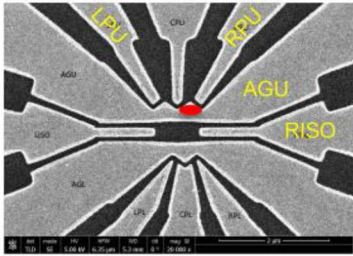
Ga implanted Ohmic contacts

Goals:

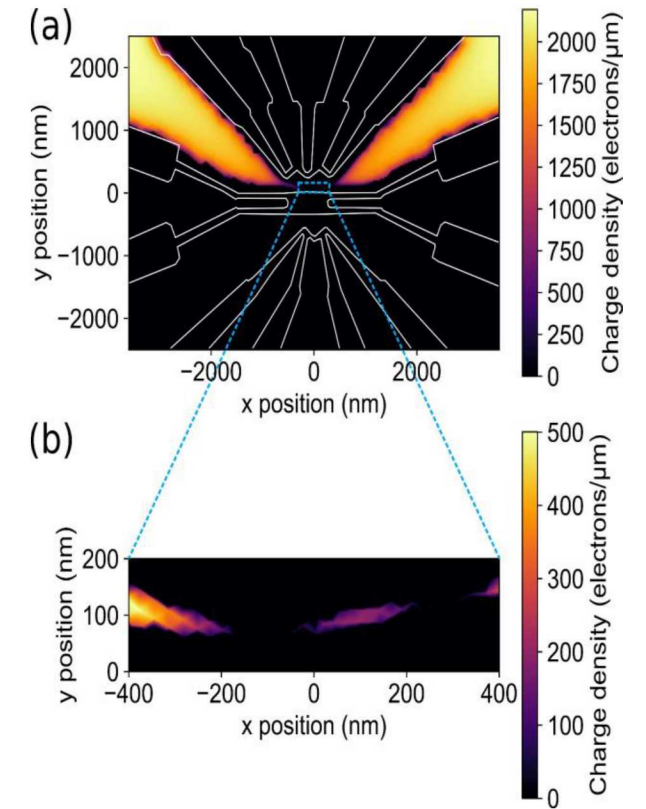
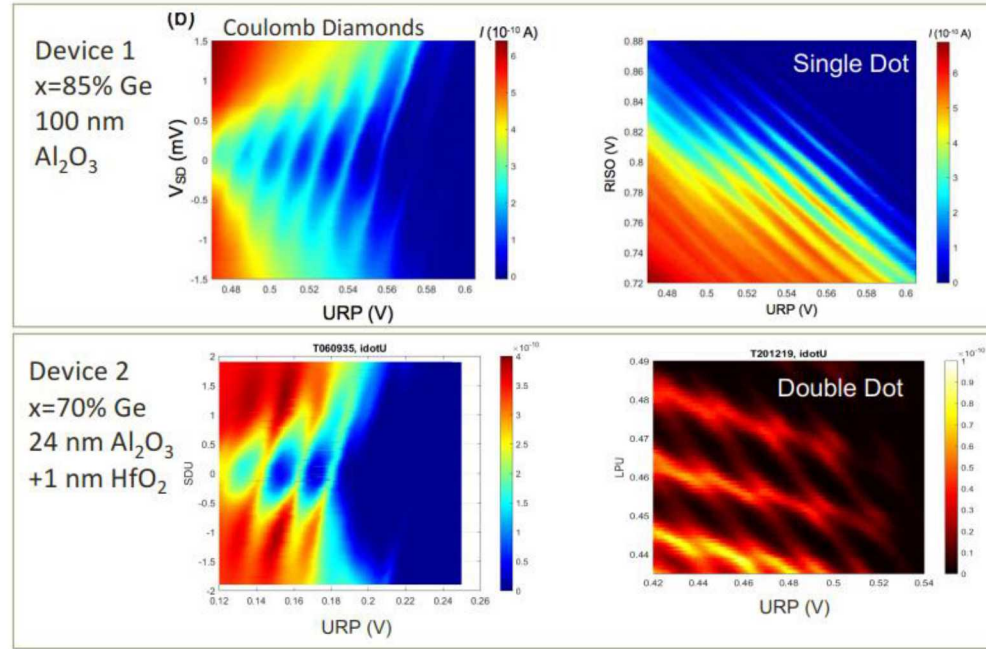
- Independent Control of occupation and tunnel barriers
- Tighter Confinement
- Low Capacitance for EDSR



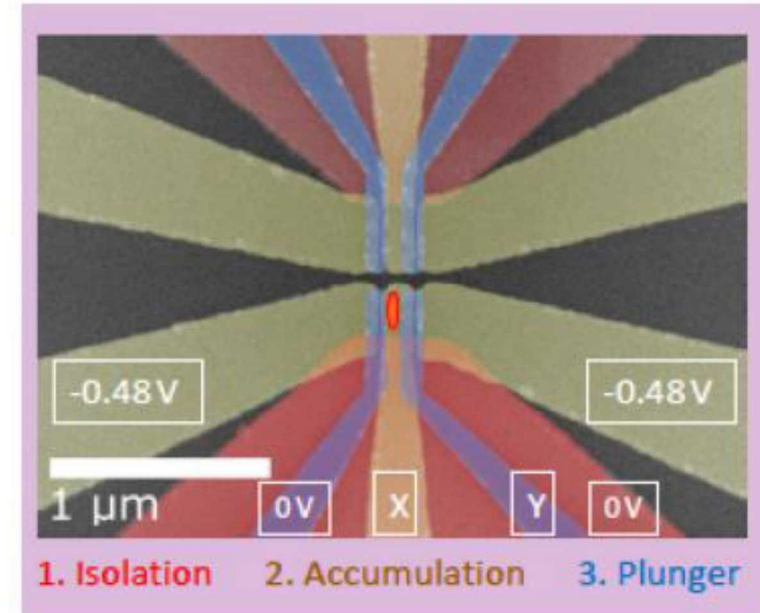
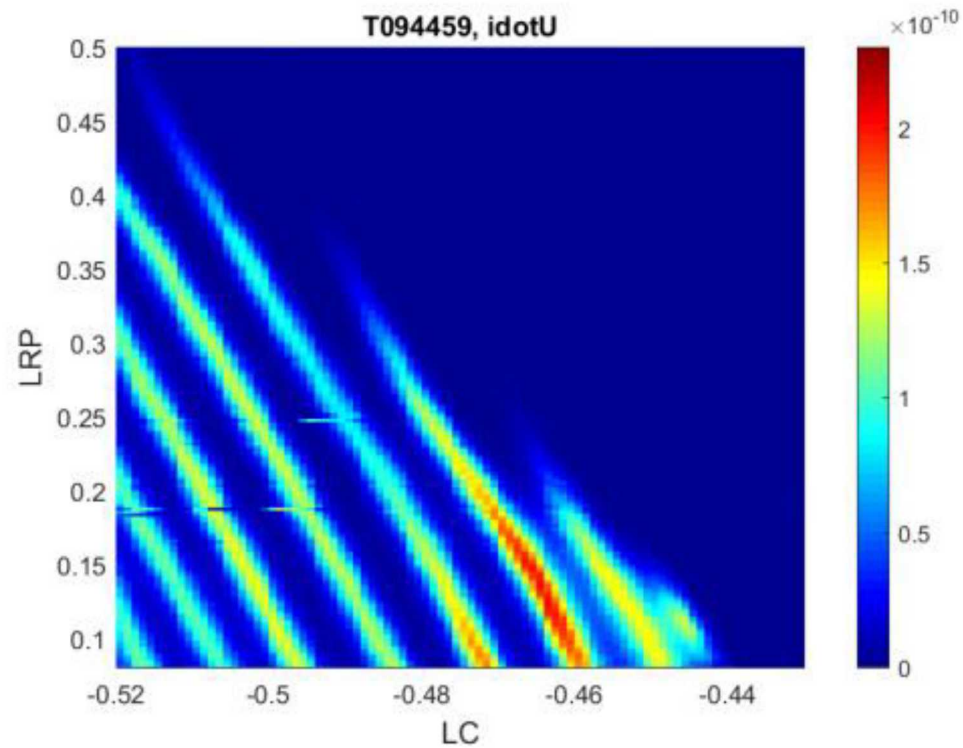
Spin qubits in Ge/SiGe



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



Three Metal Layer Device



Coulomb Blockade observed in
the three-metal-layer devices

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