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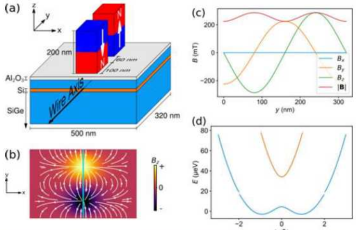
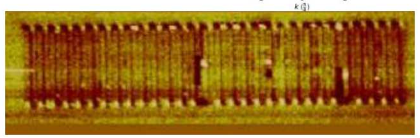
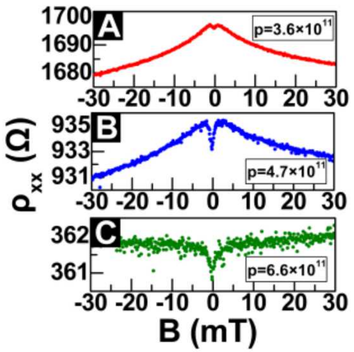
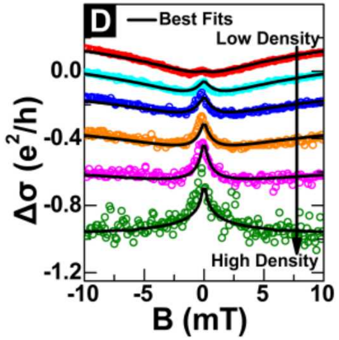
SAND2019-10623C

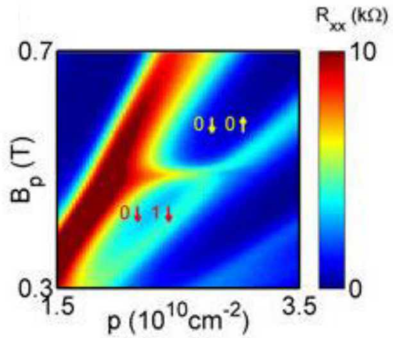
SiGe-based quantum electronic devices











Tzu-Ming Lu

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

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

BIG SCIENCE AT THE NANOSCALE

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Acknowledgements

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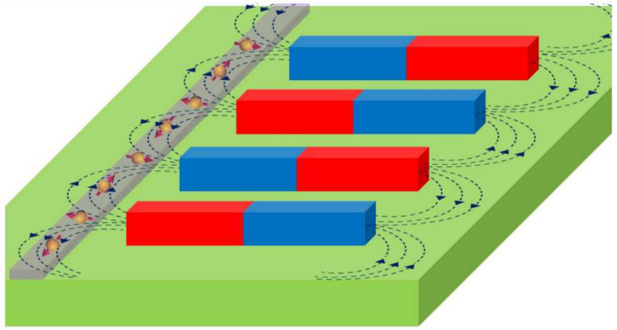
Outline

- 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

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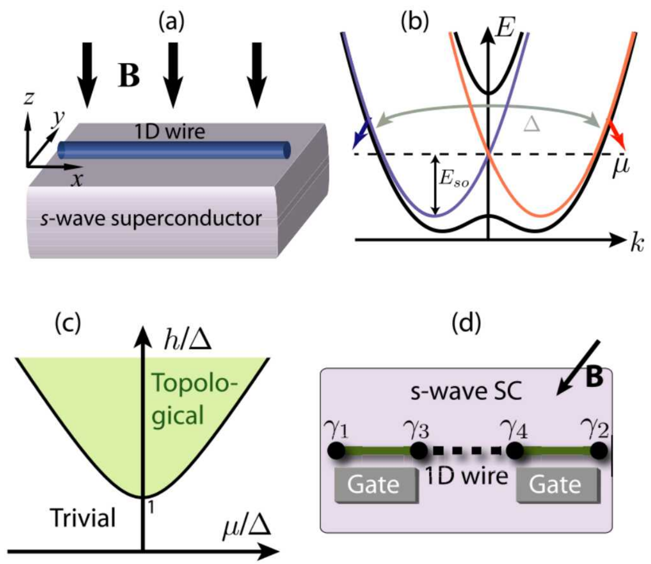
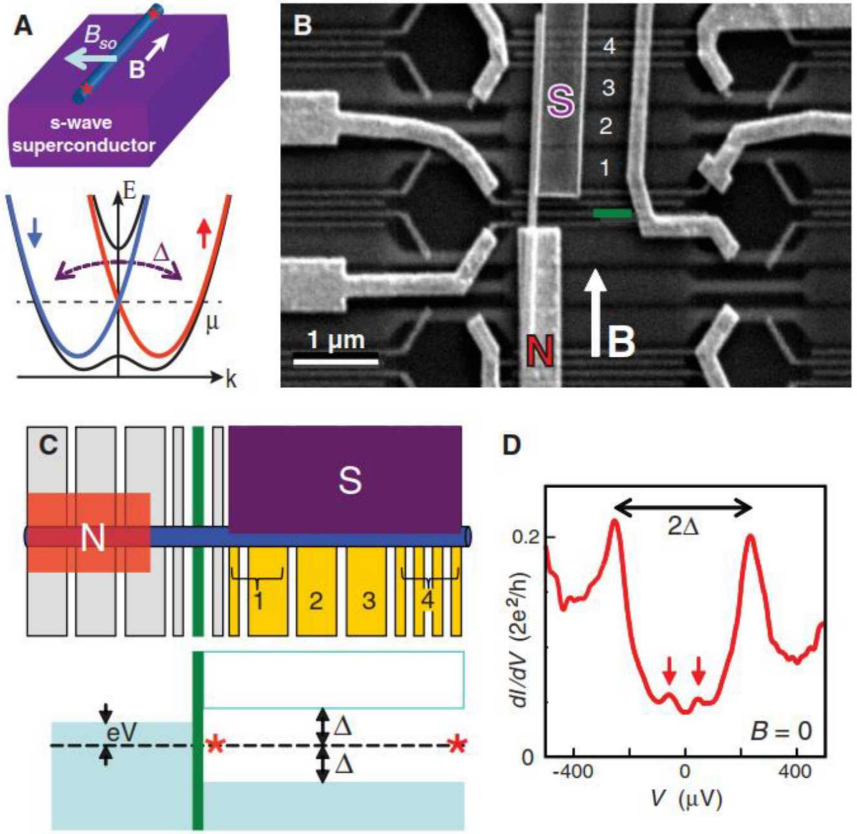
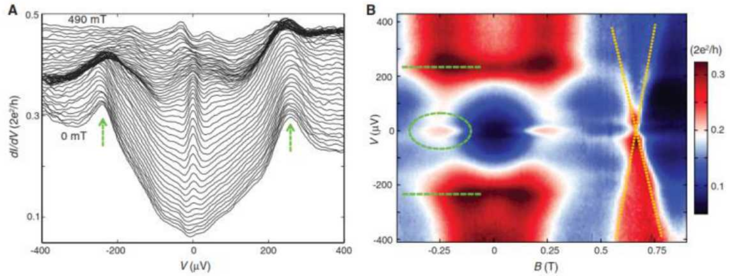


Alicea, Rep. Prog. Phys. 75, 076501





Mourik, Science 336, 1003

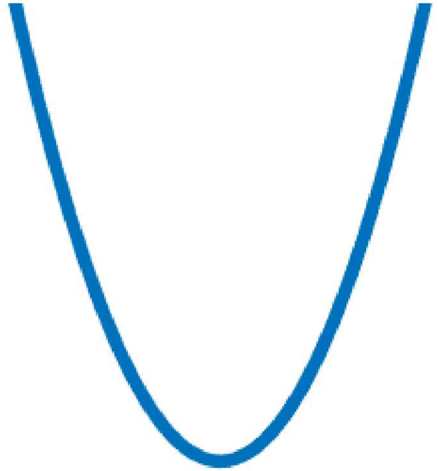
Strong spin-orbit coupling is required -> InAs, InSb

Can we do this in silicon?

1D spin orbit coupling

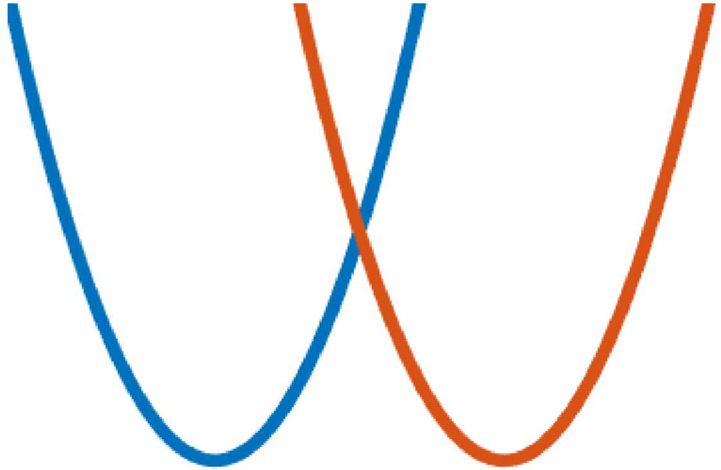
- 1D E-k_x dispersion **without** SOC:

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



- 1D E-k_x dispersion **with** SOC:
  - $B_{SO} \sim k_x \times E_z$ (along y)

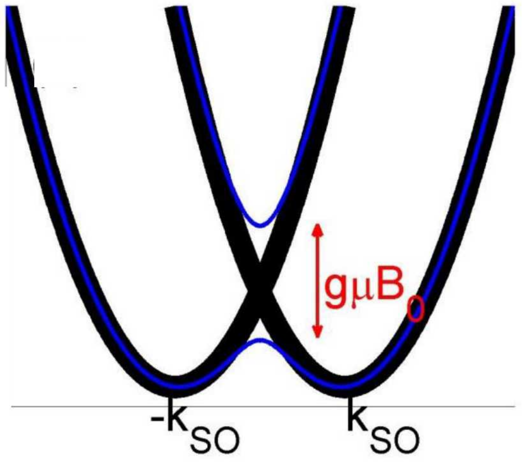
$$E \sim \frac{\hbar^2 k_x^2}{2m} + a k_x E_z\, S \sim \frac{\hbar^2 (k_x \pm k_{SO})^2}{2m}$$



1D spin orbit coupling

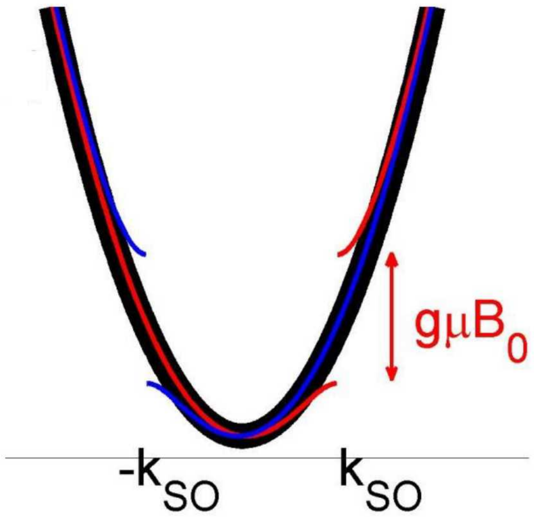
- 1D E-k_x dispersion **with** SOC with **B_0 along z**:

  Gap near k=0
  (blue curves)

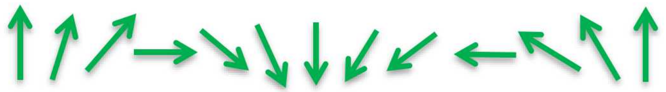


- Canonical transformation of the above case:

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

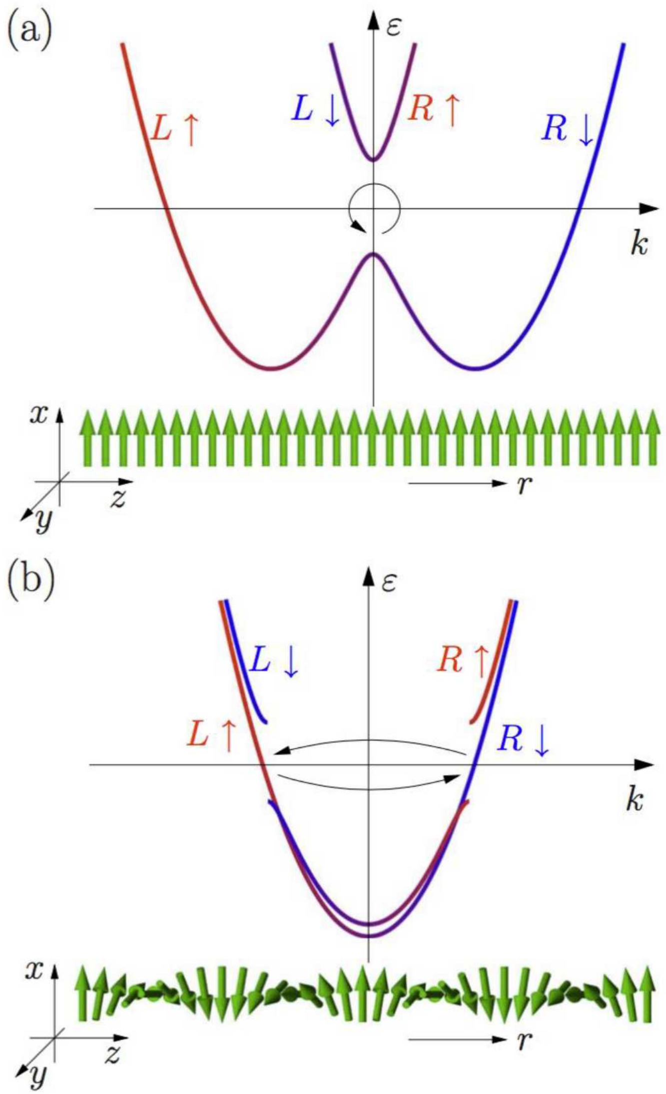


Effective magnetic field



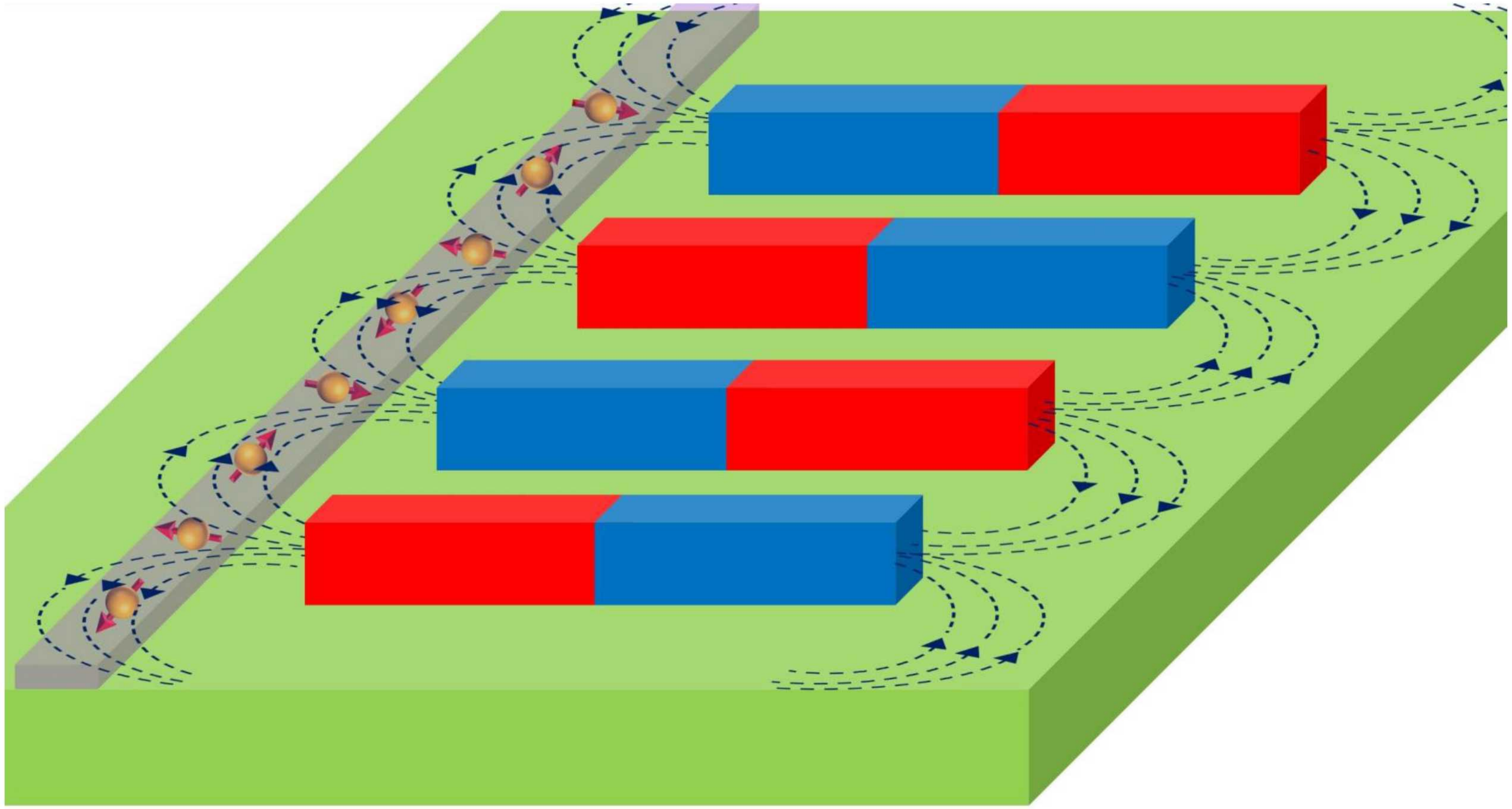
Engineer the SOC using nano-magnets

- 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)



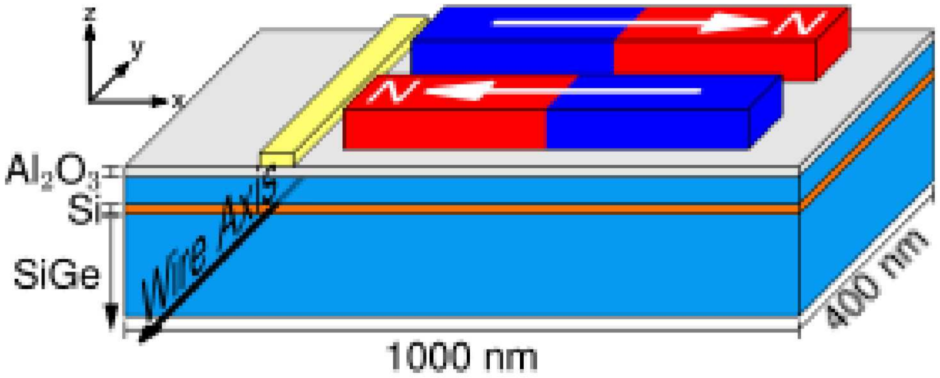
B Braunecker et al., *PRB* **82**, 45127 (2010)

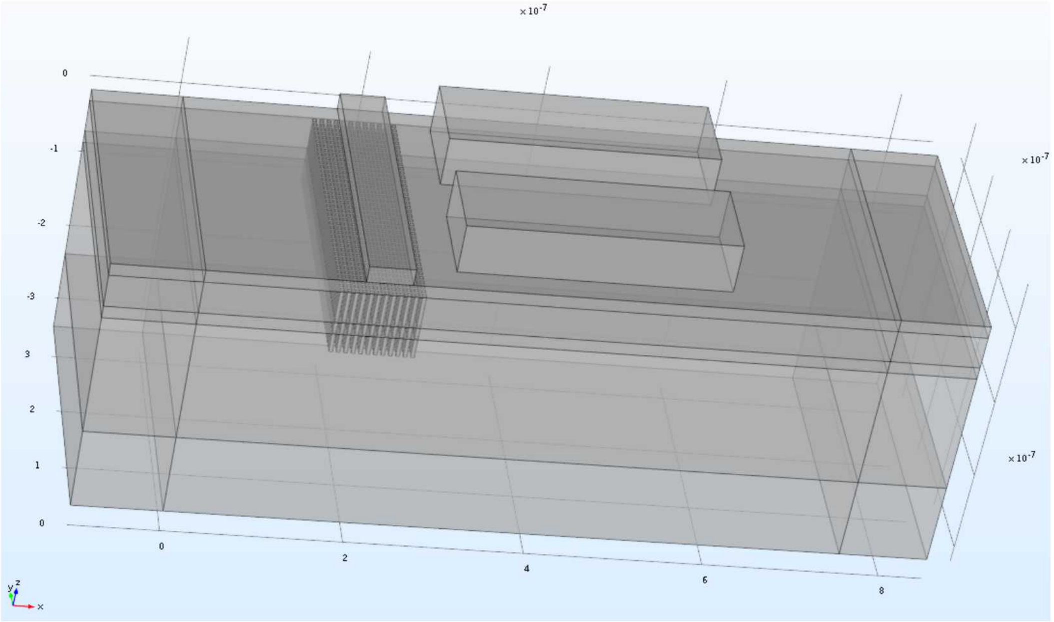
1D, spatially rotating magnetic field from nano-magnet arrays



Magnetostatics I

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

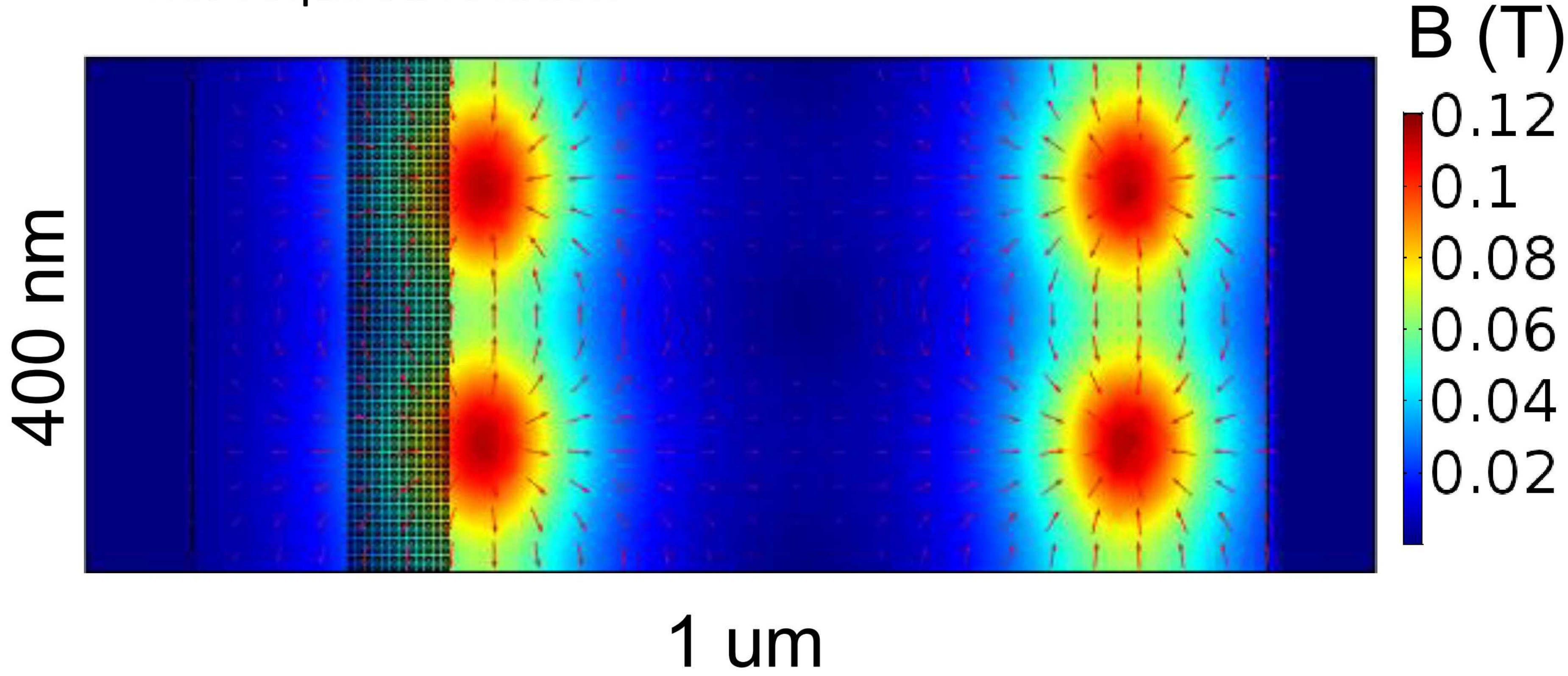




L. Maurer, PRApplied, 10, 054071 (2018)

Magnetostatics II

- Magnetic field in 2DEG plane
- Has required rotation



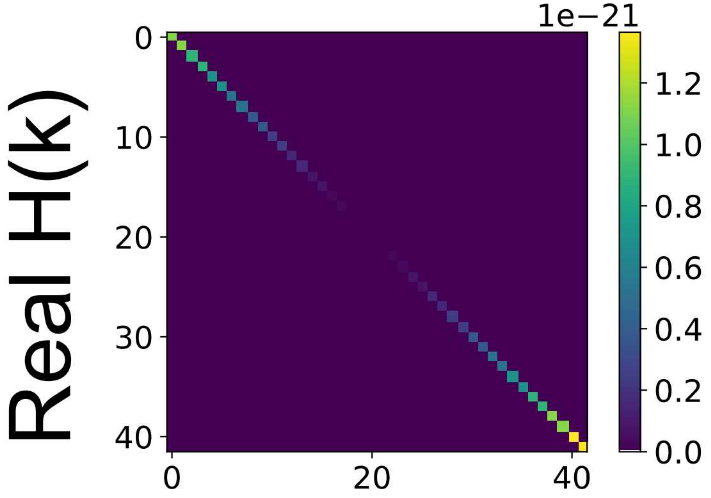
L. Maurer, PRApplied, 10, 054071 (2018)

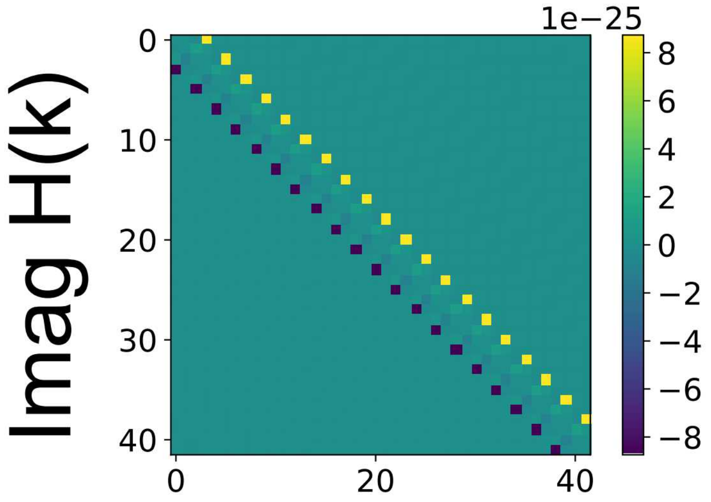
Band Structure Calculations

- 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

$$E d_q = \frac{\hbar^2}{2m}(q+k)^2 + \sum_g c_g d_{q-g}$$

- Solve with a decent number of bands

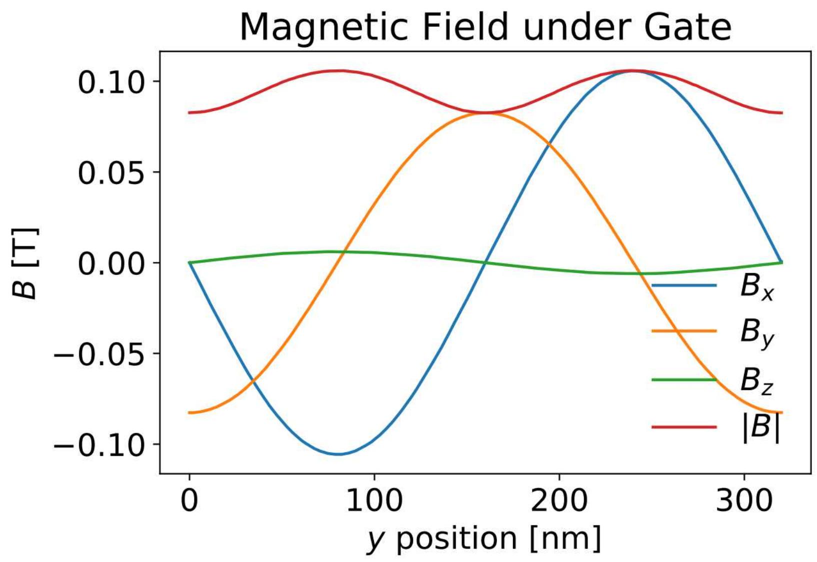


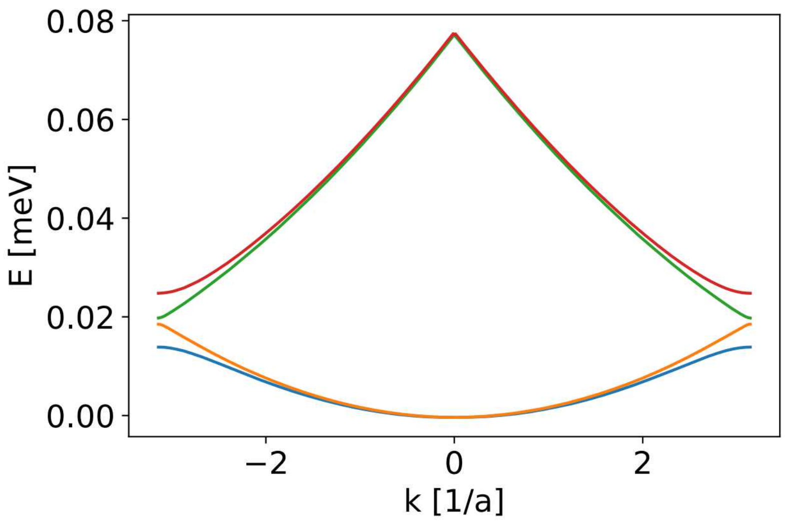


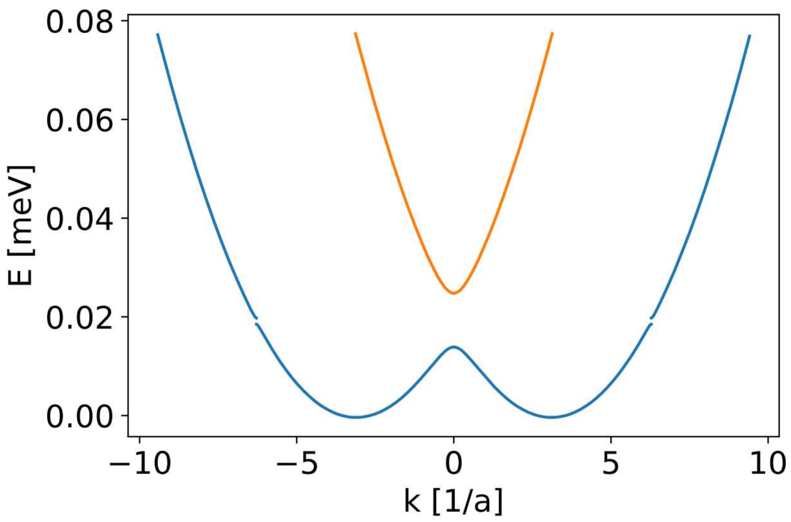
L. Maurer, PRApplied, 10, 054071 (2018)

Example Results

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

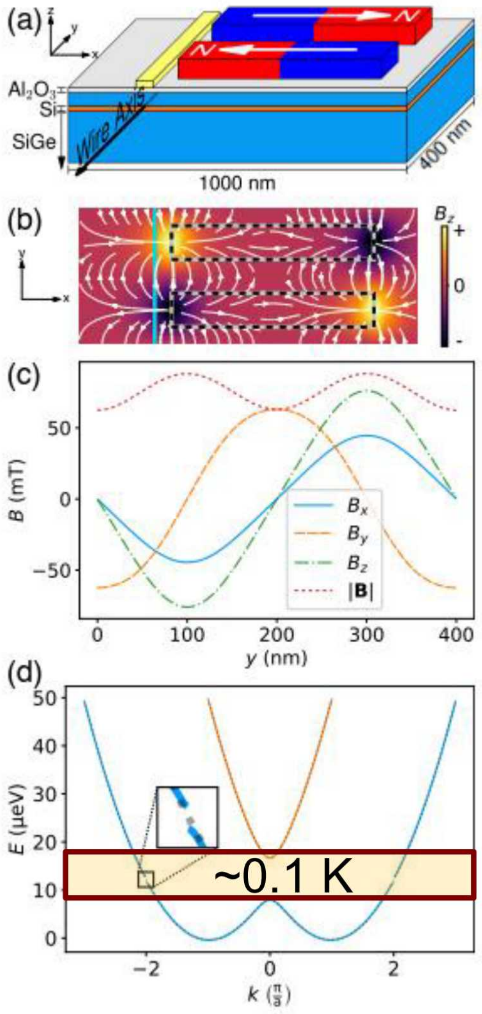


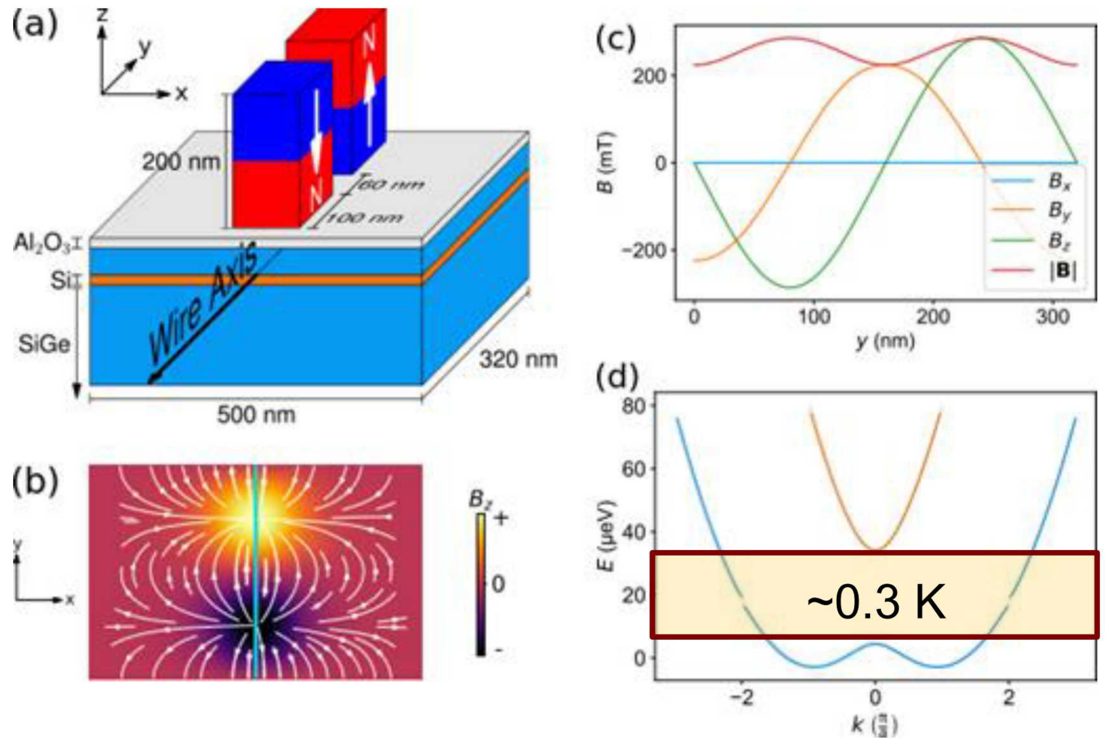




L. Maurer, PRApplied, 10, 054071 (2018)

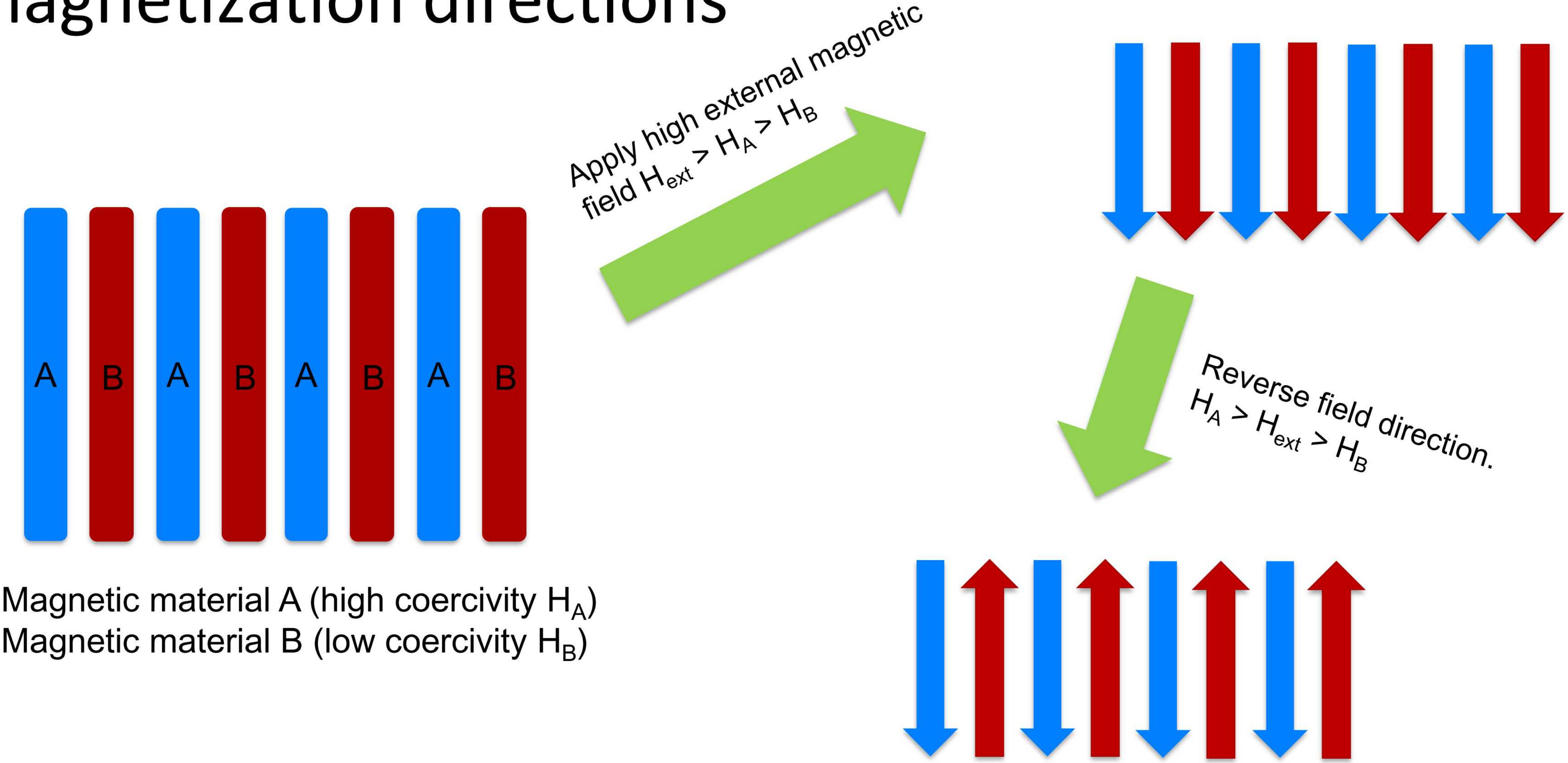
Effective spin-orbit gaps in Si/SiGe





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

Realizing nano-magnet arrays with alternating magnetization directions



Magnetic material A (high coercivity H_A)
Magnetic material B (low coercivity H_B)

Magnetic materials with high coercivity contrast

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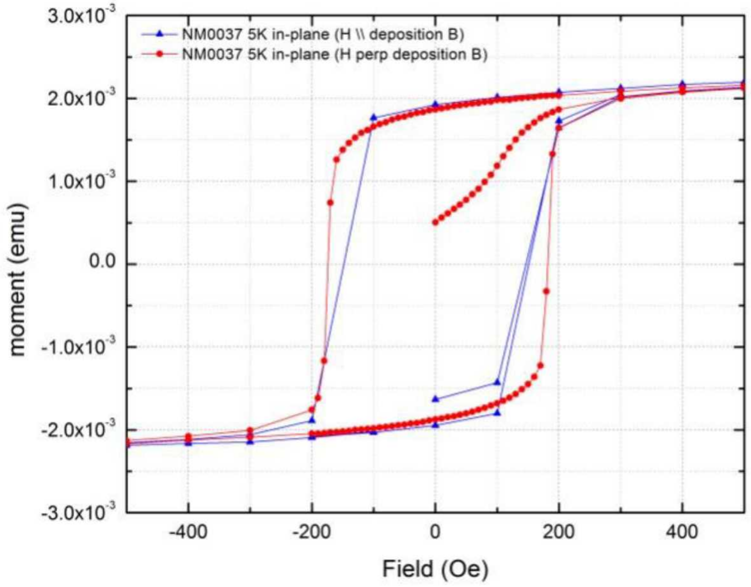
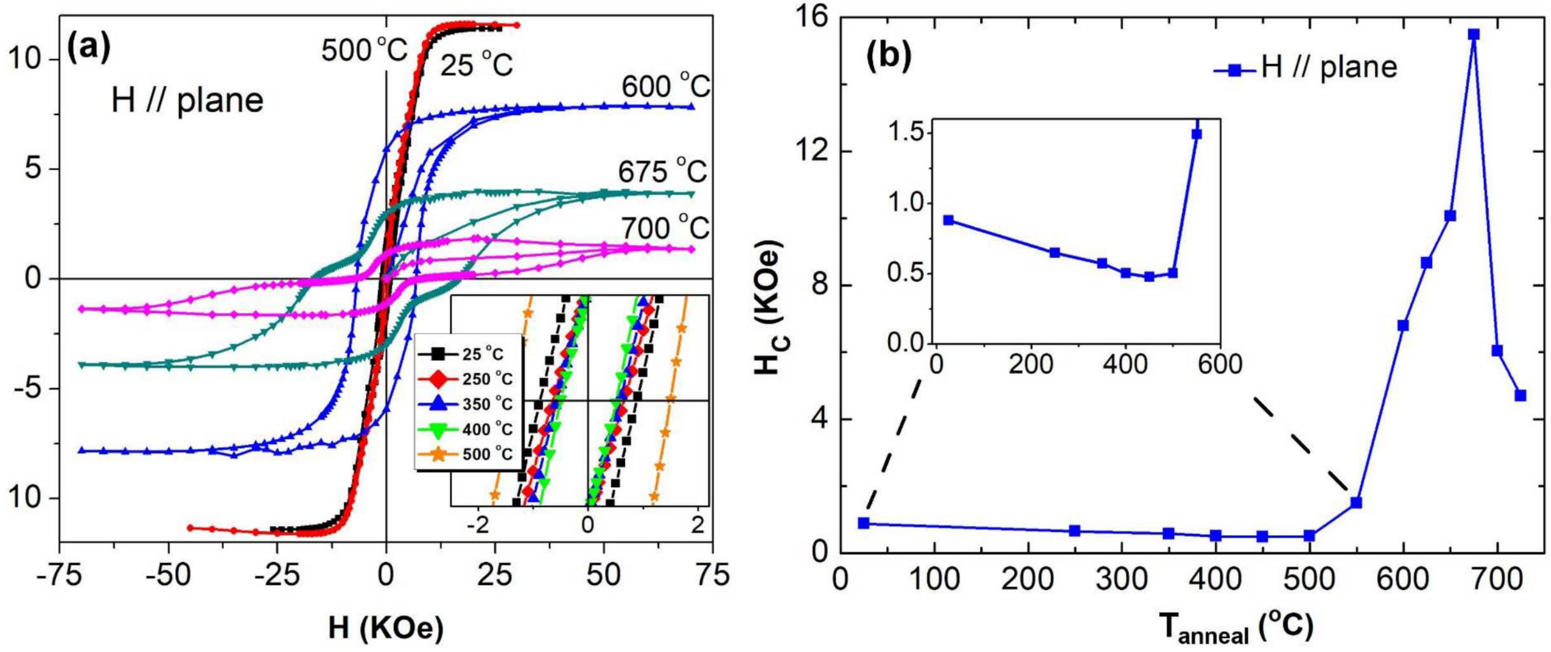
Low-coercivity (200 Oe) as-deposited Co films

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

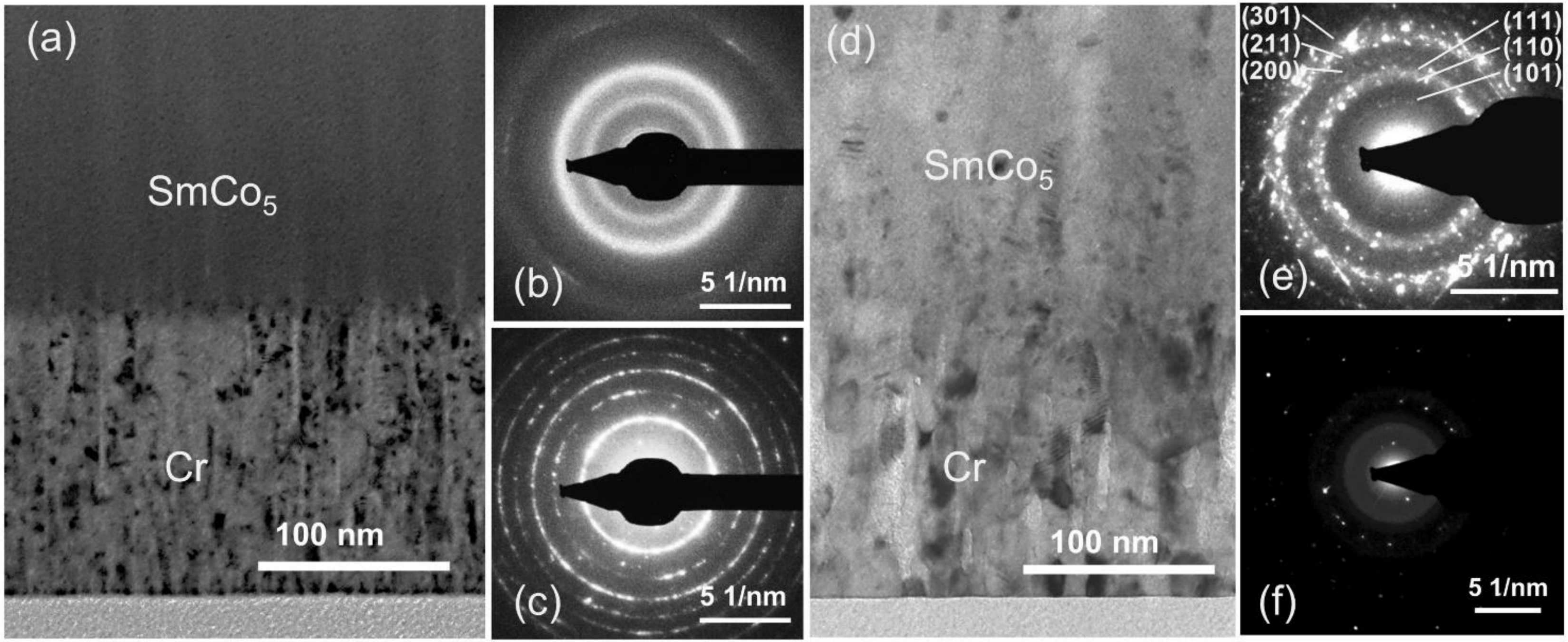




K. Sapkota, AIP Advances, 9, 075203 (2019)

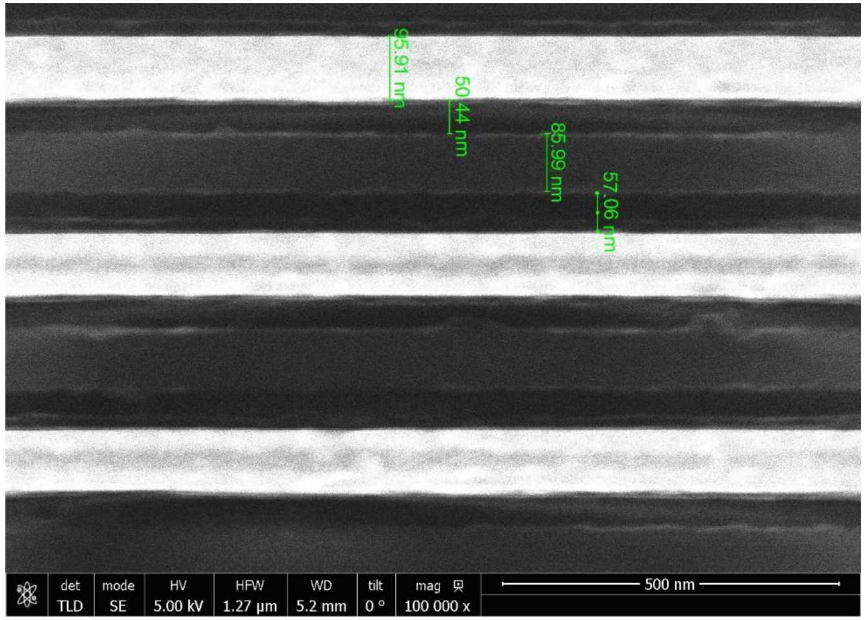
Magnetic materials with high coercivity contrast

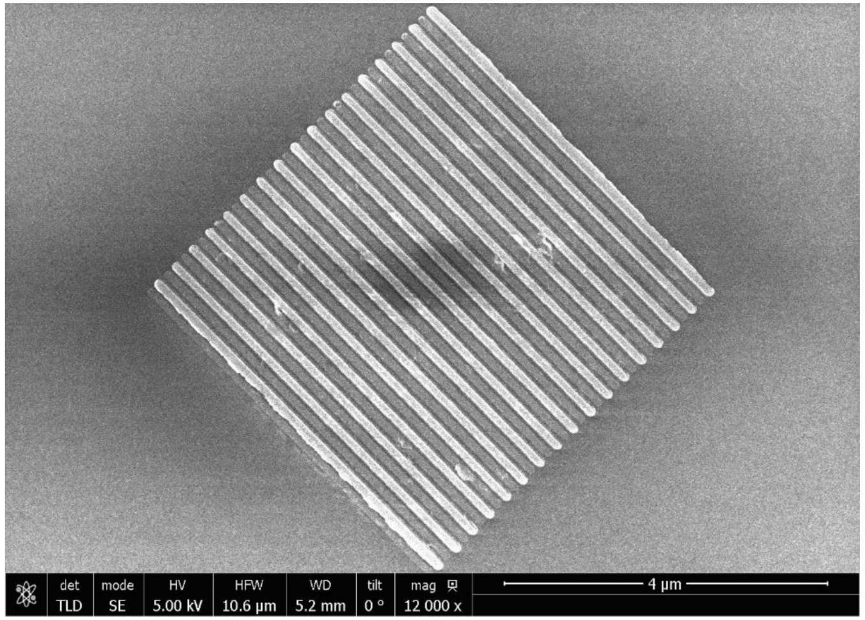
Crystallization of $SmCo_5$ leads to high coercivity.



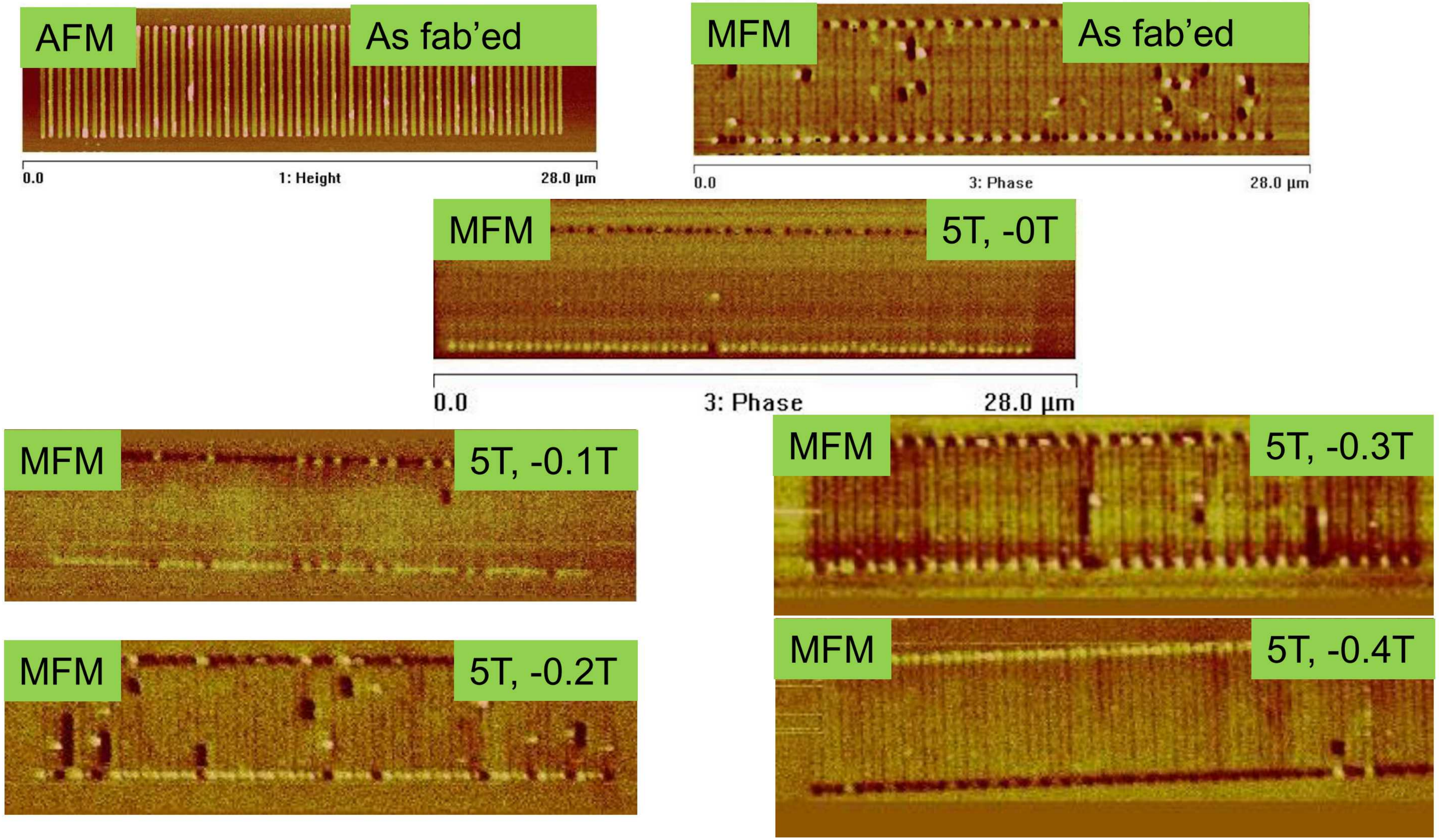
K. Sapkota, AIP Advances, 9, 075203 (2019)

Interdigitated nanomagnet arrays





Programming nanomagnets with external B field



K. Sapkota, AIP Advances, 9, 075203 (2019)

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.

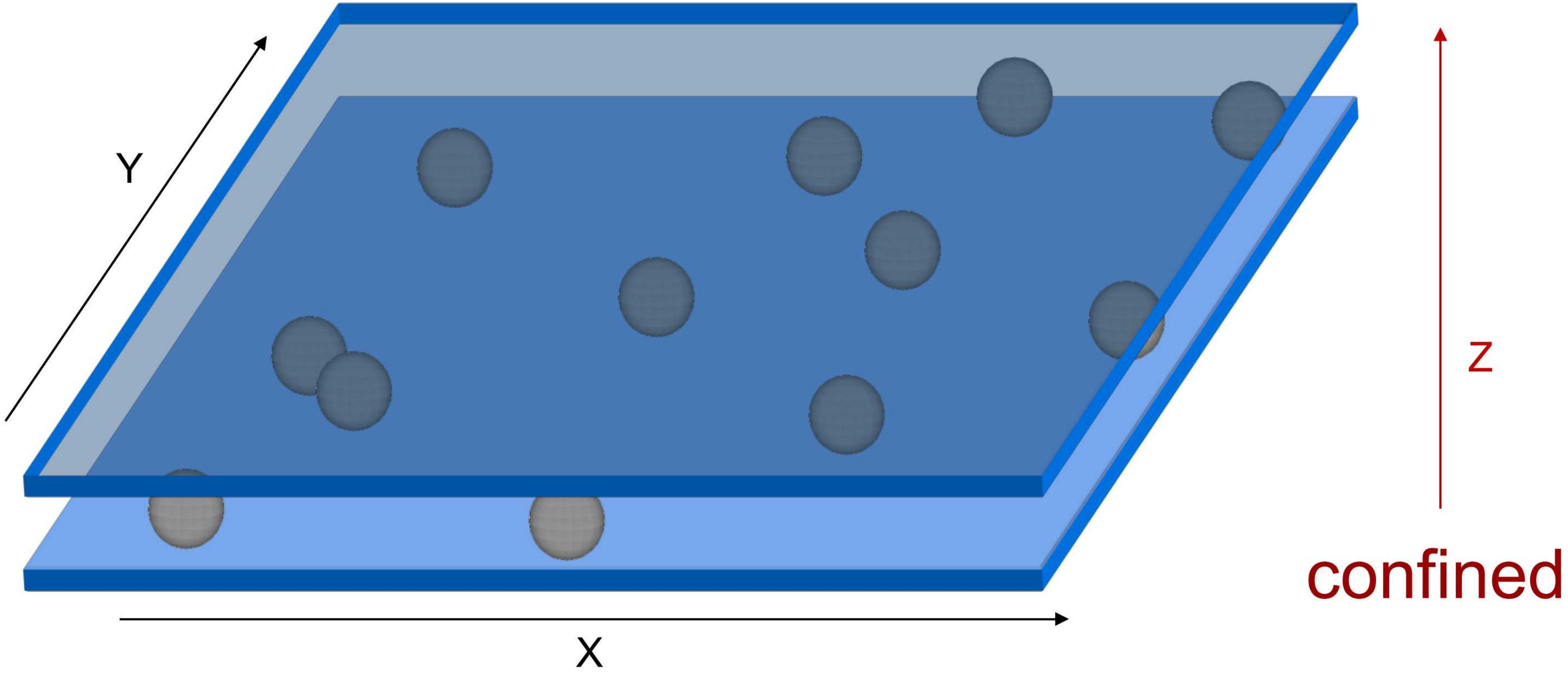
Questions to be answered

- 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

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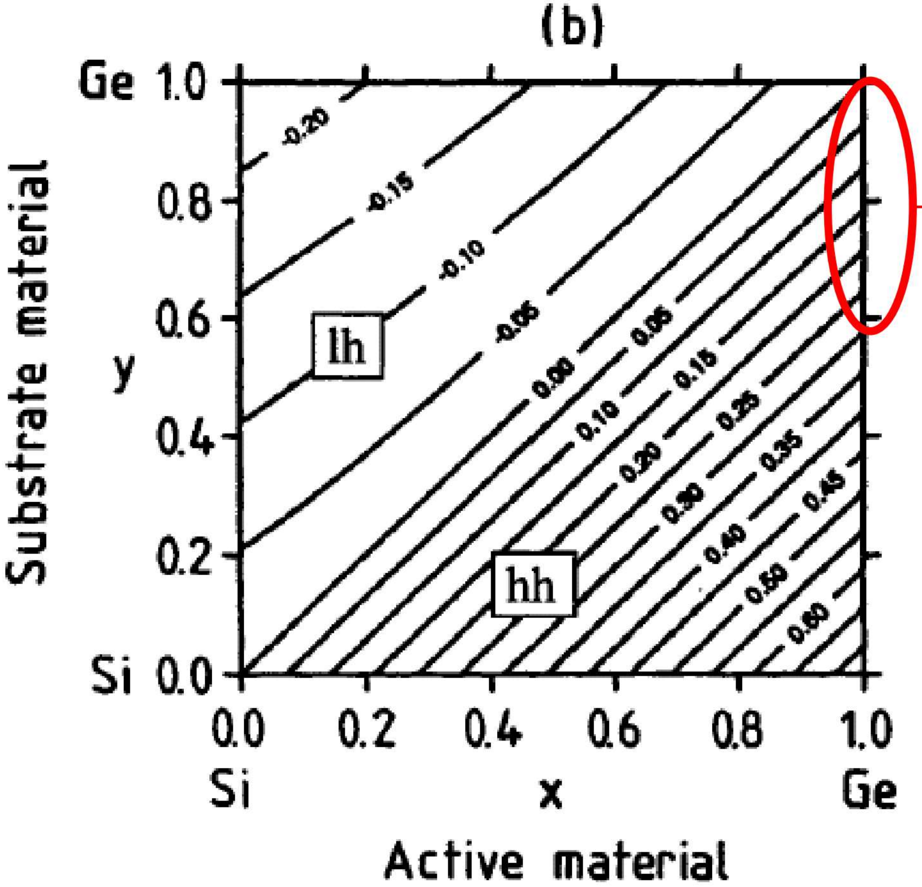

This work

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

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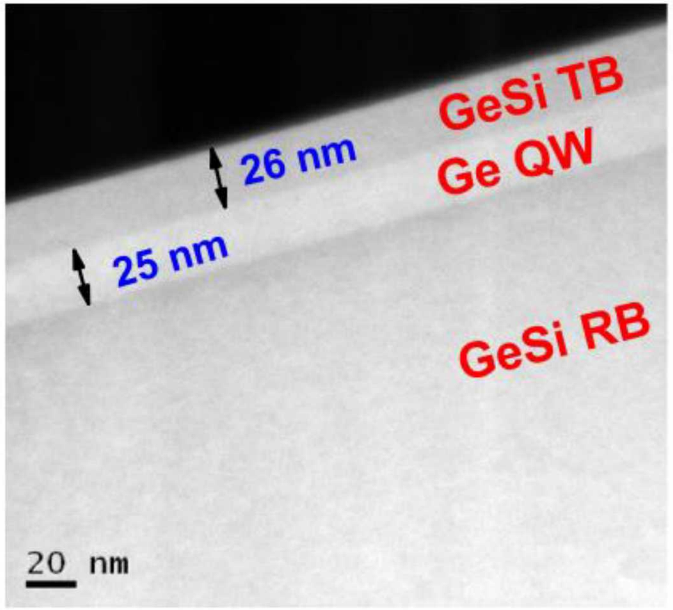
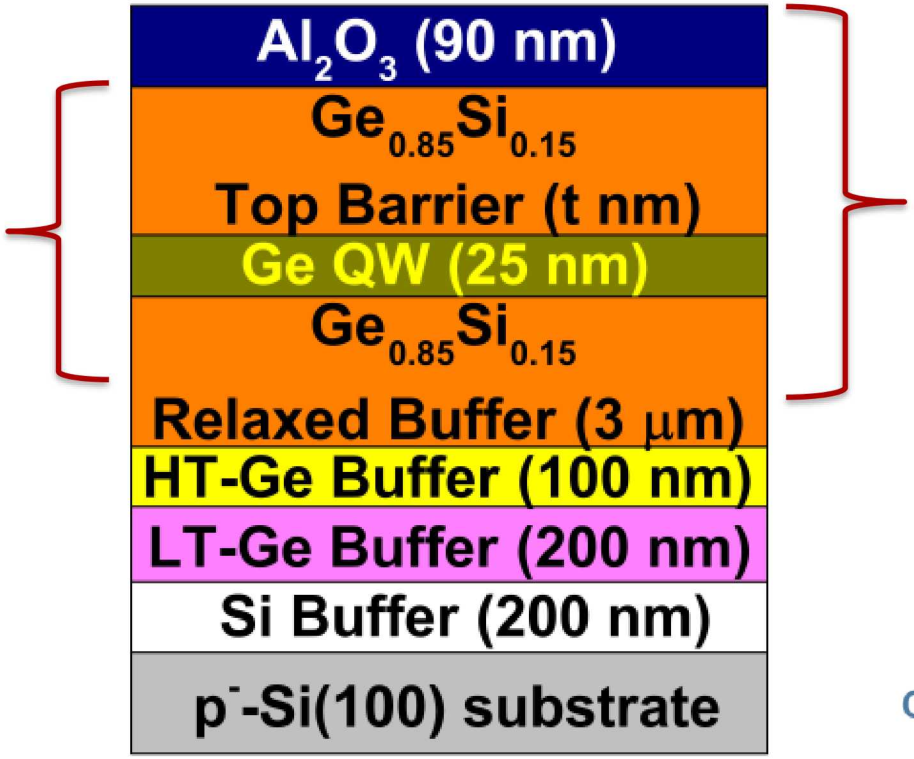
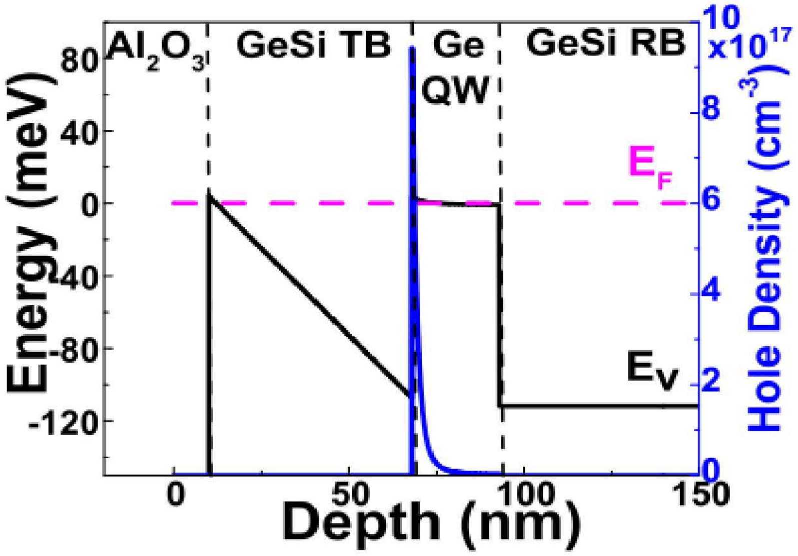
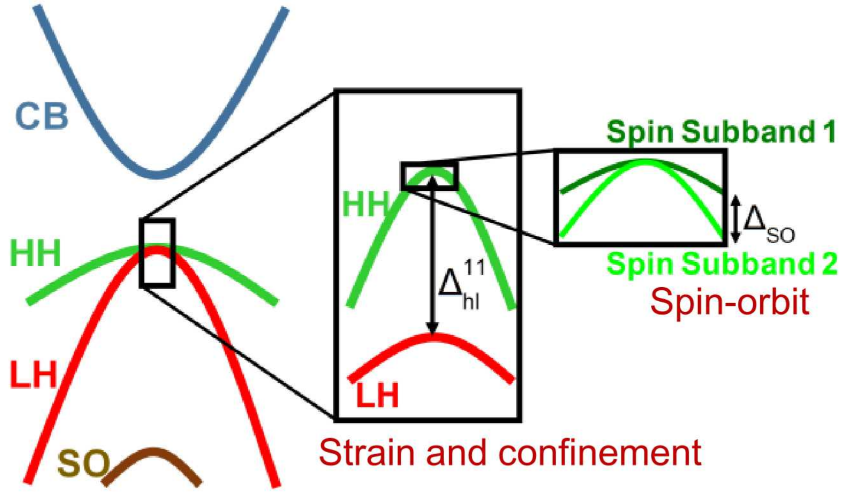








Laroche, Appl. Phys. Lett. 108, 233504 (2016)
Su, Phys. Rev. Mater. 1, 044601 (2017)

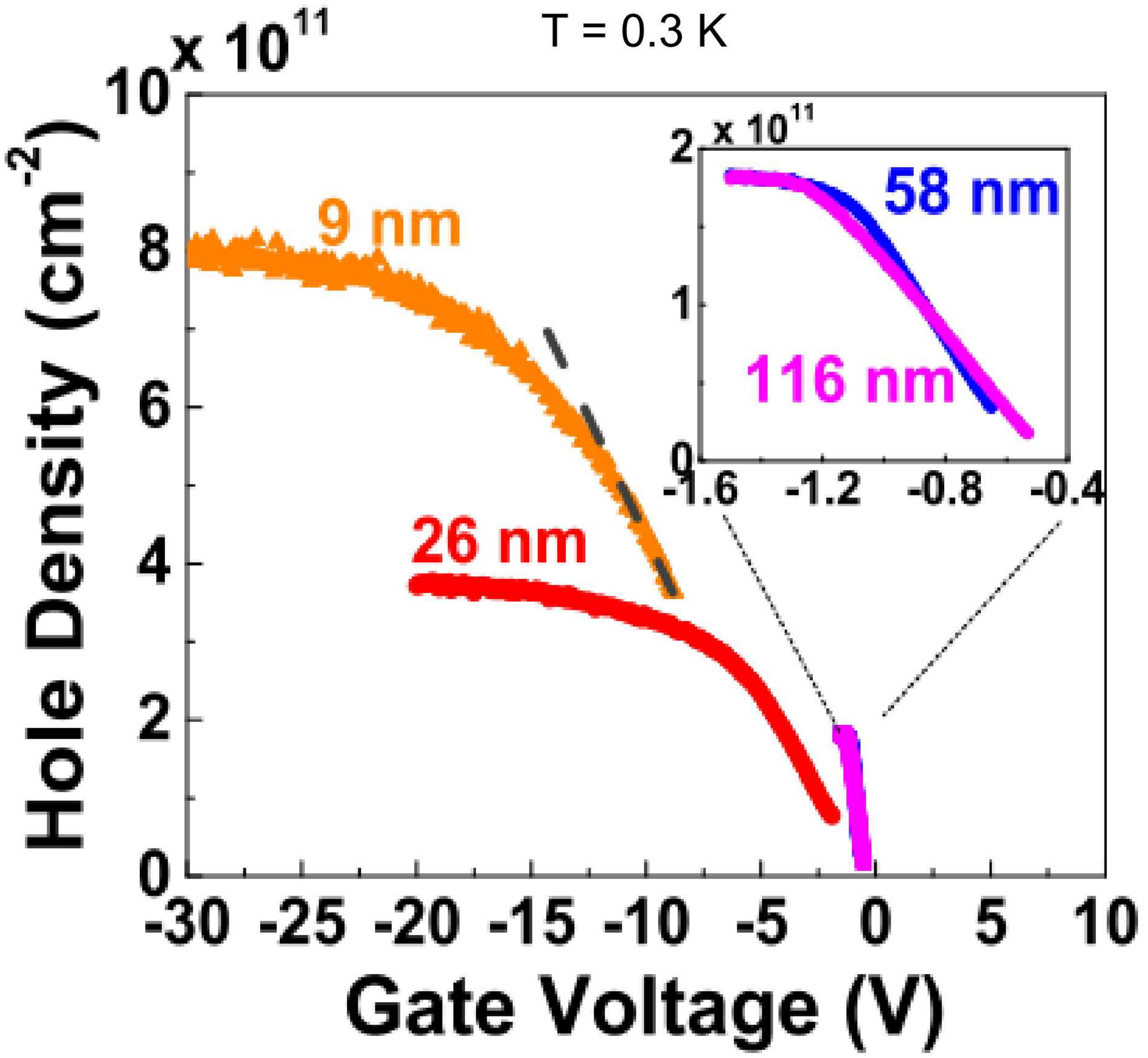
Device operation – 2D hole density

- 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)

T = 0.3 K



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

Device operation – 2D hole density

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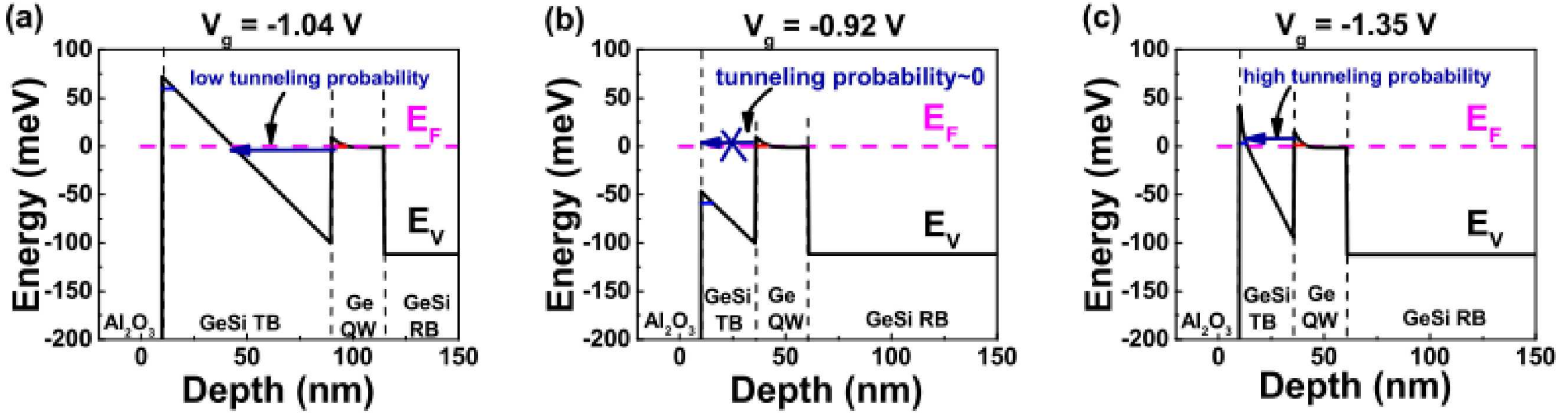
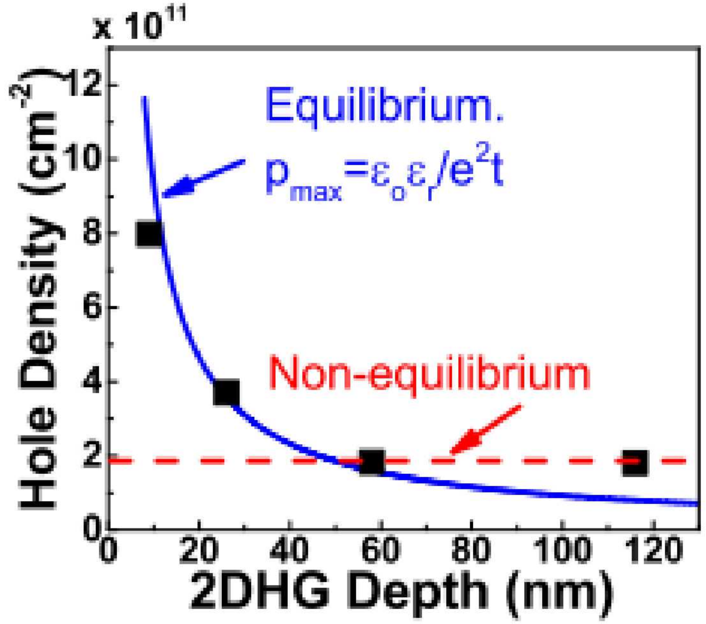




Deep channels

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!

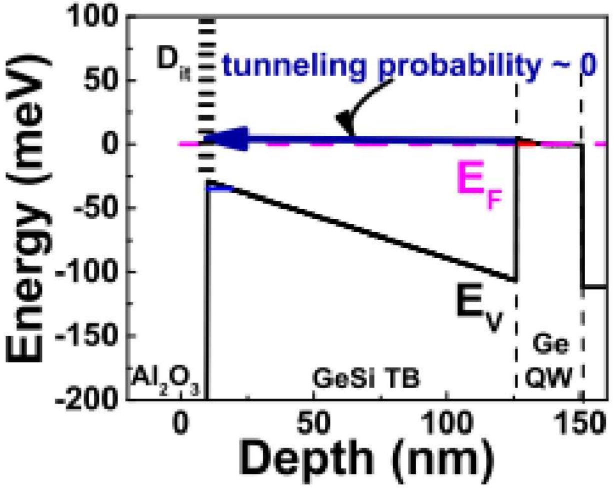
Shallow channels

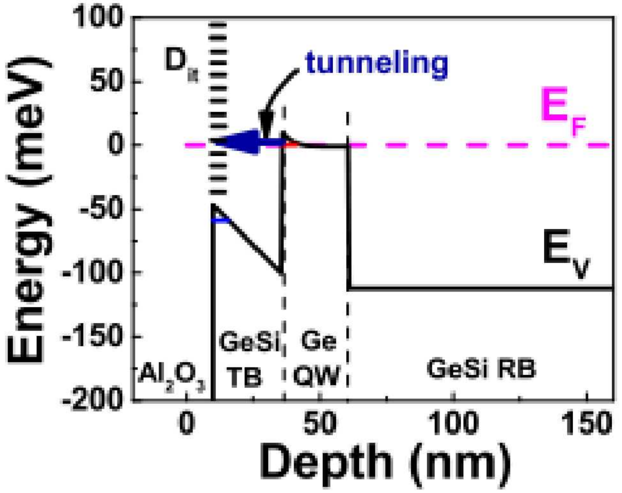
The tunneling rate is high (compared to experiment time scales).

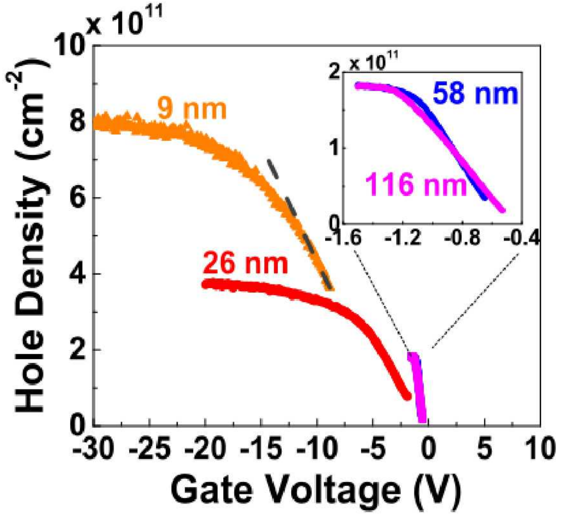
The density probed by the Hall effect approaches the equilibrium case.

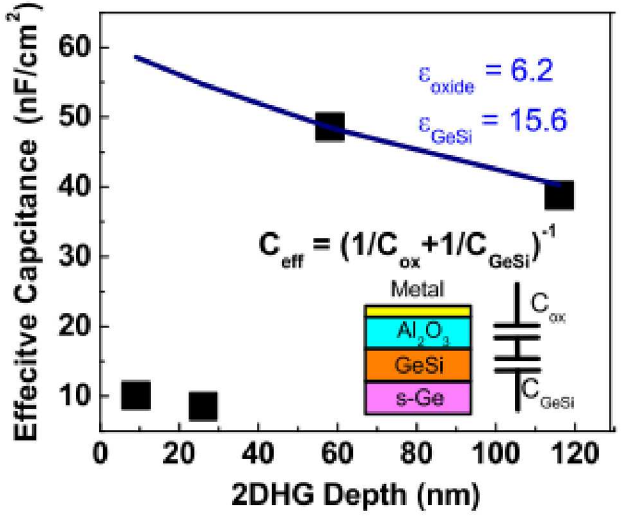
Su, Phys. Rev. Mater. 1, 044601 (2017)

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.

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

Shallow channels

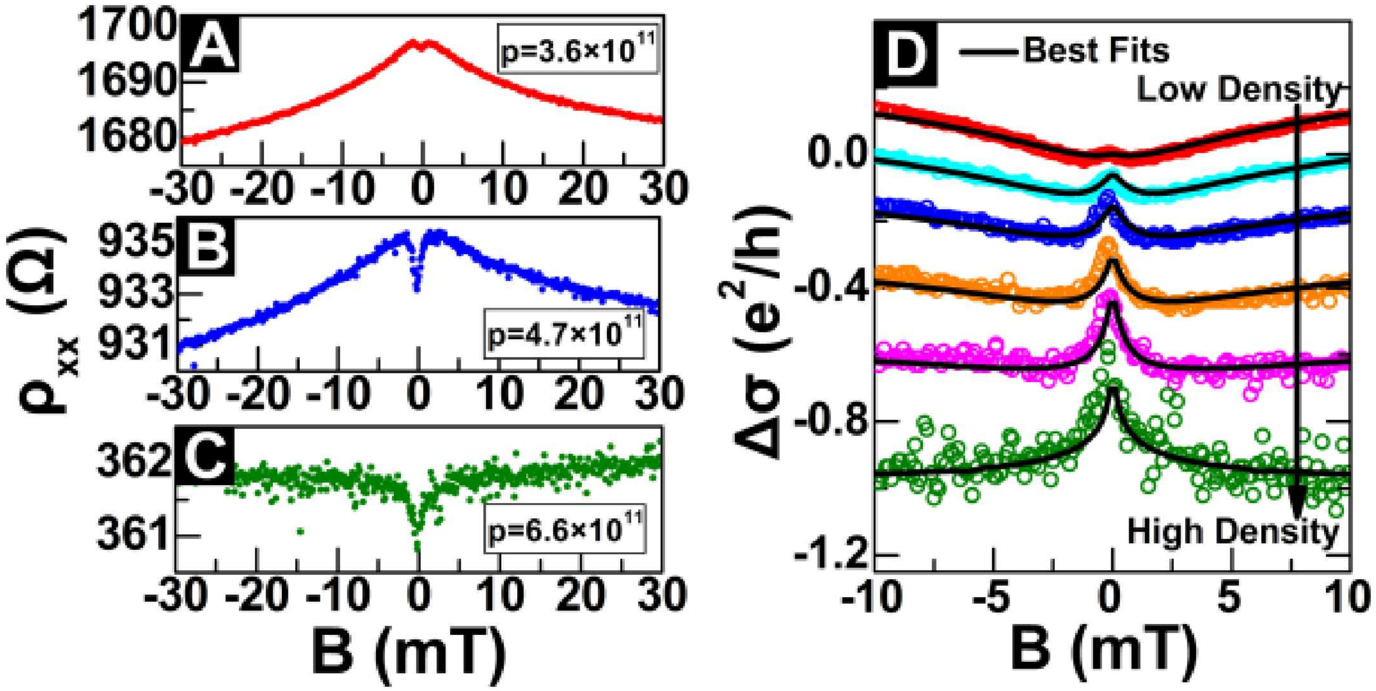
The tunnel rate is high.

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

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

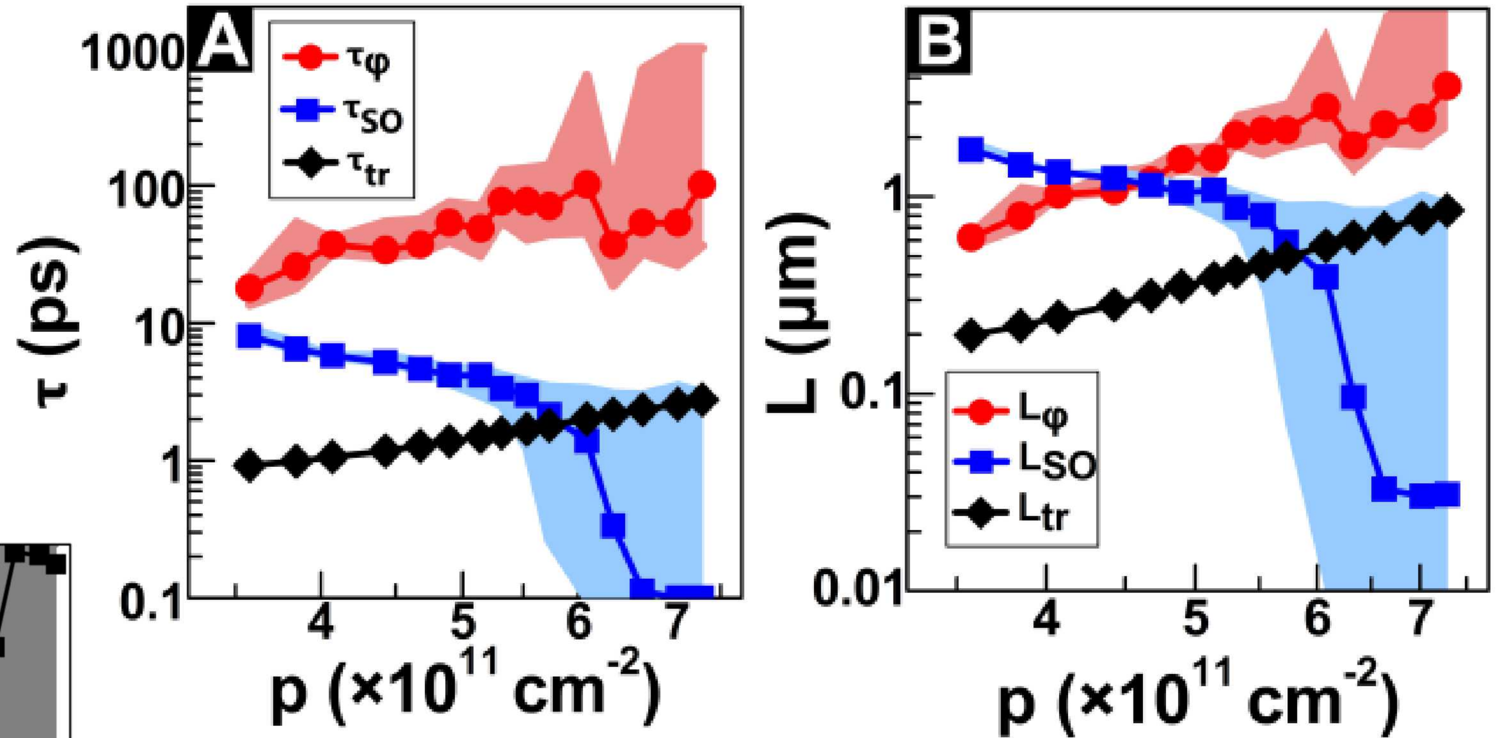


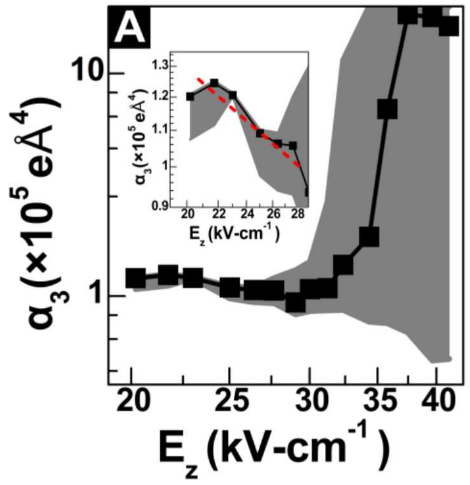
Cubic Rashba: ~(sin3θ,-cos3θ)

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.

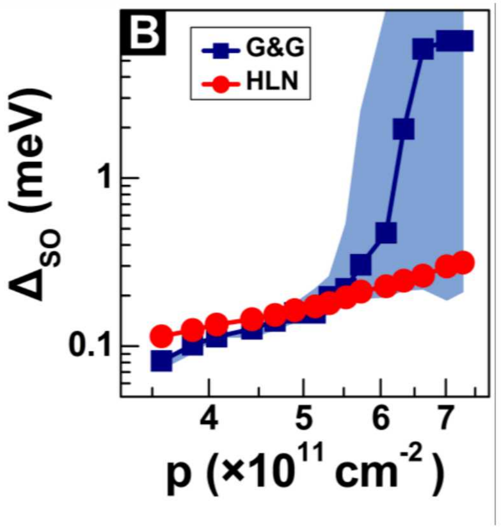




Chou, Nanoscale 10, 20559 (2018)

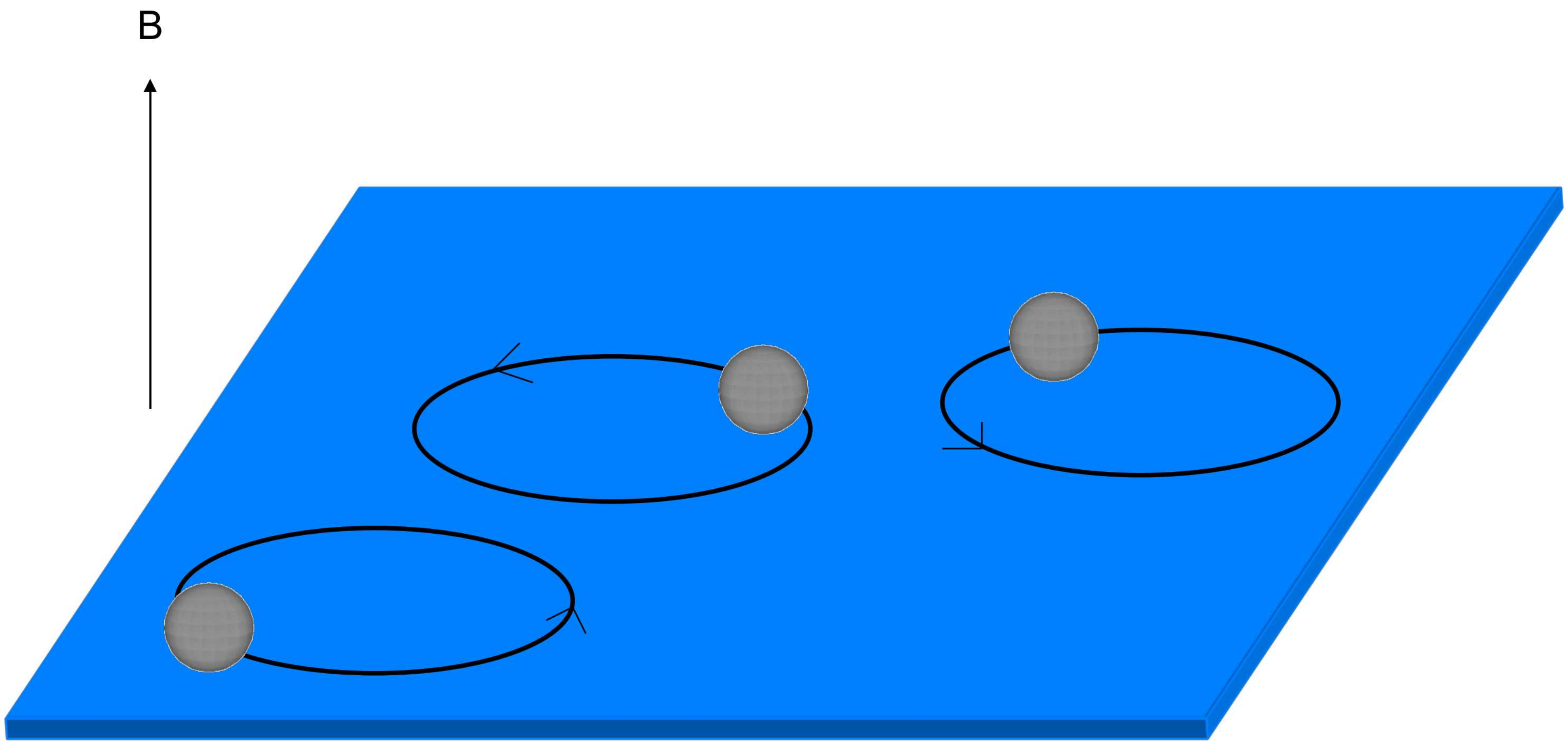
Physical properties – weak antilocalization beyond diffusive regime

- 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)

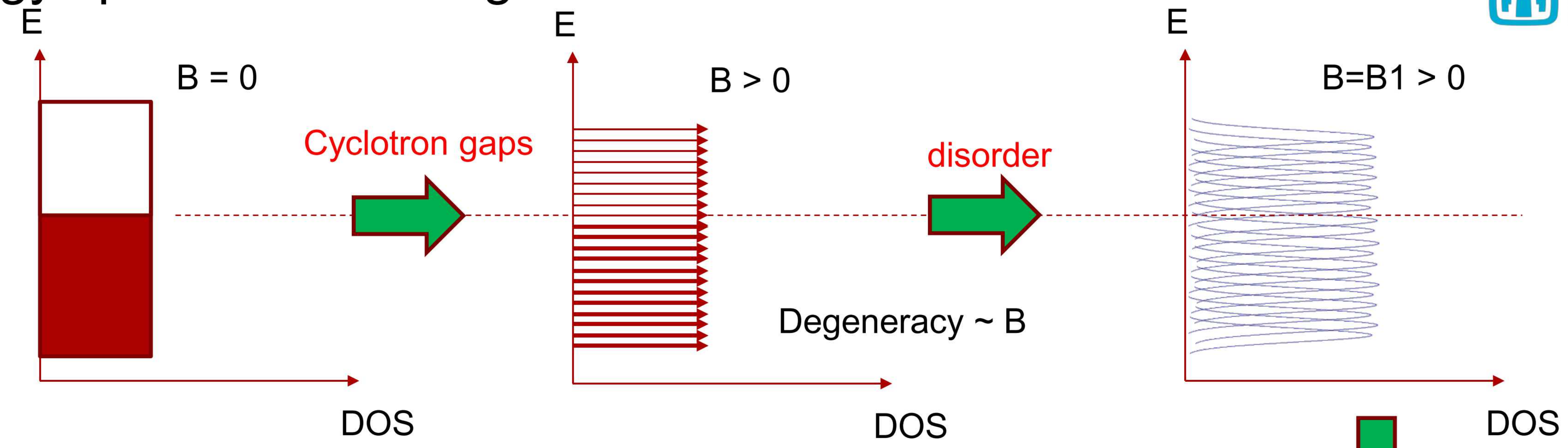
In a perpendicular magnetic field…

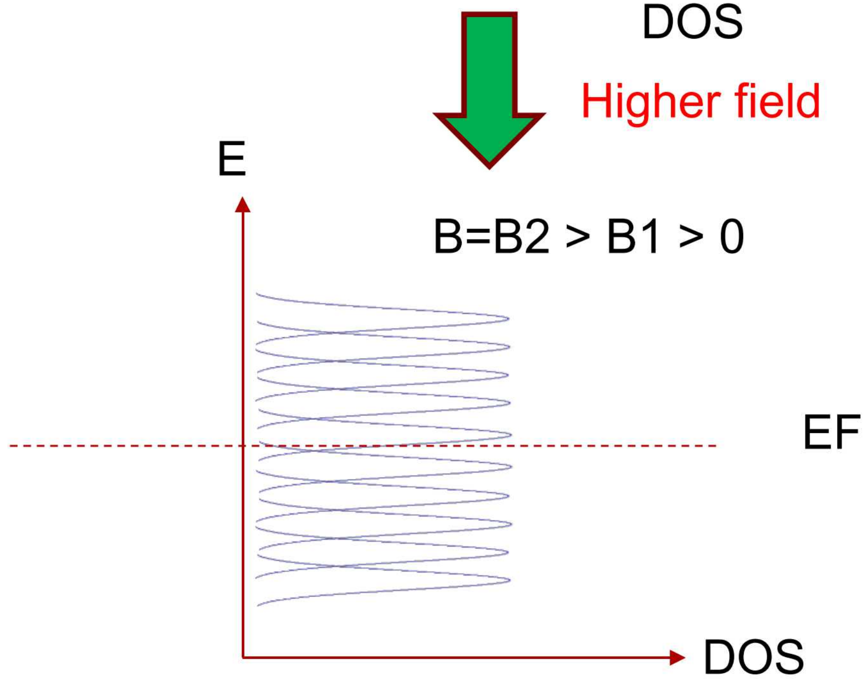


Cyclotron motion, $E_c = \hbar e B_{perp}/m^*$

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

Energy spectrum in a magnetic field





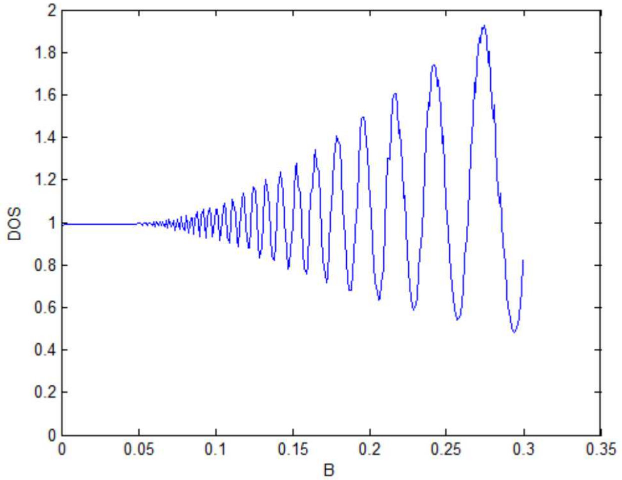
$$\frac{\Delta\rho}{\rho_0} \sim D(X)\,\frac{\Delta DOS}{DOS_0}$$

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

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

Temperature dependence
<=> cyclotron gap

DOS at Fermi energy at a fixed density



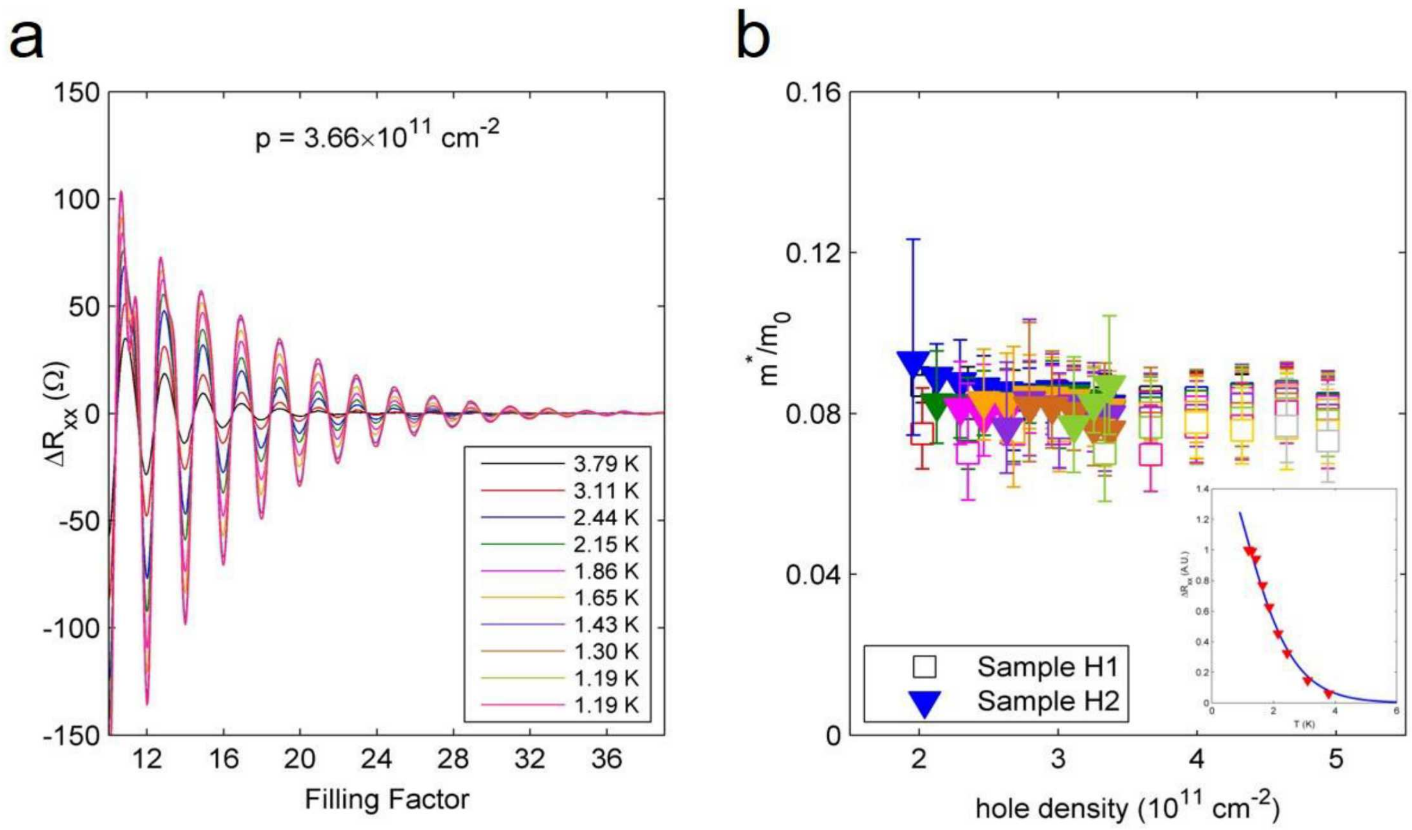
Physical properties – effective mass

- ~ 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

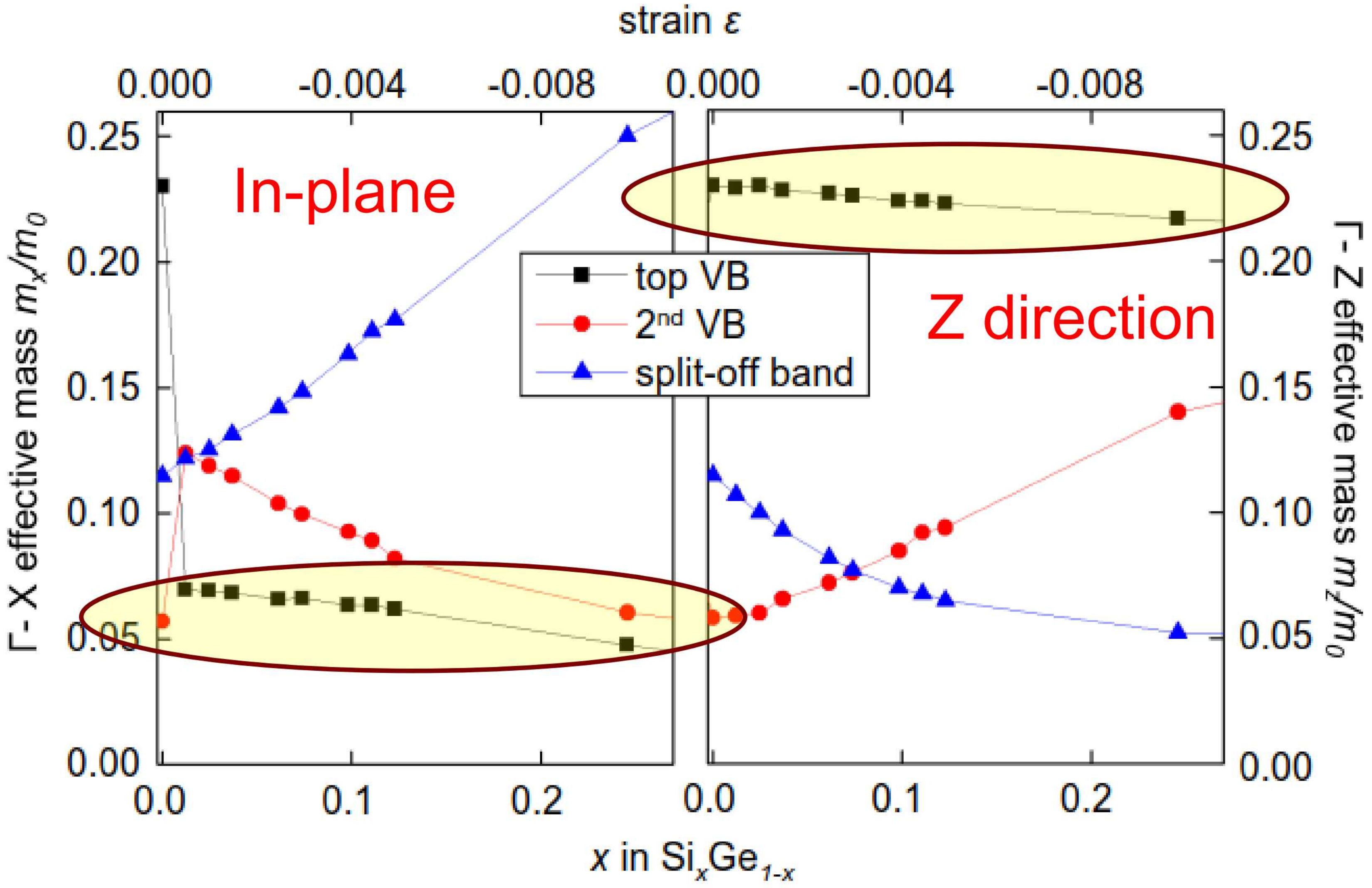
  => larger orbital gaps
  => can use higher T cryostats



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

Physical properties – effective mass

Theory



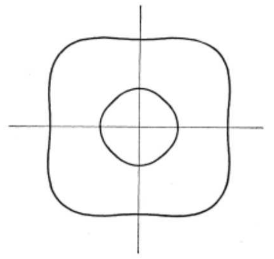


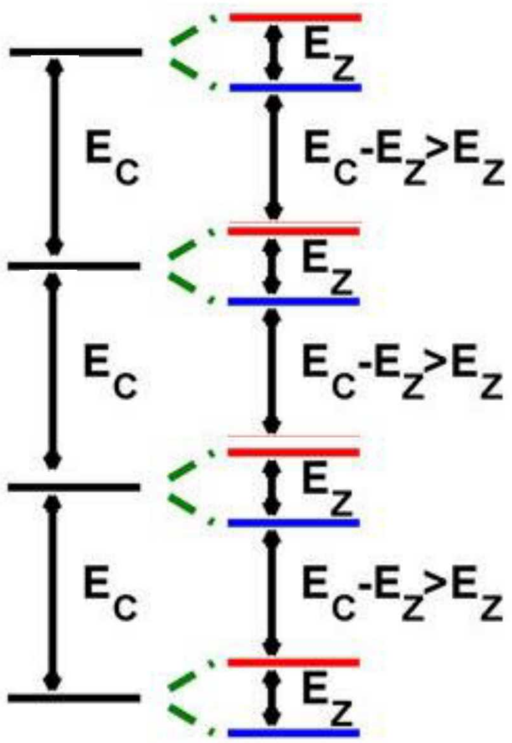
FIG. 8. Figures of constant energy in the (100) plane of k-space for the two fluted energy surfaces which are degenerate at the valence band edge; constants as for germanium.

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/(2πm*)

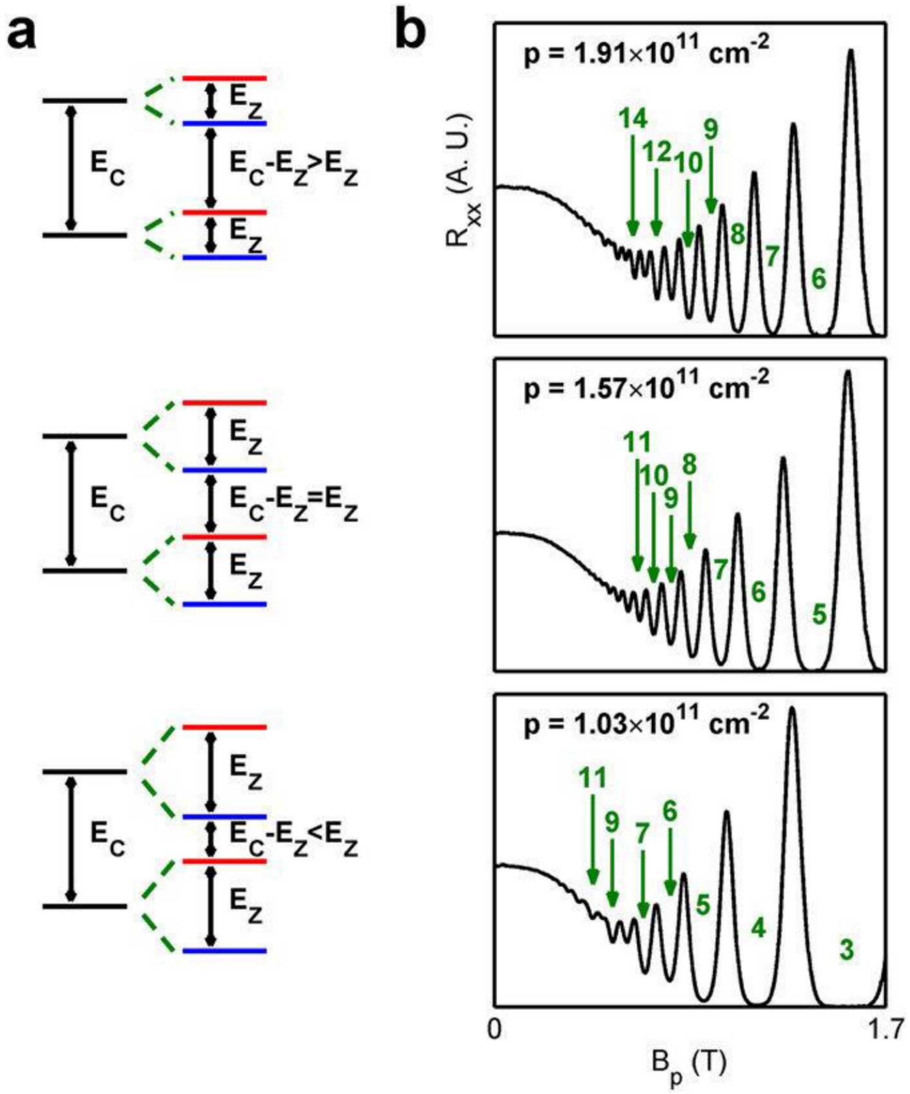
Ez is Zeeman gap: g*μB

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

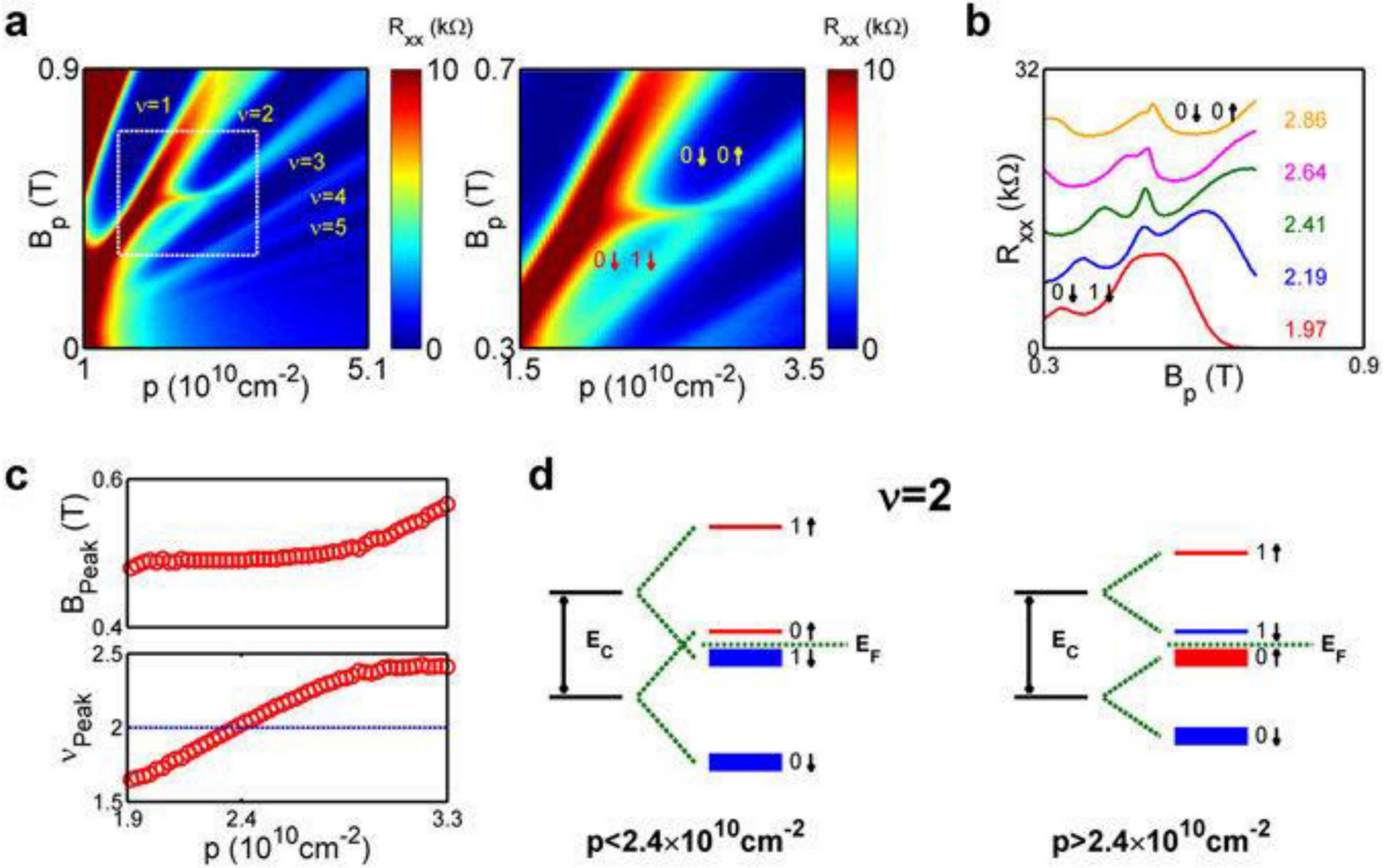
If Ec < 2Ez

⇒ 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)

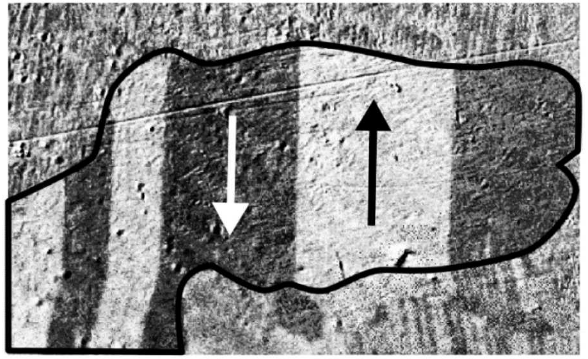
Quantum Hall ferromagnetic transition

Sandia National Laboratories

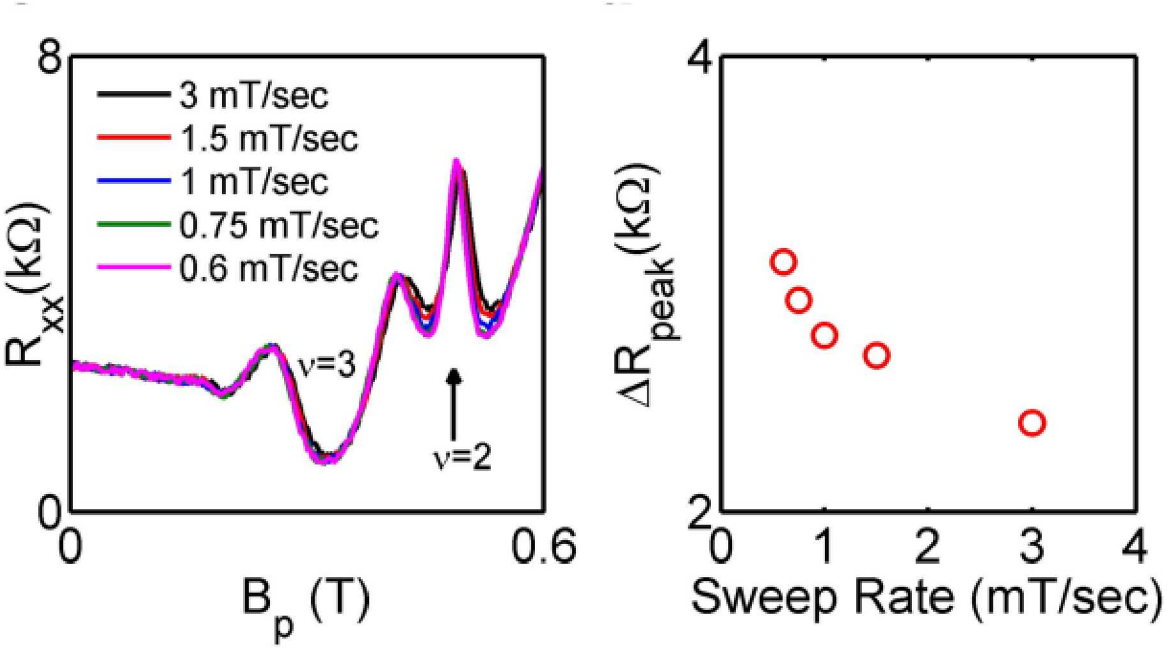
The physical picture of the system at the transition:

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.



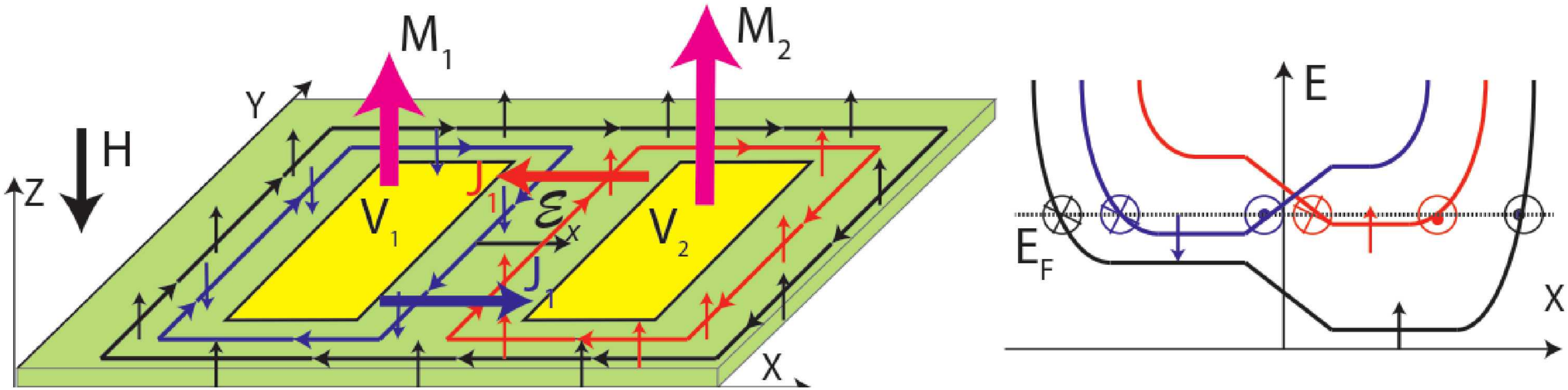
by S. Zurek, E. Magnetica, CC-BY-3.0



Lu, Scientific Reports 7, 2468 (2017)

Quantum Hall ferromagnetic transition

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

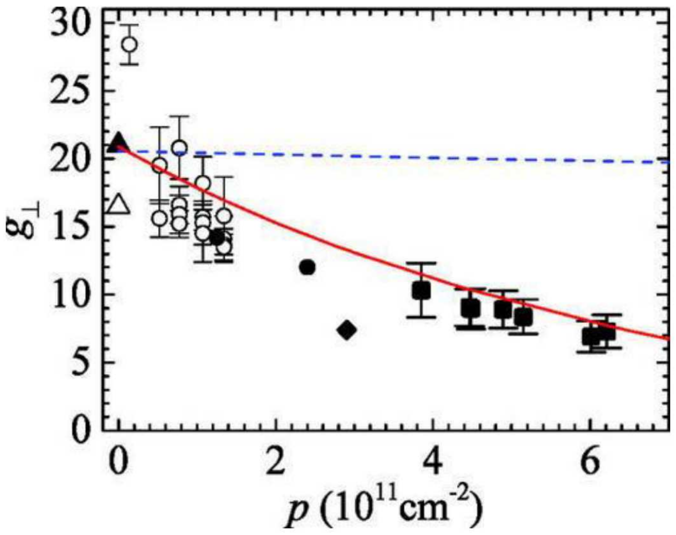


"Impurity-generated non-Abelions"
Simion Phys. Rev. B 97, 245107 (2018)

Physical properties – g factor

- ~ 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).

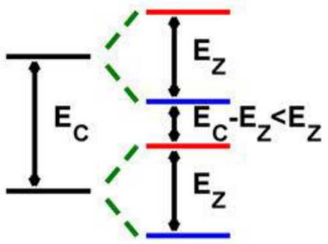


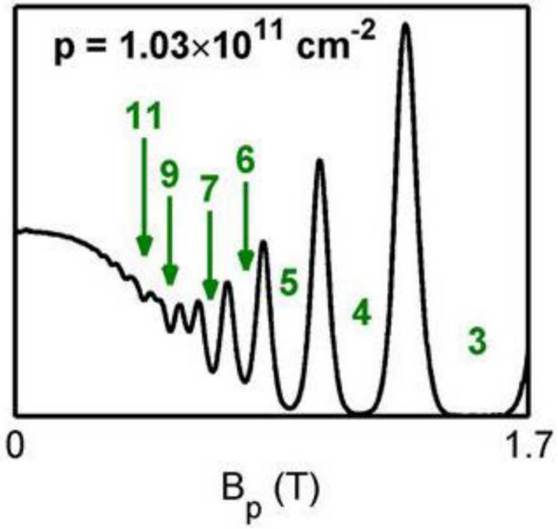
6x6 k.p

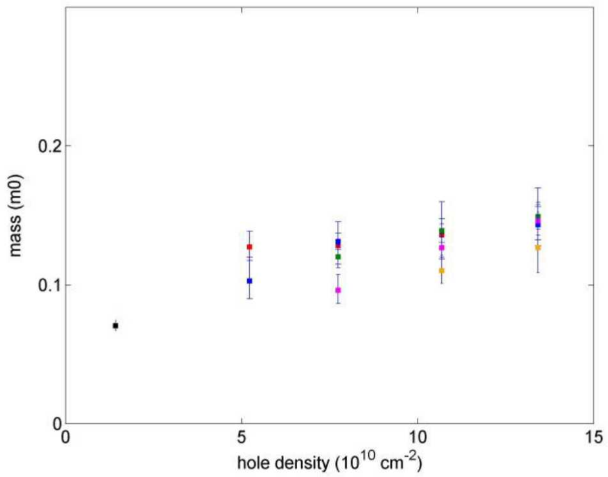
Drichko J. Appl. Phys. 123, 165703 (2018)

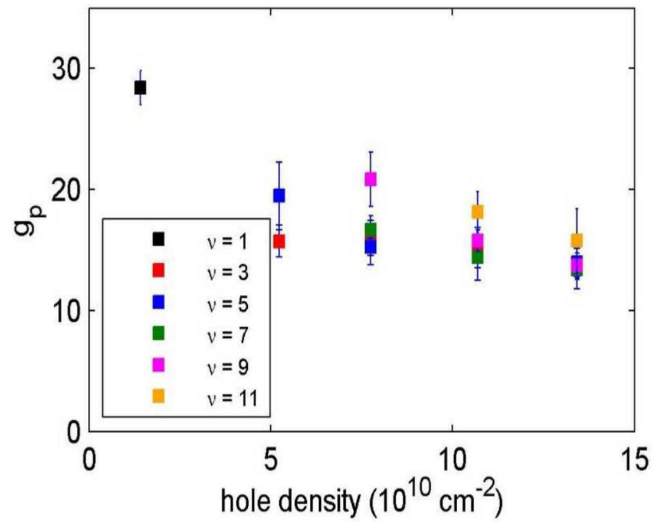
$P<1.6 \times 10^{11}\ \text{cm}^{-2}$

$0.5\ E_c < E_z < E_c$









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

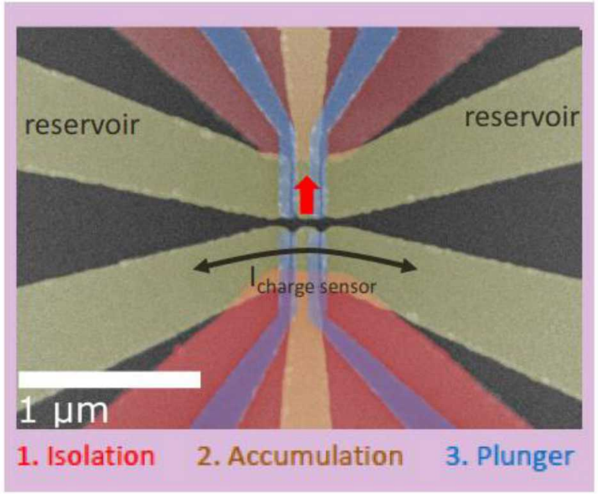
Spin qubits in Ge/SiGe

Implications for Quantum Dots

- Low Disorder
  - Help Dot-Dot Coupling
- Small Effective Mass
  - Help Dot-Dot coupling
  - Easier Lithography
- Anistropic 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

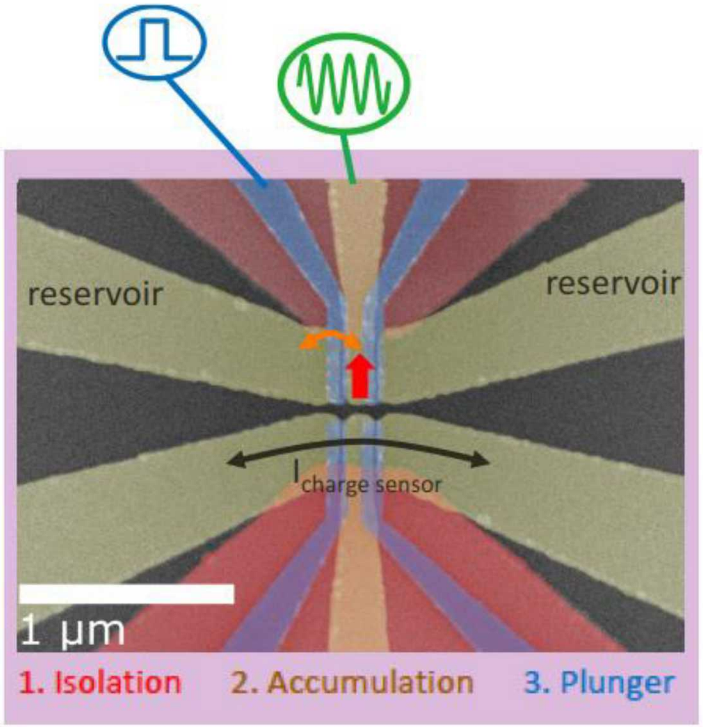
Surface electrodes used to laterally confine hole



Hardy, unpublished.

Spin qubits in Ge/SiGe

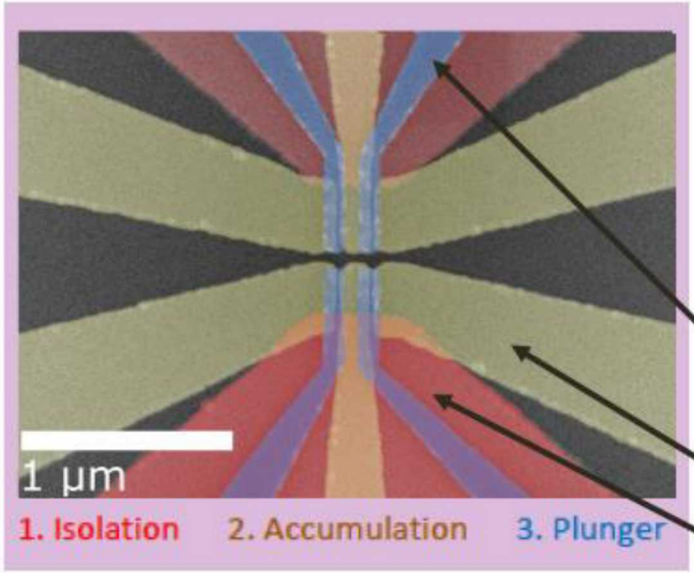
- Single Hole confined to lateral quantum dot
- Spin Qubit States: $m_j = \pm 3/2$
- Qubit readout and initialization through energy selective tunneling to reservoir
- Qubit Control through microwaves applied to gate
- Occupancy detected through nearby charge sensor



Hardy, unpublished.

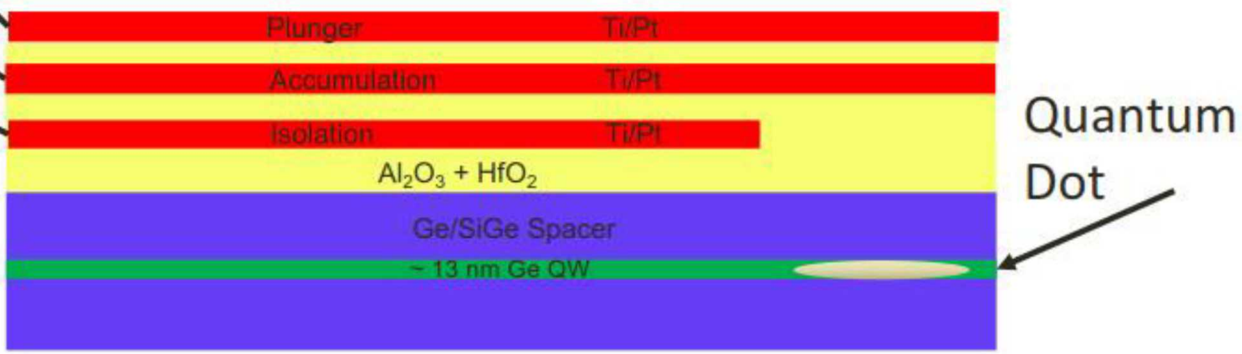
Spin qubits in Ge/SiGe

Sandia National Laboratories



Goals:

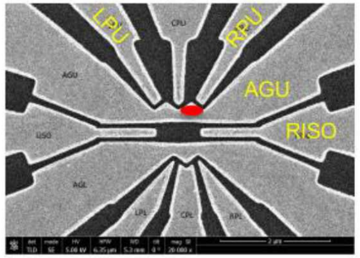
- Independent Control of occupation and tunnel barriers
- Tighter Confinement
- Low Capacitance for EDSR



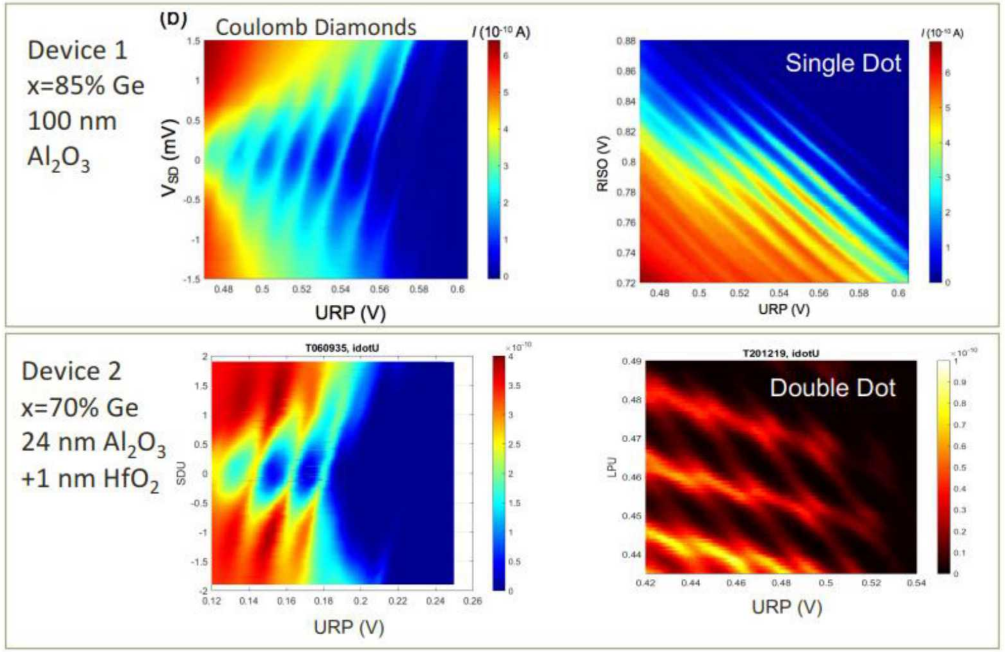
Ga implanted Ohmic contacts

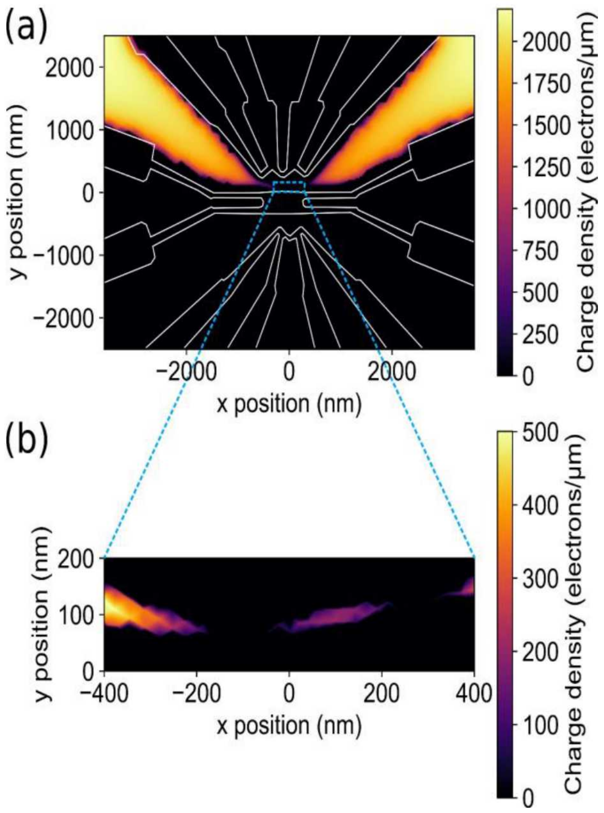
Hardy, unpublished.

Spin qubits in Ge/SiGe



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



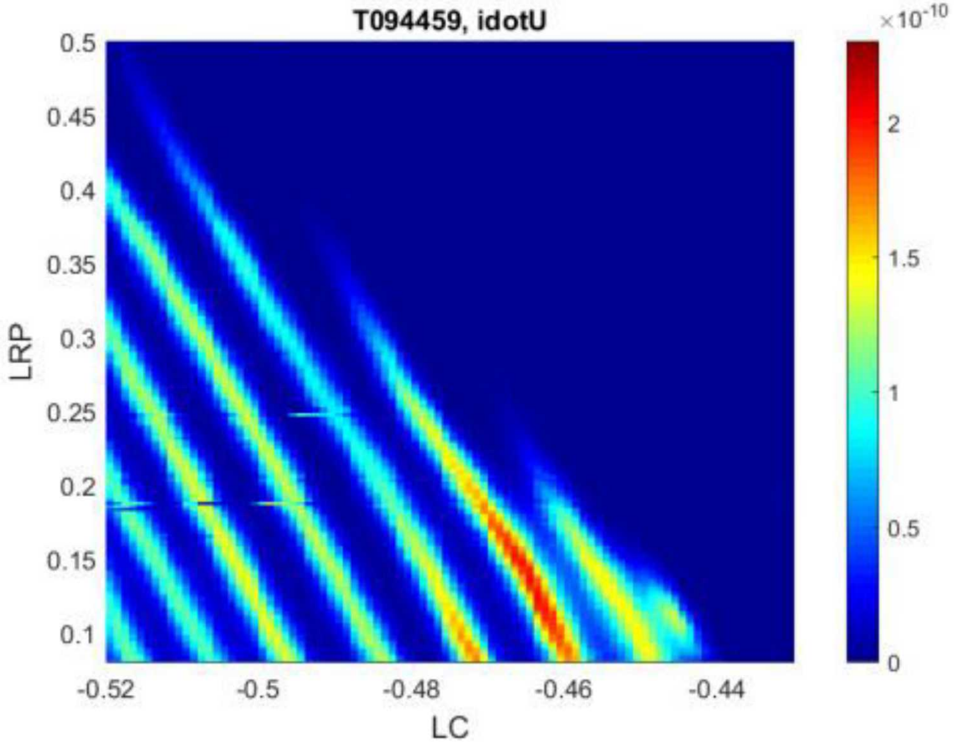


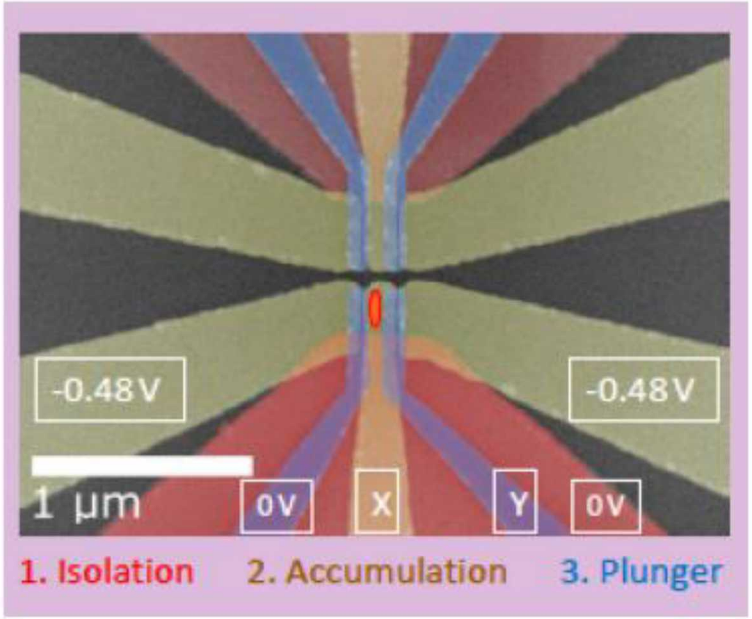
Hardy *et al.*, *Nanotechnology*, 30, 215202 (2019)

Spin qubits in Ge/SiGe

Sandia National Laboratories

Three Metal Layer Device





Coulomb Blockade observed in the three-metal-layer devices

Hardy, unpublished.

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