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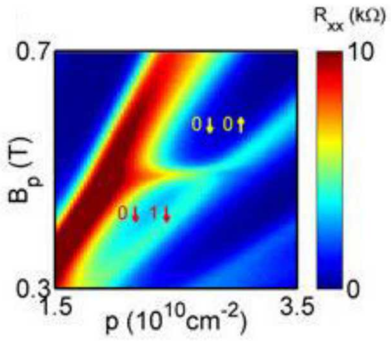
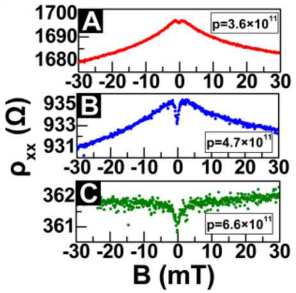
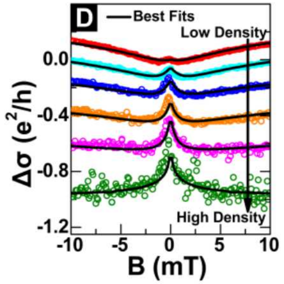
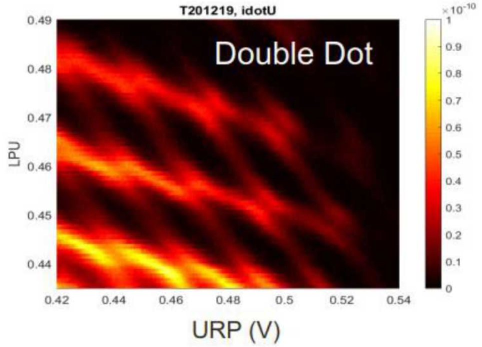
SAND2019-6343C

Holes in Germanium Quantum Wells and Their Potential Applications in Quantum Computing









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

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- NHMFL

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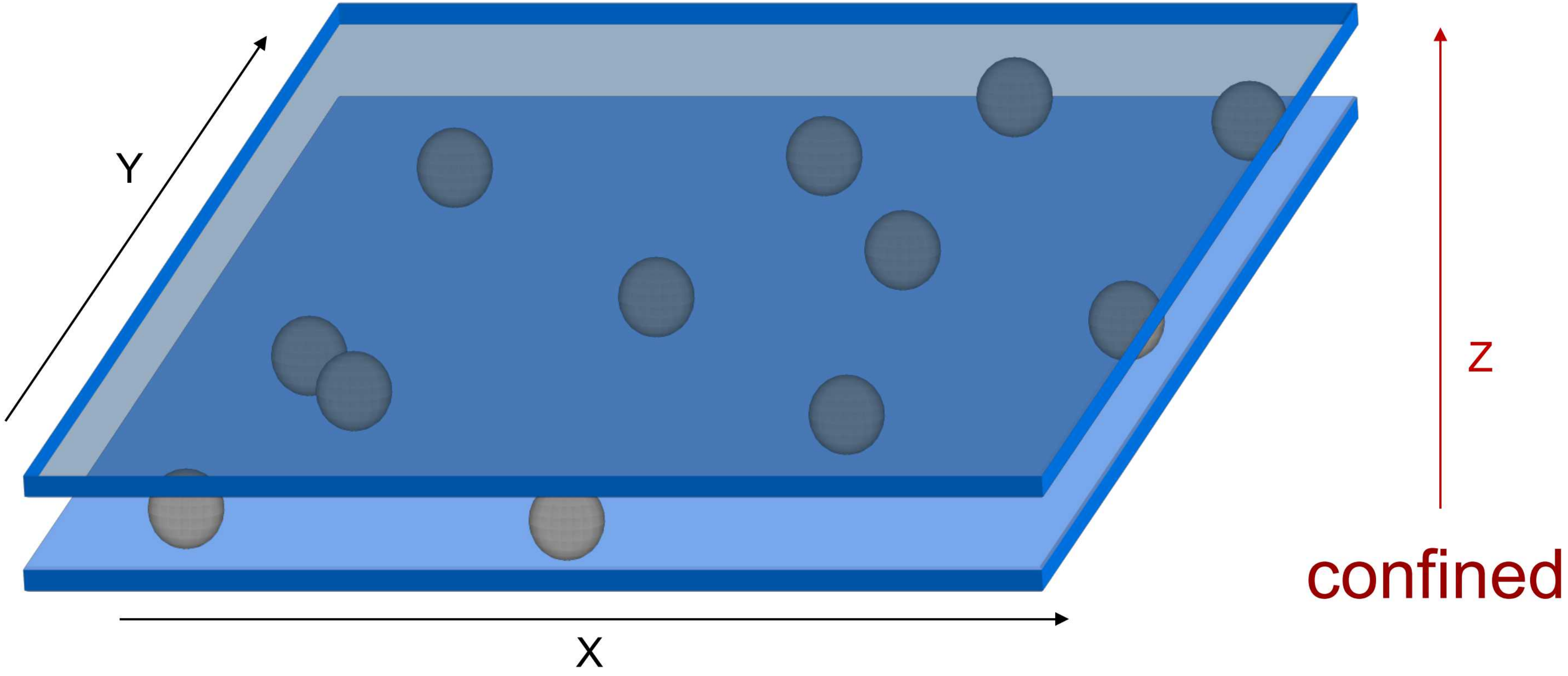
Outline

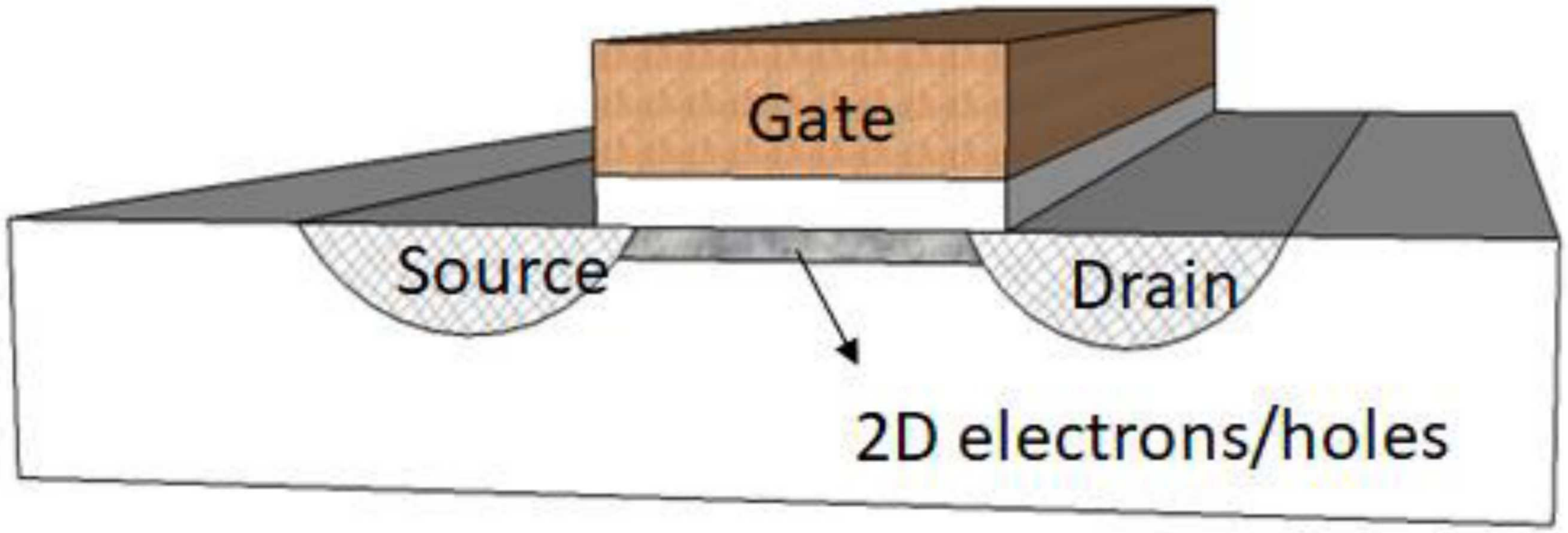
- Ge/SiGe heterostructures
- Device operation
- Properties of 2D holes in Ge/SiGe
- Quantum Hall ferromagnetic transition
- Spin qubits in Ge/SiGe
- Summary

2D electrons/holes



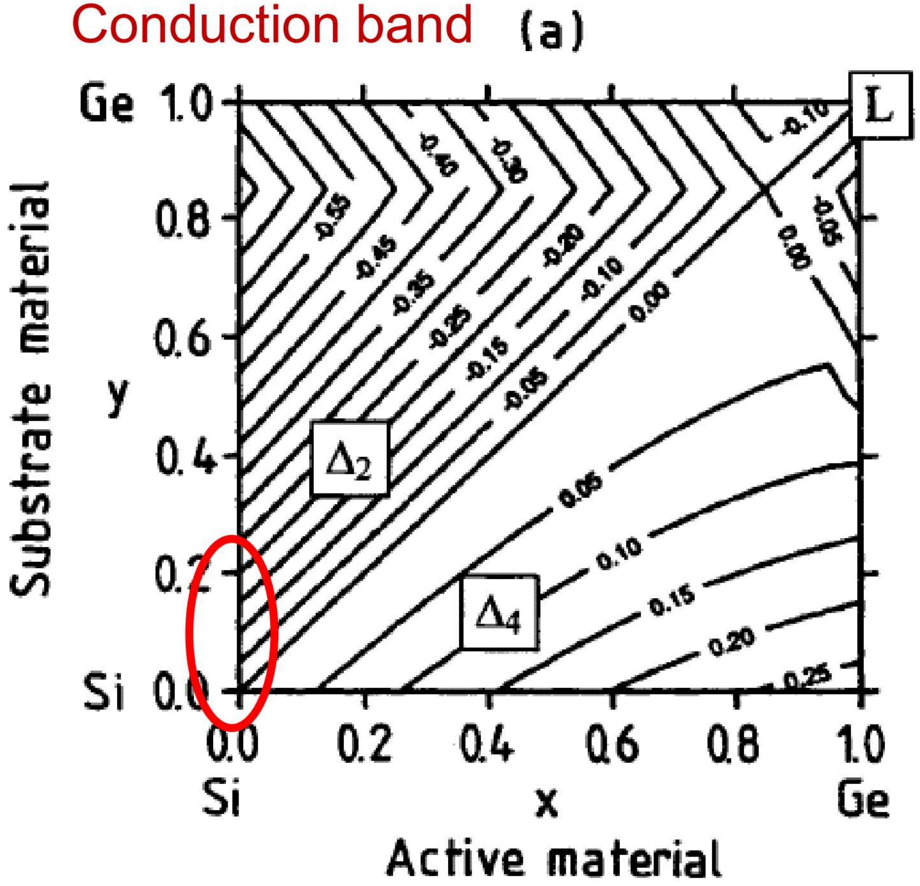
2D electrons in Si

Si MOSFET

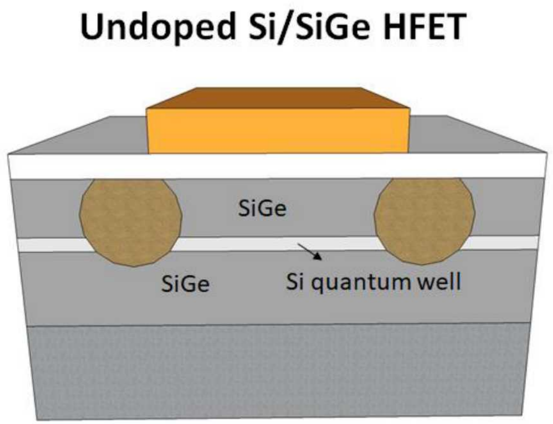


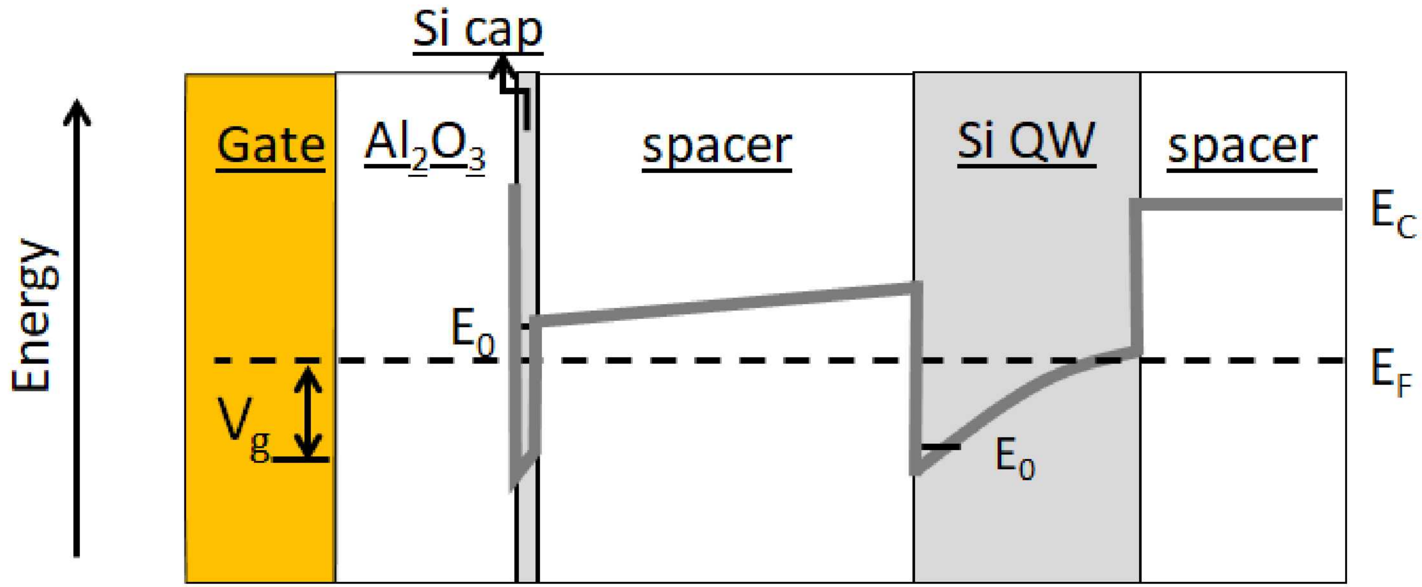
Band alignment of Si/SiGe heterostructures

Conduction band



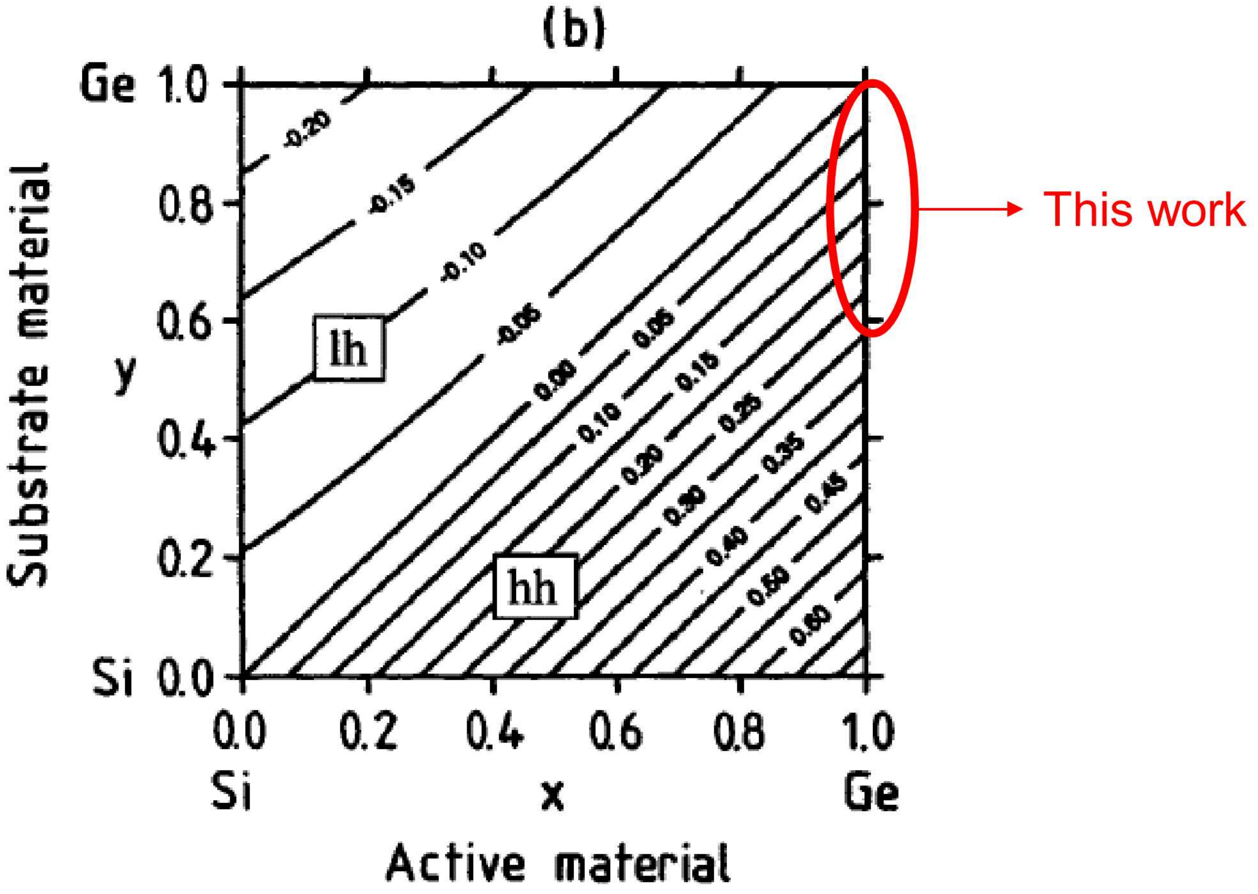
2D electrons in Si quantum wells





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

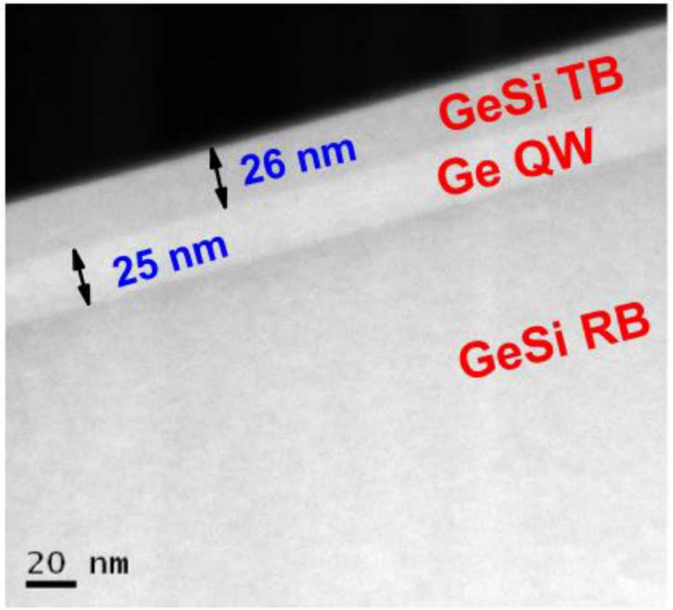
Band alignment of Ge/SiGe heterostructures

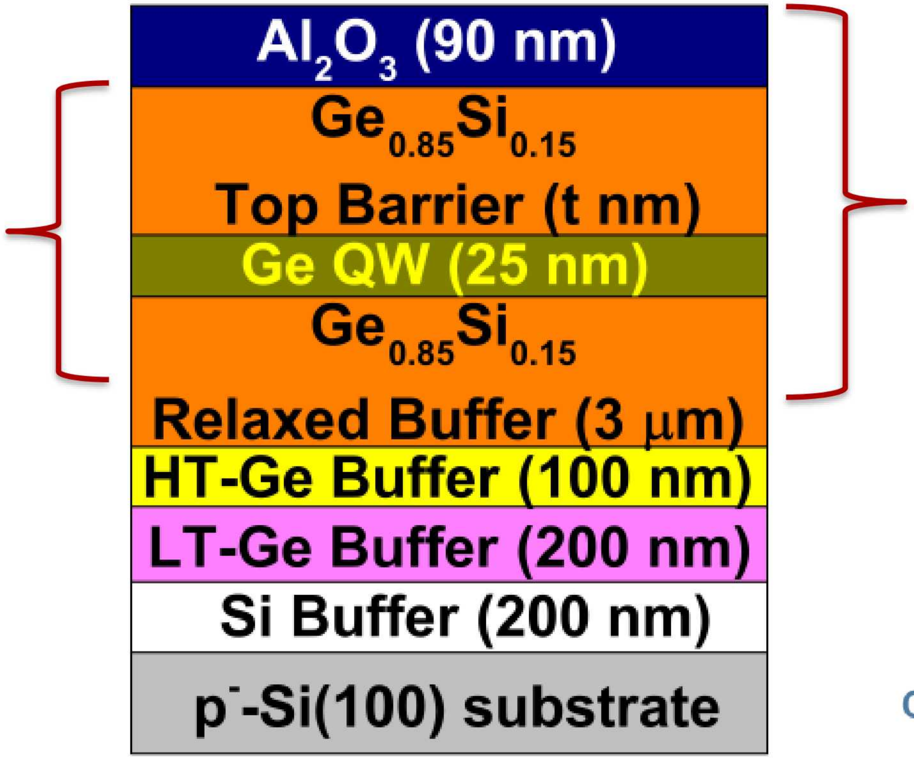


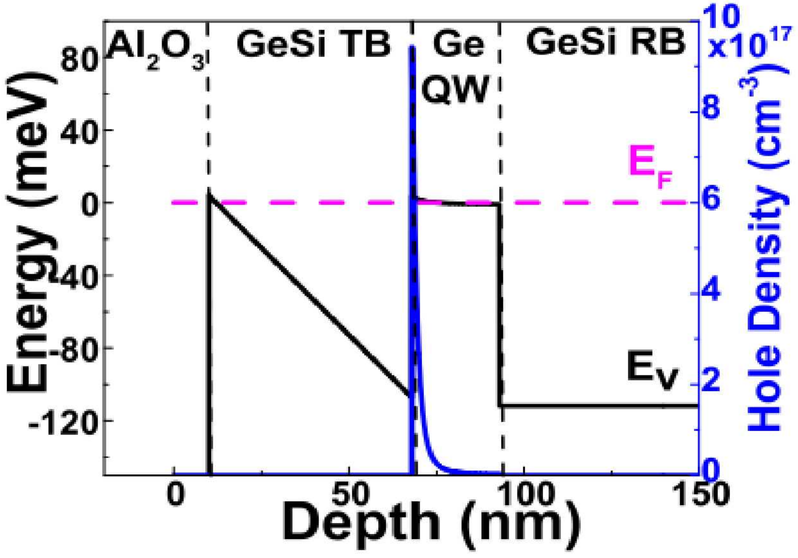
Valance band
2D holes in Ge quantum wells

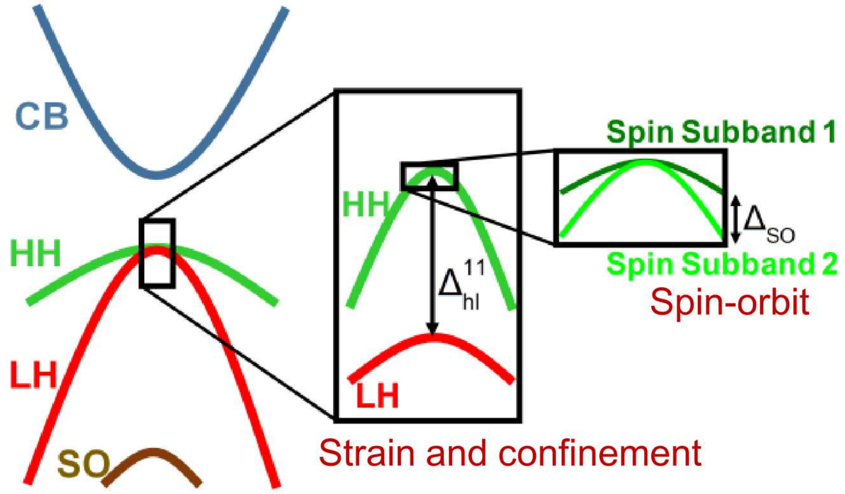
Properties of Silicon Germanium and SiGe: Carbon. Edited by: Kasper, Erich; Lyutovich, Klara (2000)

Undoped Ge/SiGe heterostructure field-effect transistors







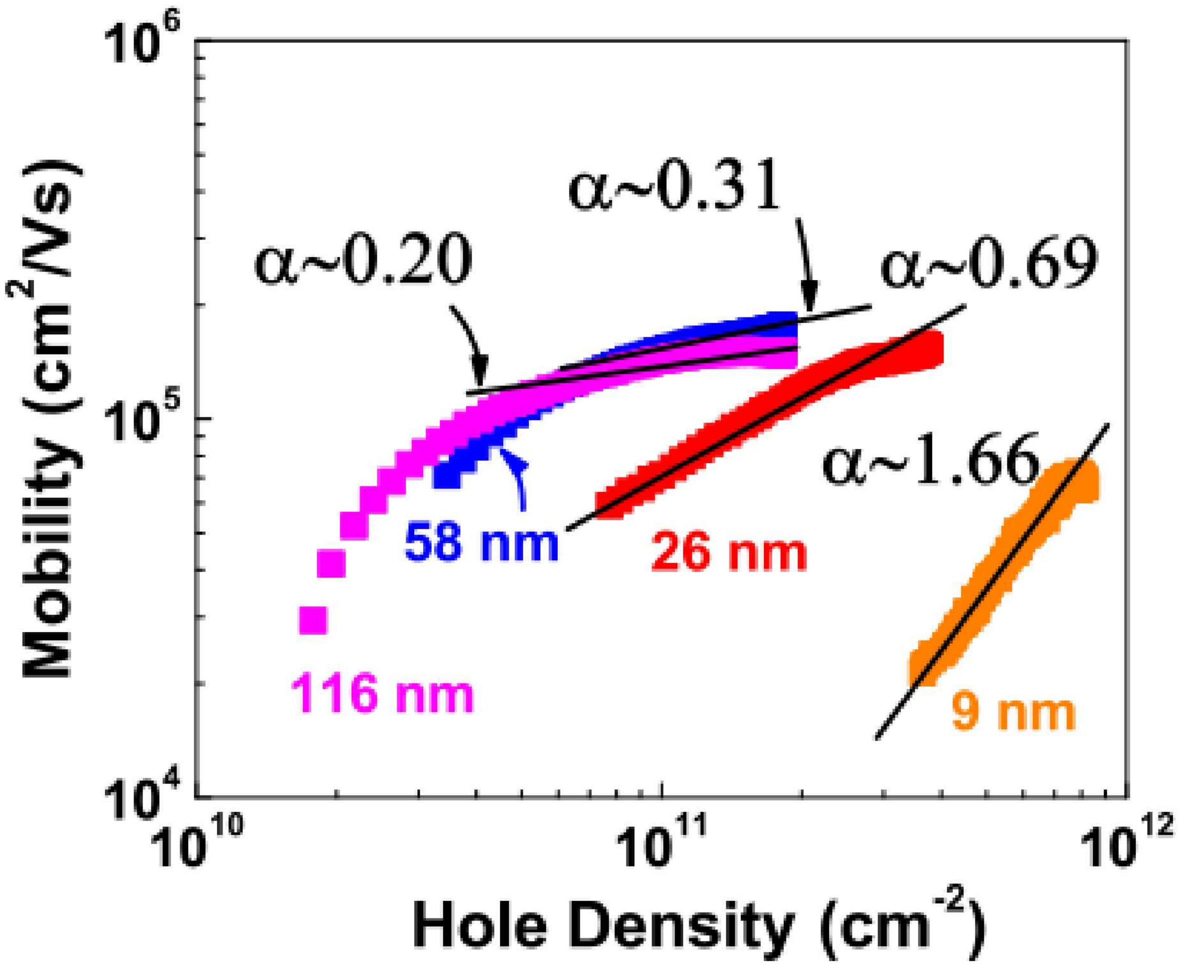


Laroche, Appl. Phys. Lett. 108, 233504 (2016)
Su, Phys. Rev. Mater. 1, 044601 (2017)

Device operation – mobility

- Mobilty on the order of 2×10^5 cm^2/Vs achievable
- Mobility increases with density
  => screening
- Shallower channels have lower mobilities
  => oxide/GeSi interface is disordered

T = 0.3 K



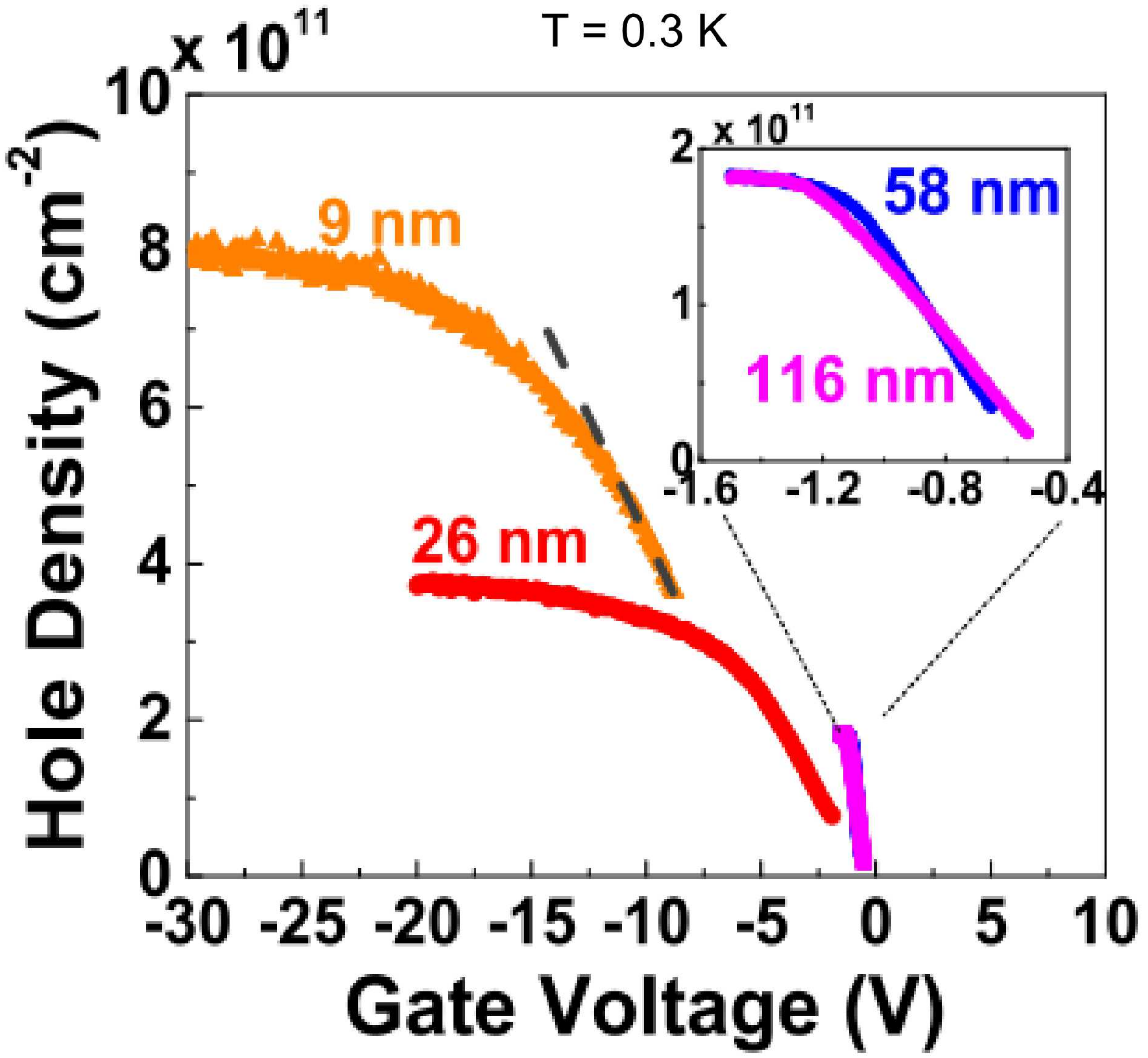
Su, Phys. Rev. Mater. 1, 044601 (2017)

Device operation – 2D hole density

- The 2D hole density saturates.

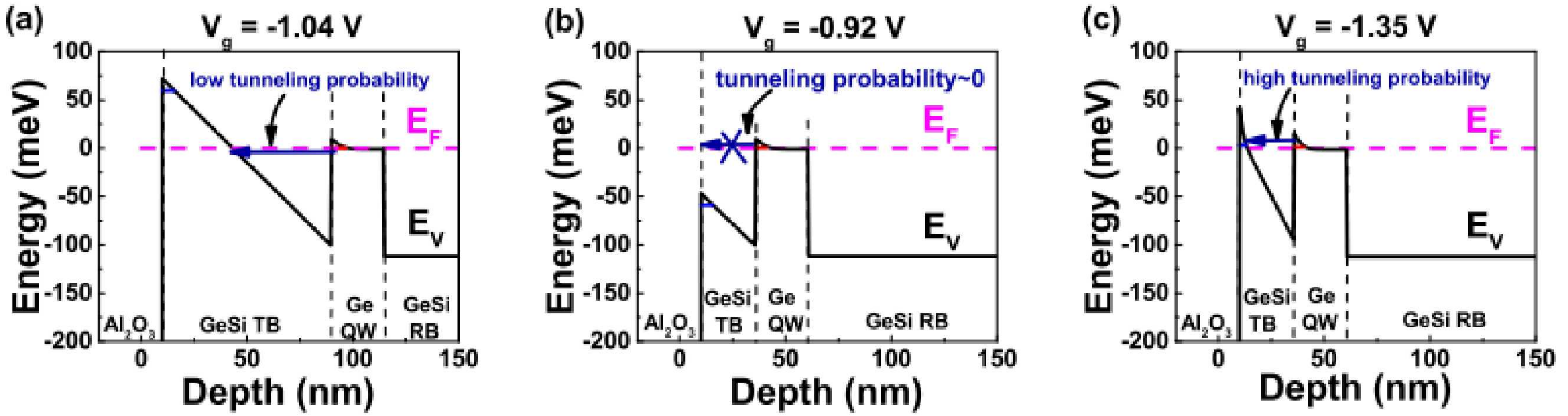
- Shallow channels
  - ➢ High saturation densities, depth dependent.
  - ➢ Small slopes (capacitances)

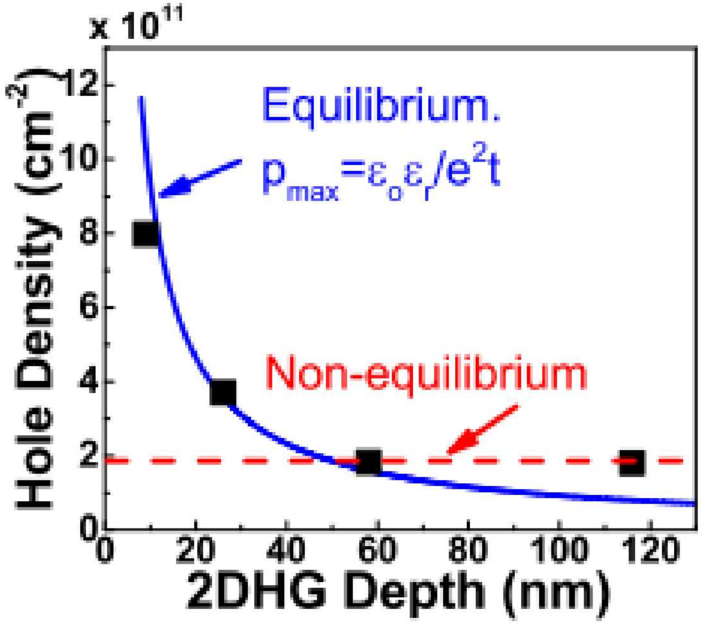
- Deep channels
  - ➢ Low saturation densities, depth independent.
  - ➢ Large slopes (capacitances)



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

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!

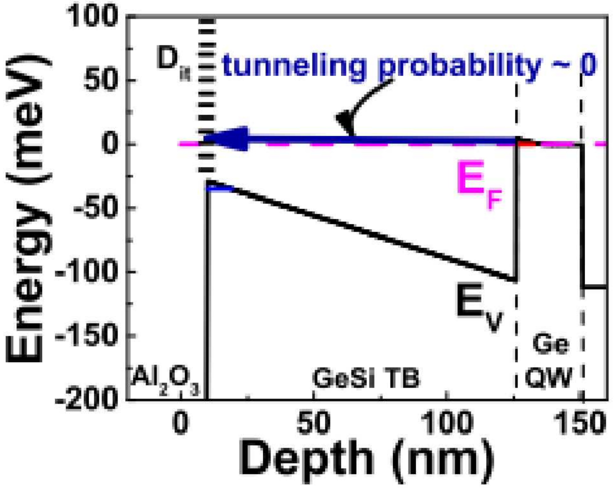
Shallow channels

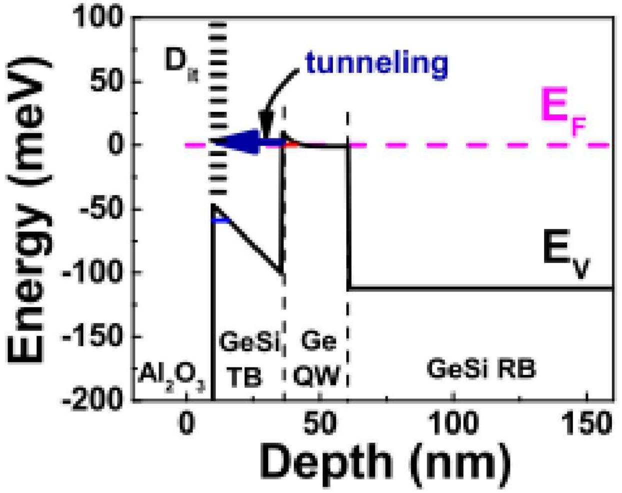
The tunneling rate is high (compared to experiment time scales).

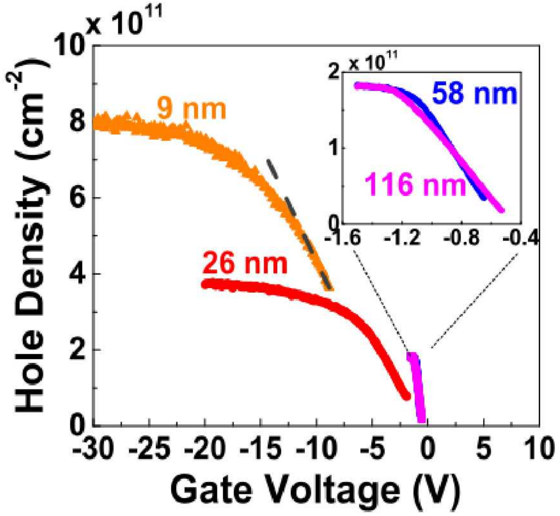
The density probed by the Hall effect approaches the equilibrium case.

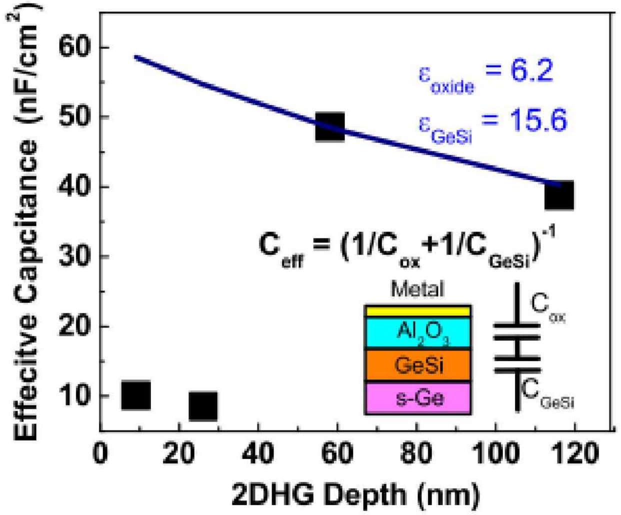
Su, Phys. Rev. Mater. 1, 044601 (2017)

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

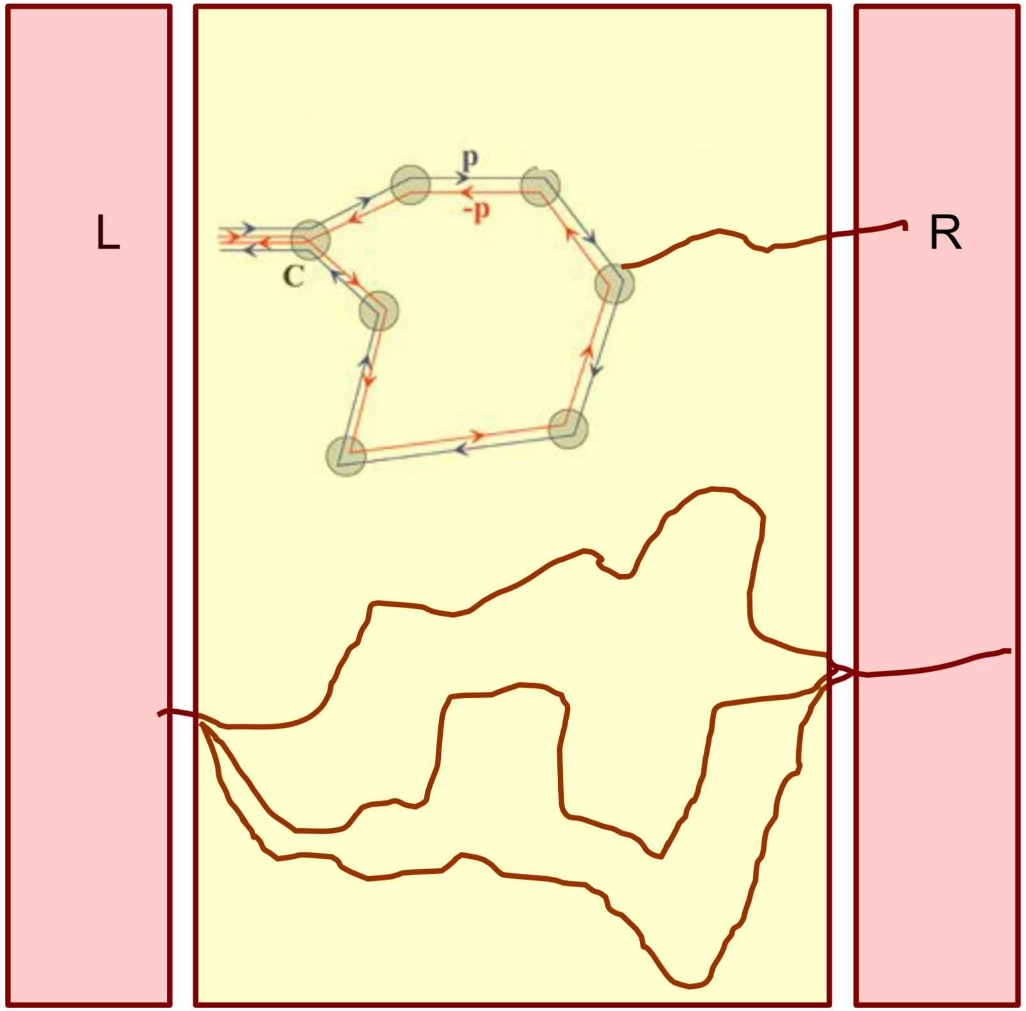
The tunnel rate is high.

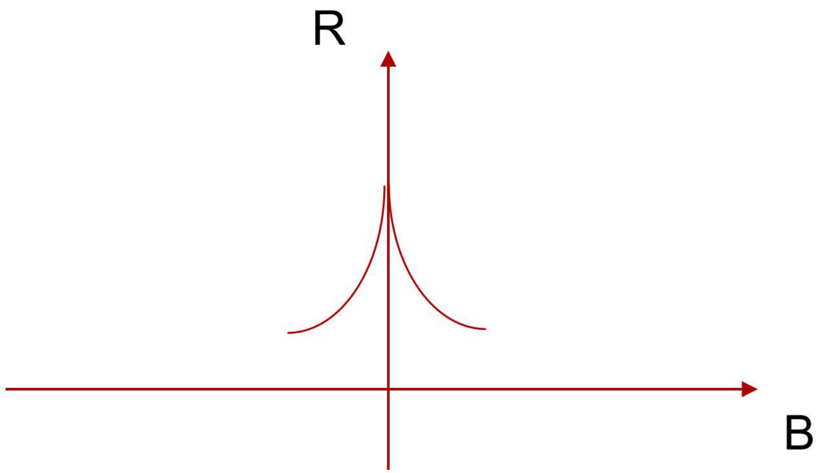
The traps at the oxide/GeSi interface need to be filled before the Fermi level can move.

$C_{eff} << C_{geometric}$

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

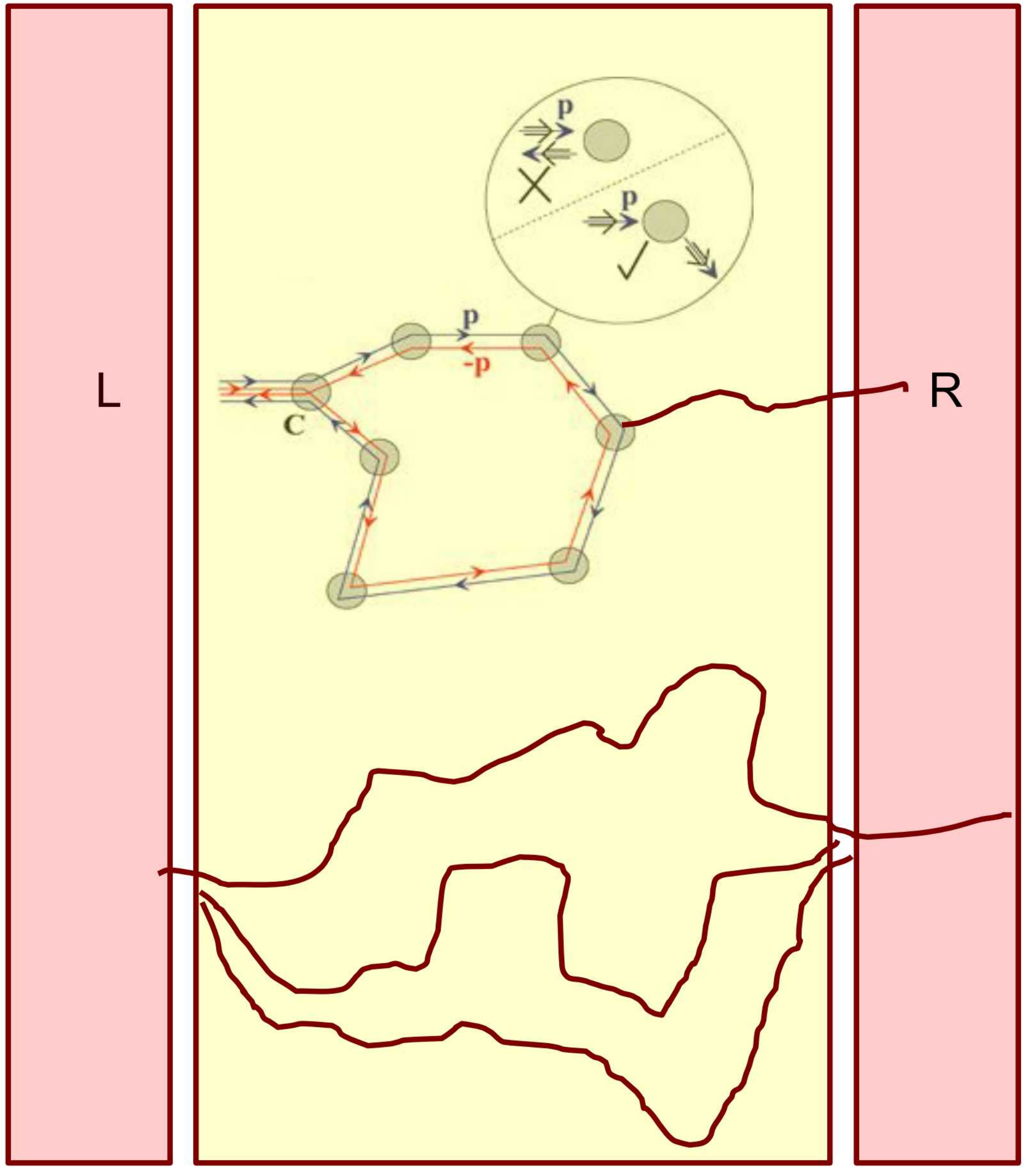
Weak localization (no spin-orbit coupling)



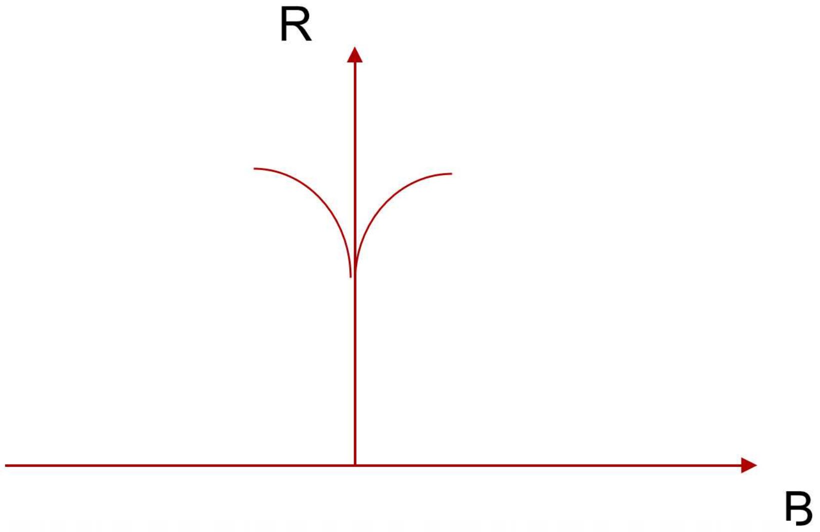


Adapted from McCann Physics 2, 98

Weak anti-localization (spin-orbit coupling)



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



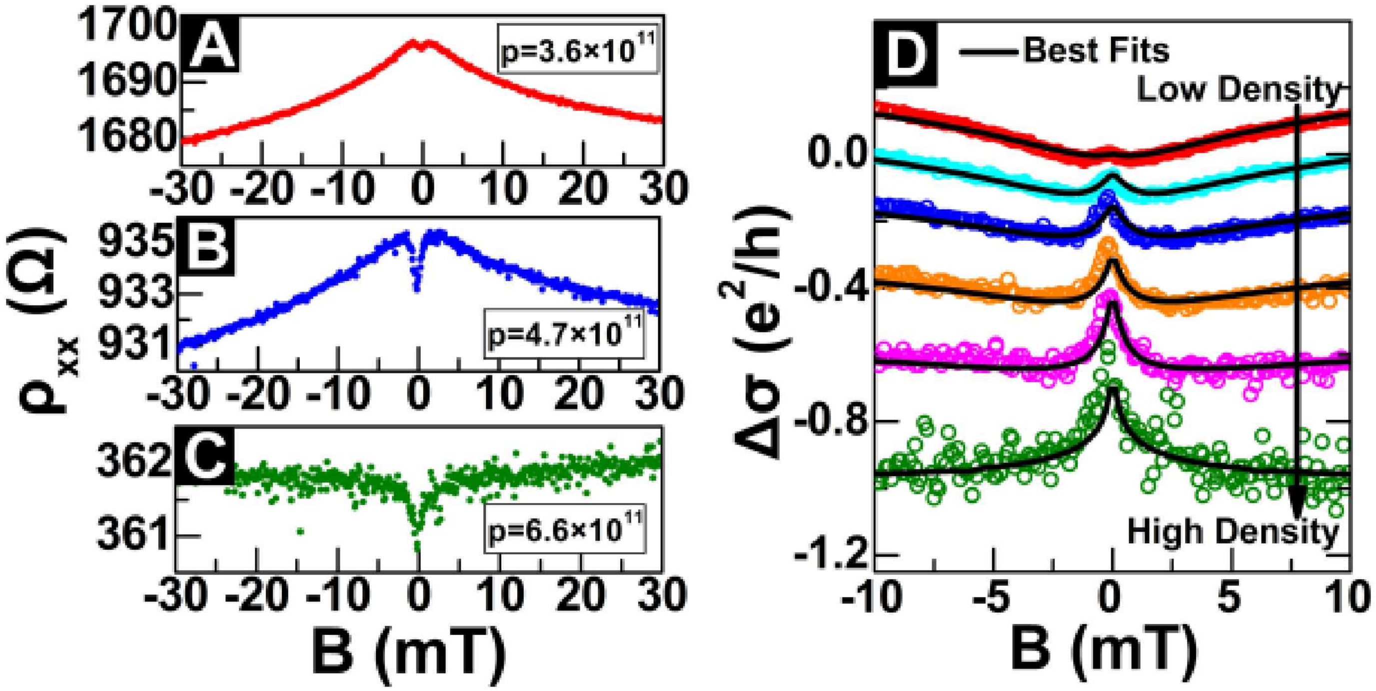
$$\Delta\sigma(B)-\Delta\sigma(0)=\frac{e^2}{2\pi^2\hbar}\left\{\psi\left(\frac{1}{2}+\frac{H_\varphi}{B}+\frac{H_{SO}}{B}\right)+\frac{1}{2}\psi\left(\frac{1}{2}+\frac{H_\varphi}{B}+\frac{2H_{SO}}{B}\right)-\frac{1}{2}\psi\left(\frac{1}{2}+\frac{H_\varphi}{B}\right)-\ln\frac{H_\varphi+H_{SO}}{B}-\frac{1}{2}\ln\frac{H_\varphi+2H_{SO}}{B}+\frac{1}{2}\ln\frac{H_\v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

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



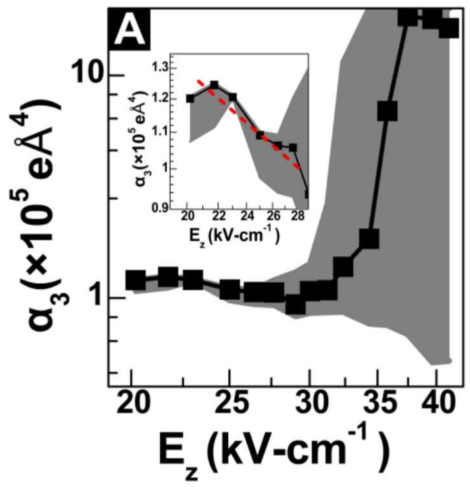
Cubic Rashba: ~(sin3θ,-cos3θ)

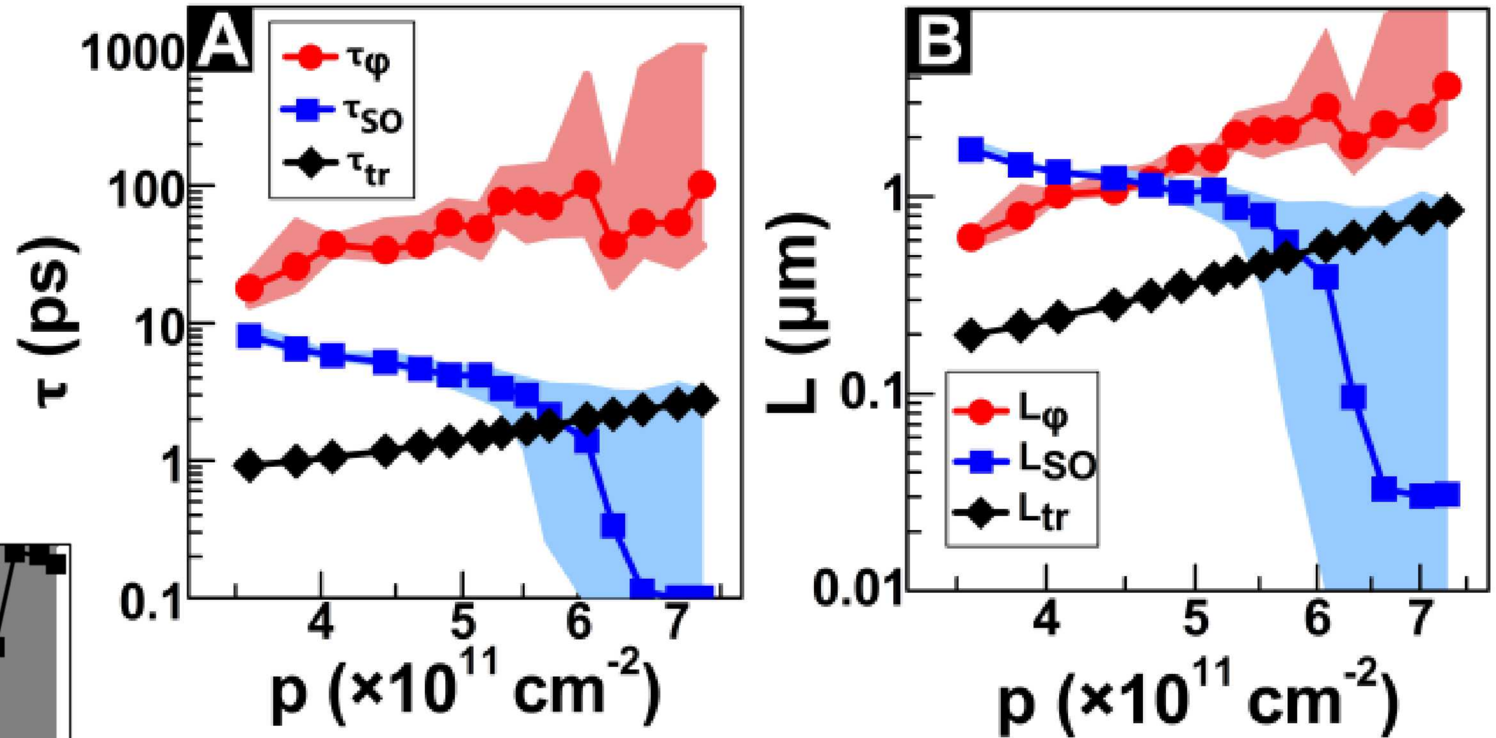
Chou, Nanoscale 10, 20559 (2018)

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.

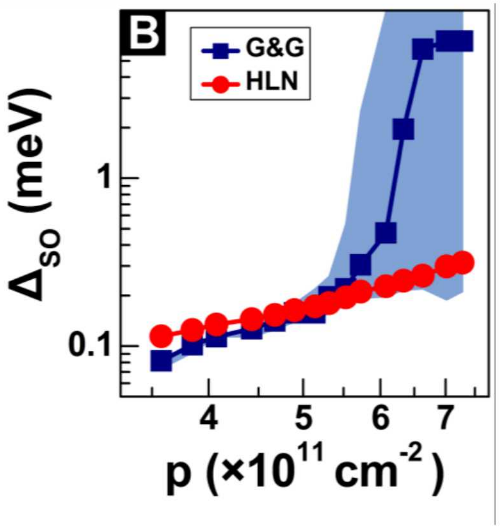




Chou, Nanoscale 10, 20559 (2018)

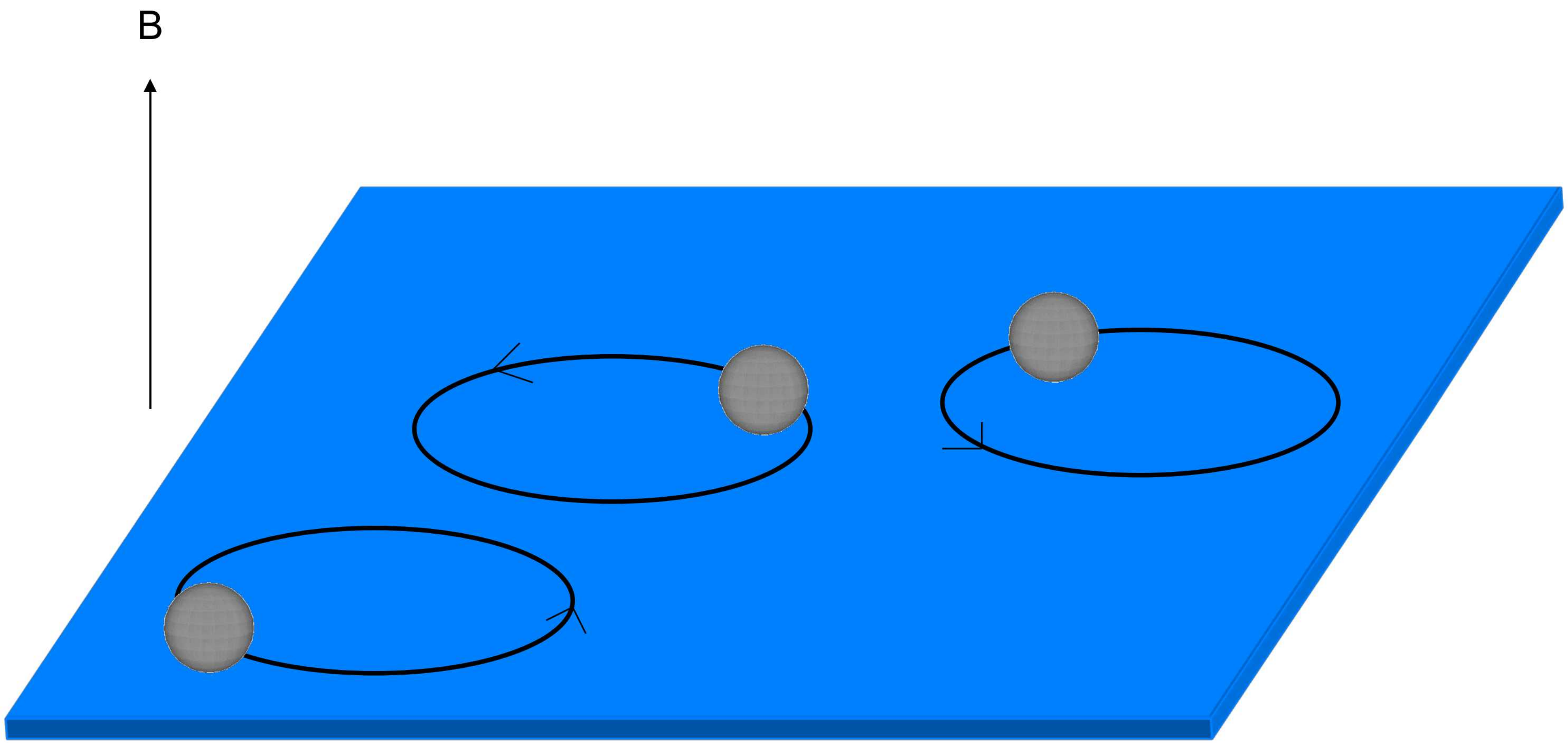
Physical properties – weak antilocalization beyond diffusive regime

- 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)

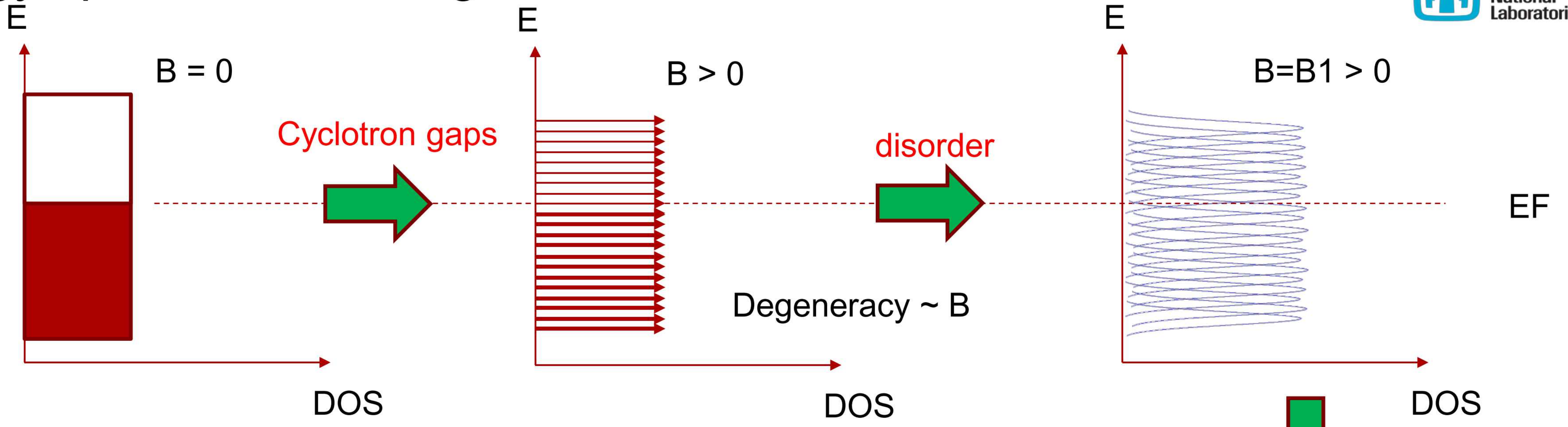
In a perpendicular magnetic field…

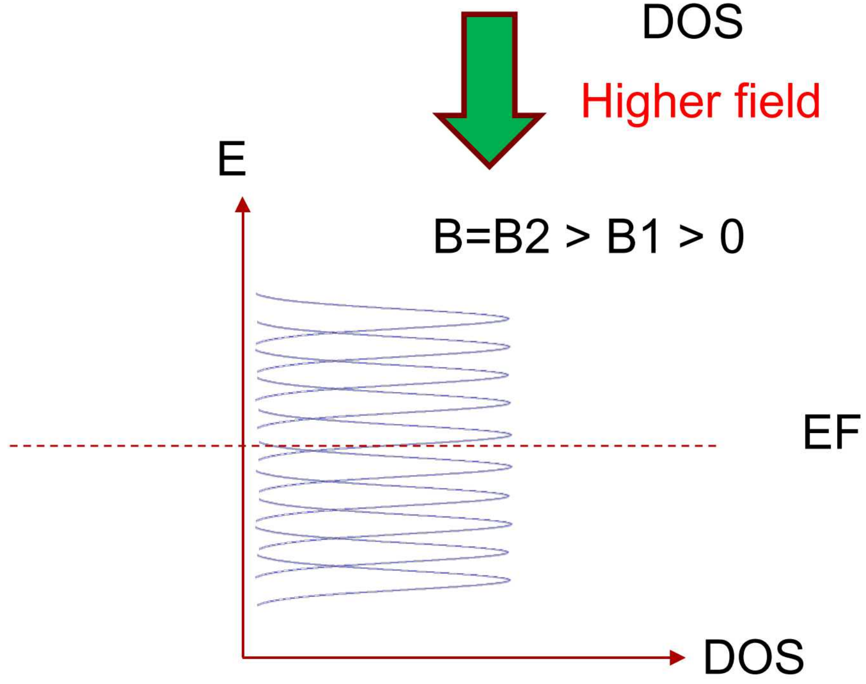


Cyclotron motion, $E_c = \hbar e B_{perp}/m^*$

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

Energy spectrum in a magnetic field

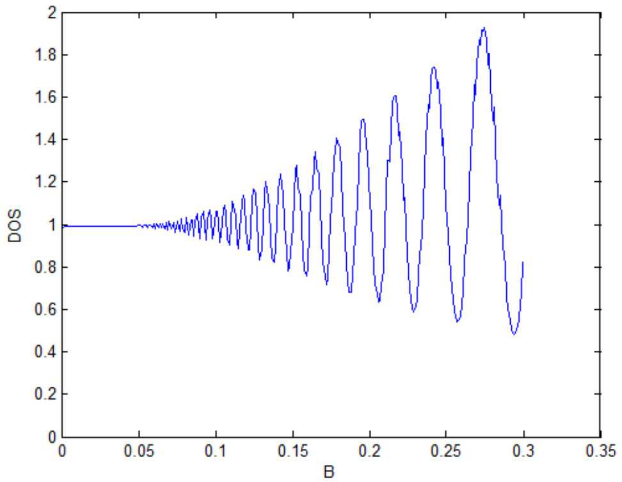




$$\frac{\Delta\rho}{\rho_0} \sim D(X)\,\frac{\Delta DOS}{DOS_0}$$
$$D(X) = X/\sinh X$$
$$X = 2\pi kT/gap$$

Temperature dependence
<=> gap

DOS at Fermi energy at a fixed density



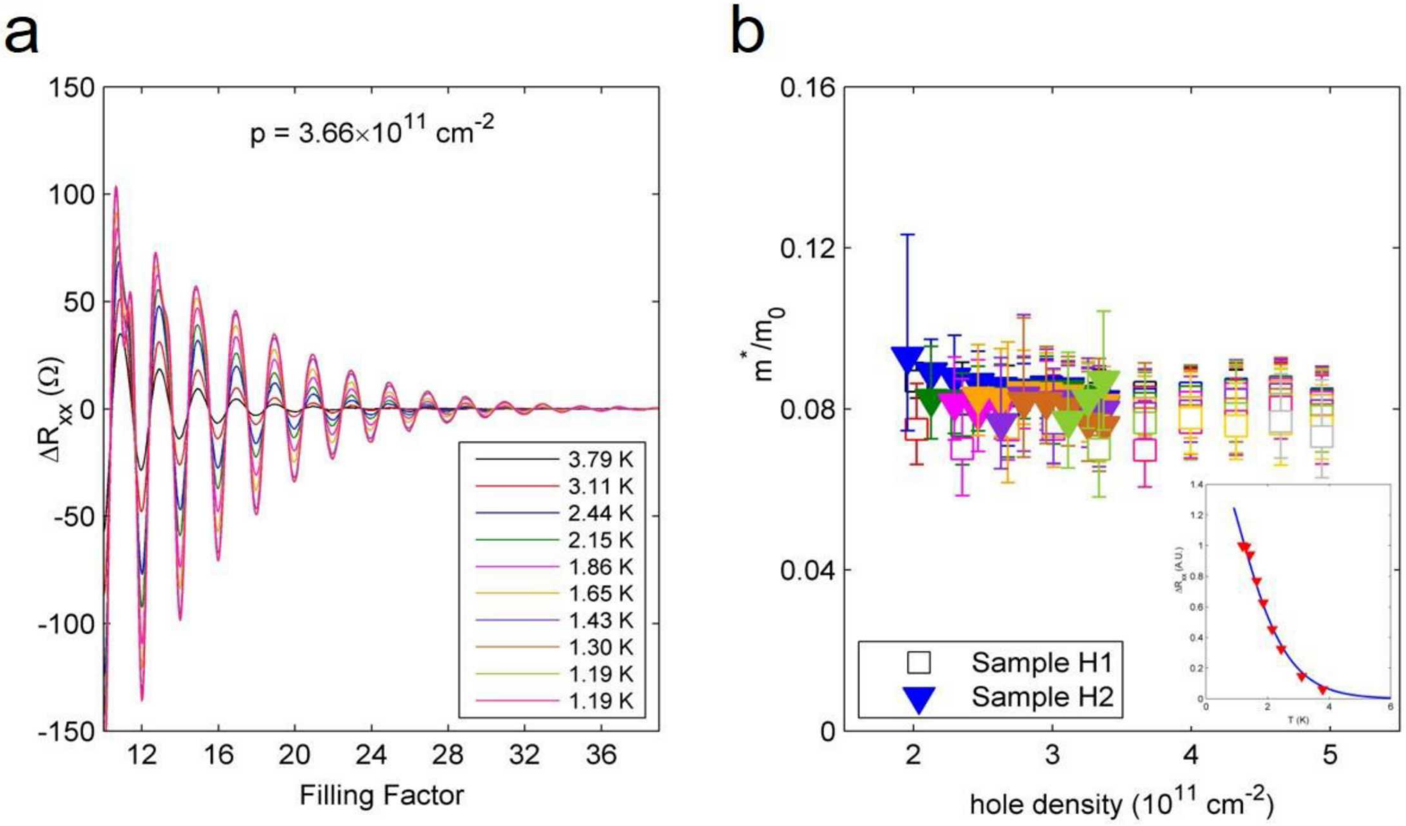
Physical properties – effective mass

- ~ 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

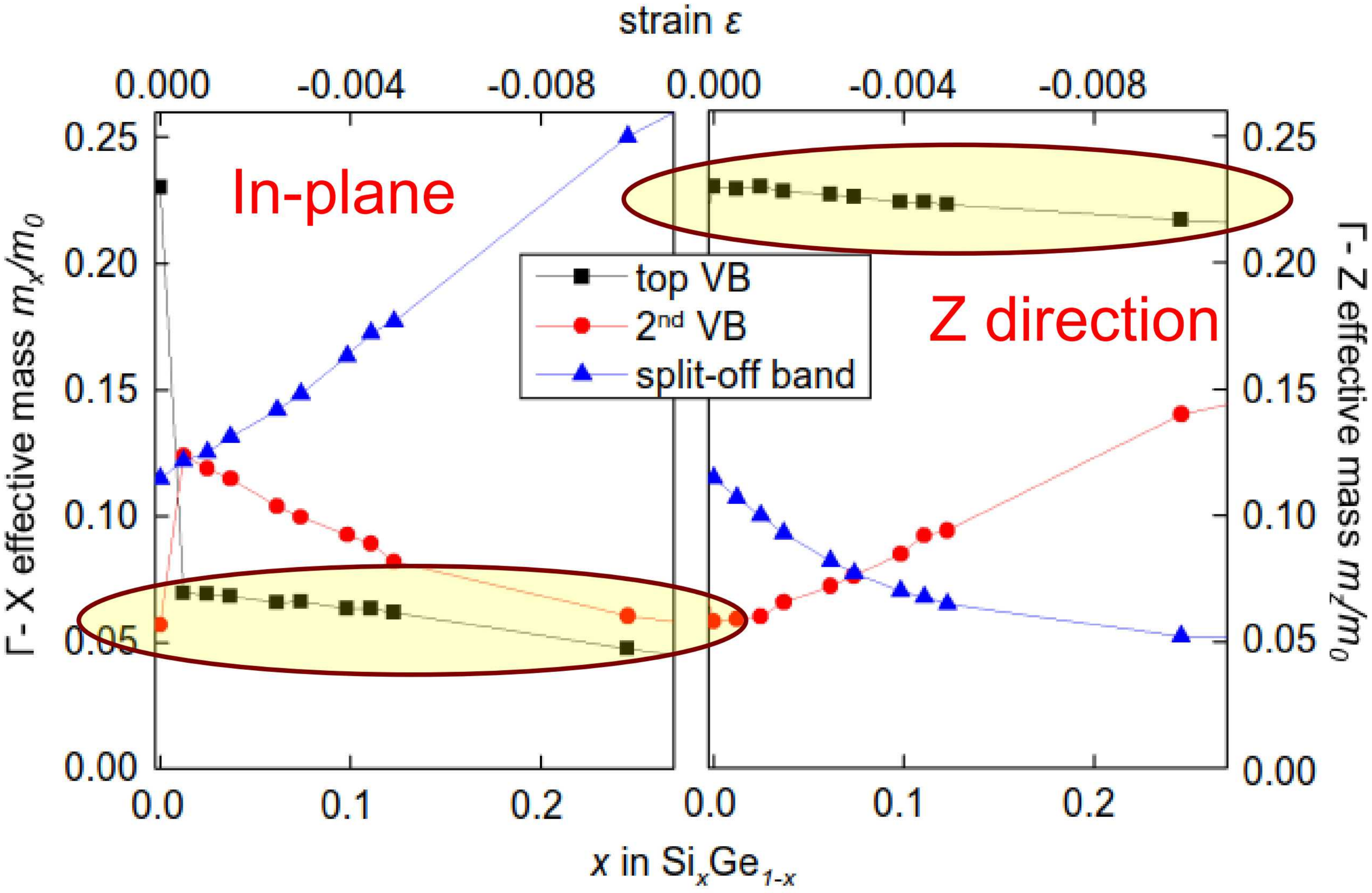
  => larger orbital gaps
  => can use higher T cryostats



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

Physical properties – effective mass

Theory



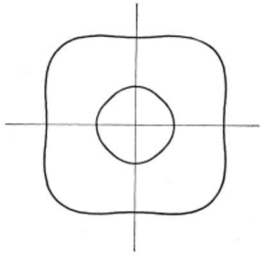


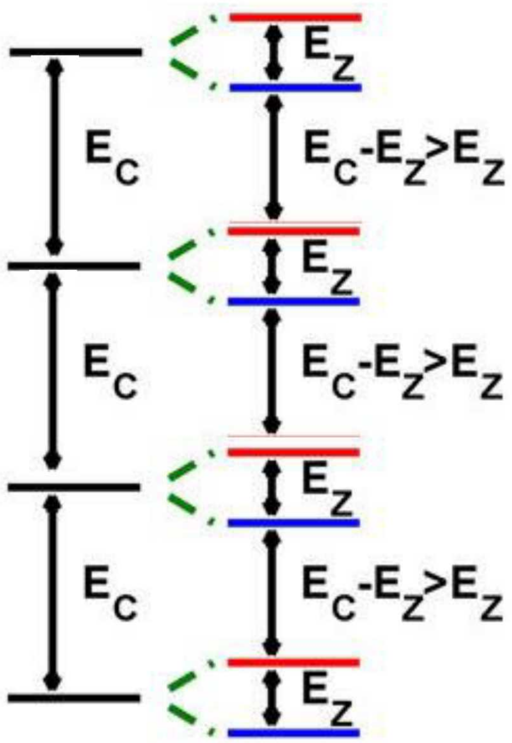
FIG. 8. Figures of constant energy in the (100) plane of k-space for the two fluted energy surfaces which are degenerate at the valence band edge; constants as for germanium.

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*)

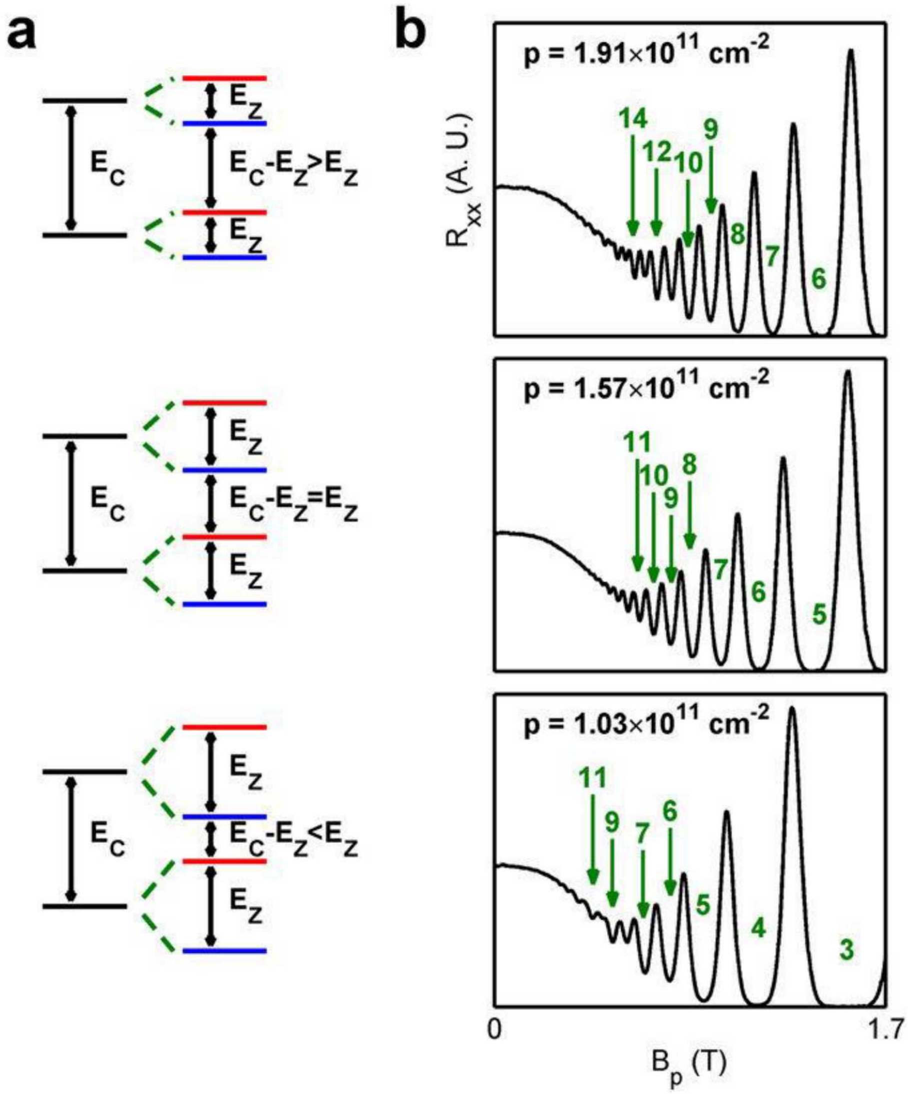
Ez is Zeeman gap: g*μB

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

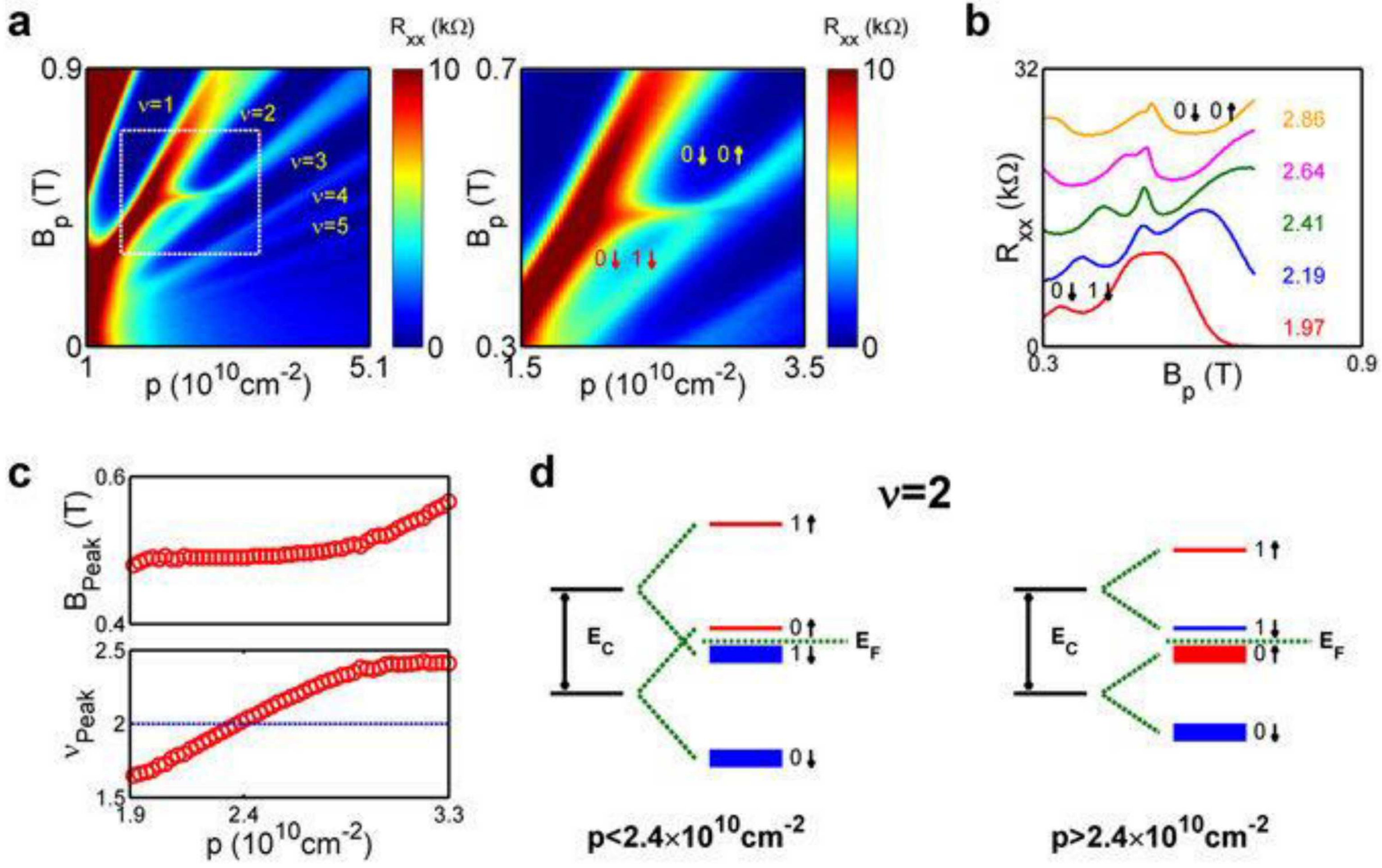
If Ec < 2Ez

⇒ 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

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

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

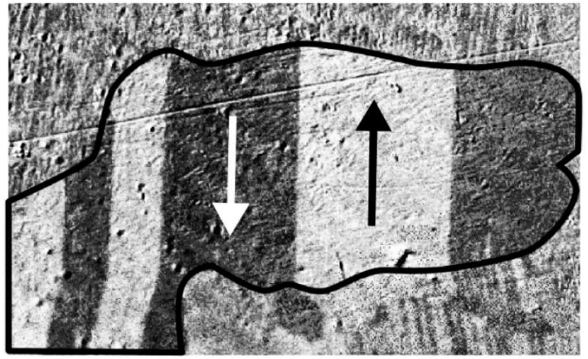
Lu, Scientific Reports 7, 2468 (2017)

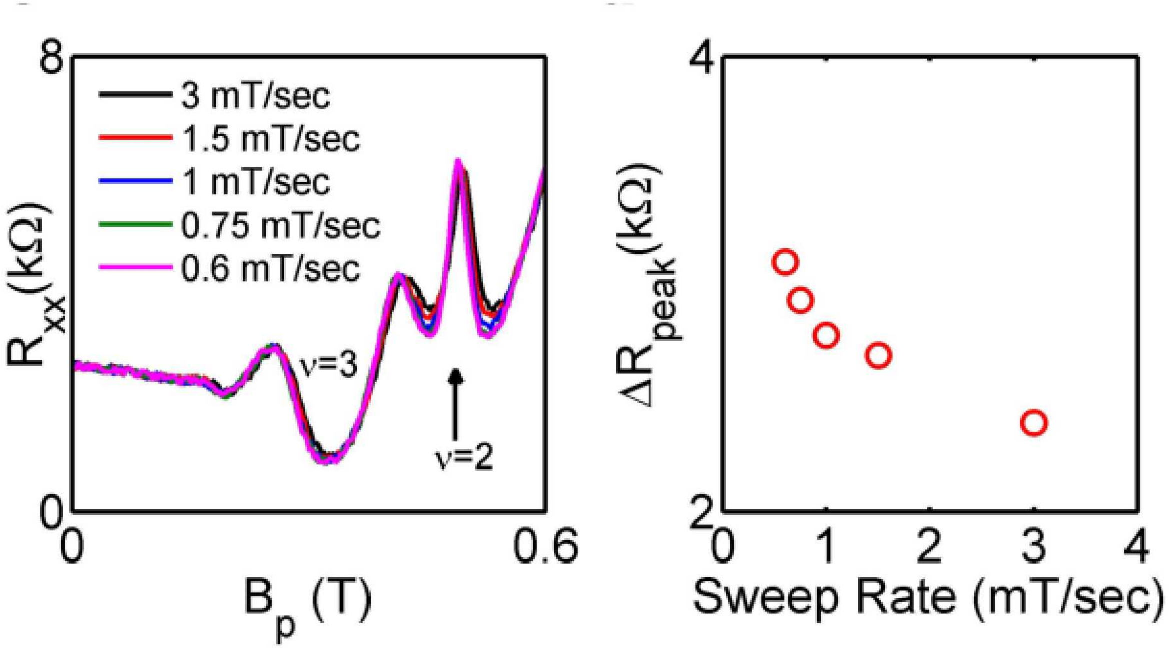
Quantum Hall ferromagnetic transition

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.

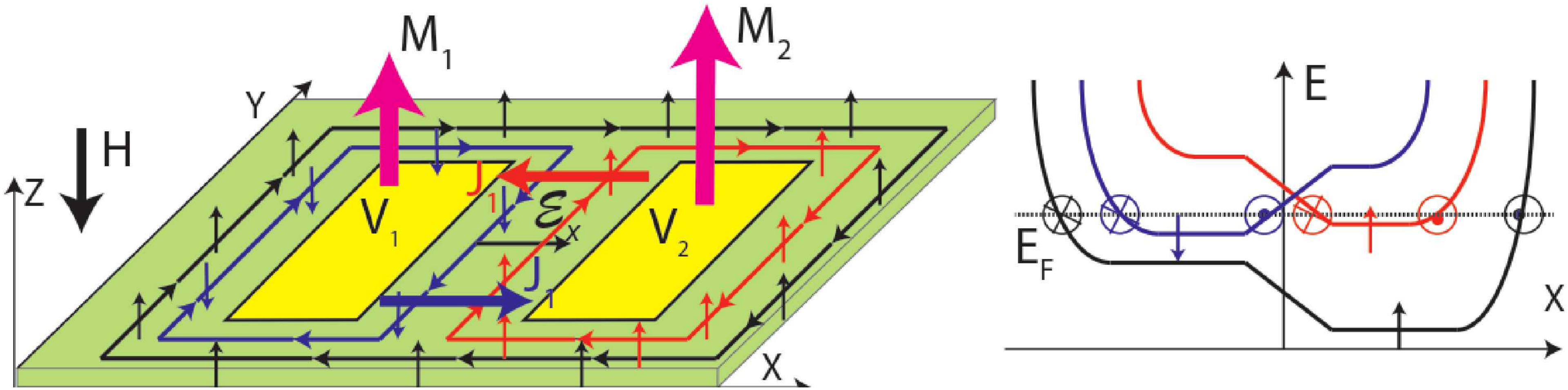




Lu, Scientific Reports 7, 2468 (2017)

Quantum Hall ferromagnetic transition

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



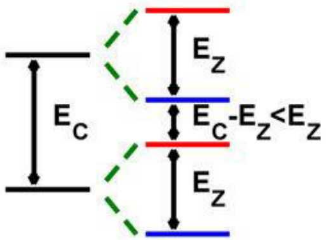
"Impurity-generated non-Abelions"
Simion Phys. Rev. B 97, 245107 (2018)

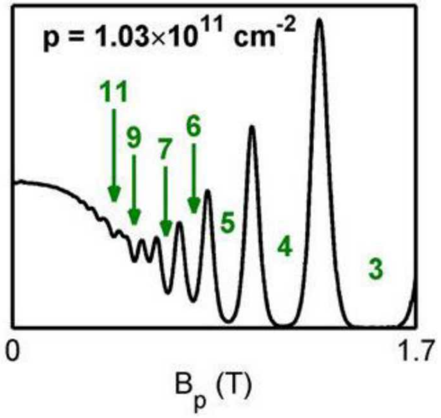
Physical properties – g factor

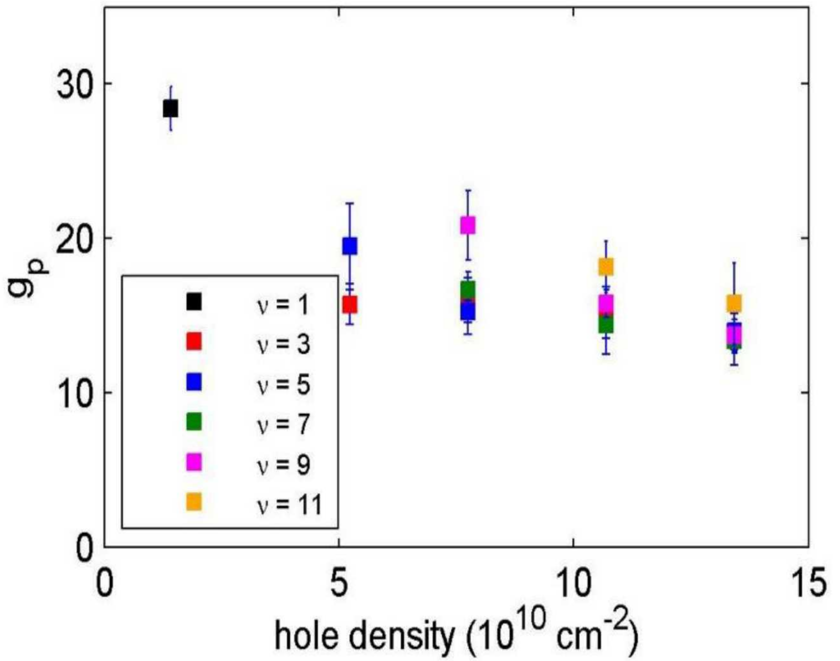
- ~ 5 – 30
- ~ density dependent.

- 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).

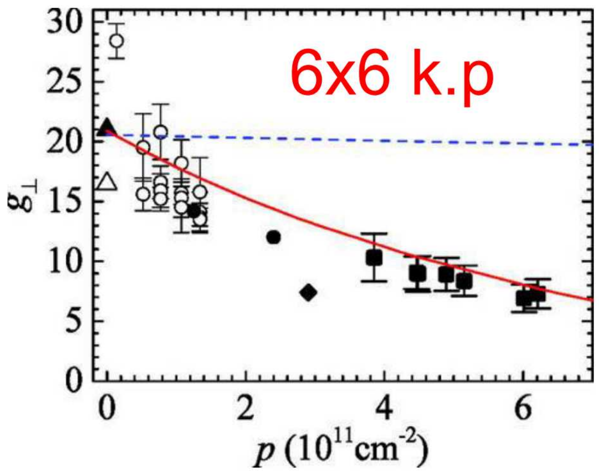
$P<1.6^{11}$ cm^{-2}
0.5 Ec < Ez < Ec







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



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

Hole spin qubits in Ge/SiGe

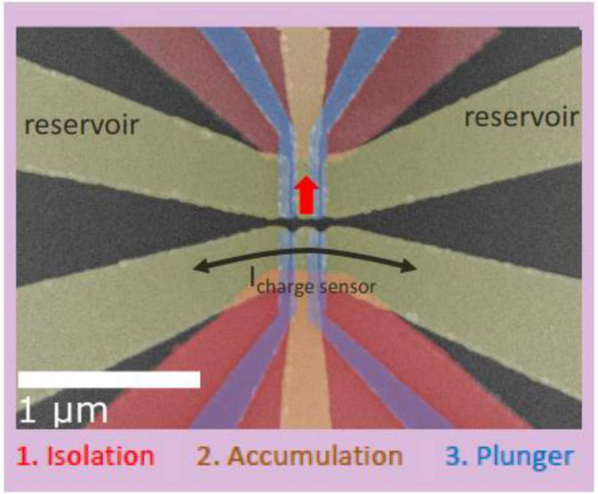
Implications for Quantum Dots

- 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

Spin qubits in Ge/SiGe

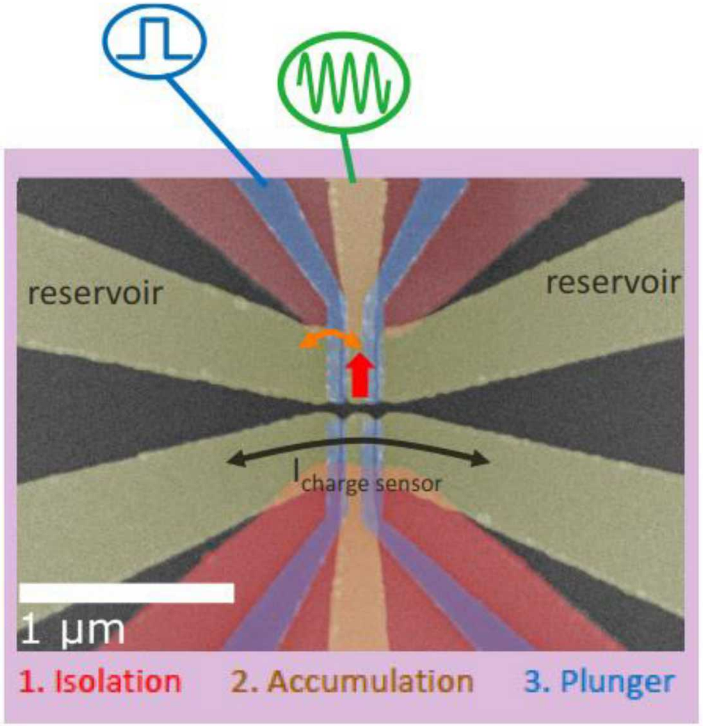
Surface electrodes used to laterally confine hole



Hardy, unpublished.

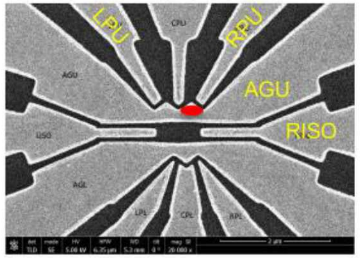
Spin qubits in Ge/SiGe

- 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

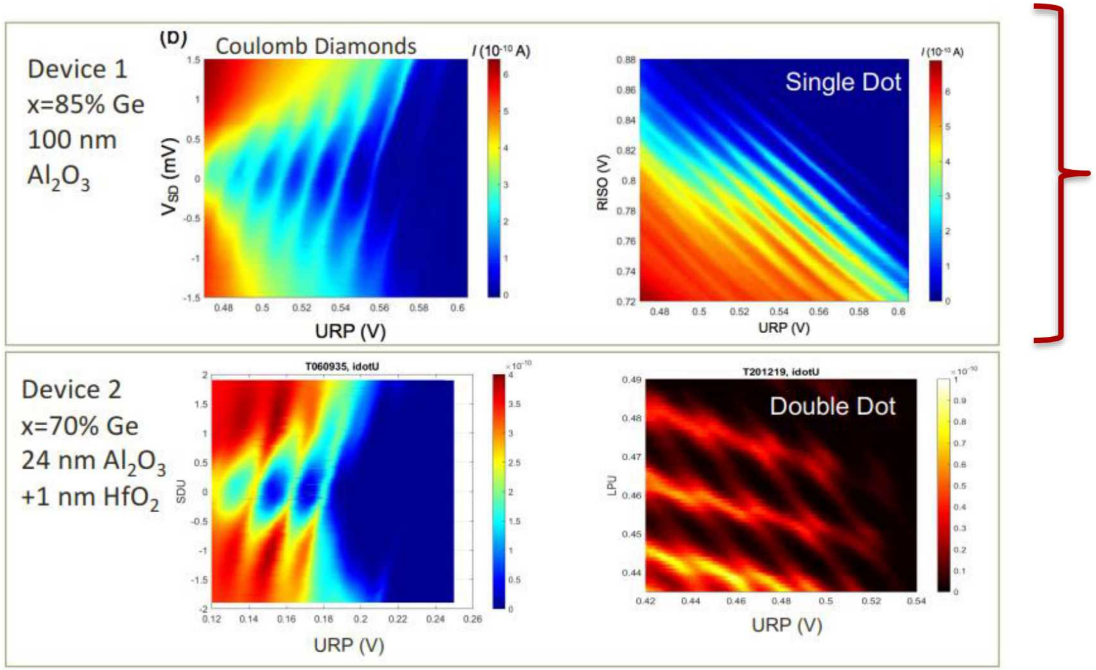


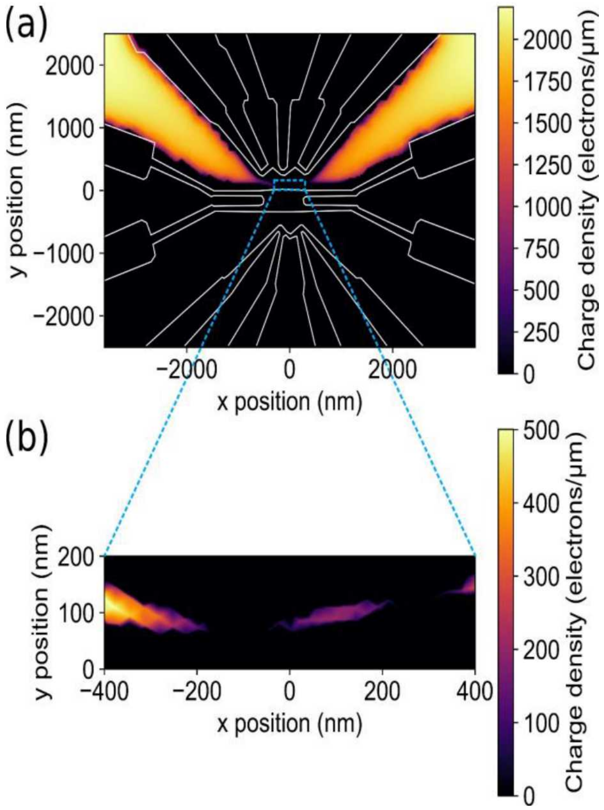
Hardy, unpublished.

Spin qubits in Ge/SiGe



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

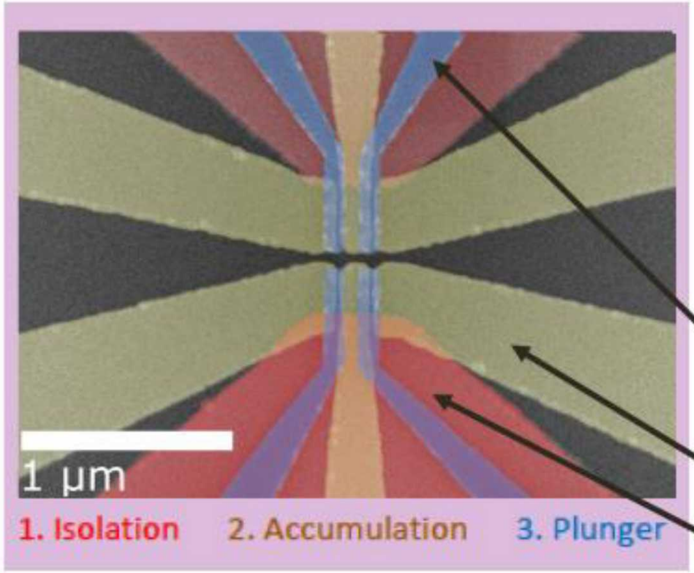




Hardy *et al.*, *Nanotechnology*, 30, 215202 (2019)

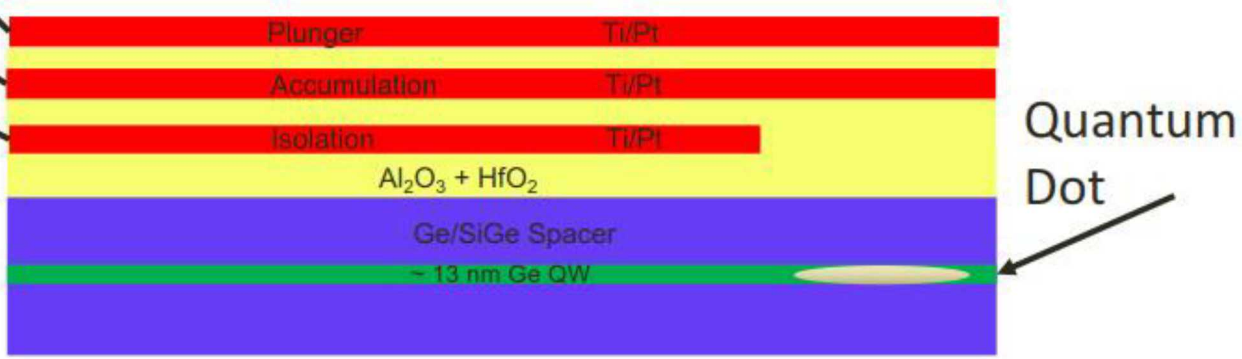
Spin qubits in Ge/SiGe

Sandia National Laboratories



Goals:

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

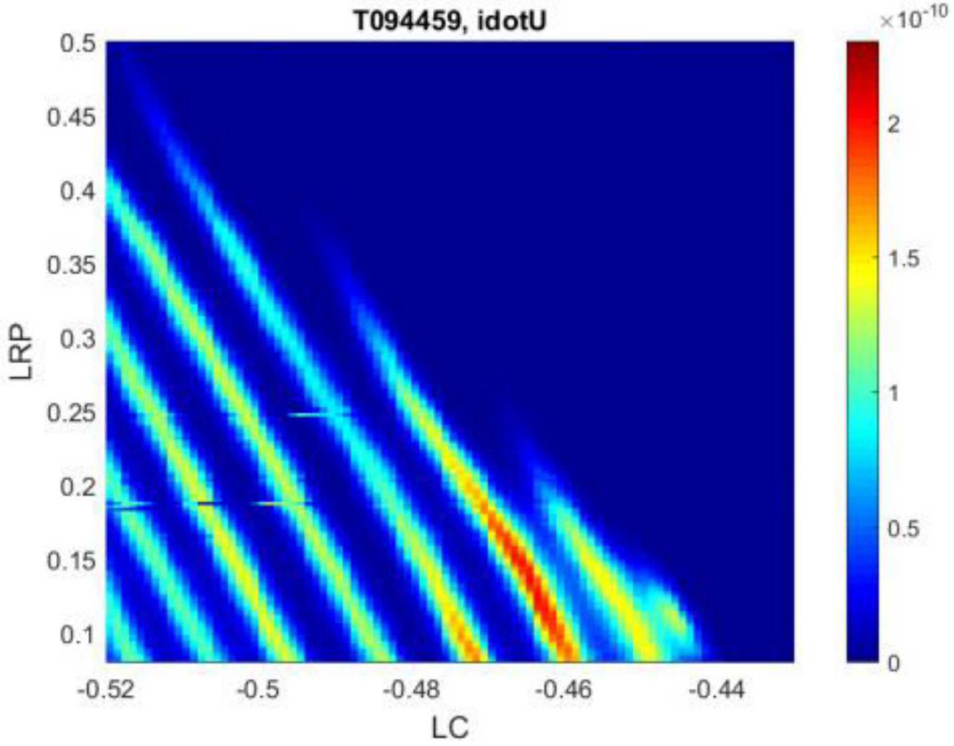


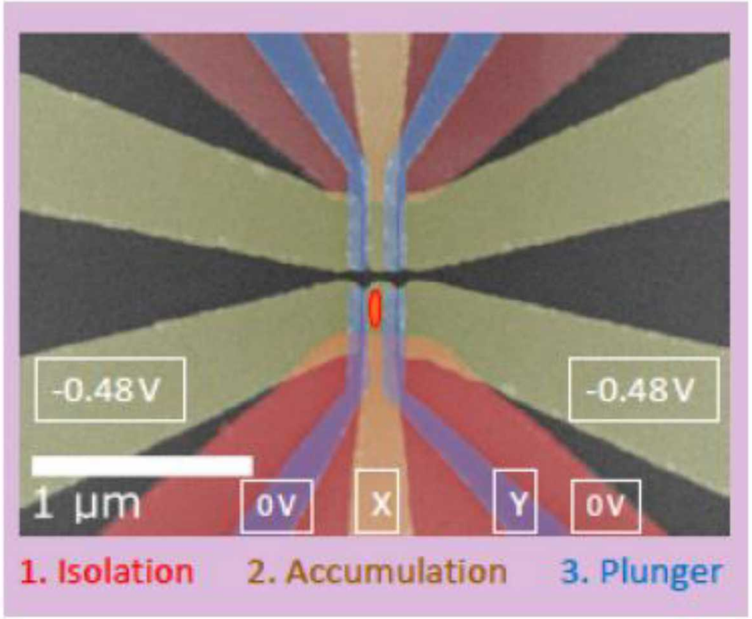
Ga implanted Ohmic contacts

Hardy, unpublished.

Spin qubits in Ge/SiGe

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