SAND2022-5475C

UF

FABRICATION AND TRANSPORT PHENOMENON IN LOW -DIMENSIONAL SYSTEMS COUPLED AT THE NANOSCALE

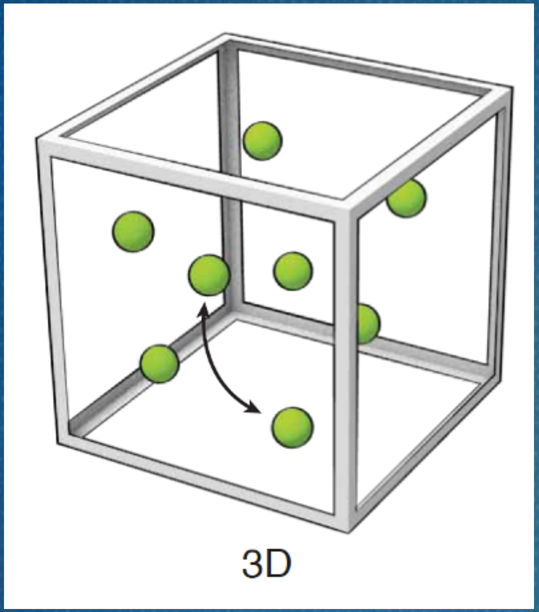
Dominique Laroche

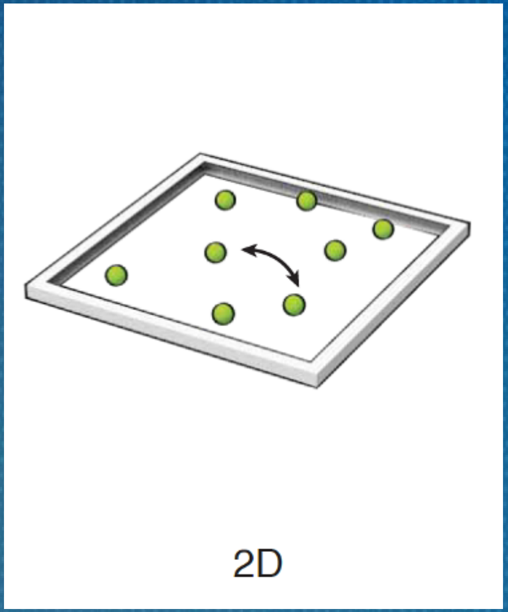
American Vacuum Society - Florida – Symposia

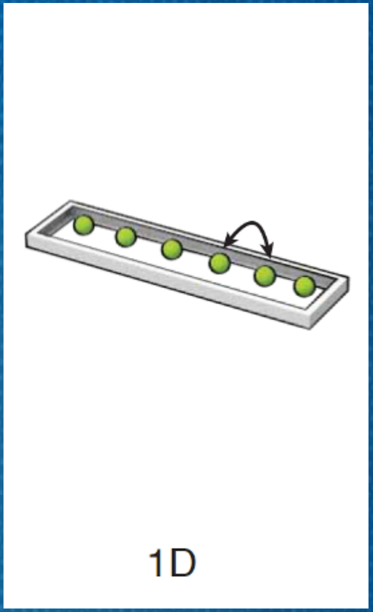
May 6th, Orlando, Fl

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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-NA0003525.

Low-dimensional systems







Reduced scattering phase-space in low dimensional systems.

Increased interactions

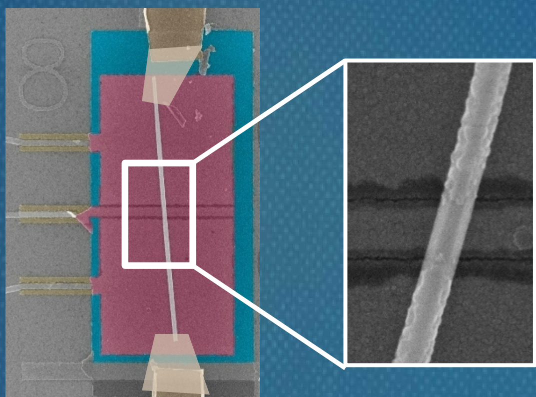
<u>Novel and exciting quantum phenomenon :</u>

- Integer and Fractional quantum Hall effect
- Luttinger liquid physics
- Non-Fermi liquids
- Quantum dots/ quantum computing
- ETC.

Coupled low-dimensional systems

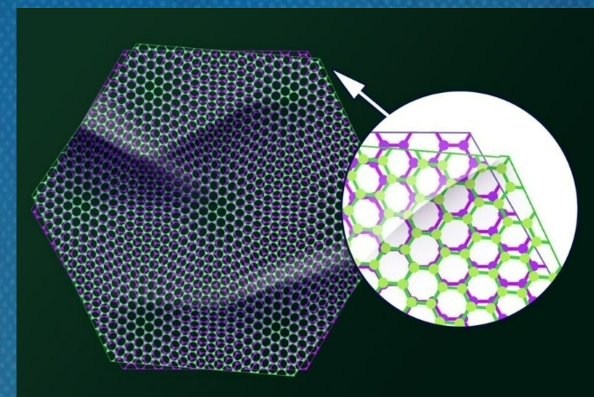
Additional properties to engineer novel quantum phenomena / phases

MBS signatures in hybrid SM-SC nanowires



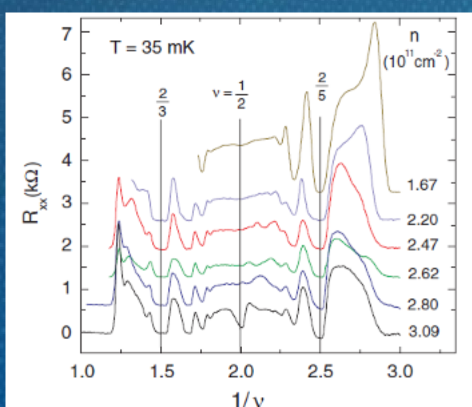
D. Laroche *et al.* Nature Comm. **10,** 245 (2019)

Superconductivity in graphene



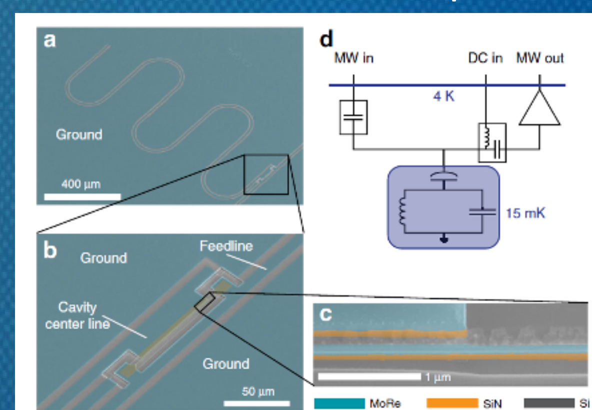
Y. Cao *et al.* Nature **556,** 43 (2018)

Exotic FQHE states



J. Shabani *et al.* PRL 103, 256802 (2009)

Electromechanics in the quantum limit



D. Bothner *et al.* Nature Comm. **11,** 1589 (2020)

Outline

- Introduction to low-dimensional systems

- Search for exciton condensation in Si quantum wells
  - Si/SiGe quantum wells
  - Exciton condensation
  - Device fabrication
  - Excitation gaps in the quantum Hall regime

- Coulomb drag between quantum wires
  - Luttinger liquids
  - Coulomb drag technique
  - Device fabrication
  - Coulomb drag measurements in laterally-coupled quantum wires

Outline

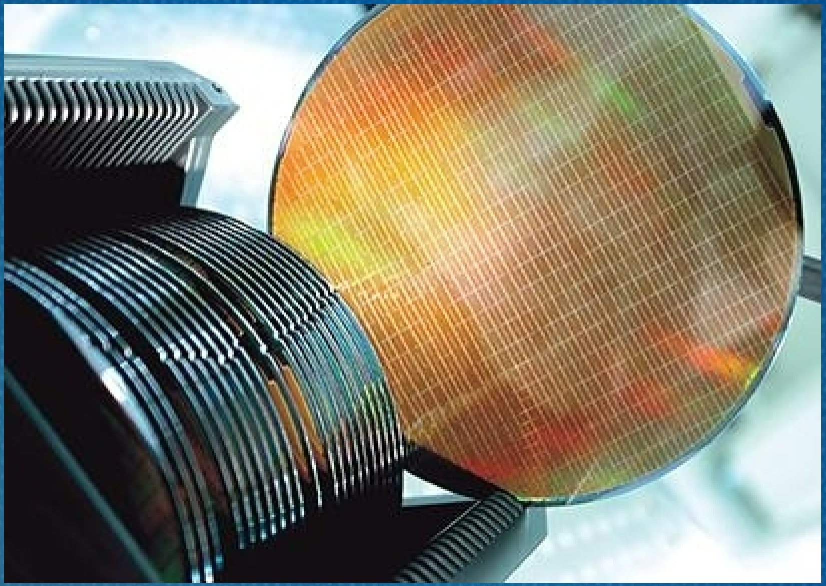
- Introduction to low-dimensional systems
- Search for exciton condensation in Si quantum wells
  - Si/SiGe quantum wells
  - Exciton condensation
  - Device fabrication
  - Excitation gaps in the quantum Hall regime
- Coulomb drag between quantum wires
  - Luttinger liquids
  - Coulomb drag technique
  - Device fabrication
  - Coulomb drag measurements in laterally-coupled quantum wires

Search for exciton condensation in Si quantum wells

Si/SiGe bilayers

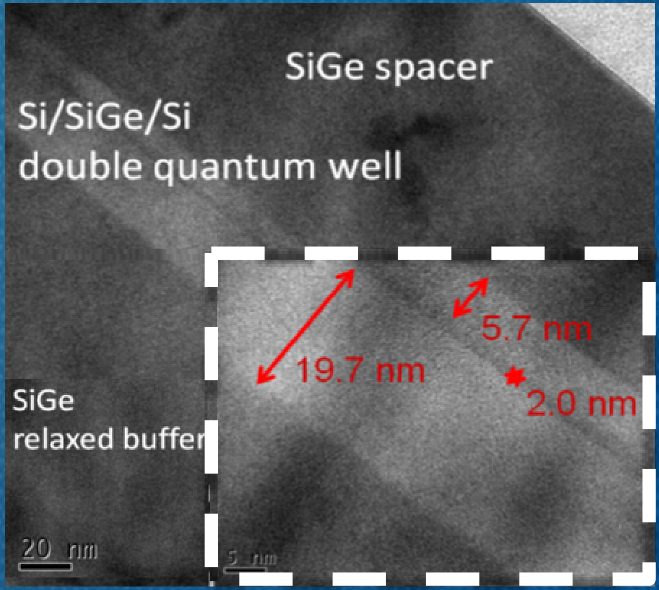
Why

- Low disorder system
- Scaling potential with CMOS foundries
  - Resistanceless devices
  - Quantum computing
- New degree of freedom : valley



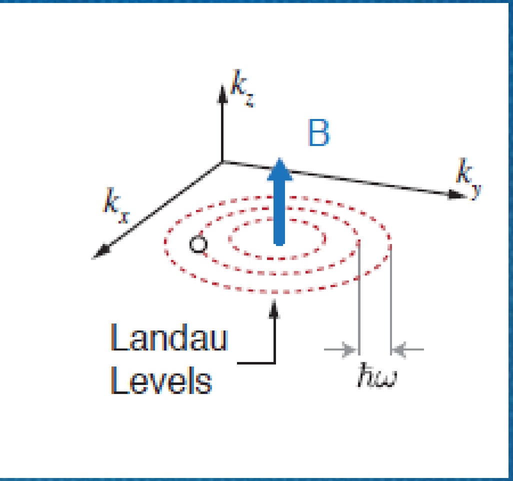
How

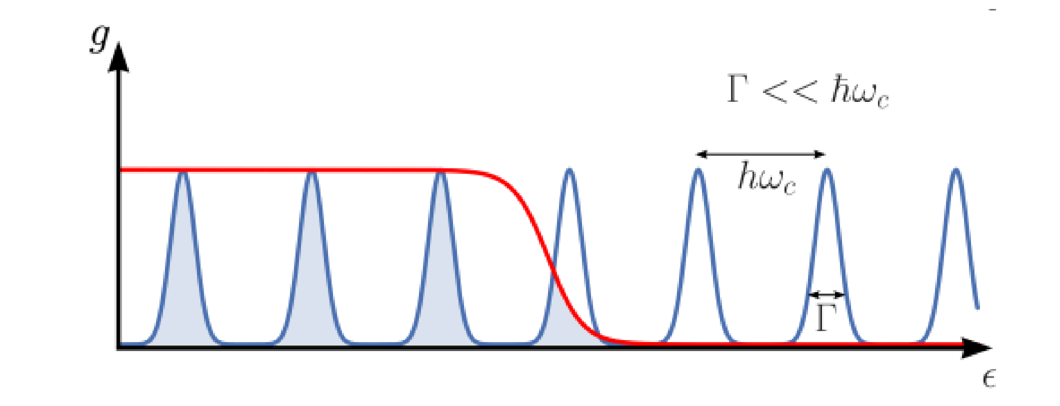
- UHVCVD growth;
  Ultra High Vacuum Chemical Vapor Deposition



Quantum Hall effect

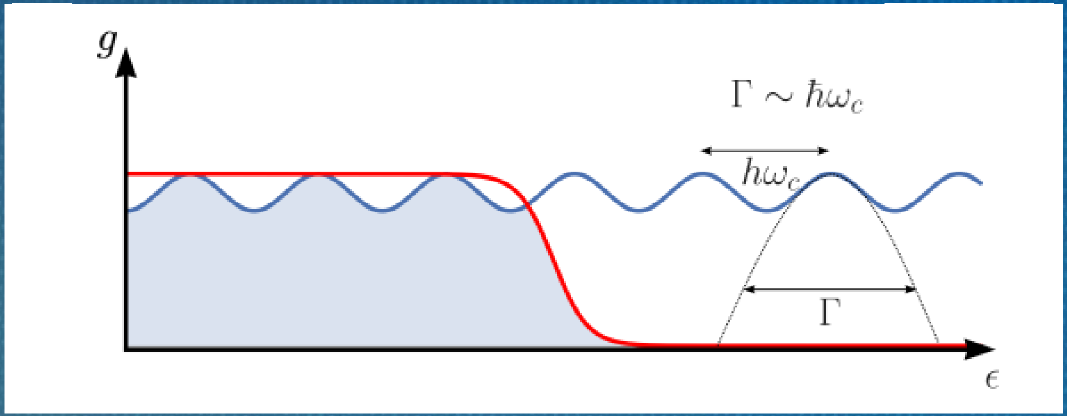
Electron motion of 2D electrons gets quantized in Landau levels with a magnetic field.



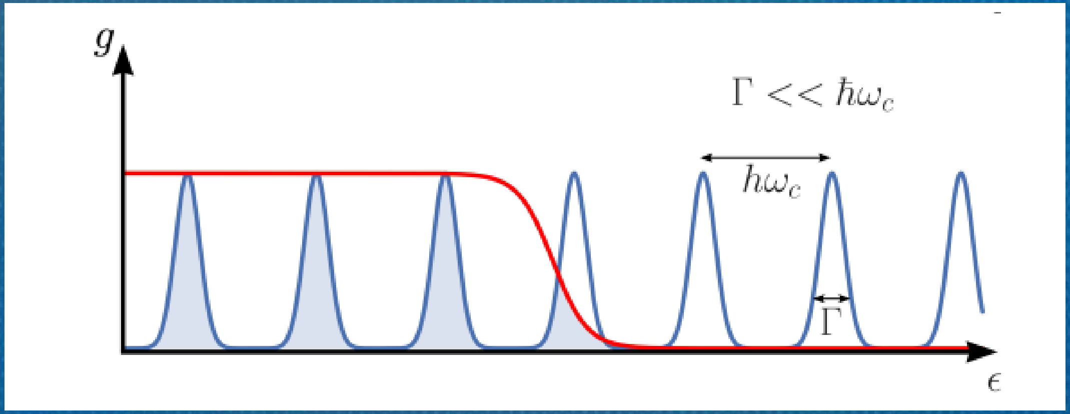


Large B, low T and disorder

Quantum Hall effect

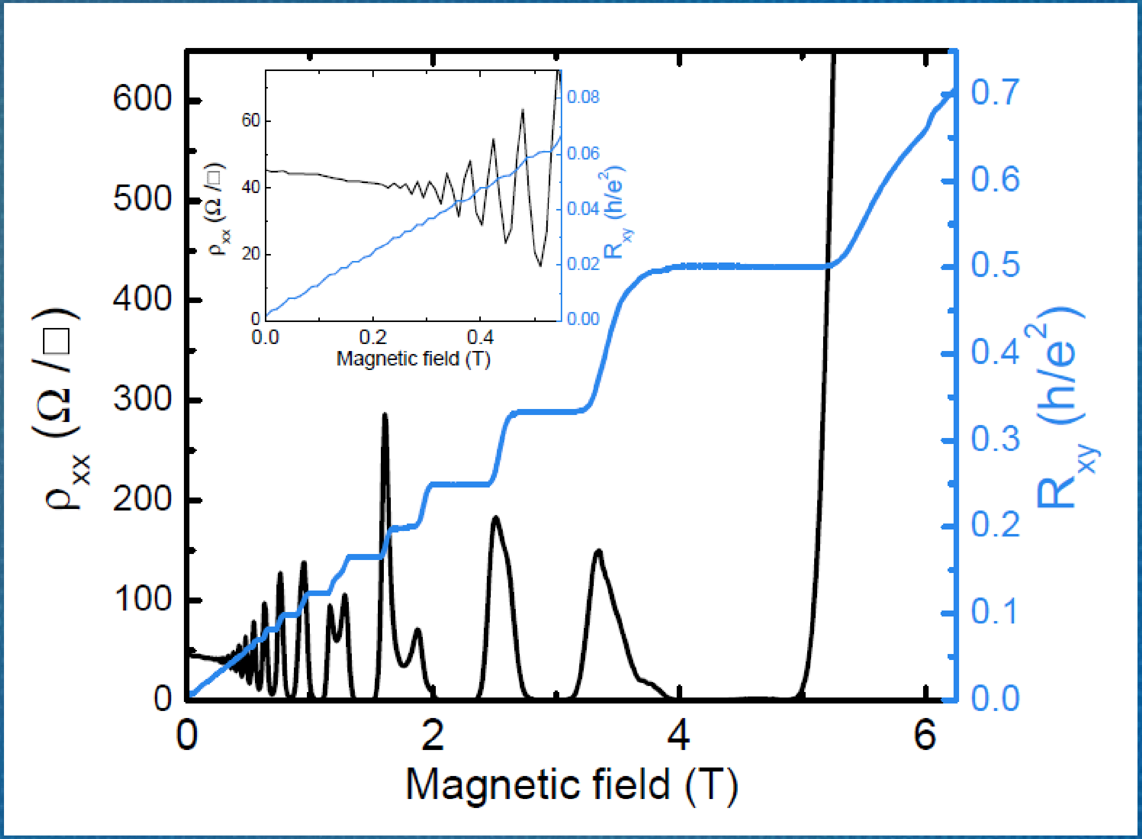


Low B, High T and disorder

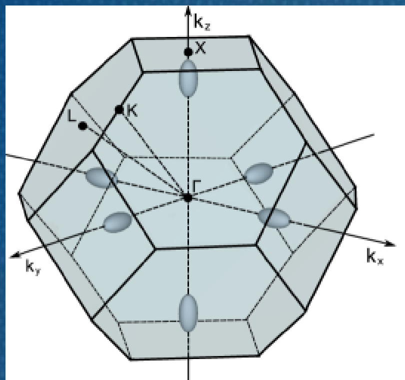


Large B, low T and disorder

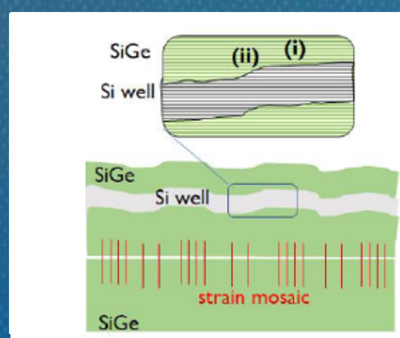
Quantum Hall effect



Si/SiGe : Valley splitting in single layer

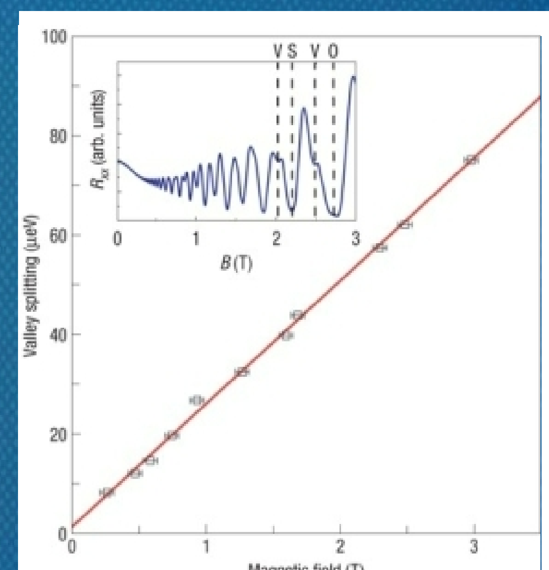


- Silicon has 6 degeneracies
- Vertical confinement + strain → m_l (2x degenerate)
  m_t (4x degenerate)
- Sharp interface → Lifts m_l degeneracy → Δv
- Interface disorder → Destructive interference
  ➡ lowers ΔE_v



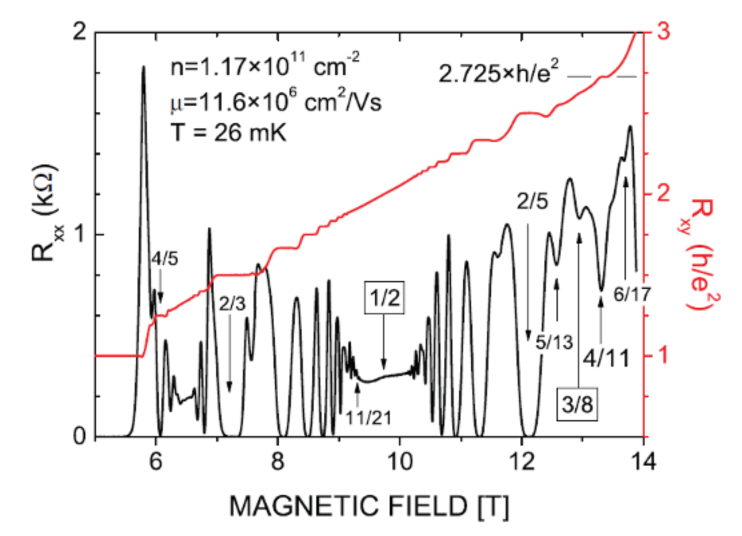
Theory matches experiments :

$\Delta E_v \sim C_v B + \Gamma$

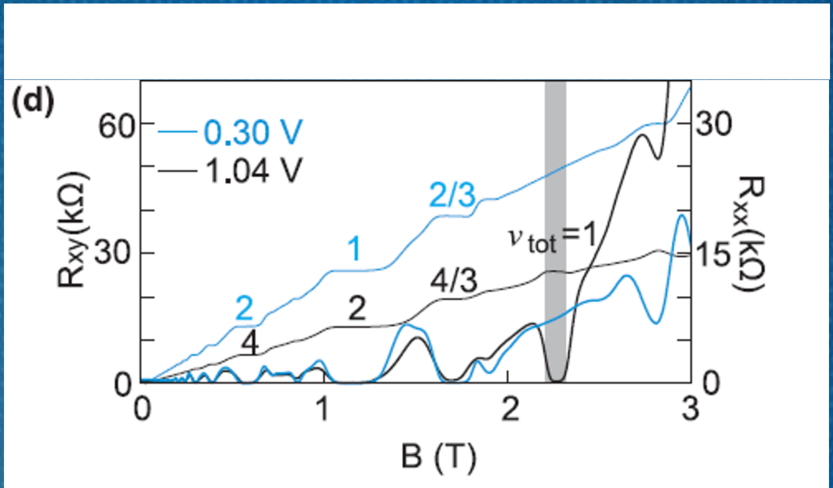


S. Goswami et al. Nature Phys. **3** 41, 2006

ν_{tot} = 1 quantum Hall state



W. Pan *et al.* PRB **91**, 041301(R) (2015)



D. Zhang *et al.* PRB **87**, 205304 (2013)

Single layers → no ν = 1/2 quantum Hall state.

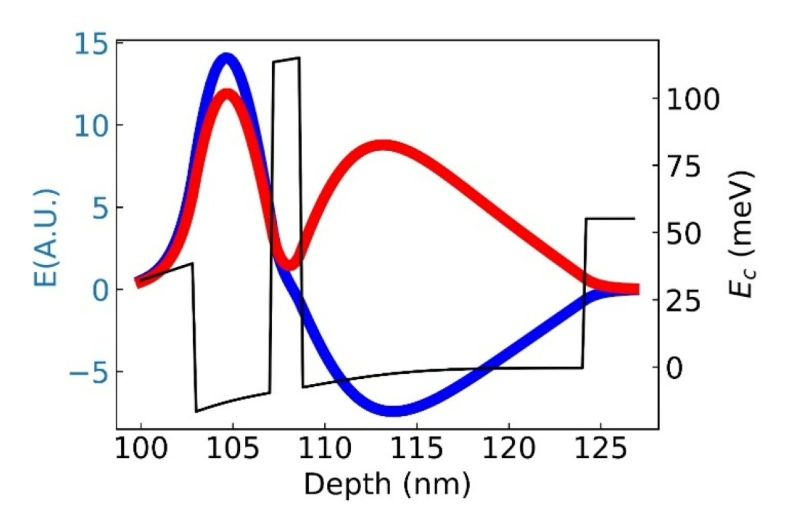
Two independent bilayers (matched density) :
$\nu_{tot} = 1 \rightarrow \nu_{1/2} + \nu_{1/2}$ = no quantum Hall state

At low density and small separation, a quantum Hall state at ν_{tot} = 1 is observed!

$\nu_{tot} = 1$ quantum Hall state

Bilayers : new degree freedom
→ Layer.

Leads to Δ_{SAS} between symmetric (S) and anti-symmetric (AS) states.

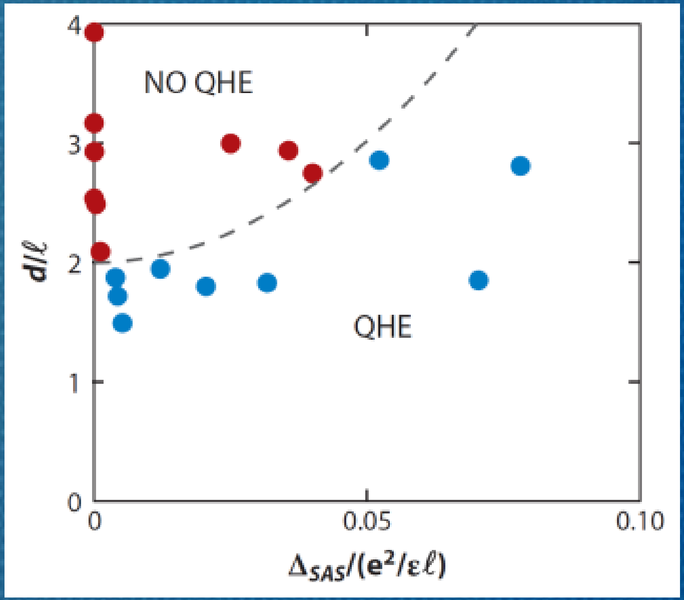


Easily captured through SP simulations

If intra- and inter-layer energies are comparable → Spontaneous interlayer coherence.

Only visible for $d/l_b < 1.8$.

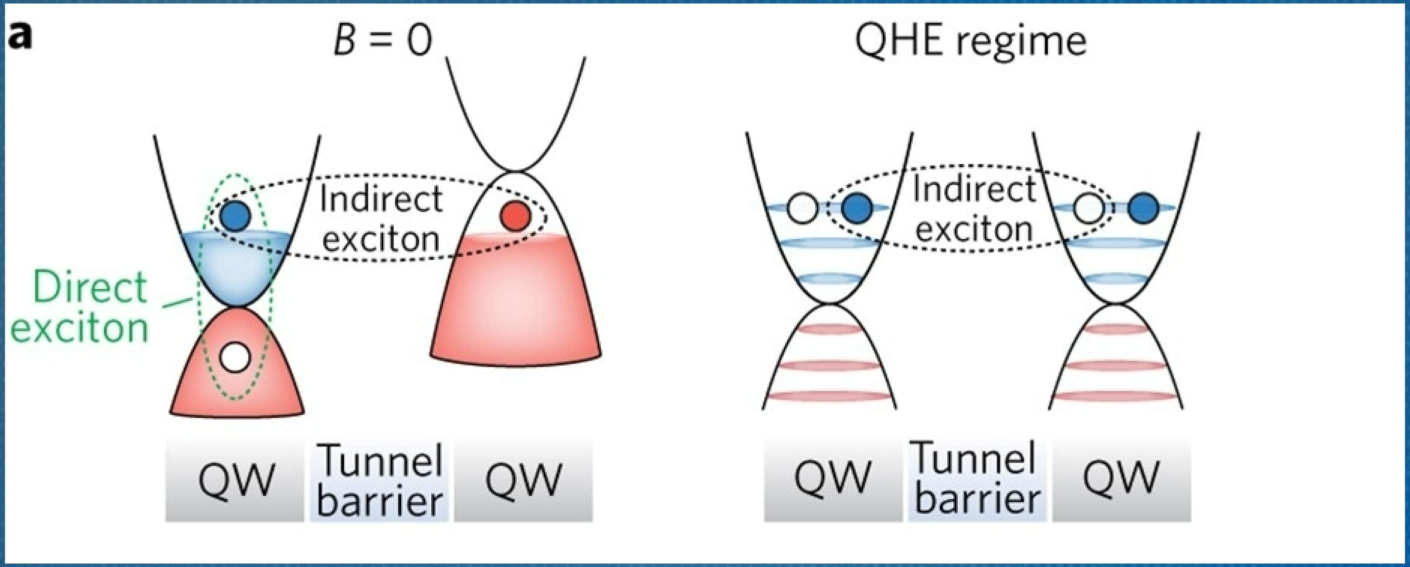
Occurs even for negligible tunneling.



Murphy SQ, et al. Phys. Rev. Lett. 72:728–31 (1994)

Exciton condensation

Pairing of an electron and a hole → Boson
Low-temperature → Condensation to a phase-coherent ground state



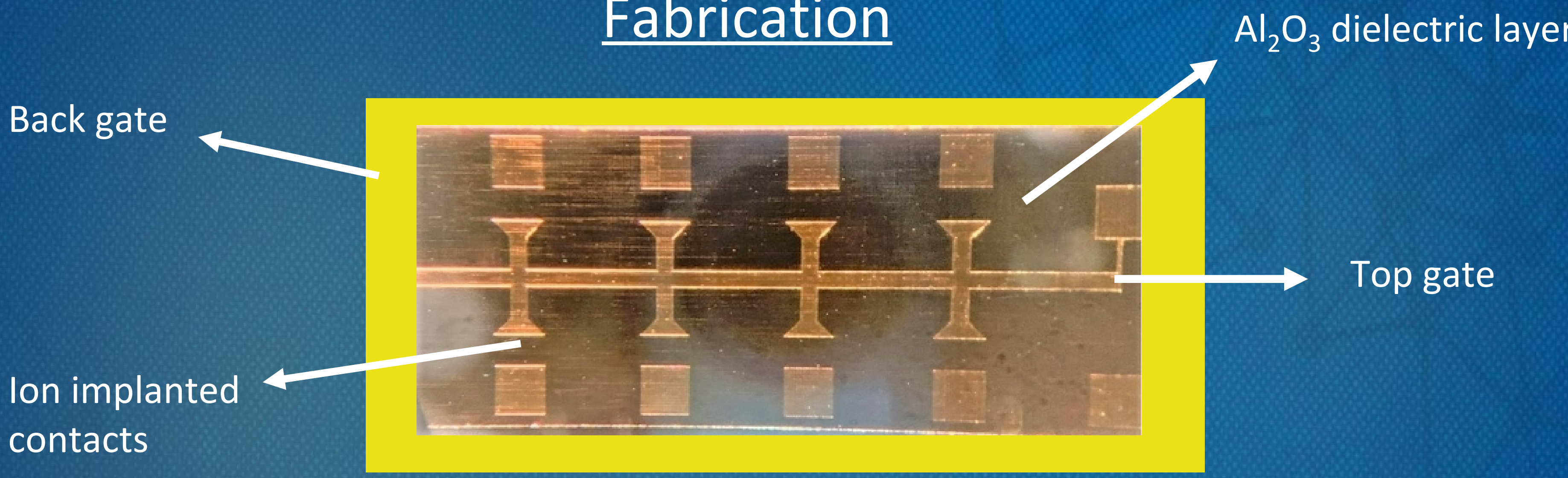
Direct excitons : Photo-induced → short lifetime ~ ps to fs

Indirect excitons : Separated electron-hole pairs → longer lifetime ~ μs to ns
B = 0 → Large interlayer voltage in undoped systems
Instabilities / Leakage
<u>QHE at half filling → More robust platform</u>

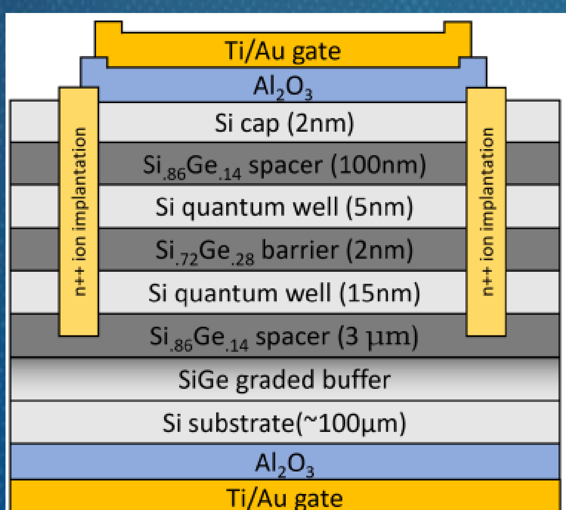
J. I. A. Li *et al.* Nature Phys. **13,** 751 (2017)

Si/SiGe bilayers

Fabrication



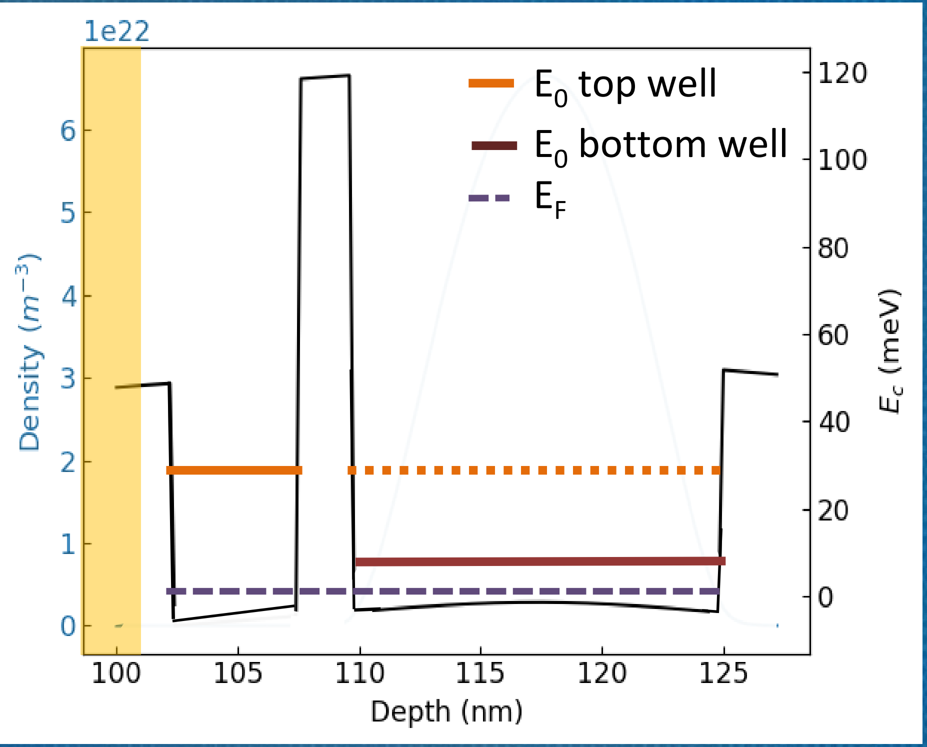
Device



- Front and back gate capabilities
- Hall densities from 5×10^{10} cm^{-2} to 3.4×10^{11} cm^{-2}; Hall mobility up to 3.08×10^{5} $cm^2/(V \cdot s)$

Asymmetric design

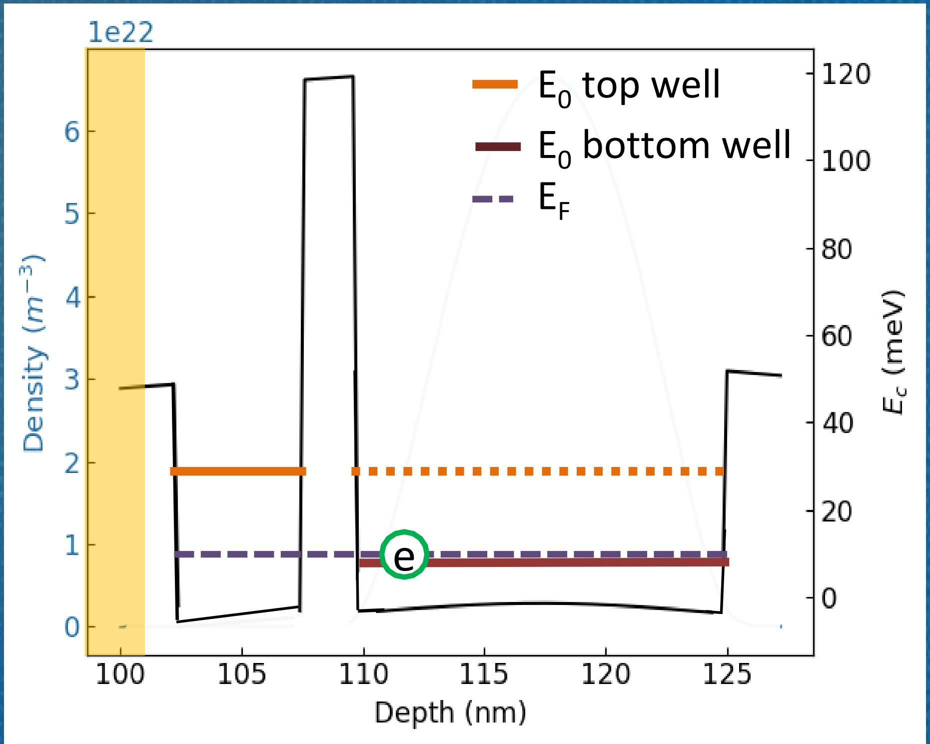
$V < V_{th}$



$$E = E_0 + \frac{\hbar^2}{2m^*}({k_x}^2 + {k_y}^2)$$

Asymmetric design

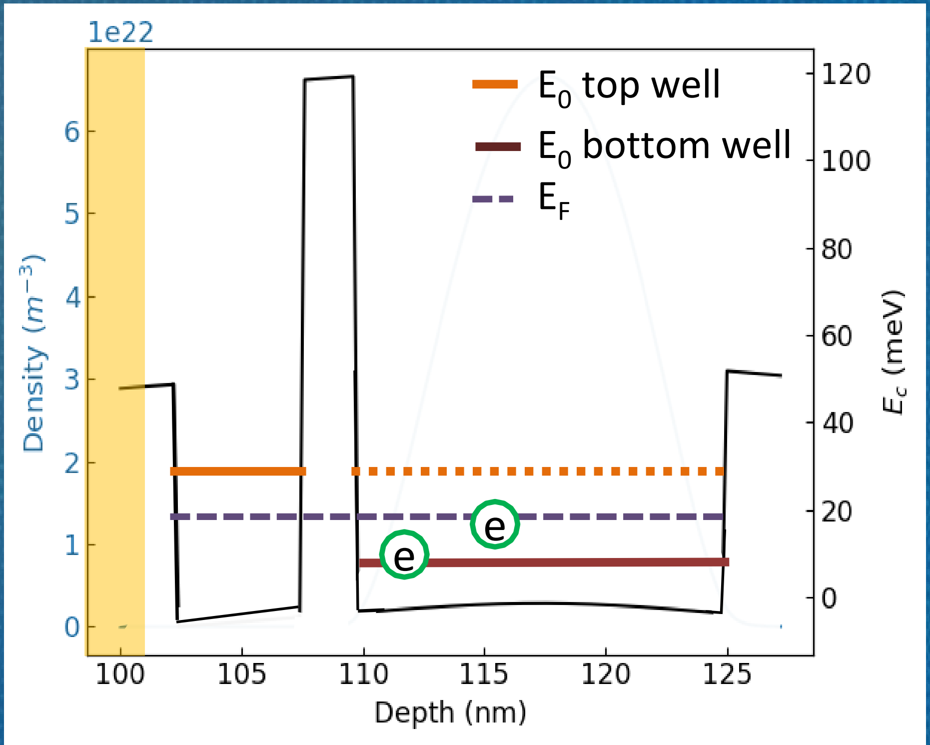
$V < V_{th}$



$$E = E_0 + \frac{\hbar^2}{2m^*}({k_x}^2 + {k_y}^2)$$

Asymmetric design

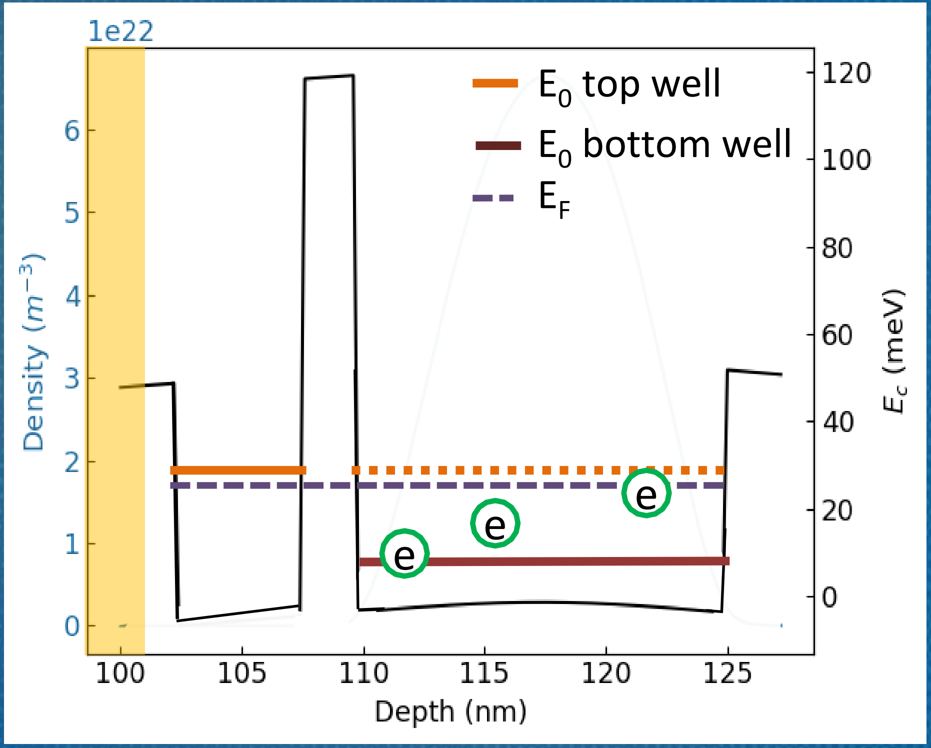
$V < V_{th}$



$$E = E_0 + \frac{\hbar^2}{2m^*}(k_x{}^2 + k_y{}^2)$$

Asymmetric design

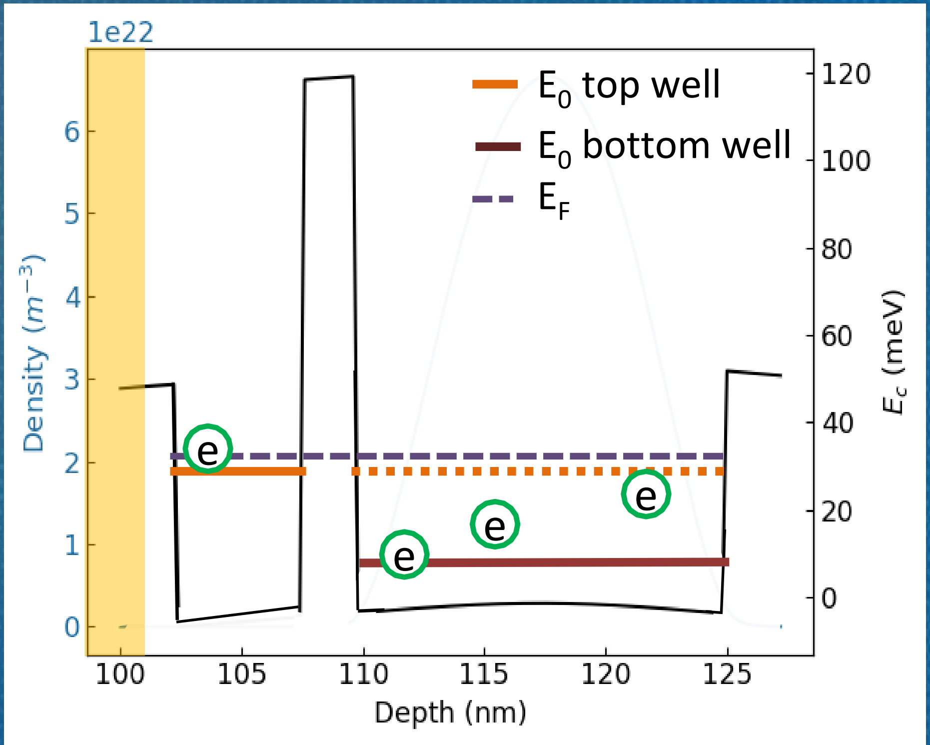
$V < V_{th}$



$$E = E_0 + \frac{\hbar^2}{2m^*}\left(k_x{}^2 + k_y{}^2\right)$$

Asymmetric design

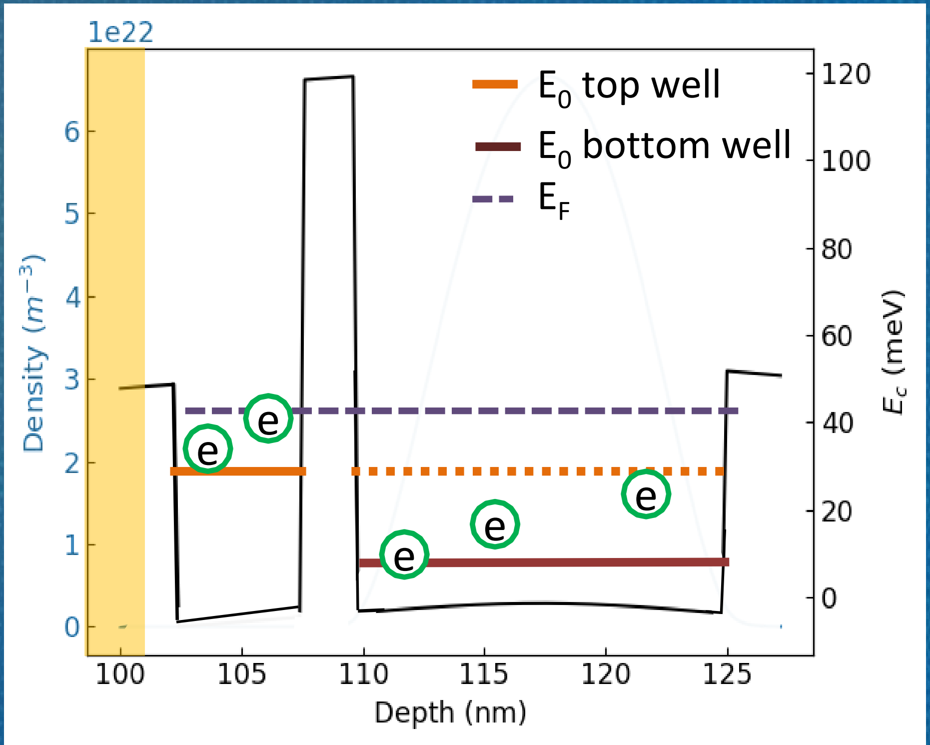
$V > V_{th}$



$$E = E_0 + \frac{\hbar^2}{2m^*}\left({k_x}^2 + {k_y}^2\right)$$

Asymmetric design

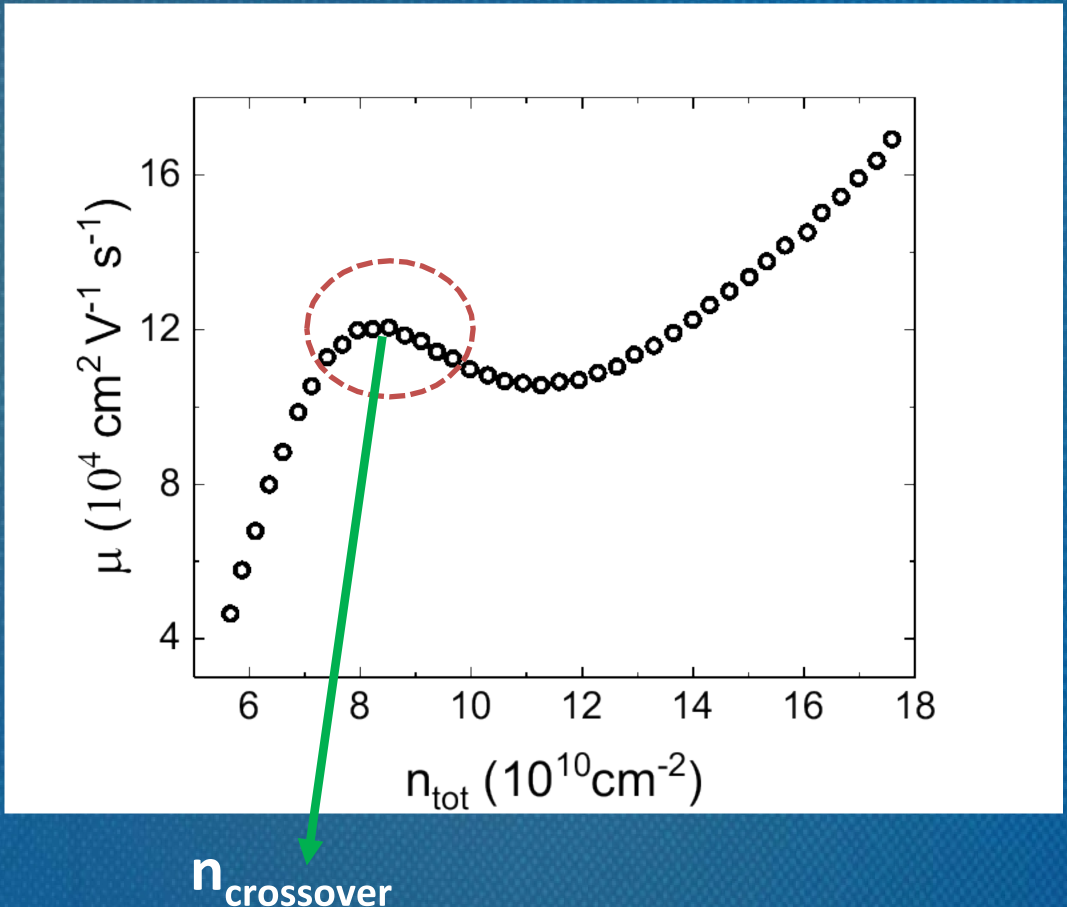
V > V_{th}



$$E = E_0 + \frac{\hbar^2}{2m^*}(k_x{}^2 + k_y{}^2)$$

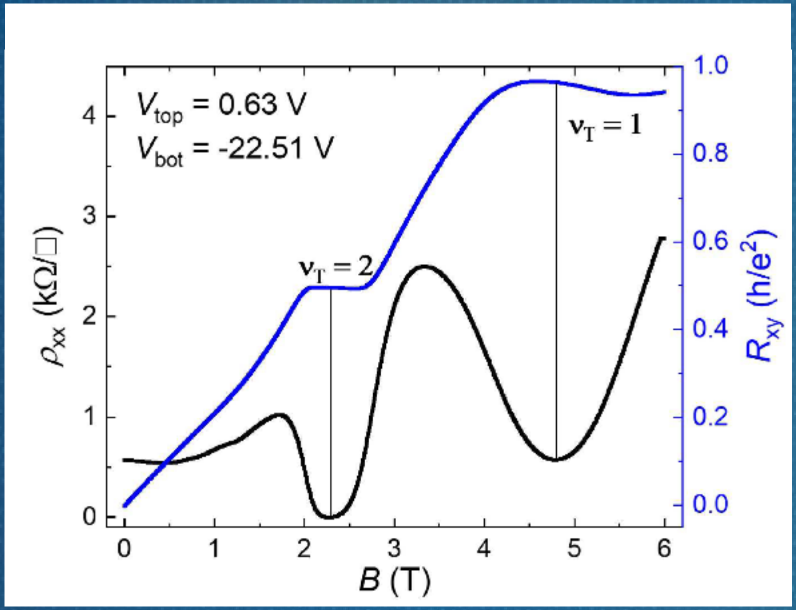
Si/SiGe : initial characterization

Bilayer behavior

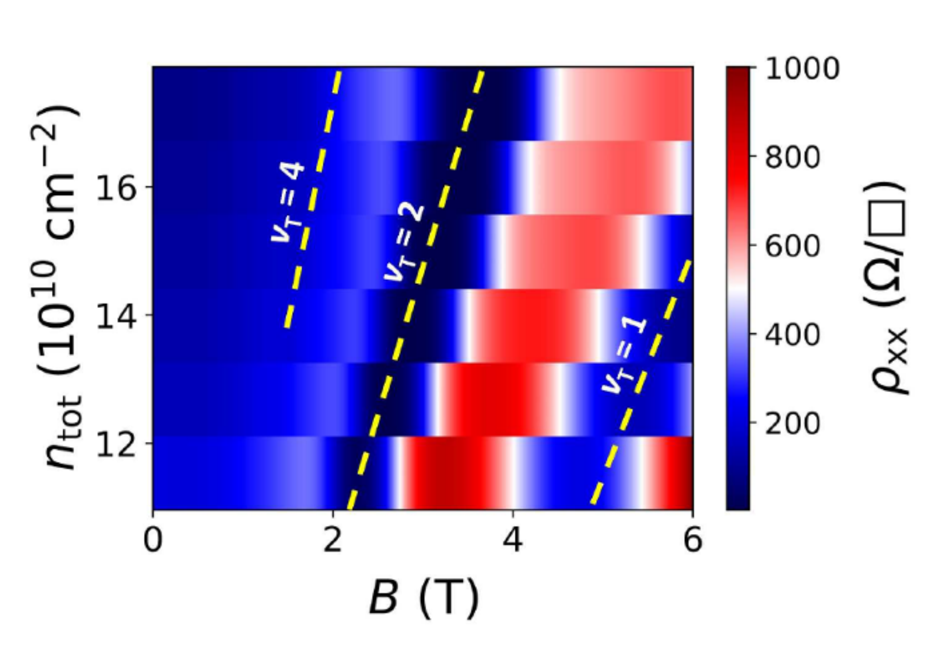


Additional inter-subband scattering causes a mobility drop

Si/SiGe : quantum Hall states

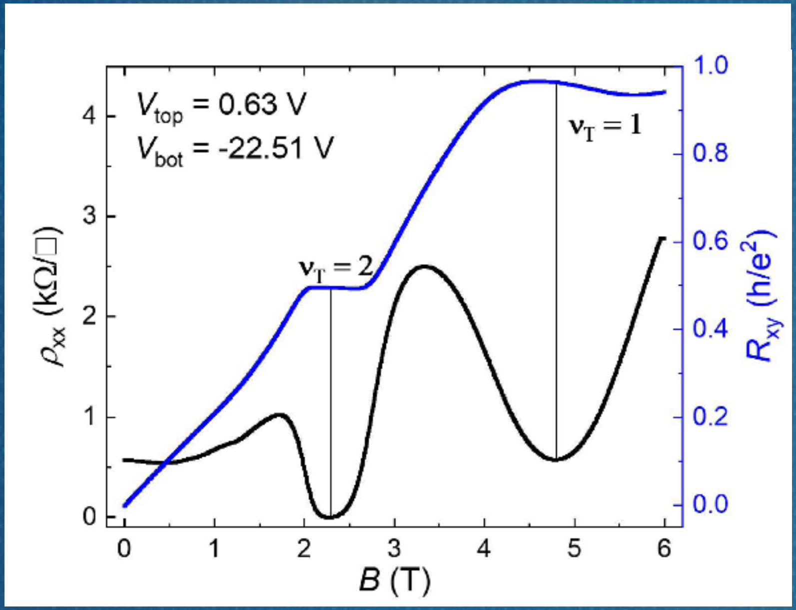


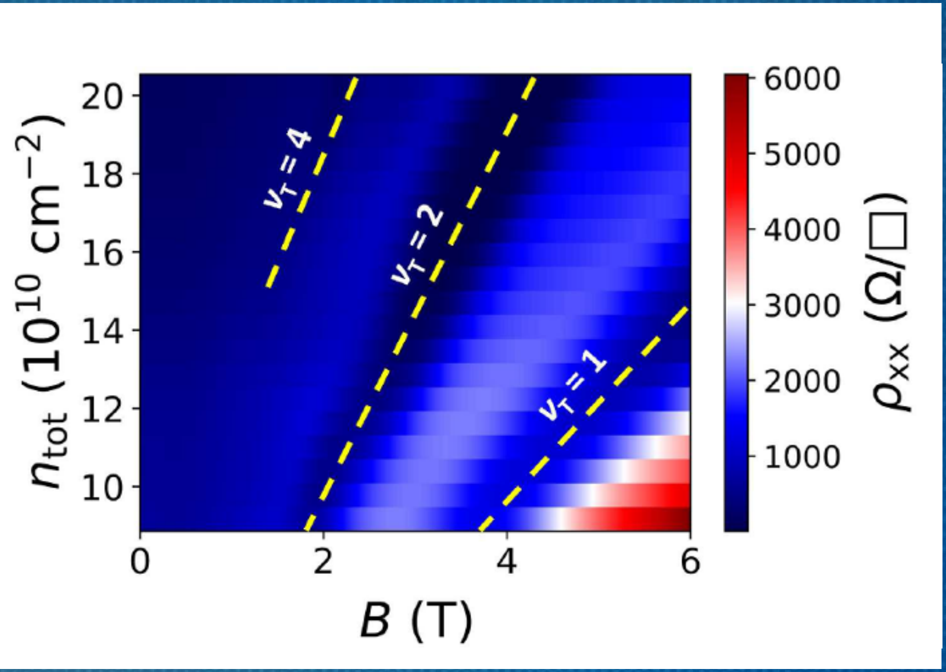
$n_{tot} = 11.23 \times 10^{10}\ cm^{-2}$



Top and bottom gating (matched density)

Si/SiGe : quantum Hall states

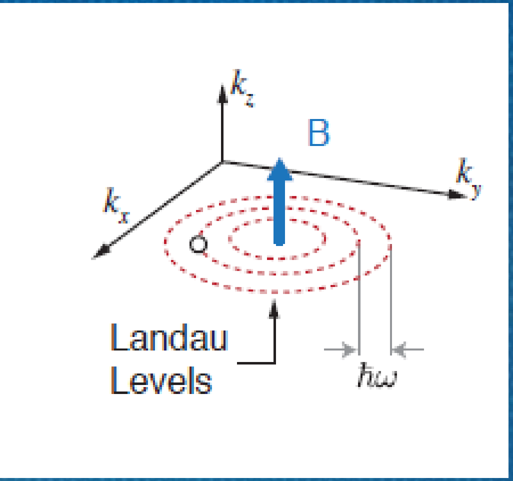


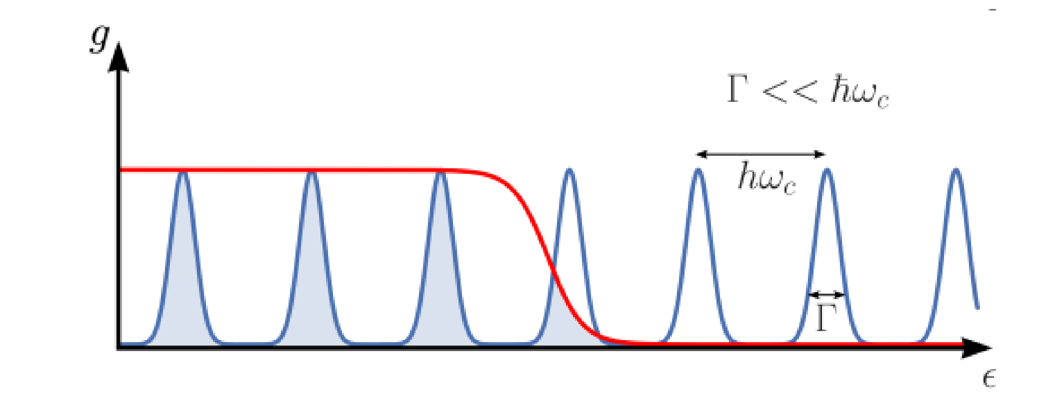


Top gating (variable density mismatch)

Quantum Hall effect

Electron motion of 2D electrons gets quantized in Landau levels with a magnetic field.

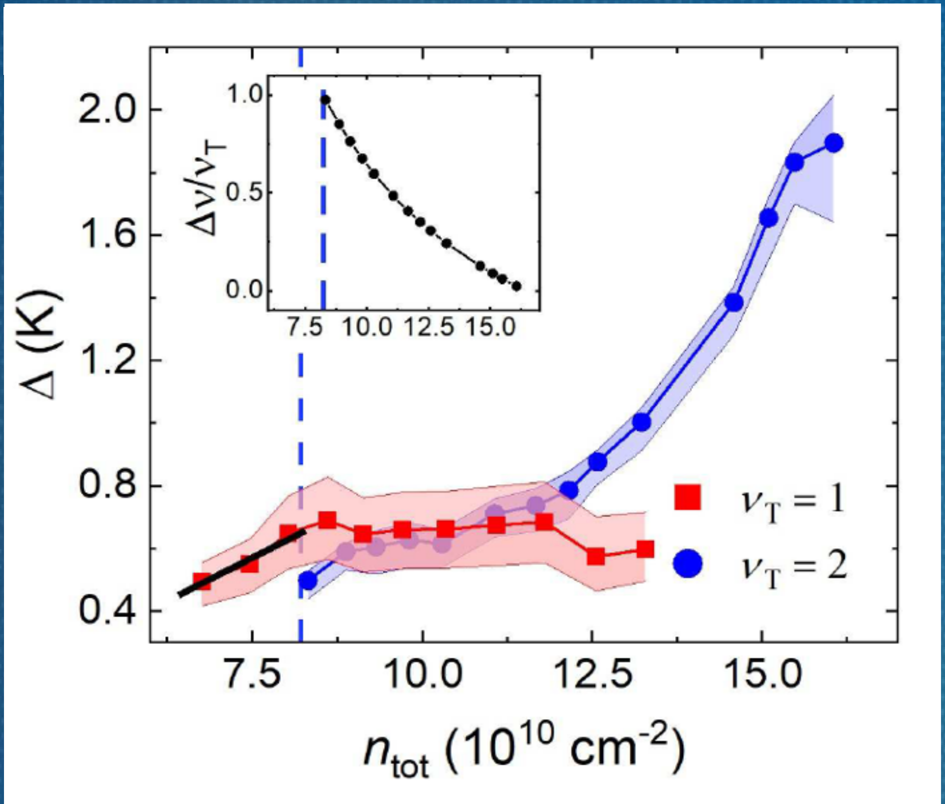


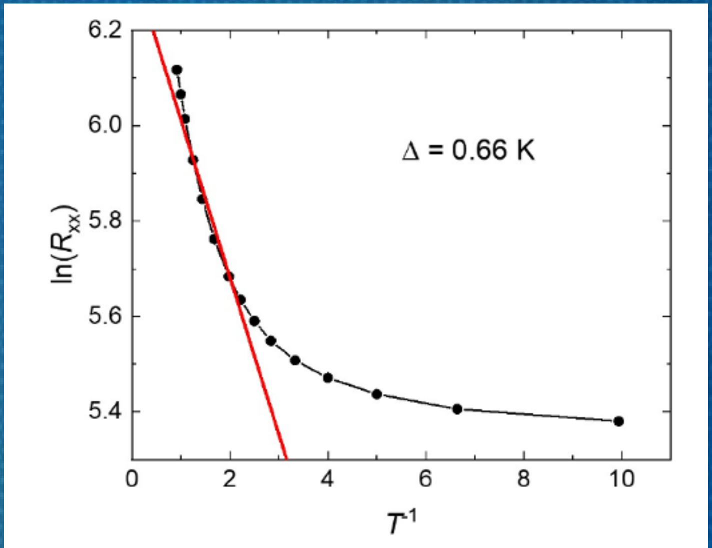


Large B, low T and disorder

Si/SiGe : Activation gaps

Variable density imbalance regime





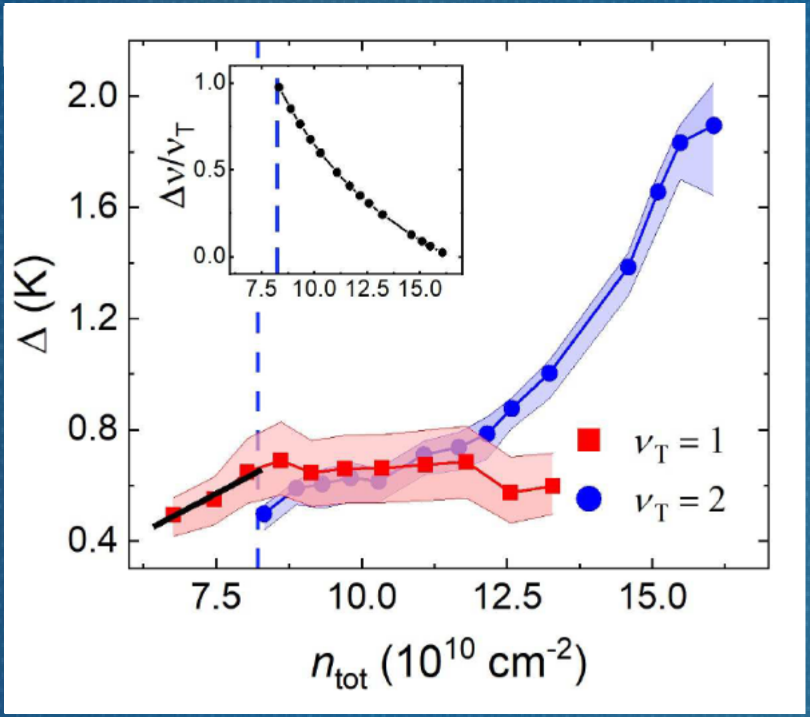
Single layer regime → $\Delta_1 = C_B B - \Gamma$
$C_B = 0.29$ K/T $\Gamma = 0.327$K

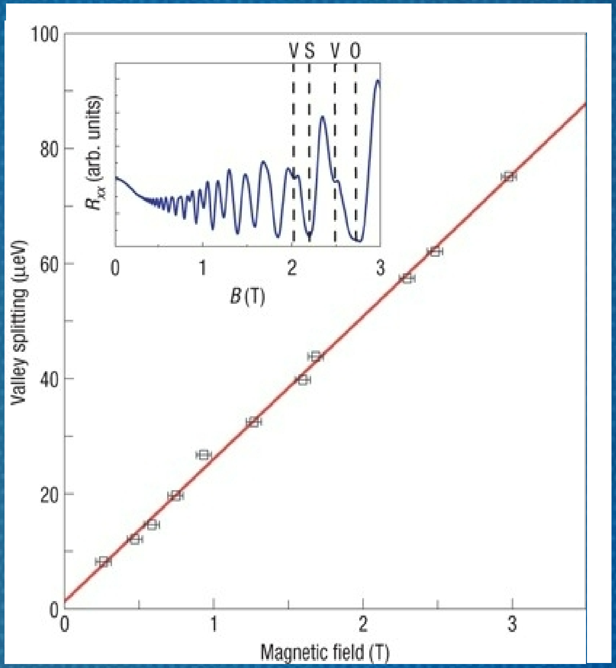
For a spin quantum Hall state,
$C_B = g\mu_B = 1.3$ K/T

Δ_1 is consistant with a valley state

Si/SiGe : ν_1 activation gaps

Variable density imbalance regime





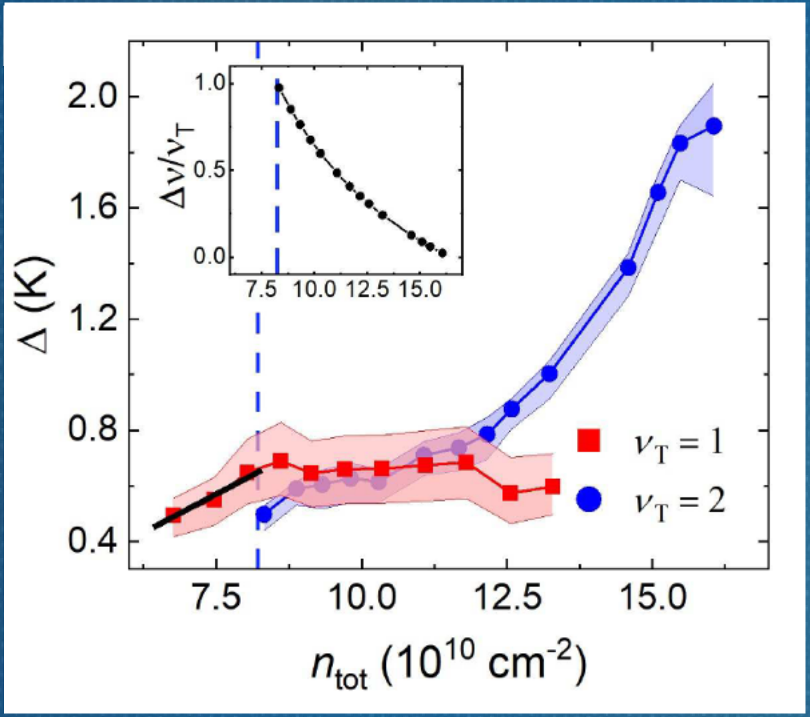
S. Goswami et al. Nature Phys. **3** 41, 2006

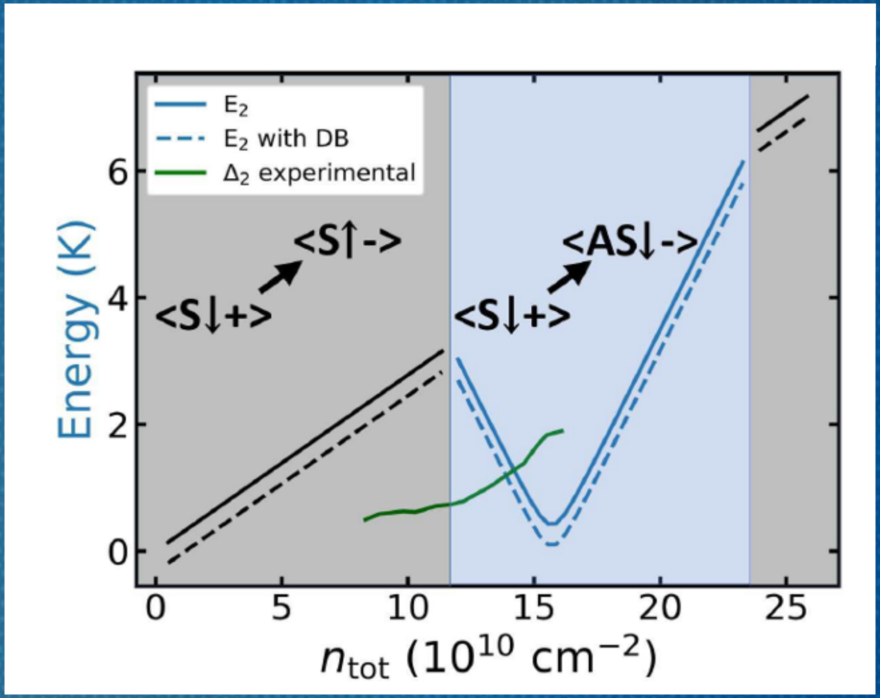
Valley splitting very different in bilayers and single layers!

- Different interference conditions?
- Ge content increases valley splitting?
- Consequence of exciton condensation?

Si/SiGe : ν_2 activation gaps

Variable density imbalance regime





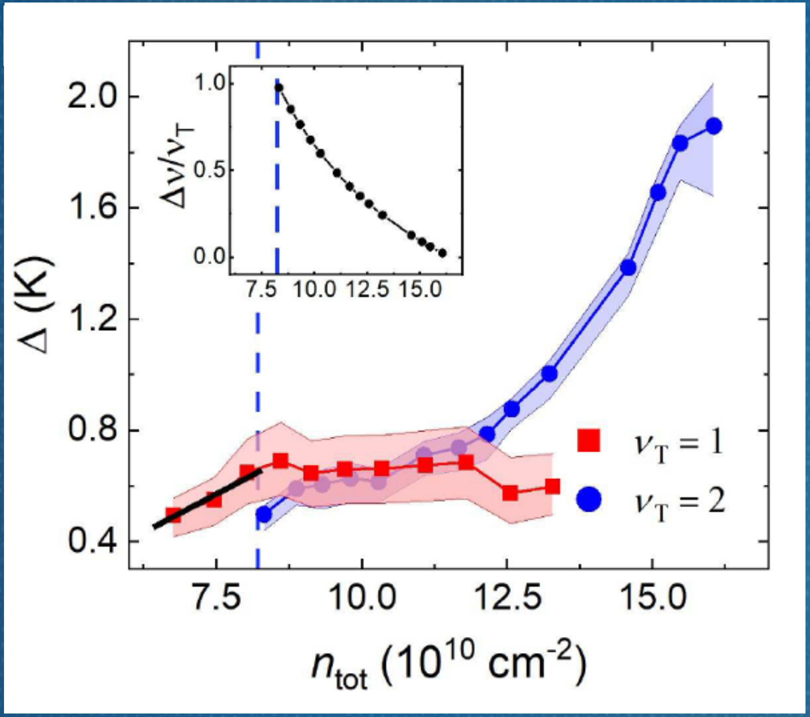
The SP simulation only produces E_2.

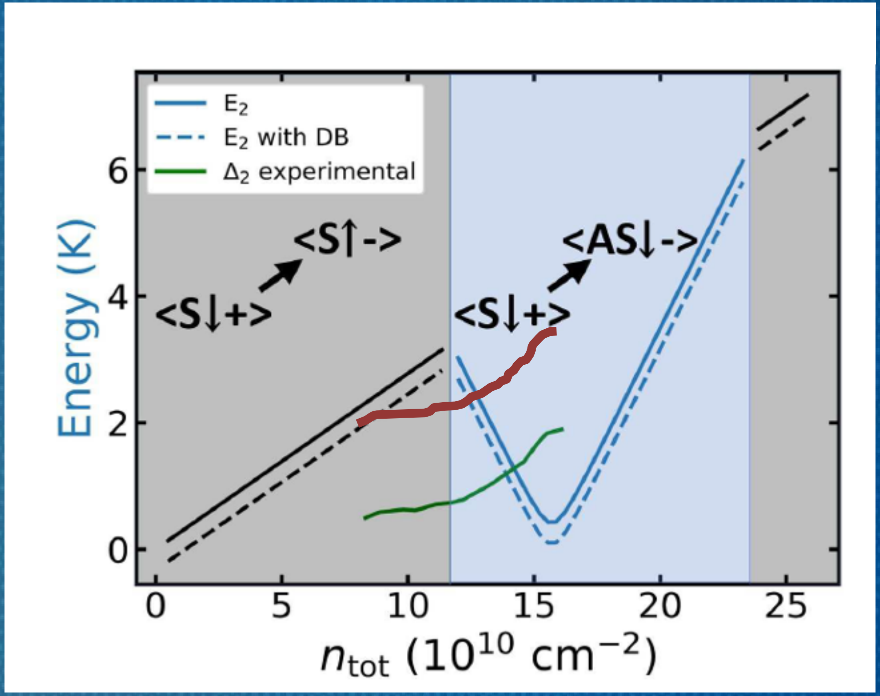
$\Delta_2 = E_{s/l} - E_v - \Gamma = E_{s/l} - \Delta_1 - 2\,\Gamma$

Δ_2 is inconsistent with a spin or a S-AS quantum state → consistent with exciton condensation*

Si/SiGe : ν_1 activation gaps

Variable density imbalance regime





Δ_2 is nearly one order of magnitude larger than the expected value from Δ_{SAS}

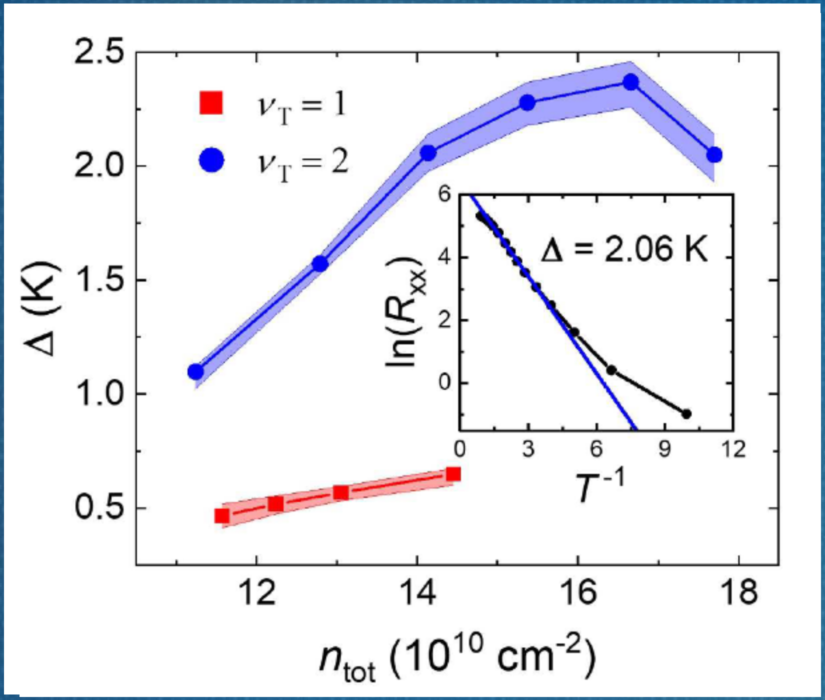
From theory :

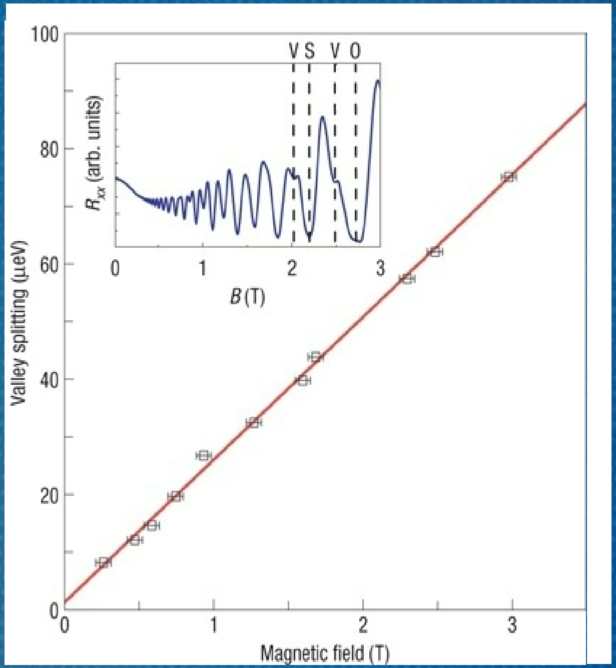
Δ_{SIC} → decreases with magnetic field, tunneling

Δ_{SIC} → increases with density imbalance

Si/SiGe : ν_1 activation gaps

Density matched regime





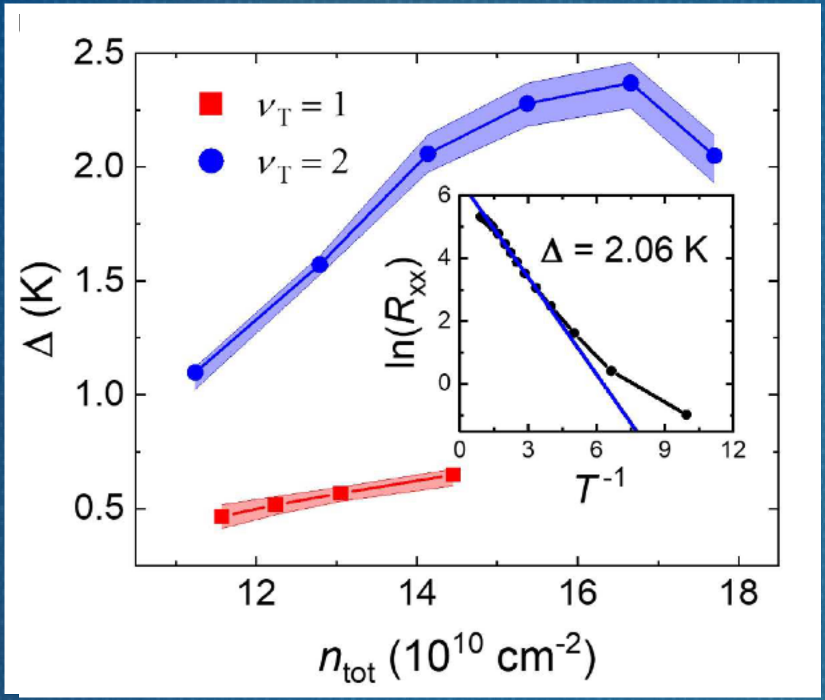
S. Goswami et al. Nature Phys. **3** 41, 2006

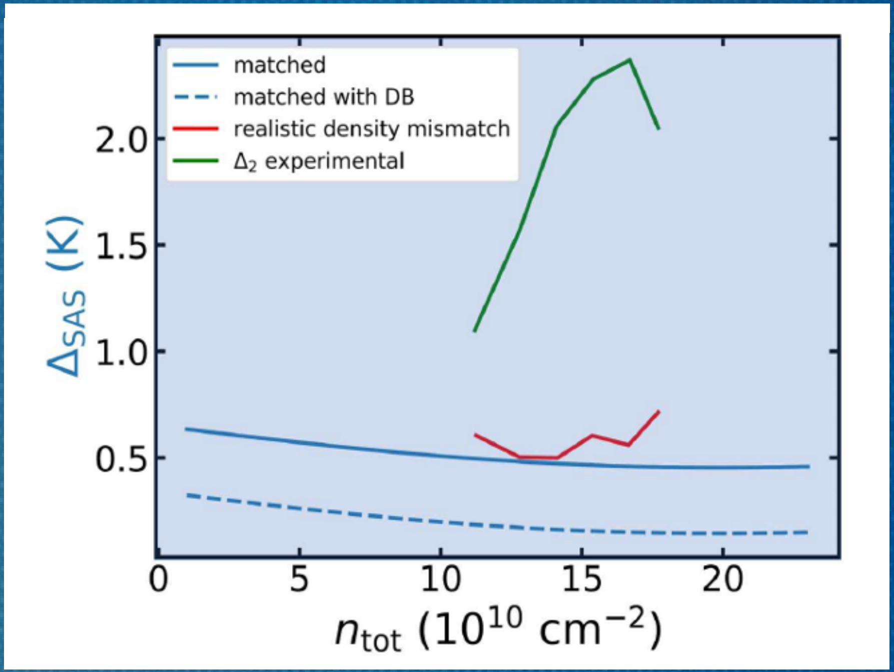
Valley splitting is linear in matched density bilayers

C_B reduced from 0.29 K/T to 0.15 K/T
Further work needed to understand valley splitting in bilayers

Si/SiGe : ν_2 activation gaps

Variable density imbalance regime





Δ_2 is nearly one order of magnitude larger than the expected value from Δ_{SAS}

Δ_2 has the opposite concavity from Δ_{SAS}

From theory :

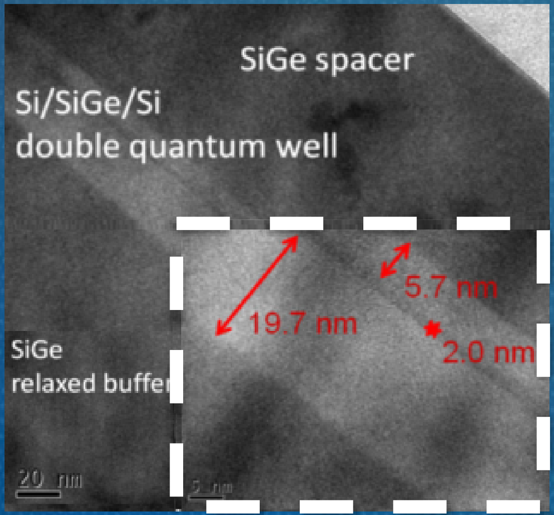
Δ_{SIC} → decreases with magnetic field, tunneling

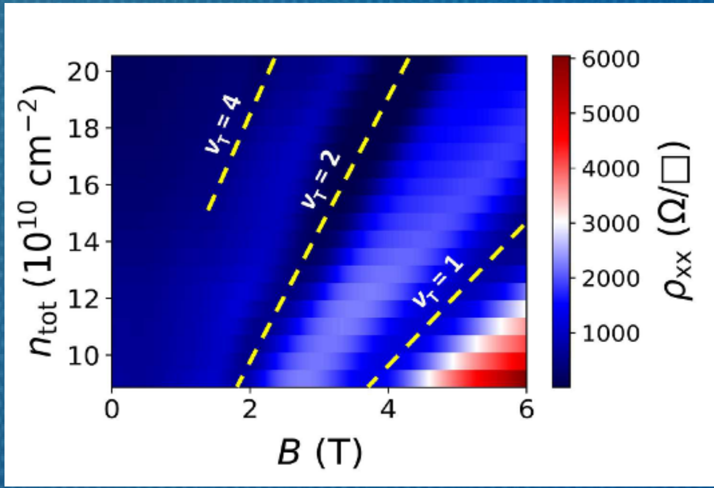
Δ_{SIC} → increases with density imbalance

Si/SiGe : Summary

- Observed bilayer effects in system → Mobility dip and ν_1 quantum Hall state
- ν_{tot} = 1 state is attributed to valley splitting
  - Behavior is clear departure from single layer valley splitting
    - Warrant further investigation!
- ν_{tot} = 2 state is attributed to layer effects
  - Behavior inconsistent with Δ_{SAS}
  - Consistent with spontaneous interlayer coherence

- Next steps : independent contact to both layers → Study tunneling, counterflow



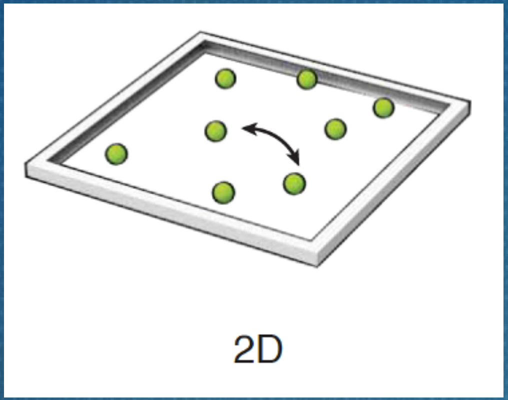


Outline

- Introduction to low-dimensional systems ☑
- Search for exciton condensation in Si quantum wells ☑
  - Introduction to Si/SiGe quantum wells
    - 2DEG
    - Growth
    - Valley splitting
  - Introduction to exciton condensation
  - Device fabrication
  - Excitation gaps in the quantum Hall regime
- Coulomb drag between quantum wires
  - Quantum wires
  - Introduction to Luttinger liquids
  - Coulomb drag technique
  - Device fabrication
  - Coulomb drag measurements in laterally-coupled quantum wires
- Future directions

2. Drag in Coupled GaAs quantum wires

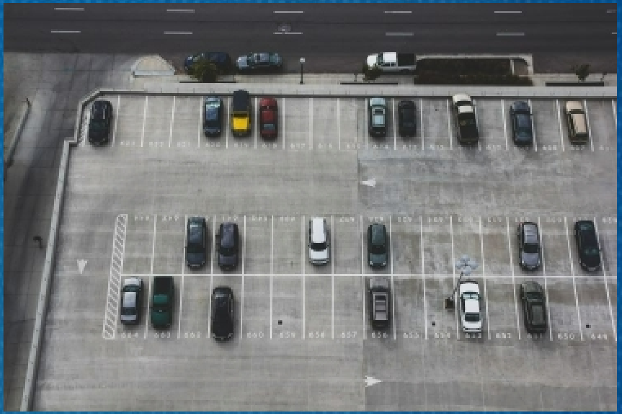
Luttinger liquid physics

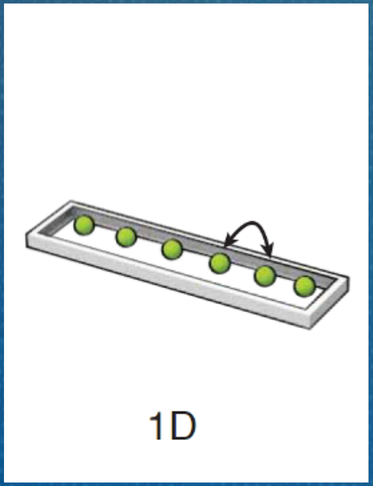


Fermi liquid

↓

Effective parameters



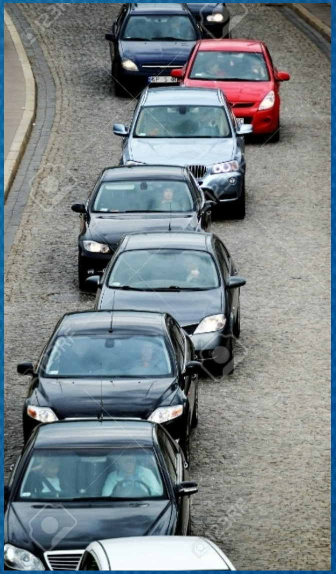


Luttinger liquid

↓

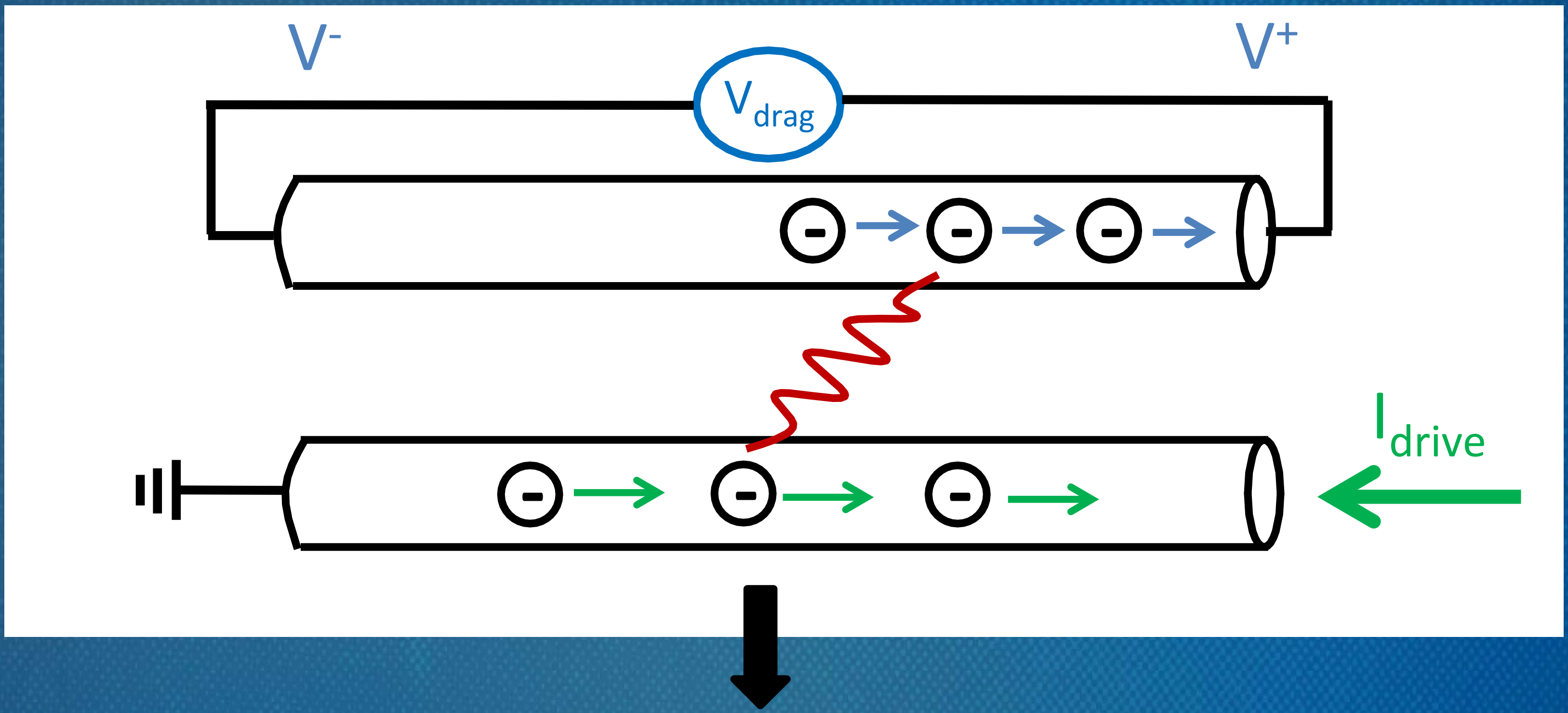
All motion is correlated

Strongly interacting system



Coulomb drag

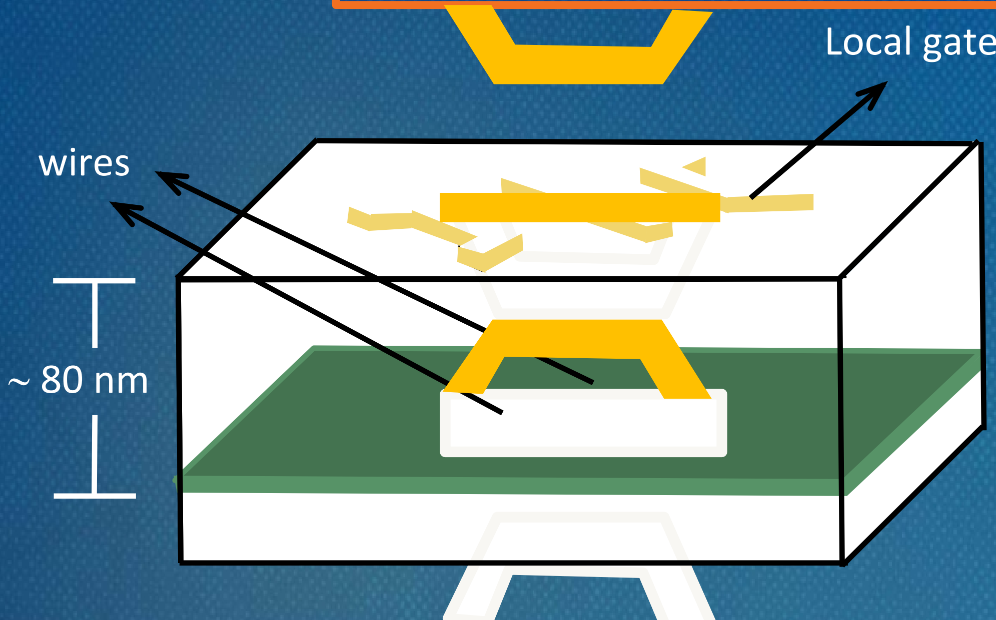
Momentum transfer models

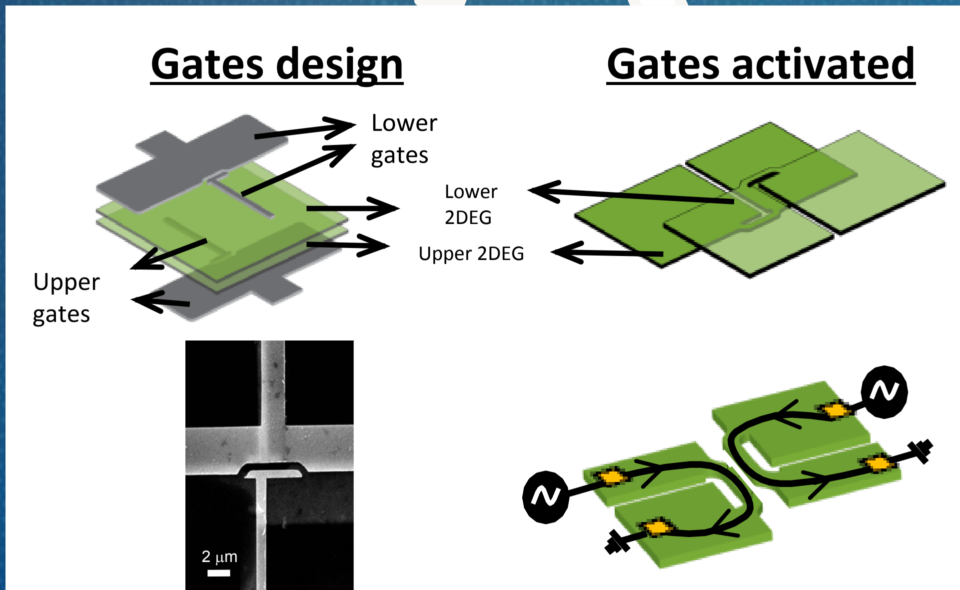


$$R_D = \frac{-V_{drag}}{I_{drive}}$$

Magnitude of frictional resistance dependes on e^- - e^- interactions

Coupled quantum wires





Laterally coupled quantum wires

Ease of fabrication
Tunable interwire separation

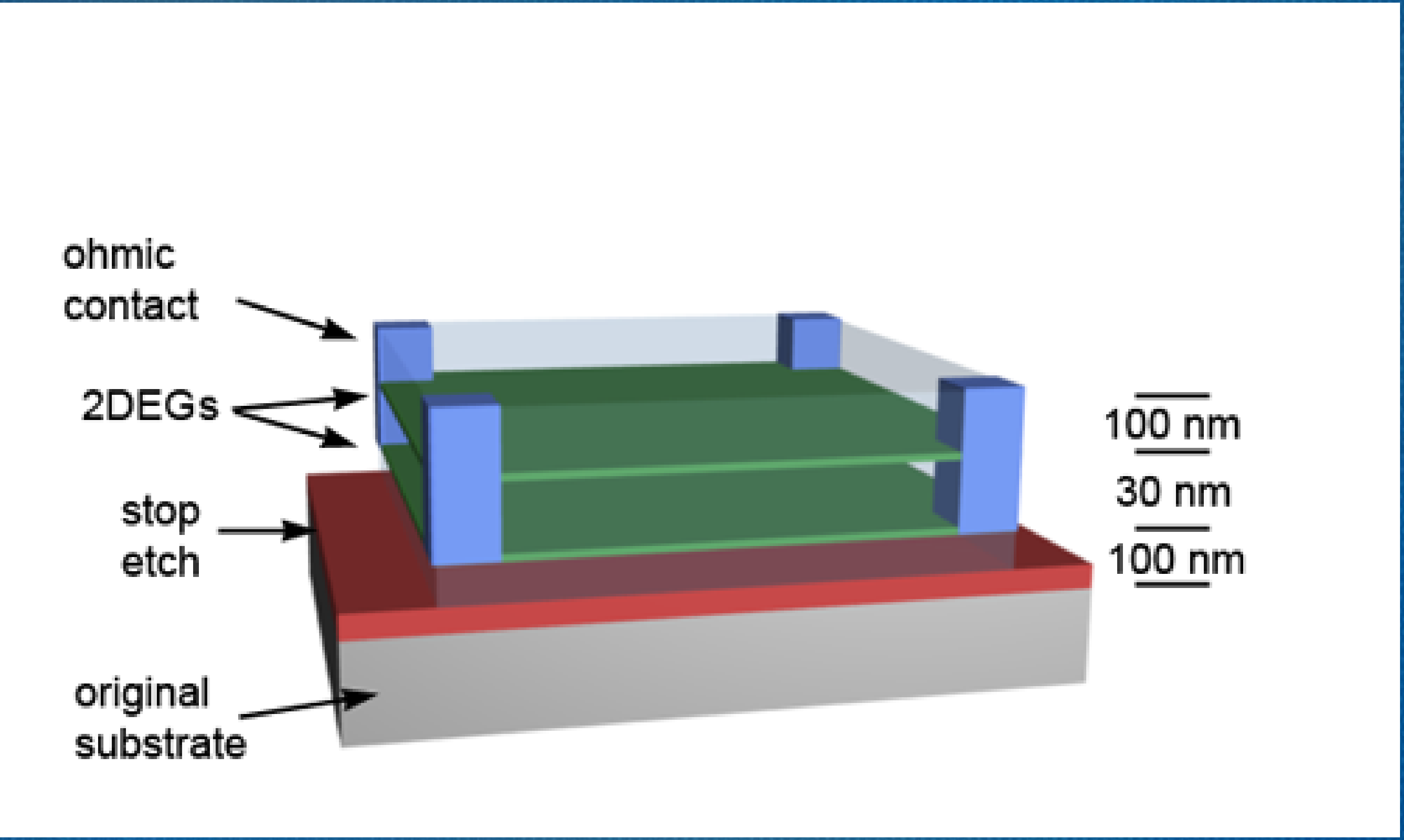
Large interwire separation
Soft electrostatic barrier

Vertically-coupled quantum wires

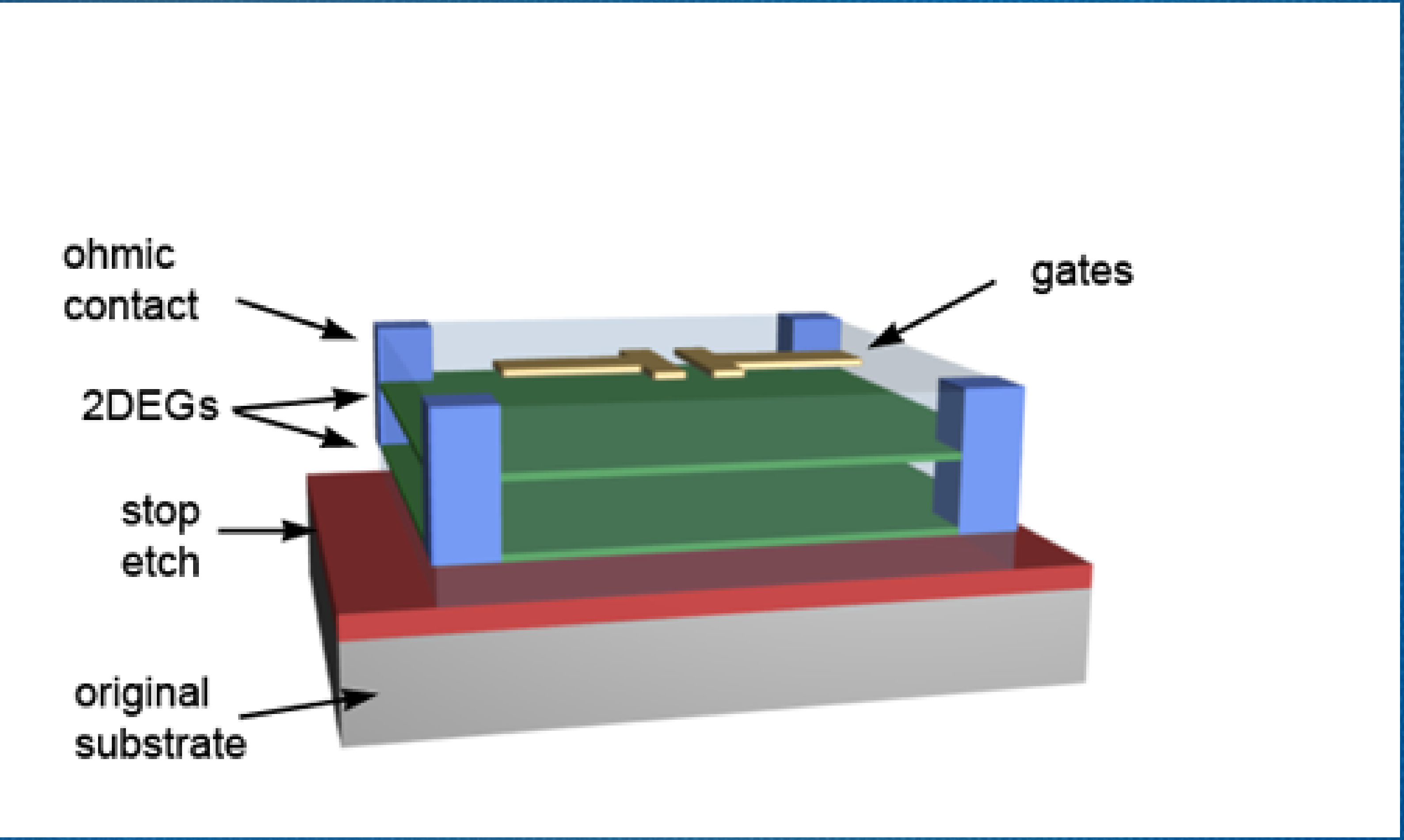
Small interwire separation
Hard dielectric barrier

Involved fabrication process

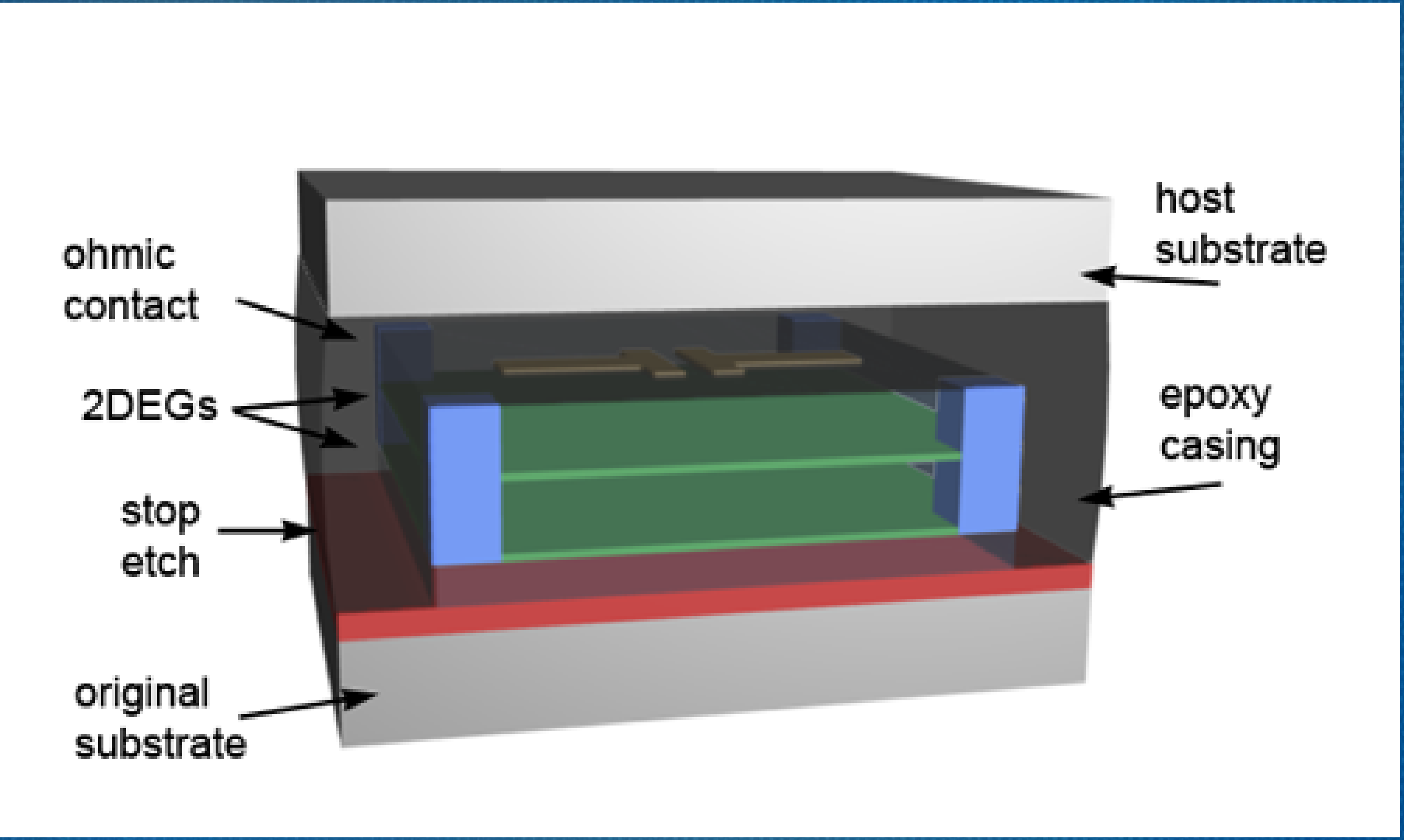
Vertically-coupled quantum wires



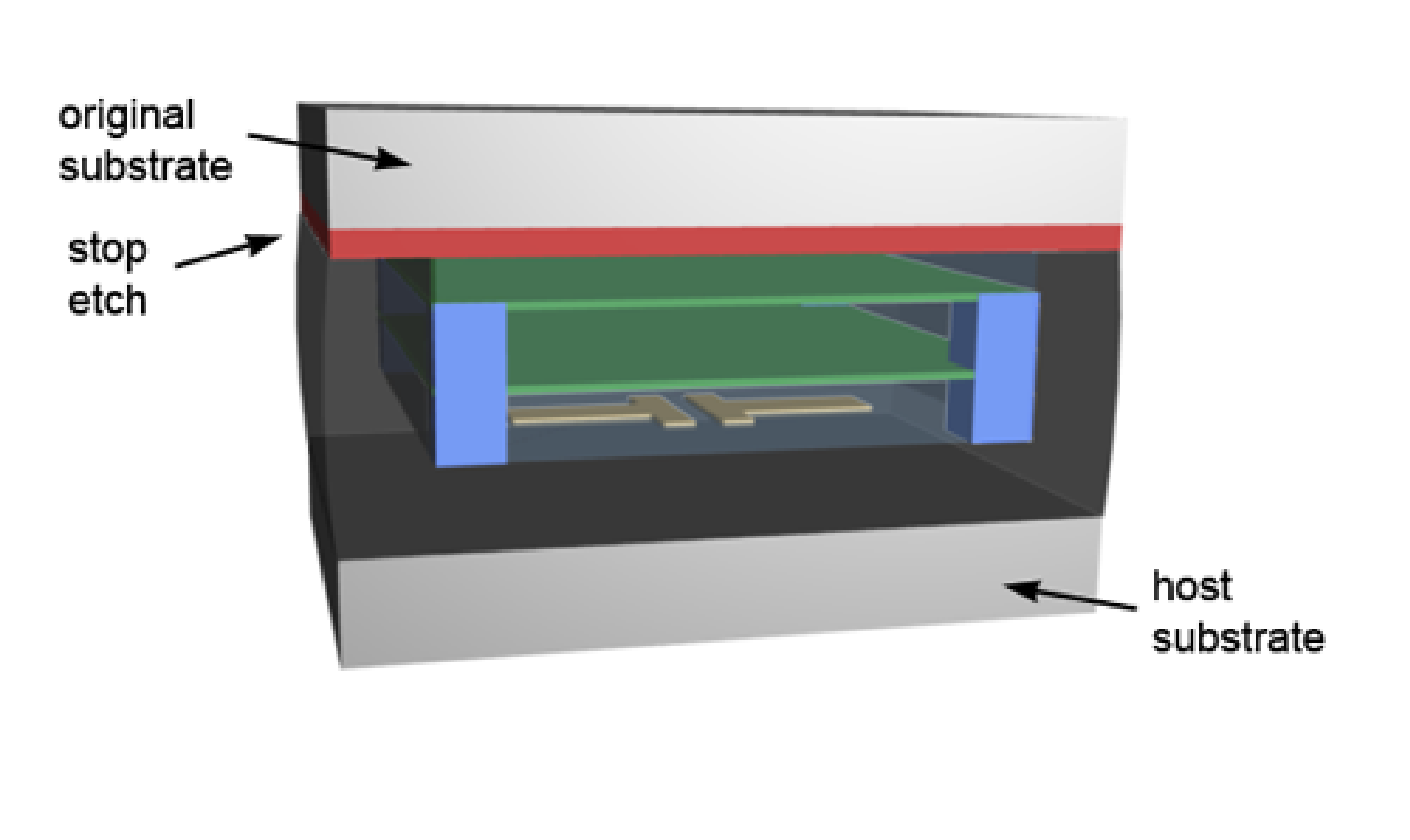
Vertically-coupled quantum wires



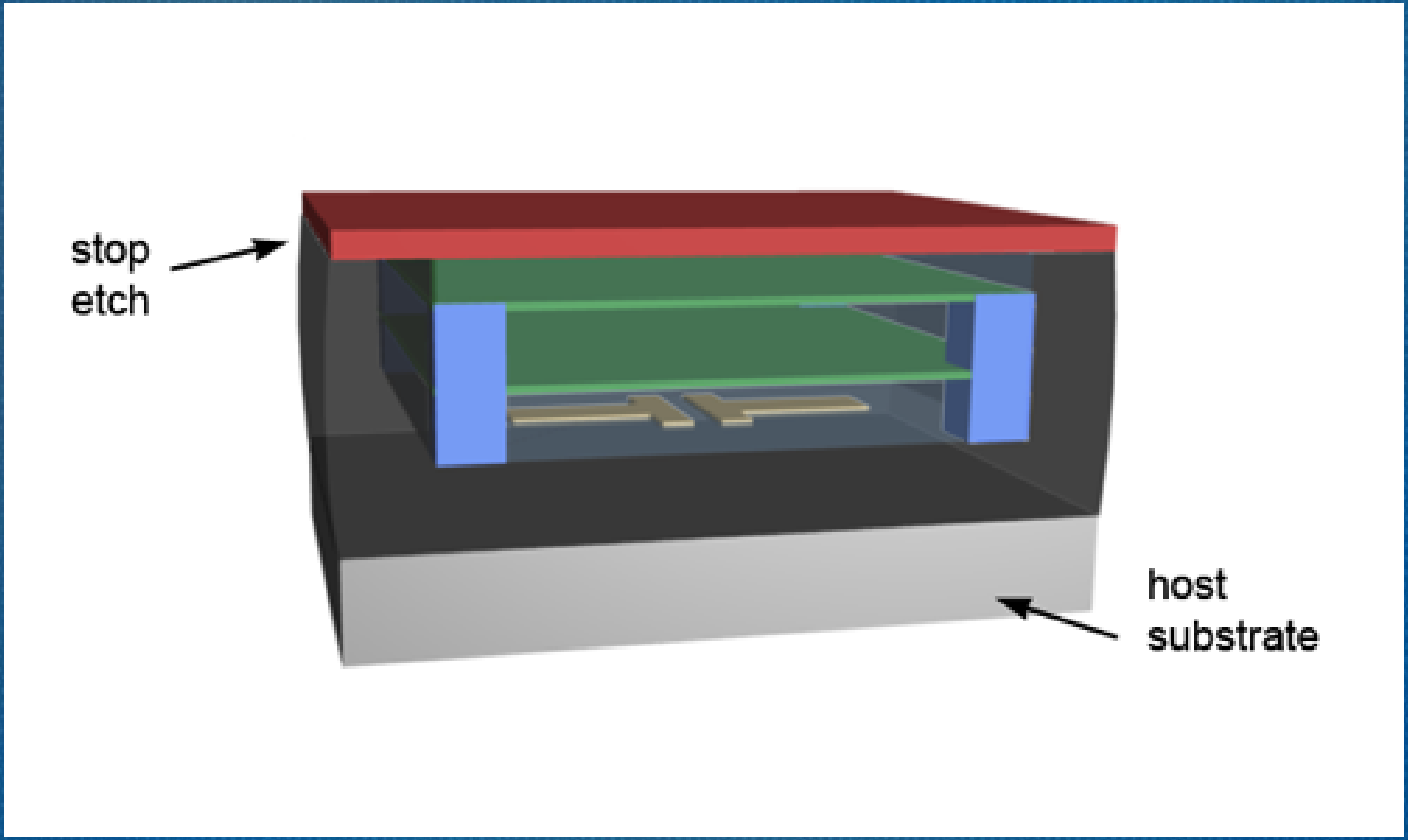
Vertically-coupled quantum wires



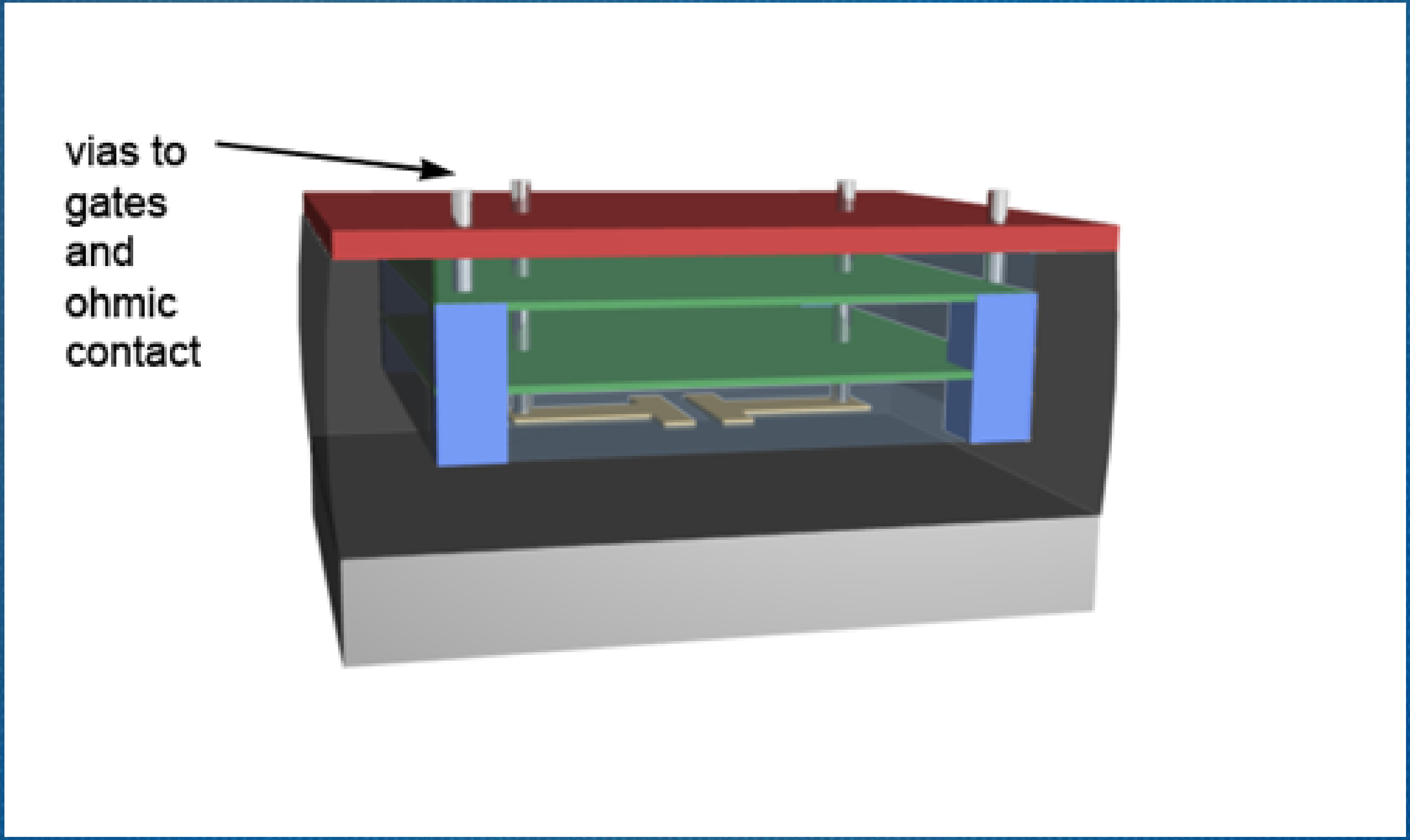
Vertically-coupled quantum wires



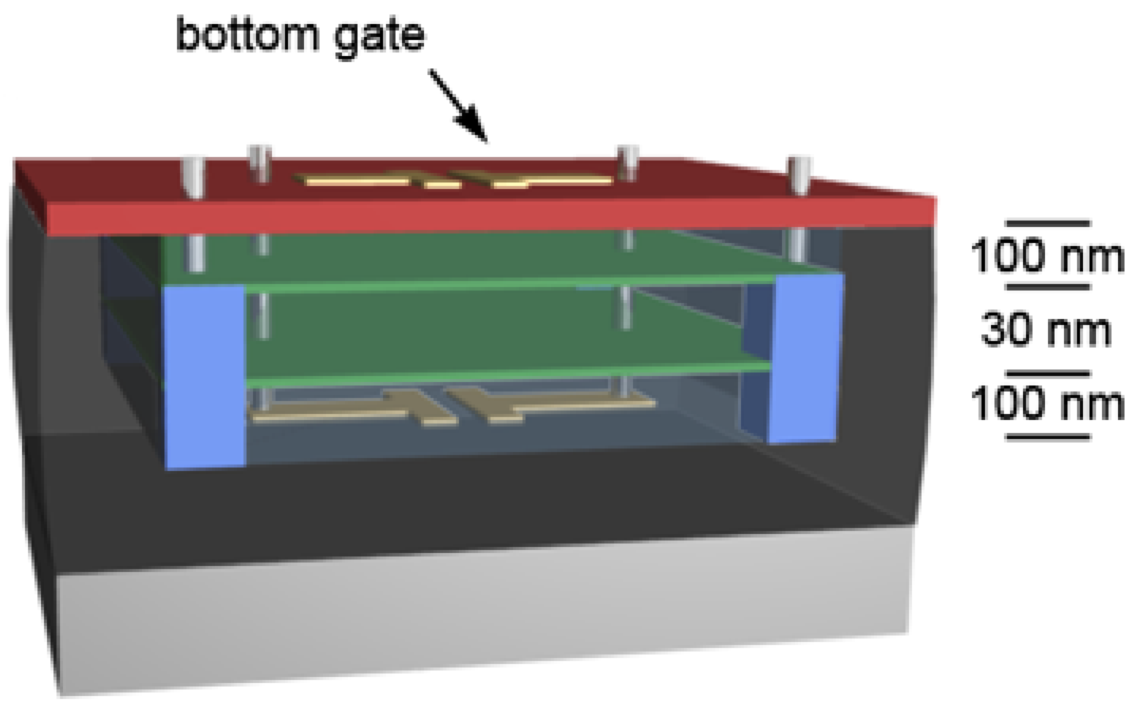
Vertically-coupled quantum wires



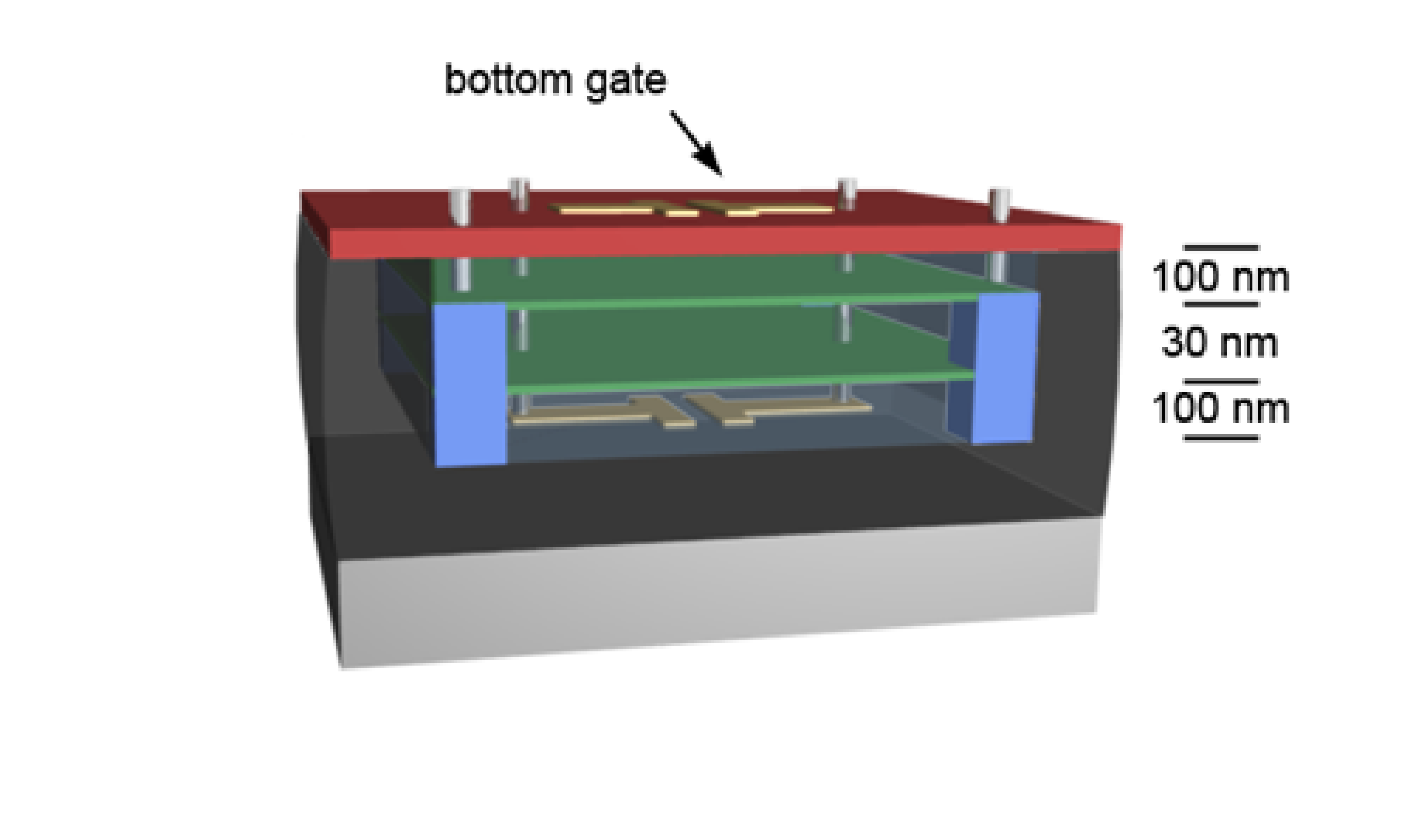
Vertically-coupled quantum wires



Vertically-coupled quantum wires



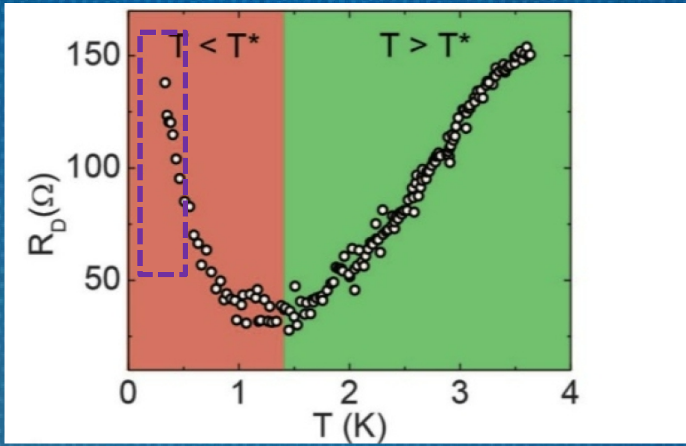
Vertically-coupled quantum wires

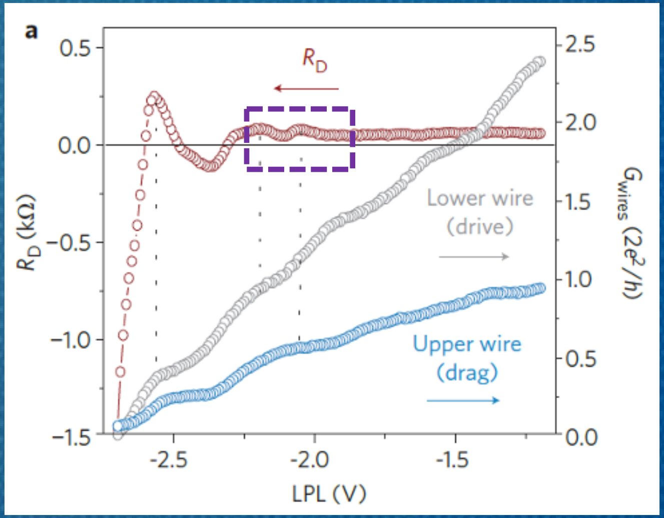


Objective : contrast the strength of electron-electron interactions as a function of geometry/separation

Open questions

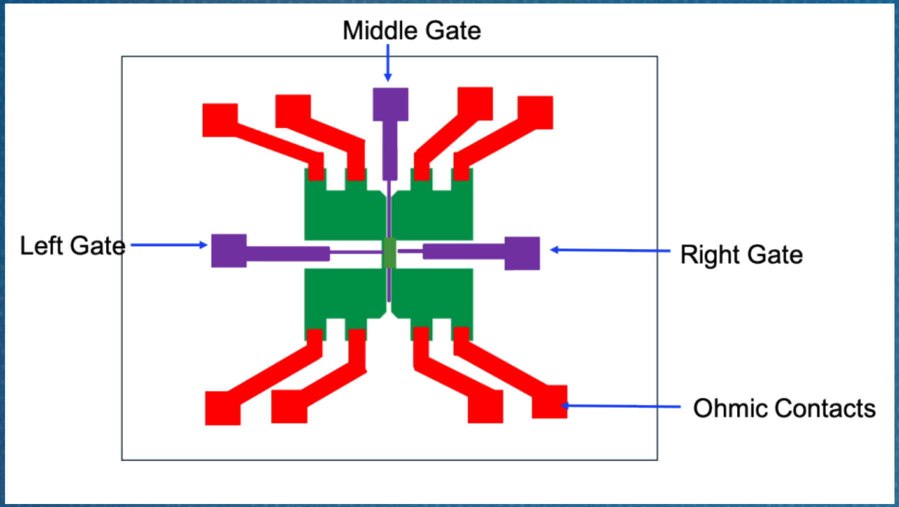
- Drag in the multi-subband regime
- Dominant drag scattering mechanism
- Impact of wire length / interwire separation
- Coulomb drag in the T=0 limit
- Drag in the spin-polarized regime

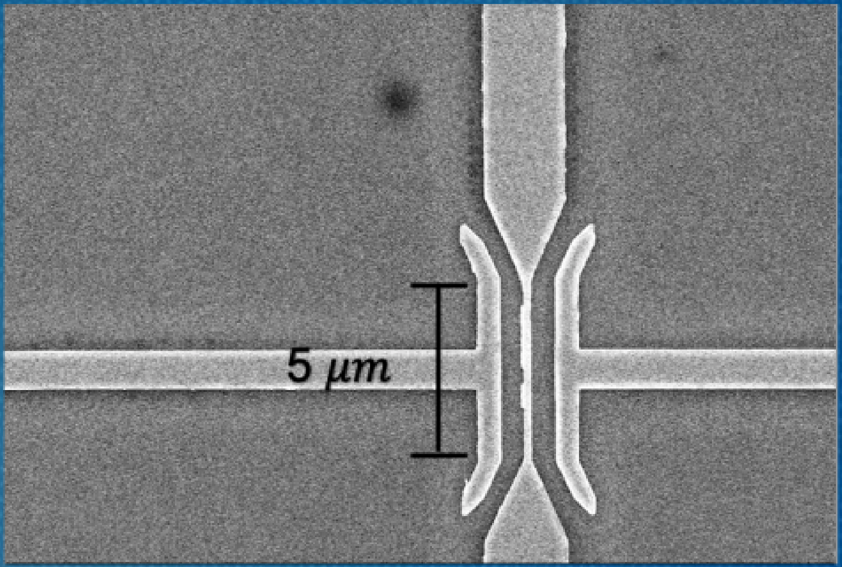




UF

Quasi-1D drag





Lateral device

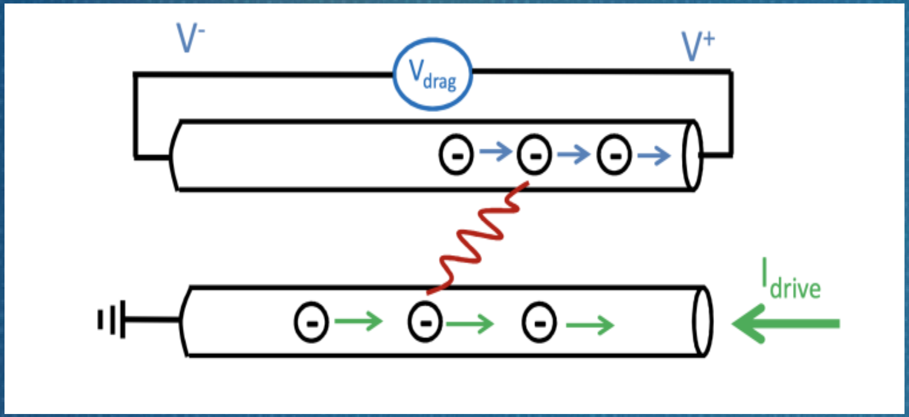
Barrier size : ~ 150 nm

5 µm long wires

Survey of drag-inducing mechanism

Momentum transfer Model

Drag current is induced through momentum transfer[1]



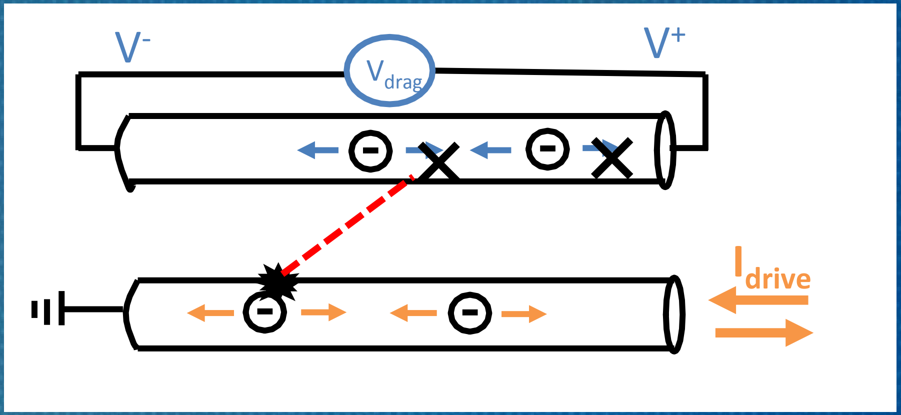
[1]Klesse, R. and Stern, A. Phys. Rev. B 62, 16912 (2000).

Expect postitive drag resistance

Expect V_{drag} to have opposite sign of I_{drive}

Charge-fluctuation Model

Arises from interlayer energy transfer[2]

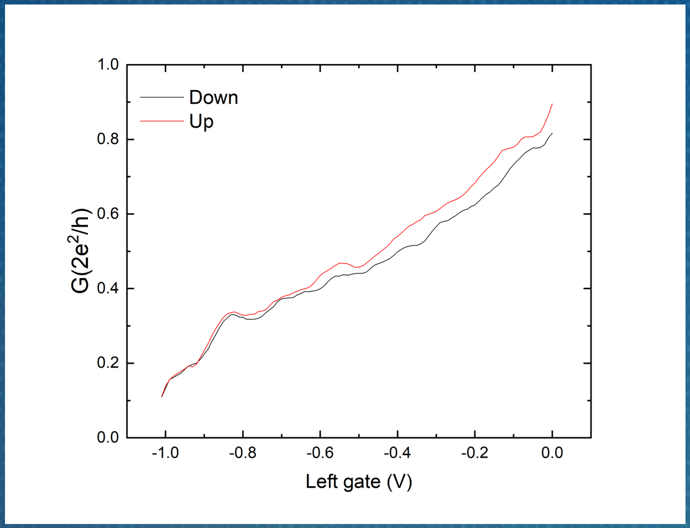


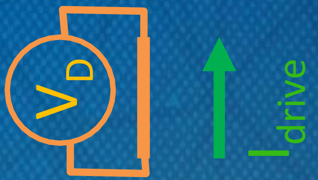
[2]Levchenko, A. and Kamenev, A. Phys. Rev. Lett. 101, 216806 (2008).

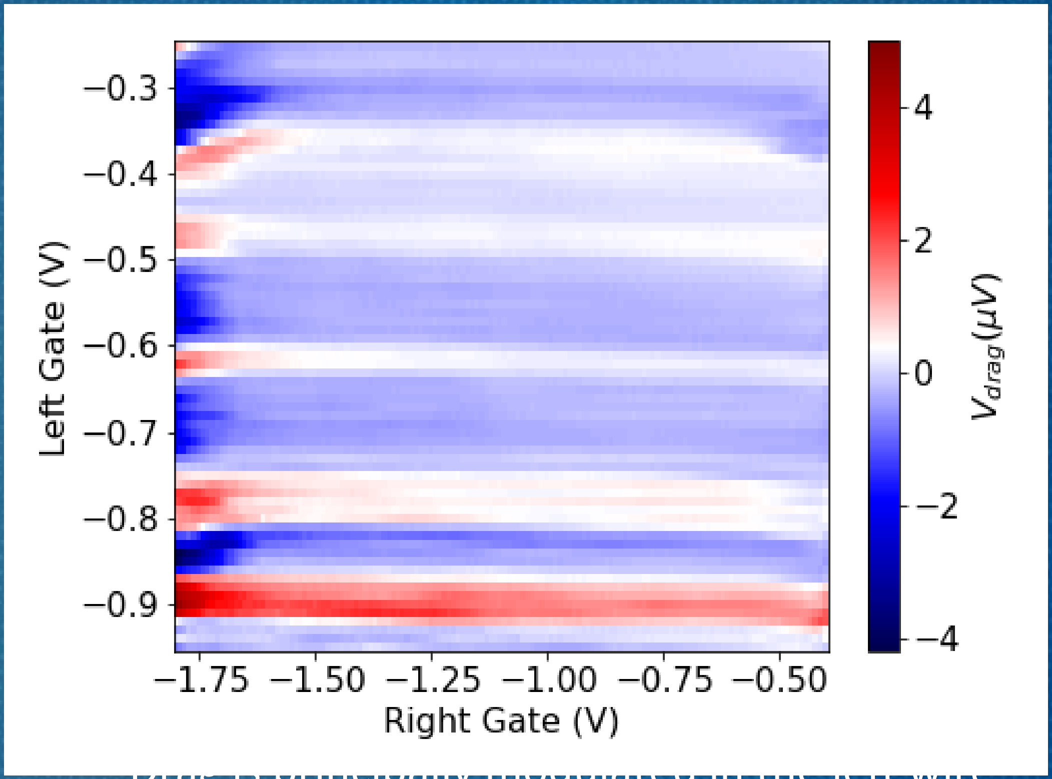
Expect rectified drag signal

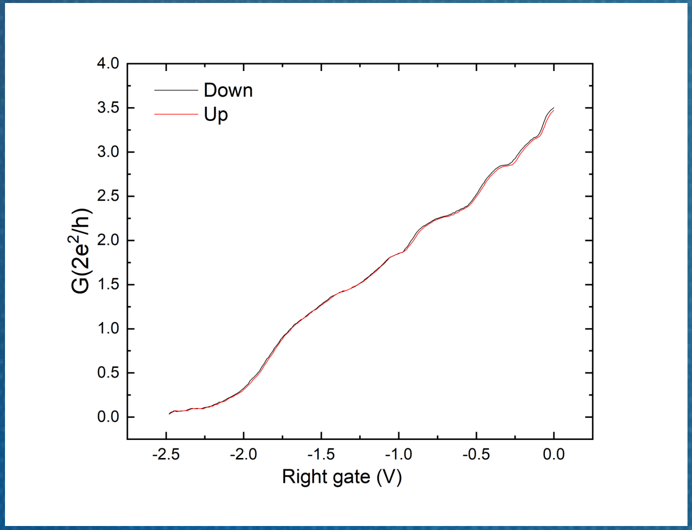
Expect V_{drag} to be independent of I_{drive} sign

Quasi-1D drag – AC data



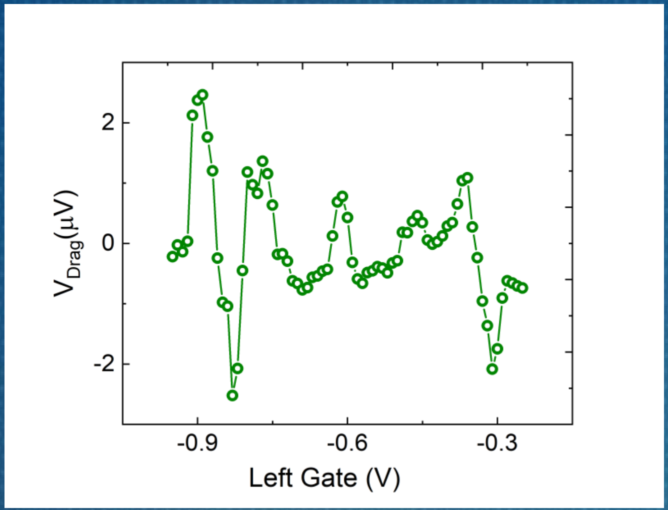


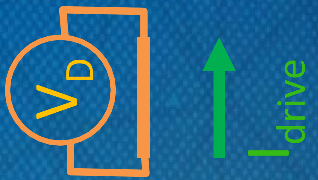


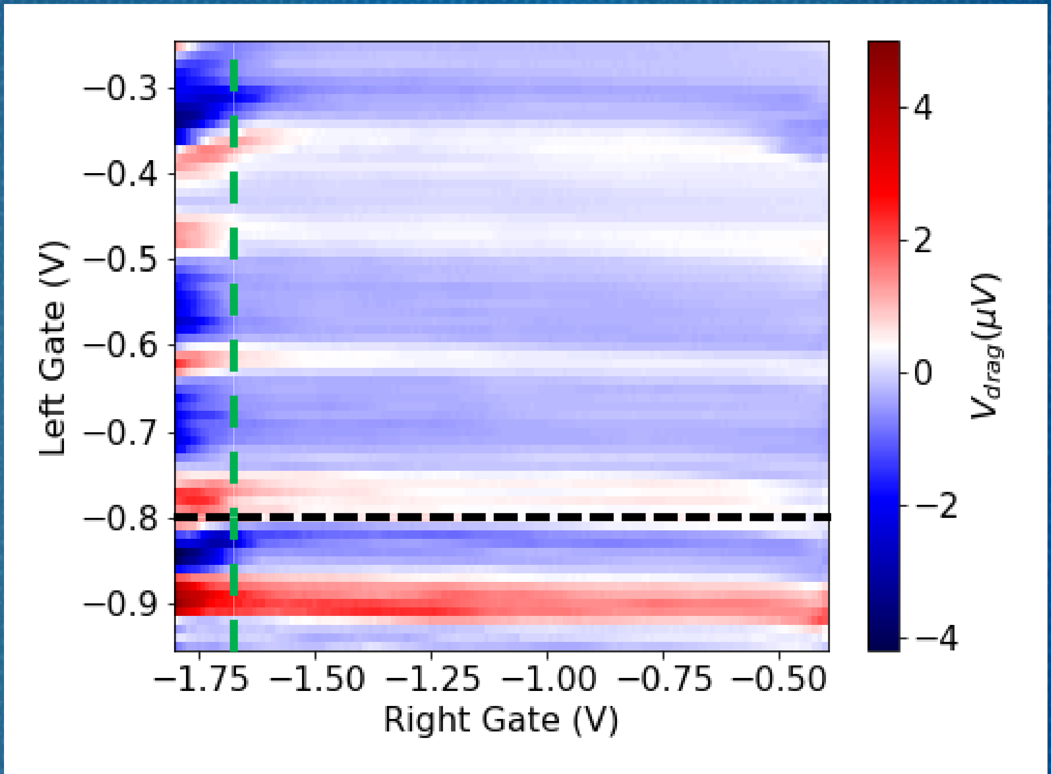


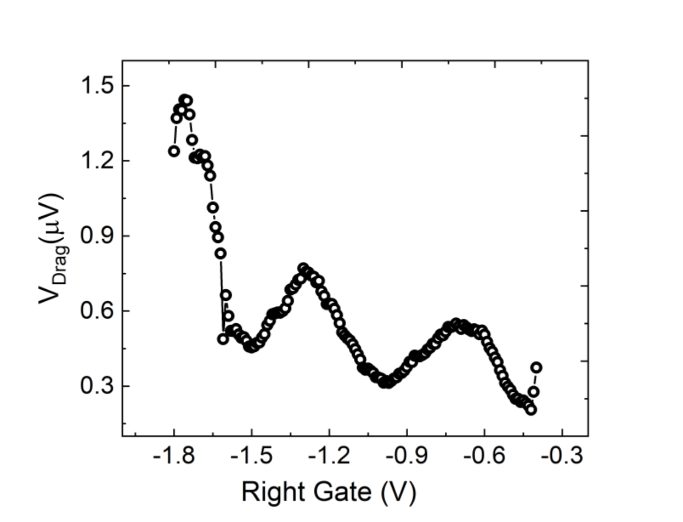
Drag is principally modulated in the left wire direction.

Quasi-1D drag – AC data



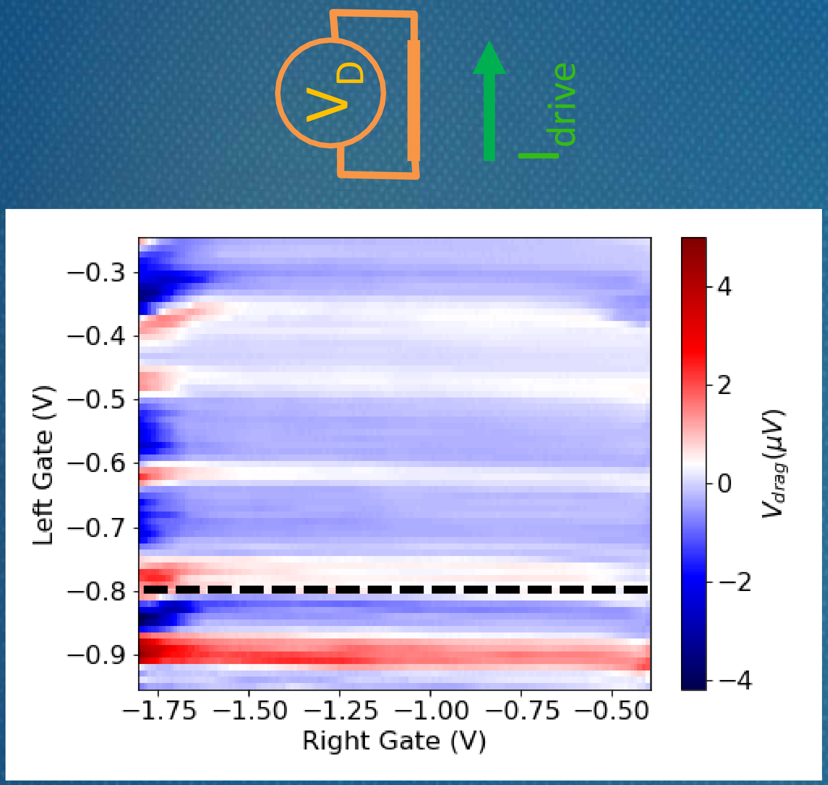


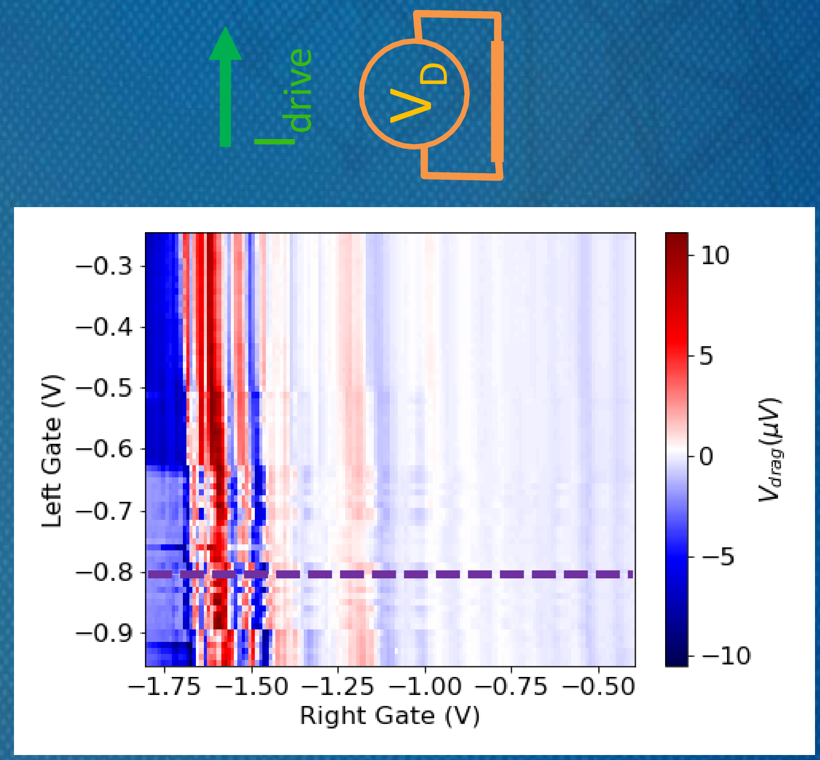




Standard drag tests

Onsager relations : drag is independent of drive/drag layer and current direction

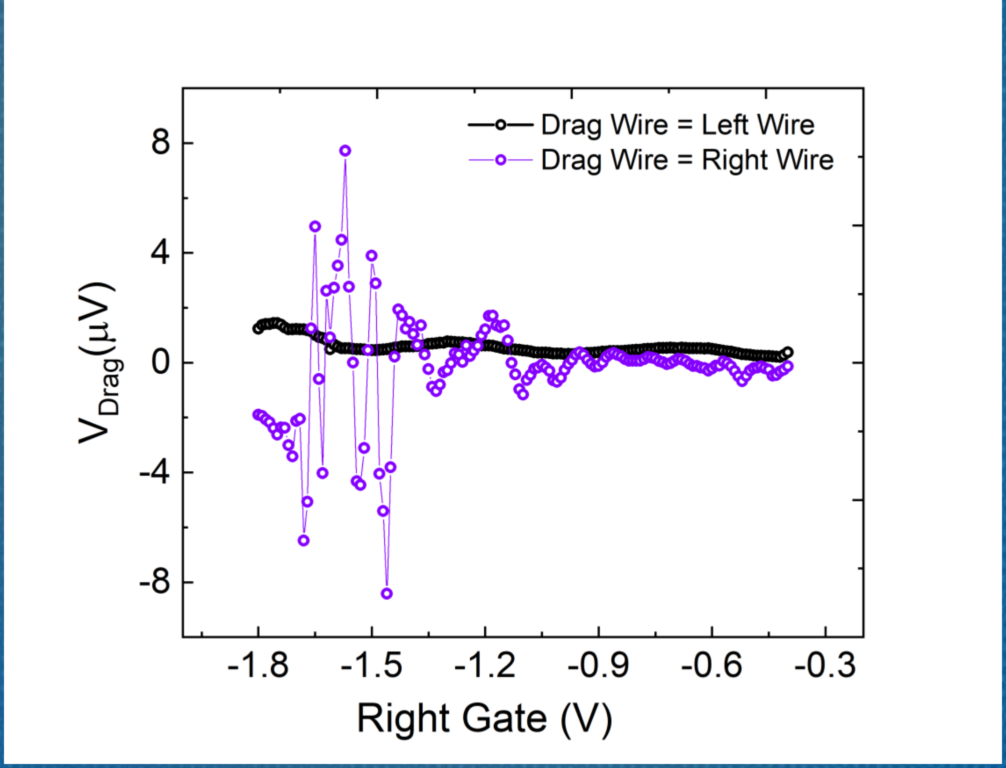




Drag voltage is strongly modulated by the drag wire!

Standard drag tests

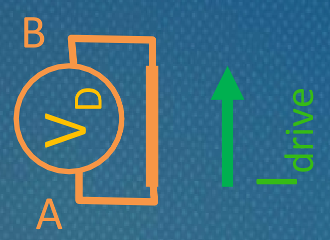
Onsager relations : drag is independent of drive/drag layer and current direction

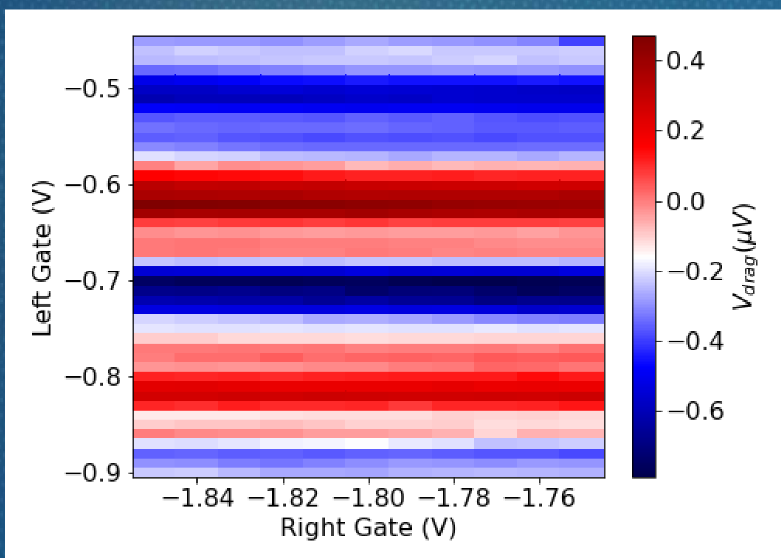


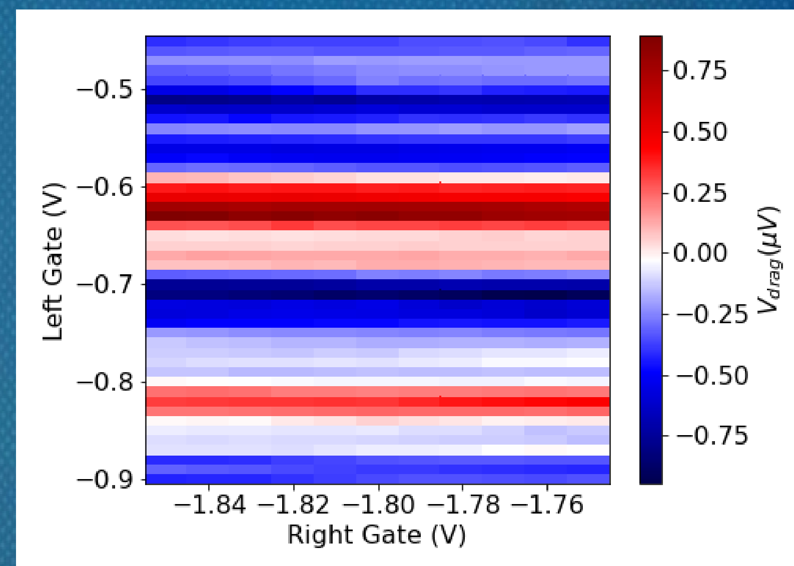
Drag is strongly modulated by the drag wire!

Standard drag tests

Onsager relations : drag is independent of drive/drag layer and current direction







Drag voltage features polarity are independent of drag direction

Consistent with rectification!

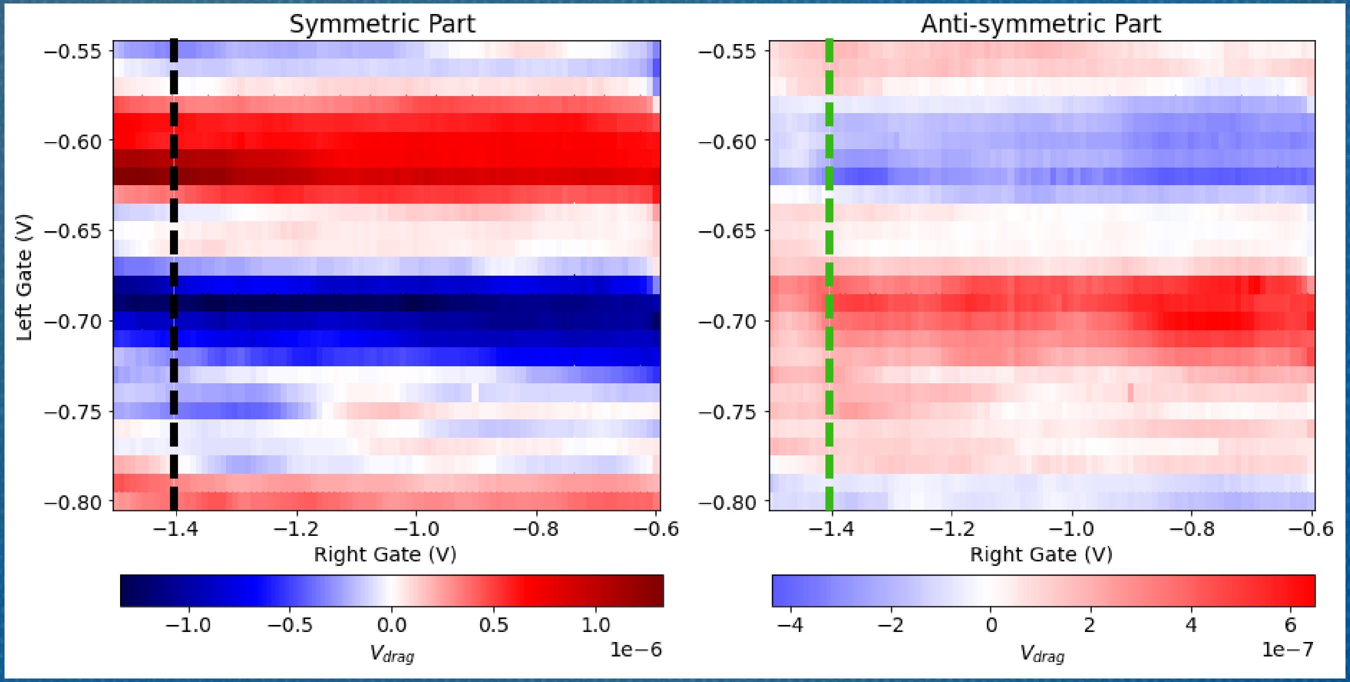
Symmetric and anti-symmetric contributions

Upon current reversal, the signal is not identical

Hypothesis : two contributions:

Symmetric : Rectification

Antisymmetric : Momentum- transfer



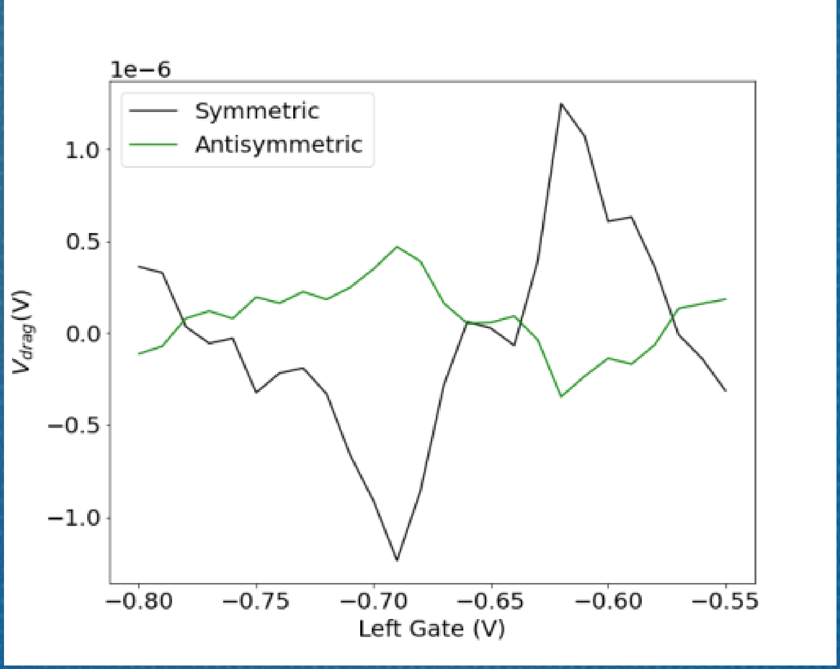
Symmetric and anti-symmetric contributions

Upon current reversal, the signal was not identical

Hypothesis : two contributions:

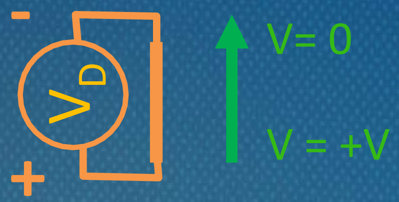
Symmetric : Rectification

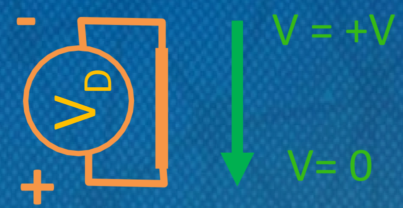
Antisymmetric : Momentum- transfer

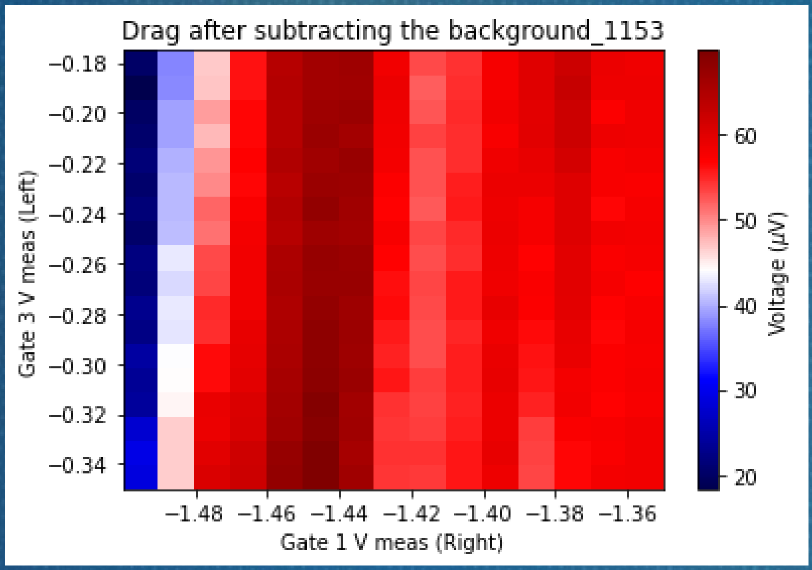


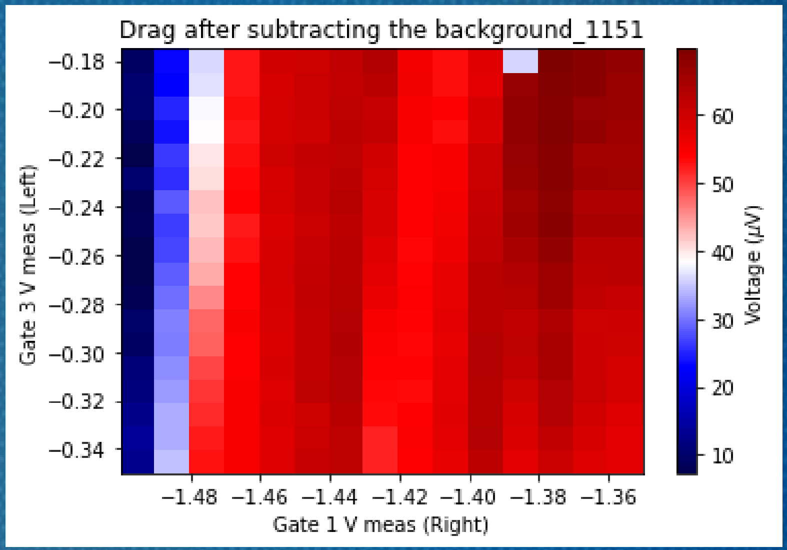
<u>Symmetric part dominates</u>

DC measurements



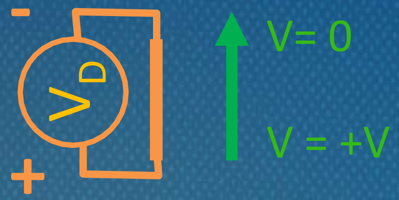


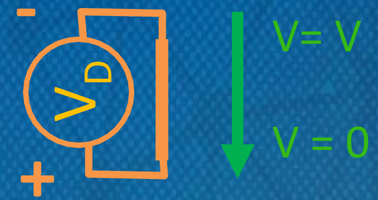


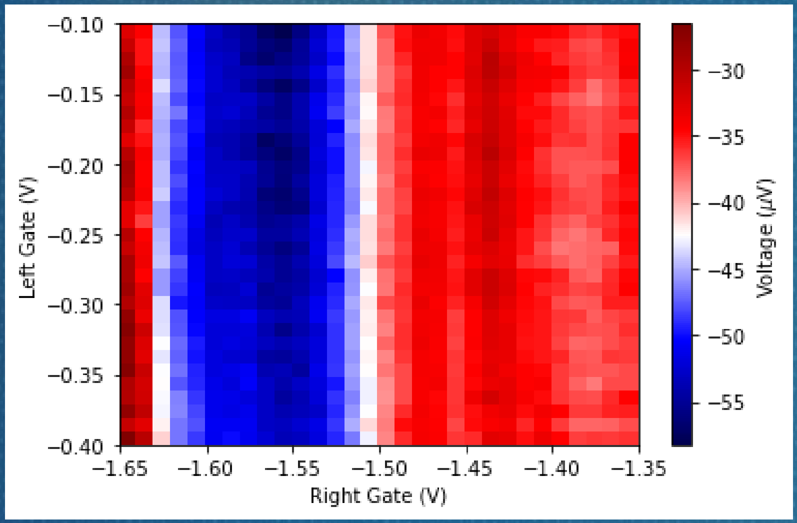


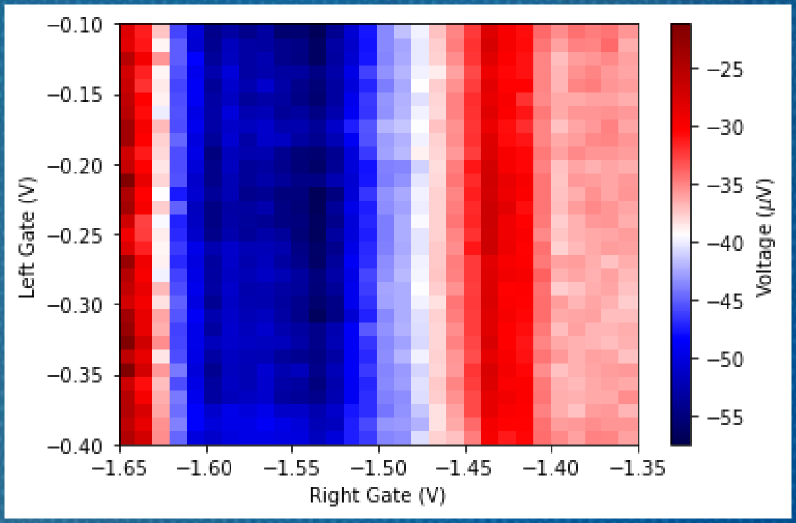
Signal is remains nearly identical
Consistent with charge fluctuations

DC measurements



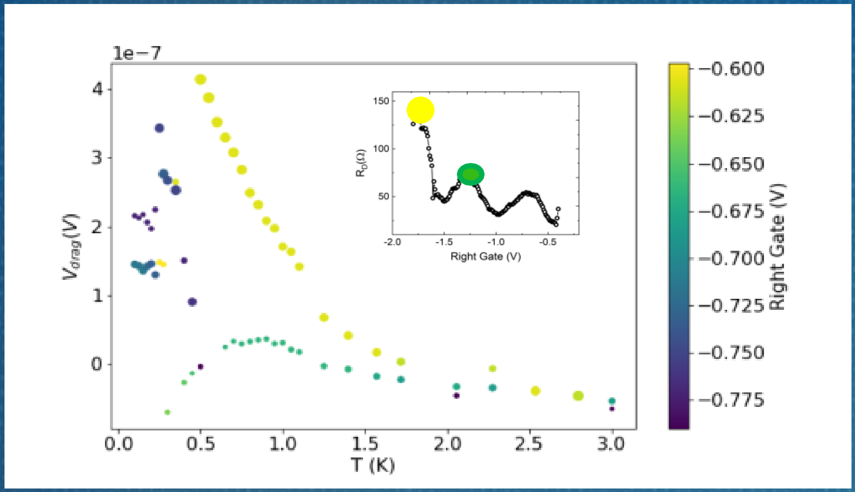




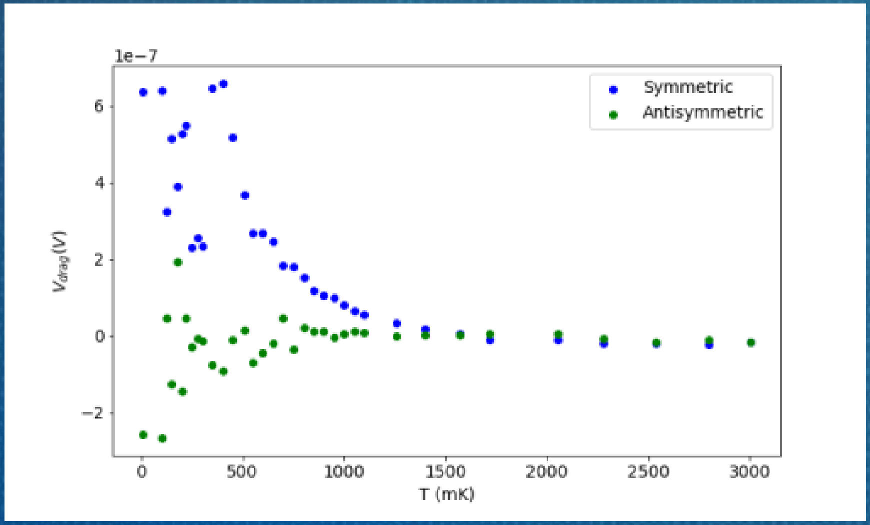


Similar rectification behavior
Currently analyzing current linearity and chemical potential influence.

Temperature dependence overview



AC total contribution

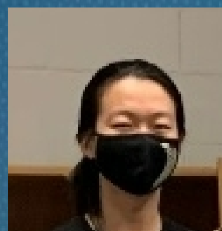
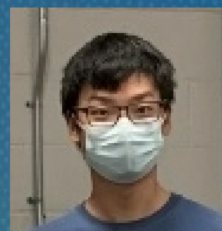


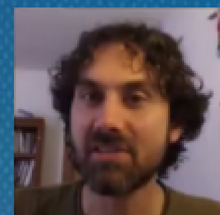
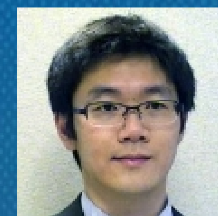
AC Symmetric vs antisymmetric contribution

Not a simple T^2 dependence

Collaborators/students

Si/SiGe exciton condensation

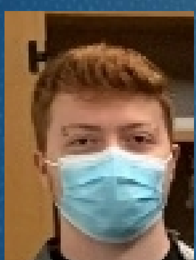




Growers at National Taiwan University

NARLabs
National Applied Research Laboratories

GaAs Coulomb drag




UF UNIVERSITY of FLORIDA

NATIONAL MAGLAB

The National High Magnetic Field Laboratory is supported by the National Science Foundation through NSF/DMR-1644779 and the State of Florida.

Center for Integrated Nanotechnologies

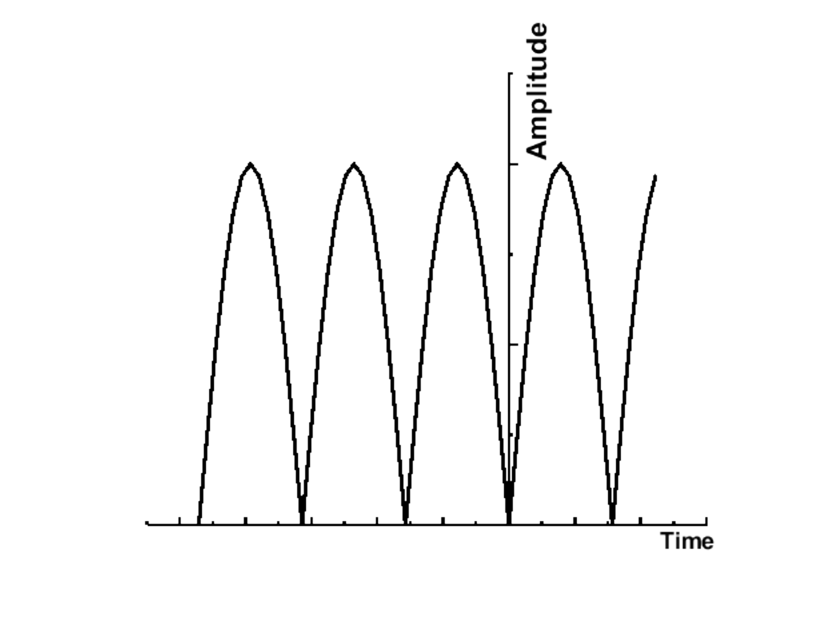
Sandia National Laboratories

Thank you for your attention

Questions?

Current rectification

Expectation

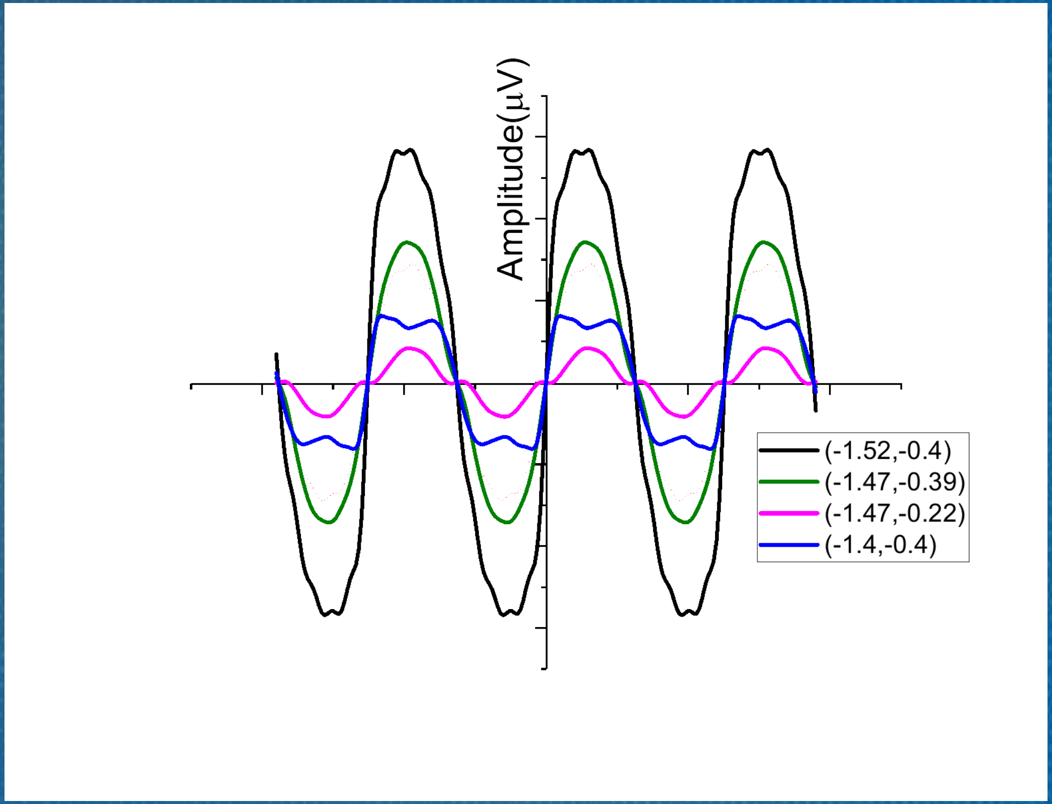


Sum of even sine terms

$V_{drag} \sim |\sin(\omega t)|$

Current recrification

Measured



Waveform depends on wires configuration

UF

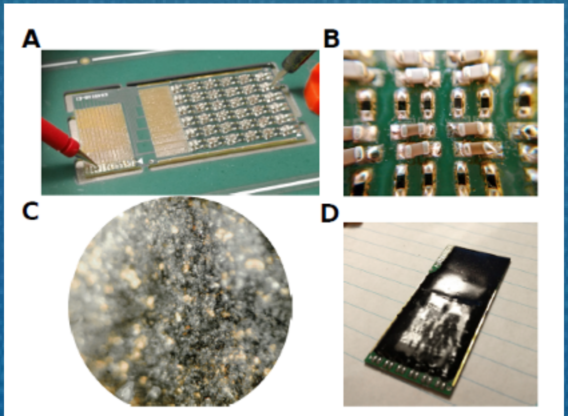
Cooling 1D electrons

- Coulomb drag in the T=0 limit → lowest electron value : 80 mK
- Drag in the spin-polarized regime → never attempted

1- Samples lattice temperatures usually limited to ~ 20 mK
2 - Electron temperatures difficult to cool in low-dimensional systems

1 - Nuclear demagnetization → Lattice temperatures ~ 0.5 mK
2 – Sample in ^{3}He immersion cell
Electrical connections with silver sintered leads
5^{th} order RC filter and continuous element filters at 30 mK

Microkelvin facilities

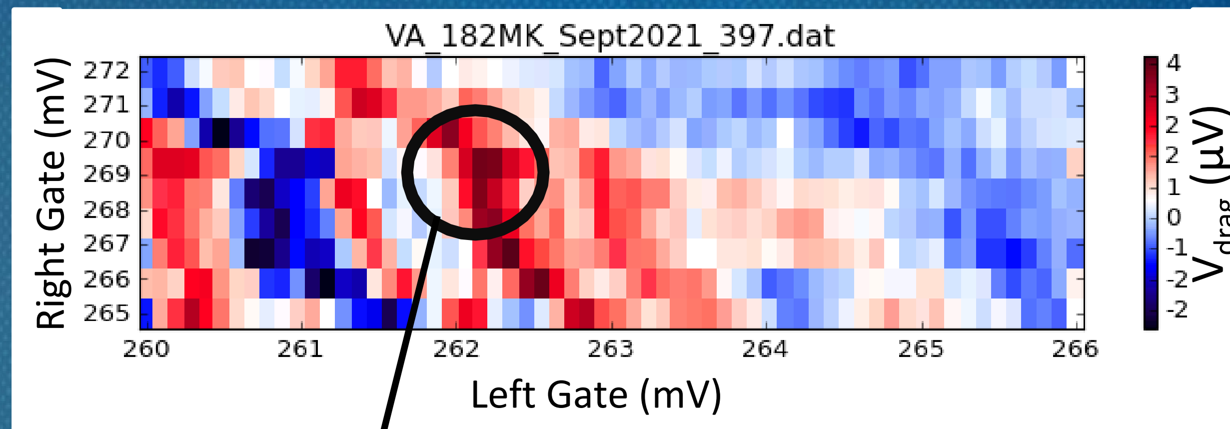


M. Sarsby *et al. Nat. Comm* ***11***, 1492 (2020)

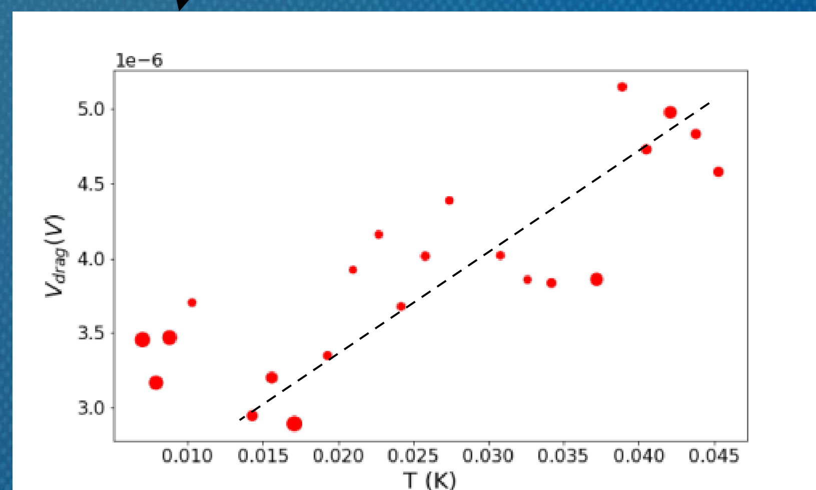
Ultra-low-temperature 1D drag

Preliminary results in laterally coupled quantum wires :

Coulomb drag is modulated with wire occupancy

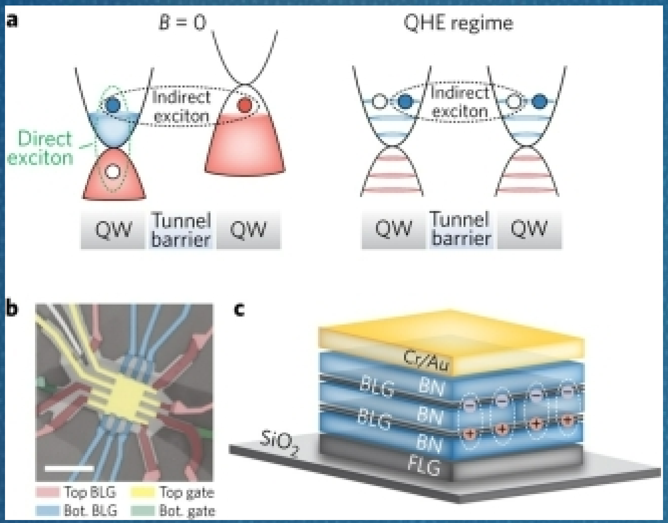


A temperature dependence is observed down to ~ 10-15 mK



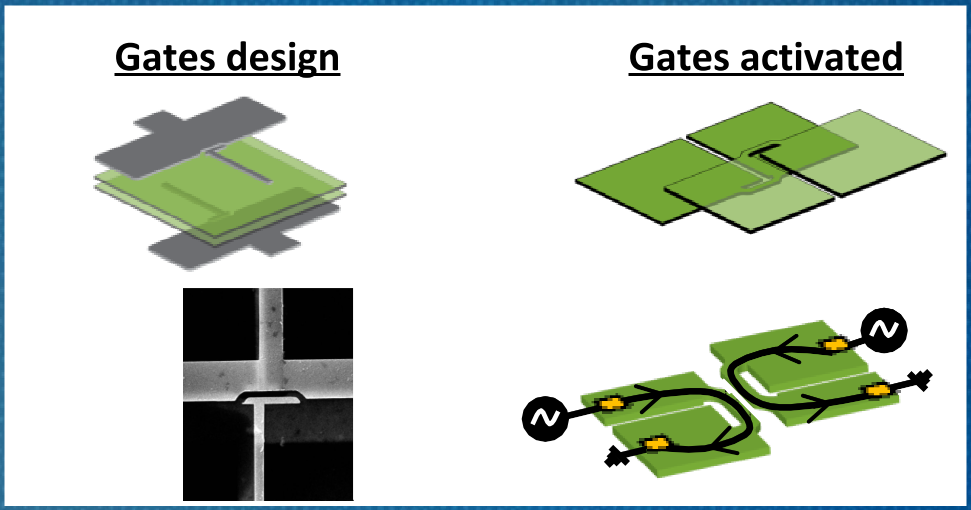
Low-dimensional systems

Exciton condensation in 2D bilayers



J. I. A. Li *et al.* Nature Phys. **13,** 751 (2017)

Signatures of Luttinger liquids in quantum wires



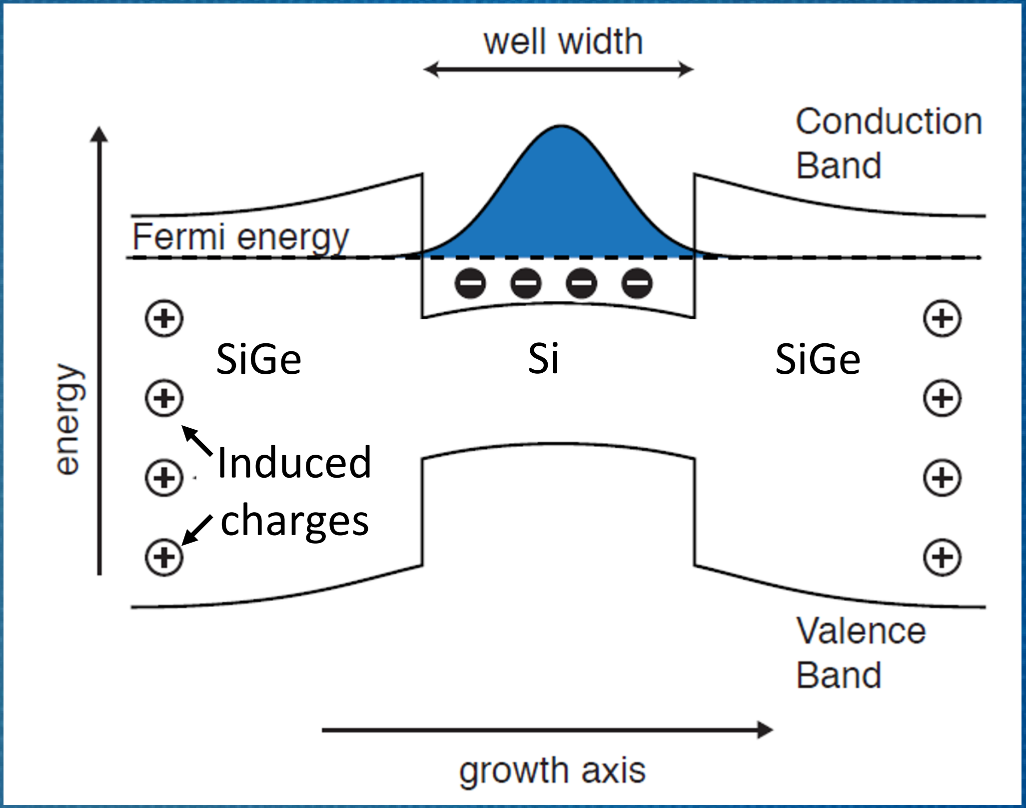
D. Laroche *et al.* Nature Nanotech. **6,** 793 (2011)

Material systems :
GaAs/AlGaAs bilayers
Graphene bilayers
Si/SiGe bilayers

Techniques:
Universal conductance scaling
1D-1D and 1D-2D resonant tunneling
Coulomb drag

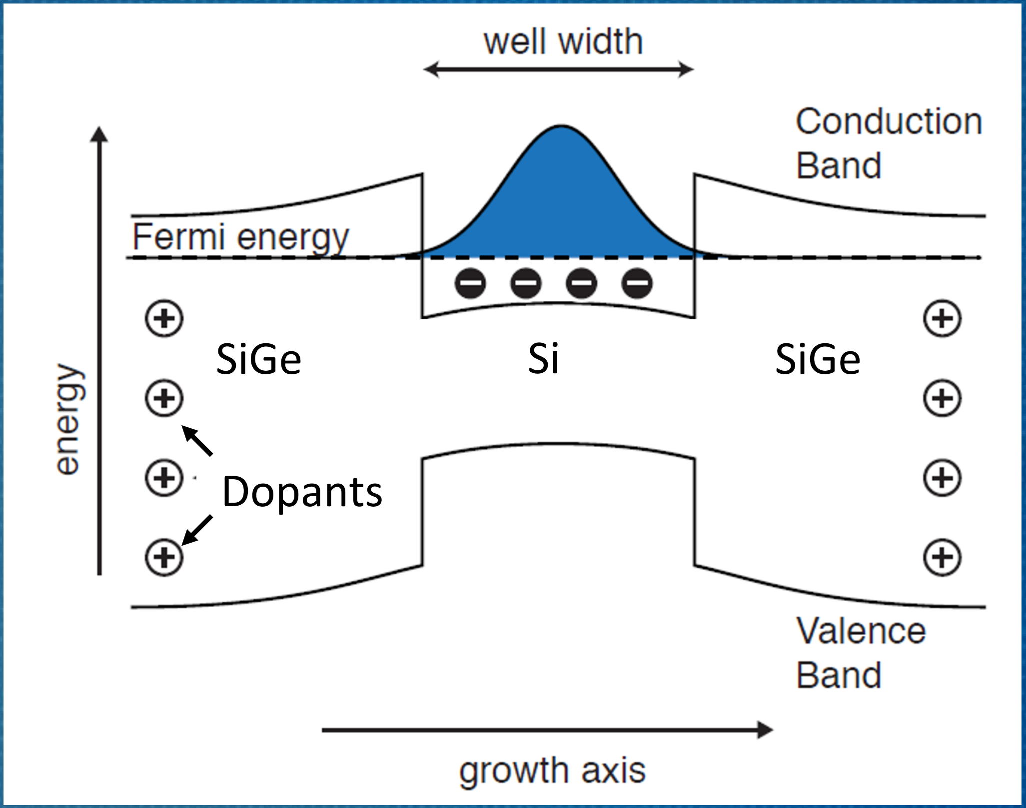
Quantum well

- Particle-in-a-box type of problem.
- A single 2D subband occupied at low-temperature
- Carriers induced by doping (intrinsic) or gating (extrinsic)
- Realized in GaAs/AlGaAs, graphene, InAs/InAlAs, $SrTiO_3$/$LaAlO_3$and many others



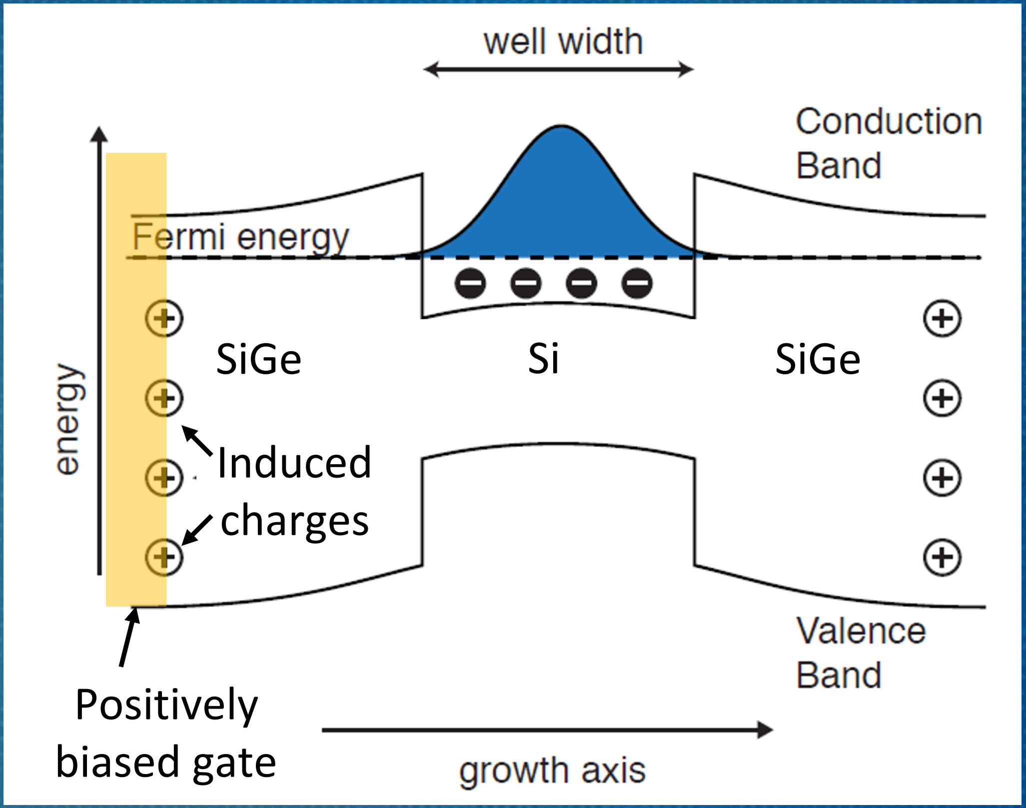
Quantum well

- Particle-in-a-box type of problem.
- A single 2D subband occupied at low-temperature
- Carriers induced by doping (intrinsic) or gating (extrinsic)
- Realized in GaAs/AlGaAs, graphene, InAs/InAlAs, $SrTiO_3$/$LaAlO_3$and many others

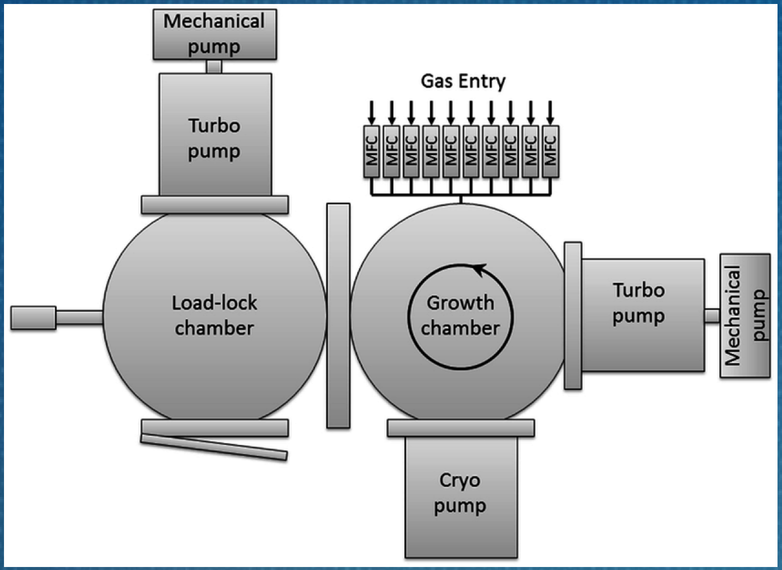


Quantum well

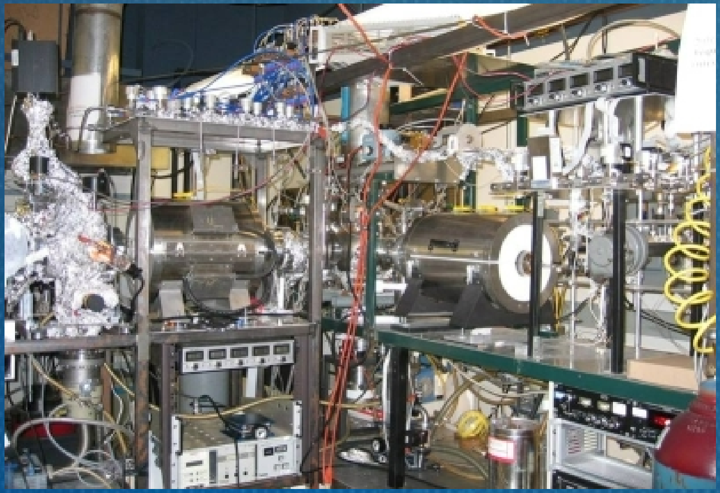
- Particle-in-a-box type of problem.
- A single 2D subband occupied at low-temperature
- Carriers induced by doping (intrinsic) or gating (extrinsic)
- Realized in GaAs/AlGaAs, graphene, InAs/InAlAs, $SrTiO_3$/$LaAlO_3$ and many others



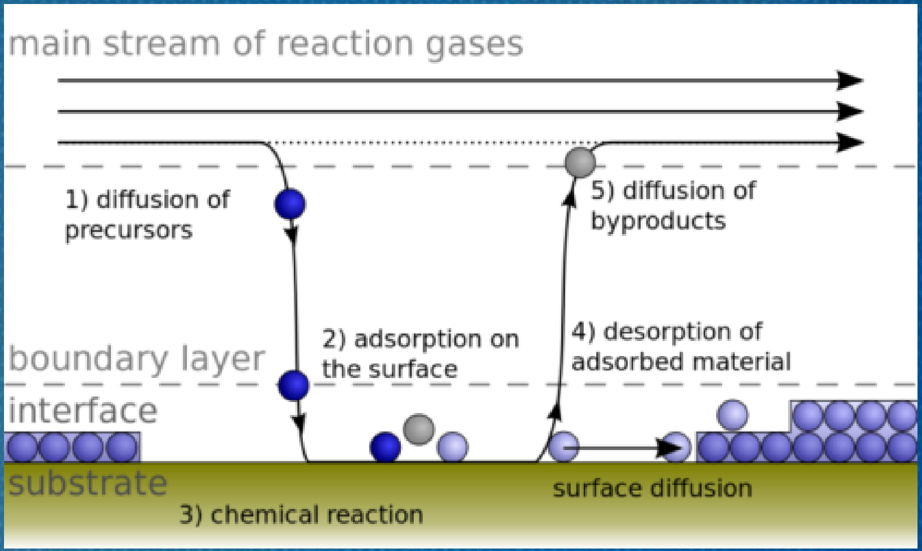
UHV-CVD



UHV-CVD machine schematics

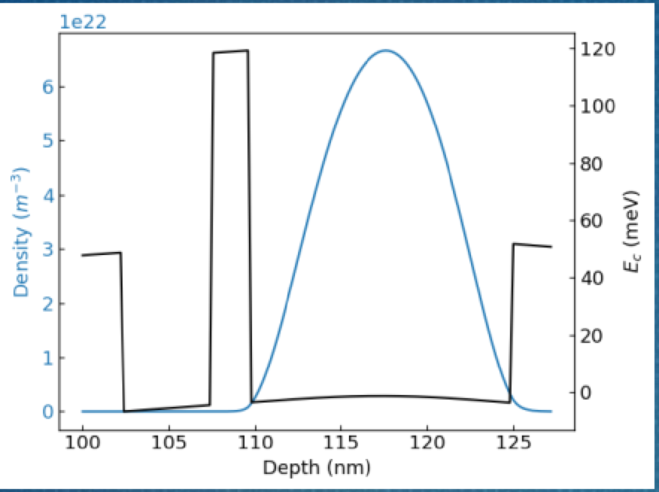


UHV-CVD from Kouvetakis group at ASU

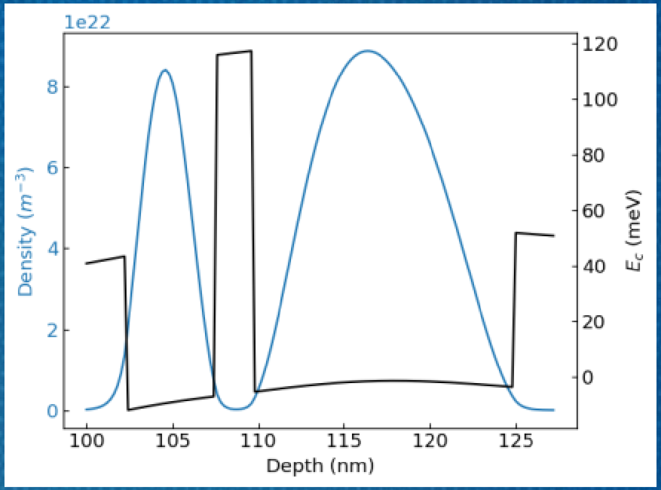


CVD process flow

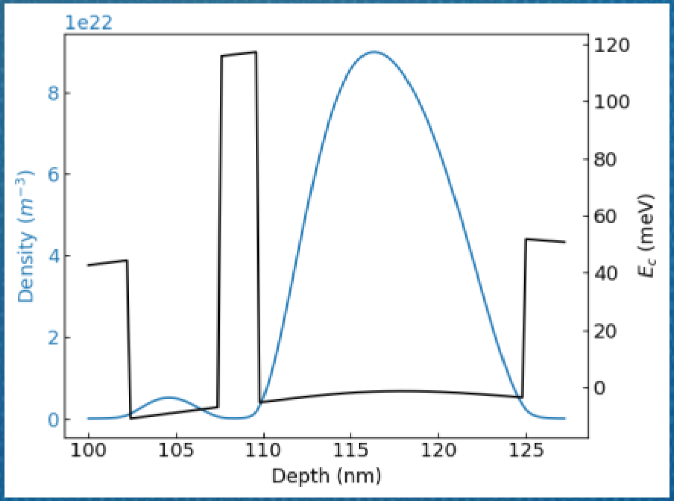
Asymmetric design - SP



n_{tot} = 6 x 10^{10} cm^{-2}



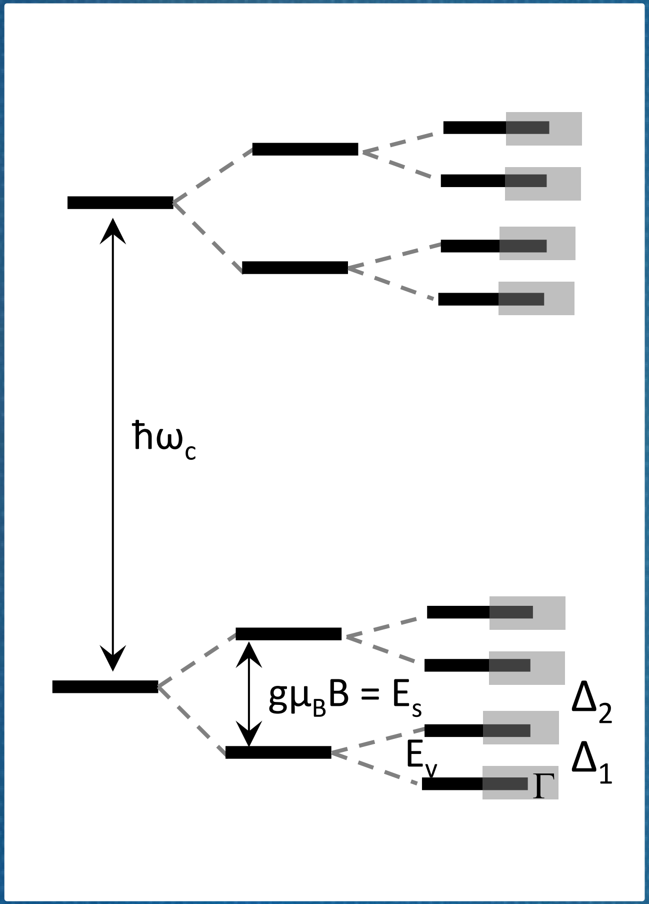
n_{tot} = 10.9 x 10^{10} cm^{-2}



n_{tot} = 8.39 x 10^{10} cm^{-2}

Si/SiGe : theoretical fan diagram

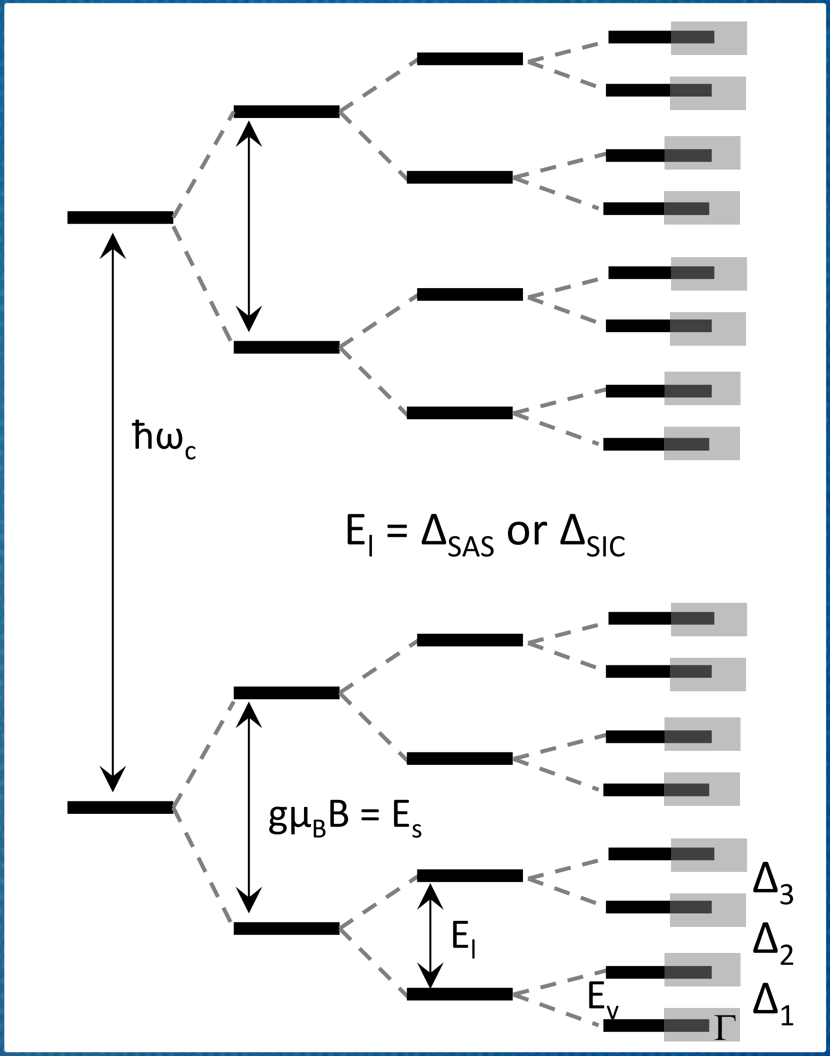
1 layer



$\Delta_1 = E_v - \Gamma$

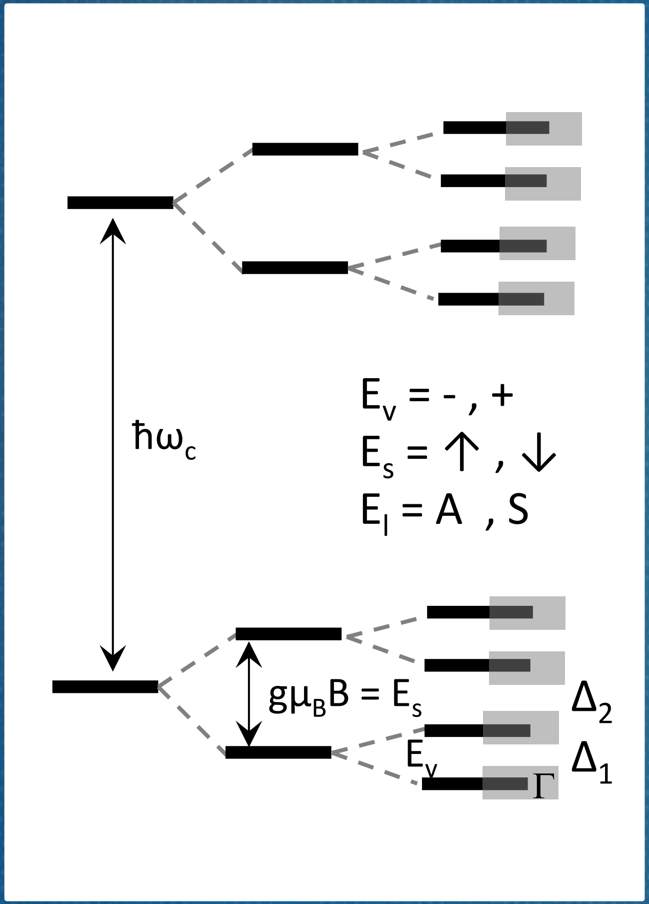
$\Delta_2 = E_{s/l} - E_v - \Gamma = E_{s/l} - \Delta_1 - 2\,\Gamma$

2 layers



Si/SiGe : theoretical fan diagram

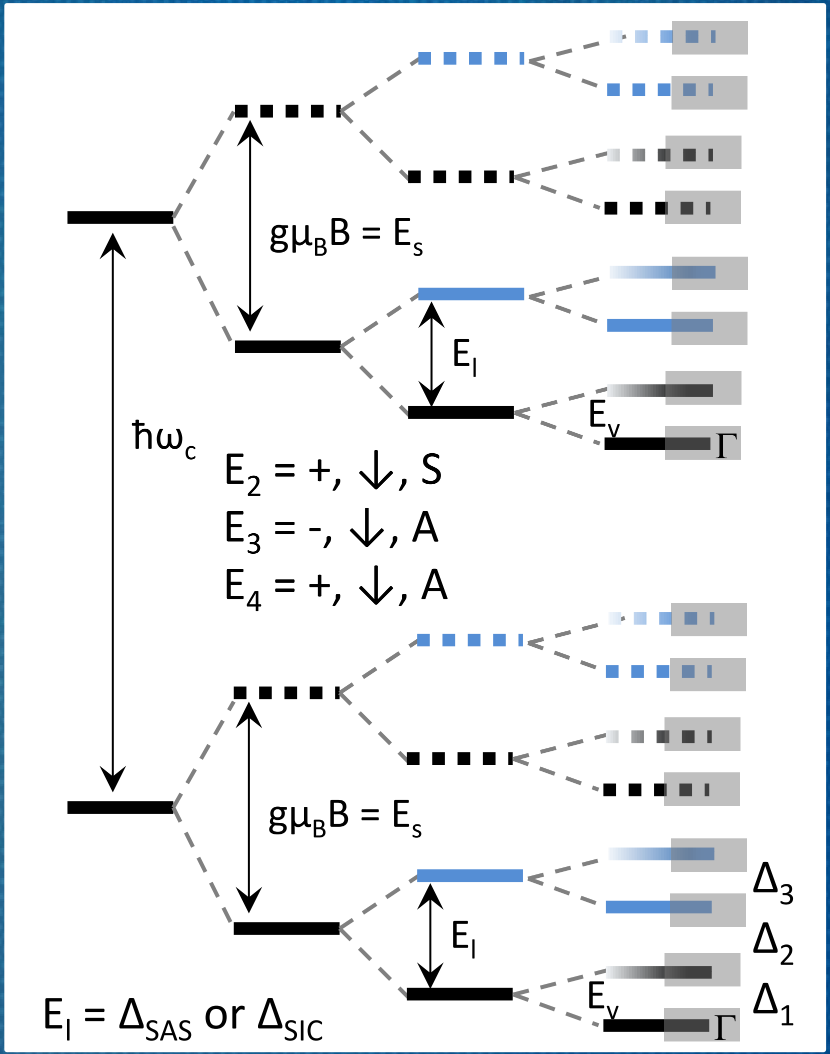
1 layer



$\Delta_1 = E_v - \Gamma$

$\Delta_2 = E_{s/l} - E_v - \Gamma = E_{s/l} - \Delta_1 - 2\Gamma$

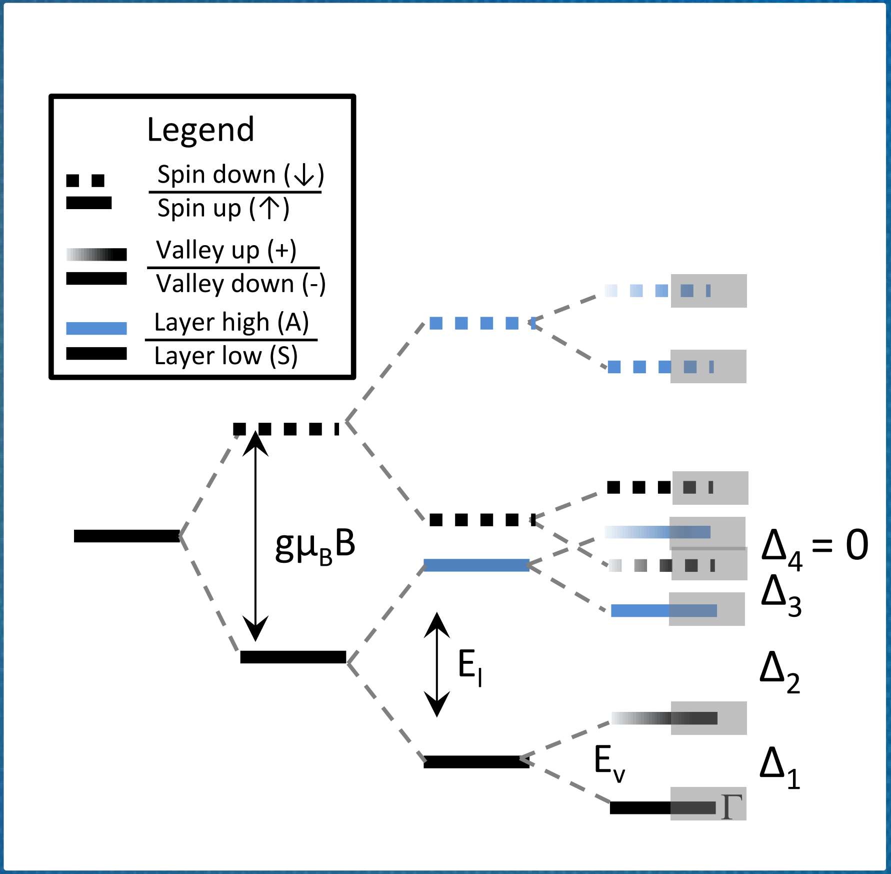
2 layers



Si/SiGe : theoretical fan diagram

Landau level crossings are possible

E_v = - , +
E_s = ↑ , ↓
E_l = A , S

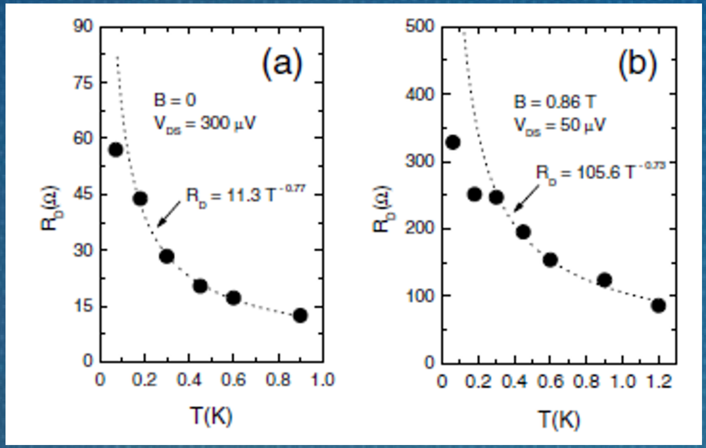


E_2 = +, ↓, S
E_3 = -, ↓, A
E_4 = -, ↑, S

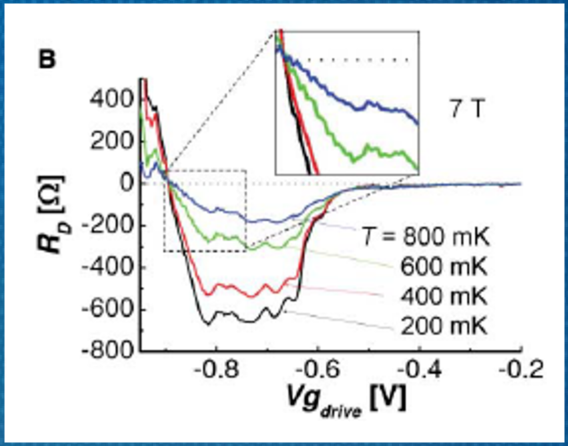
As 2 level cross, the quantum state is not observable experimentally

Previous drag studies

Laterally coupled quantum wires

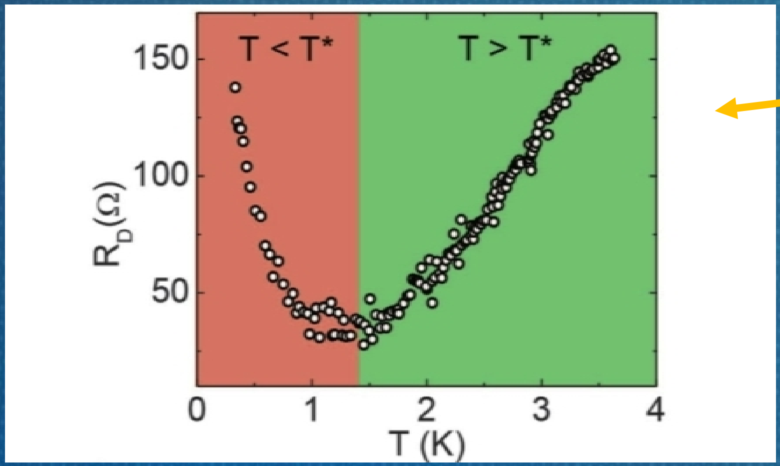


P. Debray *et al.* J. of Phys. Condes. Matter. **13**, 3389 (2001)

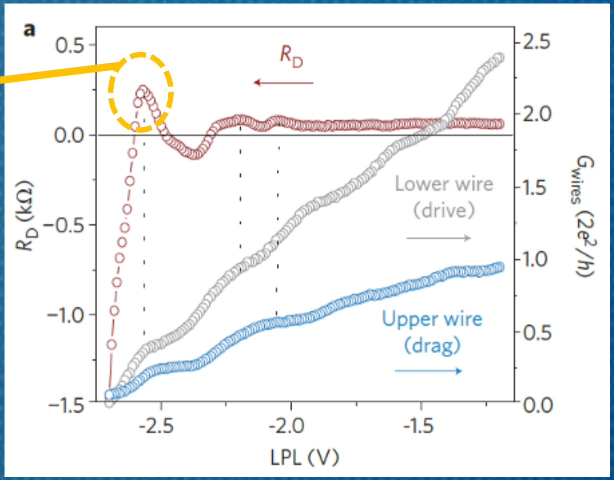


Yamamoto *et al.* Science **313**, 204 (2006)

Vertically-coupled quantum wires

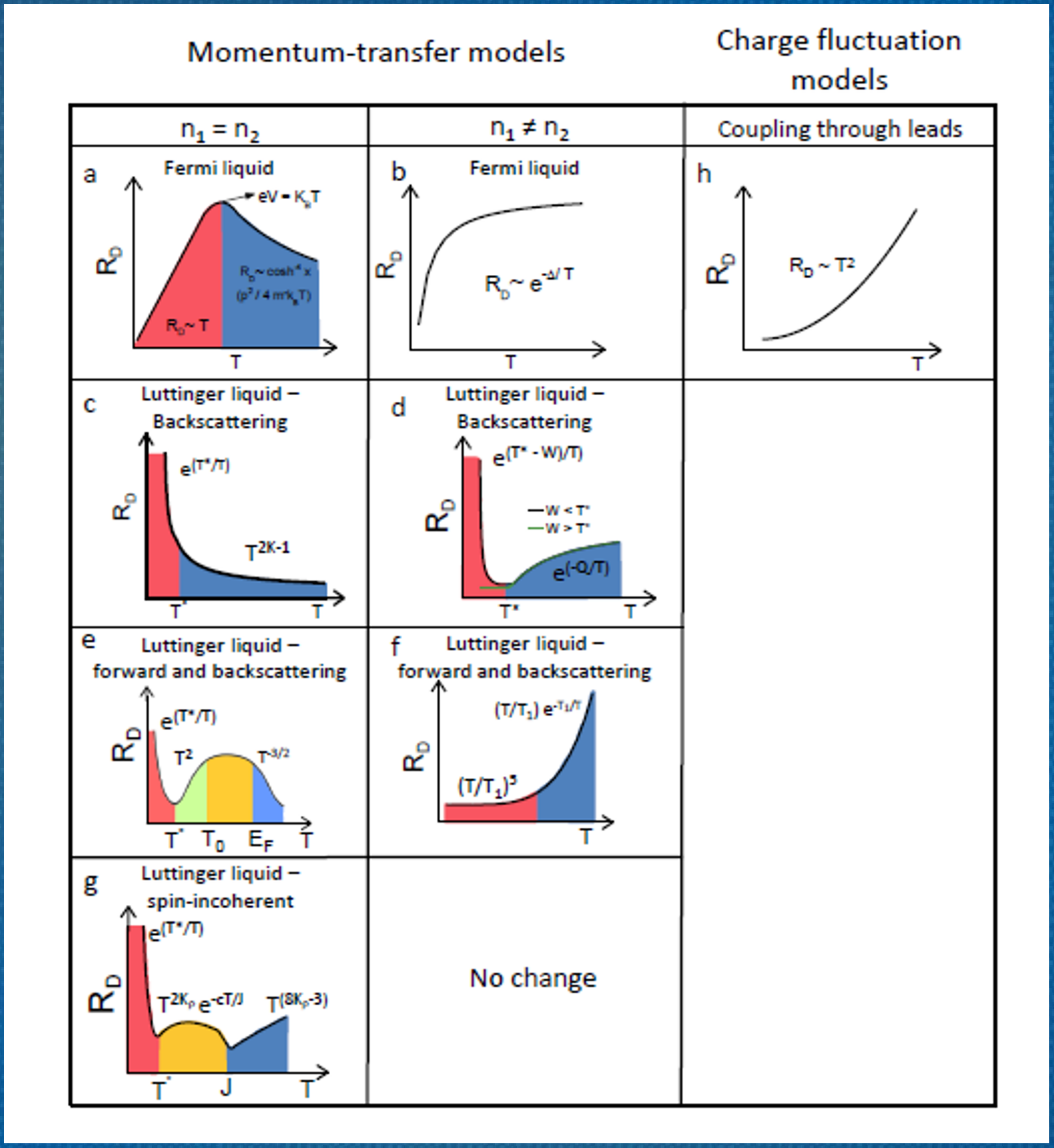


D. Laroche *et al.* Science **343**, 631 (2014)



D. Laroche *et al.* Nature Nanotech. **6,** 793 (2011)

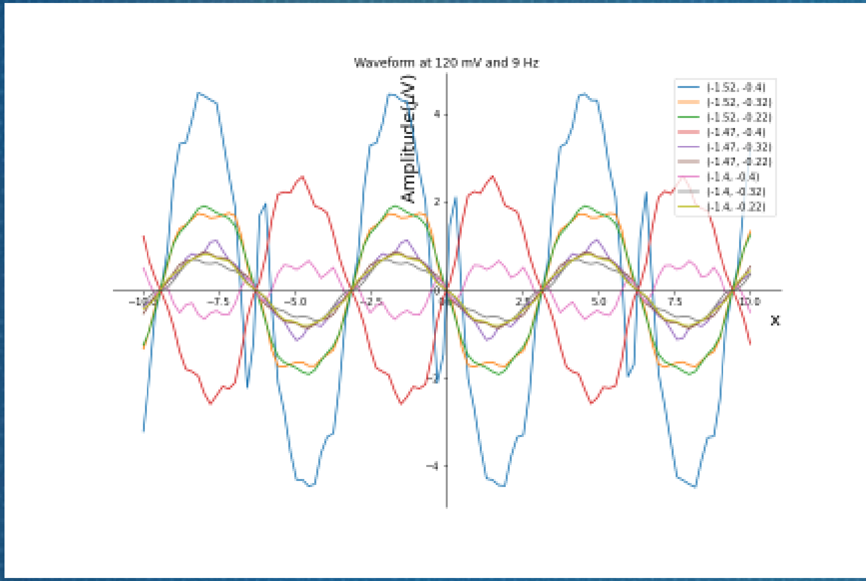
Survey of drag-inducing mechanism



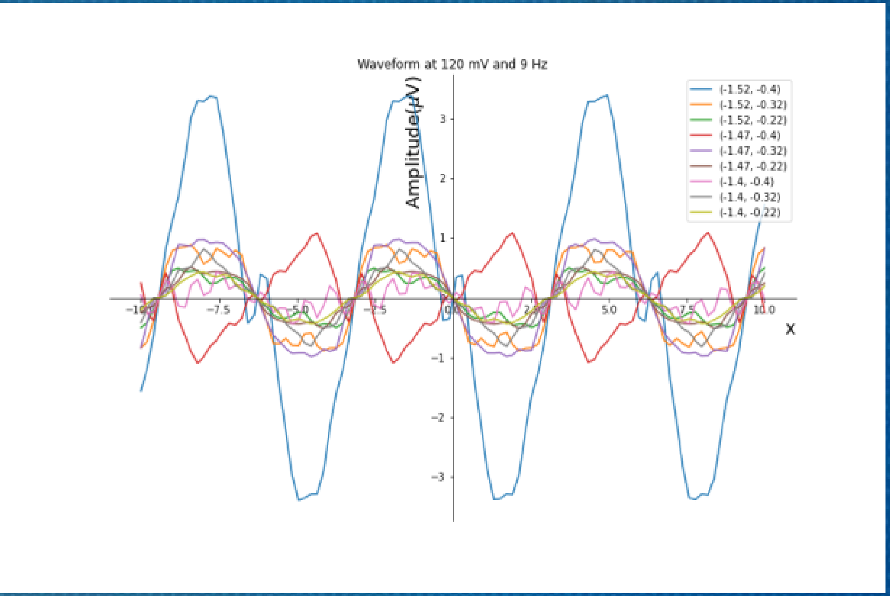
Symmetric and anti-symmetric contributions

Look at both contributions waveforms :

<u>Symmetric</u>



<u>Anti-Symmetric</u>



No clear cut waveform allowing identification of rectification or momentum transfer