InAs/GaSb –
A New Quantum Spin Hall Insulator

Rui-Rui Du

Rice University

1. **"Old Material" for New Physics**
2. **Quantized Edge Modes**
3. **Andreev Reflection**
4. **Summary**

KITP Workshop on
Topological Insulator/Superconductor

December 13, 2011

Transport

Ivan Knez

R. R. Du

Rice

MBE

Gerry Sullivan

Teledyne Scientific and Imaging

Acknowledge

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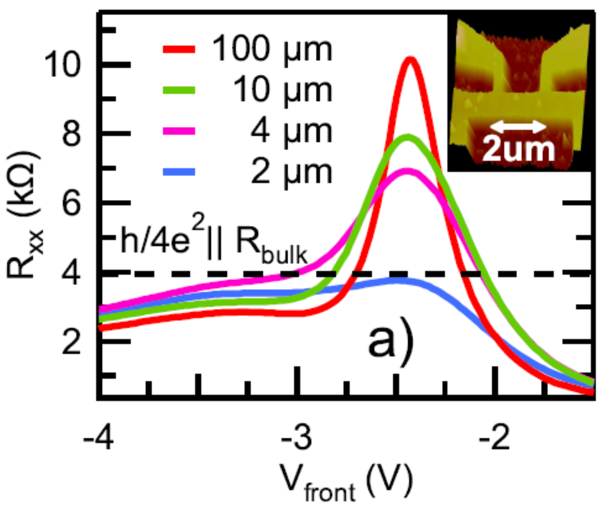
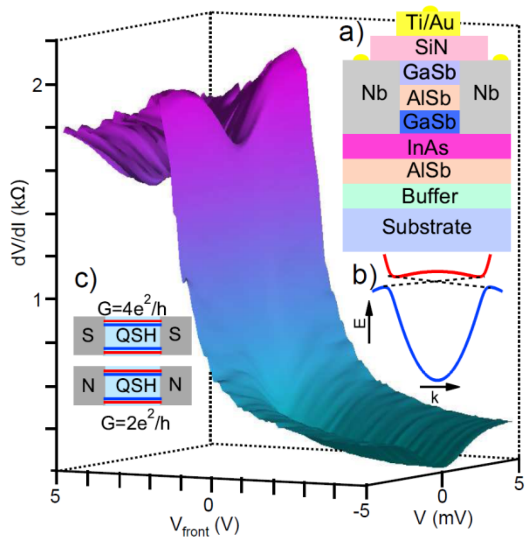
C.-X. Liu *(Stanford)*

F. Liang (MIT)

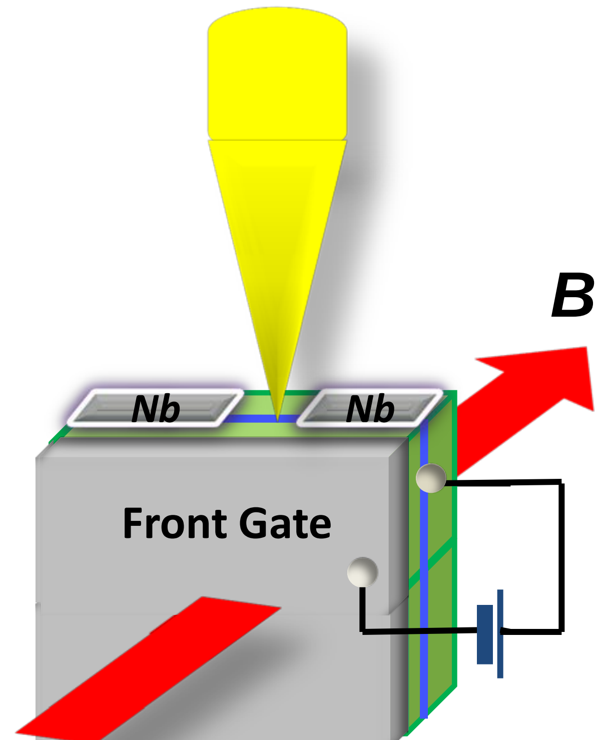
APS12 Symposium on 2DTI



PRL (2011)



ArXiv:1106.5819 (2011)



Majorana Bound State

Quantum Spin Hall Effect in Hg/Te

Day, *Physics Today*, January 2008

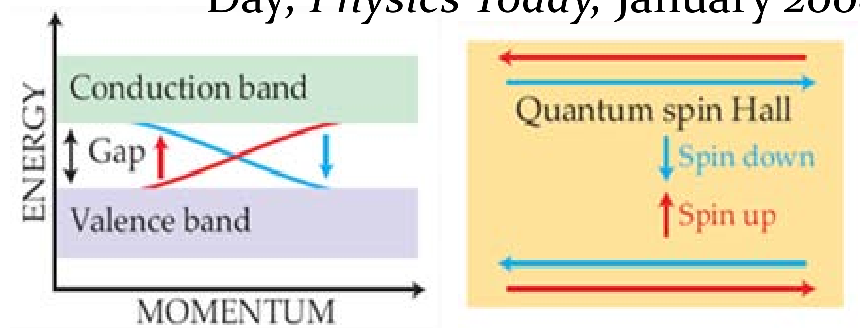
Quantum Spin Hall Effect

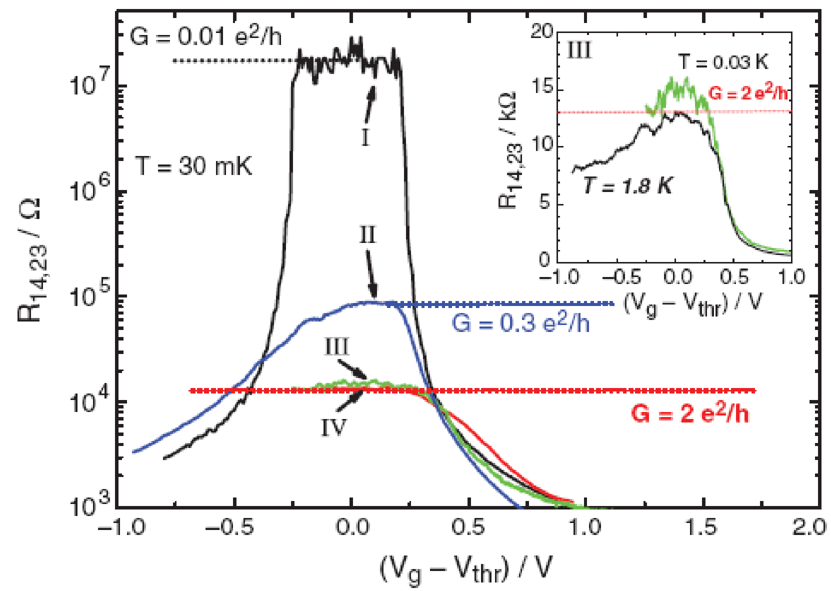
*__Bulk charge energy gap__

*__Gapless edge states__– odd number of Kramers pairs

*__Helical edge states__ –four terminal conductance of $\mathbf{2e^2/h}$

*Observed in **HgTe/CdTe QWs** in mesoscopic samples

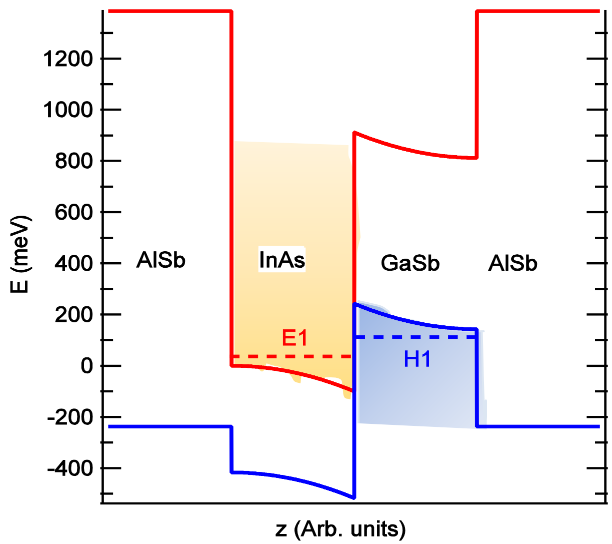


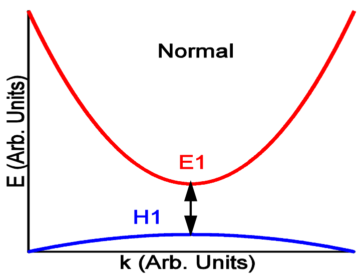


Bernevig et al, *Science*, 2006

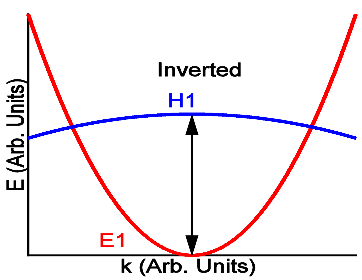
Konig et al, *Science*, 2008

Coupled Electron-Hole Double Quantum Well





Semicon. Gap



Inverted

1. **Band parameter**

   $\Delta E = E1 - H1$ $Al_xGa_{1-x}Sb$

   can be tuned by width, x, gates

2. **$\Delta E < 0$ inverted -0.15 eV to 0**

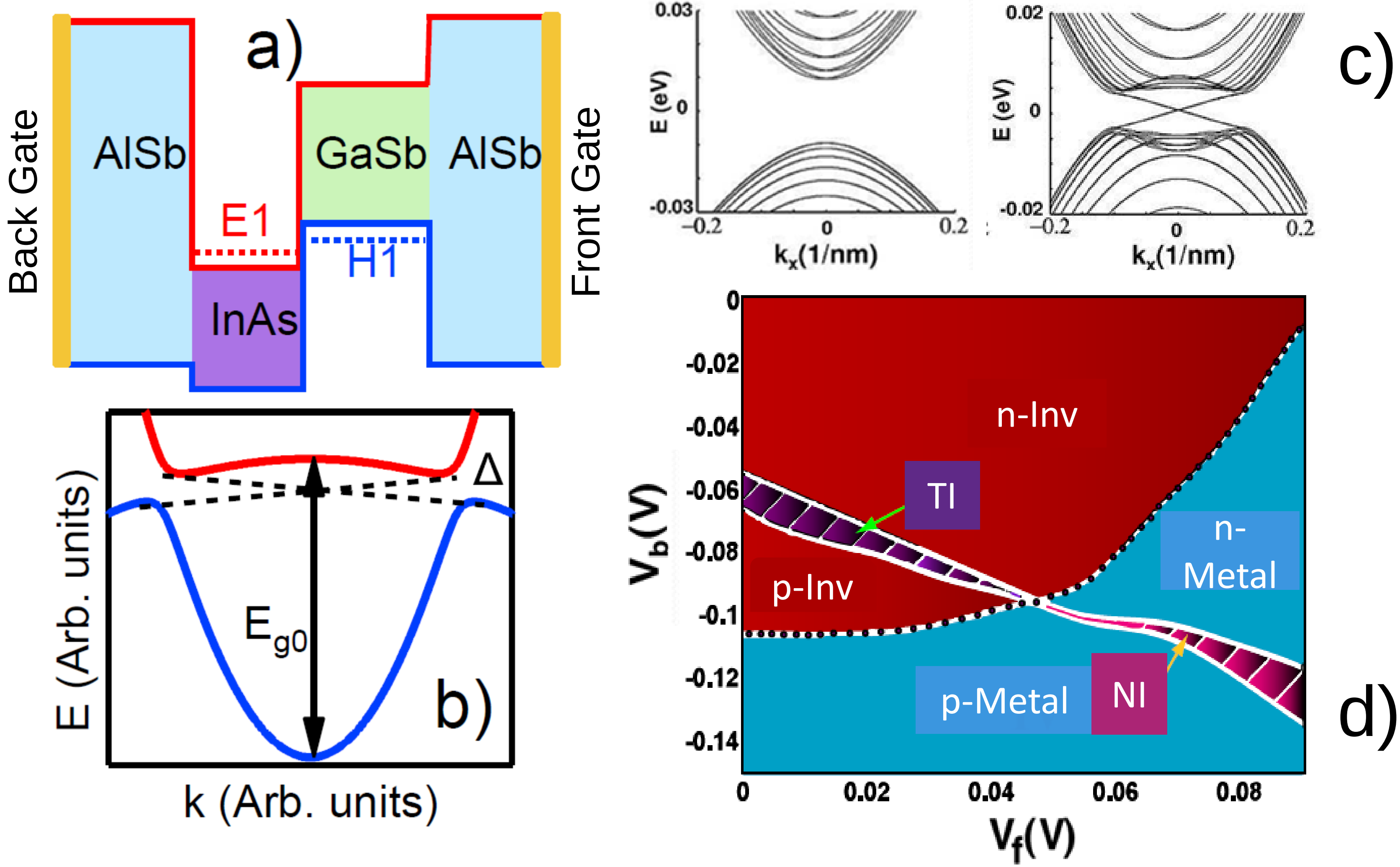
   Tunneling mix e-h and opens a gap at finite k-vector

3. **Used as infrared detector and night vision CCD**

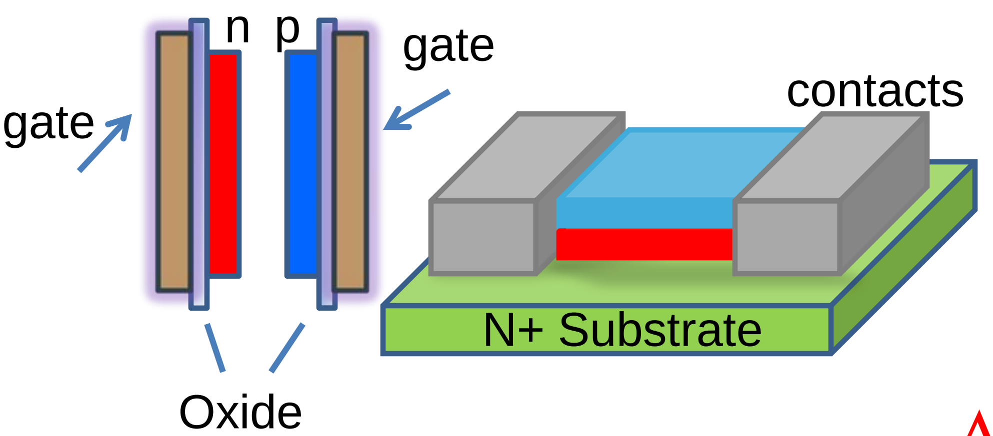
4. **High mobility MBE wafers produced in best industrial labs (1~5 x 10^5 cm^2/Vs)**

InAs/GaSb as a QSH Insulator

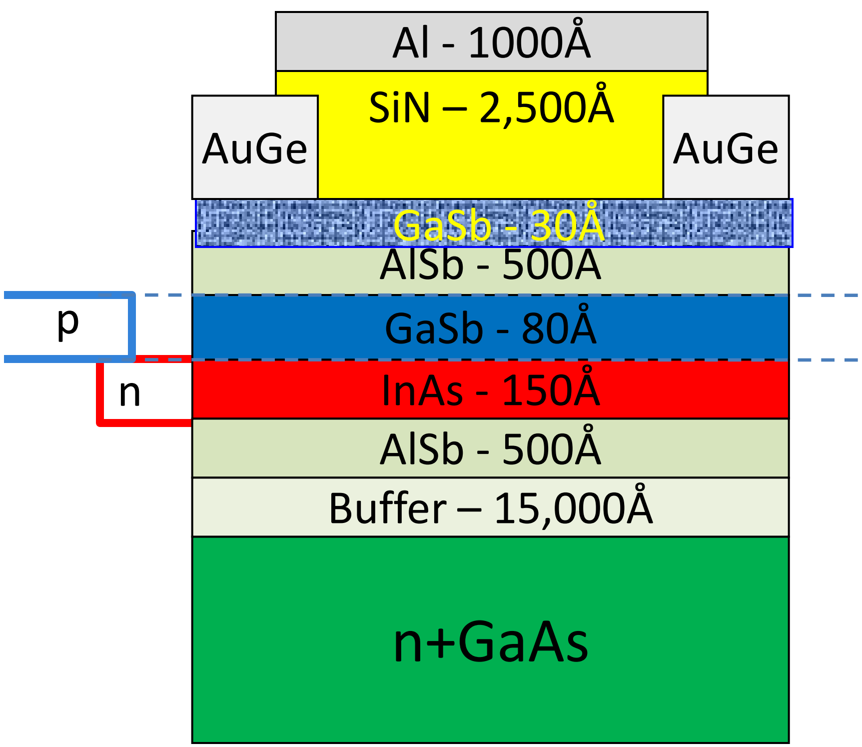
Liu *et al*, *PRL* **100**, 236601 (2008)



Band-Gap Engineering



	Wafer A	B	C
GaSb	8 nm	5nm	8nm
InAs	15nm	12.5 nm	8nm
ΔE = E1–H1	-33 meV	-18 mev	~ 0

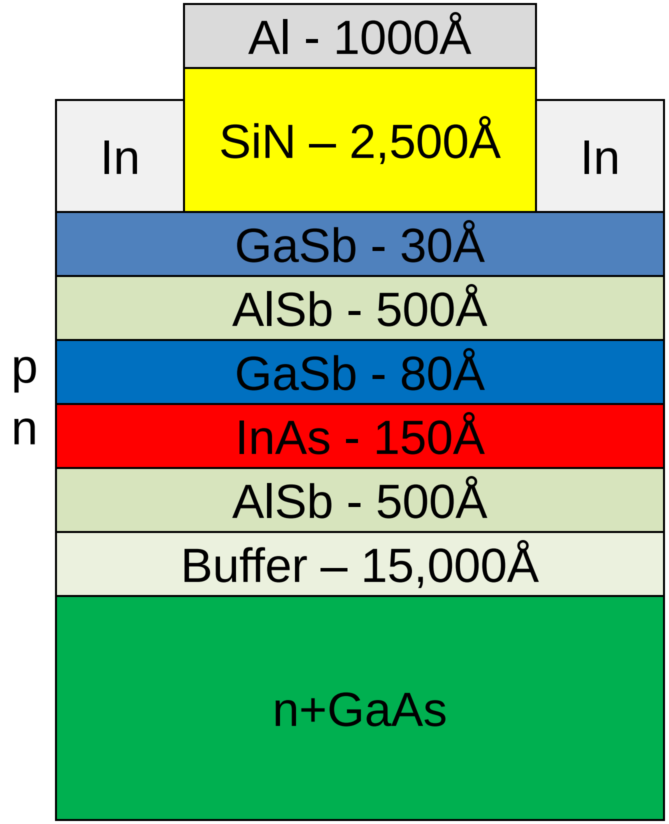


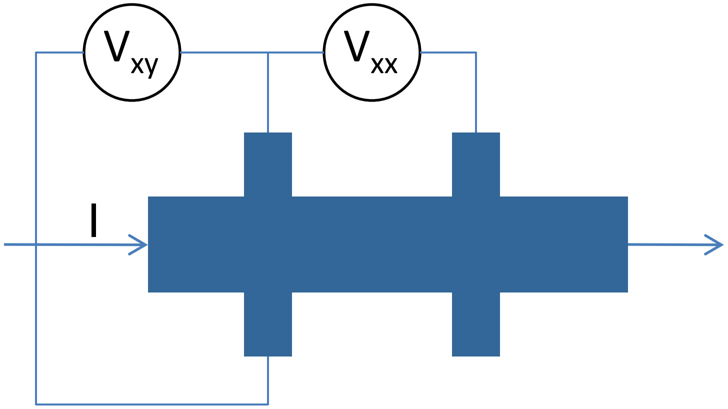
E_f , ΔE can be readily tuned by gates →

Simiconductor-TI transition
QSHE
InAs/GaSb/InAs/GaSb… Superlattice
- Helical surface states?
Re-entrant Quantum Hall Effect
Bound Excitons - BEC

Experimental details

- Wafer **A**: 150Å InAs and 80Å GaSb composite QW– inverted regime :
  E_c-E_v≈-33meV
- Hall bar
  - Sample a: 10 µm by 20µm
  - Sample b: 0.5 µm by 1.5µm
- Frontgate – Ti/Al or Ti/Au on SiN
  Backgate – n+GaAs substrate
- Transport
  T=20mK, B=18 Tesla, NHMFL
  T=0.3K, B= 4/2 Tesla, Rice

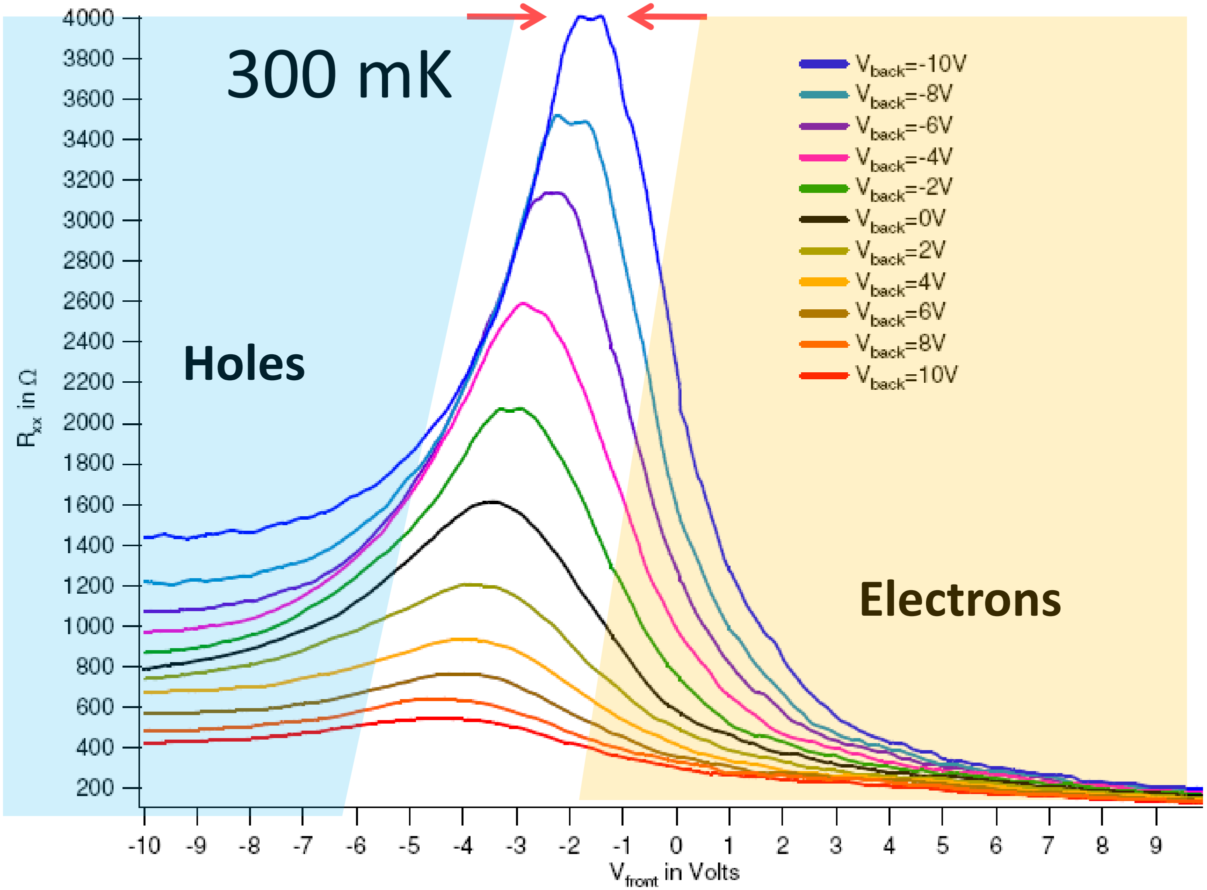


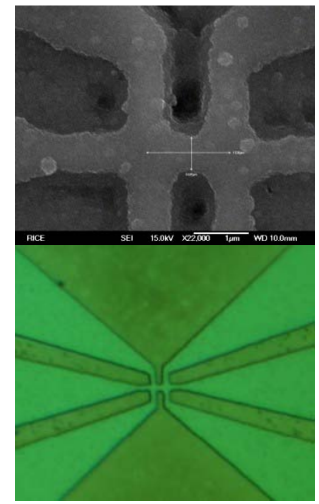


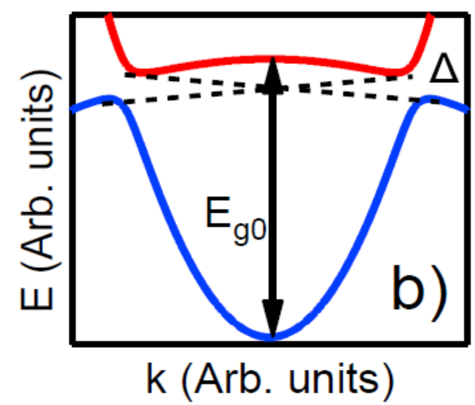
1 Tuning Through Mini Gap in Meso Samples

12.9 k ?

(Wafer A 1.5 by 0.5um Hall bar)

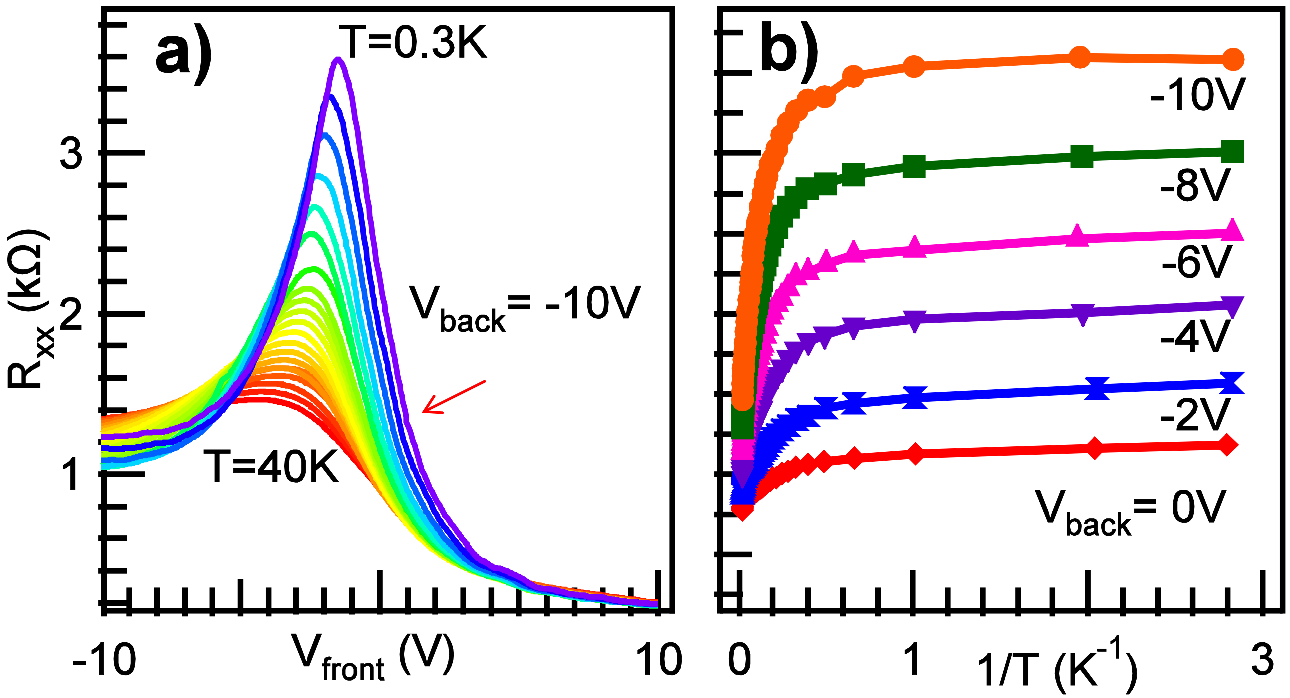






Temperature dependence

Knez *et al*, *Phys. Rev. B* 81, 201301(R) (2010)

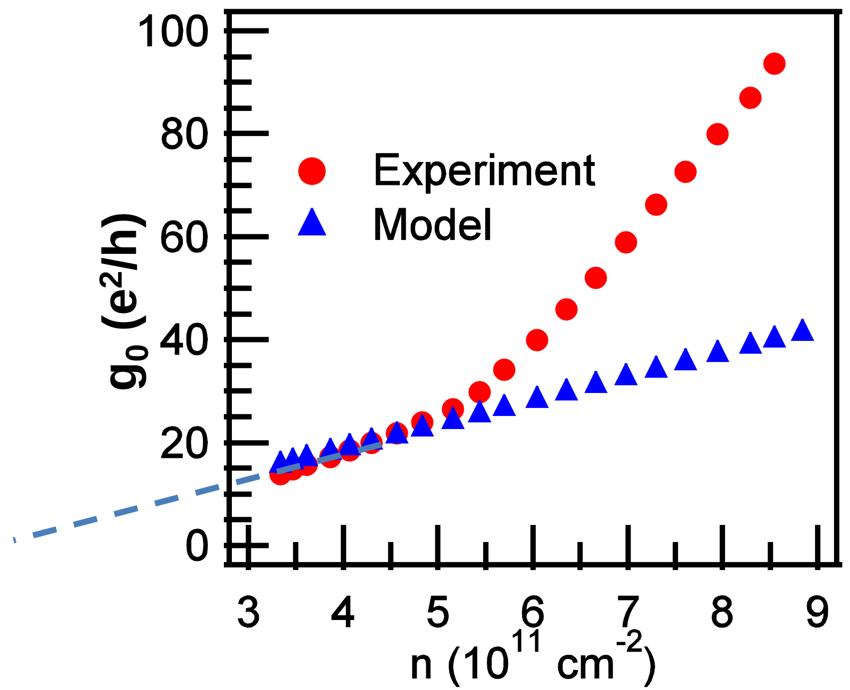


- E_f sweeps the minigap
- **Gap** energy ~ 40 K
- **Bulk conductivity** $\mathbf{g_0} > e^2/h$ (for wafer A)
- **Band-gap engineering** of $\mathbf{g_0}$

Understanding Residual Conductivity

Naveh & Laikhtman,
Euro. Phys. Lett. 55, 545(2001)

Hebrew U

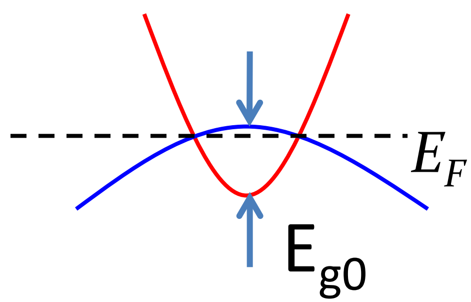


- Hybridized e-h not necessary charge neutral
- Hybridized e-h break due to impurities
- Relevant time scale: $\tau_t = \dfrac{\hbar}{2\Delta}$
- Number of scattered carriers:

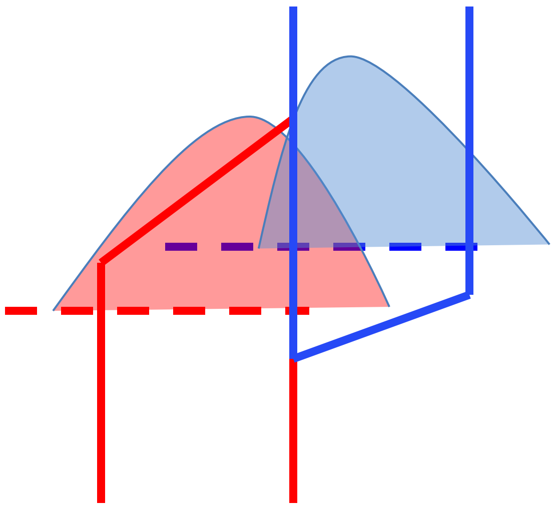
$$n_0 \cdot \left(1 - e^{-\tau_t/\tau_r}\right) = n_0 \cdot \left(1 - e^{-\Gamma/\Delta}\right)$$

- Mobility: $\mu = \dfrac{e}{m}\tau = \dfrac{e}{m}\dfrac{\hbar}{2\Gamma}$
- Conductivity: $g_0 = ne\mu \sim 3\dfrac{e^2}{h}\dfrac{E_{g0}}{\Delta}$ $\quad \Gamma << \Delta,$

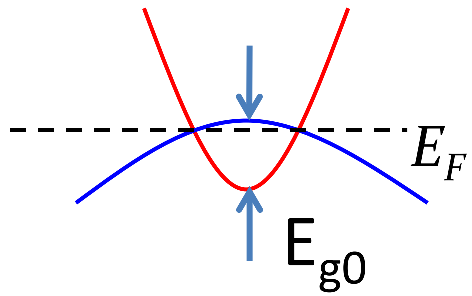
$$E_{g0} = \frac{\pi\hbar^2}{m^*} n_0$$



Band-Gap Engineering of g_0



$$\sigma_{on} \approx \frac{3e^2}{h}\frac{E_{g0}}{\Delta}$$



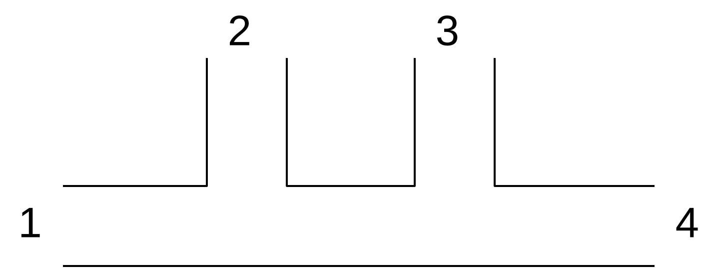
1. Less inverted
2. Narrow QWs
3. Higher mobility

Wafer A E_{go} ~ -33 meV, σ (bulk) > 12 e^2/h
Wafer B E_{go}~ -18 meV, σ (bulk) << 10 e^2/h
Wafer B E_{go} ~ 0 meV, σ (bulk) << 0.5 e^2/h

σ (bulk) ~ 10 e^2/h is a “magic” number

Edge modes de-couple from bulk transport

Helical edge modes in four probe geometry

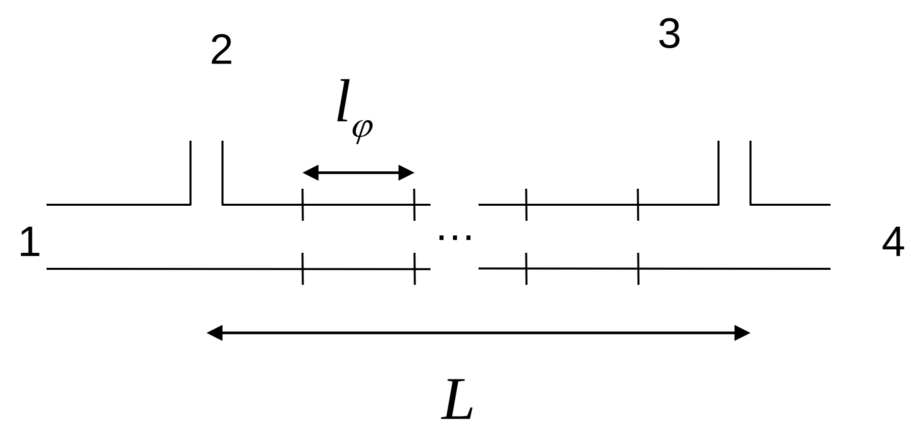


- For phase coherent samples Landauer-Buttiker formula gives conductance value:

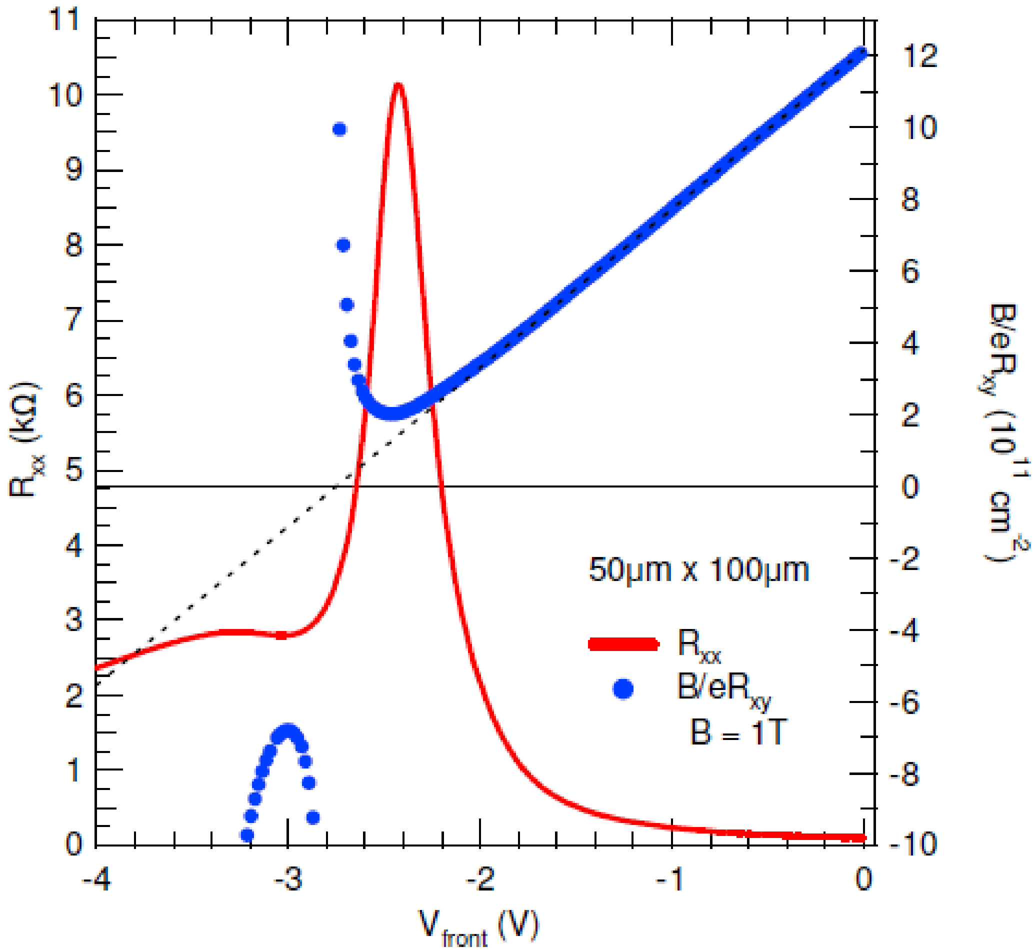
$$G_{14,23} = \frac{4e^2}{h}$$

- Longer samples can be modeled by inserting phase breaking probes and applying LB-formula:

$$G_{14,23} = \frac{2e^2}{h}\left(\frac{l_\varphi}{L} + \left(\frac{l_\varphi}{L}\right)^2\right)$$



Transport in the Mini-gap



- Size of the gap can be estimated from the width of the peak in front gate bias:

  Δ = 4 meV, while

  E_{g0}=16meV
- Resistance peak value agrees well with what is expected for bulk transport

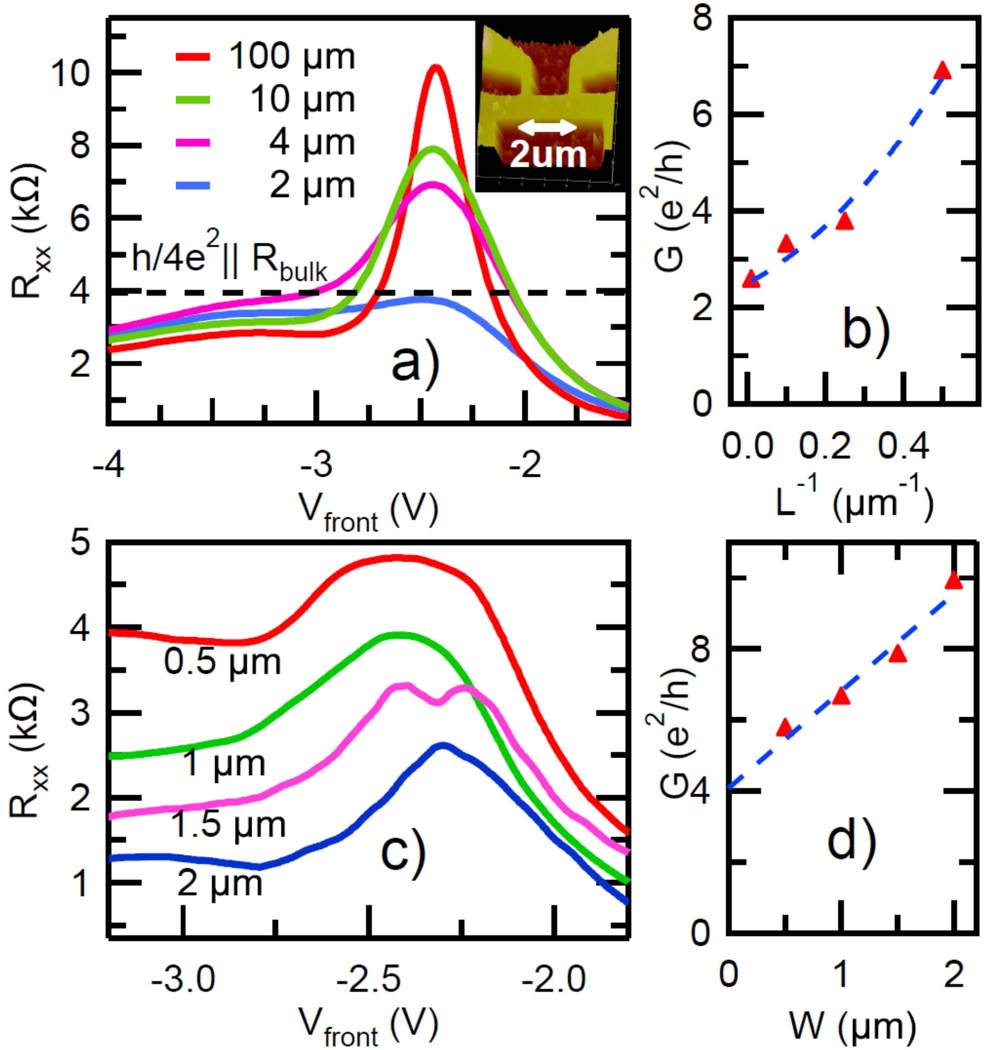
$$g_0(\text{expected}) \approx \frac{e^2}{h}\frac{E_{g0}}{\Delta} = \frac{4e^2}{h}$$

$$g_0(\text{measured}) = 5.05\frac{e^2}{h}$$

Knez *et al*, *PRL* (2011)

Scaling Evidence for The Edge Modes

Wafer B



L-Dependence, keep W =1μm

$$G_{14,23} = \frac{2e^2}{h}\left(\frac{l_\phi}{L} + \left(\frac{l_\phi}{L}\right)^2\right)$$

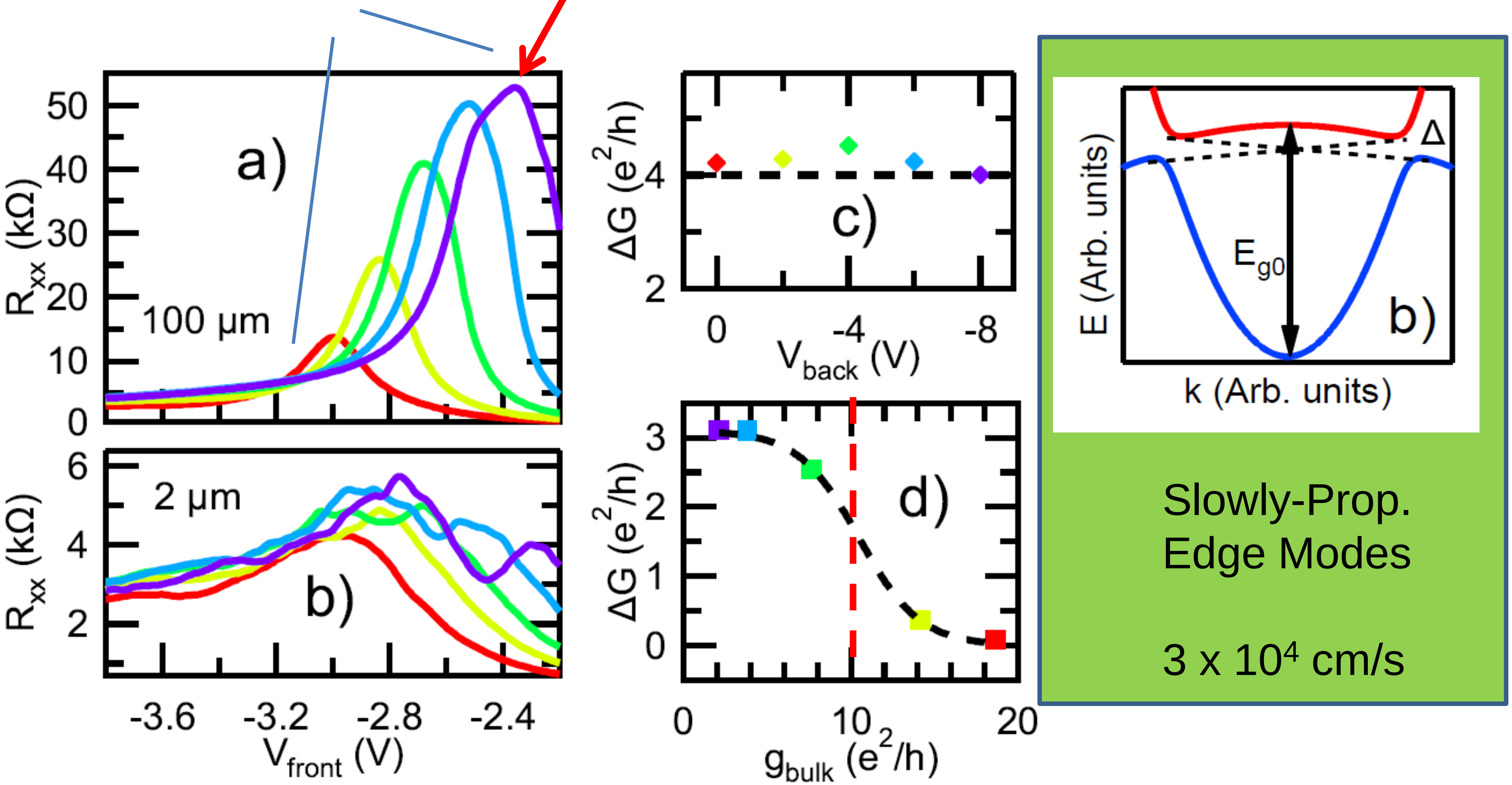
W-Dependence, Keep L/W=2

Conclusion For π geometry, the edge conductivity is ~ quantized to *4 e^2/h*

Robustness of Edge Quantization *vs* Bulk Conduct.

Back gate
To change Inversion

Small
inversion

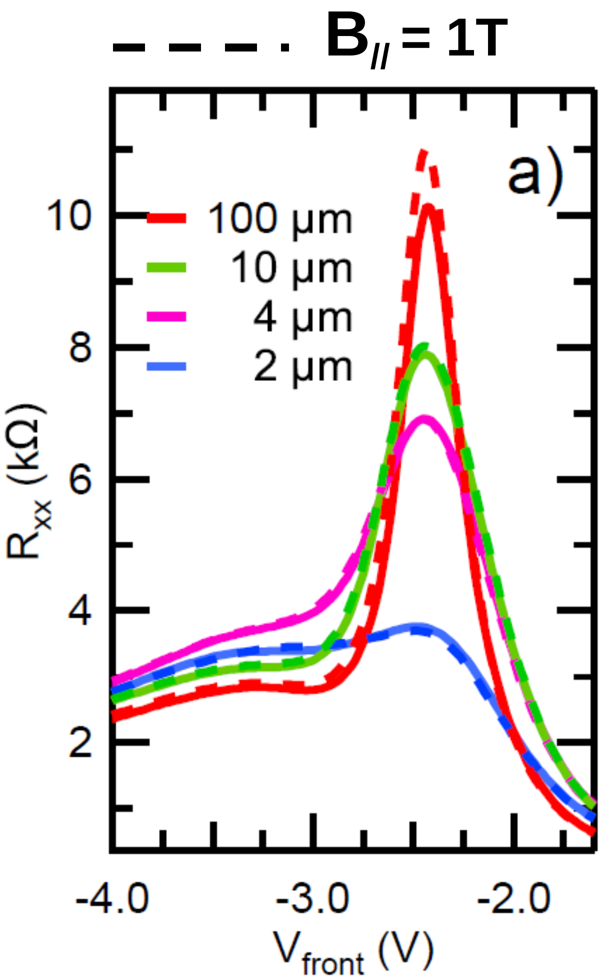


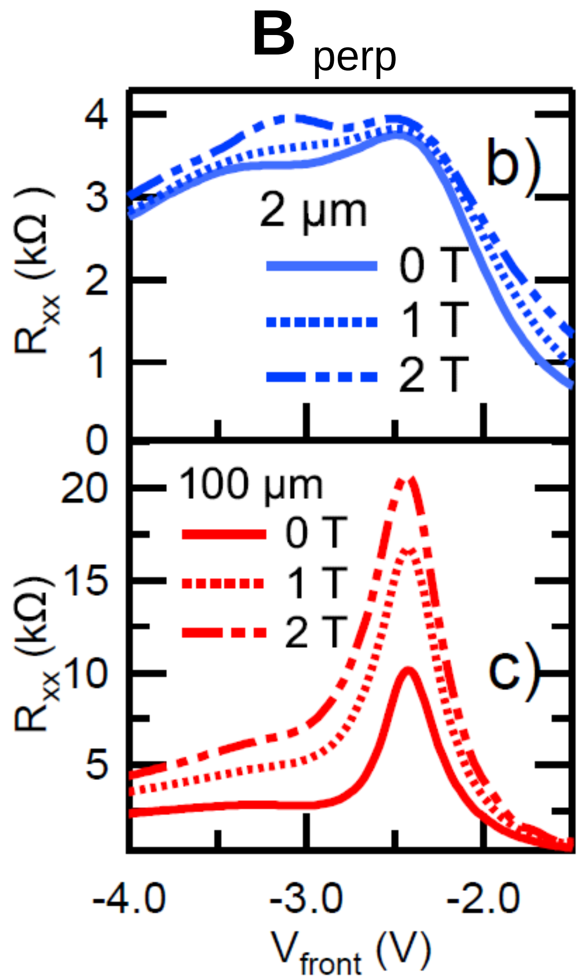
Slowly-Prop.
Edge Modes

3 x 10[4] cm/s

“Anomalous” Magnetic Field Dependence

All 300 mK

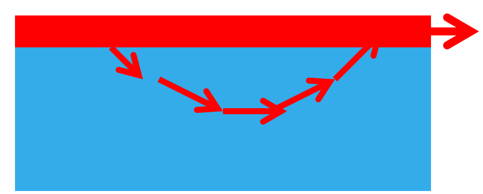




1. Long samples show stronger positive MR –bulk effect

2. µm samples weaker depend.

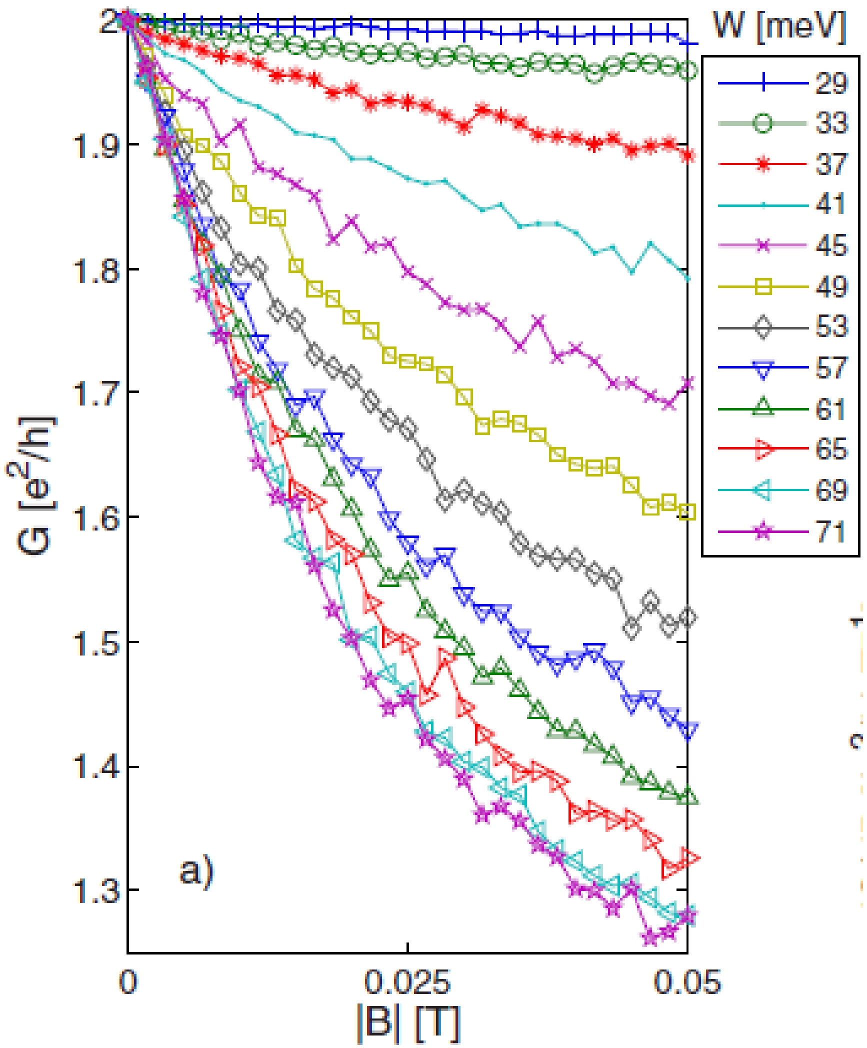
3. Edge states does not scatt. into and out of bulk – lack of loop

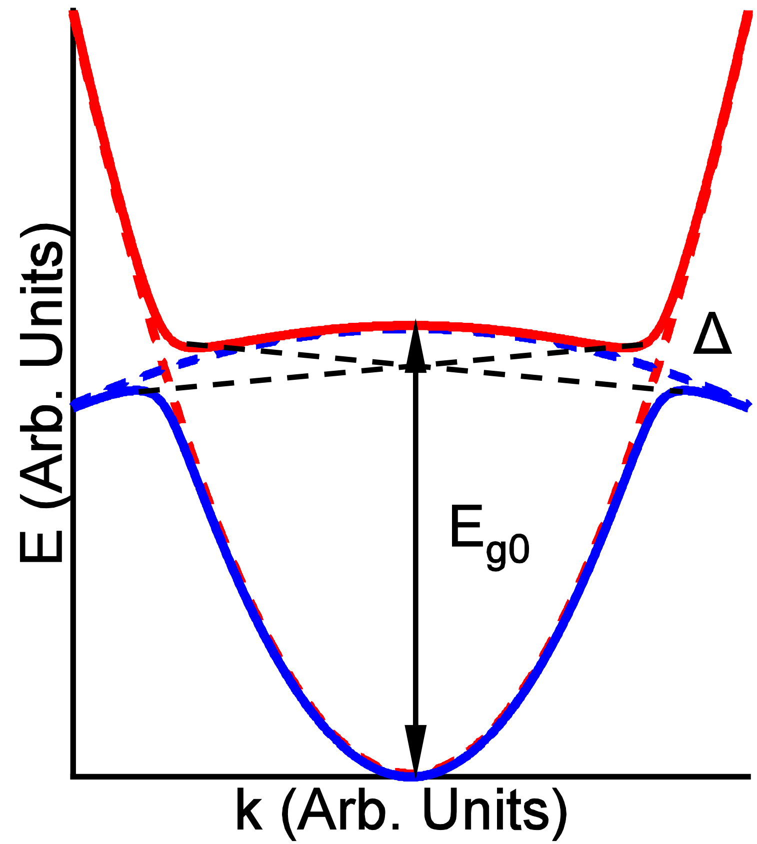


Decouple from bulk

Maciejko *et al*, *Phys. Rev. B*, **83**, 155310 (2010)

Magneto-conductance of QSH



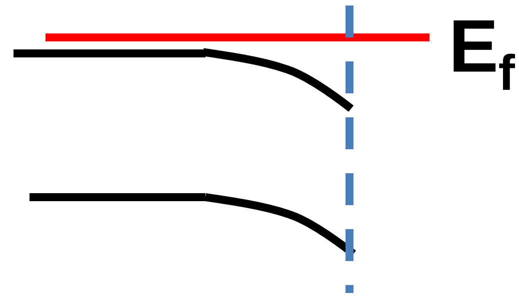


Maciejko *et al*, *Phys. Rev. B*, **83**, 155310 (2010)

Opens a Number of Exciting Experiments

1. Edge states extend all the way to the material edge

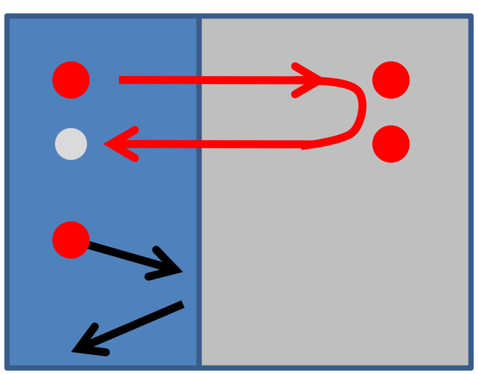
(E_f pinned above E_c for InAs)



2. Good interface with superconductors due to low Schottky barrier --- SC Hybrids

Examples

Andreev Reflection



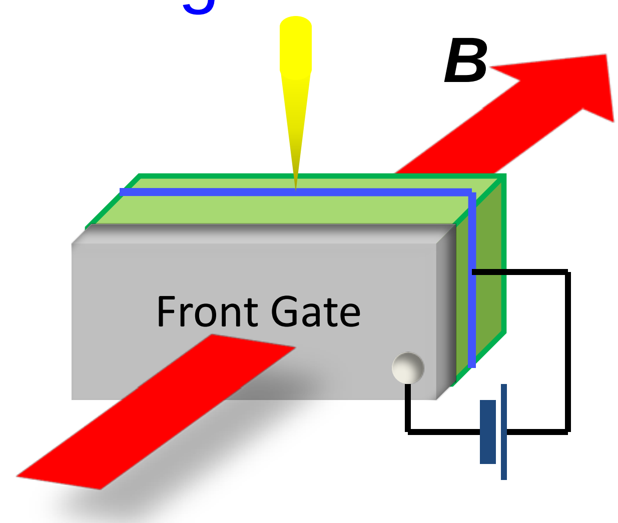
Normal SC

Majorana Bound State (MBS)

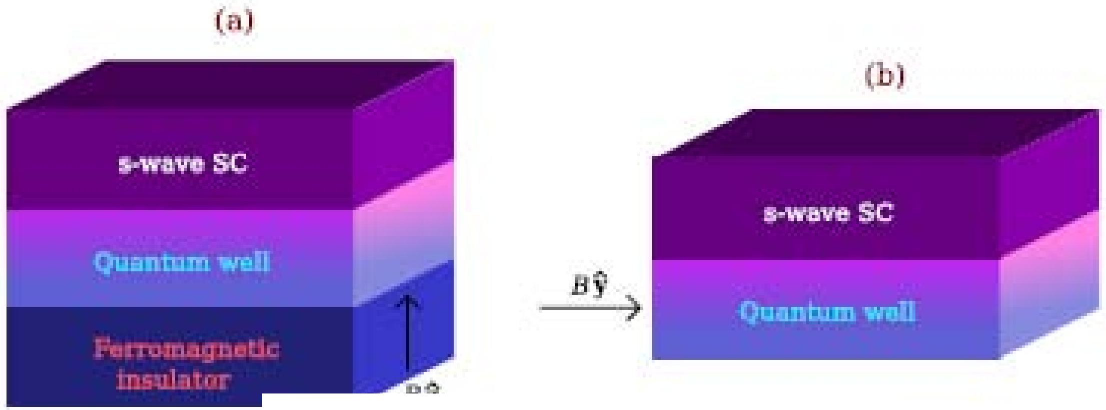
Non-Equilibrium Josephson Effect Through Helical Edge State

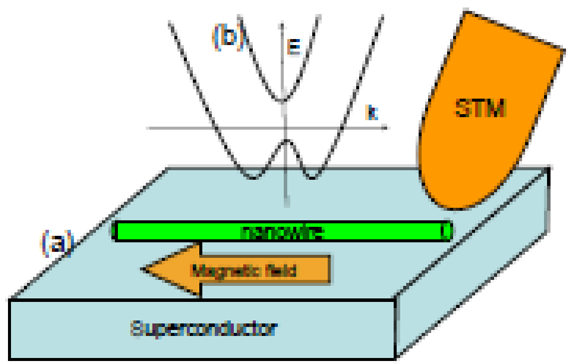
arXiv: 1108.3870

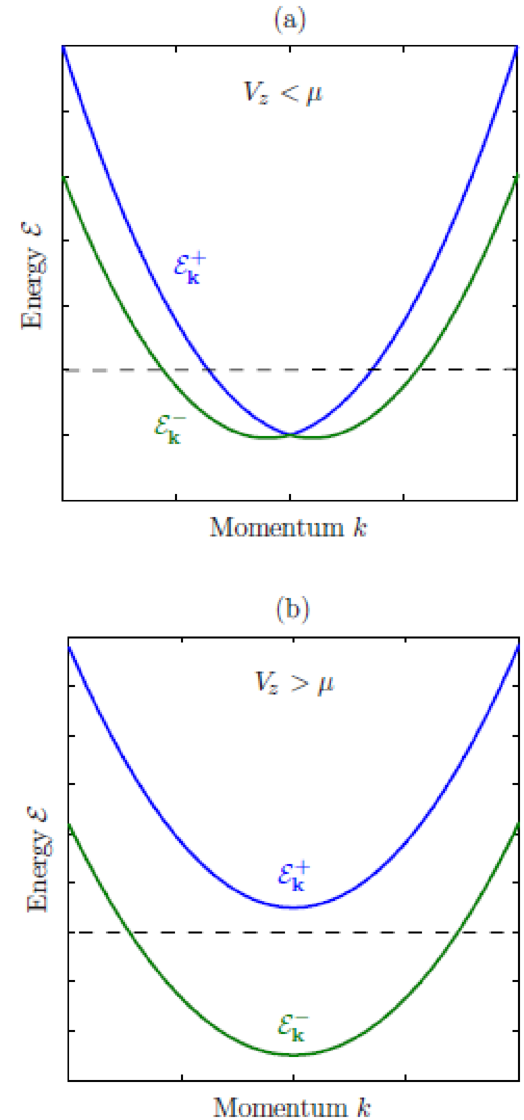
Cleavage STM/STS



Majorana Fermions in SC/InAs/SC

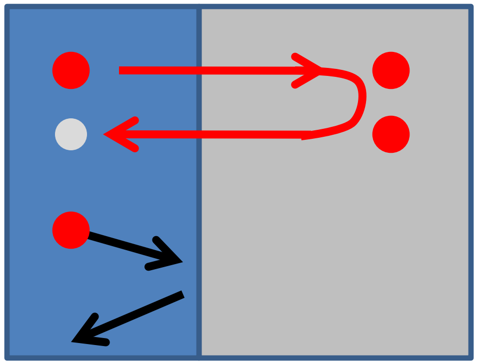






Fu & Kane, Phys. Rev. Lett, **100**, 096407 (2008)
Sau *et al*, Phys. Rev. Lett. **104**, 040502 (2010)
Alicea, Phys. Rev. B **81**, 125318 (2010)
Linder and Sudbo, Phys. Rev. B **82**, 085314 (2010)
Sau *et al*, arXiv:1006.2829 (2010)

Andreev Reflection (Single N-S)

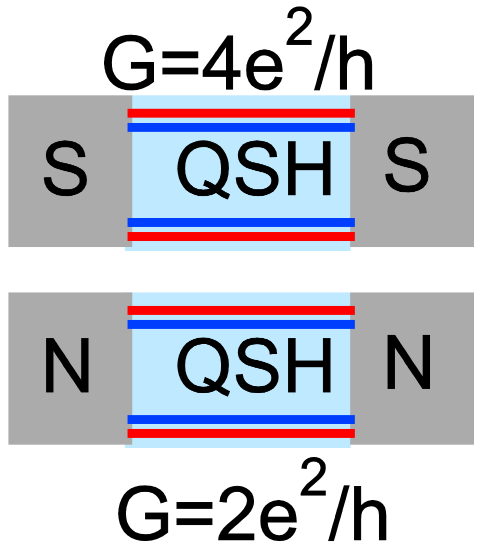


the interface. The electrical current through a single S-N interface can be calculated using the Blonder-Tinkham-Klapwijk (BTK) model:[22]

$$I = \frac{N \cdot e}{h} \int \left[f\left(E + eV\right) - f\left(E\right) \right] \left[1 + A\left(E\right) - B\left(E\right) \right] dE \quad (1)$$

where N is the number of modes in the normal conductor, $f\left(E\right)$ is the equilibrium Fermi distibution function, V is the voltage drop at the interface, and $A\left(E\right)$ and $B\left(E\right)$ are probabilities for Andreev and normal reflection (NR) of the electron at the interface. In the case of

Andreev Reflection of QSH Edges



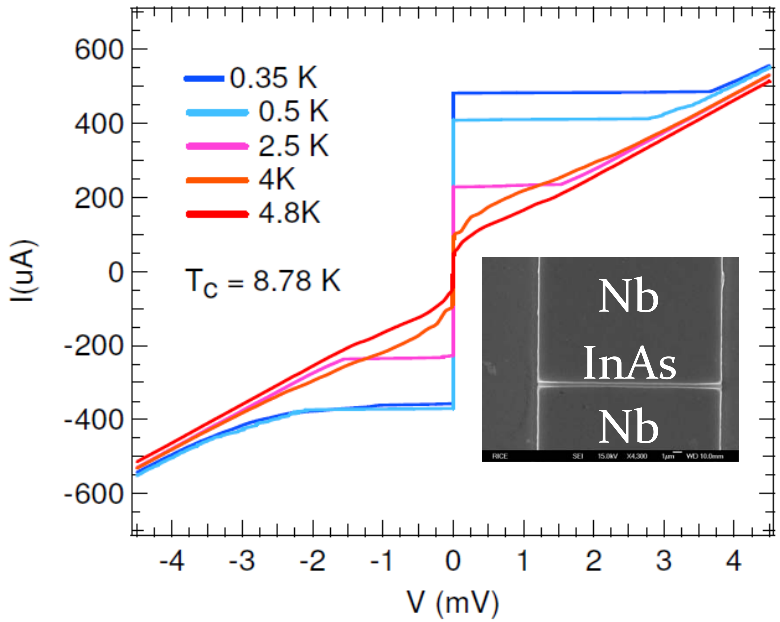
$A(E)=1 \quad V<\Delta/e$

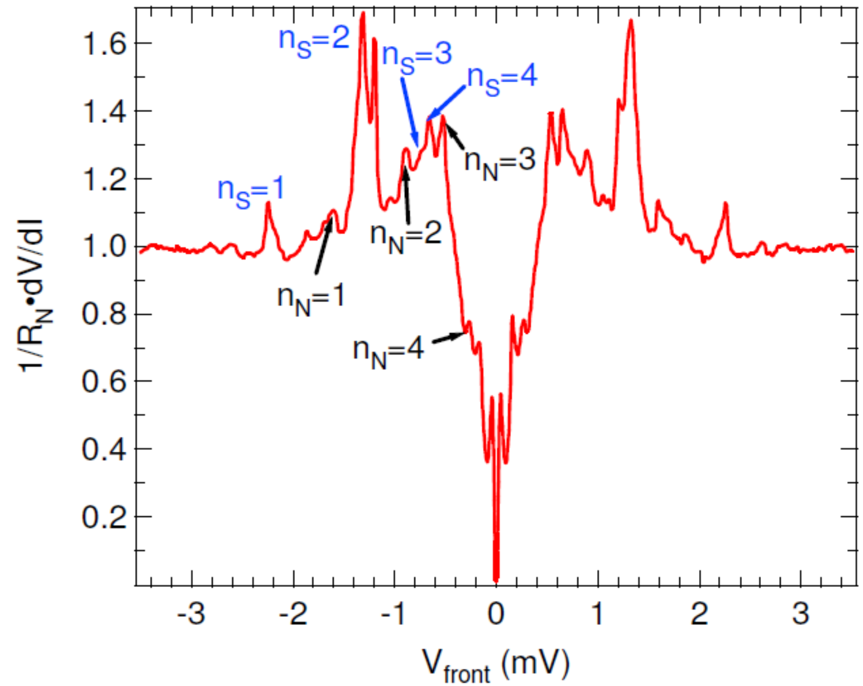
$A(E)\sim\Delta^2/4E^2 \quad V>>\Delta/e$

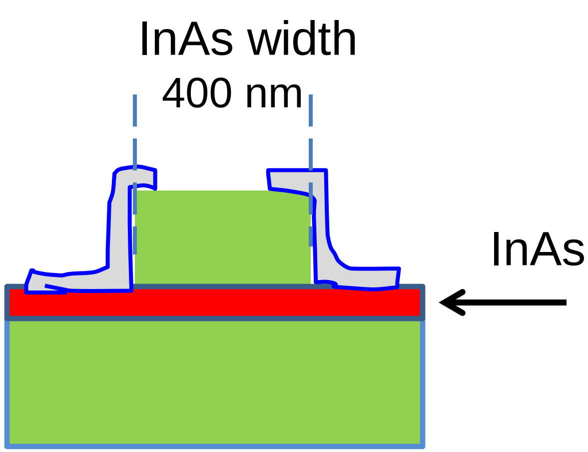
$$I=\frac{N\cdot e}{h}\int\left[f\left(E+eV\right)-f\left(E\right)\right]\left[1+A\left(E\right)-\cancelto{0}{B\left(E\right)}\right]dE$$

1.Can we make Nb/InAs Junction - Test ✓

2.Can we make Nb/InAs-GaSb Junction - New







Multiple Adreev Reflection:

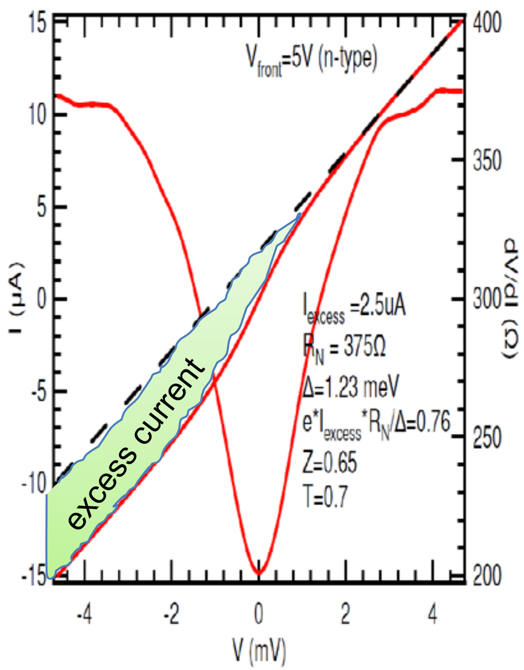
3 sets of peaks: Δ_N, Δ_S, $\Delta_N+\Delta_S$

$$V_{SGS} = \frac{2\cdot\Delta_S}{n\cdot e}, \frac{2\cdot\Delta_N}{n\cdot e}, \frac{2\cdot(\Delta_S \pm \Delta_N)}{n\cdot e}$$

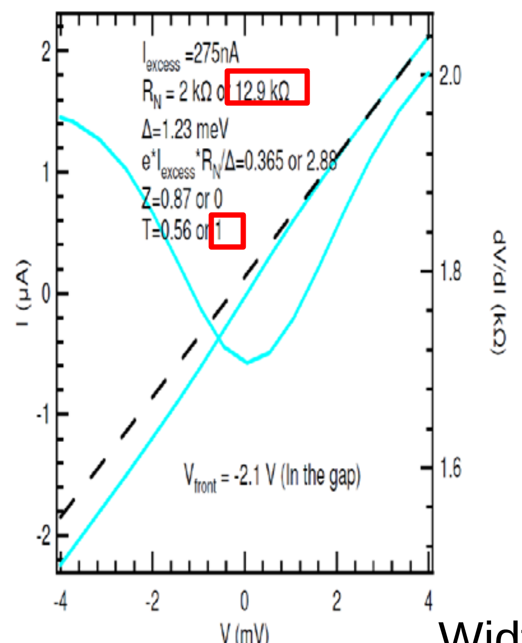
$\Delta_N/\Delta_S \sim 0.67$

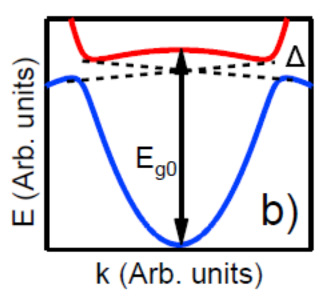
Δ_S=1.31meV ; Δ_N =0.87 meV

Andreev Reflection in 3 Regimes

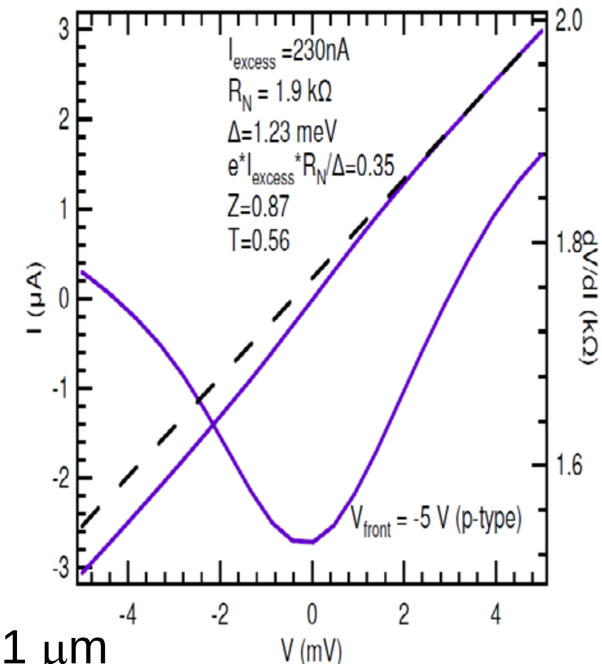


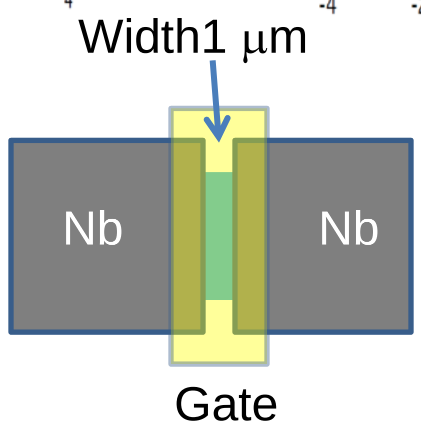
electron side





In the gap

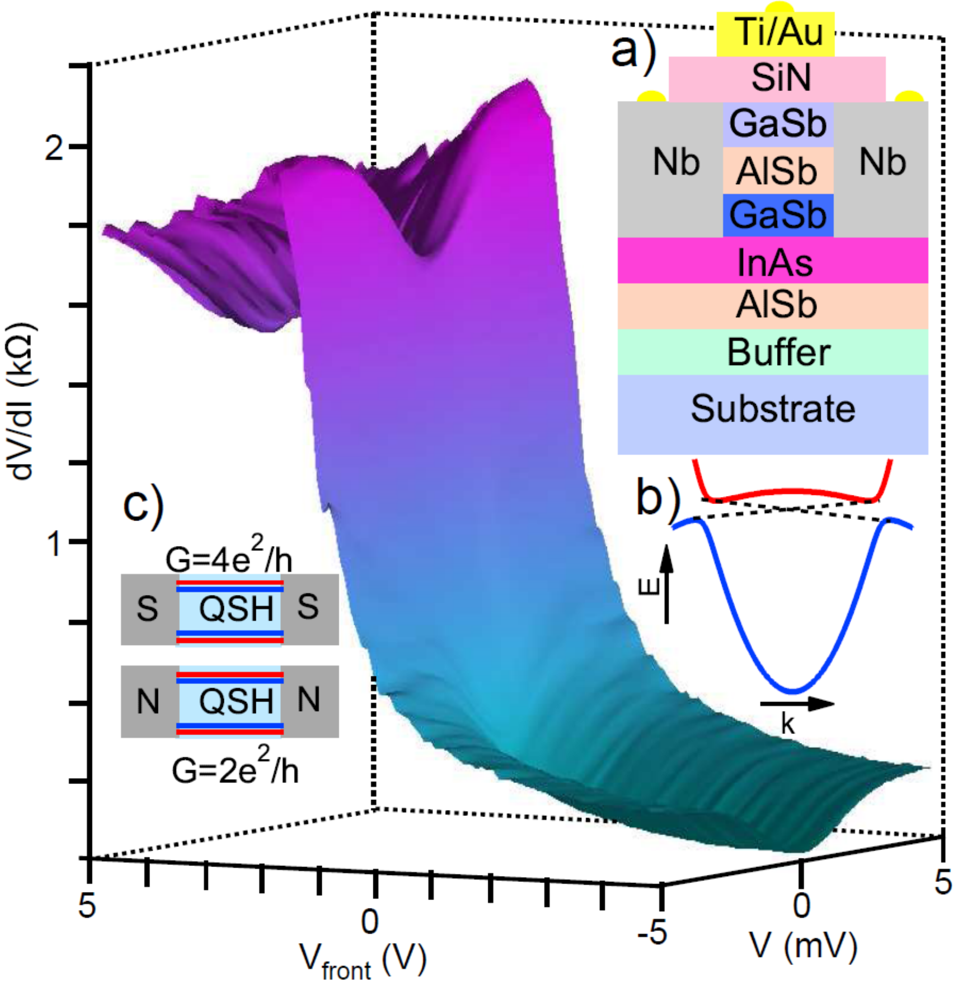




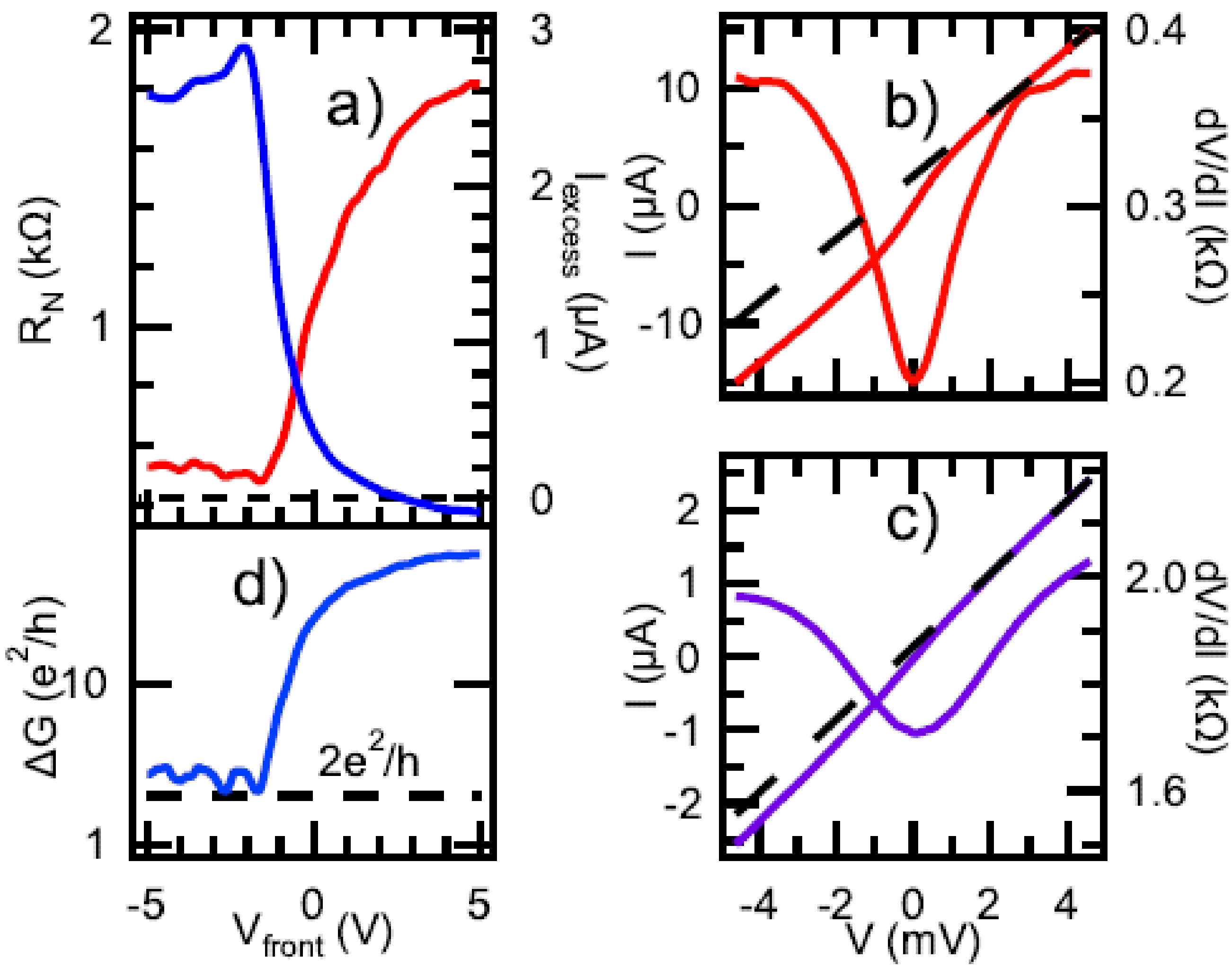
hole side

Andreev Reflection in Nb/(InAs-GaSb)/Nb

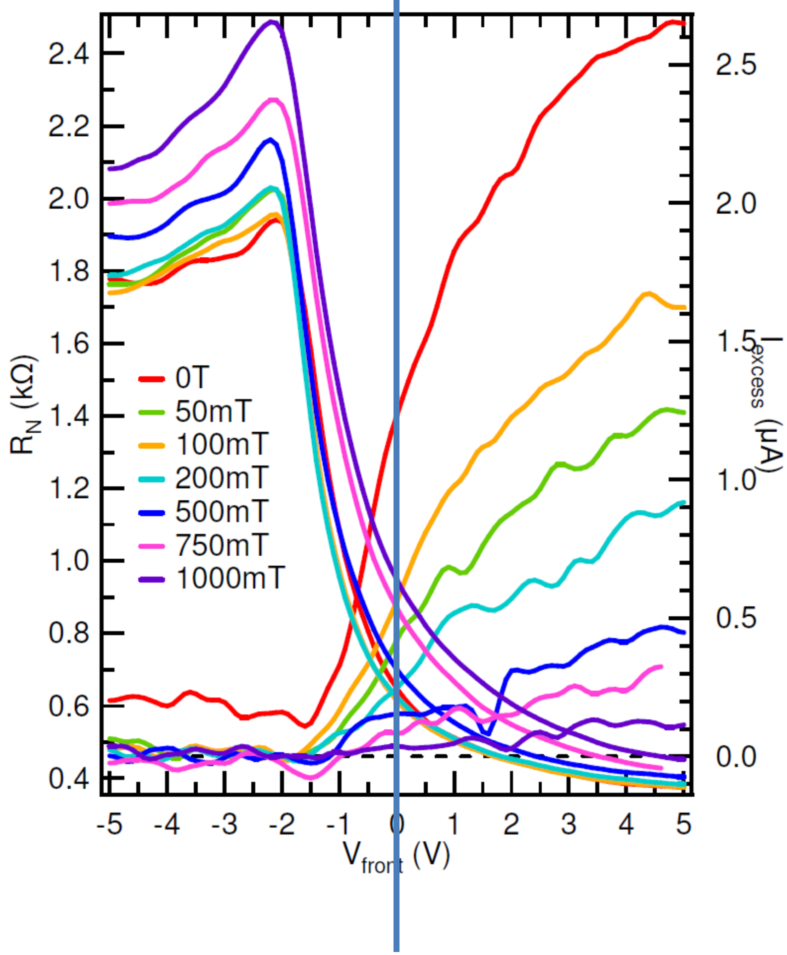
Knez, Du, Sullivan ArXiv:1106.5819 (2011)

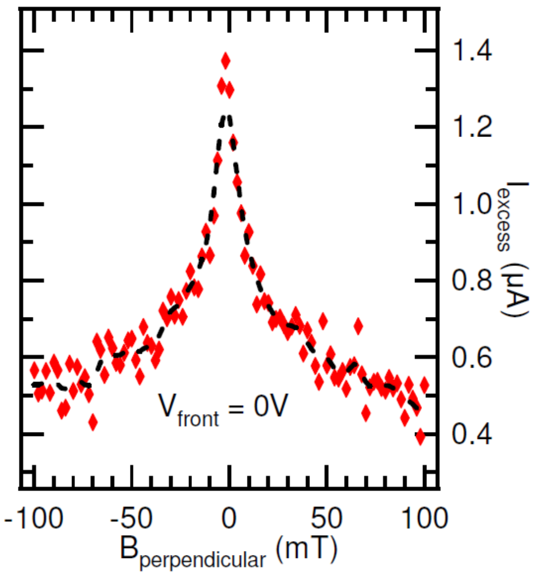


Perfect Andreev Reflection



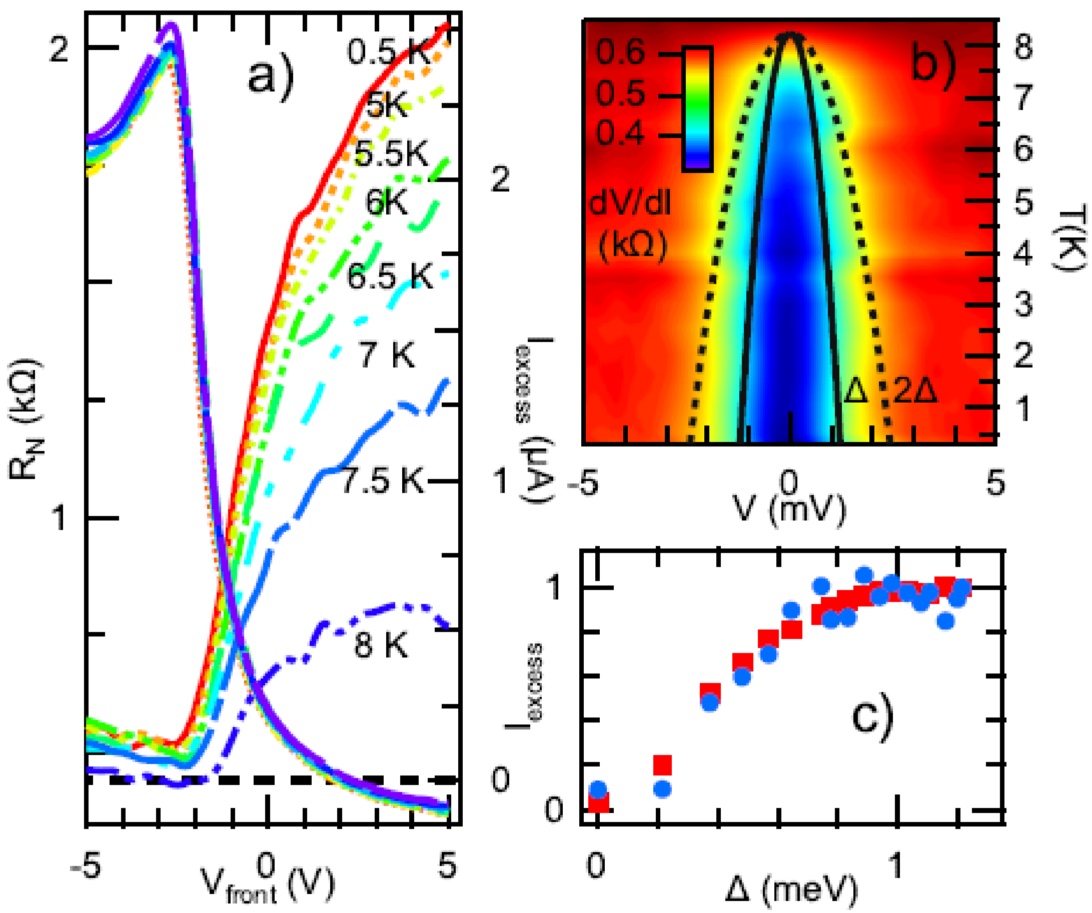
3 Excess Current Suppressed by Magnetic Fields





electron side

Temperature dependence



Challenges

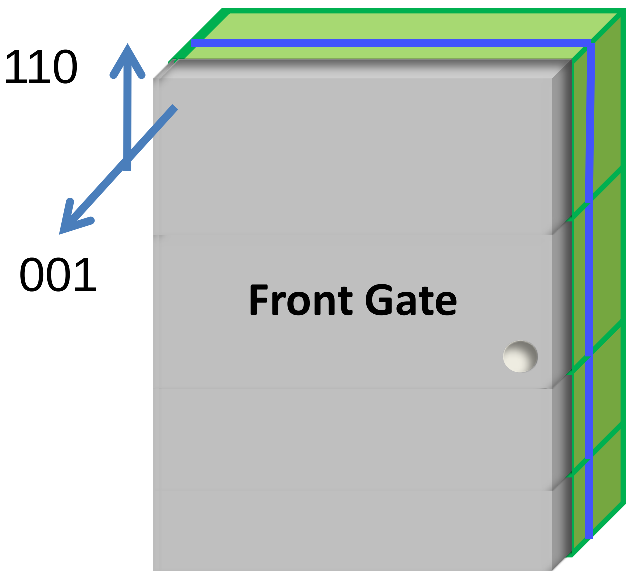
1. Geometry: SNS difficult to analyze

2. Supercurrent

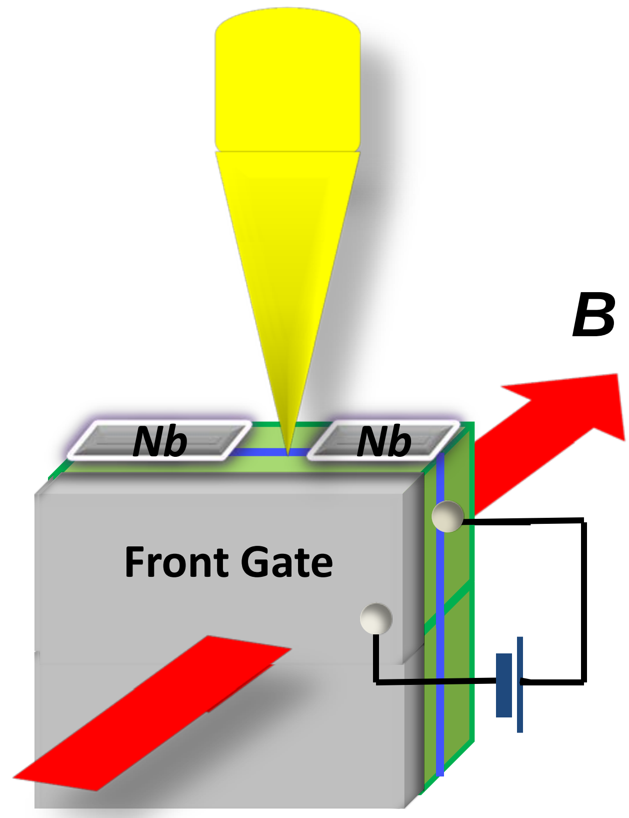
3. Interface quality

Example： STM/STS

Nb/InAs-GaSb Junction on cleaved edge



UHV
Cleavage
Deposition



STM/STS
400 mK
9/2/2 T

SUMMARY

1. We confirmed existence of hybridization gap in inverted InAs/GaSb.

2. Length and width dependence of transport coefficients in in inverted InAs/GaSb QWs suggests existence of helical edge modes

3. Edge and Bulk interaction shows critical behavior

4. Edge modes show only weak dependence on magnetic fields

5. Preliminary data for InAs/GaSb –SC Andreev reflection

THANKS