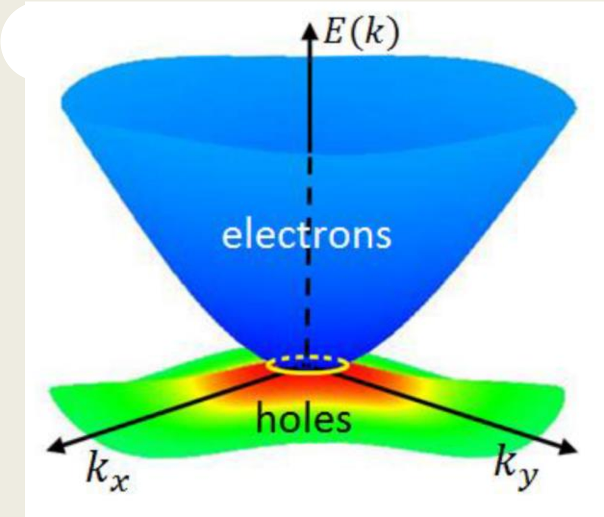
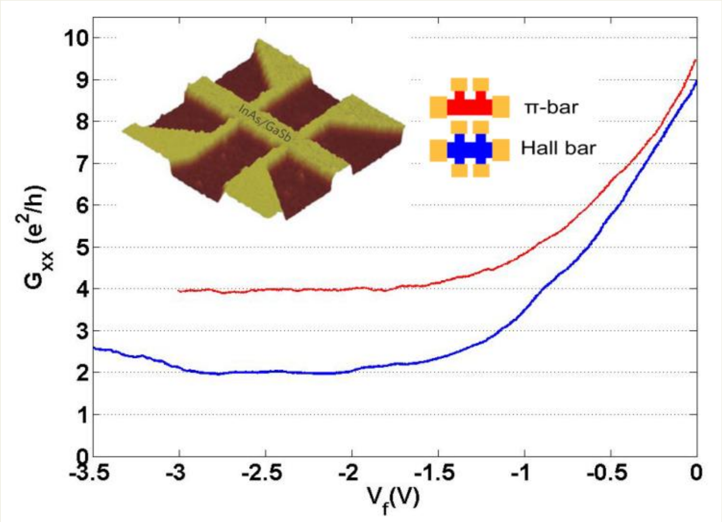
KAVLI ITS WORKSHOP 5.5.2018

InAs/GaSb Quantum Spin Hall & Beyond

Rui-Rui Du

Peking University





AKNOWLEDGE

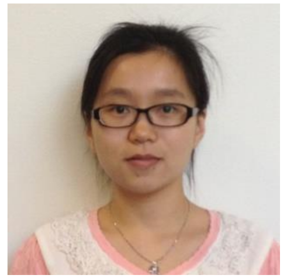
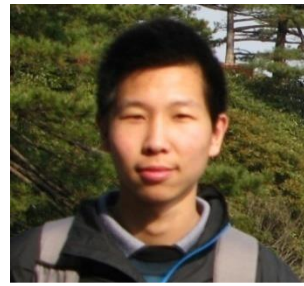
Rice

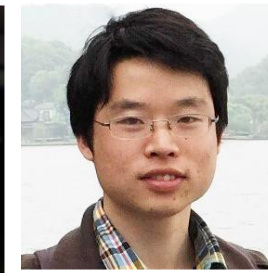
Ivan Knez **Lingjie Du** **Jie Zhang**

Peking U

Tingxin Li **Xiaoxue Liu** **Xingjian Wu**



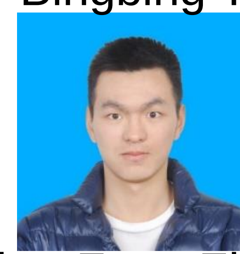






Xiaohe Zheng


Bingbing Tong


Jian-Min Zheng


Jian-Feng Zhang


Da Wu


Si-Qi Yao

Collaboration

Teledyne s

Gerry Sullivan

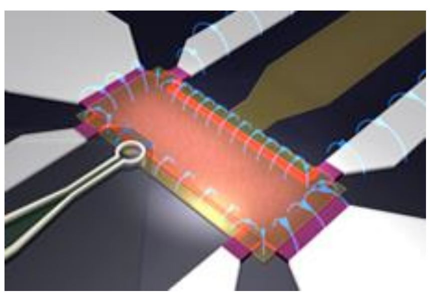
Stanford

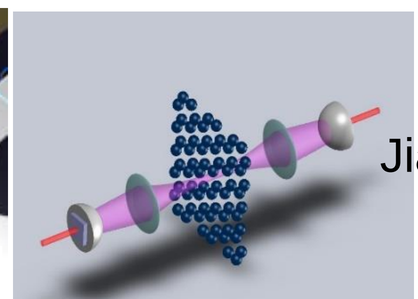
Kathryn Moler
Eric Stanton

Rice

Jun Kono
Xinwei Li

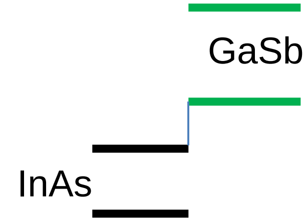

MBE


SQUID Imaging

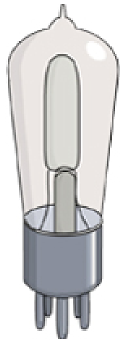

Time-Res. THz

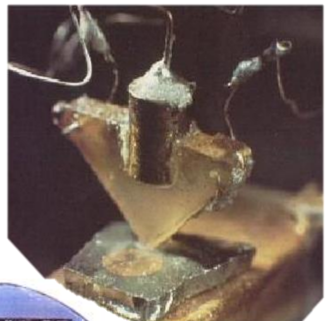
A Gift from Nature

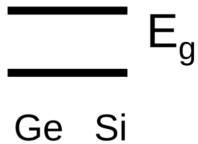
B 5	C 6	N 7
Al 13	Si 14	P 15
Ga 31	Ge 32	As 33
In 49	Sn 50	Sb 51

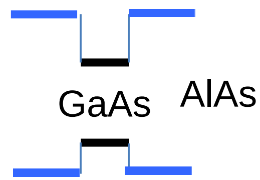


Transistor

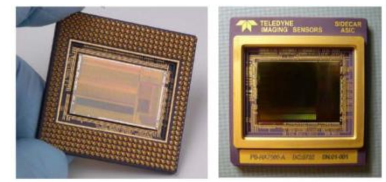




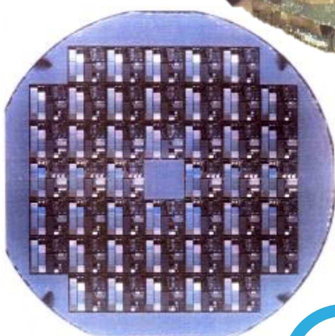


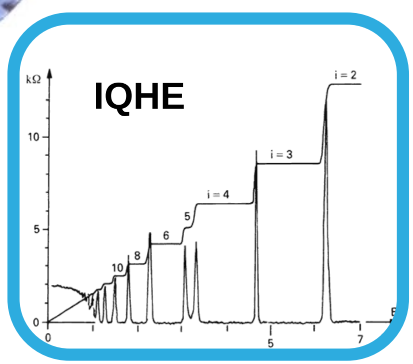


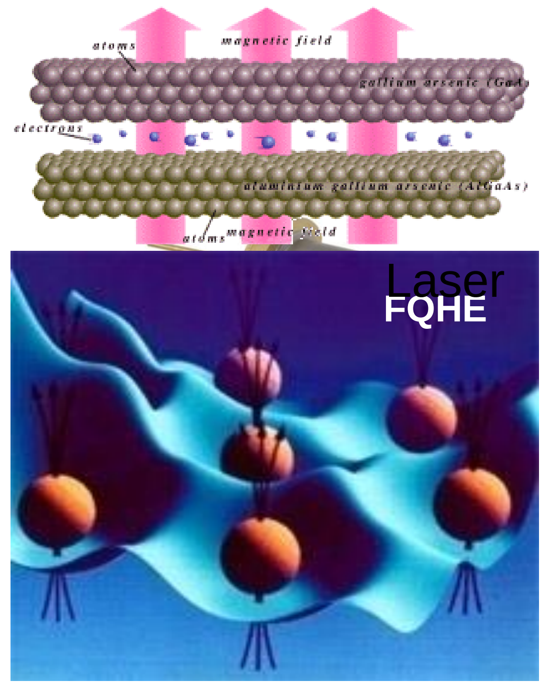
Infrared Detectors

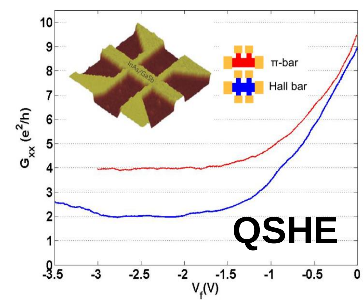


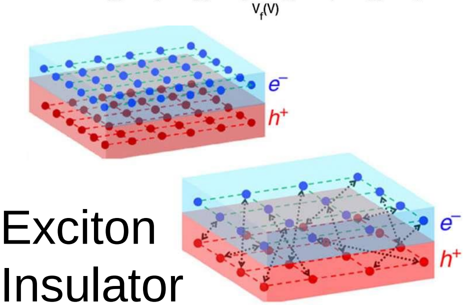
TELEDYNE TECHNOLOGIES
Everywhereyoulook





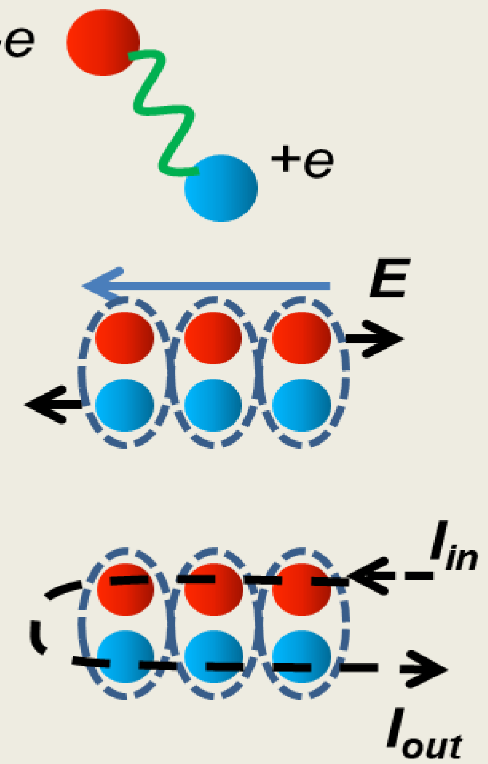




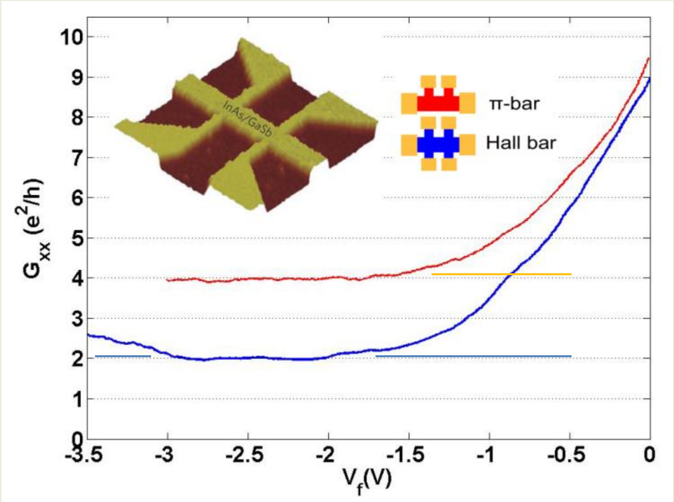


Exciton Insulator

OUTLINES



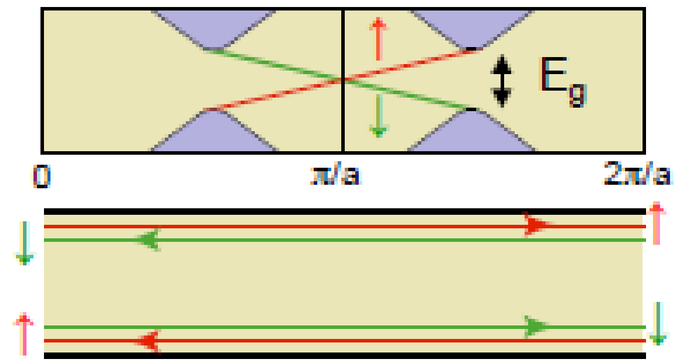
1. Introduction
2. Materials and Devices
3. Topological Exciton Insulator
4. Large Gap TI & Beyond



Two dimensions : Quantum Spin Hall Insulator

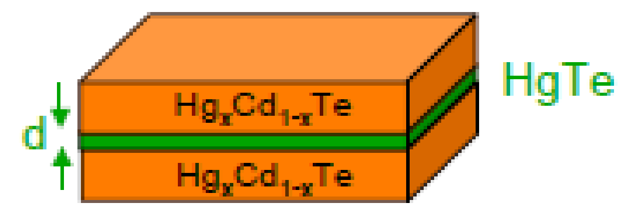
I. Graphene Kane, Mele PRL '05

- Intrinsic spin orbit interaction
  $\Rightarrow$ small (~10mK-1K) band gap
- S_z conserved : "| Haldane model |^2"
- Edge states : $G = 2\ e^2/h$



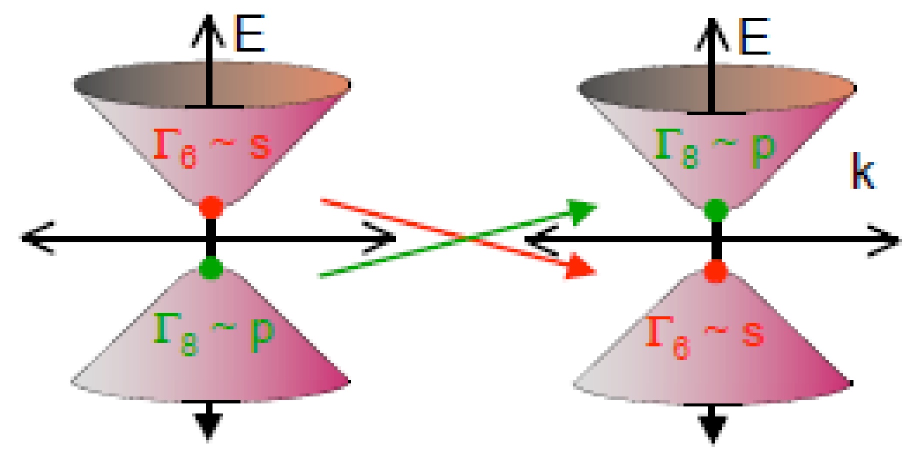
II. HgCdTe quantum wells

Theory: Bernevig, Hughes and Zhang, Science '06
Experiement: Konig et al. Science '07



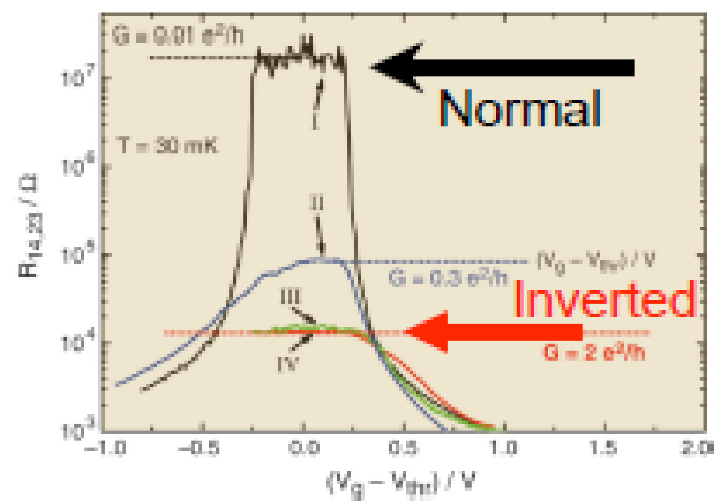
d < 6.3 nm
Normal band order

d > 6.3 nm:
Inverted band order

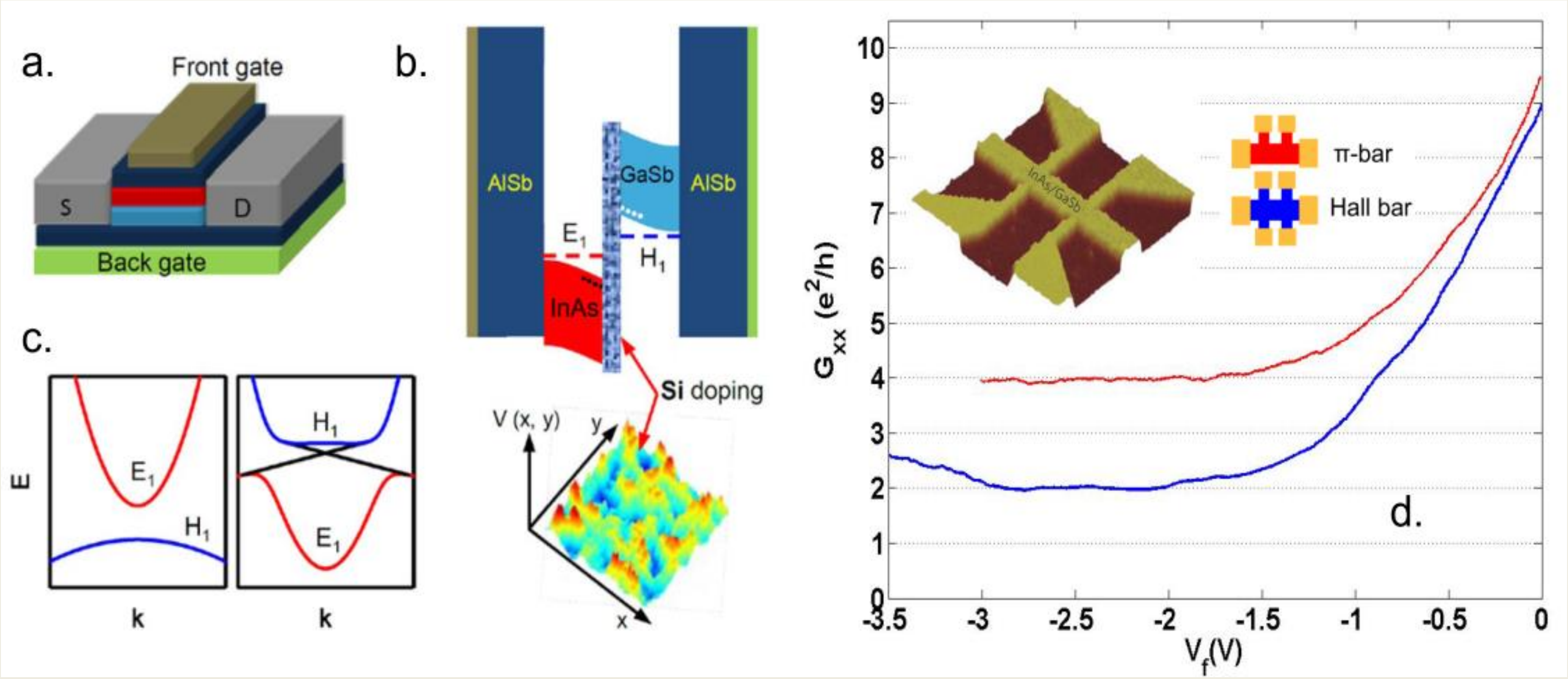


Conventional Insulator   QSH Insulator

$G \sim 2e^2/h$ in QSHI



Quantized Conductance of Edge States



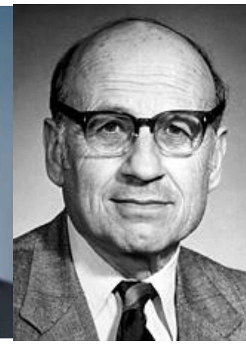
Phys. Rev. Lett. 2011, Knez et al, Evidence for edge modes
Phys. Rev. Lett. 2012, Knez et al, Perfect Andreev reflection of edge-SC junction
Phys. Rev. Lett. 2015, Du et al, Quantized edge states for small samples

Phys. Rev. Lett. 2014, Stanton et al,
Phys. Rev. Lett. 2014, Knez et al.
Phys. Rev. Lett. 2015, Li et al
Phys. Rev. Lett. 2017, Du, et al , N.Comm. 2017, Du et al

The Exciton Analog of BCS Superconductivity

Electron-Hole Pairing ⟷ Cooper Pairing





Mott, Philos Mag 1961
Knox, 1963
Keldysh, Yu.V., Fizika ,1964
Jerome, Rice, Kohn, 1967
Halperin & Rice, Rev Mod Phys, 1968

PHYSICAL REVIEW　　VOLUME 126, NUMBER 5　　JUNE 1, 1962

Bose-Einstein Condensation of Excitons

JOHN M. BLATT
Courant Institute of Mathematical Sciences, New York University, New York, New York and Applied Mathematics Department, University of New South Wales, New South Wales, Australia

AND

K. W. BÖER AND WERNER BRANDT
Department of Physics, Radiation and Solid-State Laboratory, New York University, New York, New York
(Received January 8, 1962)

Exciton Insulators

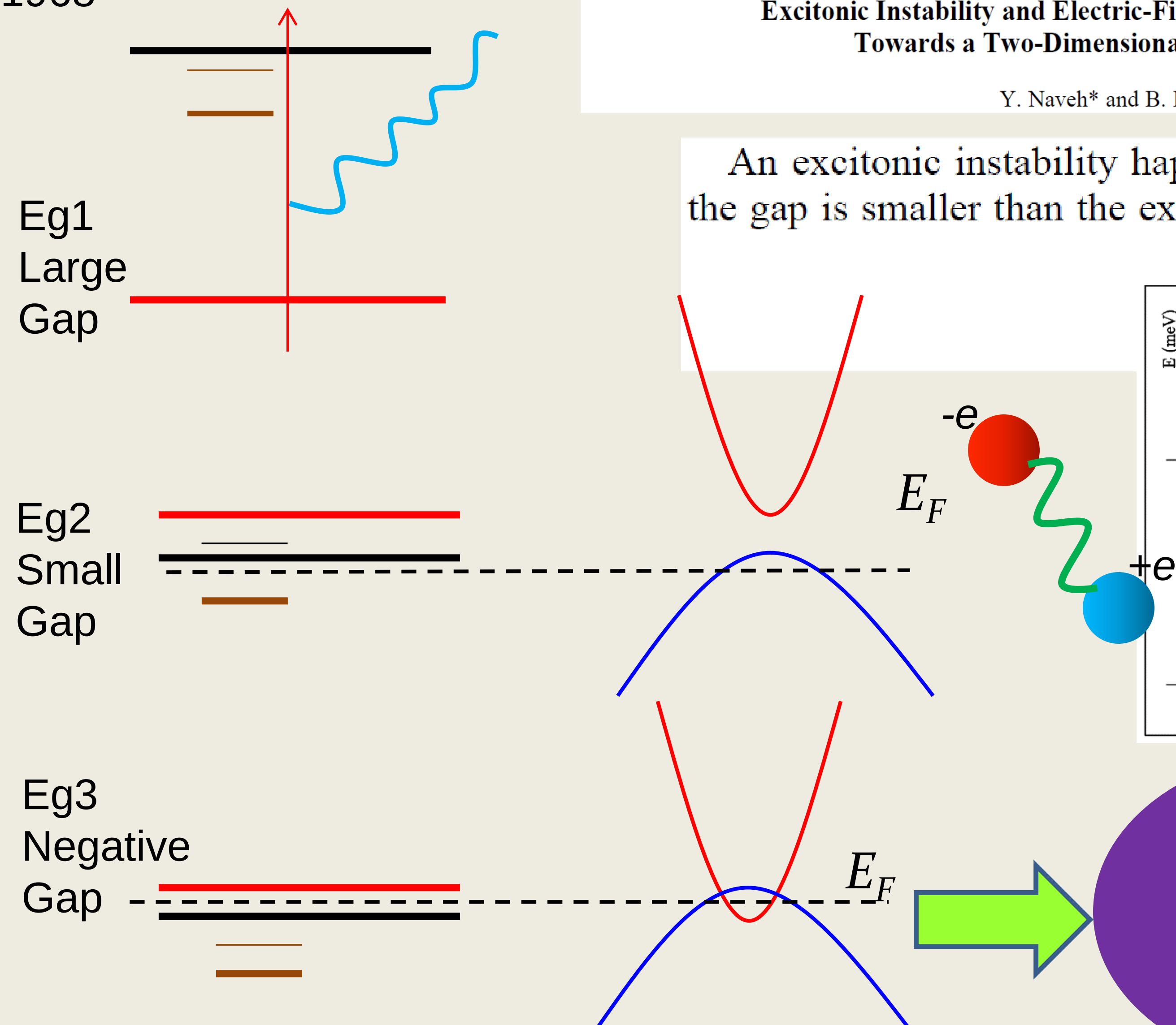
Mott, Philos Mag 1961
Keldysh, Yu.V., Fizika ,1964
Halperin & Rice, Rev Mod Phys 1968

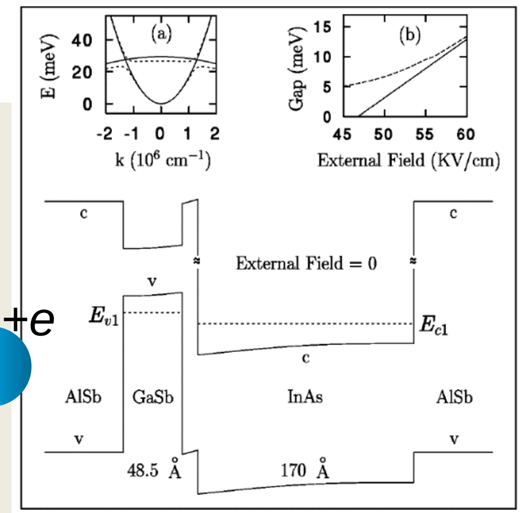
VOLUME 77, NUMBER 5 PHYSICAL REVIEW LETTERS 29 JULY 199

Excitonic Instability and Electric-Field-Induced Phase Transition Towards a Two-Dimensional Exciton Condensate

Y. Naveh* and B. Laikhtman†

An excitonic instability happens in cases (I), (II) when the gap is smaller than the exciton binding energy ε_0. In





Topological
Exciton Insulator

w/ edge states

Recent Results for Exciton Physics in 3D and 2D Quantum Materials

SOLID-STATE PHYSICS *Science* 2017

Signatures of exciton condensation in a transition metal dichalcogenide

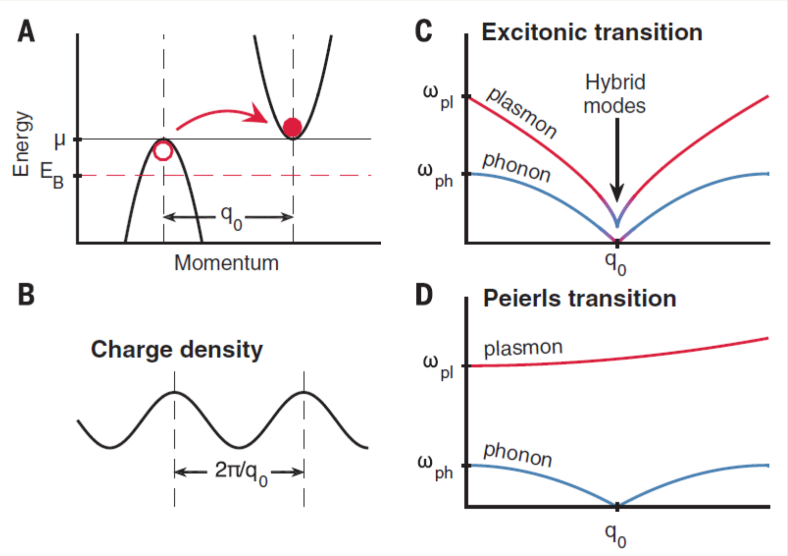
Anshul Kogar,[1] Melinda S. Rak,[1] Sean Vig,[1] Ali A. Husain,[1] Felix Flicker,[2] Young Il Joe,[1] Luc Venema,[1*] Greg J. MacDougall,[1] Tai C. Chiang,[1] Eduardo Fradkin,[1] Jasper van Wezel,[3] Peter Abbamonte[1]†

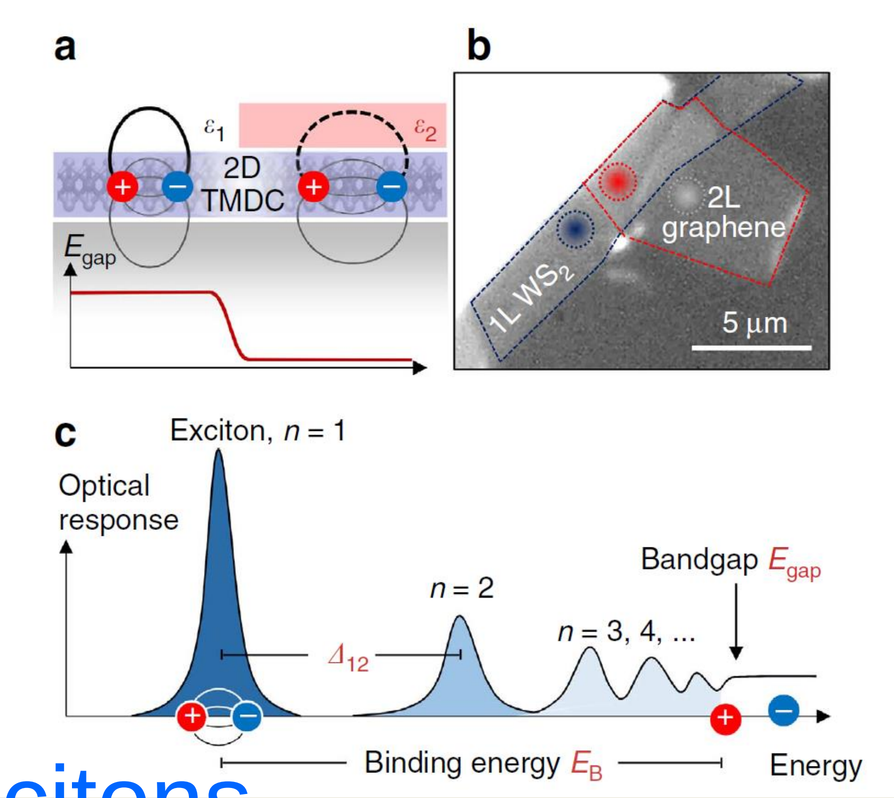
ARTICLE *Nature Commun.* 2017

Received 20 Feb 2017 | Accepted 14 Mar 2017 | Published 4 May 2017 DOI: 10.1038/ncomms15251 OPEN

Coulomb engineering of the bandgap and excitons in two-dimensional materials

Archana Raja[1,2,3,4], Andrey Chaves[2,5], Jaeeun Yu[2], Ghidewon Arefe[6], Heather M. Hill[1,3], Albert F. Rigosi[1,3], Timothy C. Berkelbach[7], Philipp Nagler[8], Christian Schüller[8], Tobias Korn[8], Colin Nuckolls[2], James Hone[6], Louis E. Brus[2], Tony F. Heinz[1,3,4], David R. Reichman[2] & Alexey Chernikov[1,8]





Optical Pumping
-Non-equilibrium Excitons

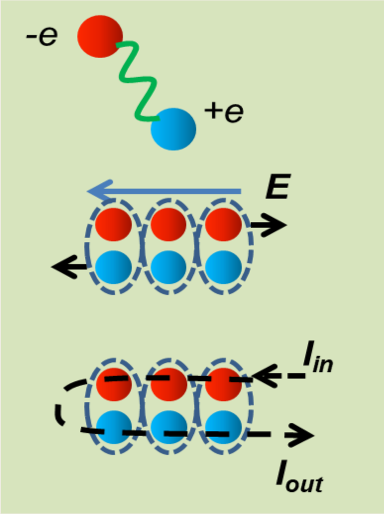
OUTLINES

1. Introduction

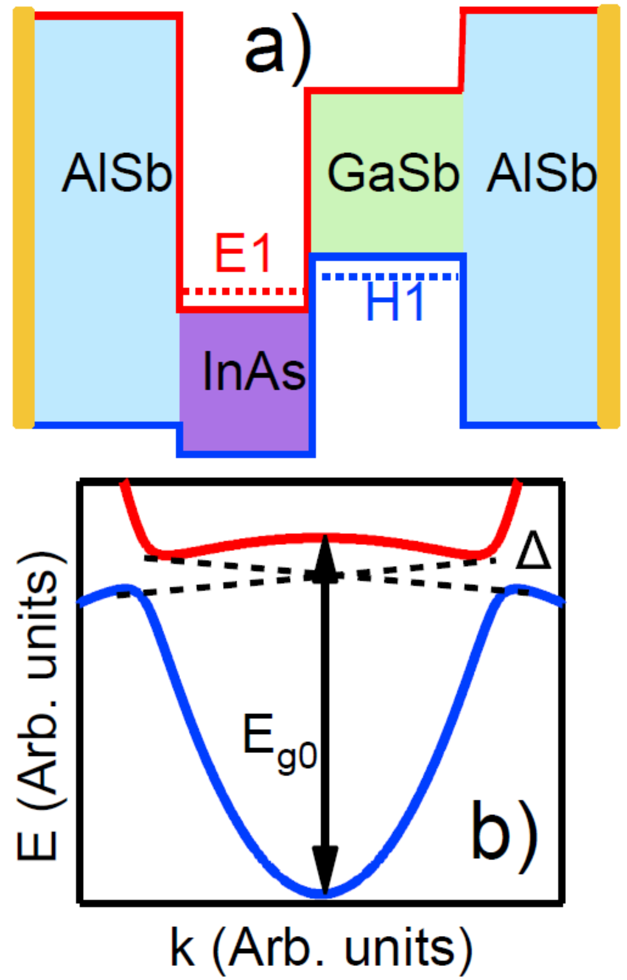
2. **Materials and Devices**

3. Topo Exciton Insulator

4. Large Gap TI



6.1 A Family

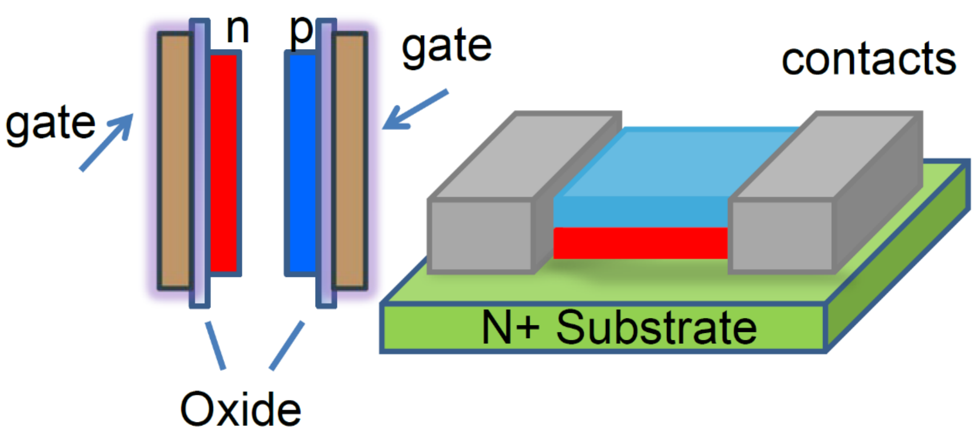


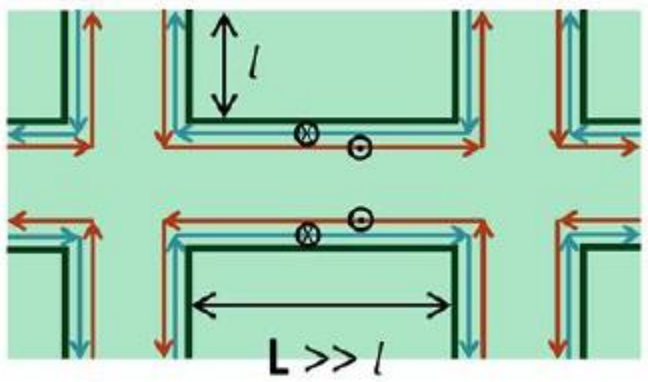
Liu, *et al*, *PRL* **100**, 236601(2008)

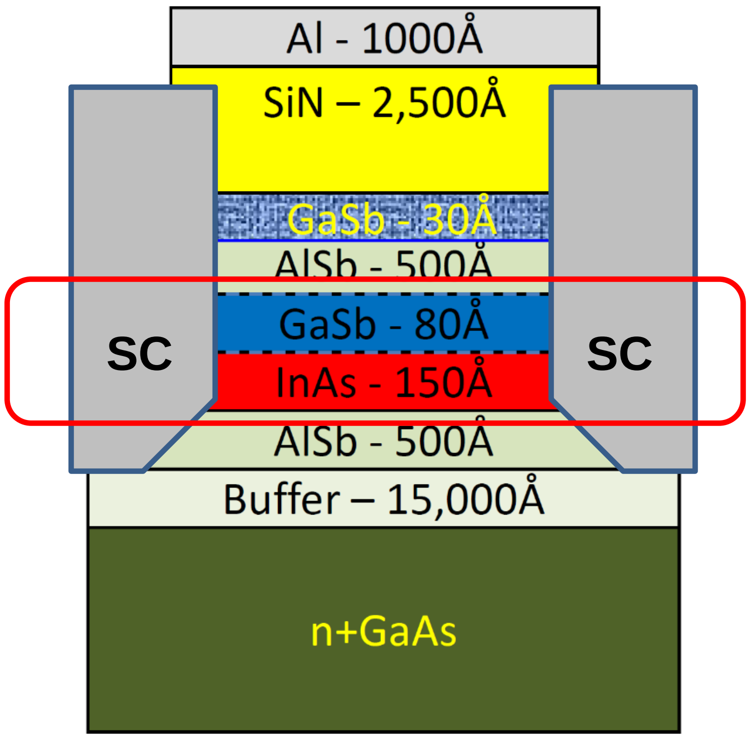
1. **Band parameter**
   $\Delta E = E1 - H1$
   tuned by width, x, gates

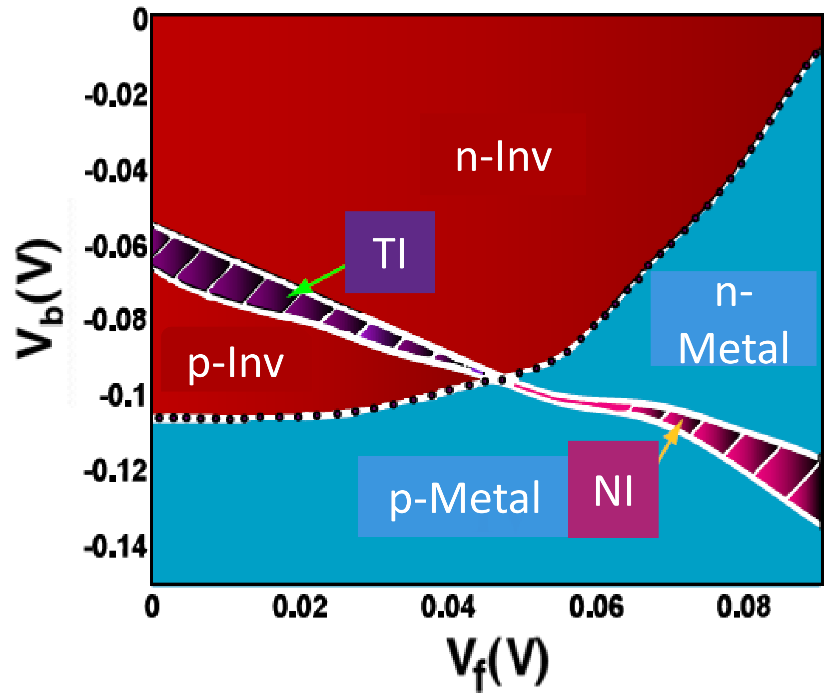
2. **$\Delta E < 0$ inverted -0.15 eV to 0**
   Tunneling mix e-h and opens
   a gap at finite *k*-vector

Wafer and Device





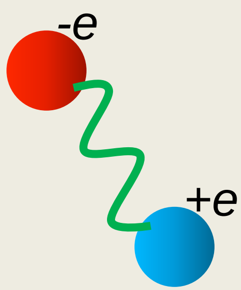




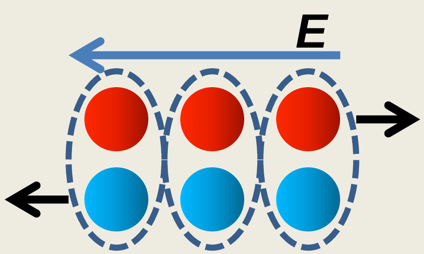
Two Limits of Coupling

Weak Tunneling
Strong Coulomb

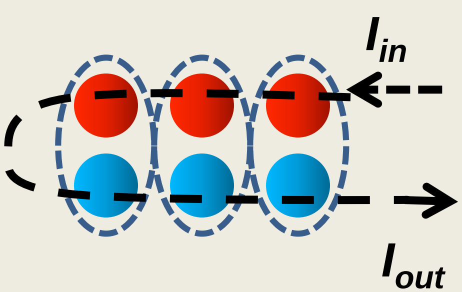
2D
Excitons



Exciton
Insulator

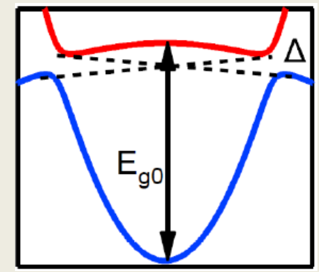


Counter flow
Superfluid

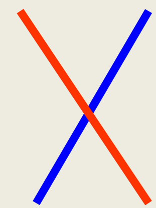


Strong
Tunneling

Mini Gap

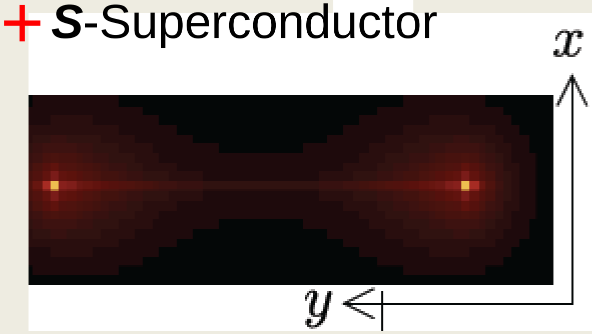


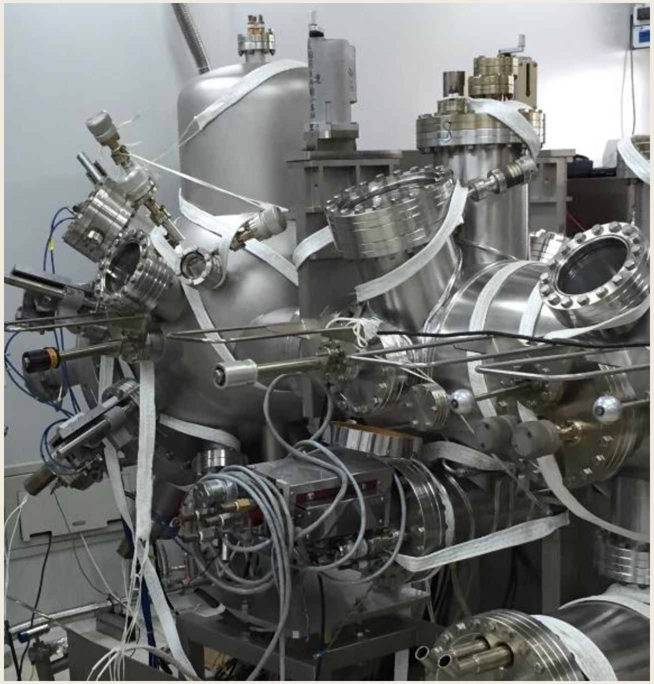
1- D
Dirac Fermions



Majorana
Pair

+ ***S***-Superconductor





ICQM PKU

Gerry Sullivan and Amal Ikhlassi
In front of GEN III MBE

TELEDYNE TECHNOLOGIES Everywhereyoulook™

全冰冰

OUTLINES

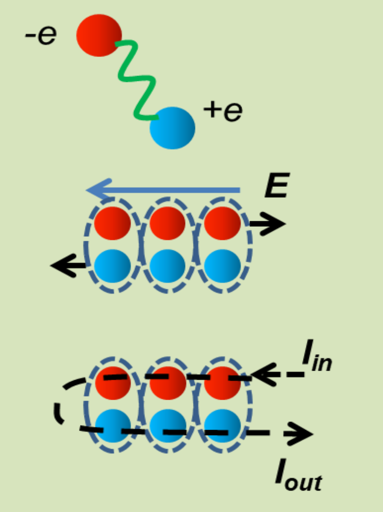
1. Topology and Physics

2. Materials and Devices

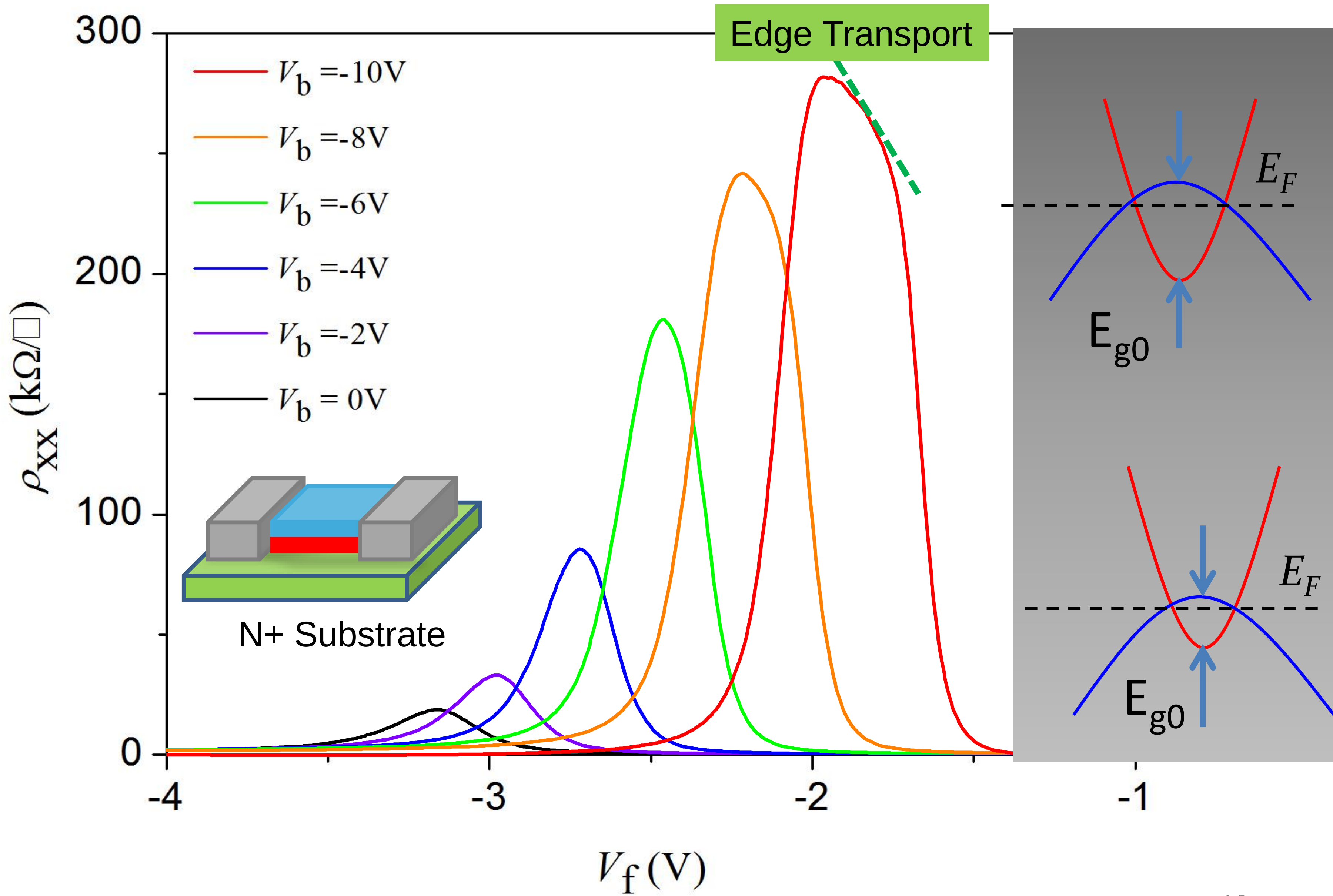
3. **ToPo Exciton Insulator**

4. Novel Edge States

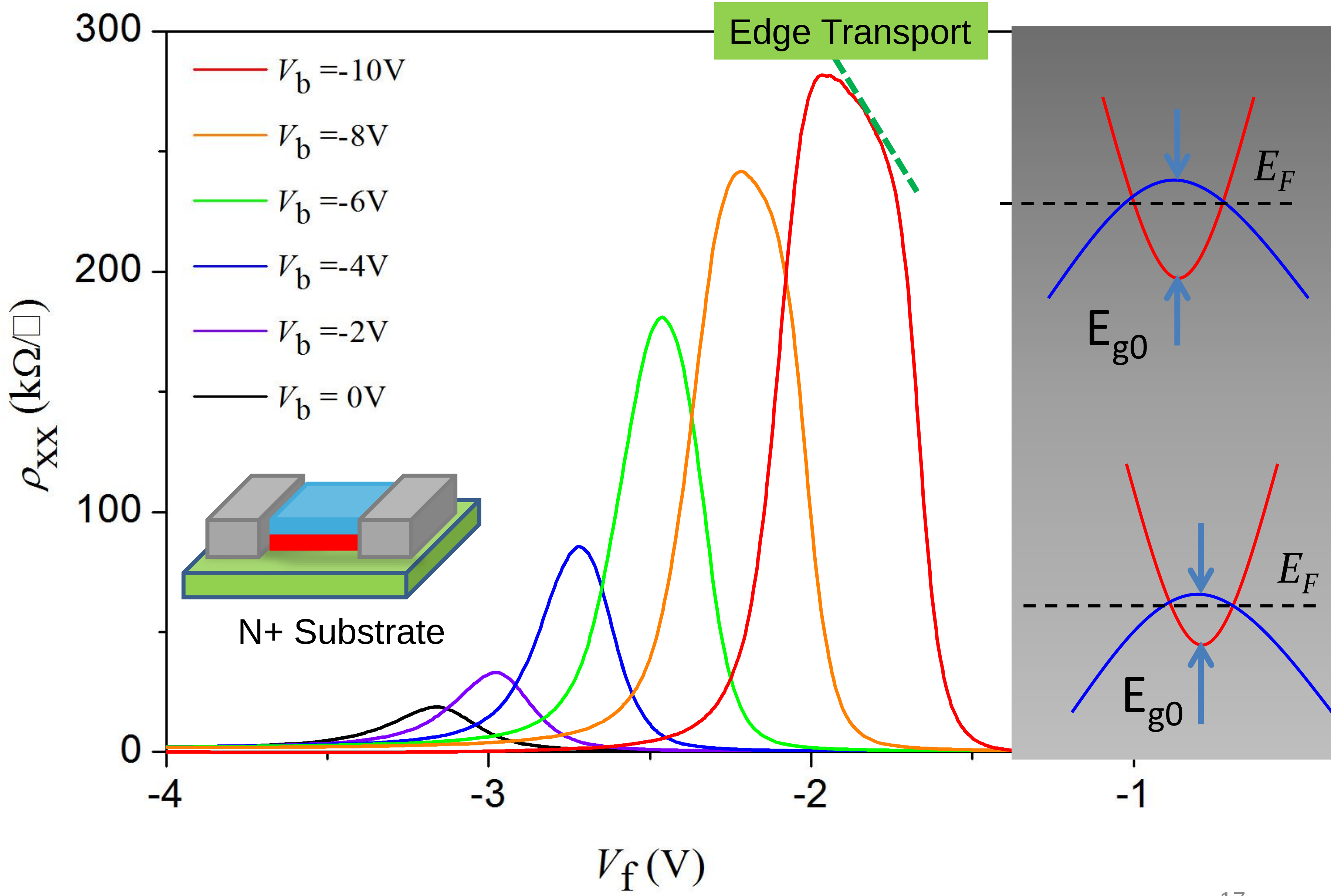
5. Outlook



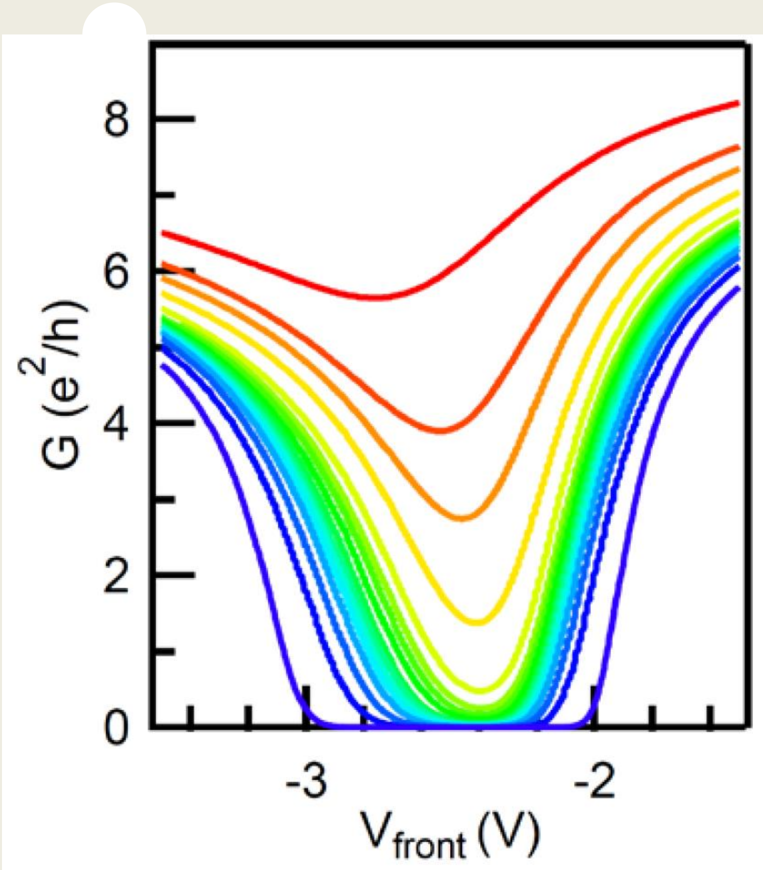
Example: *G1* T = 300 mK 50 μm Hall Bar

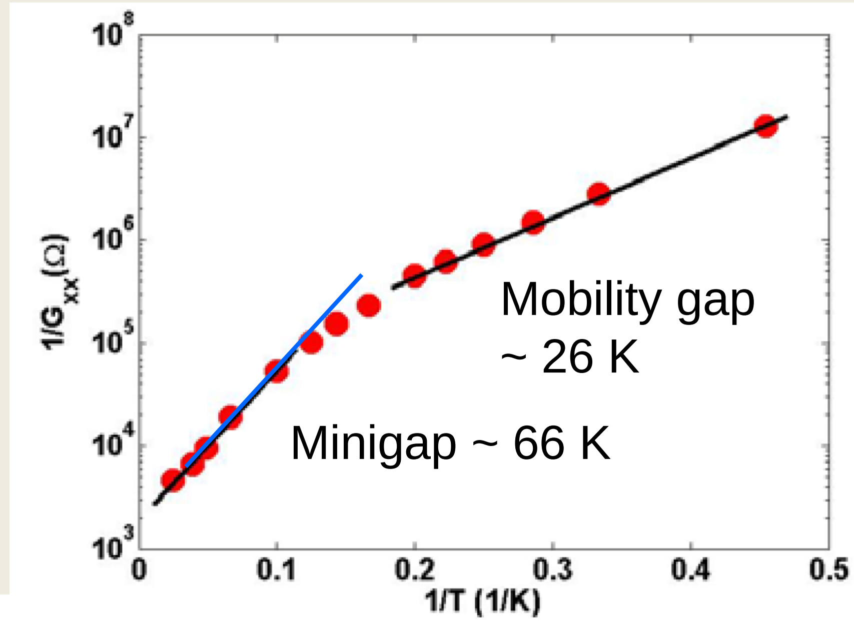


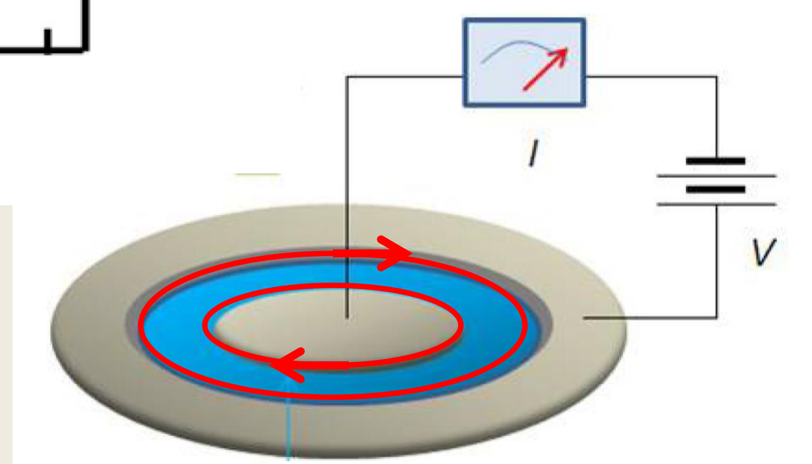
Example: *G1* T = 300 mK   50 μm Hall Bar



Truly Insulating Bulk $\rho_{Bulk} >> 10\ M\Omega$







Corbino Disk

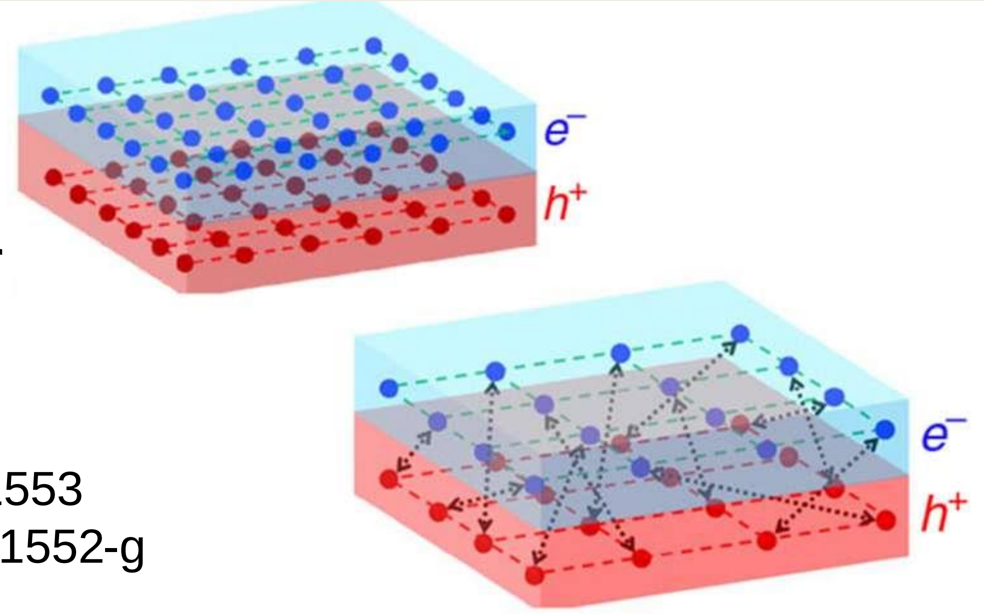
Lingjie Du

ARTICLE

DOI: 10.1038/s41467-017-01988-1 OPEN

Evidence for a topological excitonic insulator in InAs/GaSb bilayers

Lingjie Du[1], Xinwei Li[2], Wenkai Lou [3], Gerard Sullivan[4], Kai Chang[3], Junichiro Kono[1,2,5] & Rui-Rui Du[1,6]



Editors' ChoicePhysics
Probing an excitonic insulator
1.Jelena Stajic

Science 22 Dec 2017:
Vol. 358, Issue 6370, pp. 1552-1553
DOI: 10.1126/science.358.6370.1552-g


ARTICLE

DOI: 10.1038/s41467-017-01988-1 OPEN

Evidence for a topological excitonic insulator in InAs/GaSb bilayers

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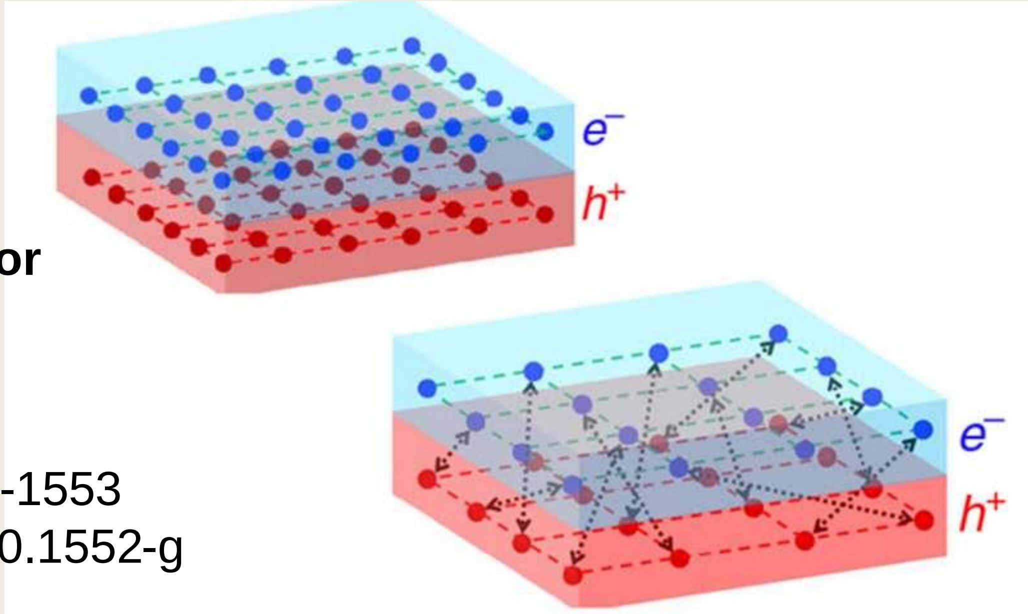

Editors' ChoicePhysics
Probing an excitonic insulator
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Science 22 Dec 2017:
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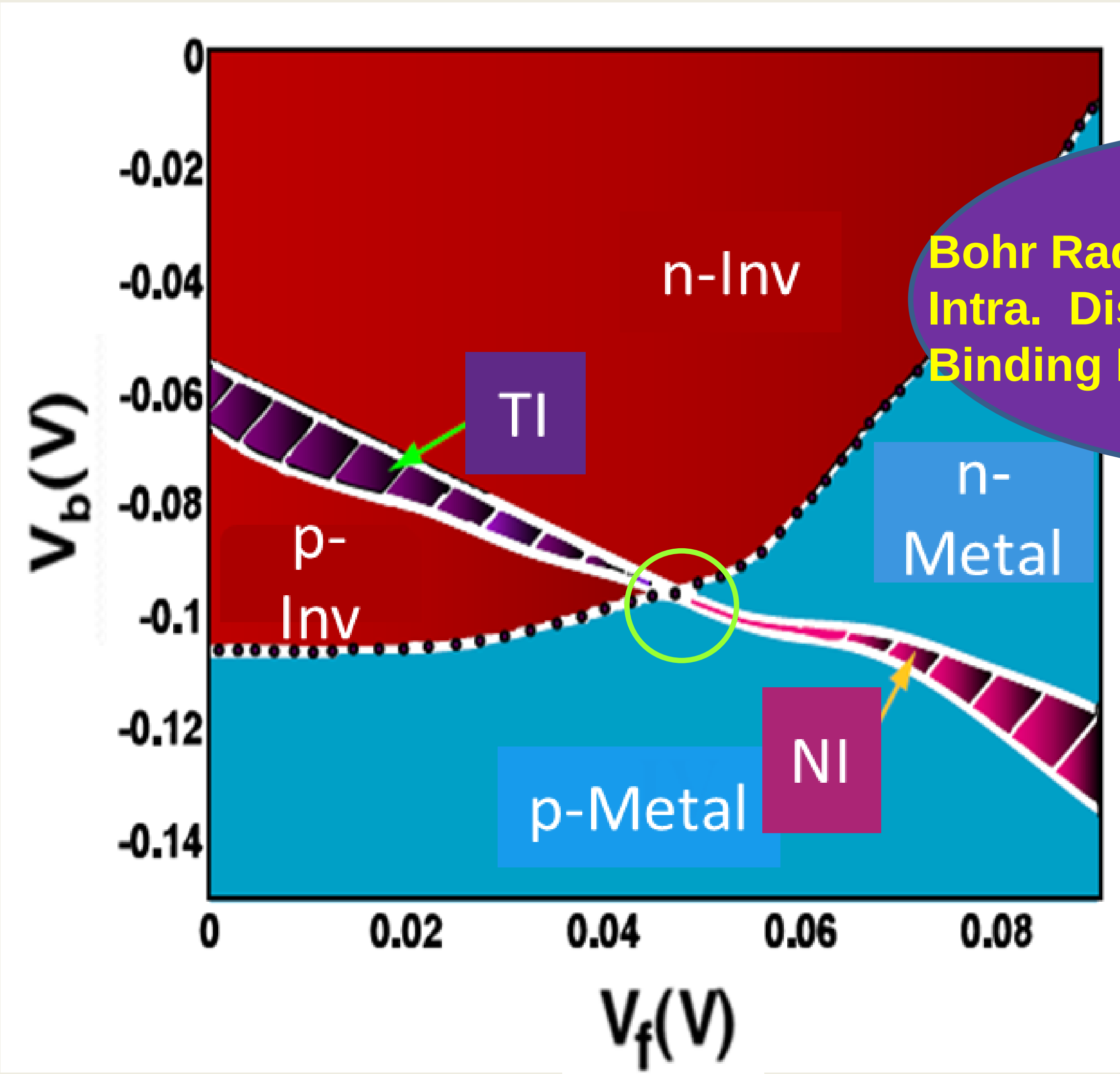
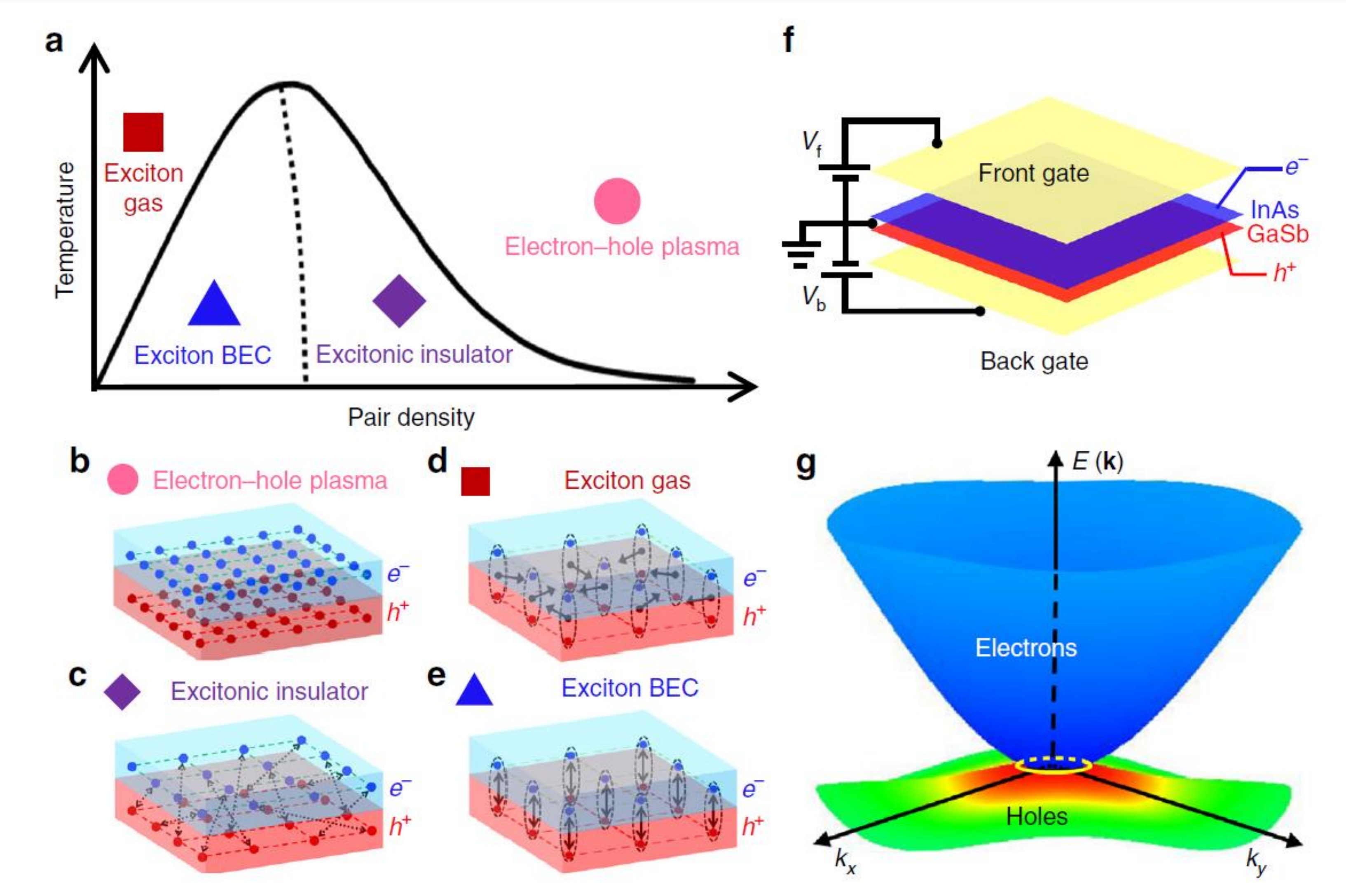
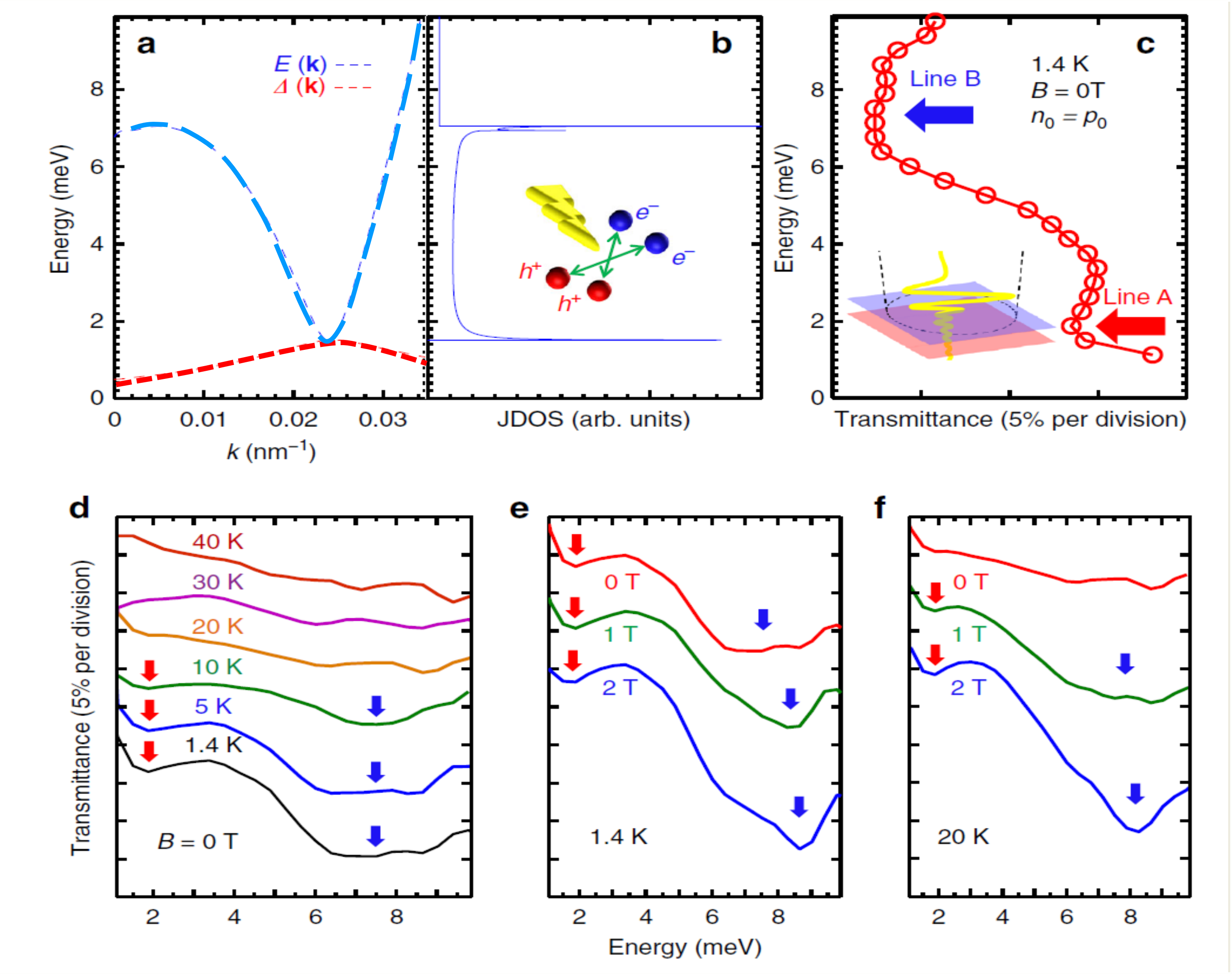


Bohr Rad. ~ 45A
Intra. Dis. ~ 100-300A
Binding E. ~100K

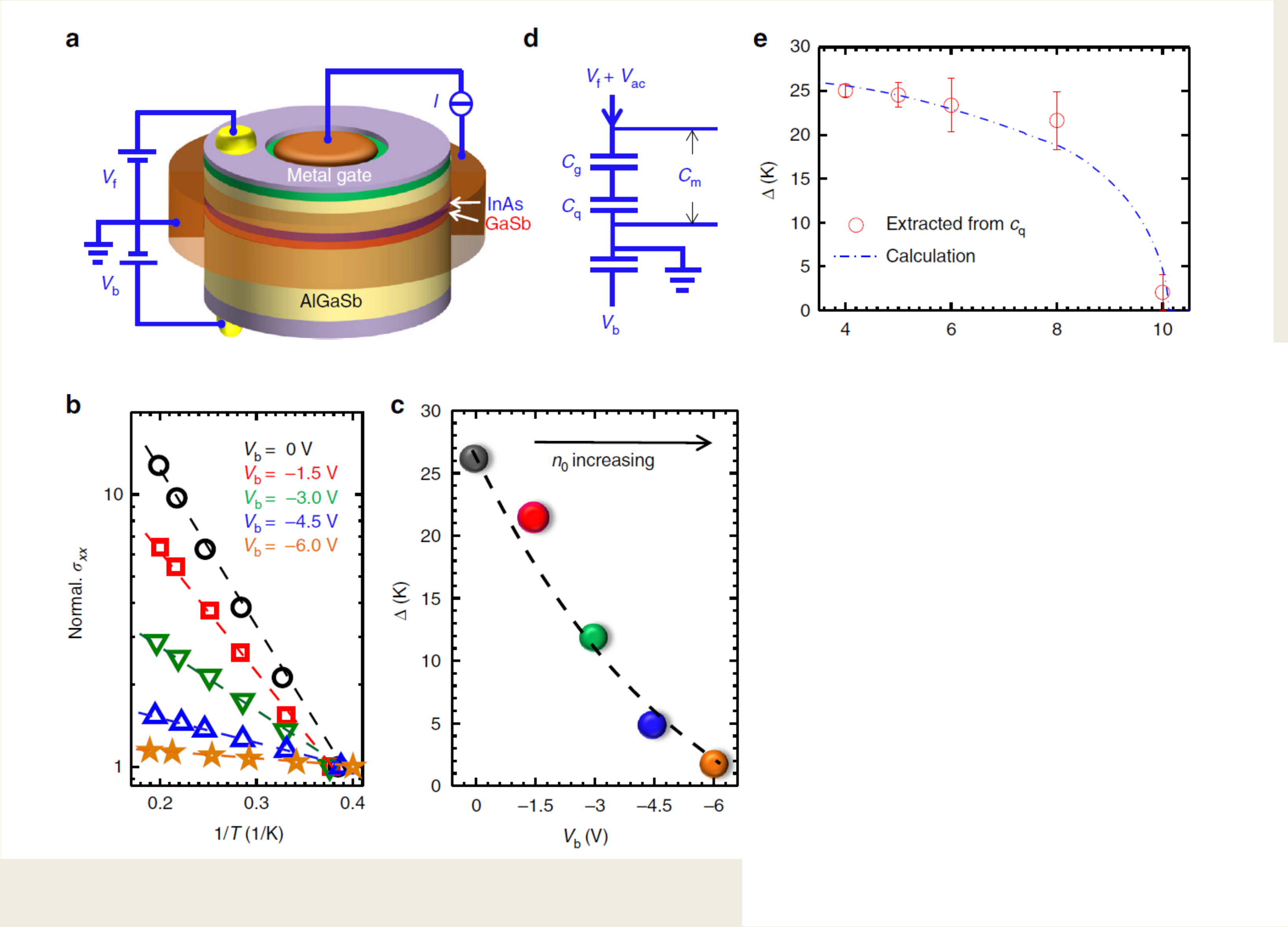


a
Temperature
Exciton gas
Electron–hole plasma
Exciton BEC
Excitonic insulator
Pair density
b
Electron–hole plasma
c
Excitonic insulator
d
Exciton gas
e
Exciton BEC
e^-
h^+
f
V_f
V_b
Front gate
InAs
GaSb
Back gate
g
E (**k**)
Electrons
Holes
k_x
k_y

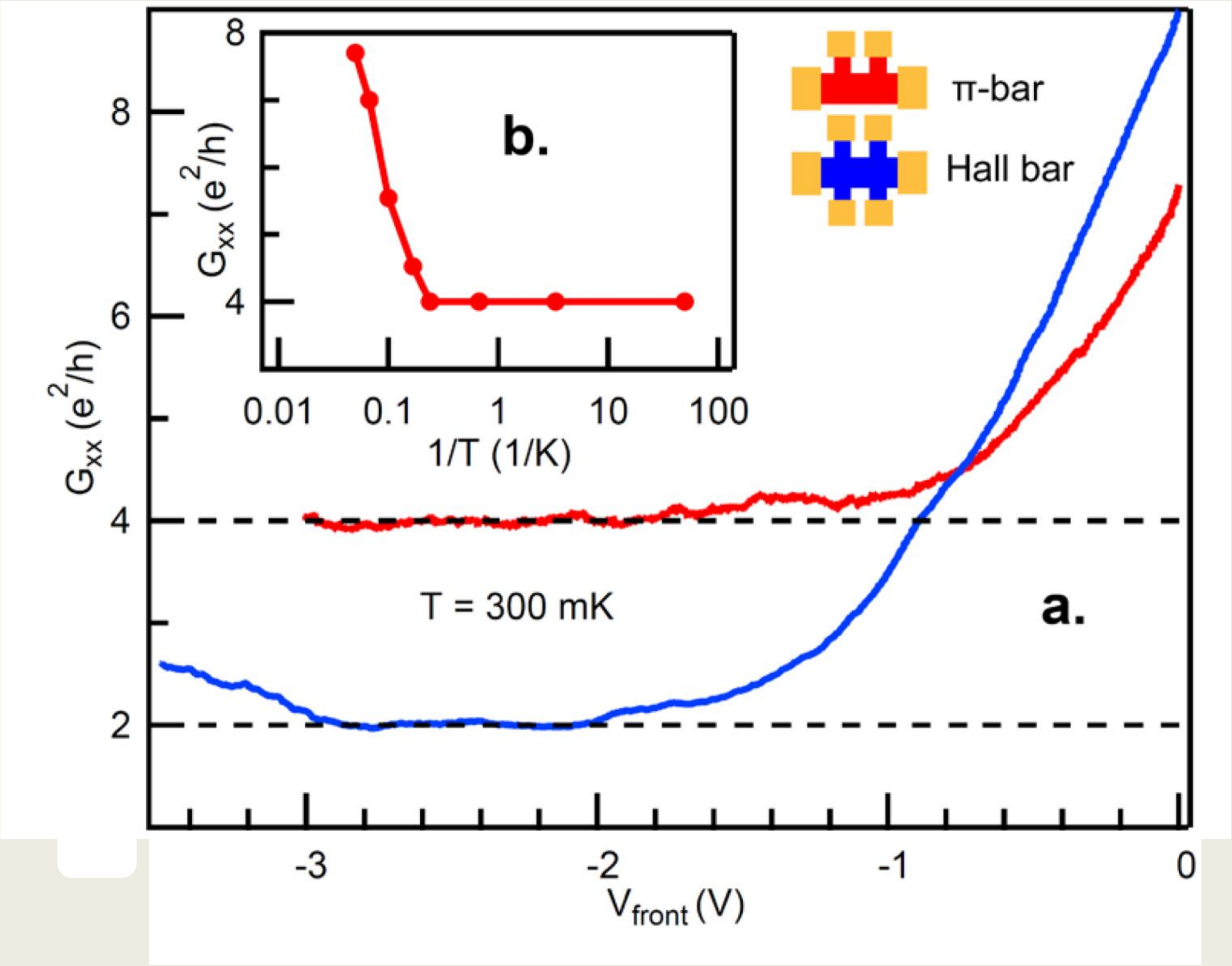
THz Absorption Spectrum



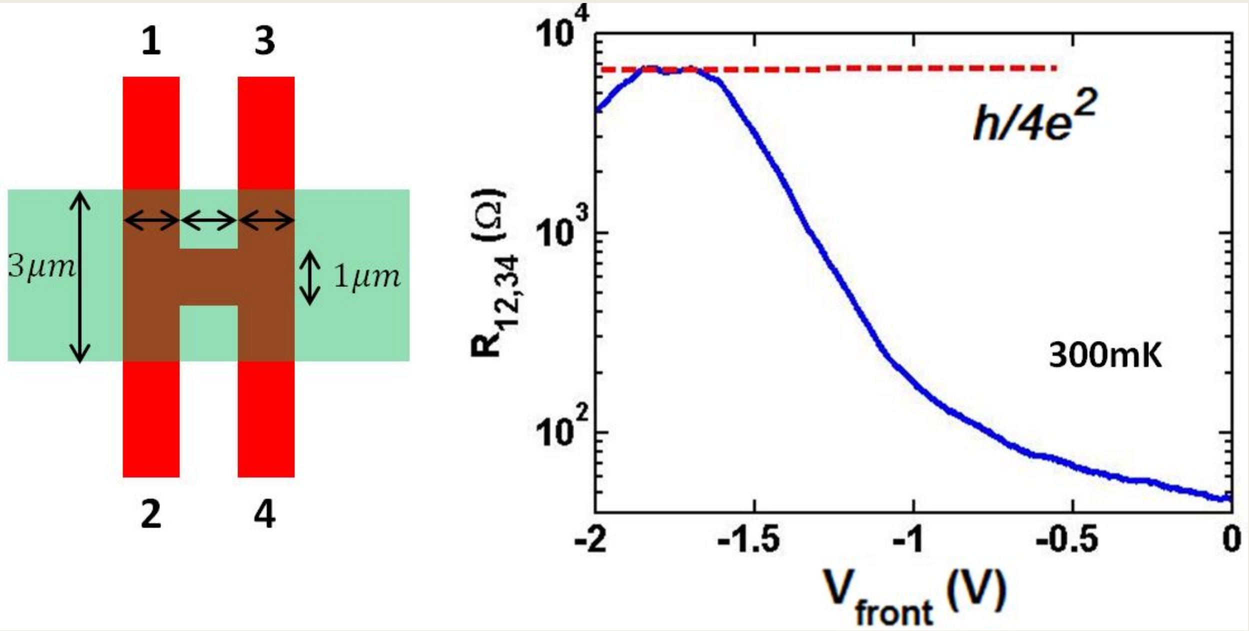
Transport Measurements



Conductance Plateau up to 4 K



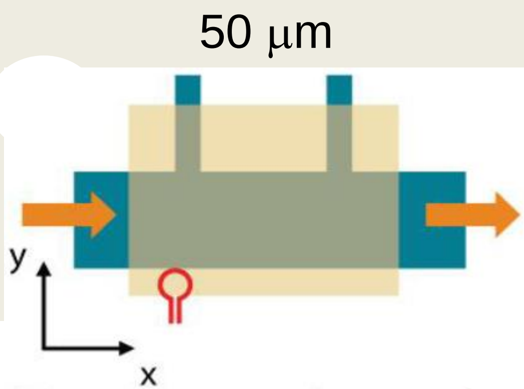
Non-Local Ede Transport: H-Bar

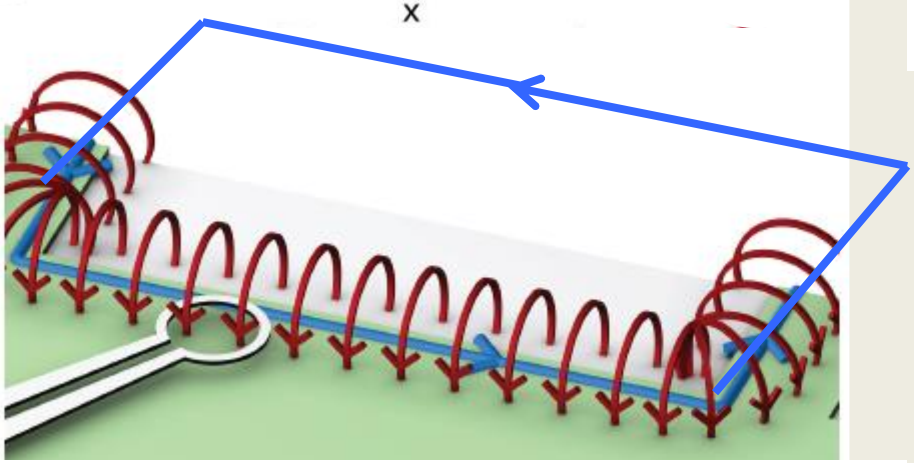


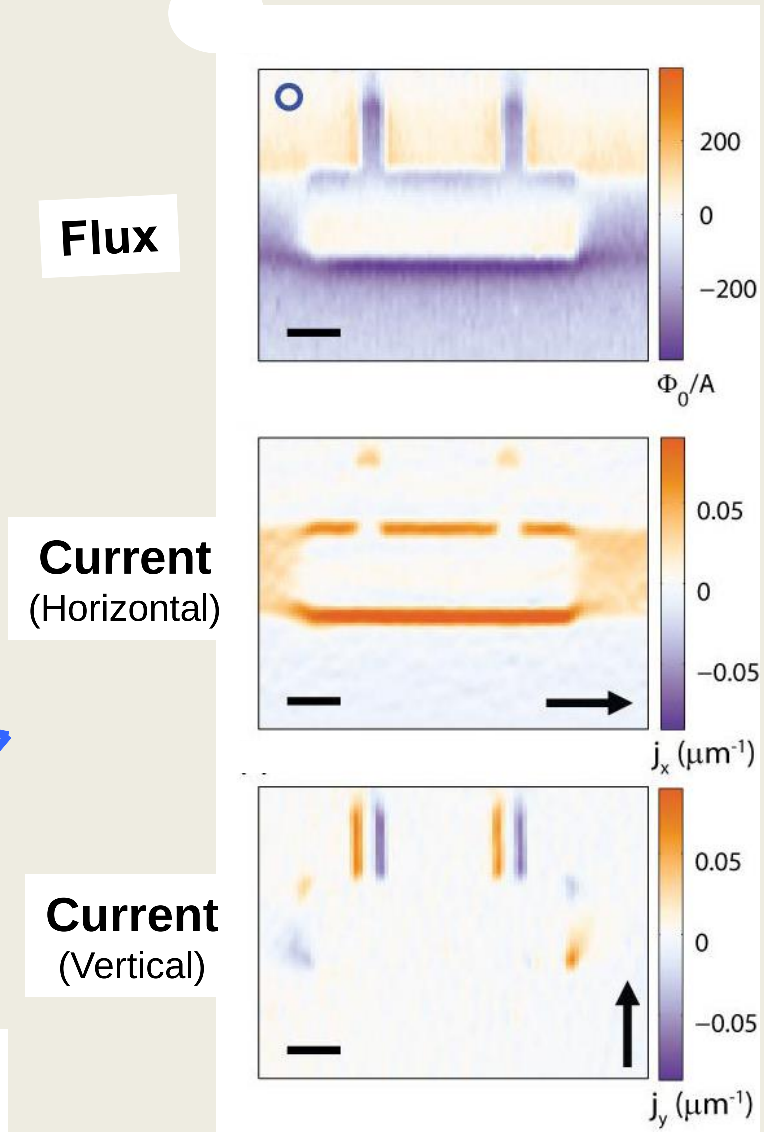
Lingjie Du

SQUID Imaging of InAs/GaSb Edge Modes

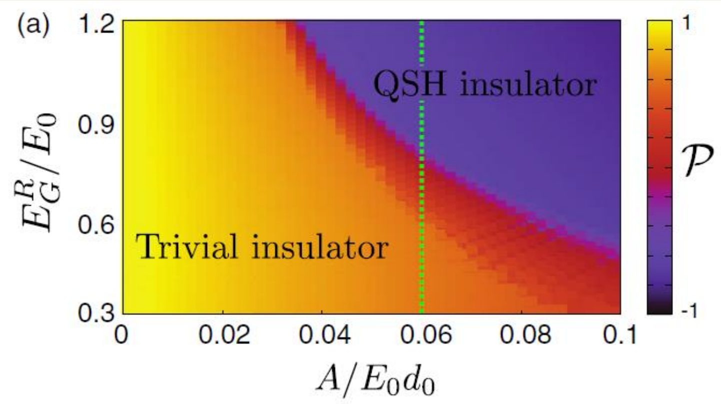
Stanford: Spanton, Moler
Rice: Lingjie Du, RRD
PRL 14







QSHE *vs.* Exciton Condensation

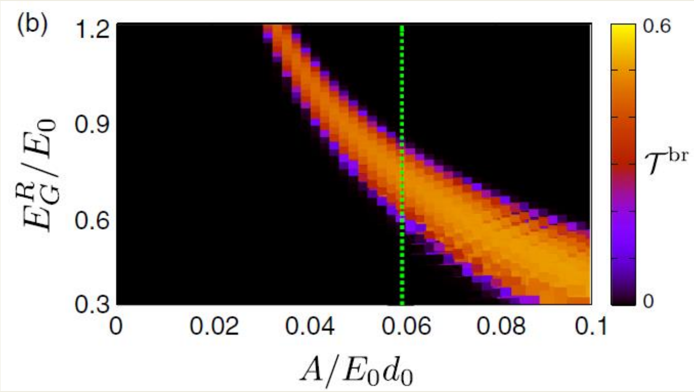


Coupling term between two layers

$$H_{12}(k) = A(\underbrace{k_x\sigma_3 + ik_y\sigma_0}_{\text{odd-parity}}) - i\underbrace{\Delta_z}_{\text{even-parity}}\sigma_2 - \Delta^{mf}(k)$$

A competition between even- and odd-parity exciton condensate

the parity of order parameter $\mathcal{P} = \dfrac{\Delta_{\rm tot}^{\rm even} - \Delta_{\rm tot}^{\rm odd}}{\Delta_{\rm tot}^{\rm even} + \Delta_{\rm tot}^{\rm odd}}$

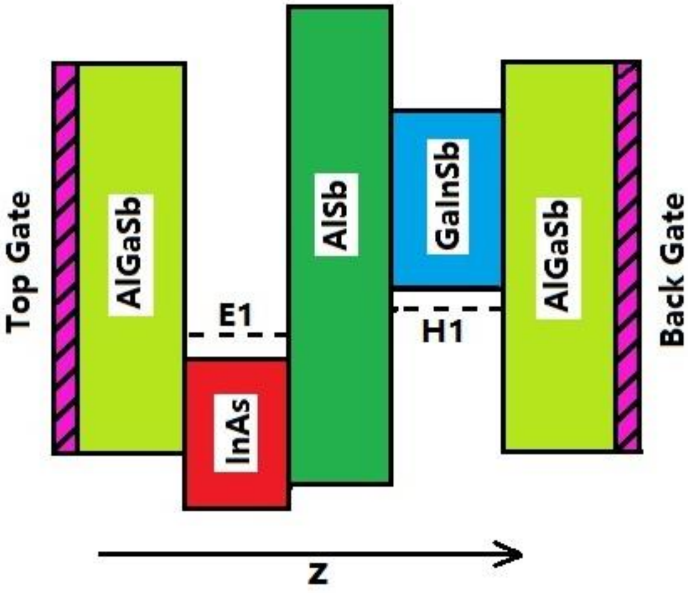


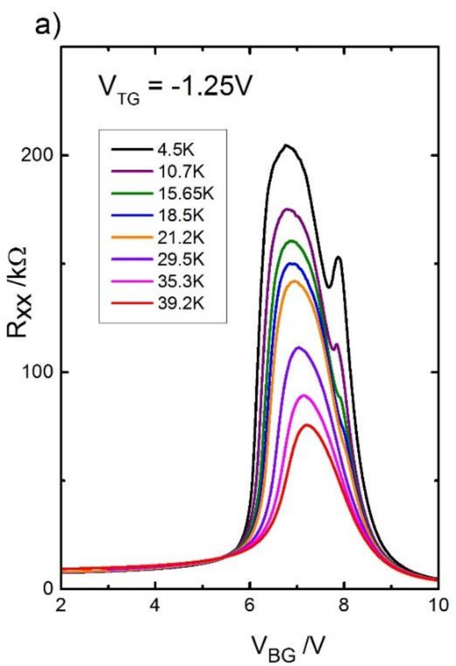
- For small A, topologically trivial *s*-wave exciton condensate phase
- For large A, topologically nontrivial QSH insulator phase with a *p*-wave exciton order parameter

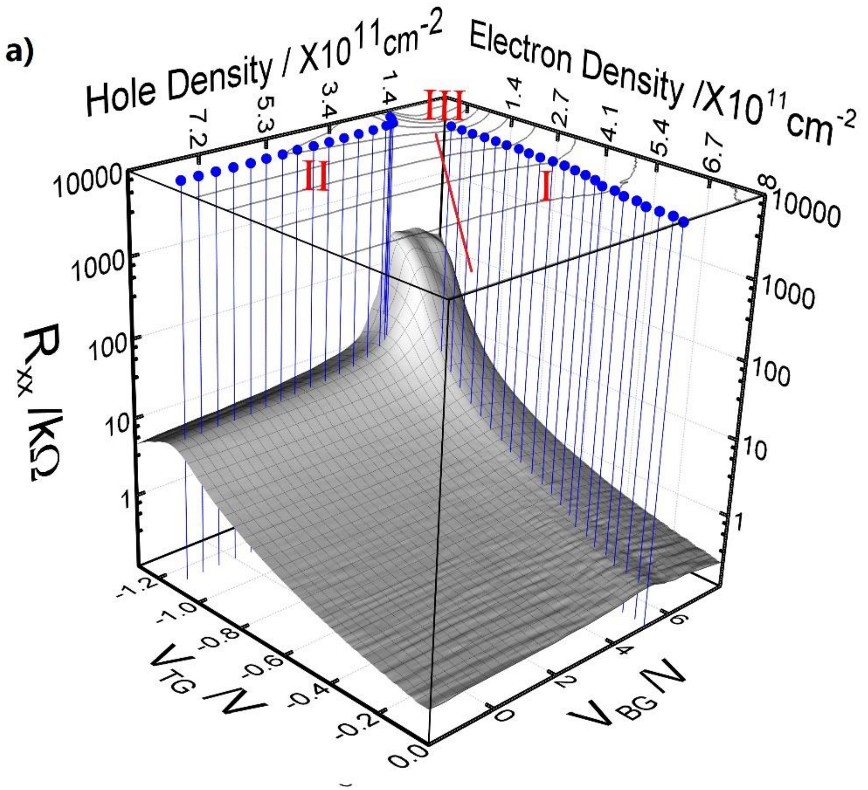
$$\mathcal{T}^{\rm br} = \frac{\Delta_{\rm tot}^{\rm br}}{\Delta_{\rm tot}^{\rm ts} + \Delta_{\rm tot}^{\rm br}}$$

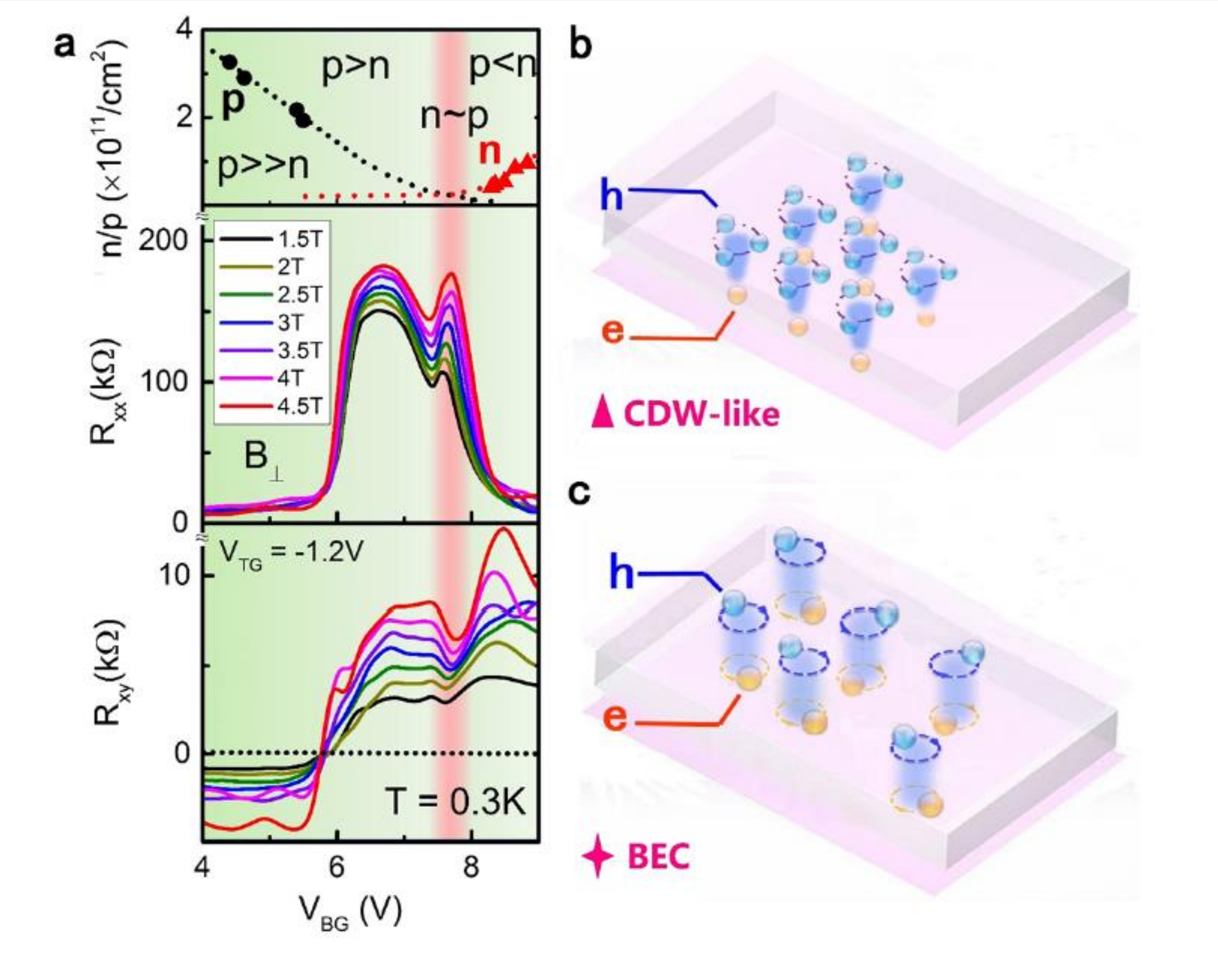
Phys. Rev. Lett.112, 176403(2014)

Exciton Condensation in e/h Bilayers with Middle Barrier





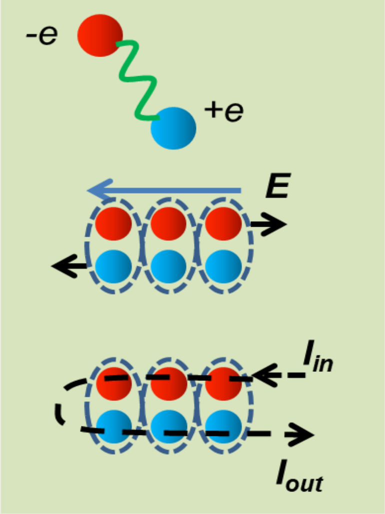




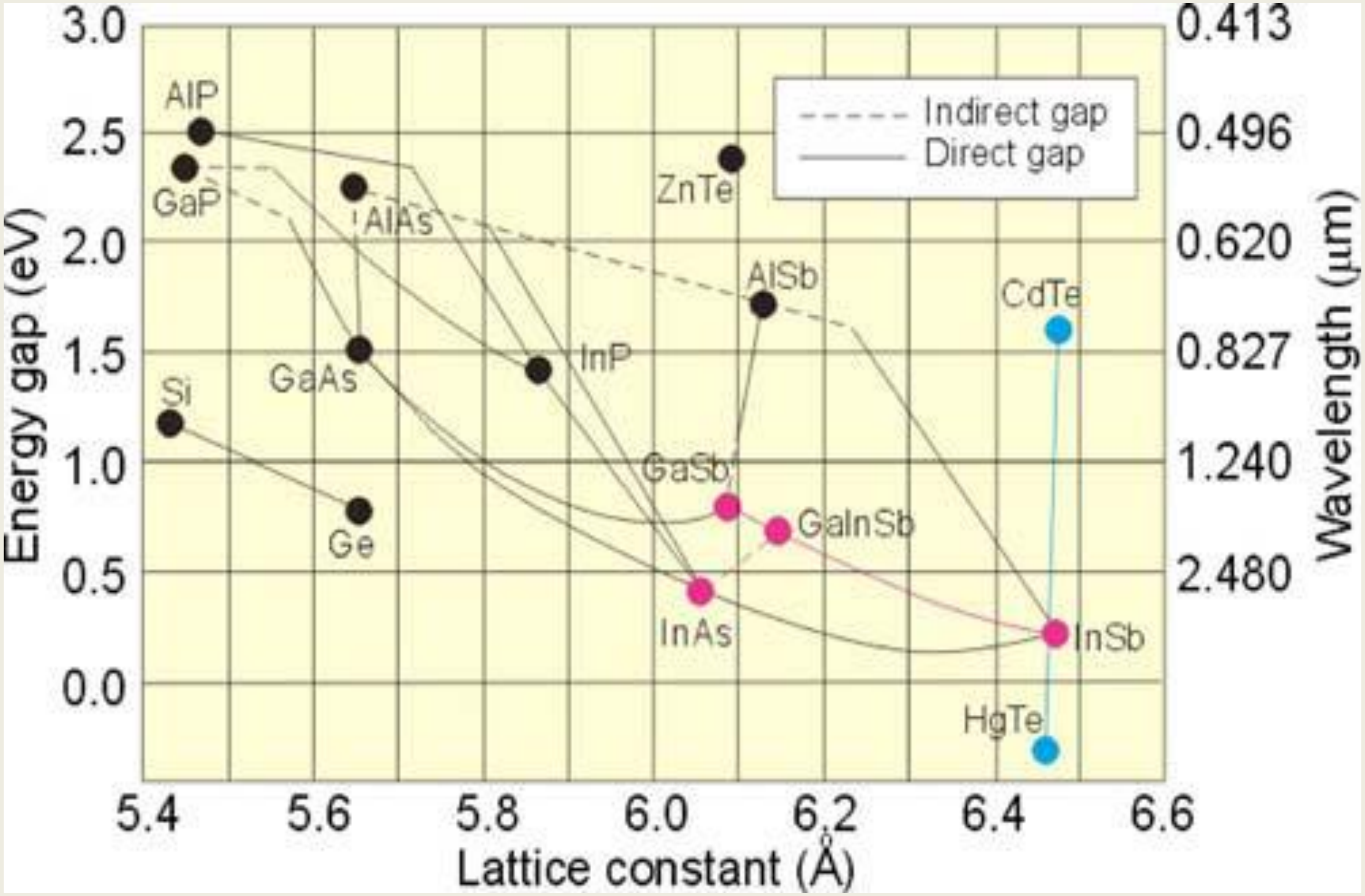
a
b
c
4
2
n/p (×10^{11}/cm^2)
p
p>>n
p>n
n~p
p<n
n
200
100
0
R_{xx}(kΩ)
1.5T
2T
2.5T
3T
3.5T
4T
4.5T
$B_\perp$
V_{TG} = -1.2V
10
0
R_{xy}(kΩ)
T = 0.3K
4
6
8
V_{BG} (V)
h
e
CDW-like
h
e
BEC

OUTLINES

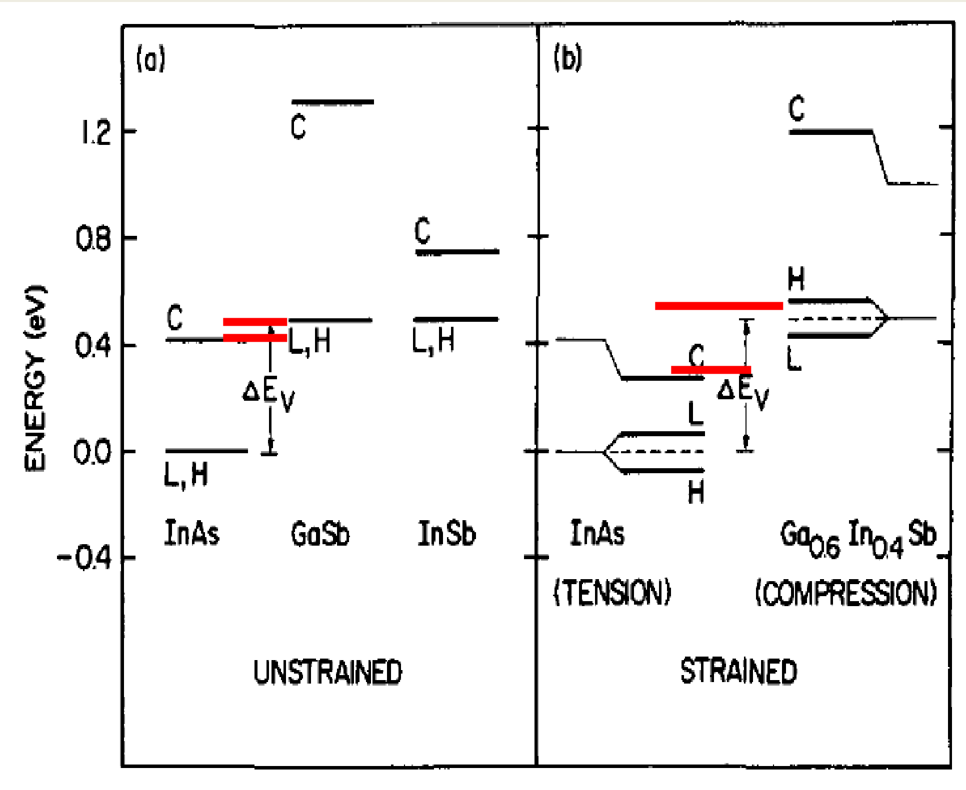
1. Topology and Physics
2. Materials and Devices
3. Exciton Insulator
4. **Large Gap TI**

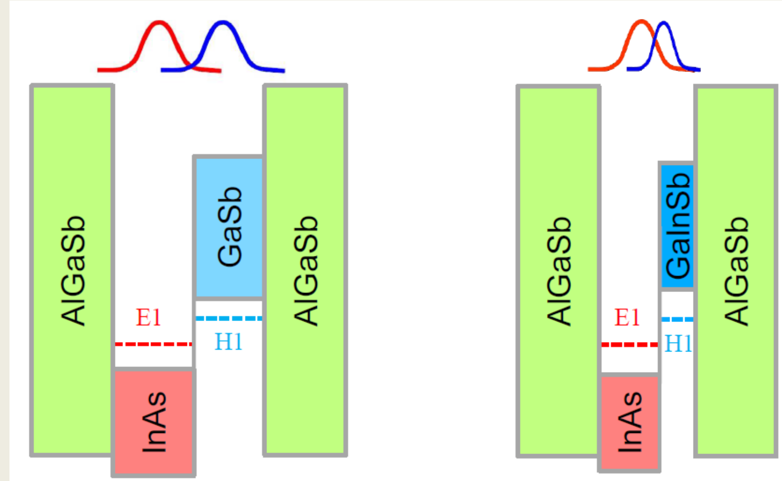


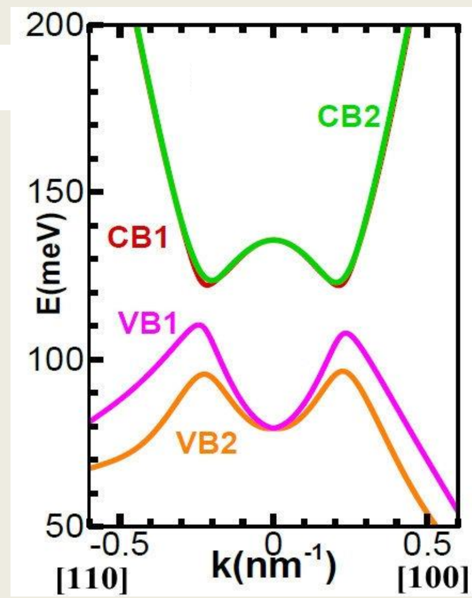
Strained QWS

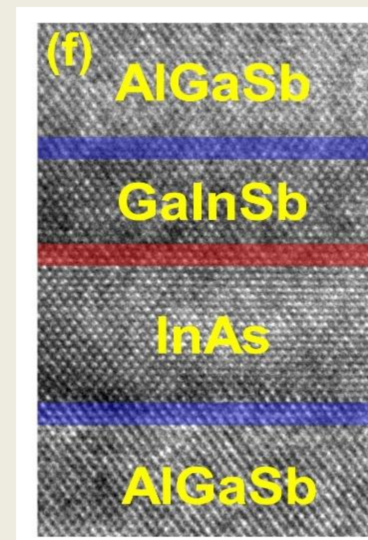


Strain Effects on the Band Structures



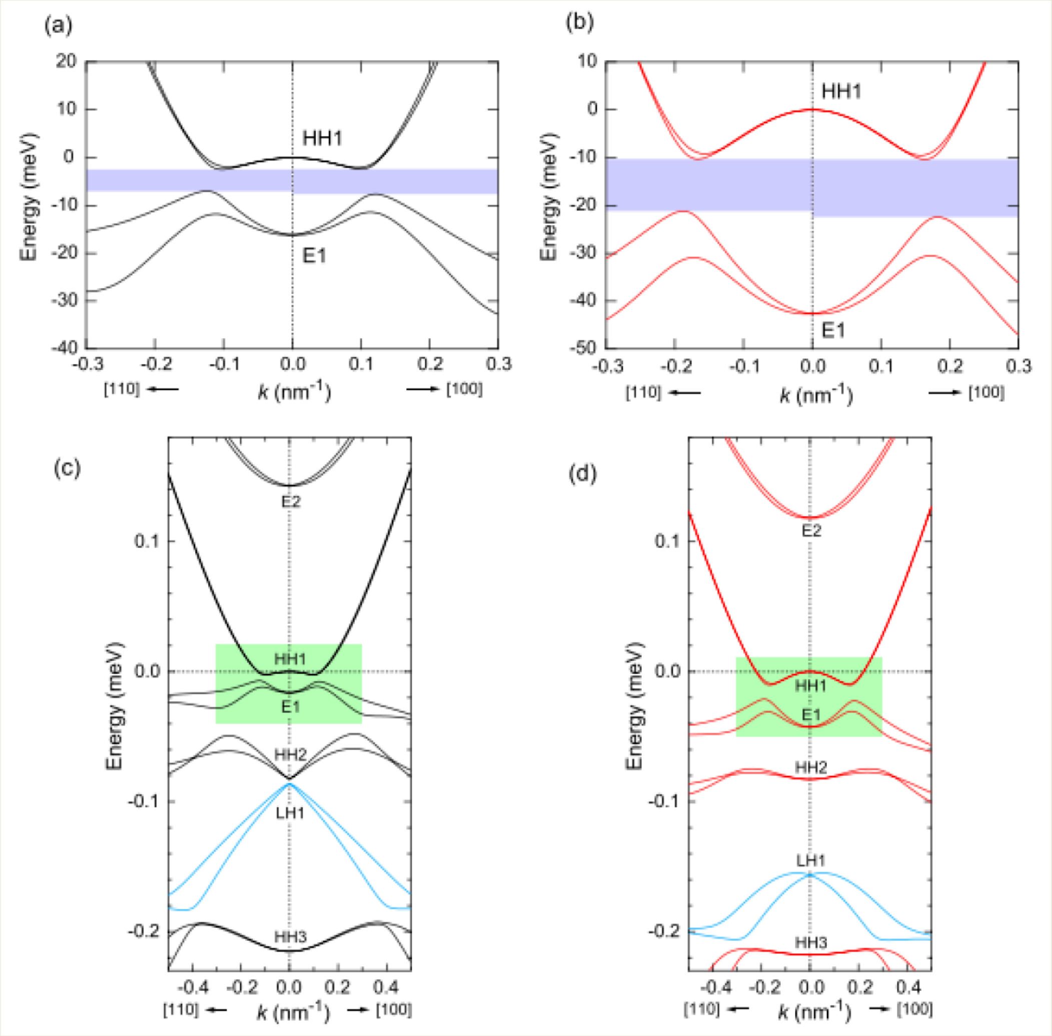






9.5 nm InAs/4 nm $Ga_{0.75}In_{0.25}Sb$

InAs/GaSb $InAs/In_{0.25}Ga_{0.75}Sb$

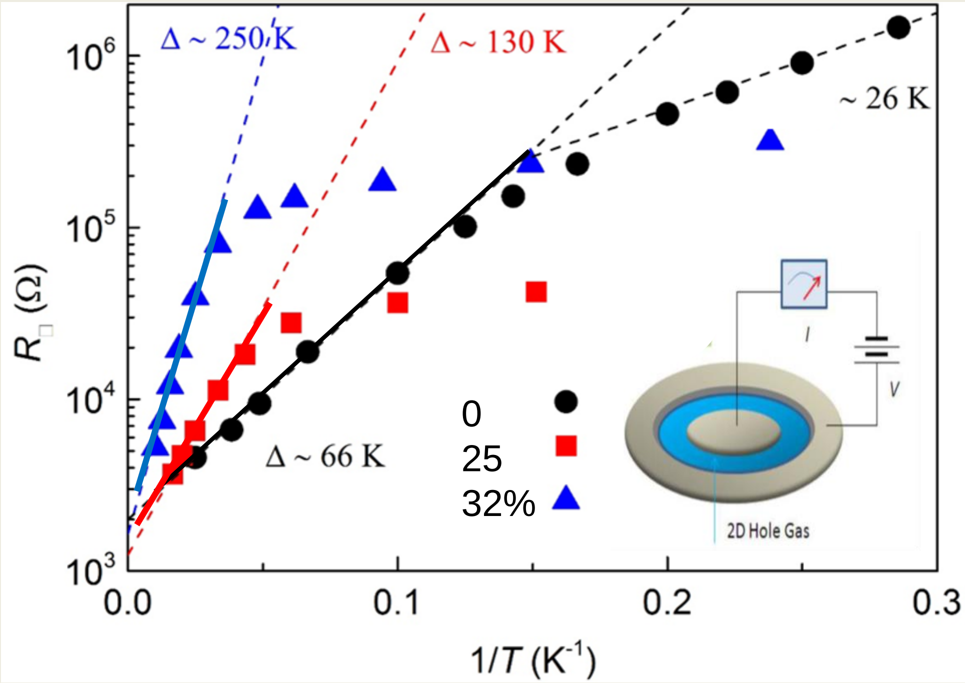


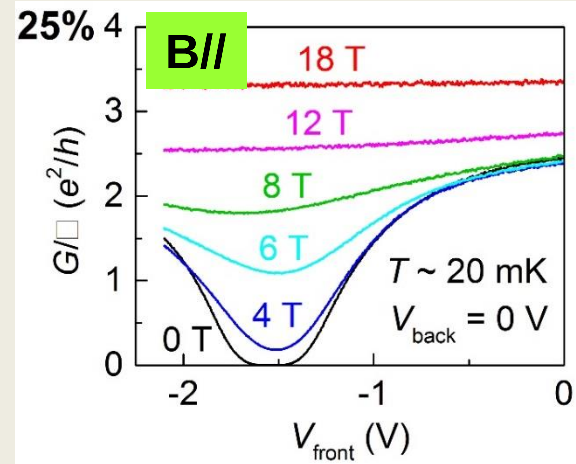
20% Indium
~ 1% strain in $In_xGa_{1-x}Sb$

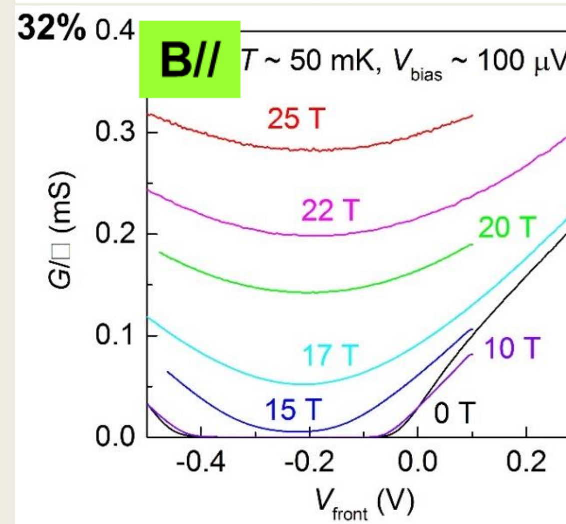
0 %	**60 K**
25%	**130 K**
32%	**250 K**
40%	**480 K**

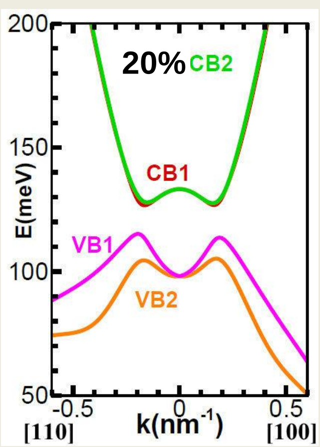
Akiho T, Couëdo F, Irie H, Suzuki K, Onomitsu K, Muraki K. Engineering quantum spin Hall insulators by strained-layer heterostructures[J]. Applied Physics Letters. 2016,109(19):192105.

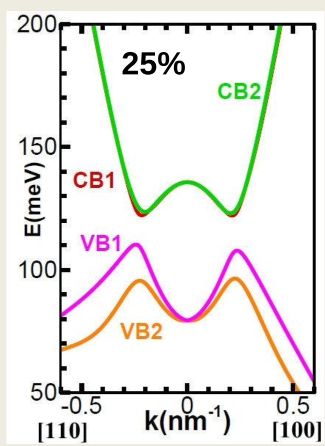
Enhanced Bulk Hybridization Gaps

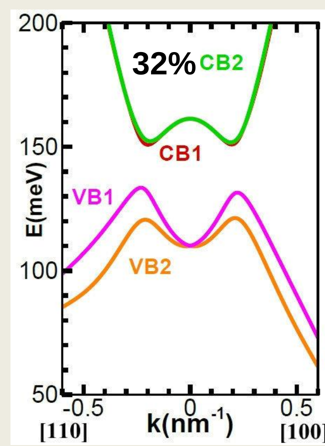


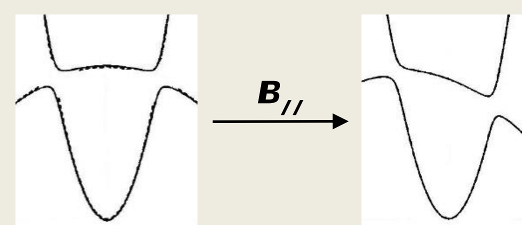




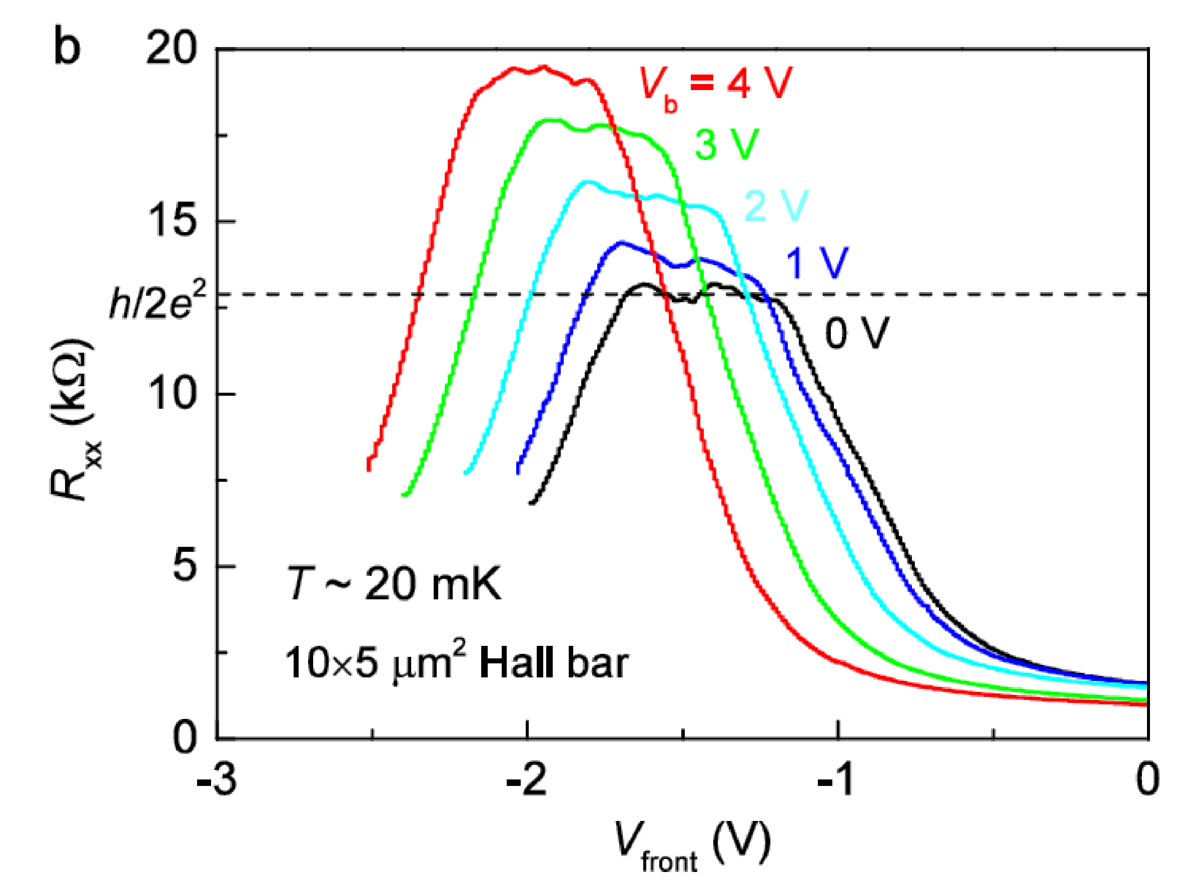






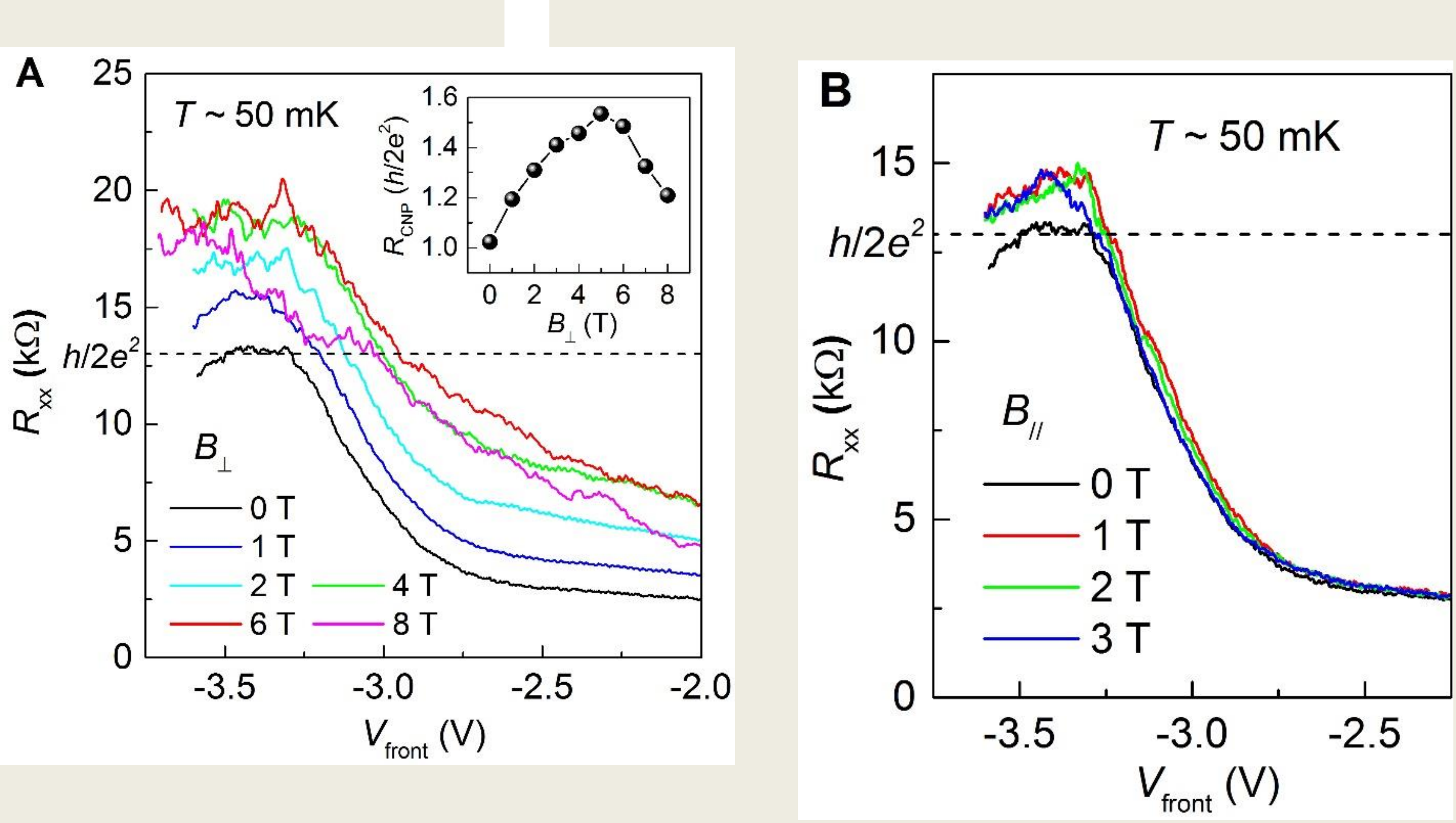


Quantized Edge Transport in 10 um Length



Quantized in a 10um Hall Bar

TRS Protected Helical Edge States



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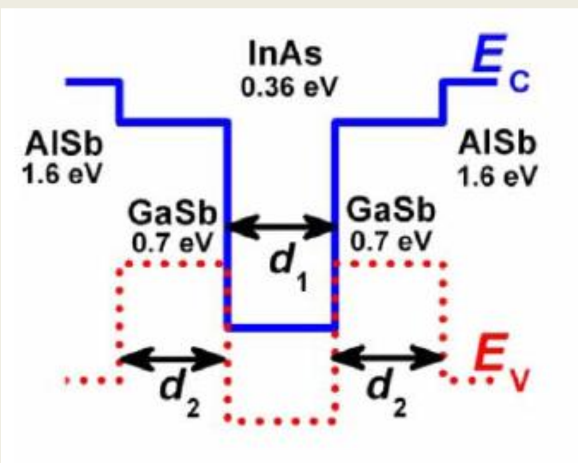
SCIENCE ADVANCES | RESEARCH ARTICLE April 2018

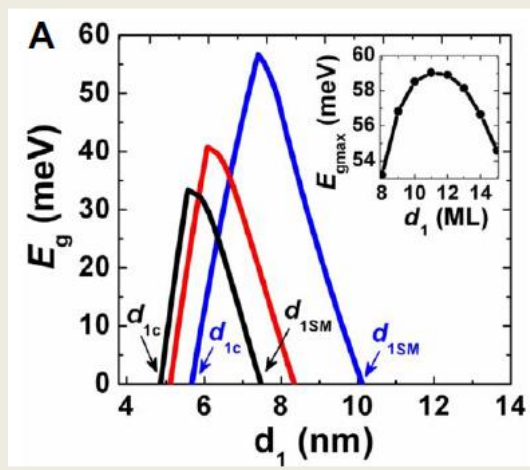
CONDENSED MATTER PHYSICS

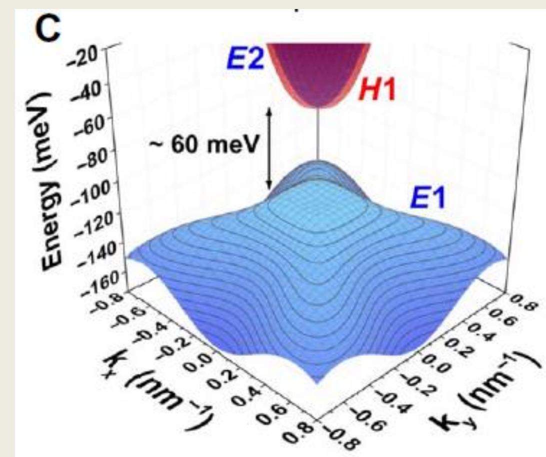
Quantum spin Hall insulator with a large bandgap, Dirac fermions, and bilayer graphene analog

Sergey S. Krishtopenko[1,2] and Frédéric Teppe[1]*

All based on InAS/GaSb and InAs/InGaSb

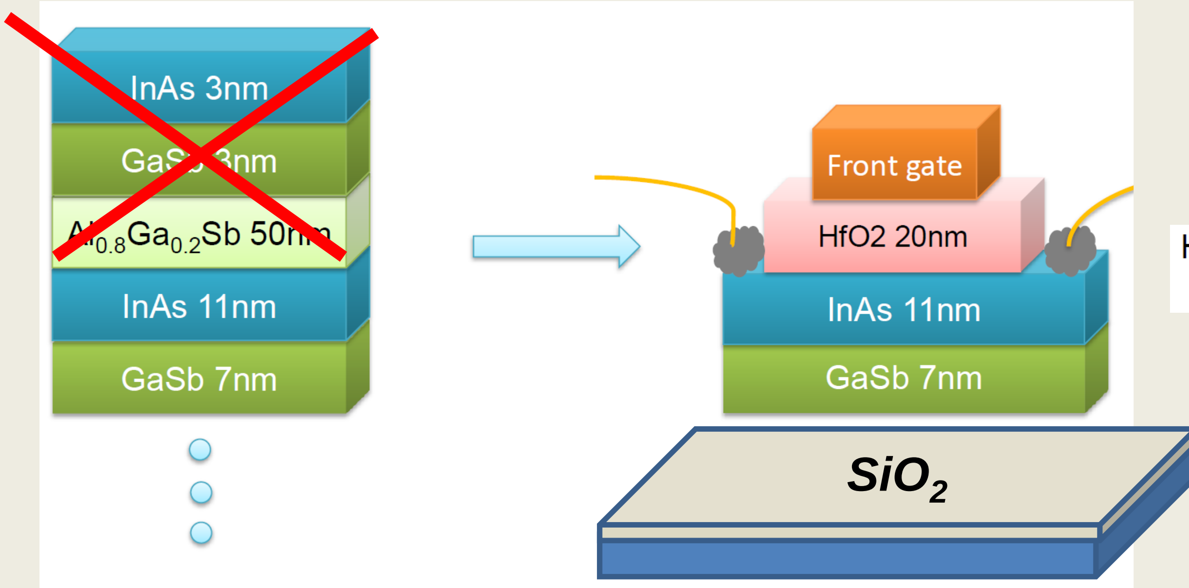




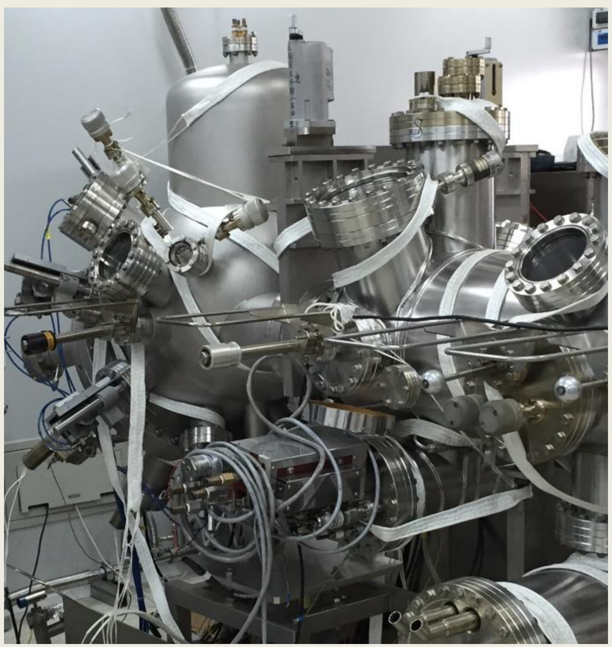


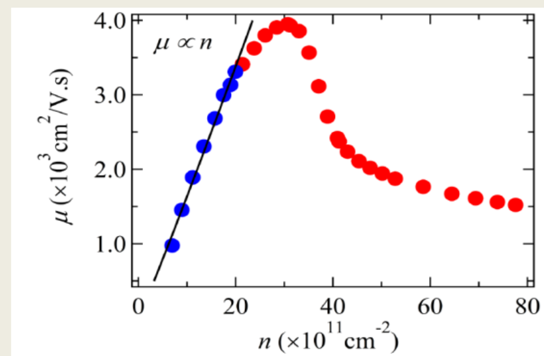
Gap > 50 meV

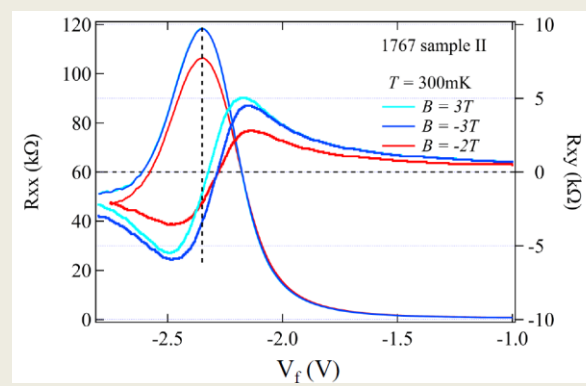
Large Fermi velocity



Hall bar geometry
75µm × 25µm







Compatible with III-V CMOS Technology

Nano Lett. 2012, 12, 3592–3595

NANO LETTERS

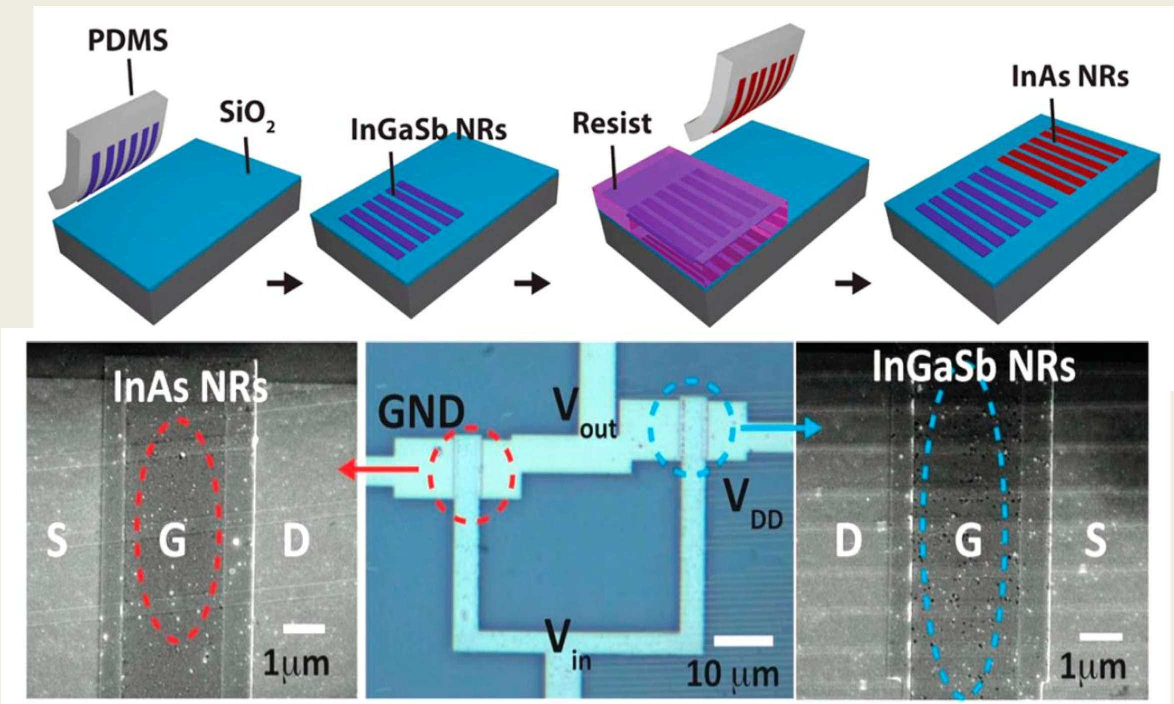
Letter

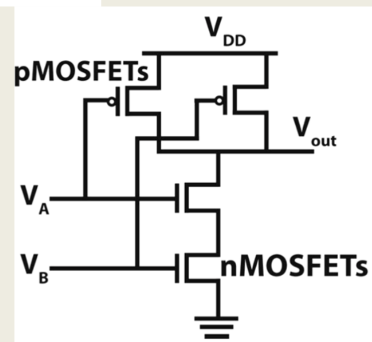
pubs.acs.org/NanoLett

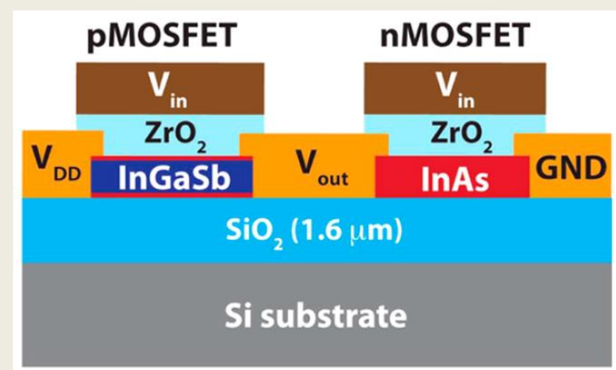
III–V Complementary Metal–Oxide–Semiconductor Electronics on Silicon Substrates

Junghyo Nah,[†,‡,§,∥,⊥] Hui Fang,[†,‡,§,⊥] Chuan Wang,[†,‡,§] Kuniharu Takei,[†,‡,§] Min Hyung Lee,[†,‡,§,#] E. Plis,[○] Sanjay Krishna,[○] and Ali Javey[†,‡,§,*]

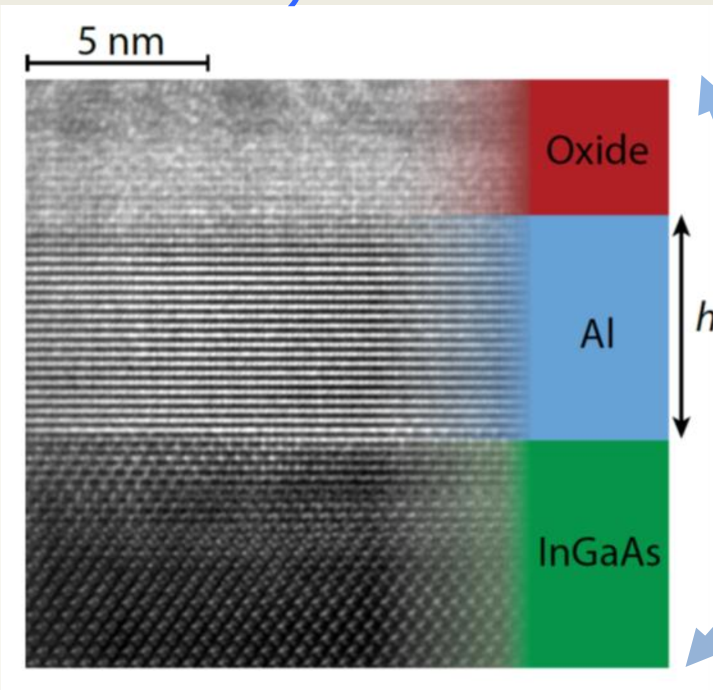
[†]Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720, United States



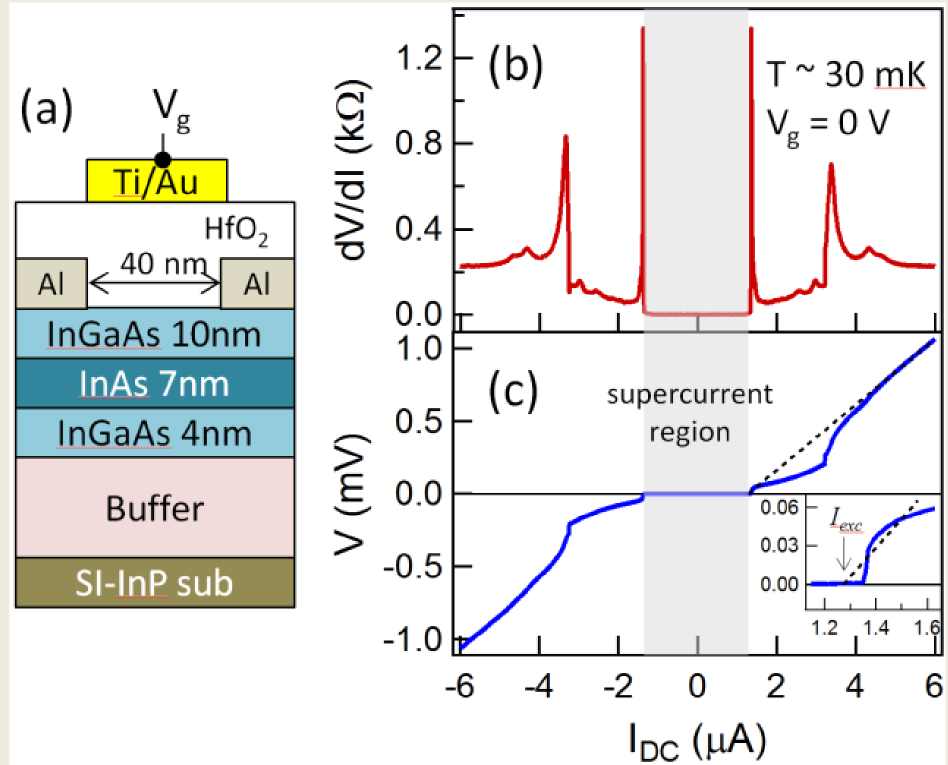




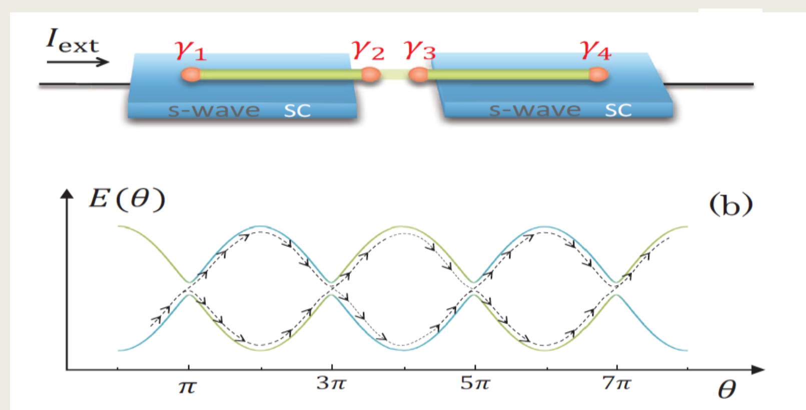
Marcus, Palmstrøm groups



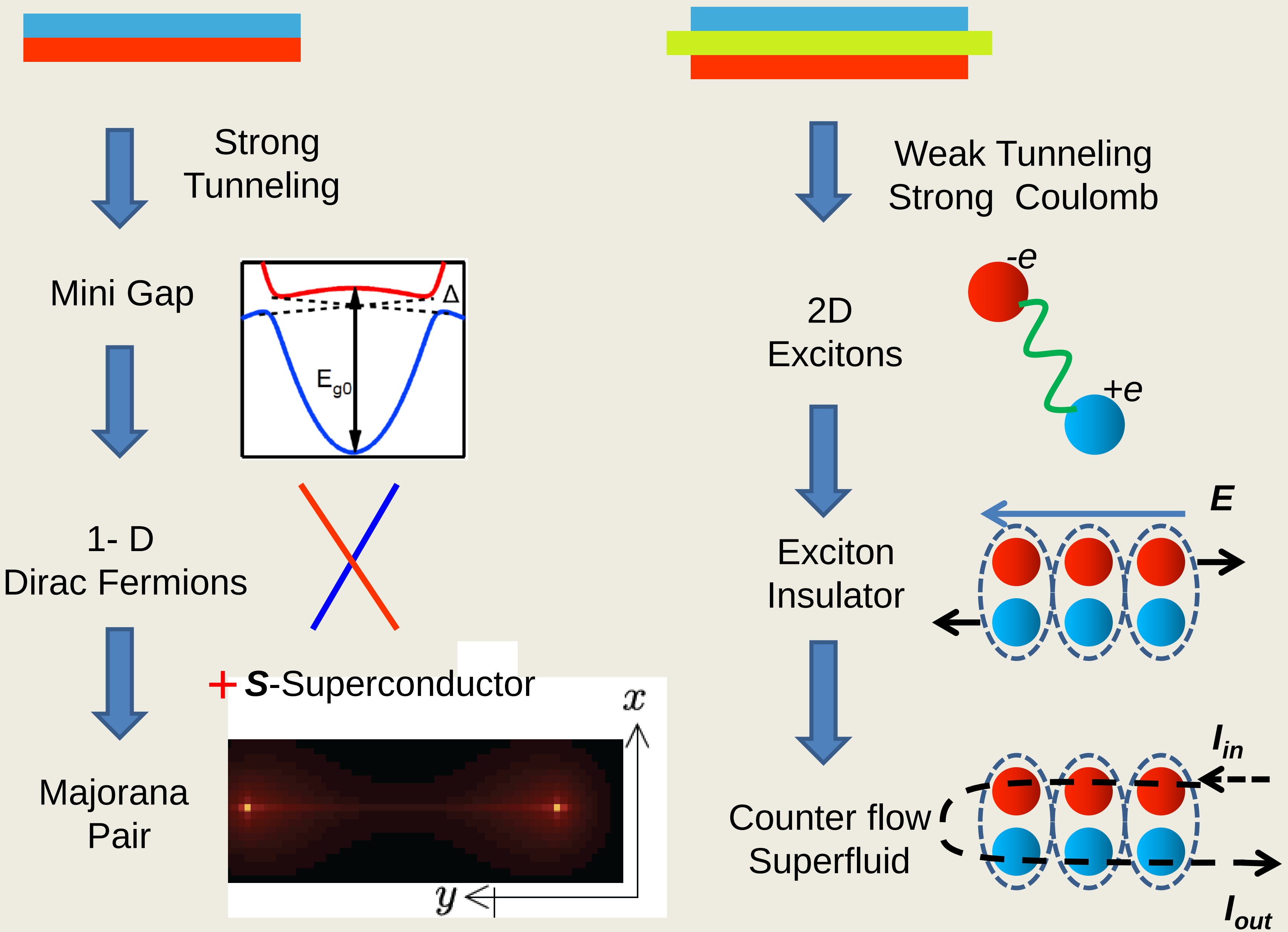
Hard Gap



Our Group



3. Double-Layer Excitonic Condensations



SUMMARY

1) Exciton Insulator observed
   –equilibrium excitonic condensation

2) Topological EI when there is no tunneling
   barrier – quantum spin Hall edge states

3) Large gap TI is within reach

4) Next : Majorana platform

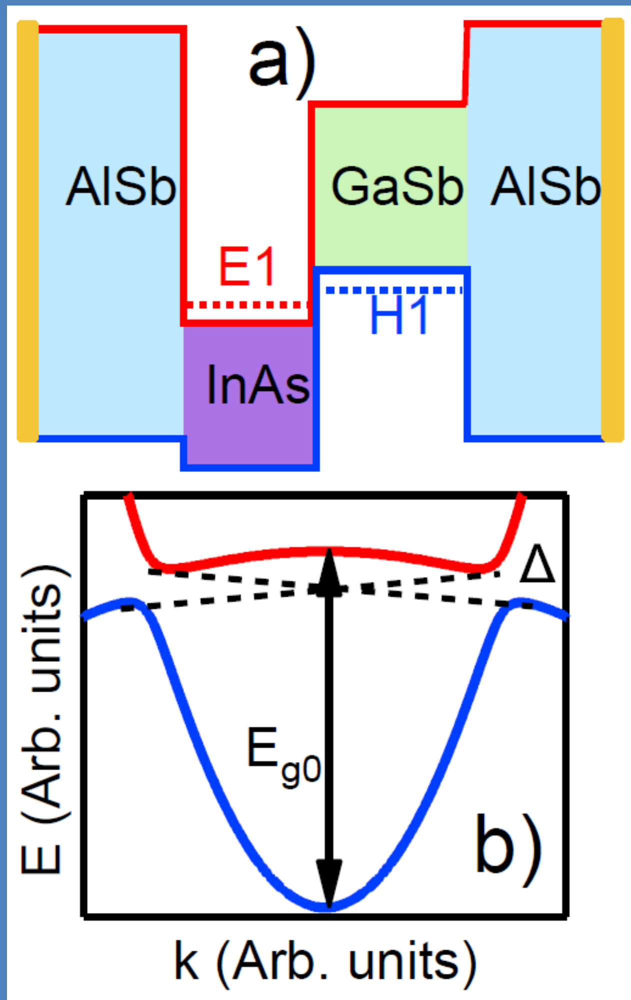
A clean laboratory for
electron/hole many-particle physics

THANKS

beyond!

1. Materials: Strained-Layer InAs/GaInSb
2. Large-Gap QSHI
3. Double-Layer Excitonic Condensation

6.1 A Family



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

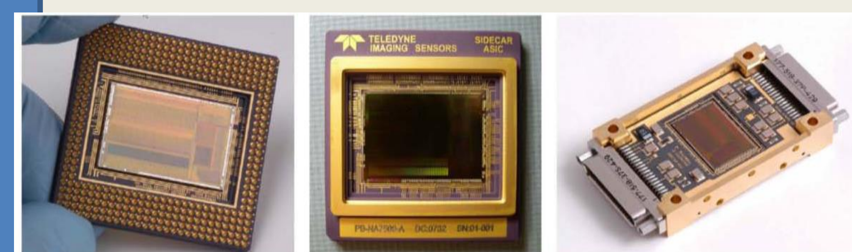
1. **Band parameter**

   $\Delta E = E1 - H1$

   tuned by width, x, gates

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

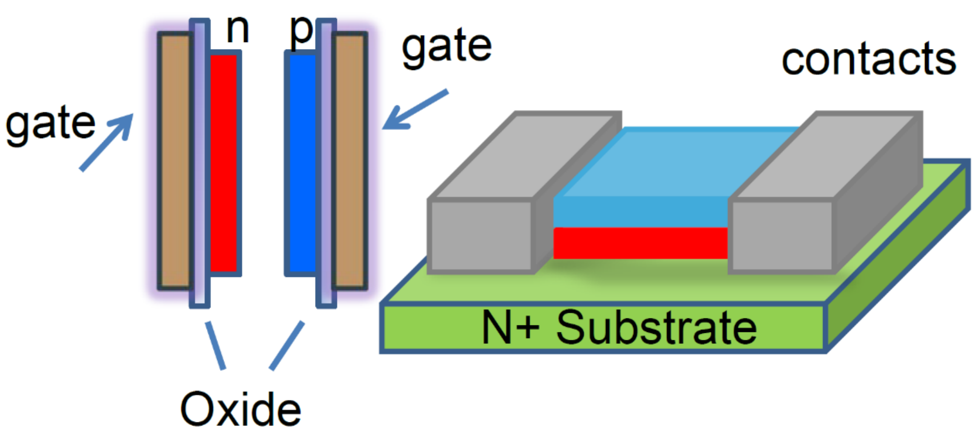
   Tunneling mix e-h and opens a gap at finite *k*-vector

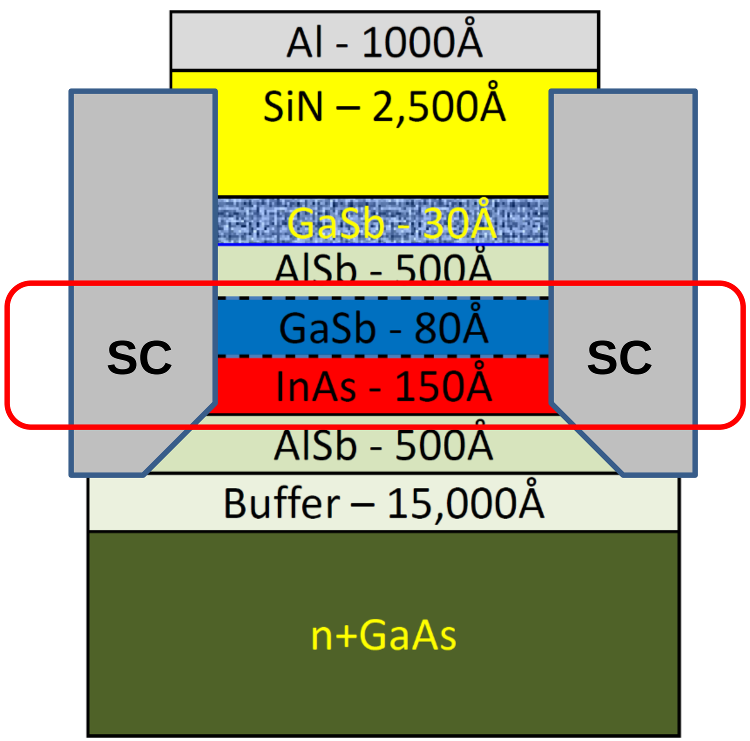


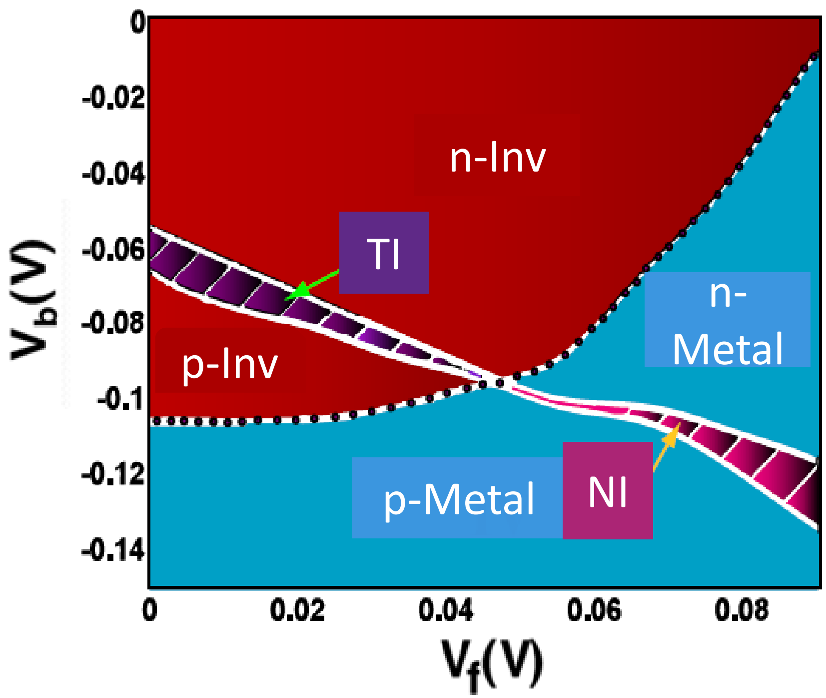
Infrared Detectors

TELEDYNE TECHNOLOGIES Everywhereyoulook

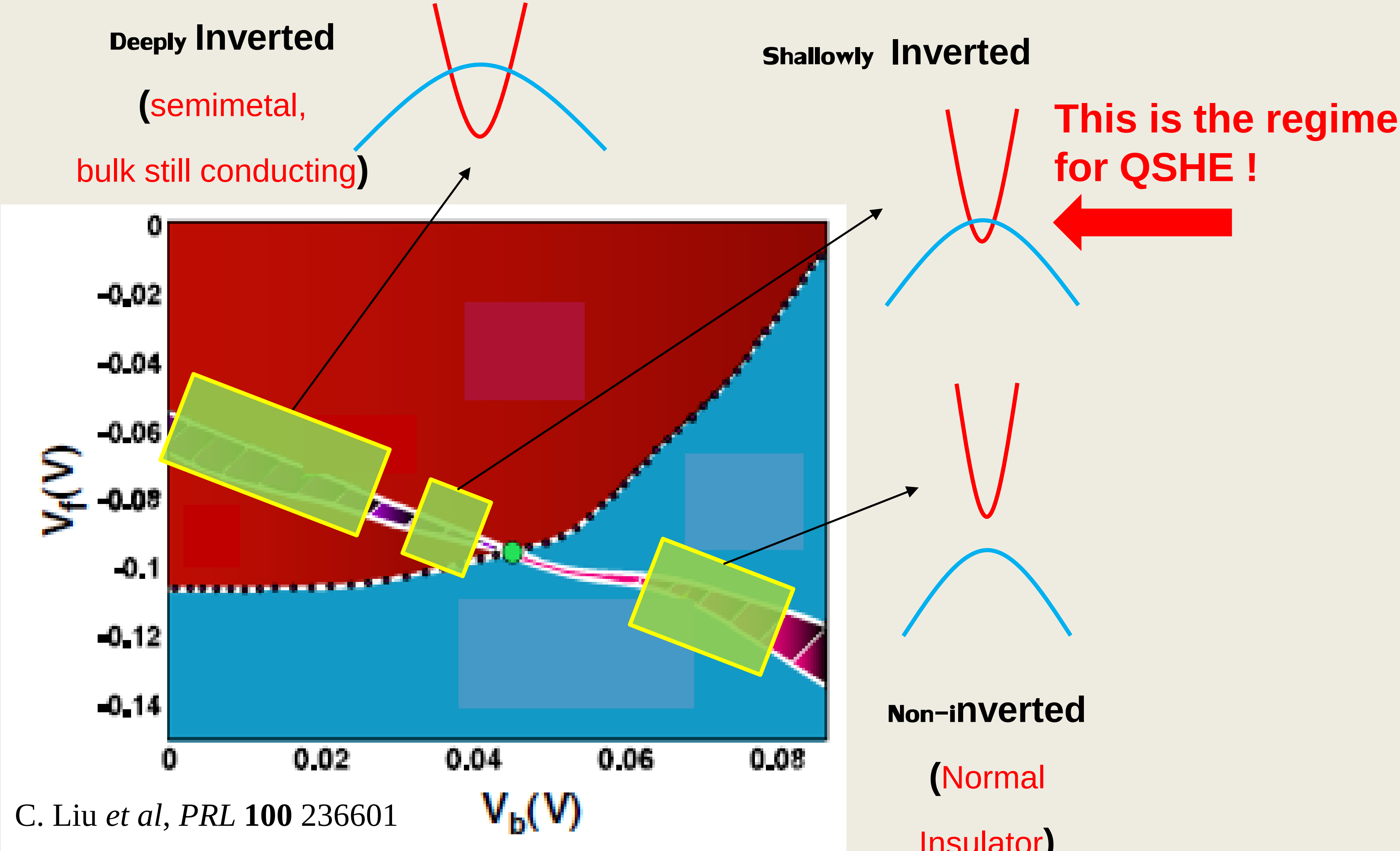
Wafer and Device







Three Regimes of InAs/GaSb System

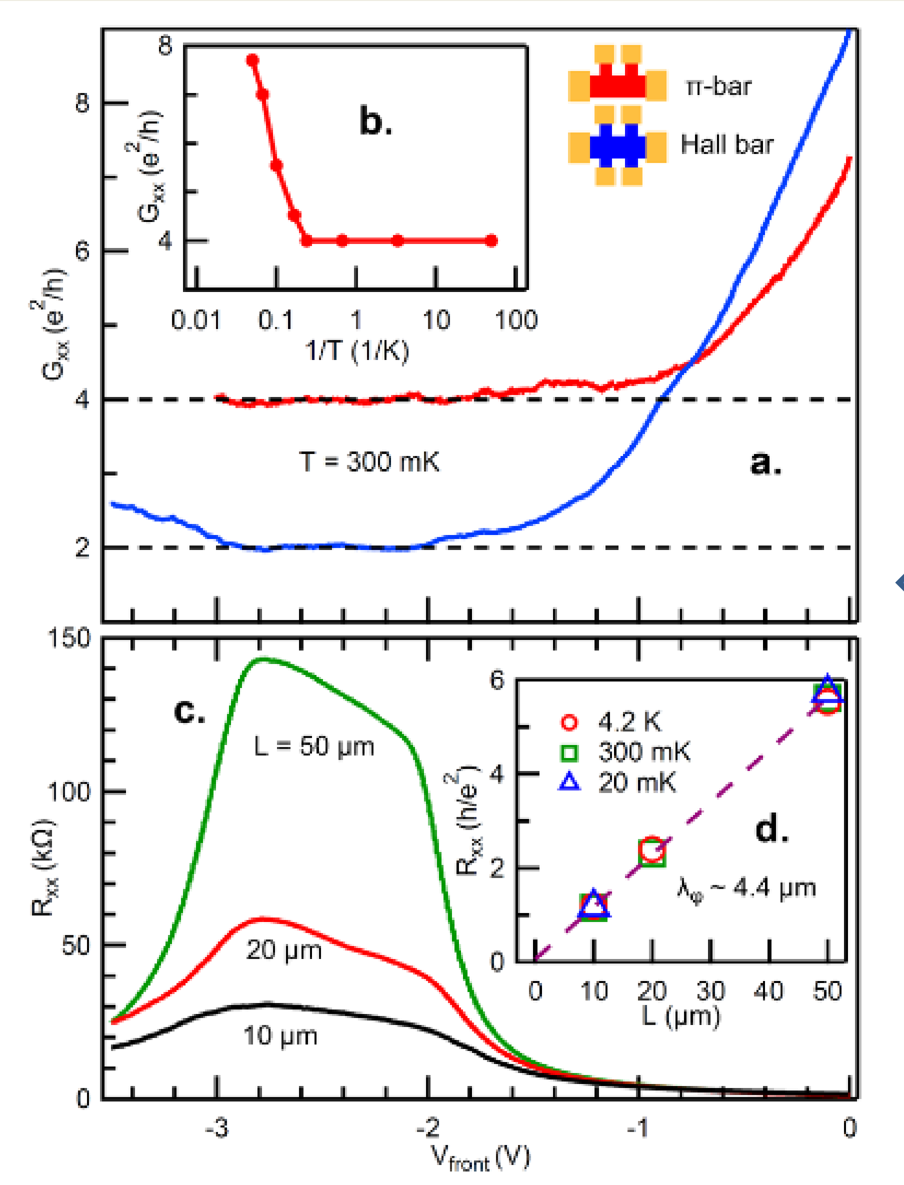


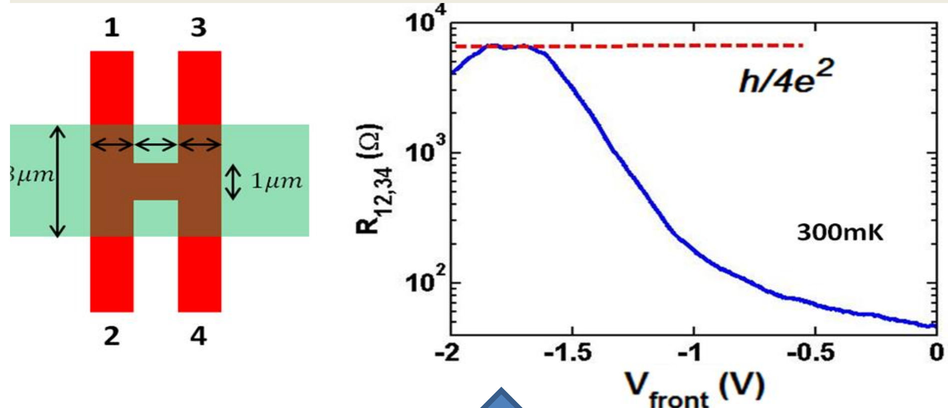
C. Liu *et al*, *PRL* **100** 236601 (2008)

Phase Diagram

Quantum Spin Hall Insulators (QSHIs)

InAs/GaSb QWs in Shallowly Inverted Regime





Small sample

Larger samples:

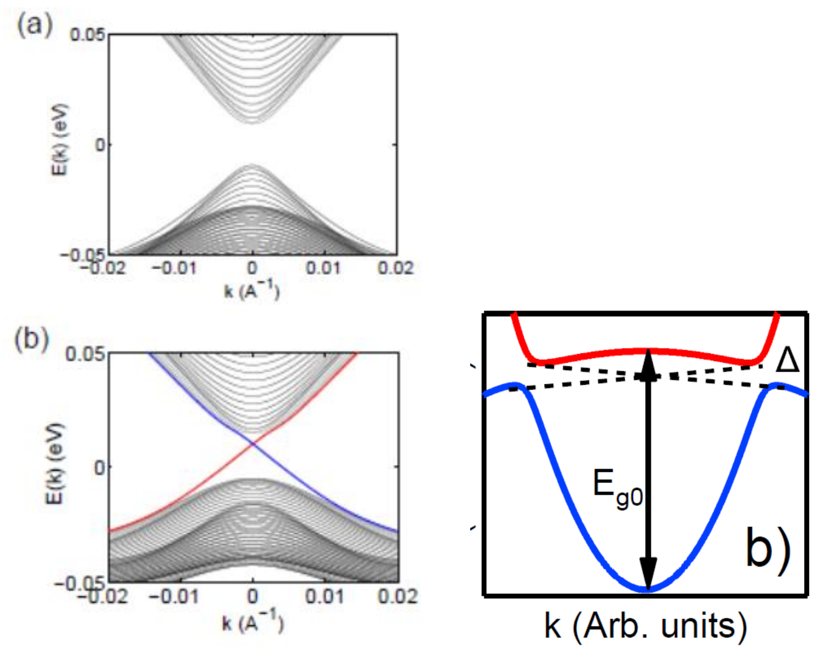
Coherent length ~ 4 μm

Some backscattering

L. Du *et al, PRL* 114 096802 (2015)

Properties of InAs/GaSb Edge States

* Quantized conductance for small samples
* Non-quantized conductance for large samples
* Conductance does not change under high B//



HgTe

5 x10^5 m/s

$$\gamma = e^2/\, \upsilon_F\, \varepsilon$$

•Low velocity of edge modes

$\upsilon_F \sim 2\ x10^4\ m/s$

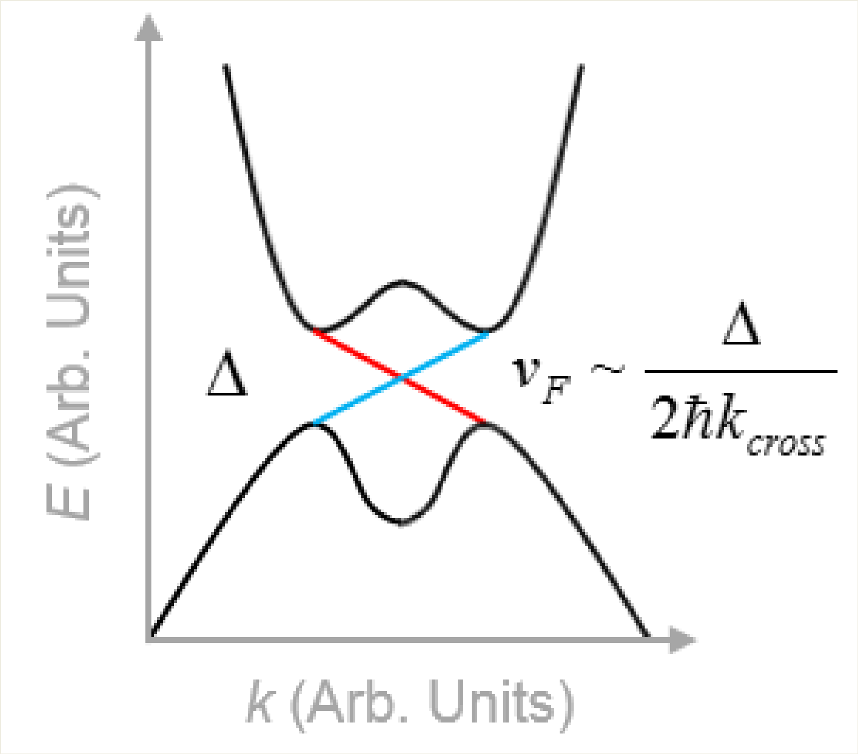
$k_F \sim 1\ x\ 10^6/cm$

•Extreme. long scattering time

$\tau=\lambda/\upsilon_F = 4\mu m/(2x10^4 m/s) \sim 200\ ps$

•Tunable mode dispersion

WHY Large-gap 2D Topological Insulators

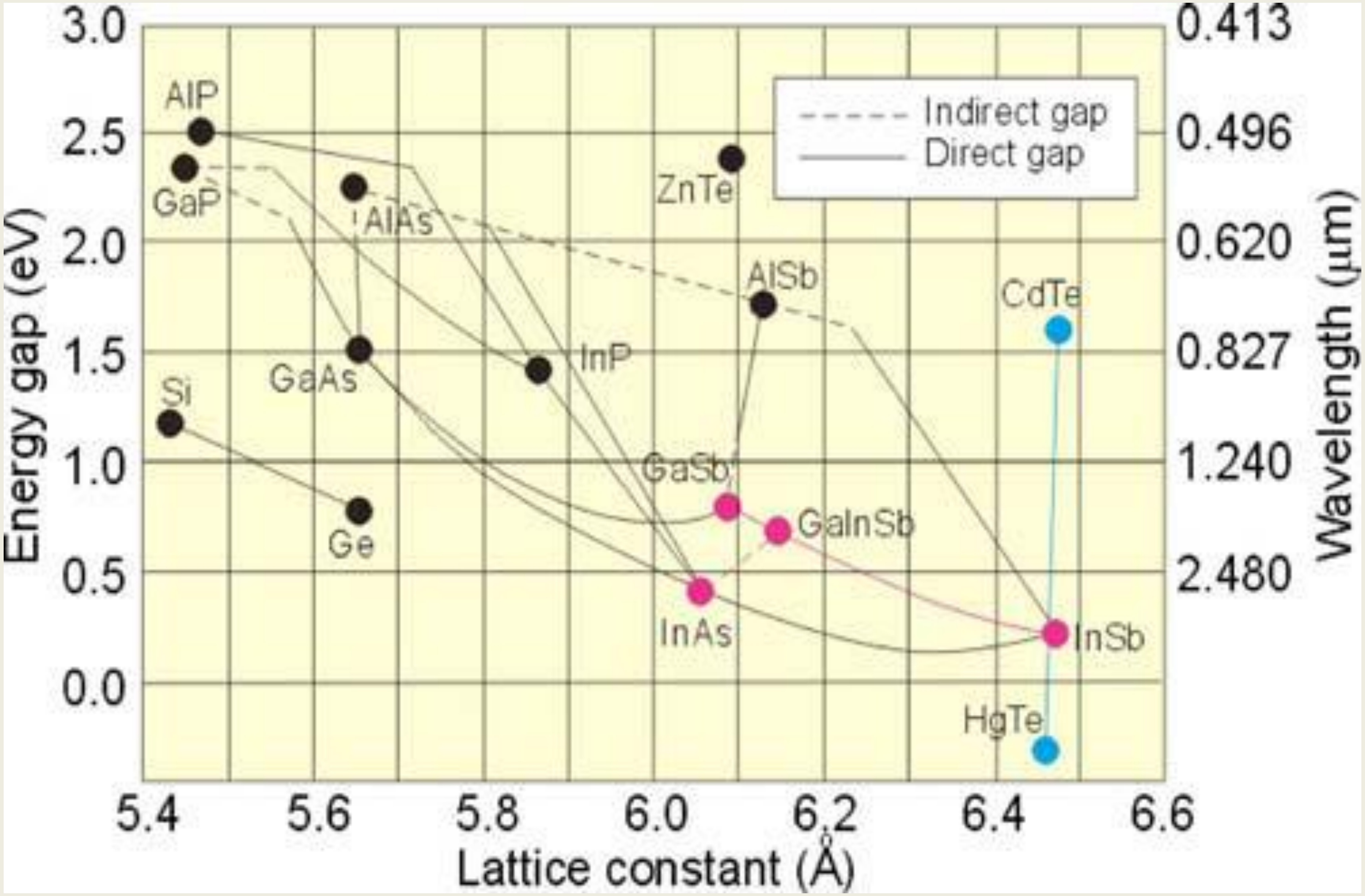


- Recover single particle properties

"Plain Vanilla QSHI"

- More insulating bulk gaps
- Long coherent length

Strained QWS



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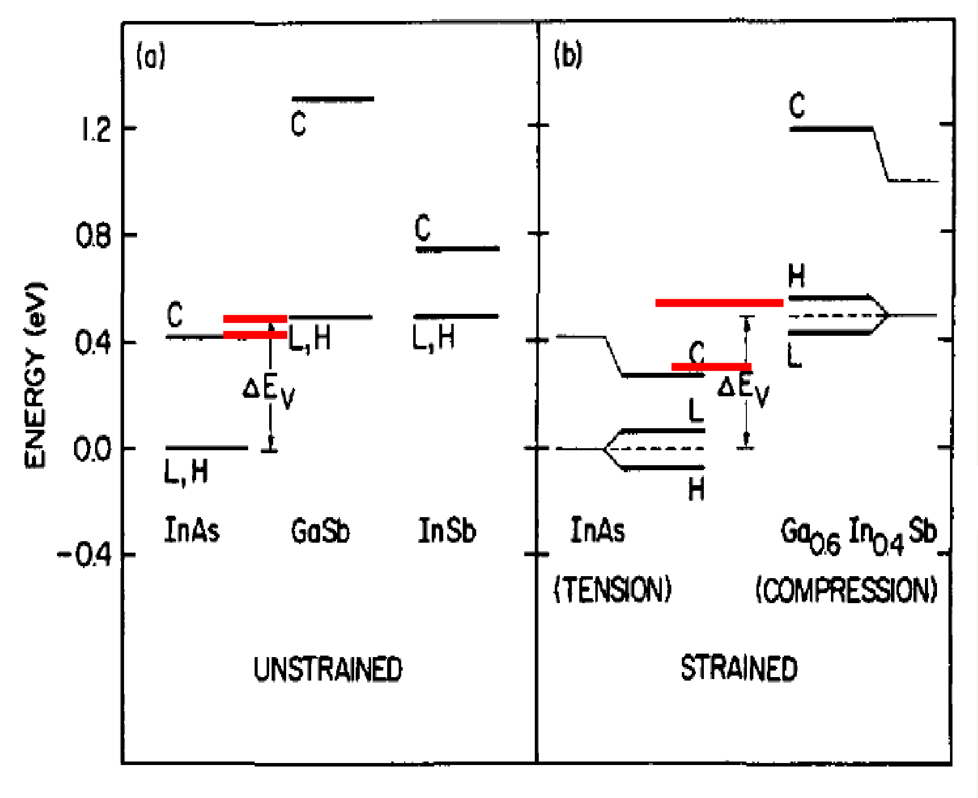

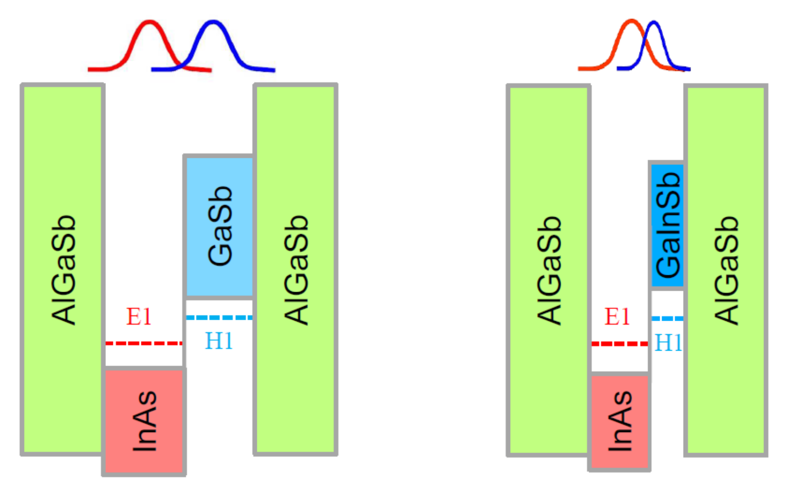

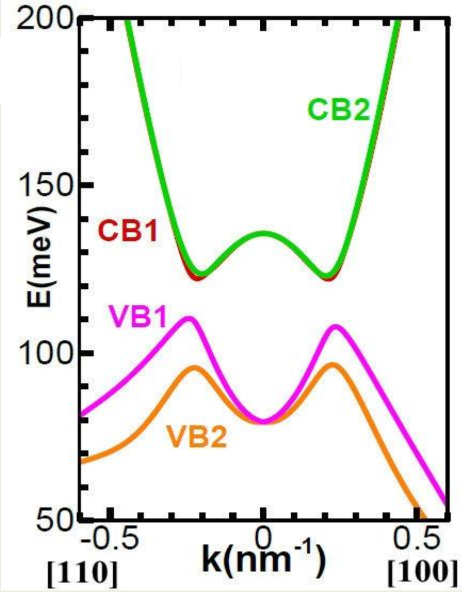

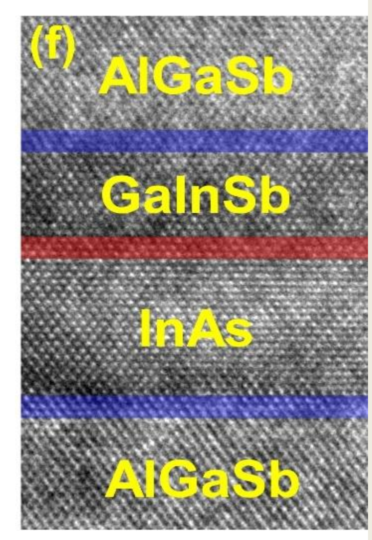

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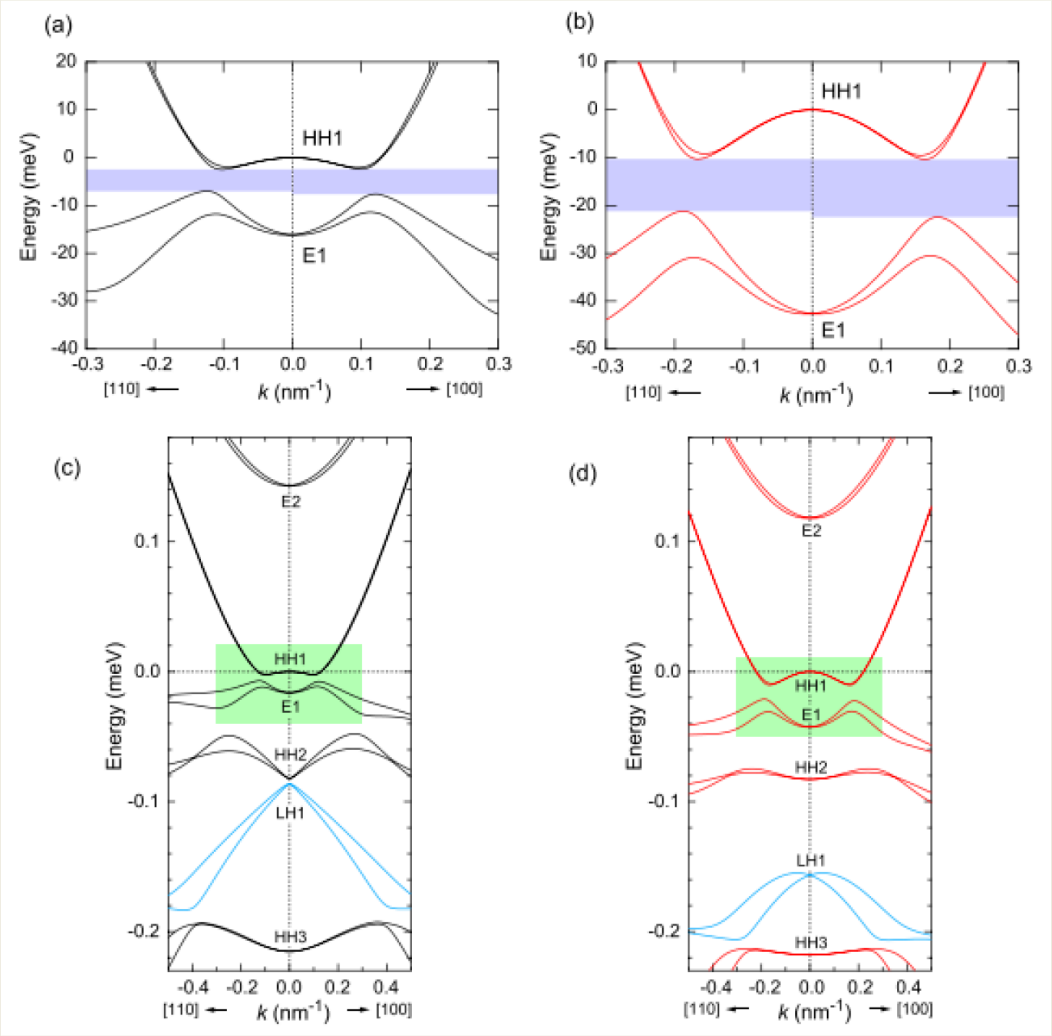
InAs/GaSb   InAs/$In_{0.25}Ga_{0.75}Sb$



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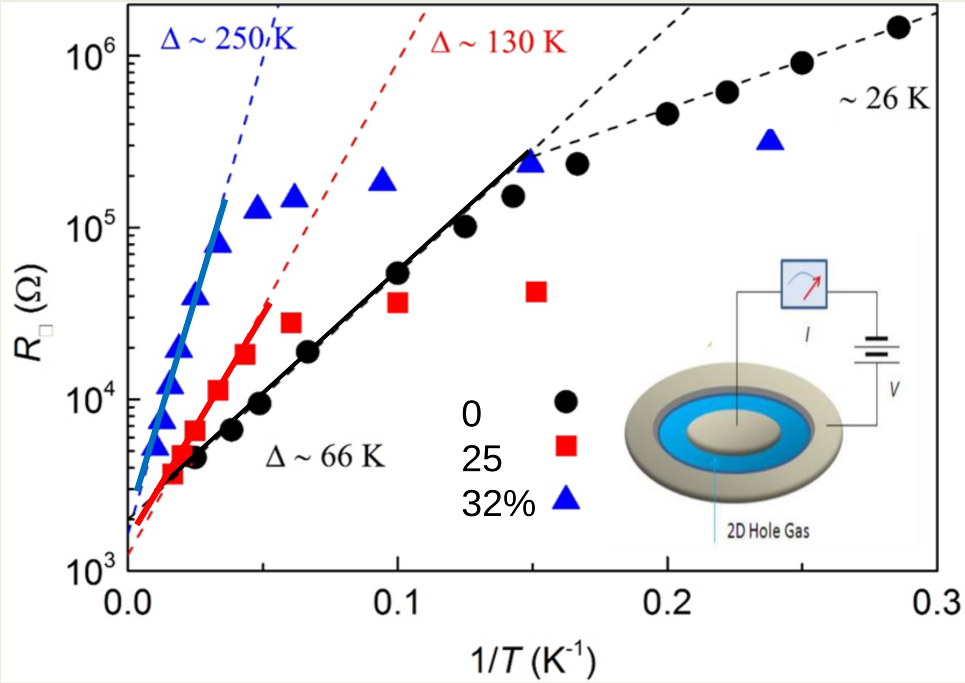
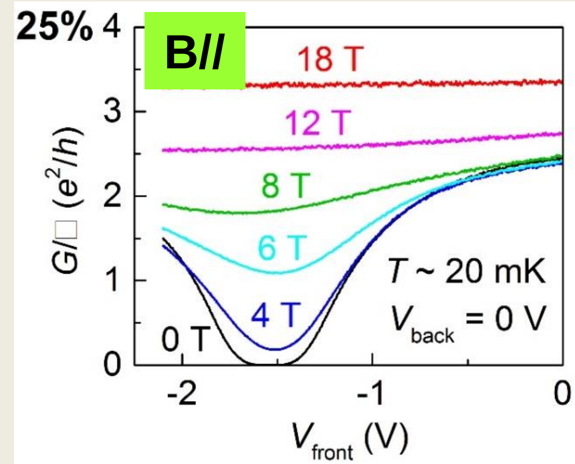
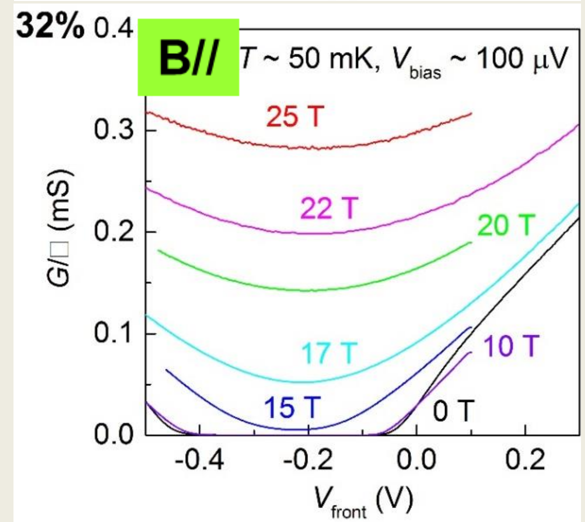
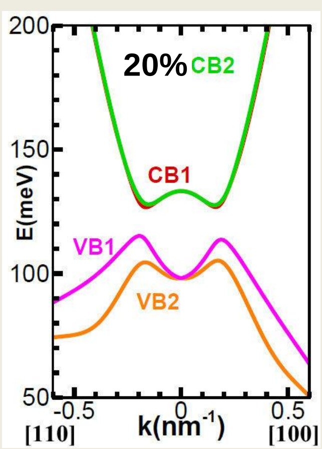
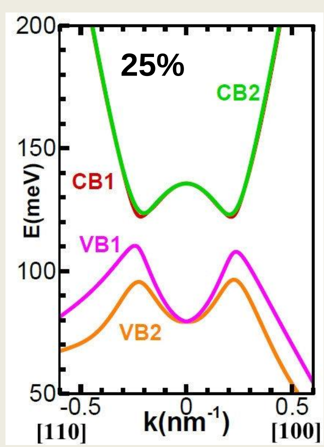
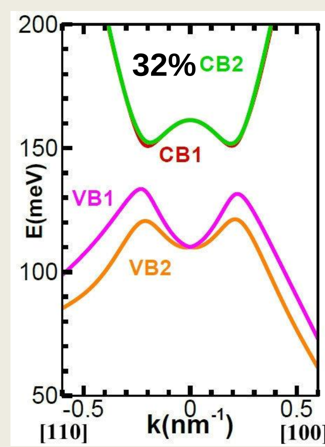


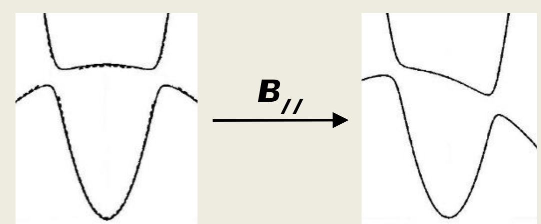




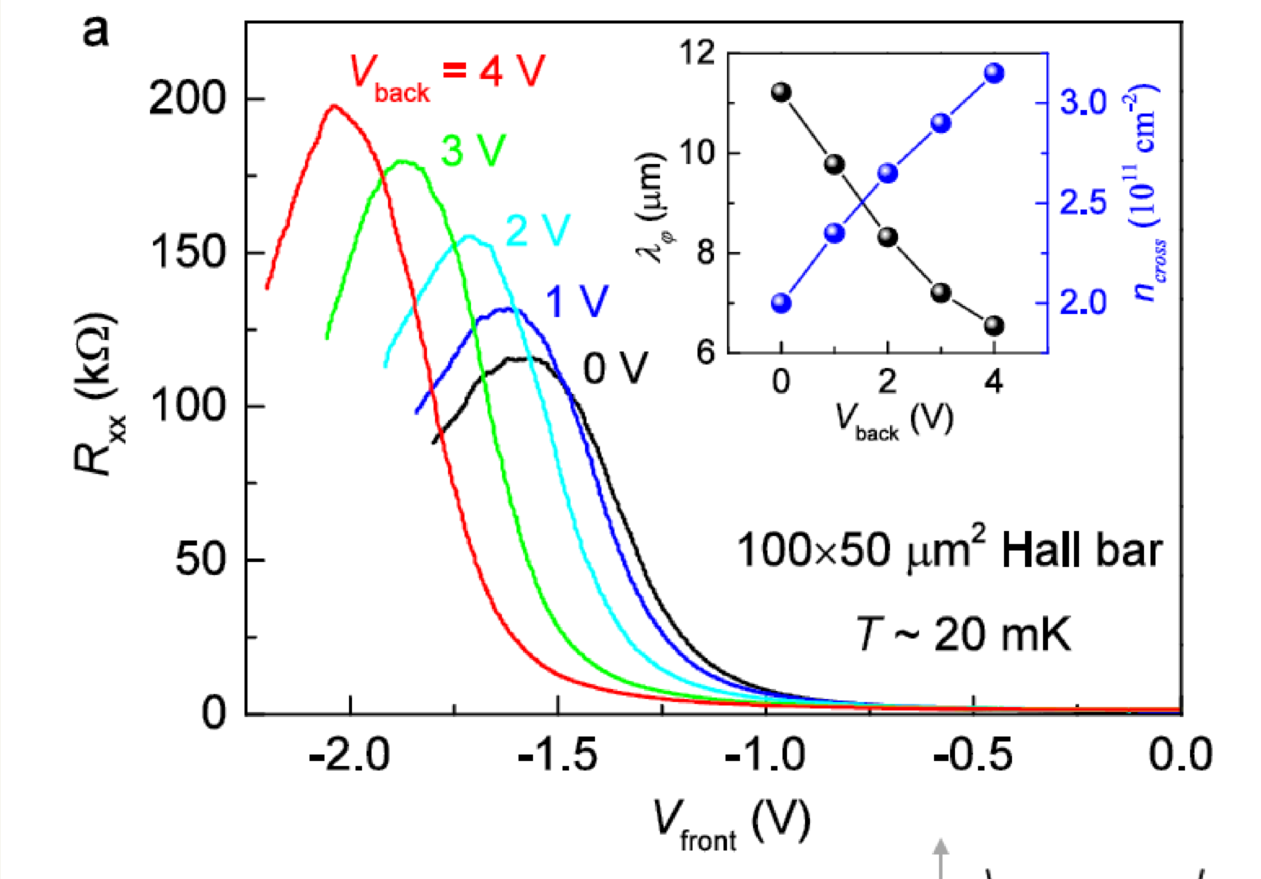








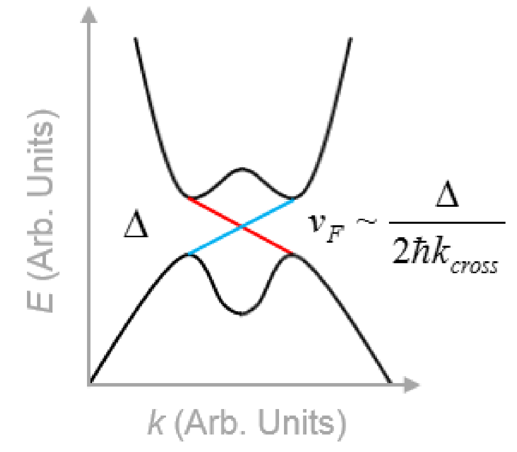
Coherent length increases with increasing V_F



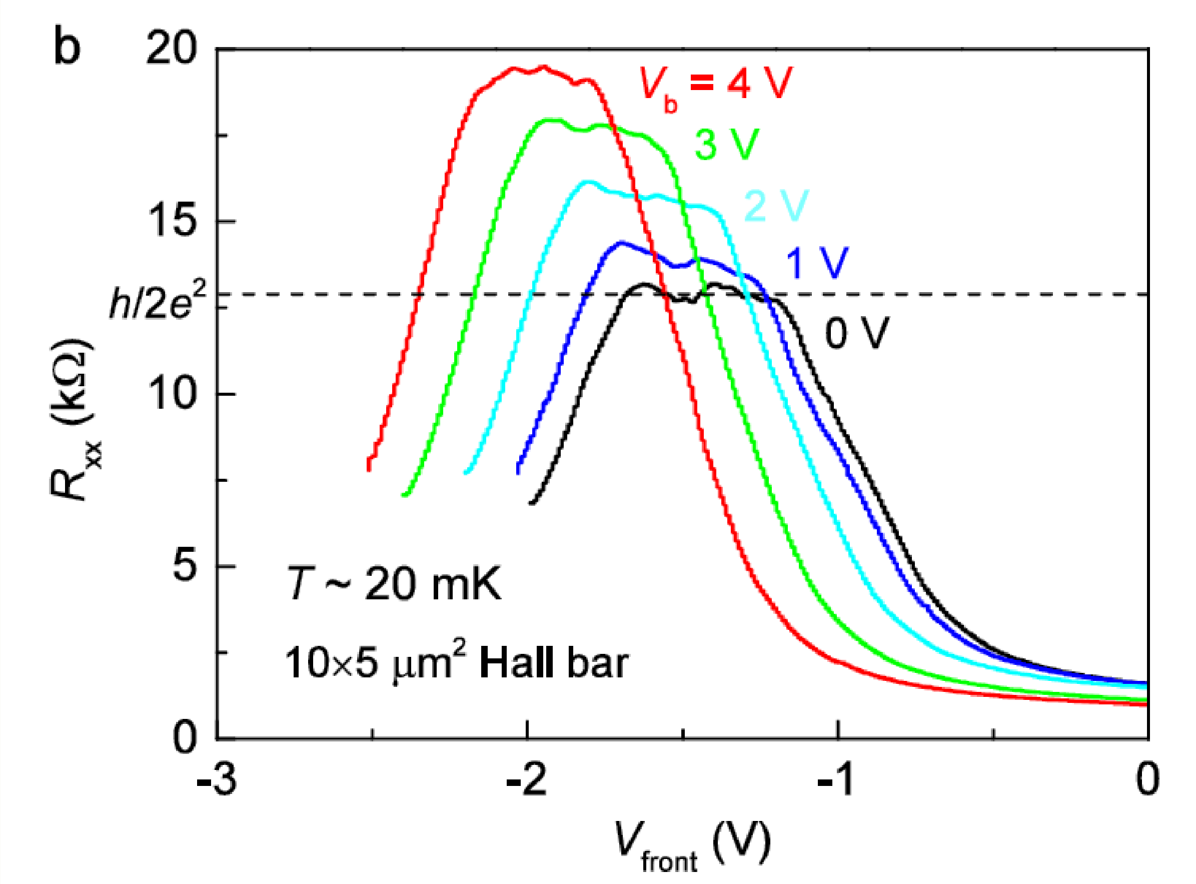
"Coherent Length" increase
with less inverted band:

Correlated with increased V_F

- Less interacting 1D Electronic system
- Move away from Luttinger

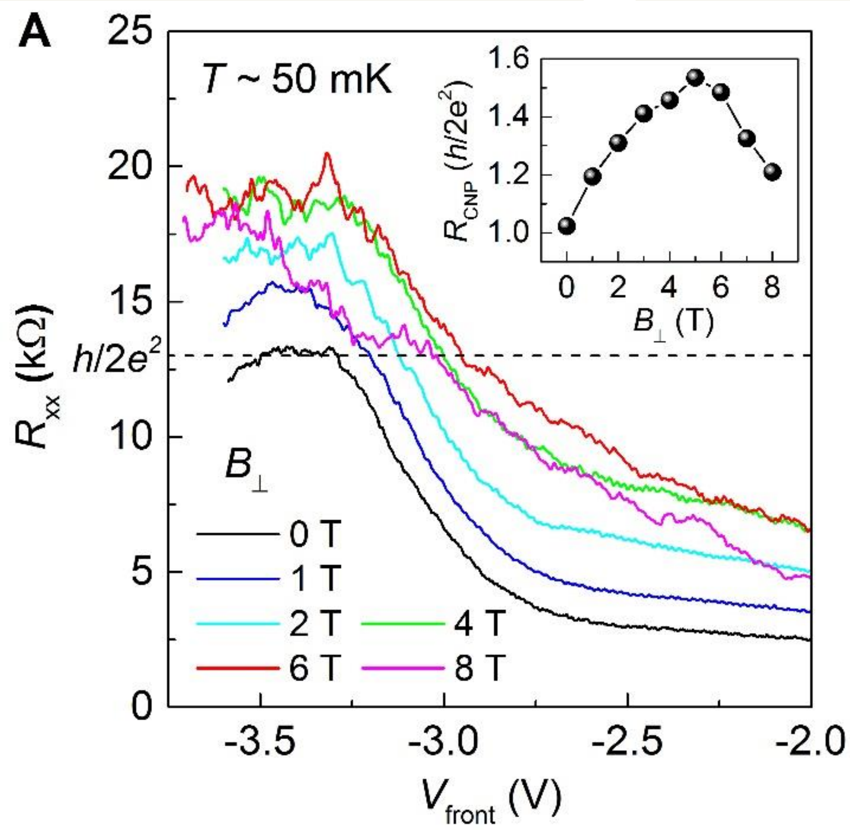


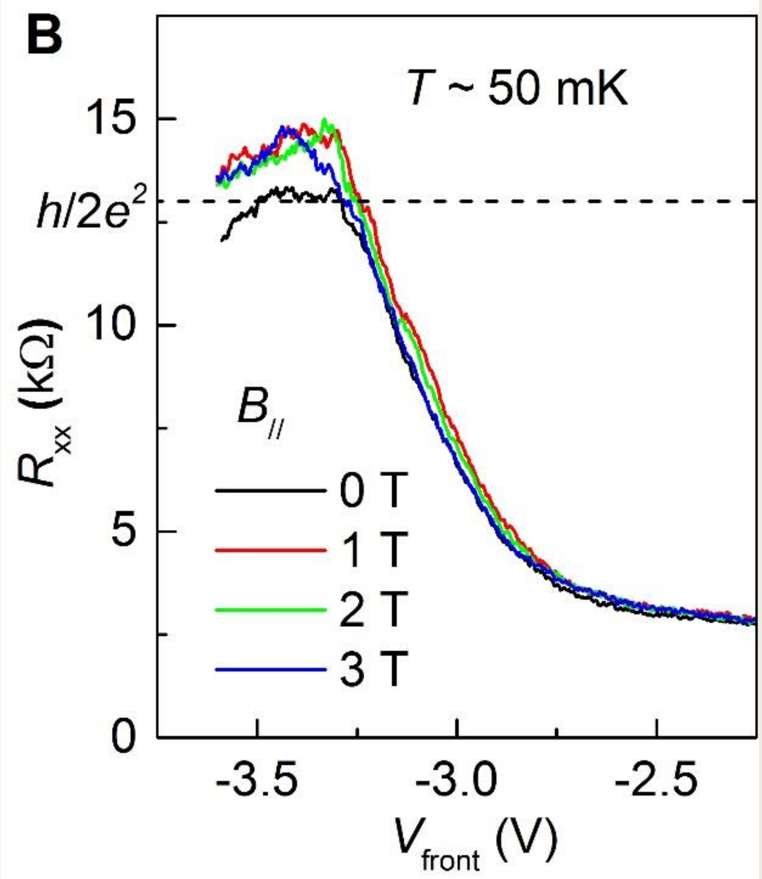
Quantized Edge Transport in 10 um Length



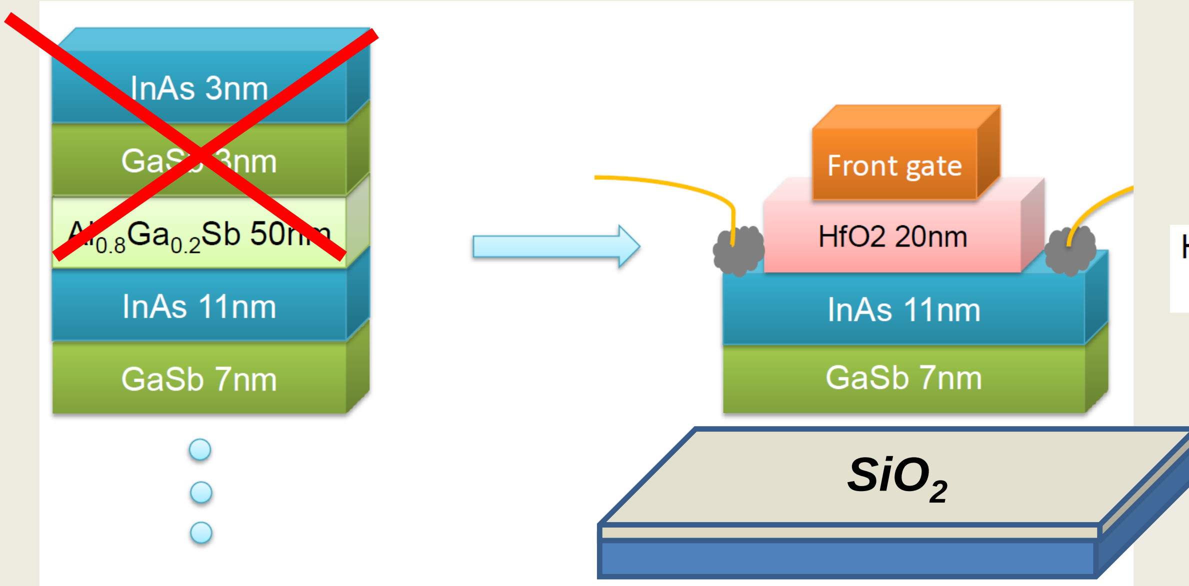
Quantized in a 10um Hall Bar

TRS Protected Helical Edge States

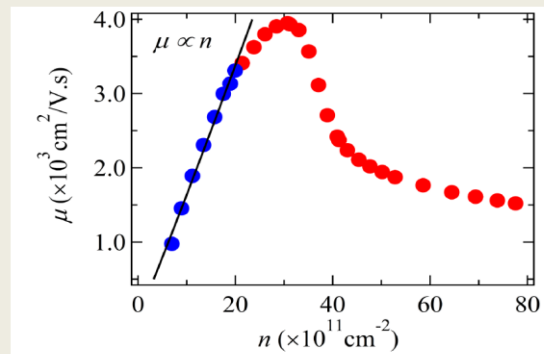


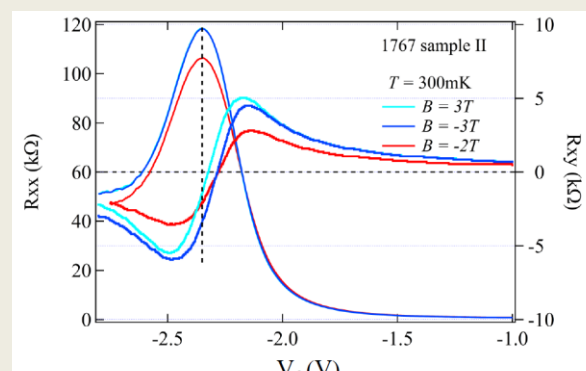


9.5 nm InAs/4 nm $Ga_{0.75}In_{0.25}Sb$



Hall bar geometry
75μm × 25μm





Compatible with III-V CMOS Technology

Nano Lett. 2012, 12, 3592−3595

NANO LETTERS

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III−V Complementary Metal−Oxide−Semiconductor Electronics on Silicon Substrates

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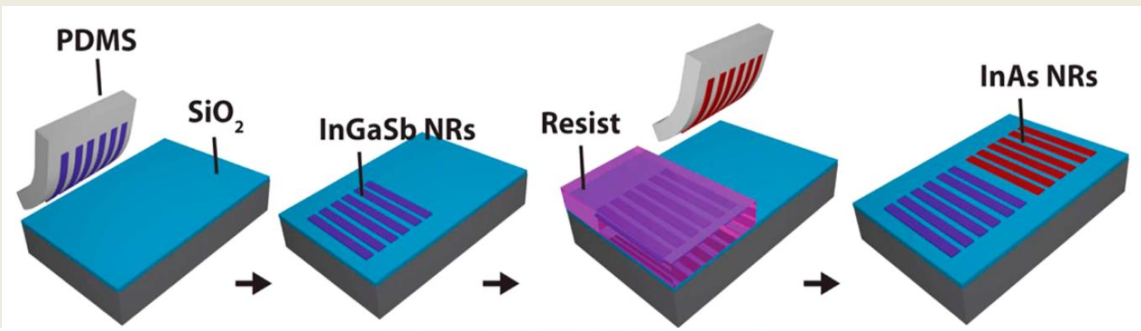
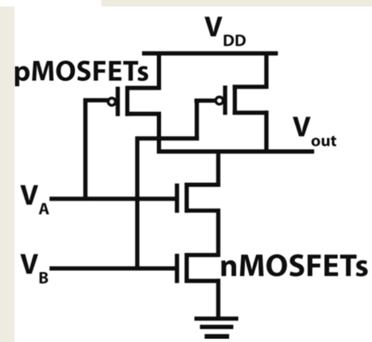
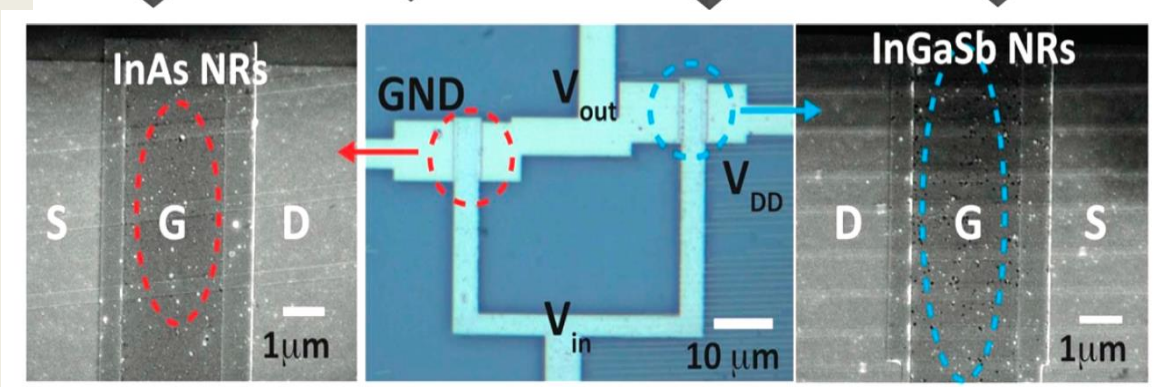
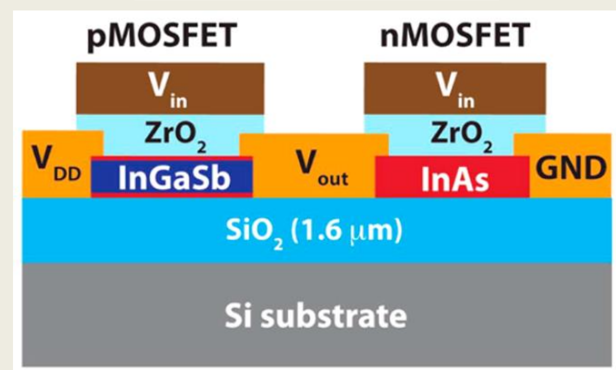
[†]Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720, United States

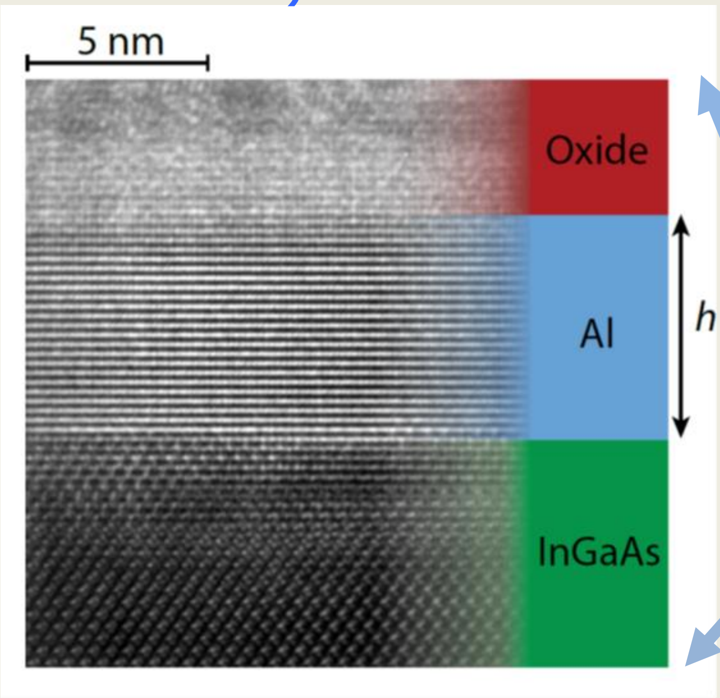




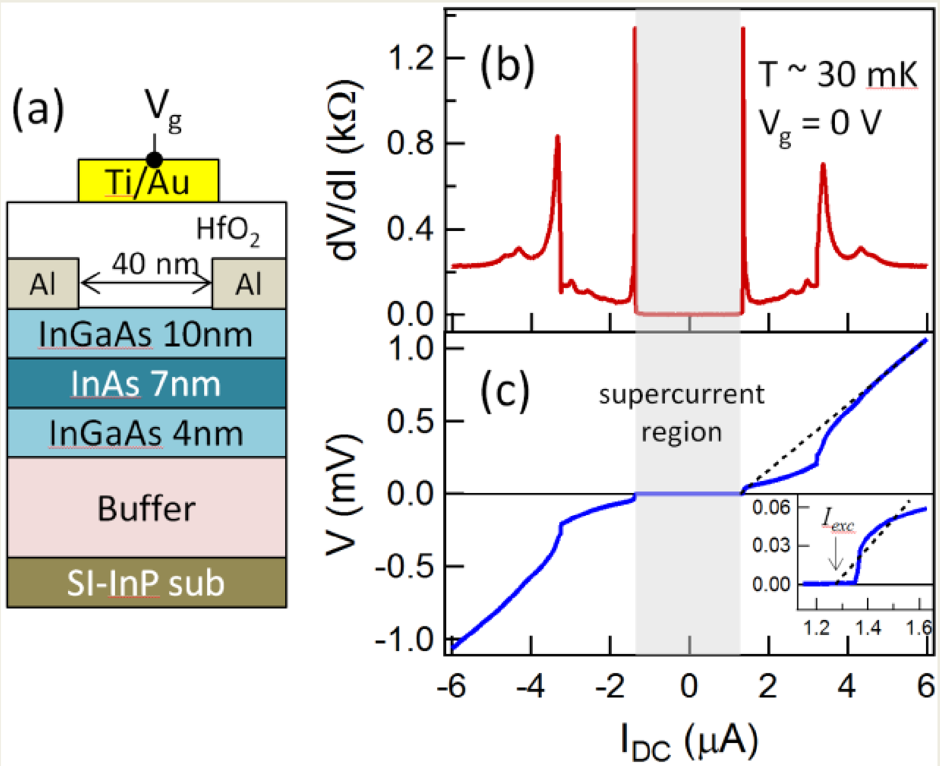




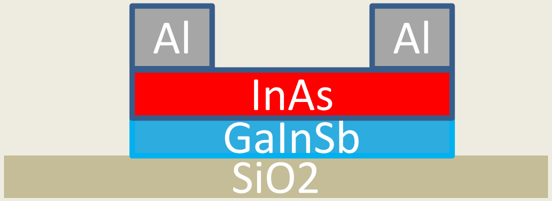
Marcus, Palmstrøm groups

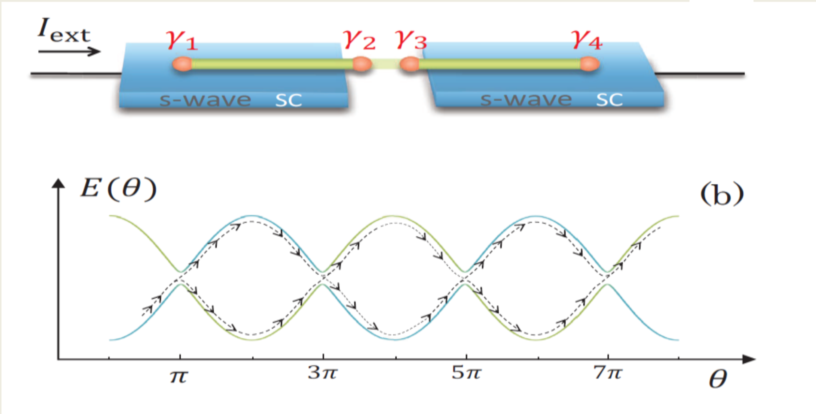


Hard Gap

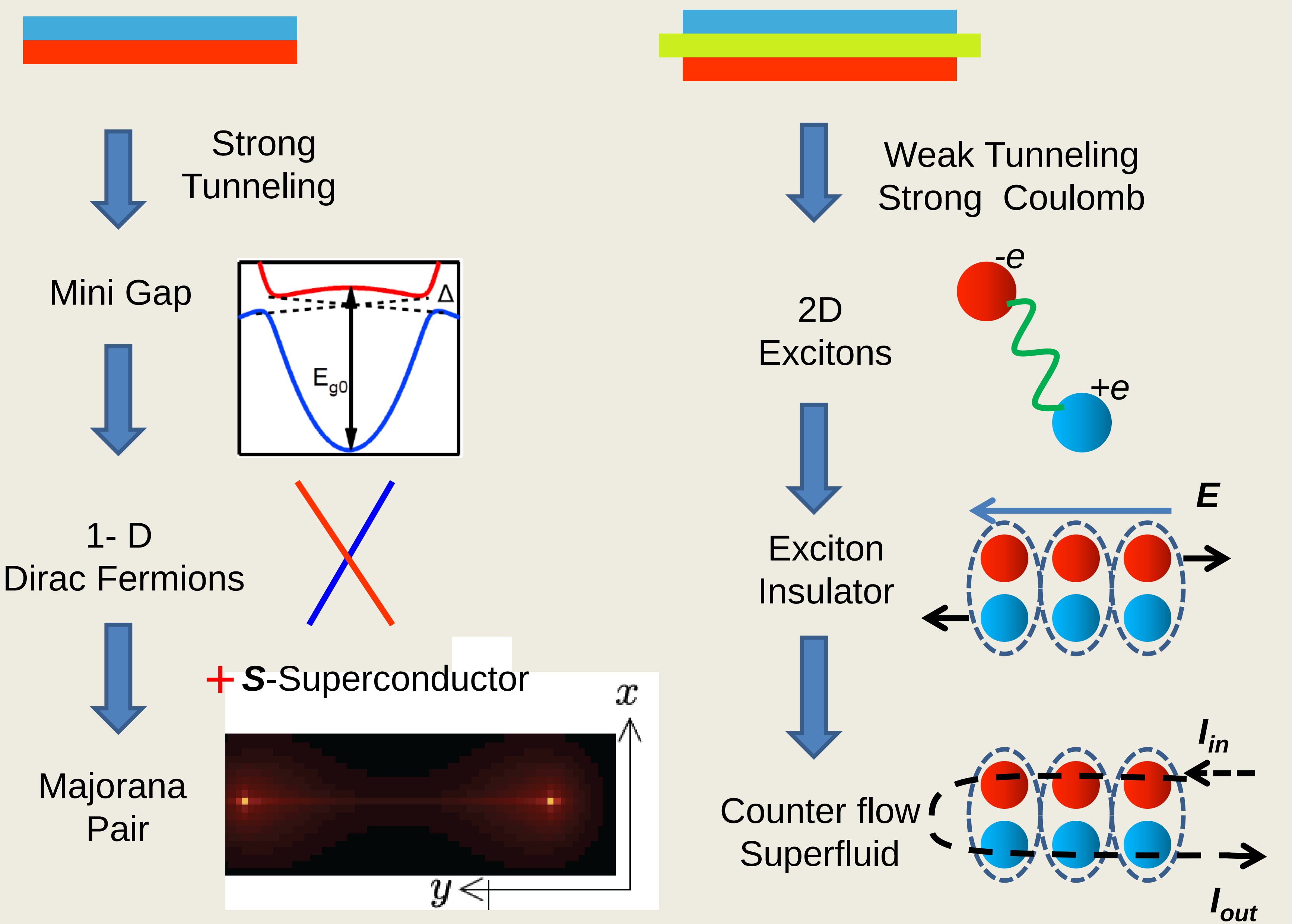


Our Group





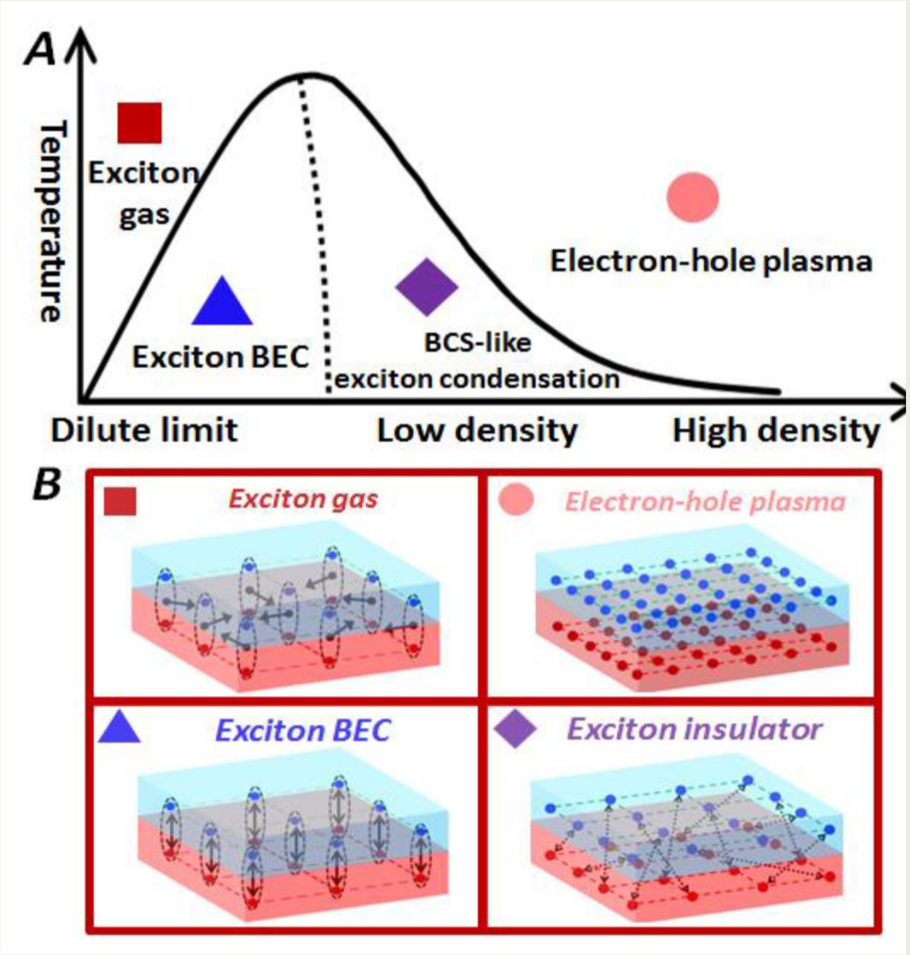
3. Double-Layer Excitonic Condensations

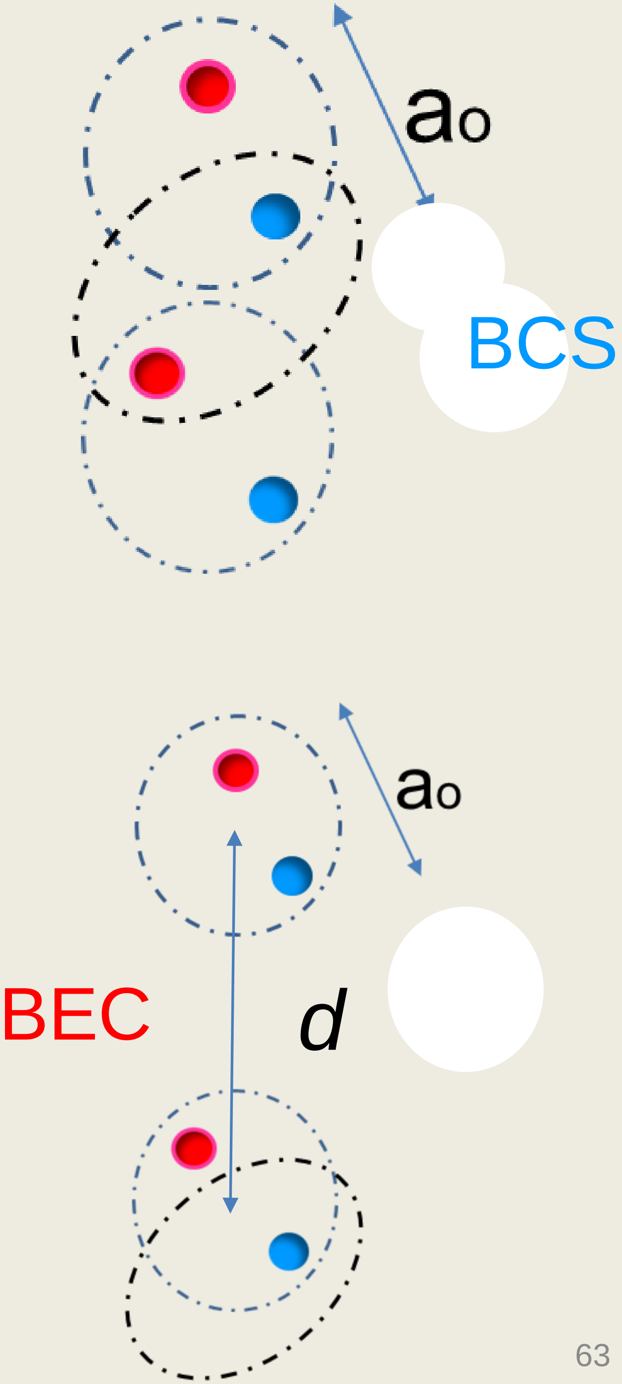


The Exciton Analog of BCS Superconductivity

Electron-Hole Pairing ⟷ Cooper Pairing

Mott, Philos Mag 1961
Knox, 1963
Keldysh, Yu.V., Fizika ,1964
Jerome, Rice, Kohn, 1967
Halperin & Rice, Rev Mod Phys, 1968

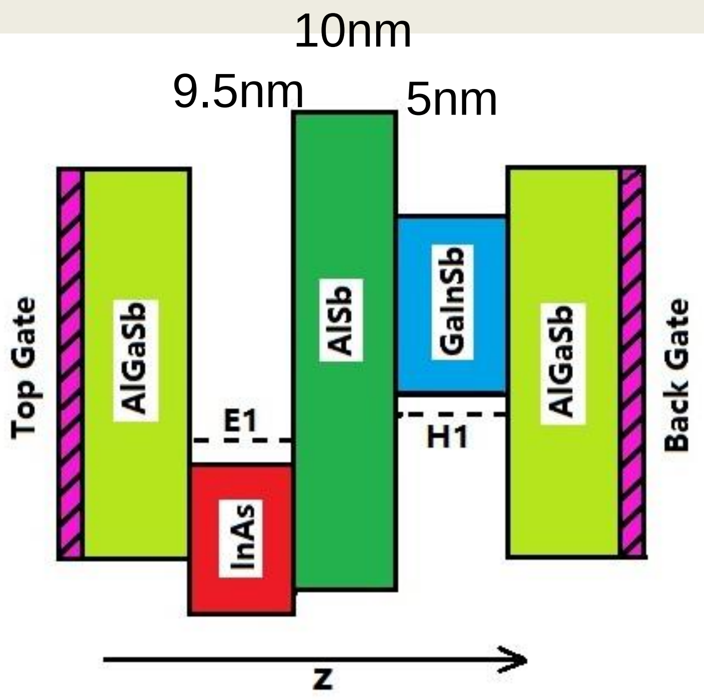


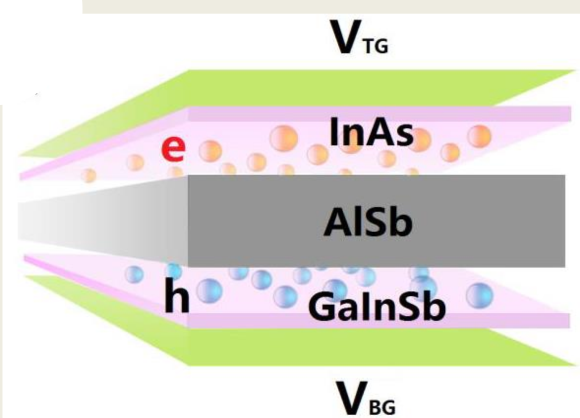


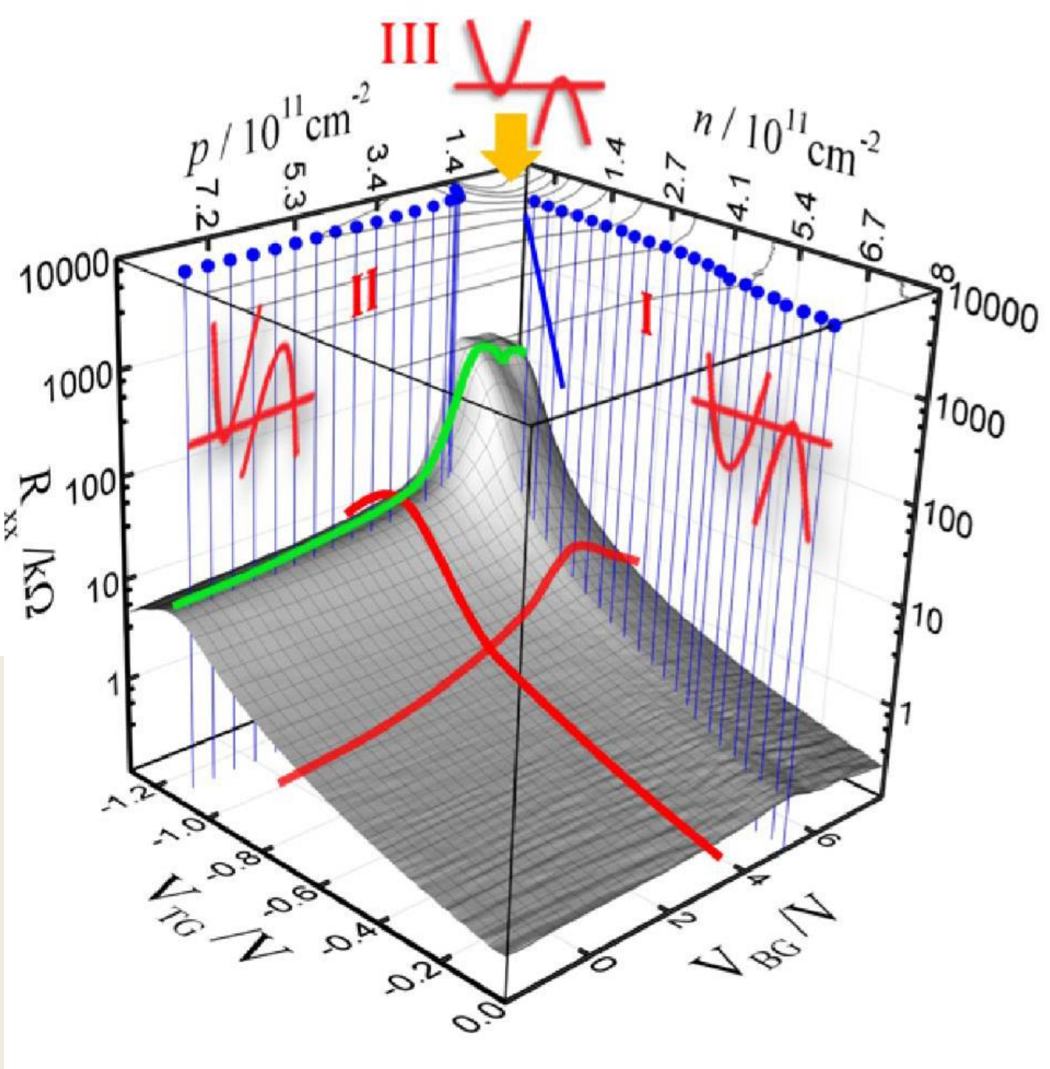
Dilute limit: 5 x 10^{10}/cm^2

Reasonably high mobility 10^5 cm^2/Vs

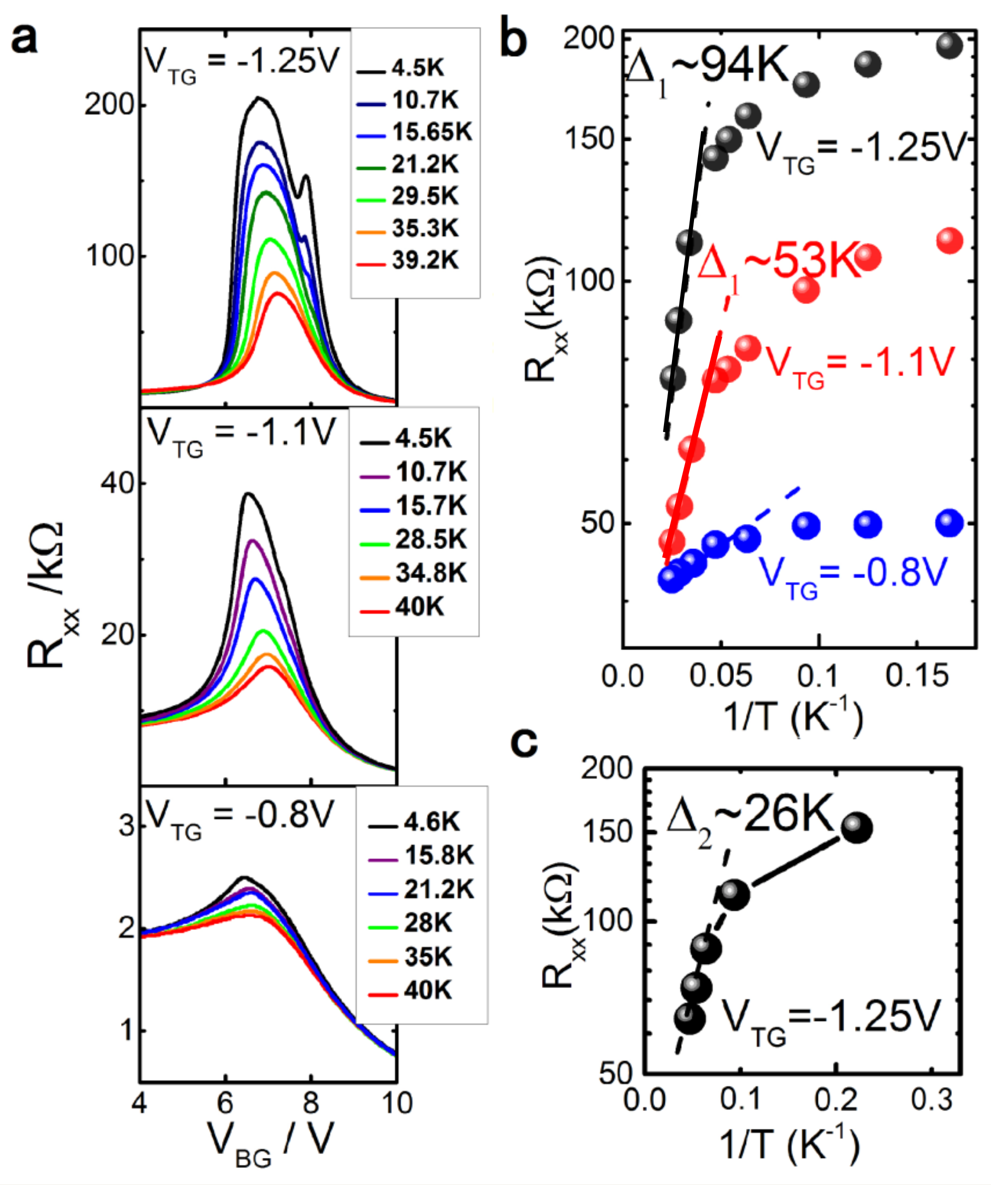
Electron-hole symmetry


10nm
9.5nm
5nm
Top Gate
AlGaSb
E1
InAs
AlSb
GaInSb
H1
AlGaSb
Back Gate
z


V TG
InAs
e
AlSb
h
GaInSb
V BG


III
p / 10^11 cm^-2
n / 10^11 cm^-2
7.2
5.3
3.4
1.4
1.4
2.7
4.1
5.4
6.7
8
II
I
10000
1000
100
10
1
R xx /kΩ
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
V TG /V
0
2
4
6
V BG /V

Large Energy Scale



Observation

T > 4 K

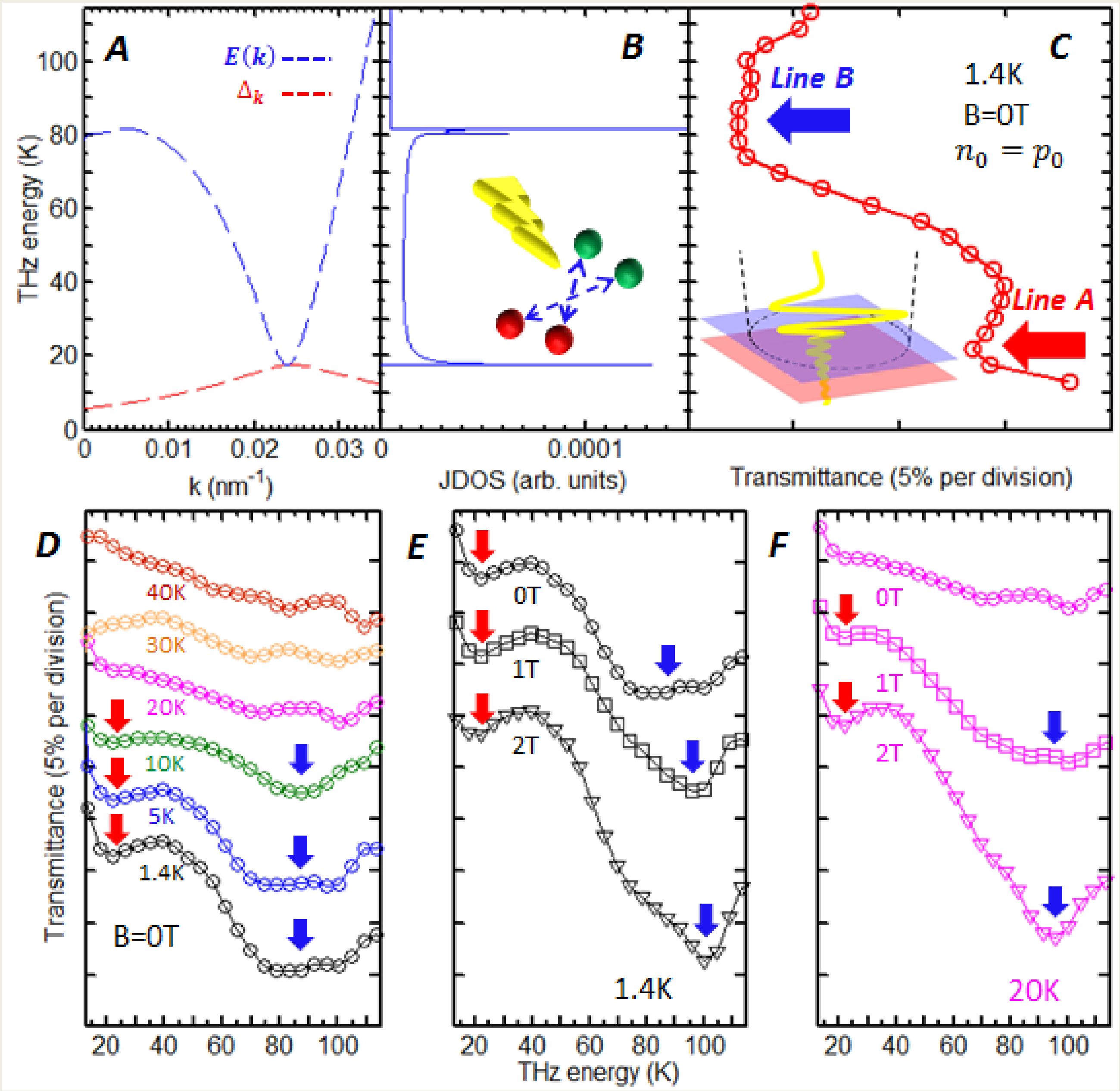
Main Peak

Onset 40 K
Gap 90 K

Side Peak

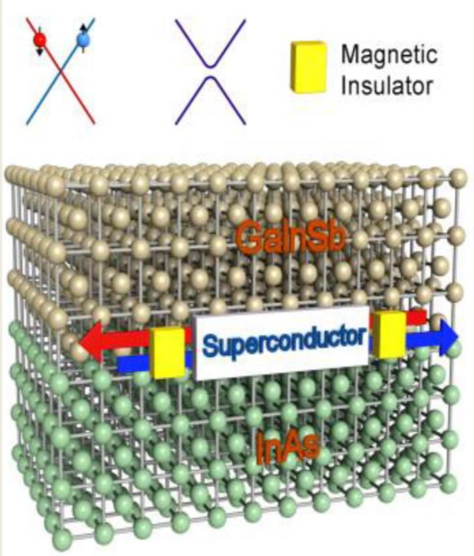
Onset 15 K
Gap 25 K

THz Absorption Shows e-h Pair-breaking Excitation



Summary for Large Gap QSHI in Strained Layer QWs

- The strained InAs/$Ga_{1-x}In_xSb$ QWs offers
  - ➢ Larger bulk insulating gap up to 50 meV
  - ➢ Z2 2D topological insulator
  - ➢ Double-layer exciton condensation
- Future work:
- SC Proximity + Edge States + FM Insulator
- Counter-flow experiments



QSH Edge
Majorana Platform

THANKS