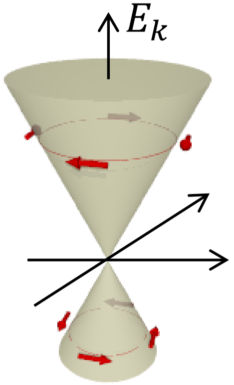


Manipulating Spins in Topological Insulators

Joon Sue Lee

California NanoSystems Institute, UC Santa Barbara

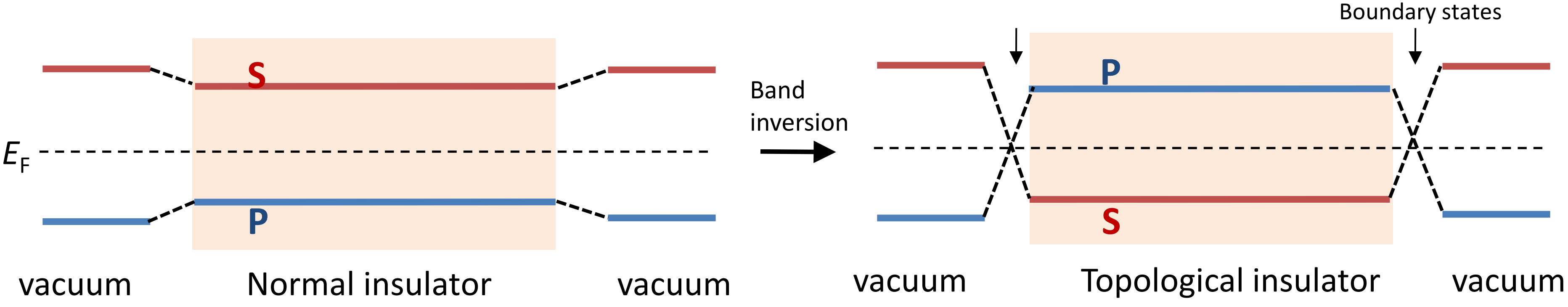
Korea University, Sep 8, 2016

Introduction to topological insulators

Topology: mathematical study of the properties
that remain under continuous deformations.

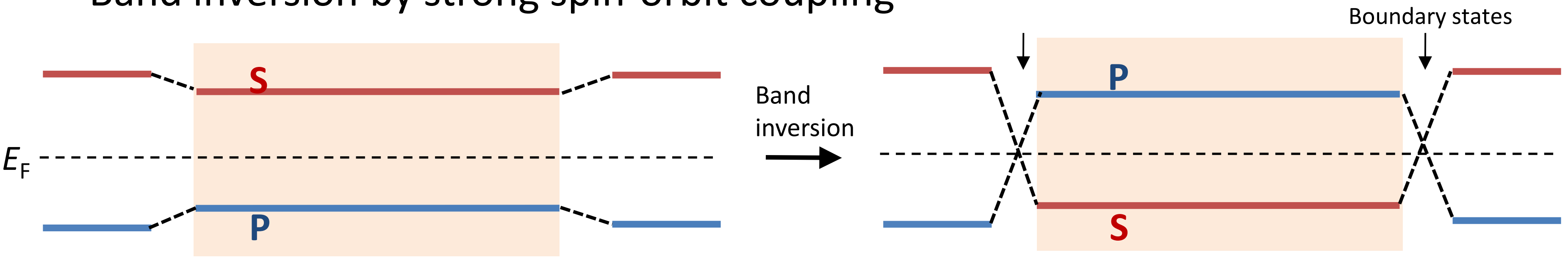
Graphic: www.pinterest.com

In condensed matter physics,
continuous deformation → change without closing a bulk energy gap.



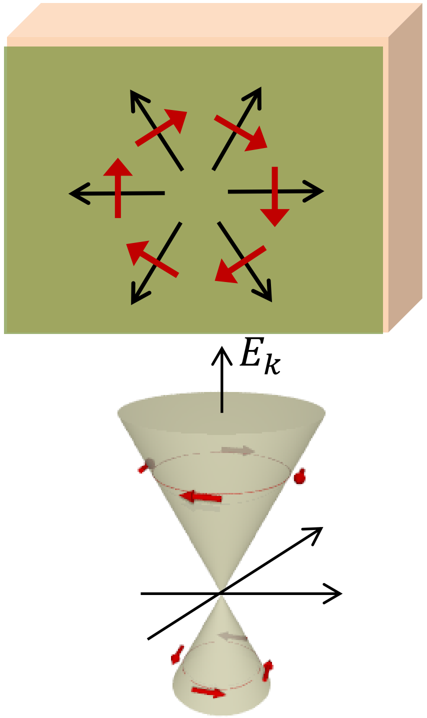
Introduction to topological insulators

- Band inversion by strong spin-orbit coupling



3D topological insulator

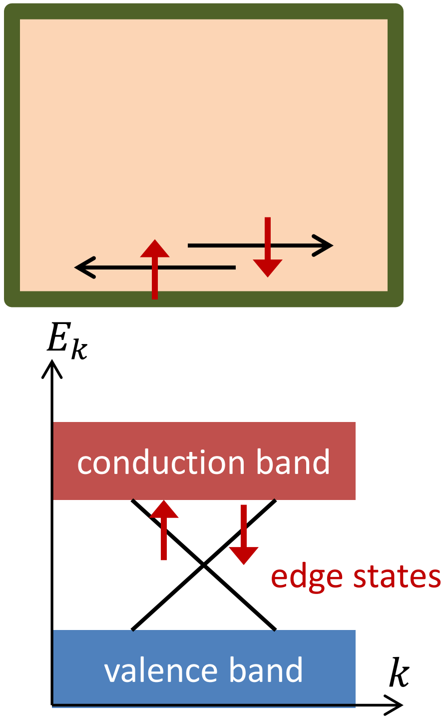
Surface states



Hasan & Kane, *Rev. Mod. Phys.* (2010)
Qi & Zhang, *Physics Today* (2010)

2D topological insulator

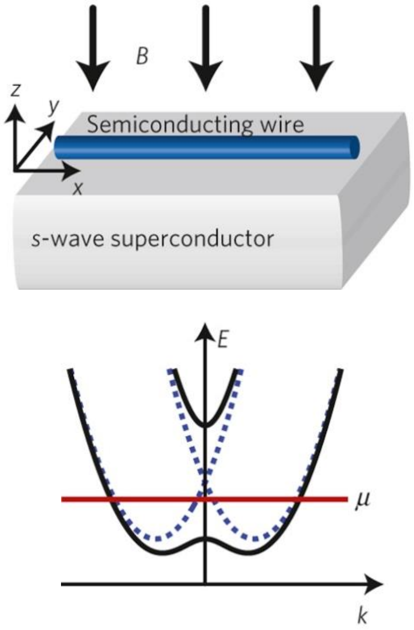
Edge states



Moore, *Nature* (2010)
Qi & Zhang, *Rev. Mod. Phys.* (2011)

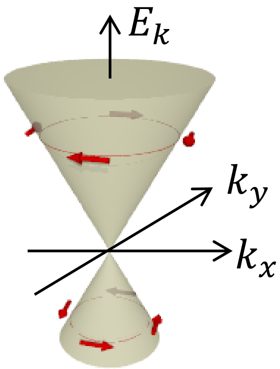
1D topological superconductor

End states
(Majorana zero modes)

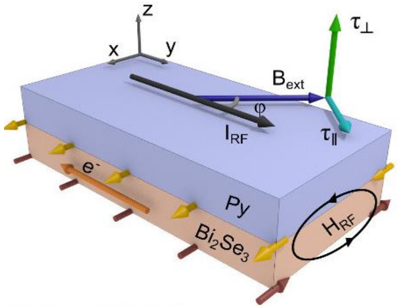


Moore & Balents, *Phys. Rev. B* (2007)

Outline

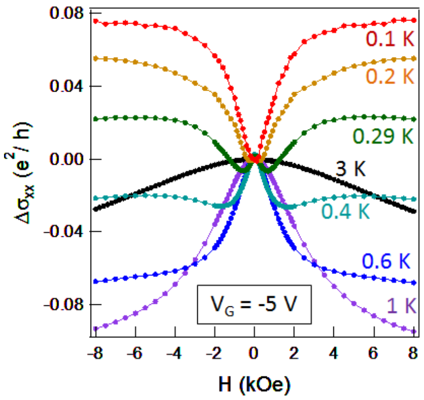


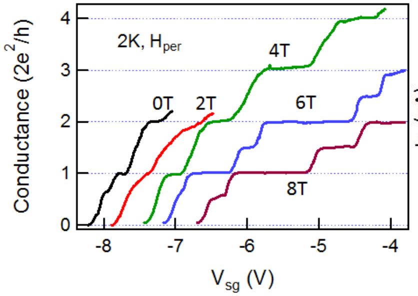
1. Spin-polarized surface states in 3D topological insulators
   - Electrical detection of spin polarization

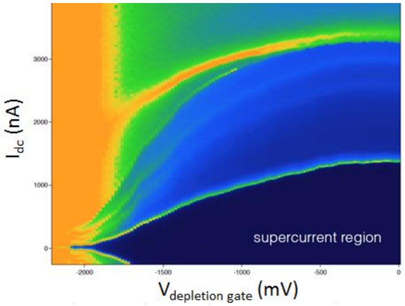


2. Spin-charge conversion in topological insulators
   - Charge-to-spin conversion: spin transfer torque
   - Spin-to-charge conversion: spin pumping

3. Modified surface states by breaking time-reversal symmetry
   - Interfacing a ferromagnetic insulator to a TI

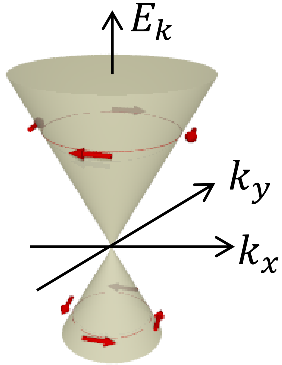




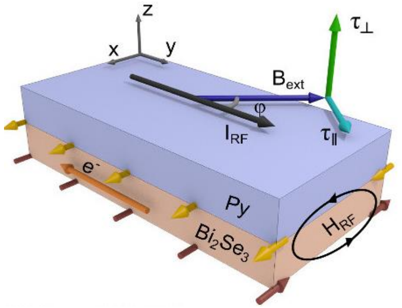


4. Topological superconductivity towards quantum computation
   - 1D transport and superconducting proximity effect in epi-Al/2DEG

Outline



1. Spin-polarized surface states in 3D topological insulators
   - Electrical detection of spin polarization



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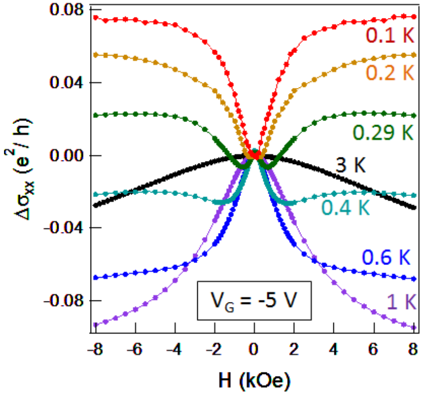
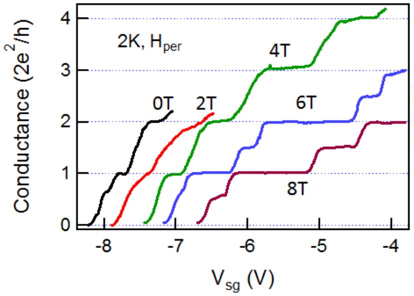
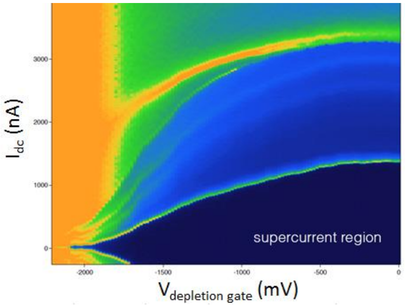


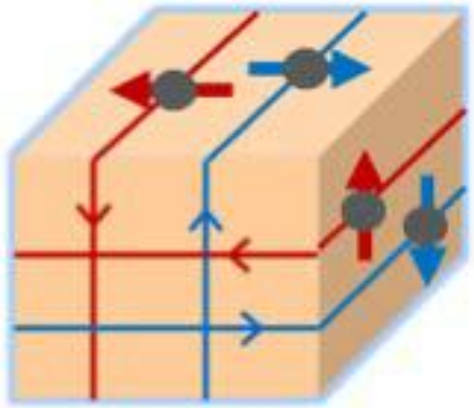


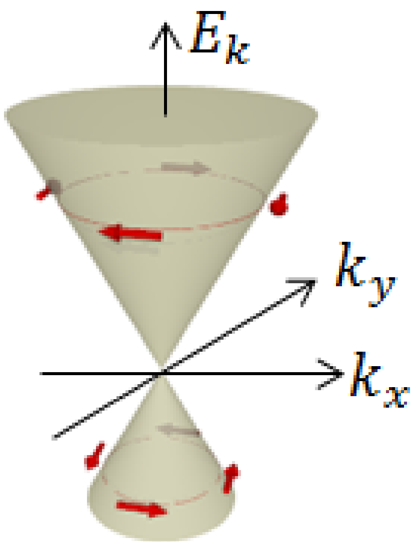


4. Topological superconductivity towards quantum computation
   - 1D transport and superconducting proximity effect in epi-Al/2DEG

3D topological insulators

A state of matter that has an insulating bulk and spin-dependent surface states due to spin-orbit coupling.

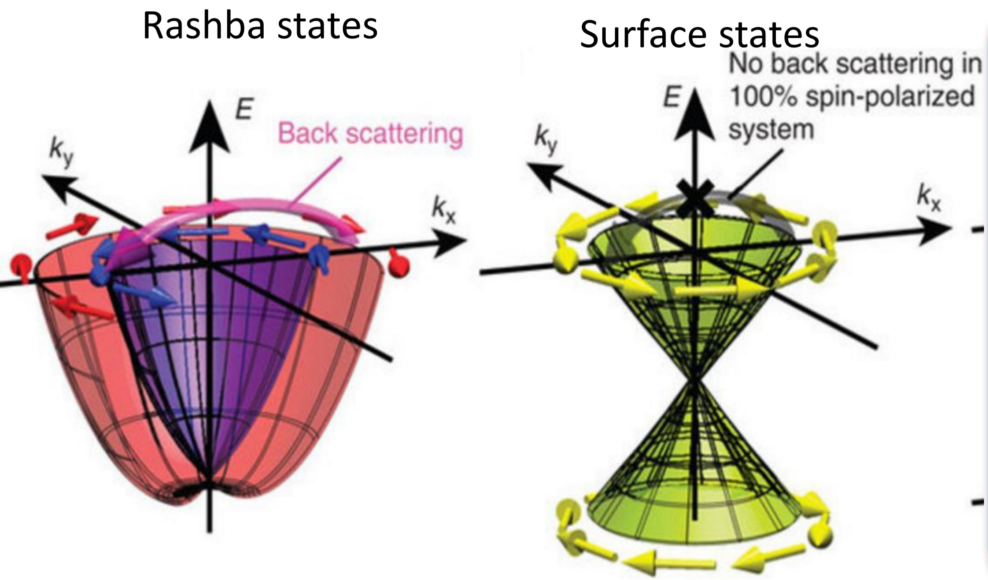




Surface states

$$H_{surf} = \hbar v_F(\sigma^x k_y - \sigma^y k_x)$$

- Spin-momentum locking
- Protected by time-reversal symmetry
- Robust against back-scattering



Graphic: Sakamoto, *et al., Nat. Commun.* (2013)

Time-reversal switches both the direction of electron motion and the direction of spin.

Time-reversal invariance:

$$\boxed{\mathrm{T}H(k)\mathrm{T}^{-1} = H(-k)}$$

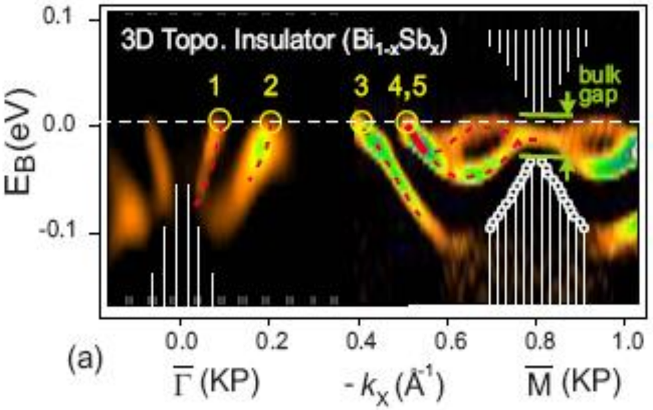
$$\mathrm{T}H(k)\mathrm{T}^{-1} = \hbar v_F[(-\sigma^x)k_y - (-\sigma^y)k_x]$$

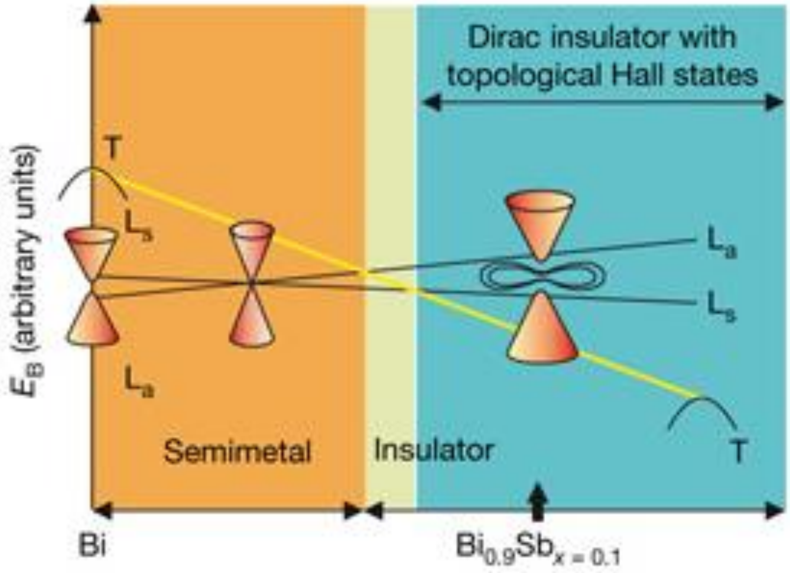
$$H(-k) = \hbar v_F[\sigma^x(-k_y) - \sigma^y(-k_x)]$$

Invariant!

3D topological insulators

$Bi_{1-x}Sb_x$: the first 3D topological insulator

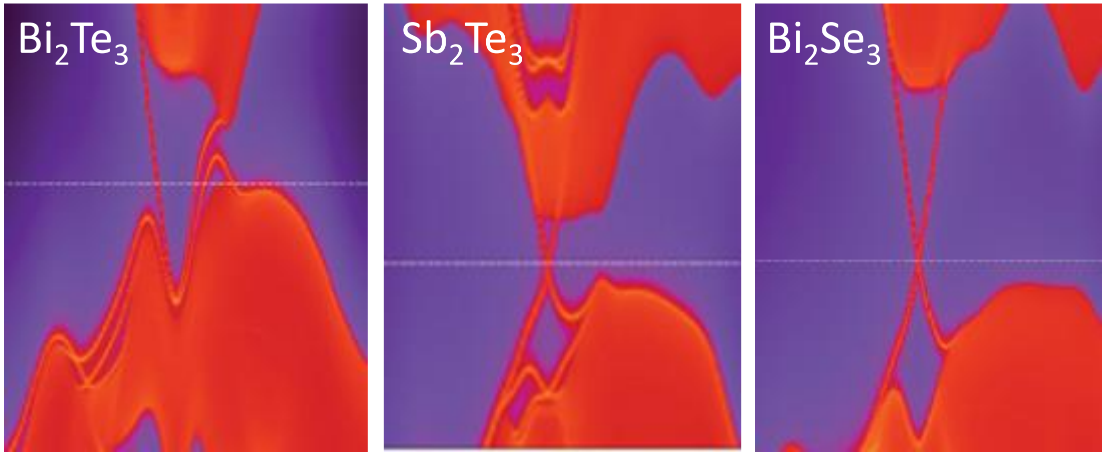




Prediction: Fu & Kane, *Phys. Rev. B* **76,** 045320 (2007).
Experiment: Hsieh, *et al.*, *Nature* 452 (2008)

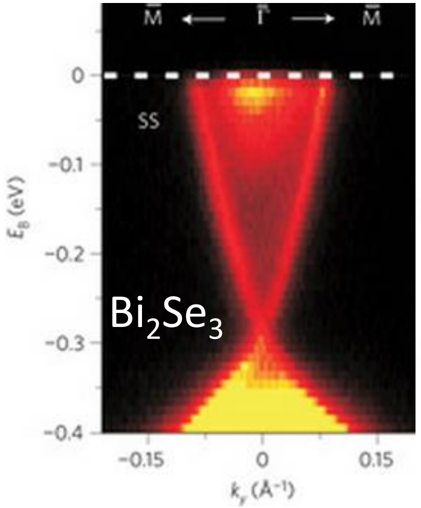
Bi-chalcogenides with a single Dirac cone

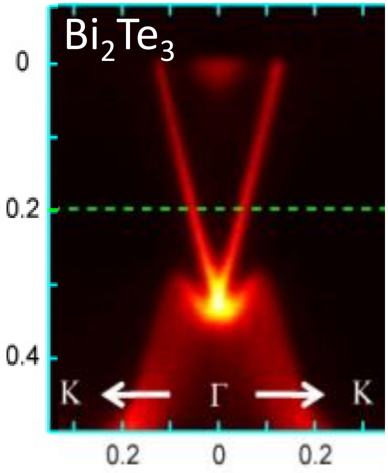
<First-principles electronic structure calculations>



Prediction: Zhang, *et al.*, *Nat. Phys.* **5**, 438 (2008)

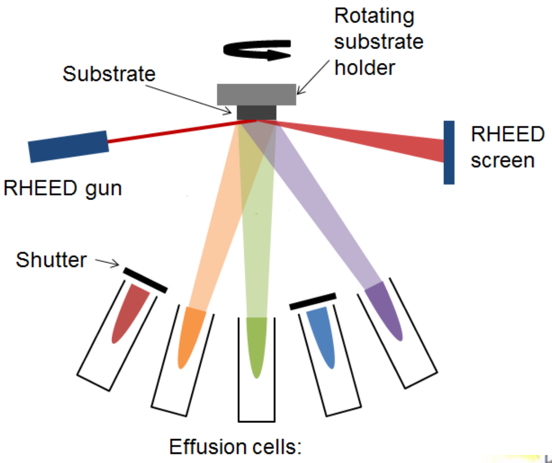
<Angle-resolved photoemission spectroscopy>



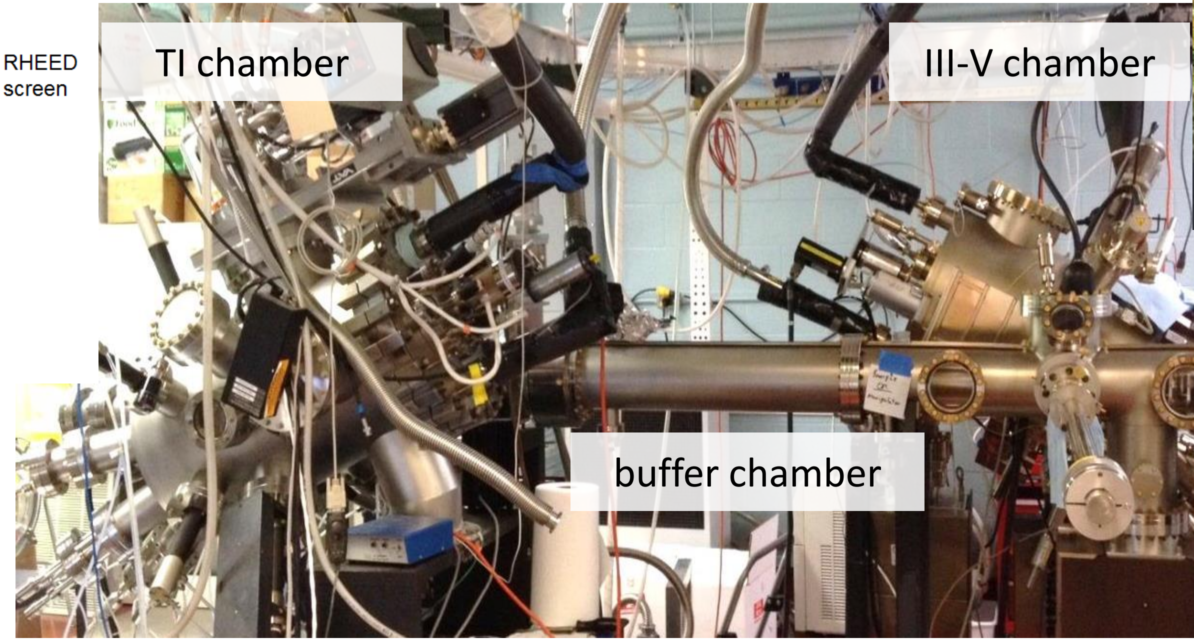


Experiment: Xia, *et al.*, *Nat. Phys.* **5**, 398 (2009)
Chen, *et al.*, *Science* **325**, 178 (2009)

Topological insulator thin films by MBE



MBE systems at Penn State (Nitin Samarth group)



Bi, Sb, Se, Te, Mn, and Cr.
(e-beam sources: Fe, Co, Nb, and V)

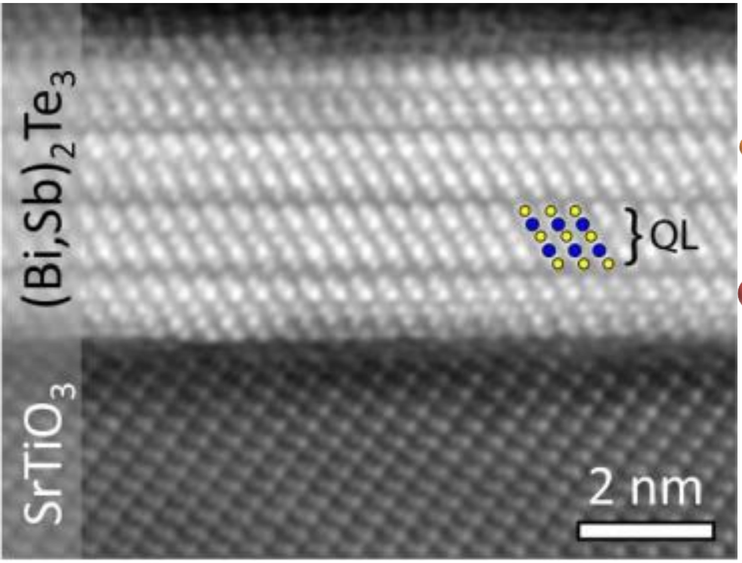
Ga, Al, In, As, Sb, Si, Be and Mn.

Molecular beam epitaxy (MBE) of topological insulators

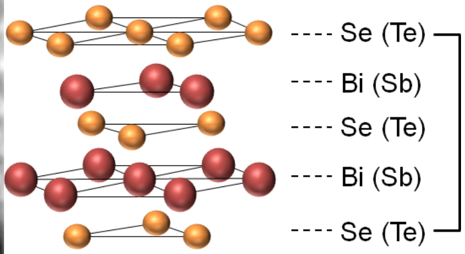
- Bi-chalcogenides: Bi_2Se_3, Bi_2Te_3, Sb_2Te_3 and $(Bi,Sb)_2(Te,Se)_3$ …
- Magnetic doping: Cr, Mn, and V
- On various substrates: InP, GaAs, ZnSe, Si, sapphire, diamond, $SrTiO_3$, graphene, h-BN, NbSe2, YIG, LuIG, BaM, EuS, BSSCO, …

Topological insulator thin films by MBE

Cross-sectional STEM

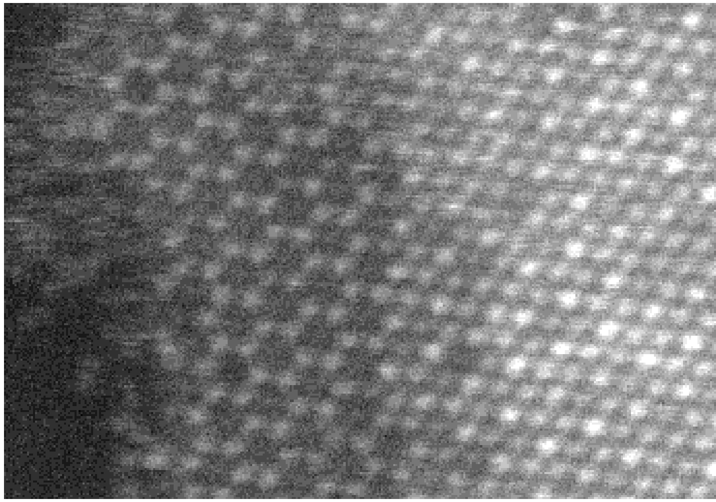


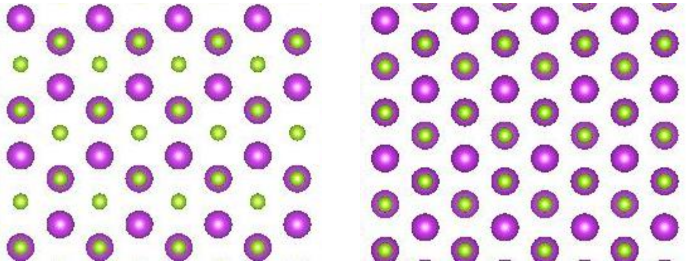
Rhombohedral crystal structure



- Quintuple layer (QL)
- van der Waals bonding between QLs

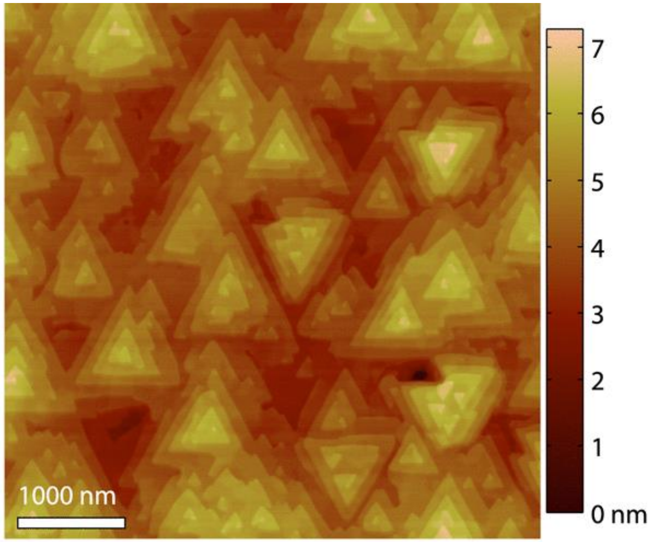
Plan-view STEM of $(Bi,Sb)_2Te_3$/h-BN





1 QL multiple QLs

AFM of Bi_2Se_3 on InP

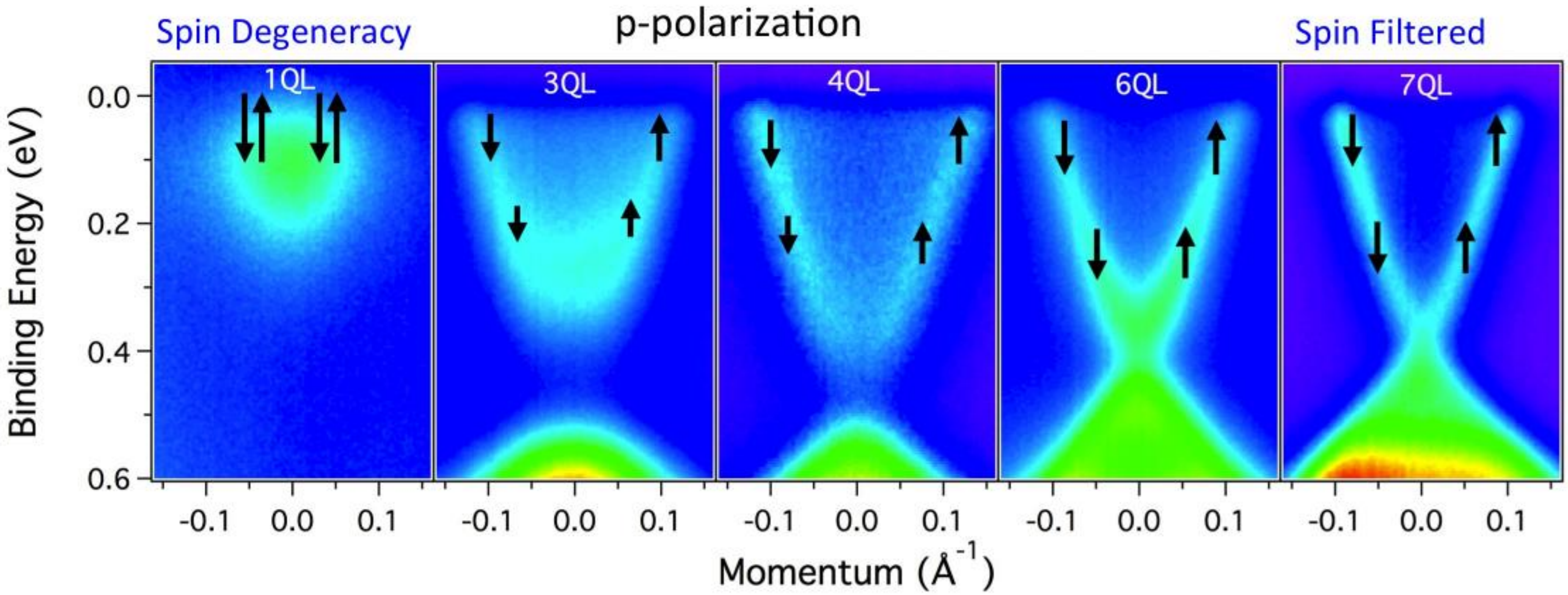


Film quality is limited by defects, such as vacancies, dislocations, twin boundaries, and large grains.

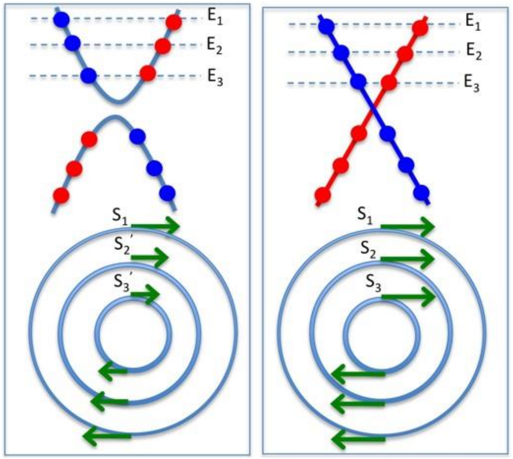
- Typical density: $1x10^{17} – 1x10^{19}$ cm^{-3}
- Typical electron mobility < 2,000 cm^2/Vs

Spin texture in 3D topological insulators

Spin-resolved ARPES in 1-7 QL Bi_2Se_3 thin films show an evolution of the spin-polarized Dirac surface state.

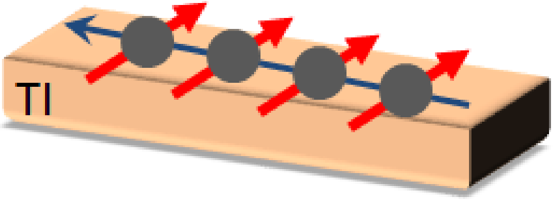


M. Neupane *et al.*, *Nat. Comm*. **5**, 3841 (2014)



- A gap by hybridization between top and bottom surfaces (< 6 QL).
- The inherent spin-polarized surface state motivates for developing spin channel transport devices.

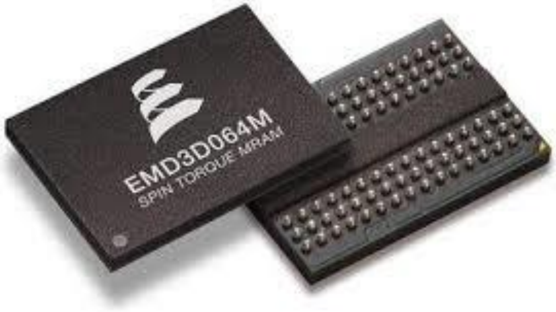
Topological spintronics



Spin polarized surface states in 3D topological insulators
→ Motivation for developing spintronic device applications

Spintronics (spin-based electronics)
: a field of electronics by control of electron spins for manipulation, storage, and transfer of information.

Spintronic effects:
- GMR → 2007 Nobel prize
- TMR
- Spin Hall effect
- Spin transfer torque
- Spin pumping
- Exchange bias with antiferromagnet



MRAM

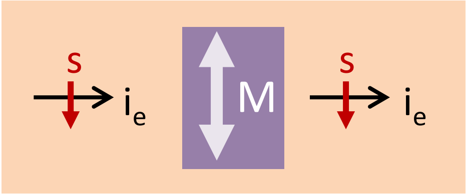
Hard disc drive

How to exploit the spin polarization in topological insulators?

Electrical detection of spin polarization in TIs

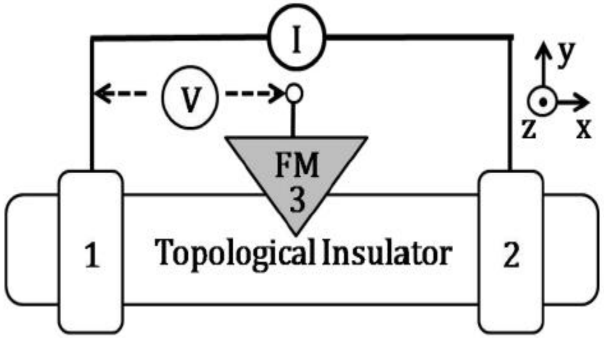
Experimental challenges:

- **How to “electrically” measure the spin polarization in topological insulators?**



Theoretical proposal:

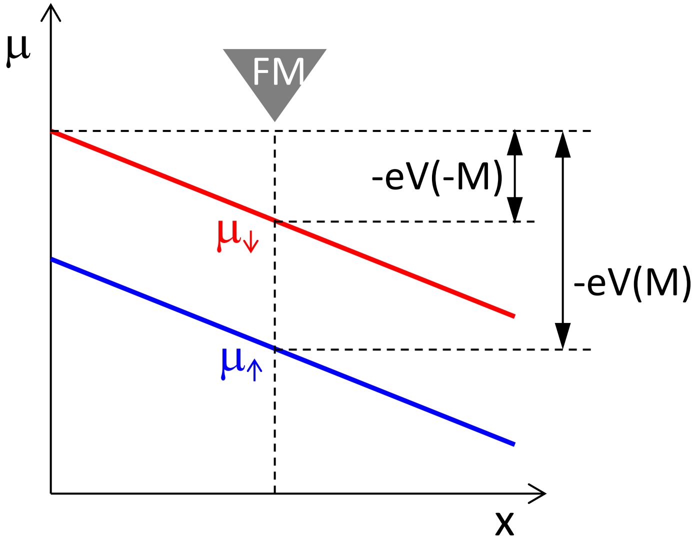
potentiometric geometry



Hong *et al., Phys. Rev. B.* **86**, 085131 (2012)

$$\left[V\left(\vec{M}\right) - V\left(-\vec{M}\right)\right]/I = R_B(\vec{p}\cdot\vec{m})$$

ΔV is proportional to the projection of the TI spin polarization onto FM.



$(\mu_\uparrow - \mu_\downarrow)$

: spin electrochemical potential difference

Electrical detection of spin polarization in TIs

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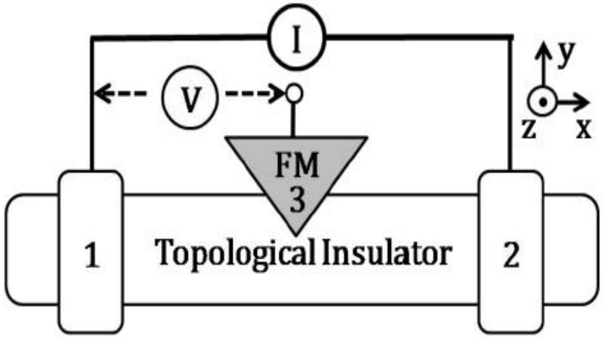

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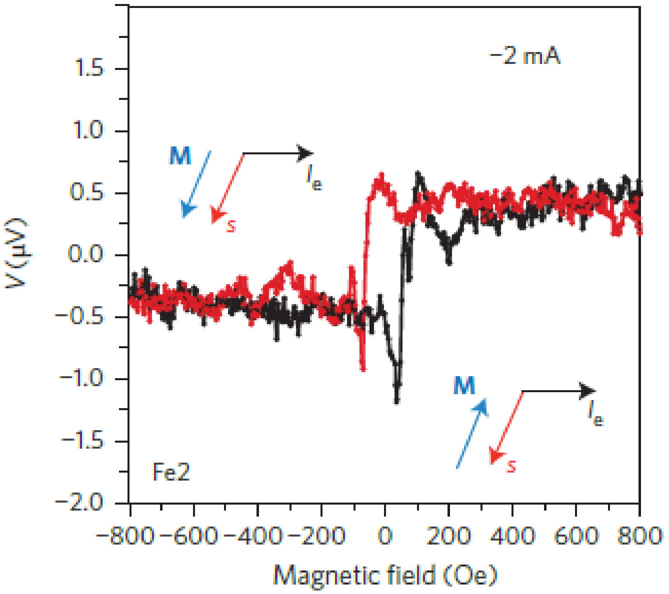
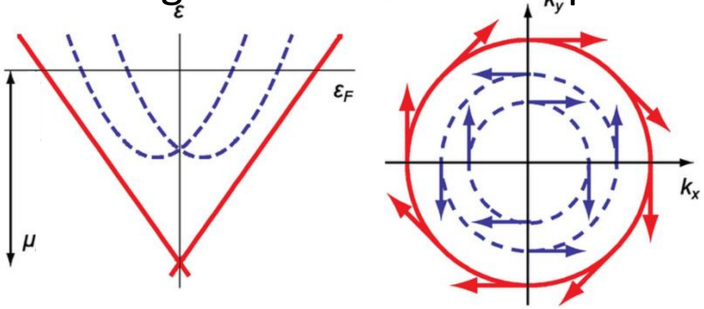


Li, *et al., Nature Nano.* **9**, 218 (2014)

Tang *et al.*, *Nano Lett* 14, 5423 (2014)
Ando *et al.*, *Nano Lett.* 14, 6226 (2014)
Tian *et al.*, *Sci. Reports* 5, 14293 (2015)

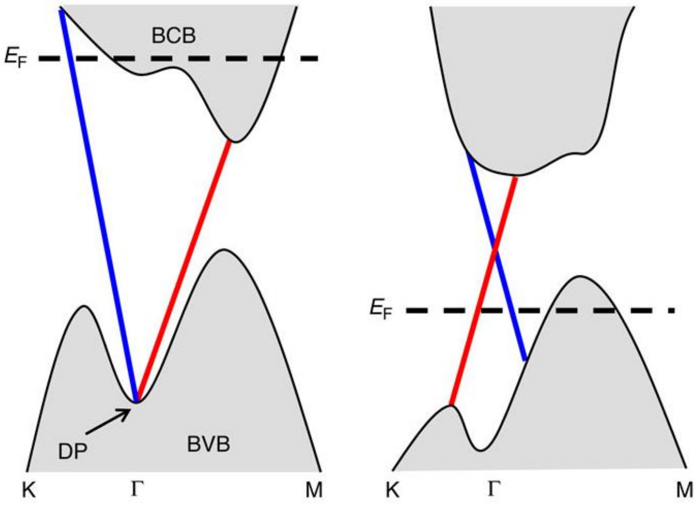
→ Measuring at a fixed chemical potential.



Can we measure as we tune the chemical potential?

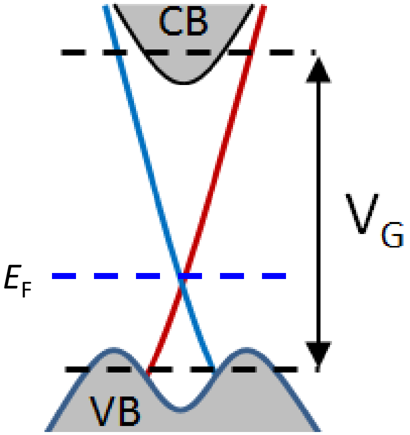
Ambipolar transport in a topological insulator film

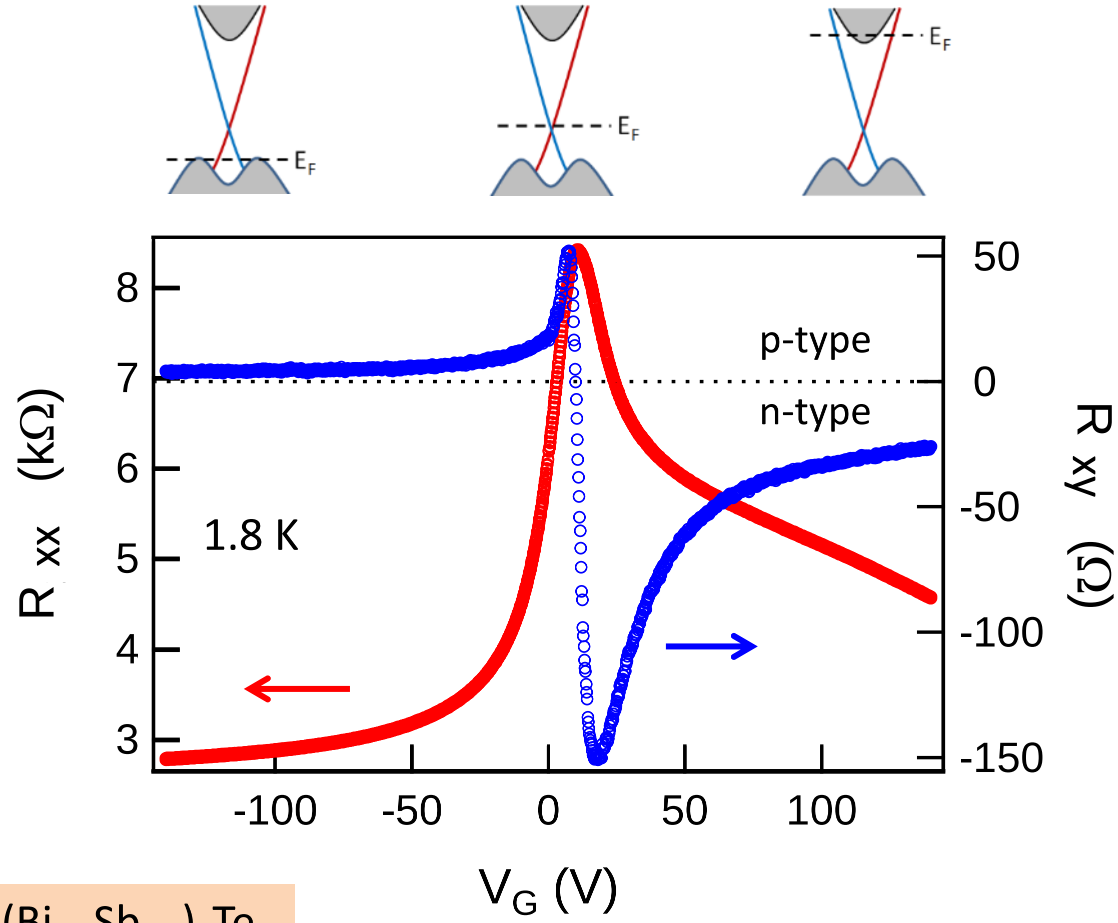
Bi_2Te_3, n-type Sb_2Te_3, p-type

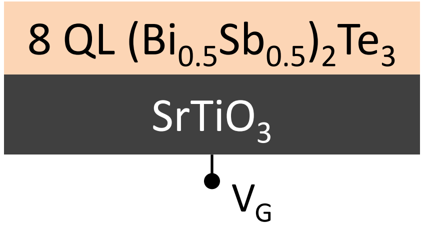


Zhang, *et al.*, *Nat. Commun. 2, 574* (2011)

$(Bi,Sb)_2Te_3$
- E_F near the Dirac point



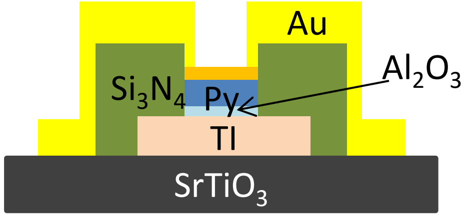


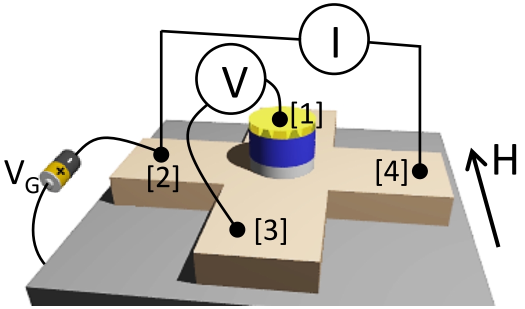


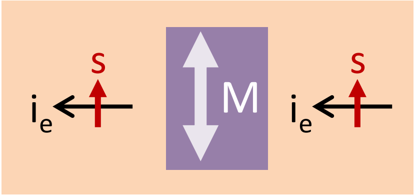
V_G tunes the TI chemical potential through Dirac point.

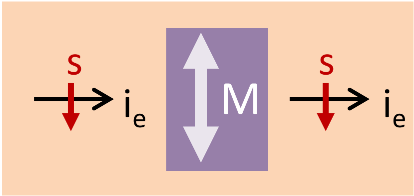
Electrical detection of spin polarization

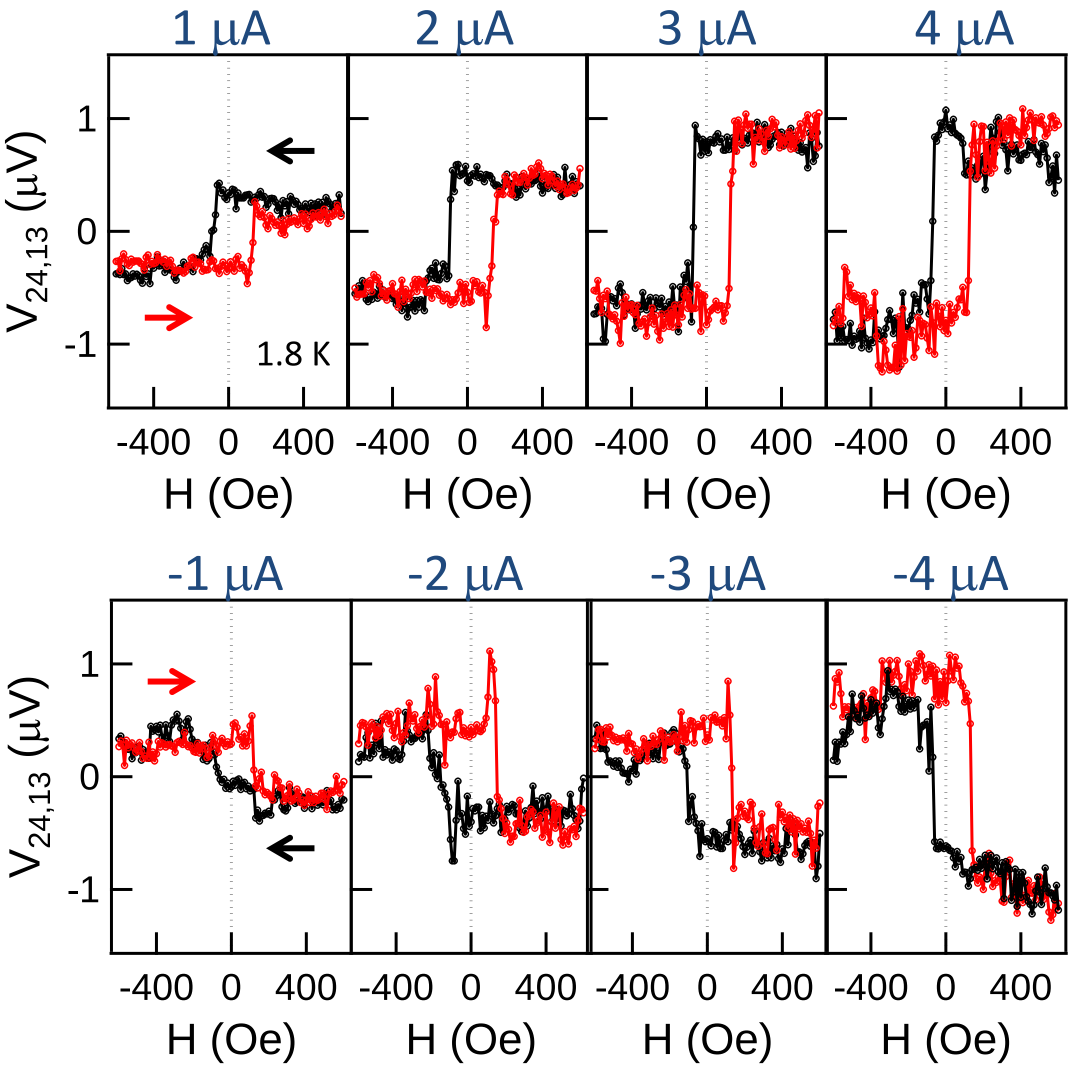
Lee *et al.*, *Phys. Rev. B* **92**, 155312 (2015)





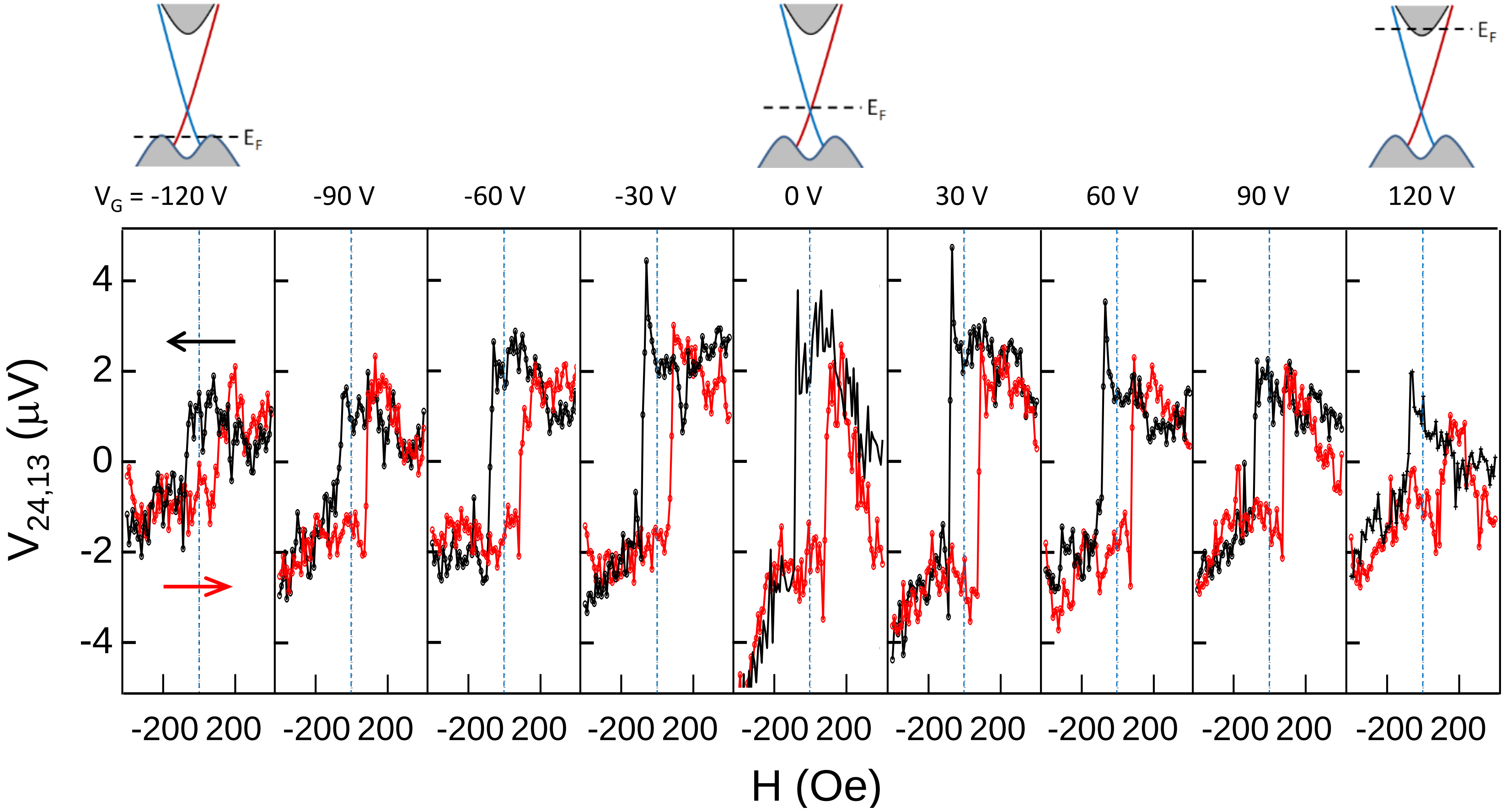






Hysteretic spin signal associated with TI spin polarization and Py switching.

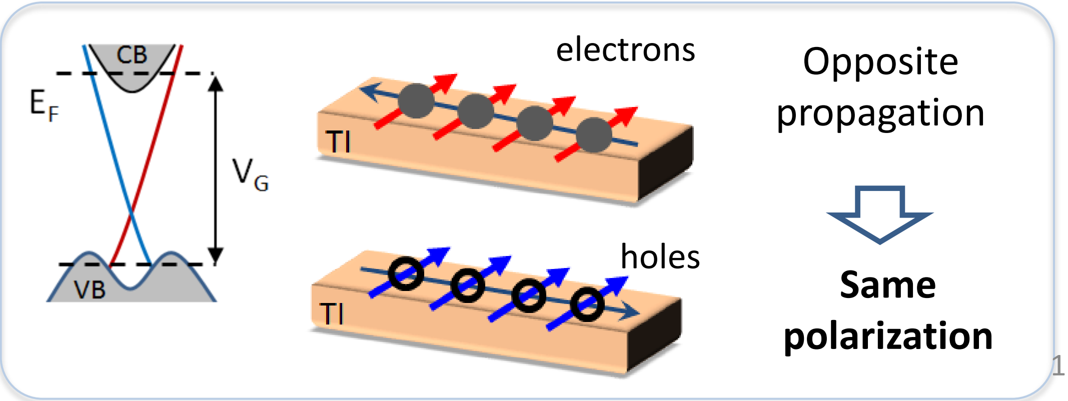
Detection of spin polarization with back gating



- Larger spin signals with the chemical potential near DP.
  → Minimal bulk effects.
- No change in the direction of spin polarization across DP.

Lee *et al.*, *Phys. Rev. B* **92**, 155312 (2015)

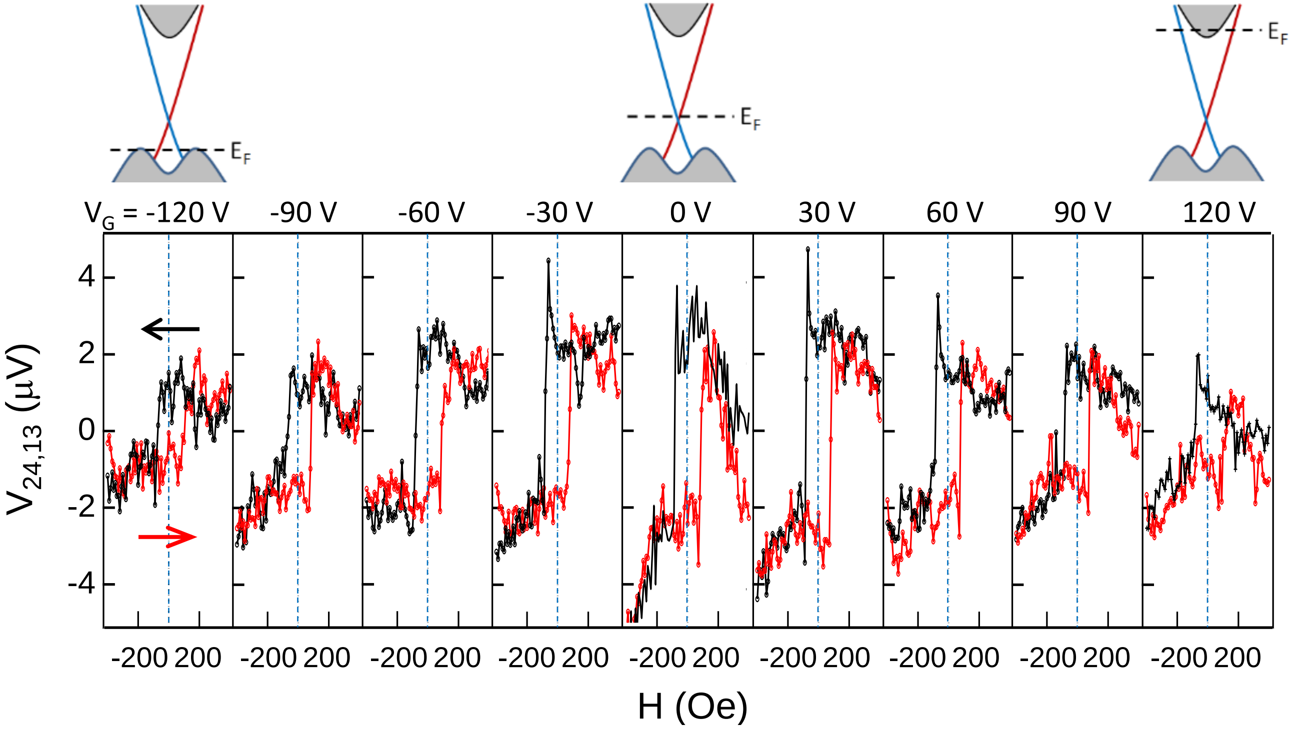
With a fixed DC current,



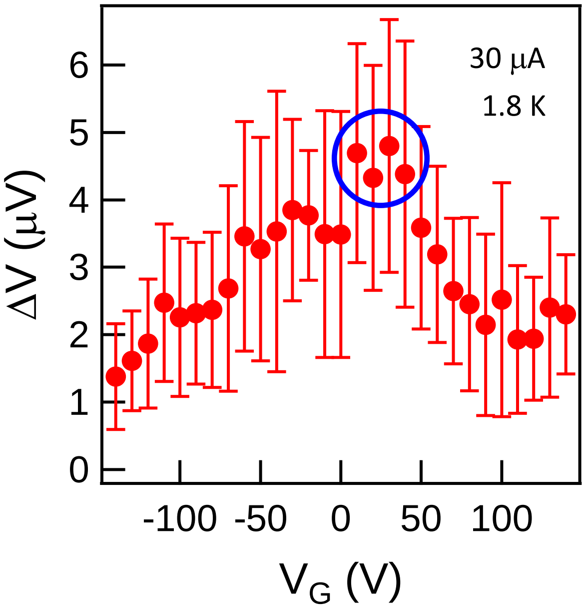
Opposite propagation

Same polarization

Detection of spin polarization with back gating



Lee *et al.*, *Phys. Rev. B* **92**, 155312 (2015)



Spin polarization of TI

$$\Delta V = I R_B \boxed{P_{TI}} P_{FM}$$

ΔV : detected spin signal

I : bias current

P_{FM} : spin polarization of Py

R_B : ballistic resistance

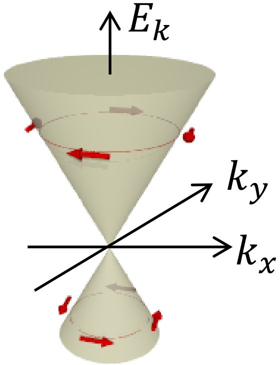
For μ near Dirac point,

P_{TI} = **0.42** ± 0.15 (Device A), **0.78** ± 0.26 (Device B)

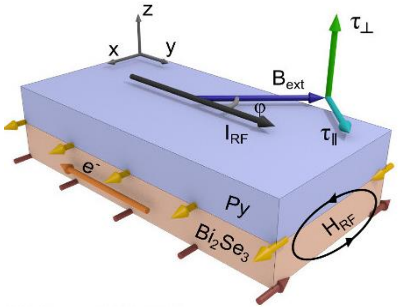
→ Comparable with theoretical calculations **0.5** ~ **2/π**.

Hong *et al., Phys. Rev. B.* **86**, 085131 (2012)
Yazyev *et al.,* Phys. Rev. Lett. **105**, 266806 (2010)

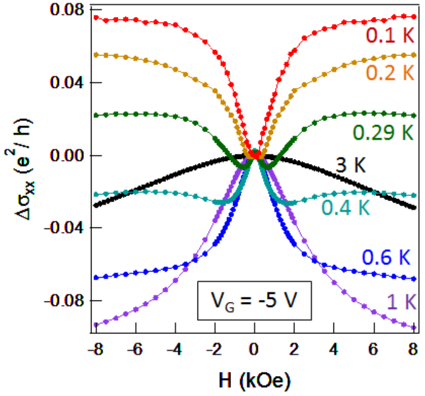
Outline



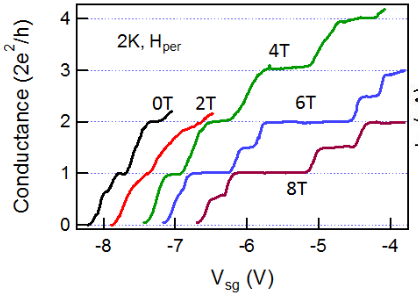
1. Spin-polarized surface states in 3D topological insulators
   - Electrical detection of spin polarization

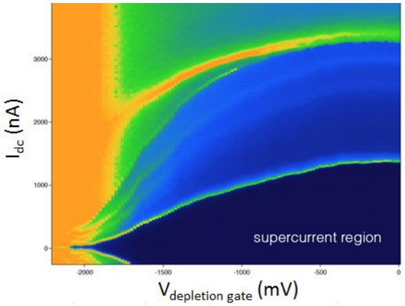


2. Spin-charge conversion in topological insulators
   - Charge-to-spin conversion: spin transfer torque
   - Spin-to-charge conversion: spin pumping



3. Modified surface states by breaking time-reversal symmetry
   - Interfacing a ferromagnetic insulator to a TI

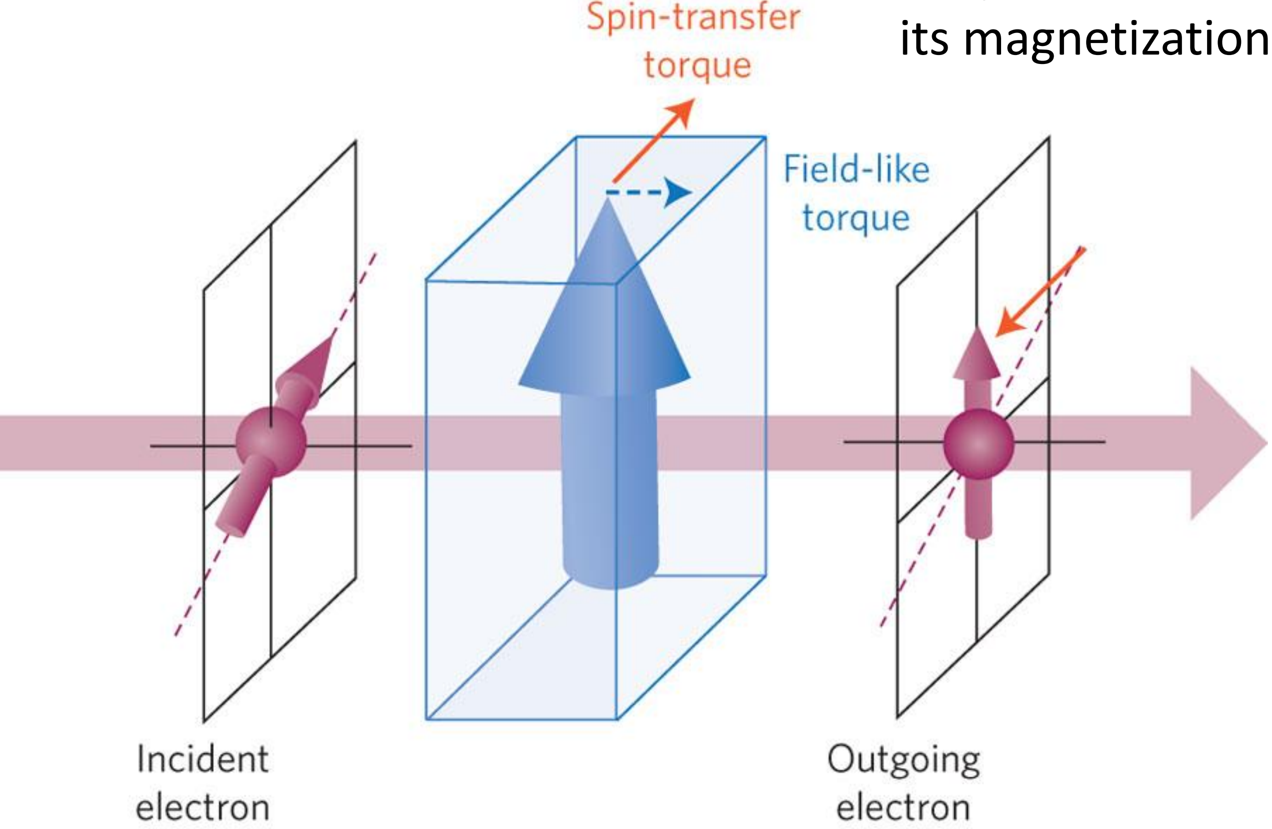




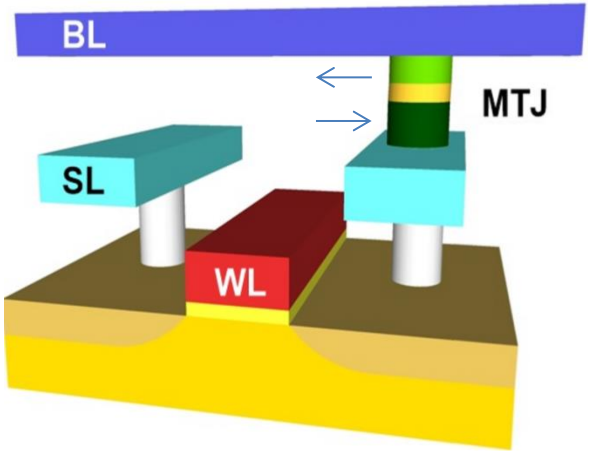
4. Topological superconductivity towards quantum computation
   - 1D transport and superconducting proximity effect in epi-Al/2DEG

Spin-transfer torque

Incident spin-polarized electron exerts a torque to a ferromagnet to precess/reverse its magnetization orientation.



Brataas, *et al., Nat. Mater.* **11**, 372 (2012)



cspin.umn.edu/newsletter

Applications:

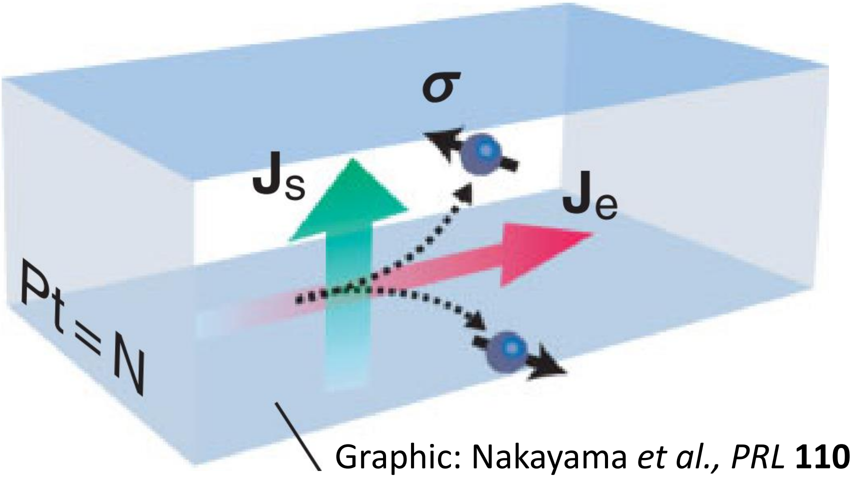
Magnetic random access memory (MRAM)

- Written by spin-transfer torque, read by tunnel magnetoresistance.

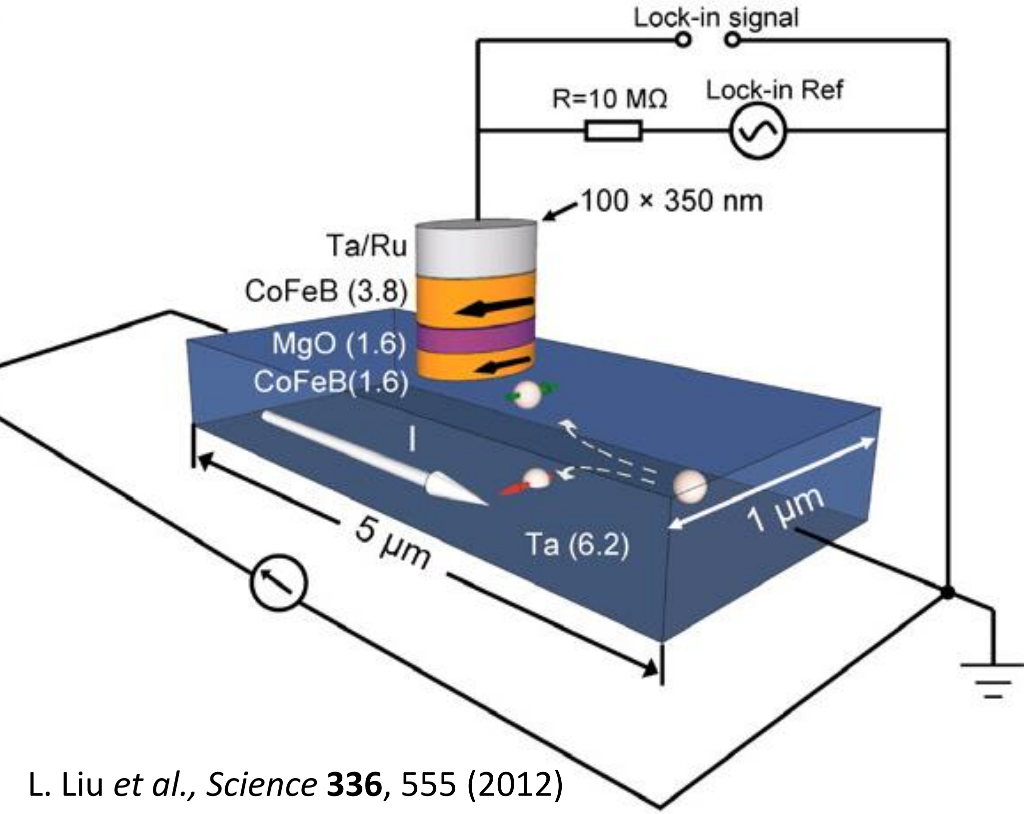
Source of spin current for spin-transfer torque

Spin Hall effect:

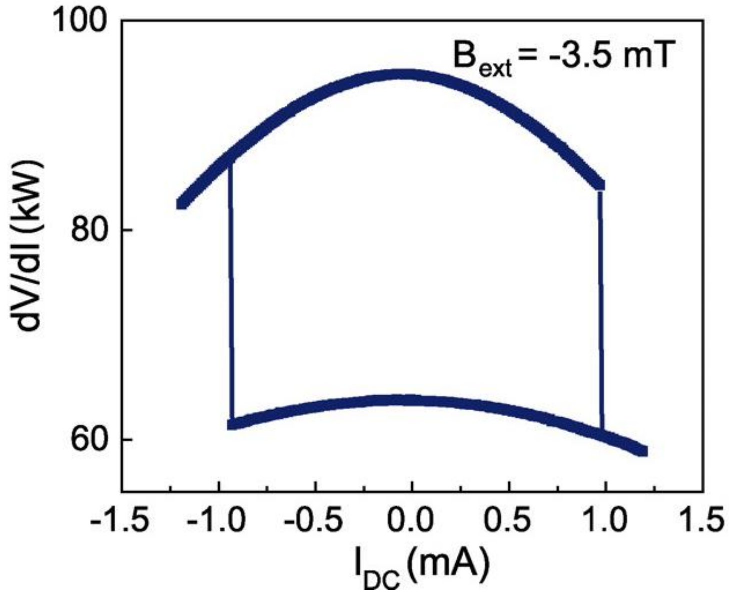
Strong spin-orbit interaction induces spin polarization and spin accumulation in semiconductors and heavy metals.



Graphic: Nakayama *et al.*, *PRL* **110**, 206601 (2013)



L. Liu *et al.*, *Science* **336**, 555 (2012)

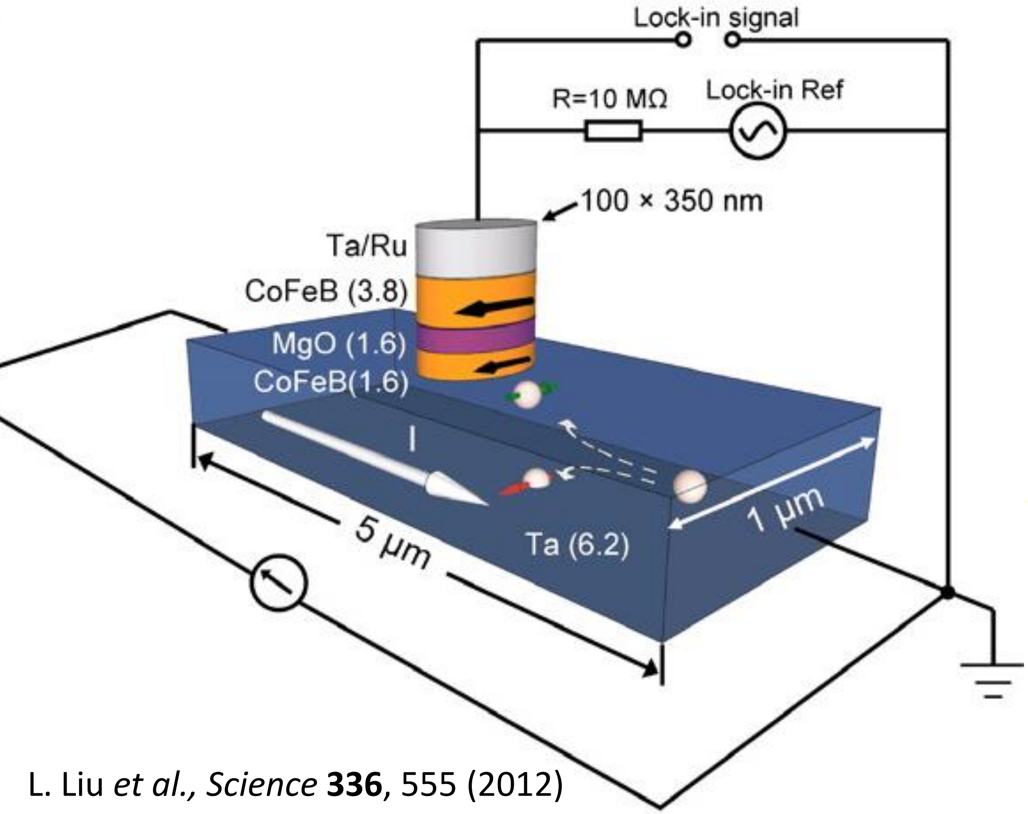


- Spin-transfer torque by spin Hall effect
- Measured by tunnel magnetoresistance

Source of spin current for spin-transfer torque

Spin Hall effect:

Strong spin-orbit interaction induces spin polarization and spin accumulation in semiconductors and heavy metals.



L. Liu *et al., Science* **336**, 555 (2012)

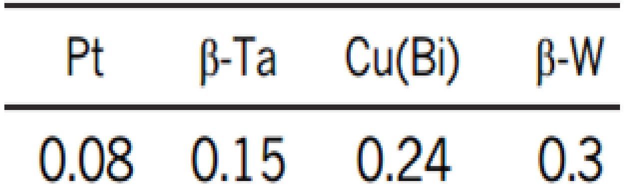
- Spin-transfer torque by spin Hall effect
- Measured by tunnel magnetoresistance

Charge-to-spin conversion efficiency:

- Spin Hall angle
- Spin torque ratio

$$\theta_{||} \equiv \frac{2e}{\hbar}\frac{J_{s,||}}{J} = \frac{2e}{\hbar}\frac{\sigma_{s,||}}{\sigma}$$

Currently studied materials



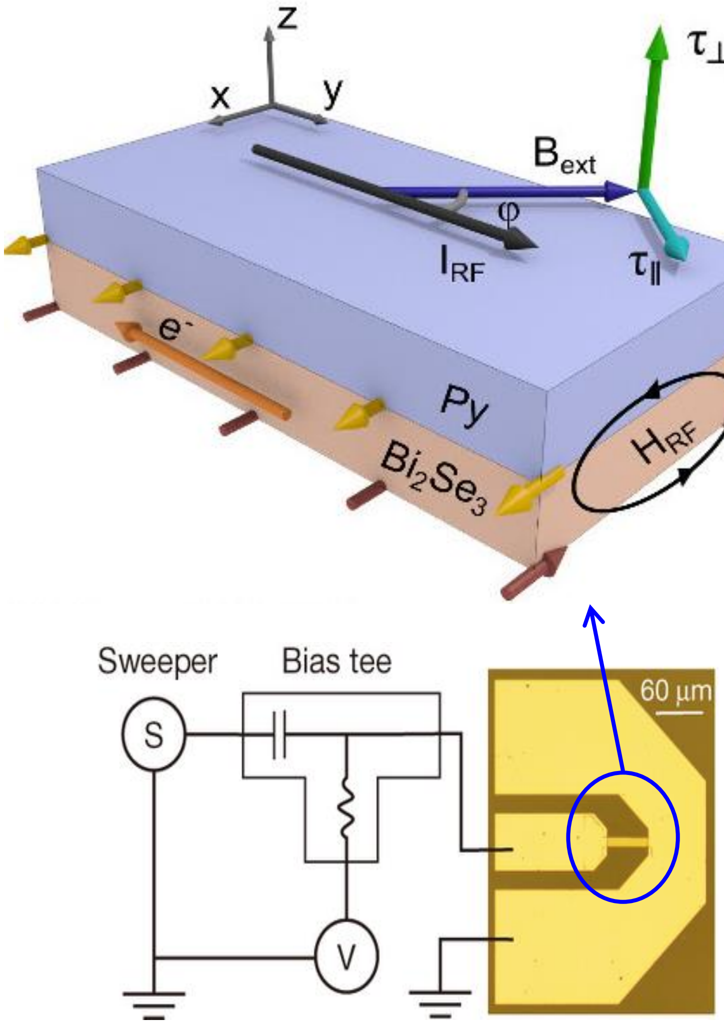
Pt	β-Ta	Cu(Bi)	β-W
0.08	0.15	0.24	0.3

Liu *et al.*, *PRL* **106**, 036601 (2011)
Miron *et al. Nature* **476**, 189 (2011)
Niimi *et al.*, *PRL* **109**, 156602 (2012)
Pai *et al.*, *APL* **122**, 101404 (2012)

More efficient charge-to-spin conversion by topological insulators?

Spin-transfer torque by a topological insulator

Current-induced spin current in Bi_2Se_3 exerts strong spin-transfer torque to Py layer.



Spin-torque measured by ferromagnetic resonance (FMR)

rf-current through Bi_2Se_3/Py with B_{ext}

↓

Precessing Py magnetization & oscillating TI spin current

↓

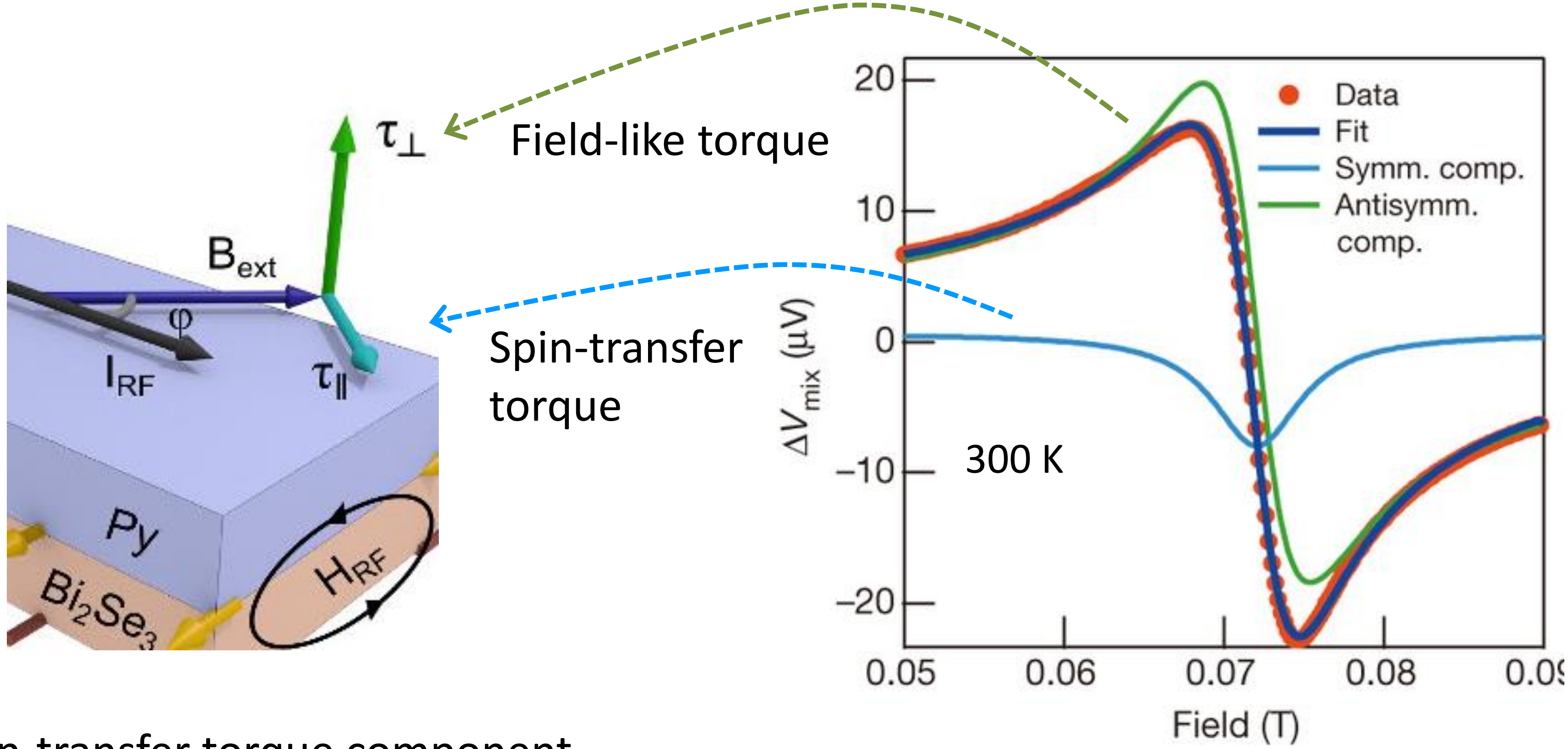
Precession perturbed by torques from the spin current

↓

Measure DC mixing voltage

Mellnik, Lee *et al.*, *Nature* **511**, 449 (2014)

Spin-transfer torque by a topological insulator



Field-like torque

Spin-transfer torque

300 K

Spin-transfer torque component could be induced by TI surface states or Rashba states.

→ sign consistent with topological surface states

$$\theta_{||} \equiv \frac{2e}{\hbar}\frac{J_{s,||}}{J}$$

Bi_2Se_3	Pt	β-Ta	Cu(Bi)	β-W
1 ± 0.4	0.08	0.15	0.24	0.3

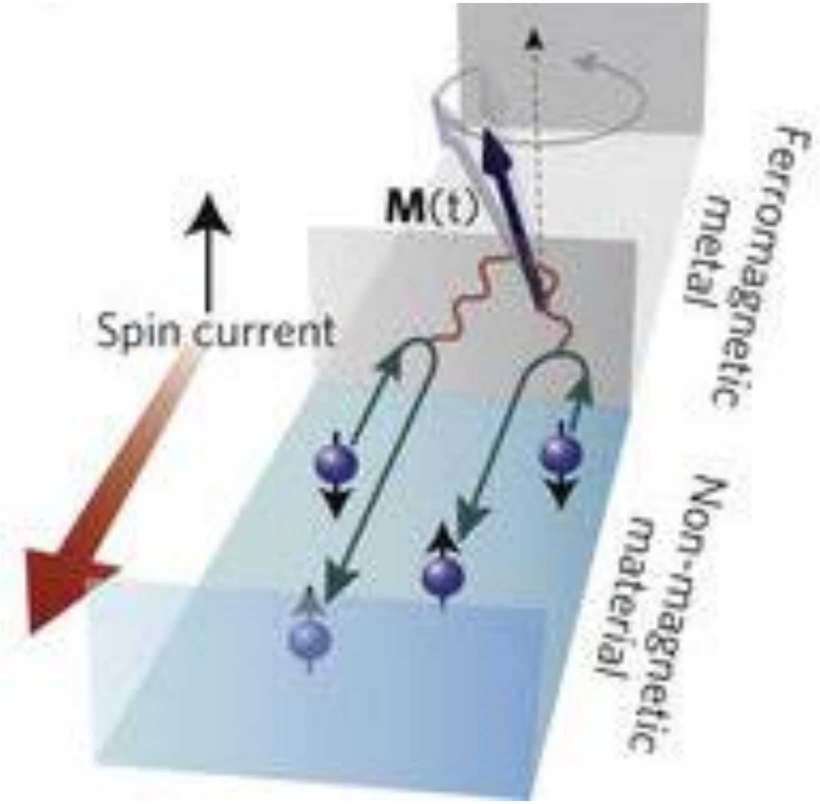
Mellnik, Lee *et al.*, *Nature* **511**, 449 (2014)

Efficient charge-to-spin conversion by topological surface states.

Spin-to-charge conversion by spin pumping

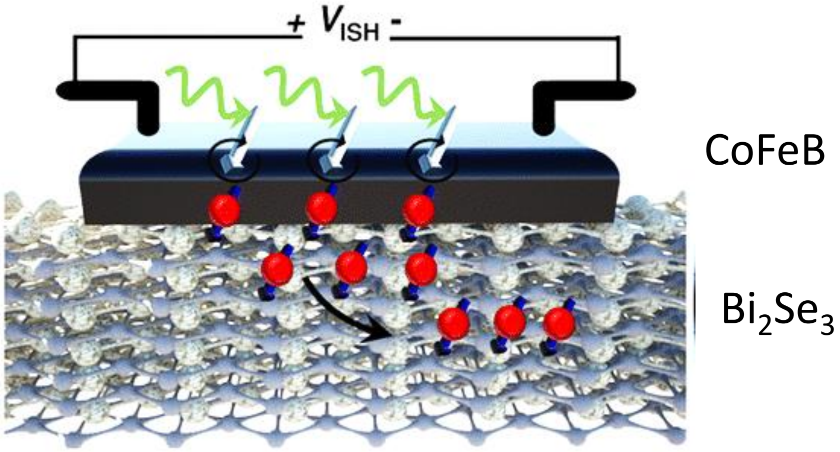
Spin pumping:

Precessional magnetization dynamics of a ferromagnet injects a spin current into an adjacent layer.



Ando *et al.*, *Nature Mater.* **10**, 655 (2011)

Spin pumping into Bi_2Se_3 from CoFeB



FMR-driven spin pumping

Precessing FM magnetization by external rf-magnetic field

↓

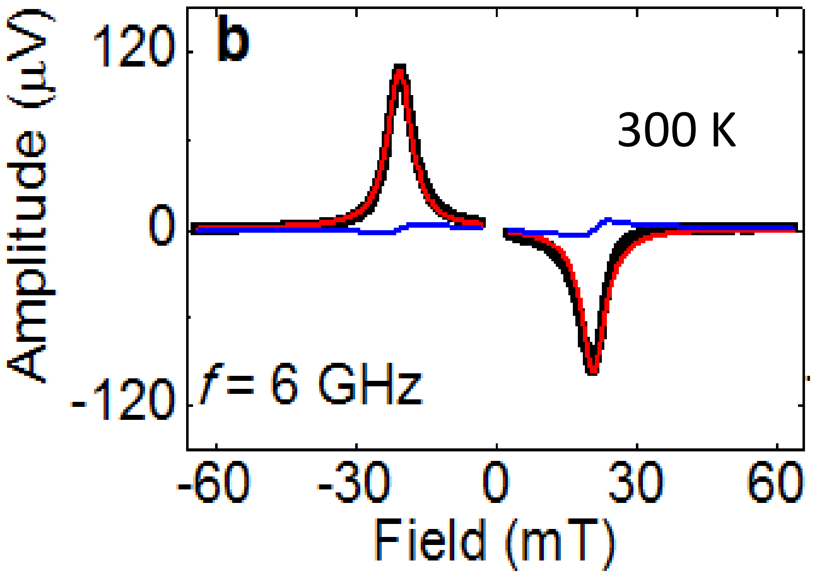
Injecting a spin current into Bi_2Se_3

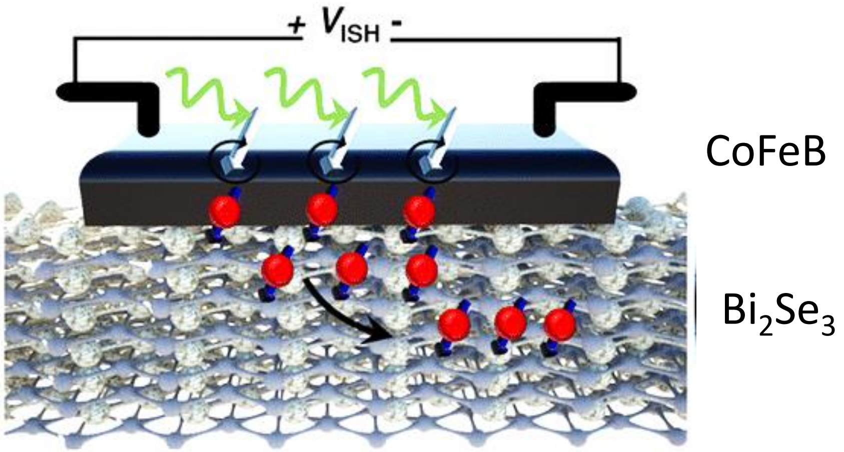
↓

Spin current into charge current by inverse spin Hall effect

Jamali, Lee *et al.*, *Nano Lett.* **15**, 7126 (2015)

Spin pumping into Bi_2Se_3 from a metallic FM





Jamali, Lee *et al.*, *Nano Lett.* **15**, 7126 (2015)

$$\theta_{\|} \equiv \frac{2e}{\hbar}\frac{J_{s,\|}}{J} = \frac{2e}{\hbar}\frac{\sigma_{s,\|}}{\sigma}$$

Resulting spin Hall angle:
0.43 at room temperature

Spin-to-charge conversion mechanisms

1) Inverse Edelstein effect (IEE) by surface states
2) <u>Inverse spin Hall effect (ISHE) by bulk</u>

→ dominent!

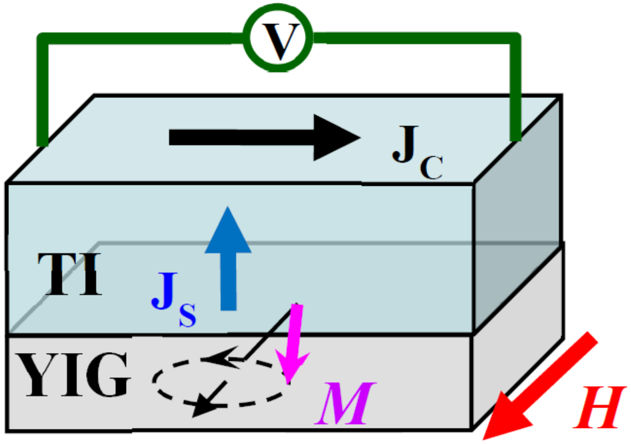
Issues in spin-charge conversion experiments

- “Surface effect” vs “Bulk effect”
- Shunting of charge current by metallic FM

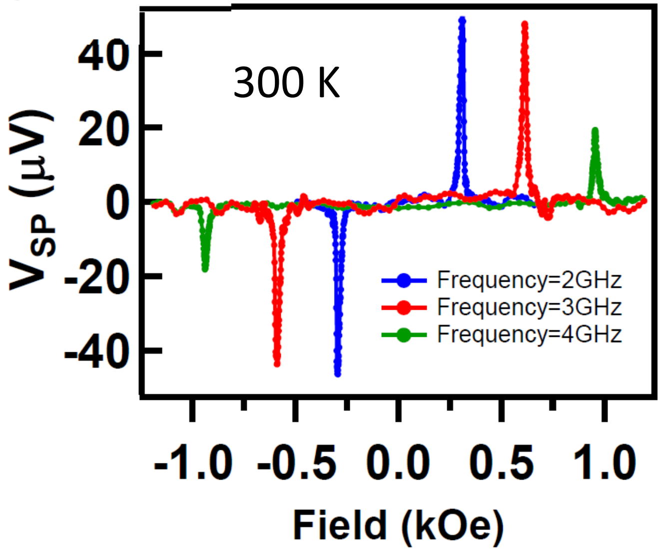
Spin pumping into Bi_2Se_3 from an insulating FM

Avoiding shunting of current using an Insulating ferromagnet.

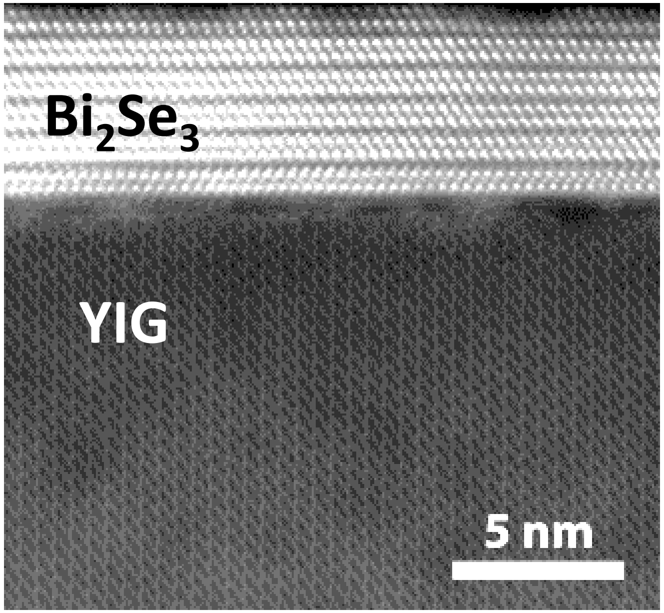
$Y_3Fe_5O_{12}$ (YIG) : insulating ferromagnet with a low damping constant



FMR-driven spin pumping



MBE-grown Bi2Se3 on YIG

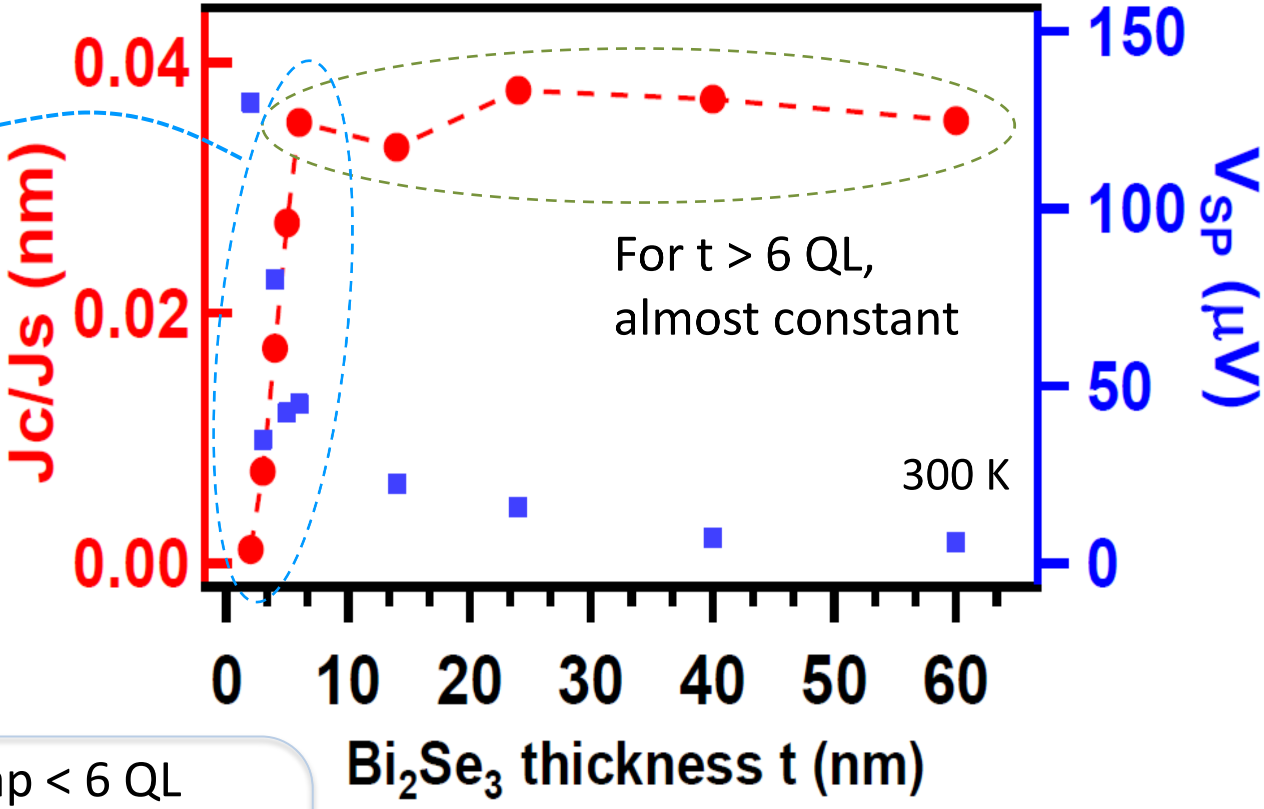


- Two-step growth of Bi2Se3 film
- Disorders at the interface (~1 nm)

Wang, Kally, Lee *et al*., Phys. Rev. Lett. **117**, 076601 (2016)

Thickness dependence of spin pumping using YIG

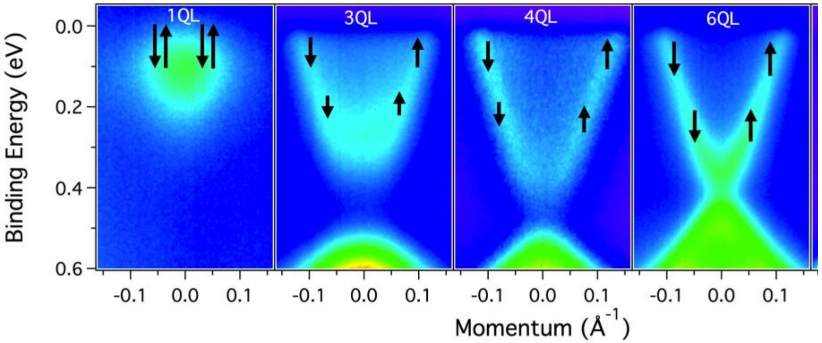
Jc/Js = Spin-to-charge conversion efficiency. (Jc, Js: spin, charge current density)



For t < 6 QL, Spin-to-charge efficiency drops rapidly.

For t > 6 QL, almost constant

Recall – hybridization gap < 6 QL



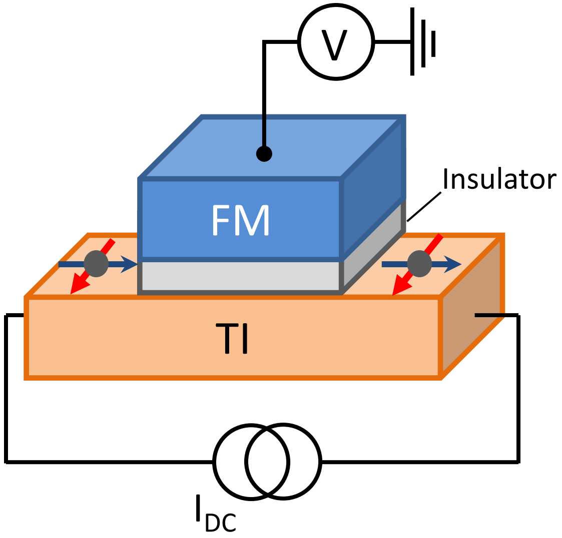
M. Neupane *et al.*, *Nat. Comm*. **5**, 3841 (2014)

Surface states are dominant in spin-to-charge conversion in Bi_2Se_3.

Wang, Kally, Lee *et al.*, Phys. Rev. Lett. **117**, 076601 (2016)

Summary of Part 1 and 2

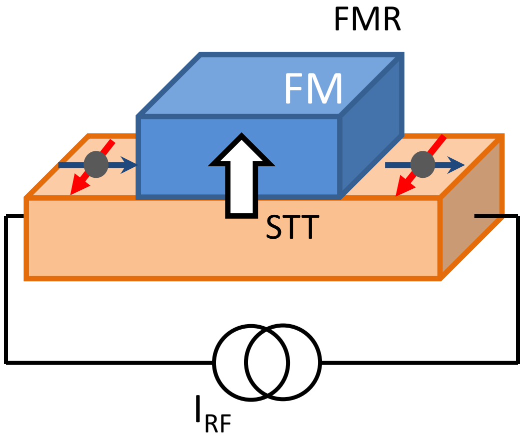
Detecting Spin polarization in topological surface states



- DC current through TI generates spin polarization.
- Use FM as a spin detector.

Lee *et al.*, *PRB* (2015)

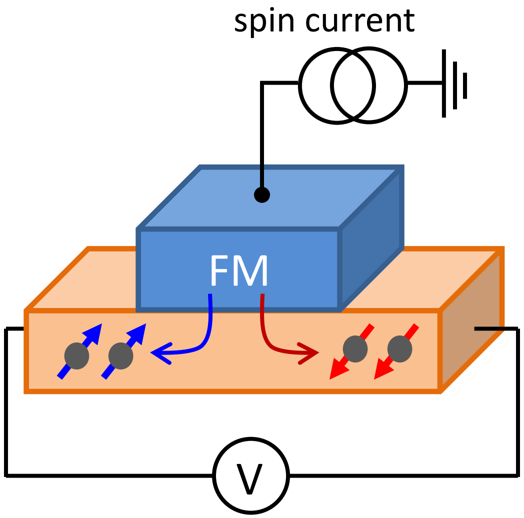
Charge-to-spin conversion Spin-transfer torque by TI



- rf current through TI exerts spin-transfer torque onto FM.
- Detected by FMR.

Mellnik, Lee *et al.*, *Nature* (2014)

Spin-to-charge conversion Spin pumping into TI



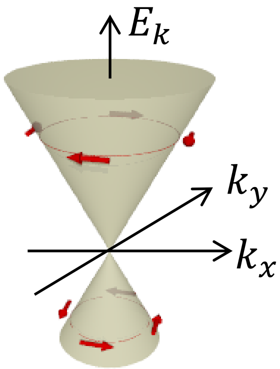
- Spin current from FM into TI.
- Detection of electromotive force by spin-orbit interaction.

Jamali, Lee *et al.*, *Nano Lett.* (2015)

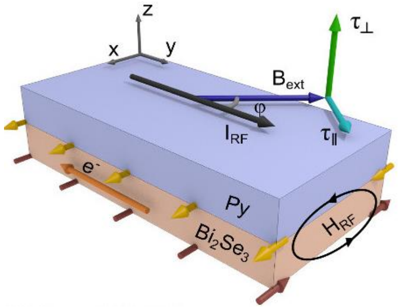
Wang, Kally, Lee *et al.*, *PRL (*2016)

Anything more to consider near Dirac point?

Outline



1. Spin-polarized surface states in 3D topological insulators
   - Electrical detection of spin polarization



2. Spin-charge conversion in topological insulators
   - Charge-to-spin conversion: spin transfer torque
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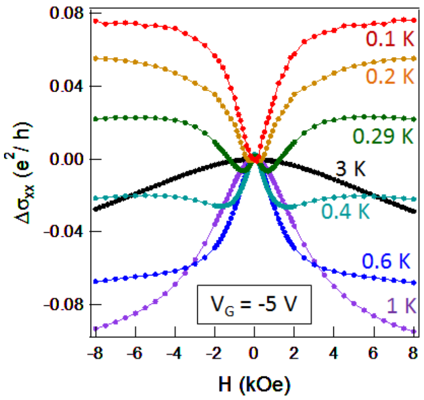
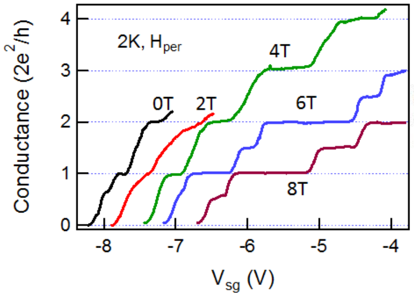
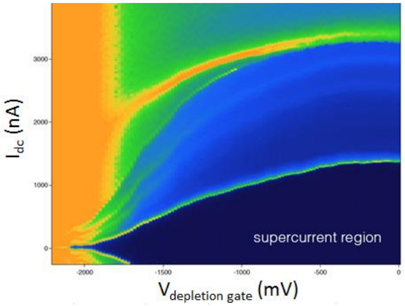
3. Modified surface states by breaking time-reversal symmetry
   - Interfacing a ferromagnetic insulator to a TI







4. Topological superconductivity towards quantum computation
   - 1D transport and superconducting proximity effect in epi-Al/2DEG

Magnetic surface phases modified by broken TR symmetry

TI surface states can be modified by introducing magnetism.

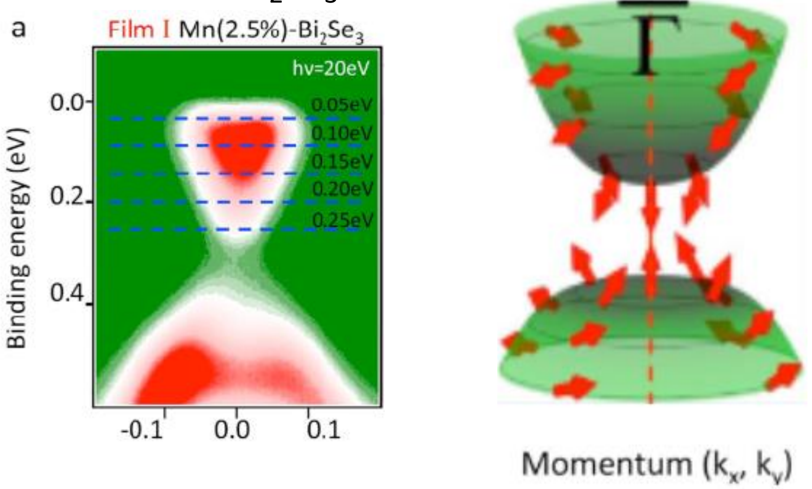
$$H_{surf}(k_x, k_y) = \hbar v_F(\sigma^x k_y - \sigma^y k_x) + \sum_{a=x,y,z} m_a \sigma^a$$

$$E_k = \pm\sqrt{(\hbar v_F k_y + m_x)^2 + (\hbar v_F k_x - m_y)^2 \boxed{+ {m_z}^2}}$$

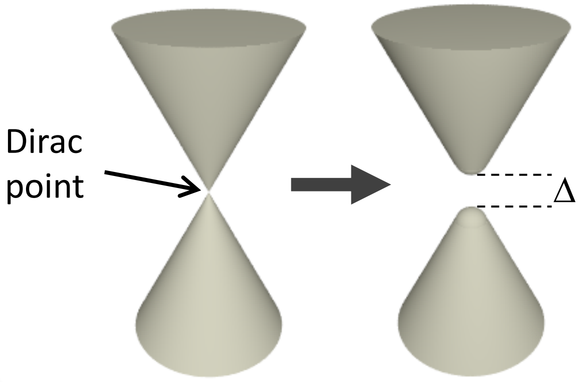
m_z induces an energy gap.

Hedgehog-like spin texture

Mn-Bi$_2$Se$_3$



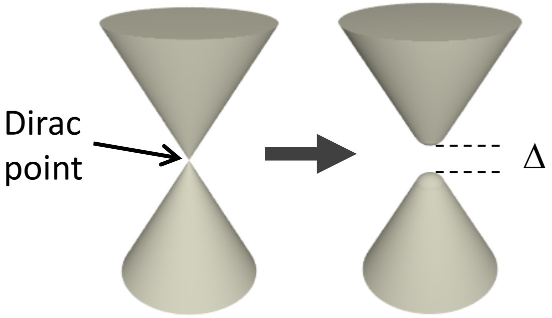
Xu *et al.*, *Nat. Phys.* **8**, 616 (2012)



- m_z can be introduced by
  - magnetic doping
  - interfacing a magnetic layer

Interfacing insulating FM to a topological insulator

Interfacing a magnetic layer breaks time-reversal symmetry and opens a gap at the Dirac point.



Experimental challenge:

How to measure the modified surface state from the buried interface?

- No ARPES and no STM. Probably electrical transport?

Need to develop…

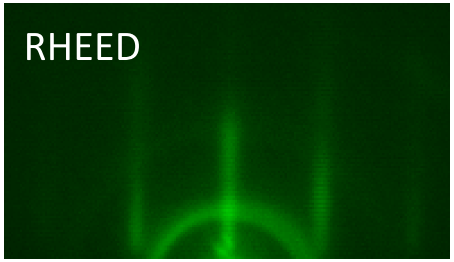
(1) Topological insulator with E_F near the Dirac point.
(2) Insulating FM with perpendicular magnetization.
(3) Clean, well-defined TI/FM interface.

Topological insulator/GaMnAs heterostructure by MBE

☑ Topological insulator with E_F near the Dirac point.
☑ Insulating FM with perpendicular magnetization.
☐ Clean, well-defined TI/FM interface.

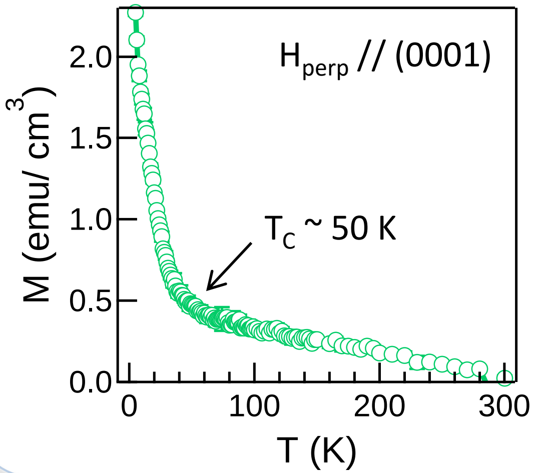
[TI] $(Bi,Sb)_2(Te,Se)_3$

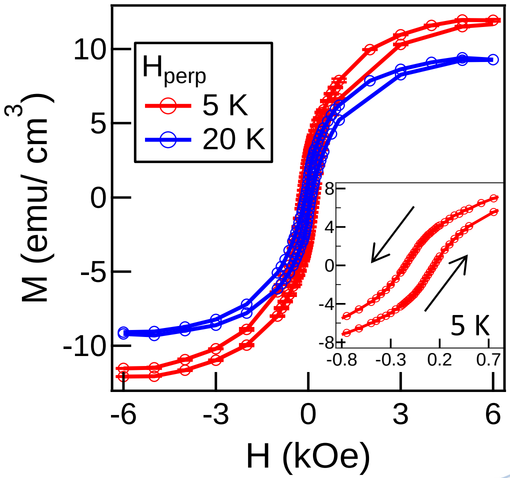
- ~8 QL TI thin film grown by MBE.
- E_F in the surface state.
  (Bi:Sb≈1:1, Te:Se ≈2:1)
- Further E_F tuning by top-gating.



[FM] $(Ga_{1-x}Mn_x)As$ on InP (111)A

- Perpendicular component of magnetization.
- Low Mn doping (Mn≈0.05) → highly resistive.



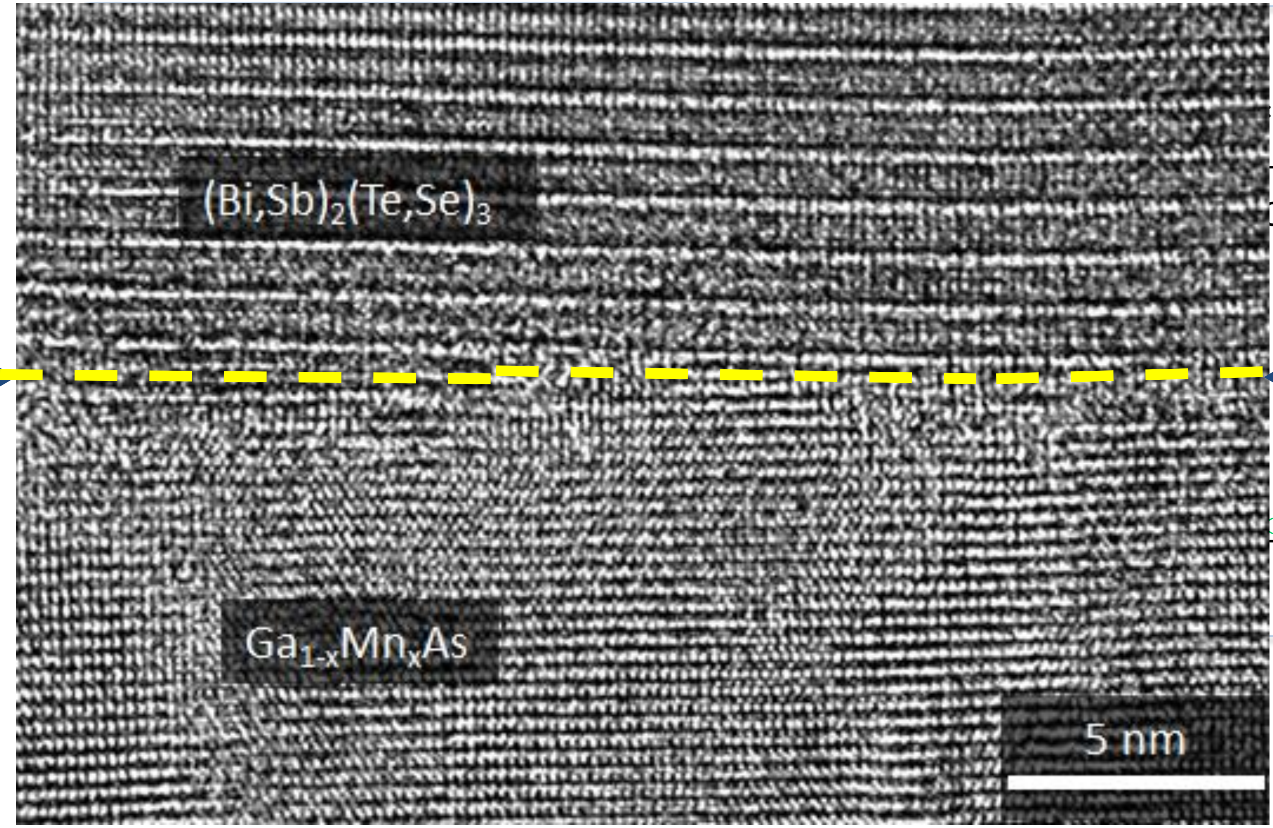


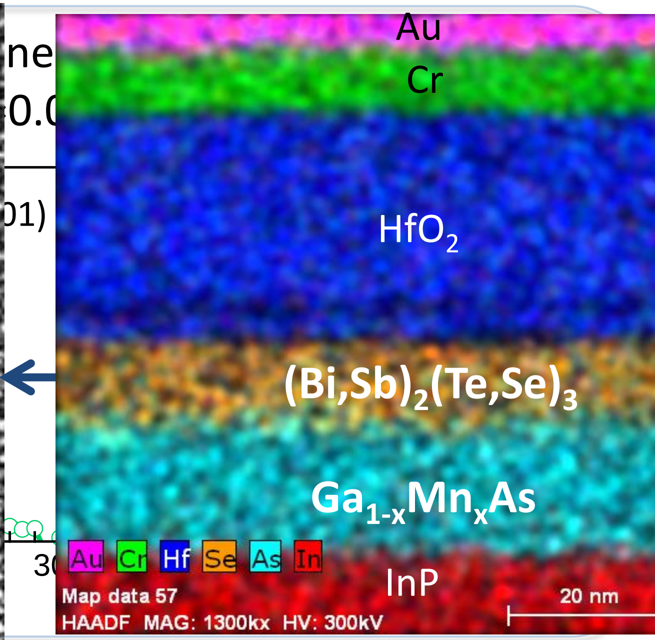
Topological insulator/GaMnAs heterostructure by MBE

- ☑ Topological insulator with E_F near the Dirac point.
- ☑ Insulating FM with perpendicular magnetization.
- ☑ Clean, well-defined TI/FM interface.

[TI] $(Bi,Sb)_2(Te,Se)_3$

[FM] $(Ga_{1-x}Mn_x)As$ on InP (111)A

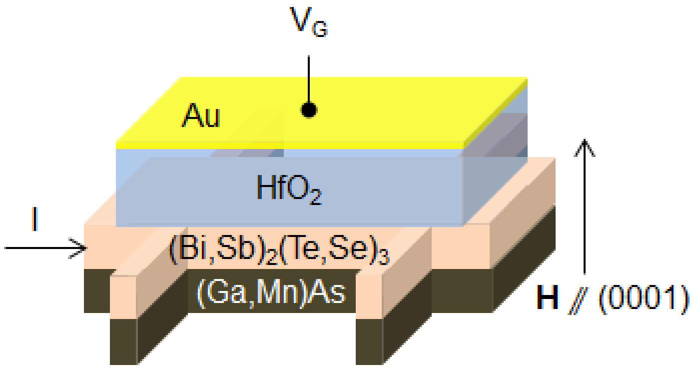


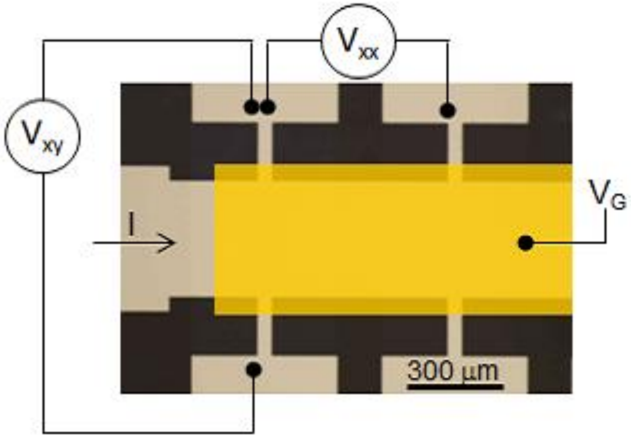


Energy dispersive x-ray spectroscopy

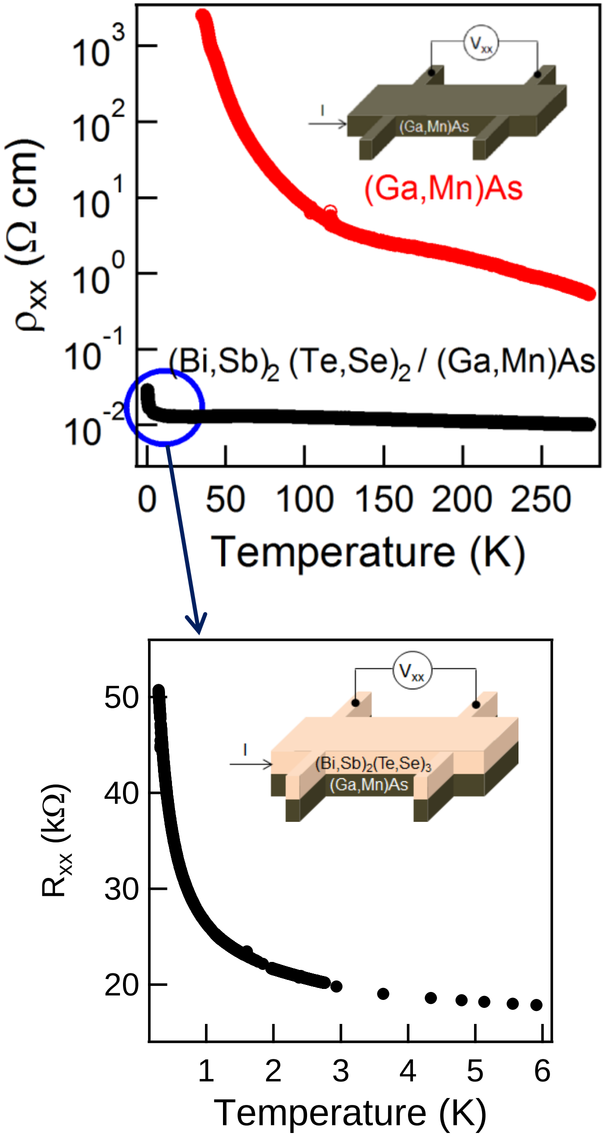
Electrical transport using a top-gated Hall bar device

Our approach: Transport measurements
for evidencing the modified surface states



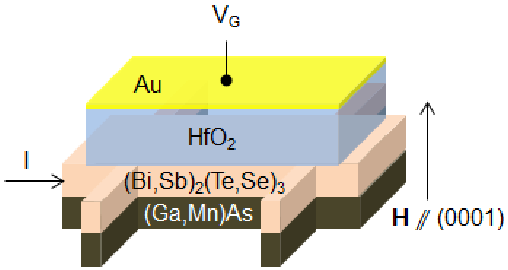


- HfO_2 (25 ~ 30 nm) by evaporation and ALD.
- Hall bar: 650 μm x 400 μm
- Patterned by standard photo-lithography.

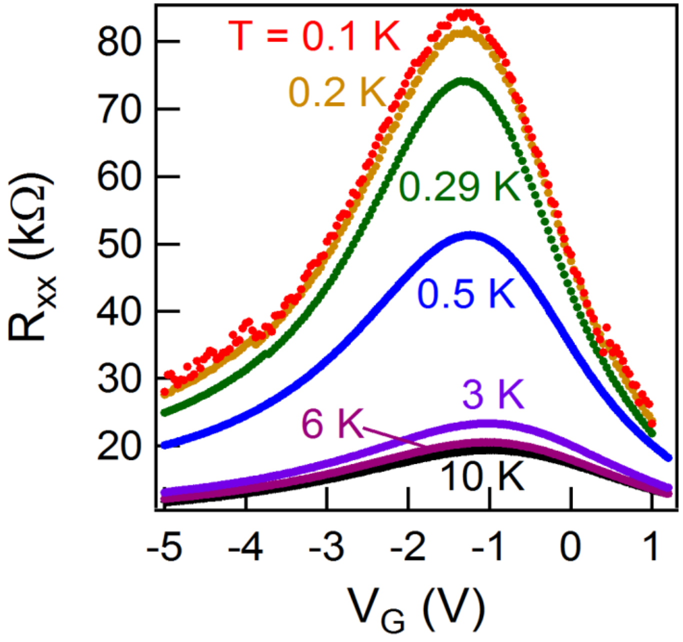


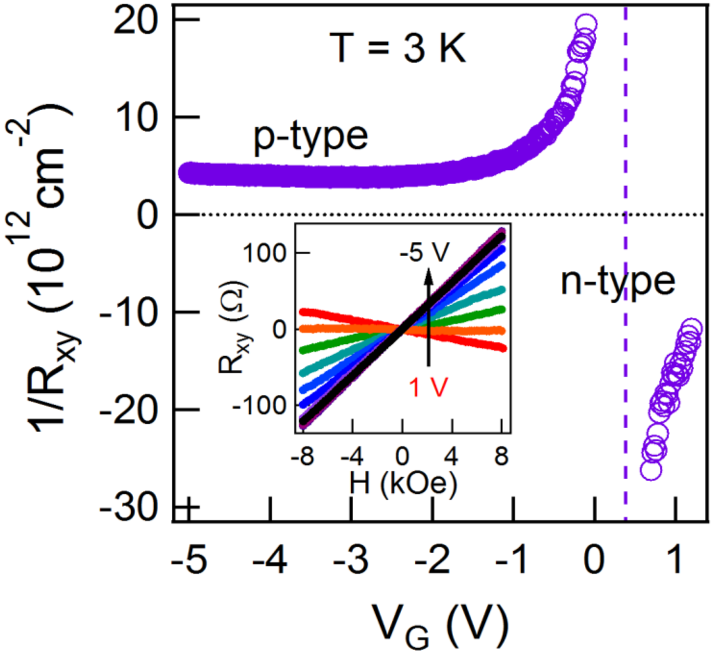
→ Current flows through TI layer.

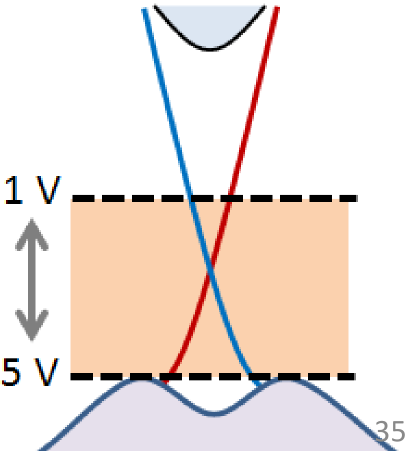
Ambipolar transport in $(Bi,Se)_2(Se,Te)_3$/GaMnAs



- Gate-voltage dependence reveals ambipolar transport.

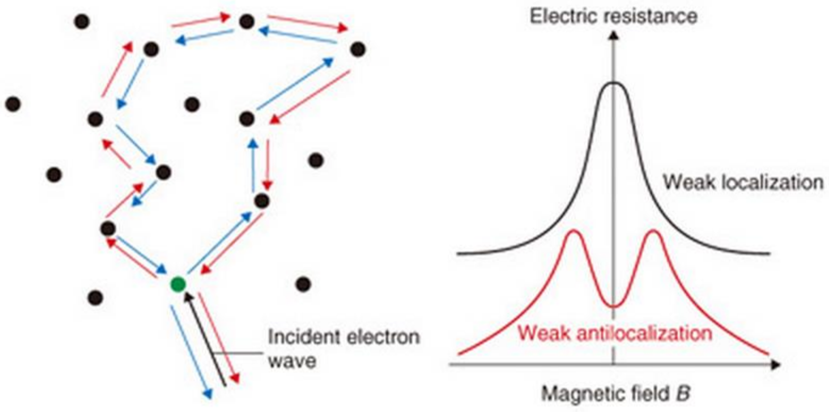






- n-type to p-type change.
- In the V_G range, chemical potential is in a region where bulk is depleted.

Quantum corrections of weak (anti)localization



https://www.nttreview.jp/anqtest/archive/ntttechnical.php?contents=ntr201209fa4.html

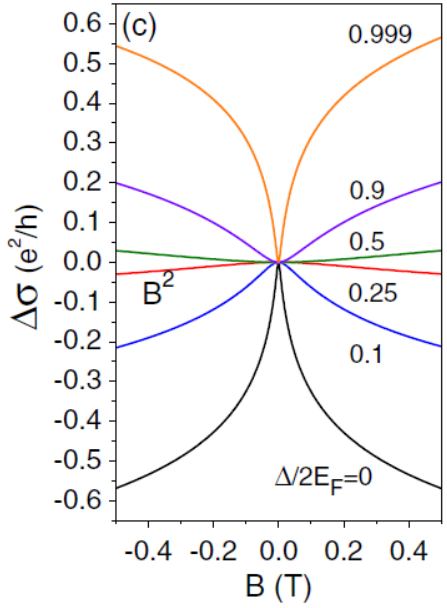
Weak (anti-)localization

Constructive (destructive) interference between time-reversal paths around self-intersecting loops when phase coherence is maintained leads to WL (WAL).

- 3D topological insulators: WAL

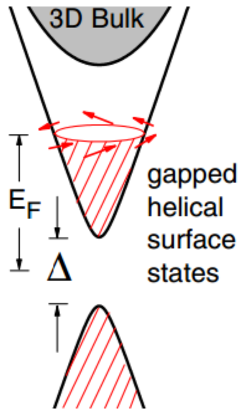
  - from the π Berry phase of electrons going around the Fermi circle of the Dirac surface state.

Crossover between WAL and WL in TI



WL

WAL



Modified Berry phase

$$\psi_{\mathbf{k}}(\mathbf{r}) = \pi\left(1-\frac{\Delta}{2E_F}\right)$$

(Δ: gap, E_F: Fermi energy)

$$\begin{cases} \text{For } \Delta = 0 \text{ or } E_F \gg \Delta: & \varphi = \pi \\ \text{For } \Delta = 2E_F: & \varphi = 0 \end{cases}$$

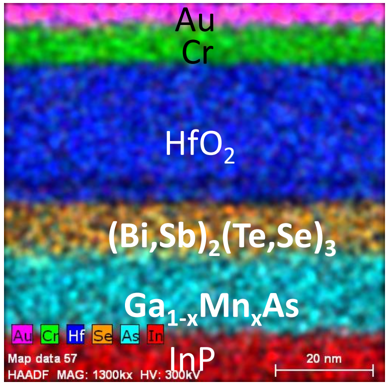
Lu *et al.*, Phys. Rev. Lett. **107**, 076801 (2011).

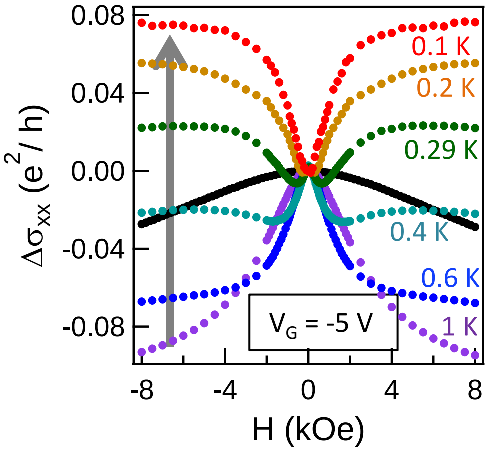
Summary of Part 3

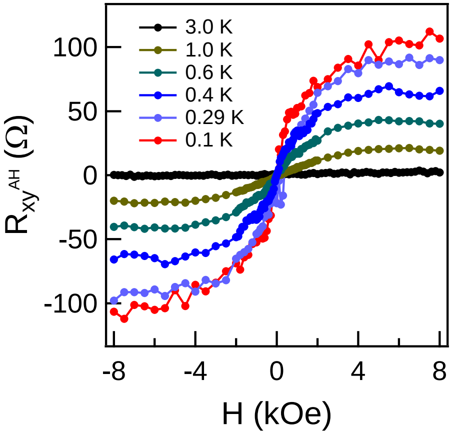
- To evidence the modified surface states by broken TR symmetry, we developed $(Bi,Sb)_2(Te,Se)_3/(Ga,Mn)As$ heterostructure.

- Crossover between WAL and WL as well as systematic emergence of AHE with varying T and V_G.
  → interpreted as a result of the Berry phase modification by a gap opening and chemical potential tuning.

- The results suggest that systematic changes in WAL and AHE can be used as probes of modified surface states.

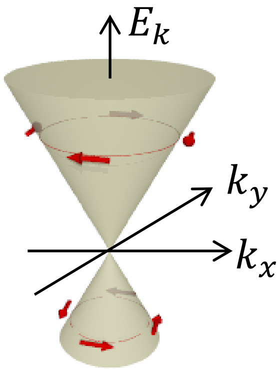




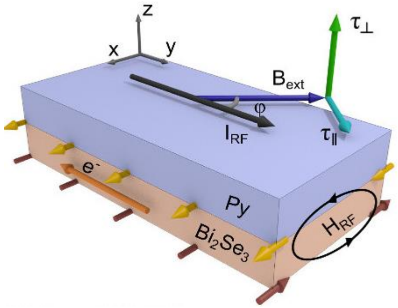


Lee *et al., in preparation*

Outline

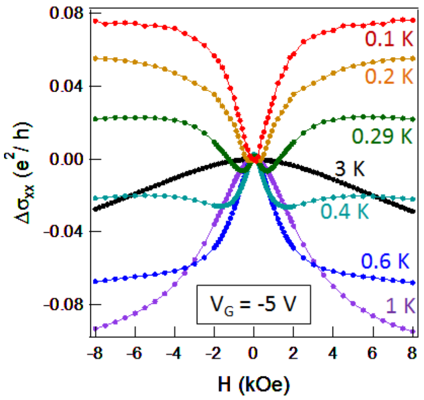


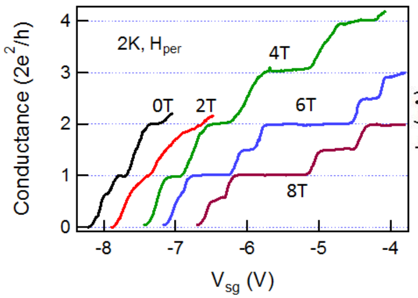
1. Spin-polarized surface states in 3D topological insulators
   - Electrical detection of spin polarization

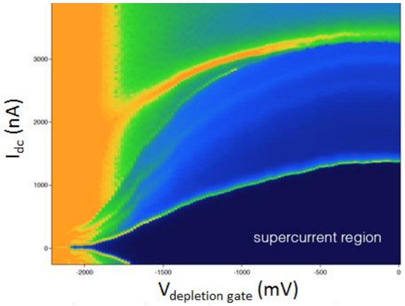


2. Spin-charge conversion in topological insulators
   - Charge-to-spin conversion: spin transfer torque
   - Spin-to-charge conversion: spin pumping

3. Modified surface states by breaking time-reversal symmetry
   - Interfacing a ferromagnetic insulator to a TI



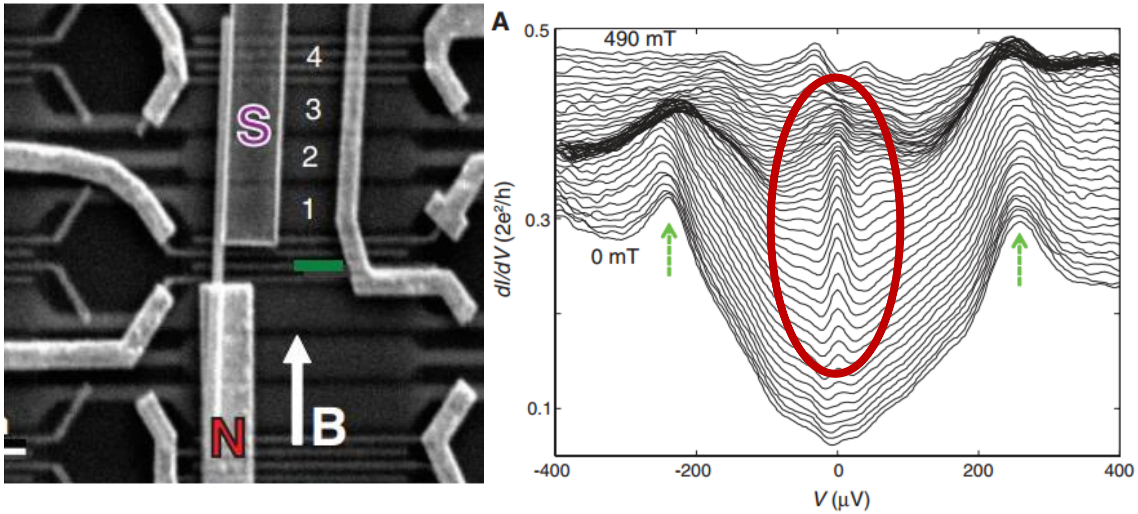




4. Topological superconductivity towards quantum computation
   - 1D transport and superconducting proximity effect in epi-Al/2DEG

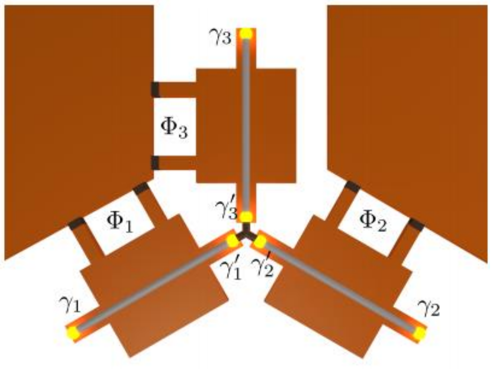
Motivation for epi-Al/InAs QW

Majorana fermions – zero energy mode



Mourik *et al., Science* **336**, 1003 (2012)

Braiding Majorana fermions for quantum computation



Beenakker, *Annu. Rev. Condens. Matter* **4**, 113 (2013)

Current issues: 1) soft gap of superconducting proximity,
2) difficulties in large scale fabrication using nanowires.

Current approach

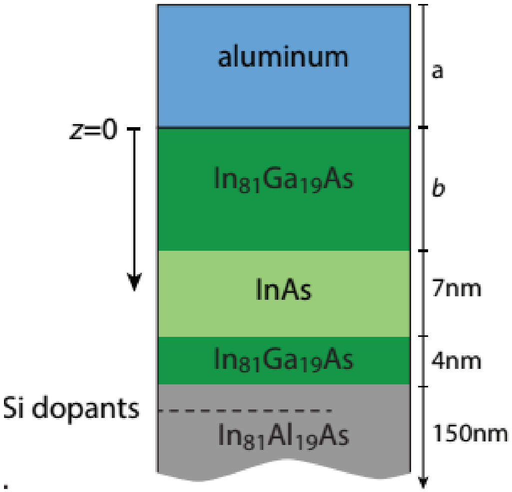
1. 1D nanowire with strong spin-orbit coupling
2. Superconducting proximity <sputtered vs epitaxial>

Our approach

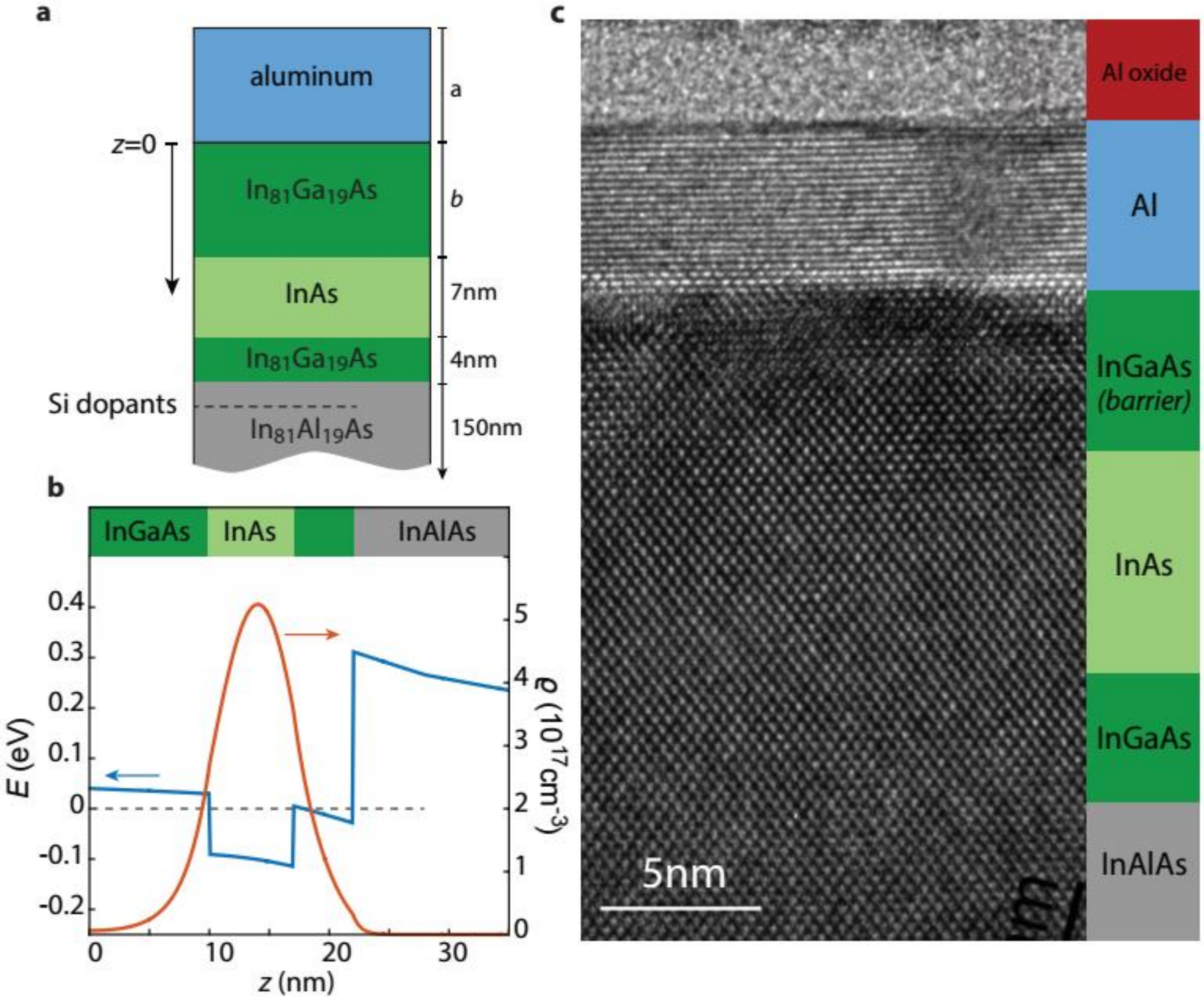
Fabricated 1D structure from 2DEG

Epitaxial superconductor

Epitaxial Al on InAs QW



Epitaxial Al/InAs QW on InP substrate



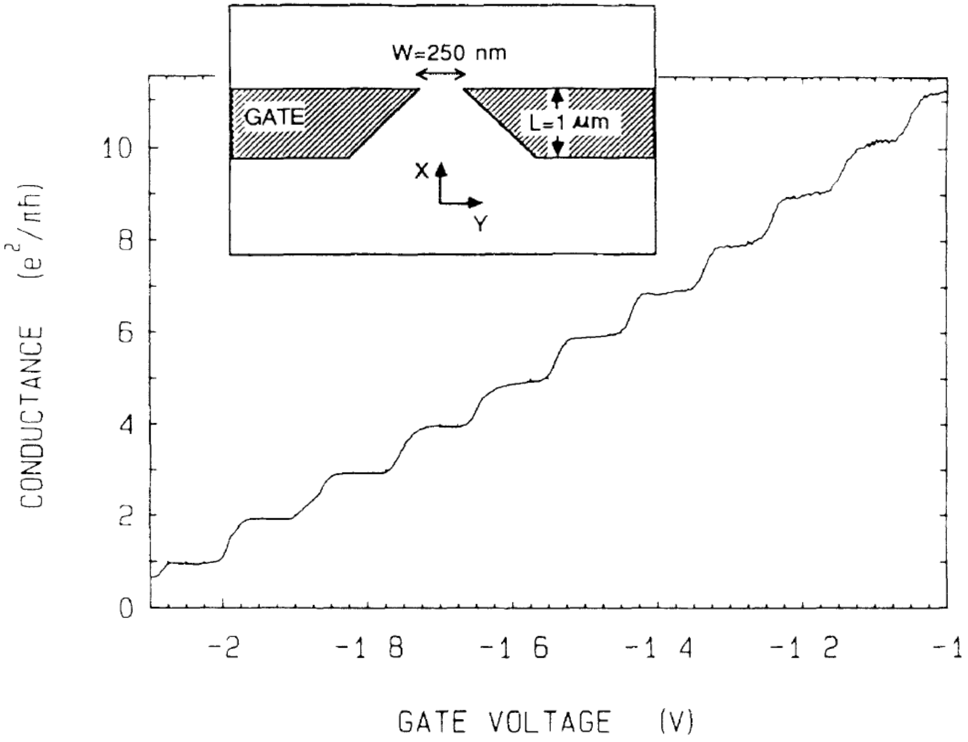
Shabani *et al.*, *PRB* **93**, 155402 (2016)

1D ballistic transport: Quantum point contact

QPC: narrow constriction in a 2DEG

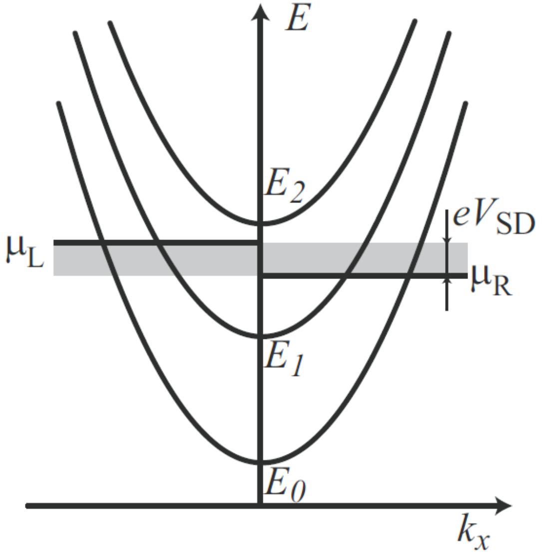
width (W) ~ Fermi wavelength (λ_F)
W << mean free path

Quantized conductance: $G = \frac{2e^2}{h} N$



Van Wees *et al.*, *PRL* **60**, 848 (1988)

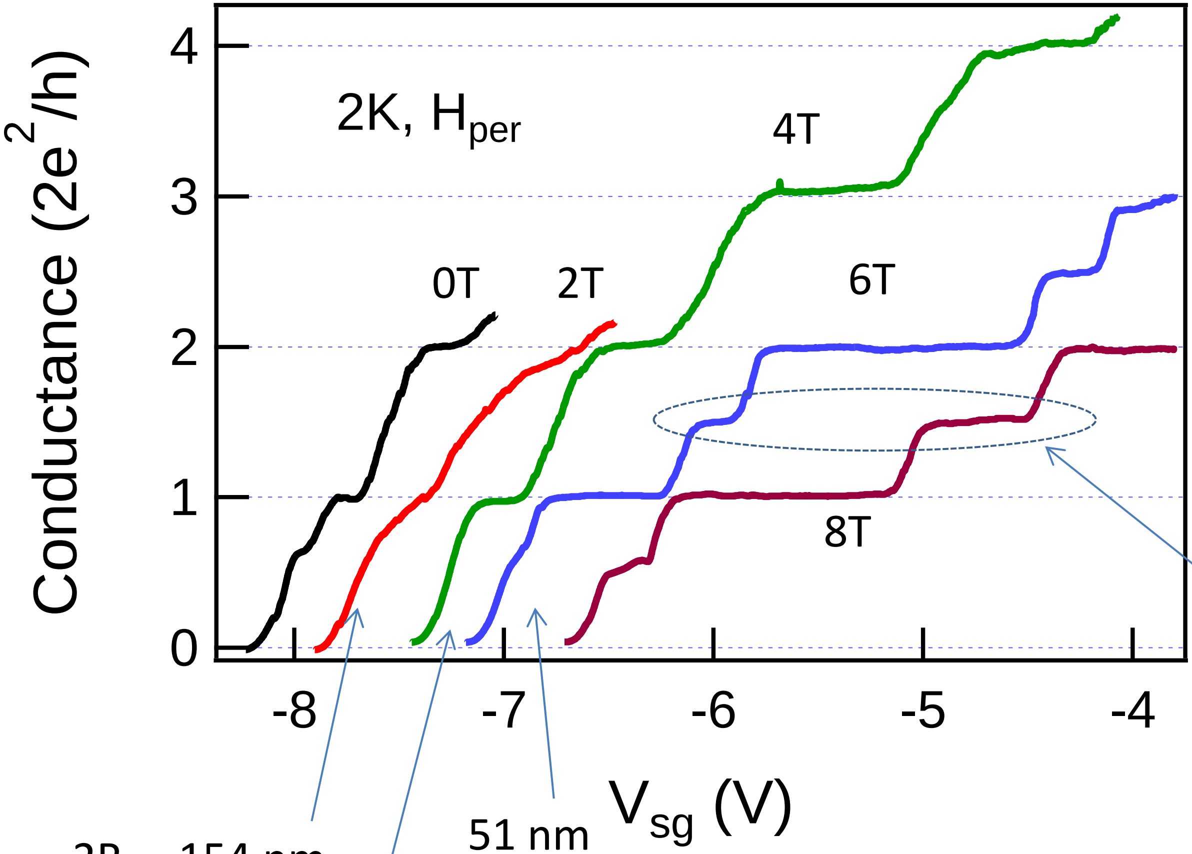
1D channel energy dispersion



T. Ihn, Semiconductor Nanostructures (2010)

1D ballistic transport: Quantum point contact

<Magnetic field dependence>

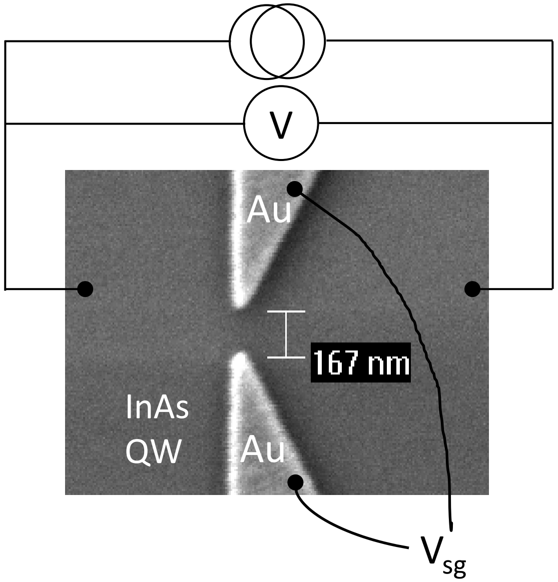


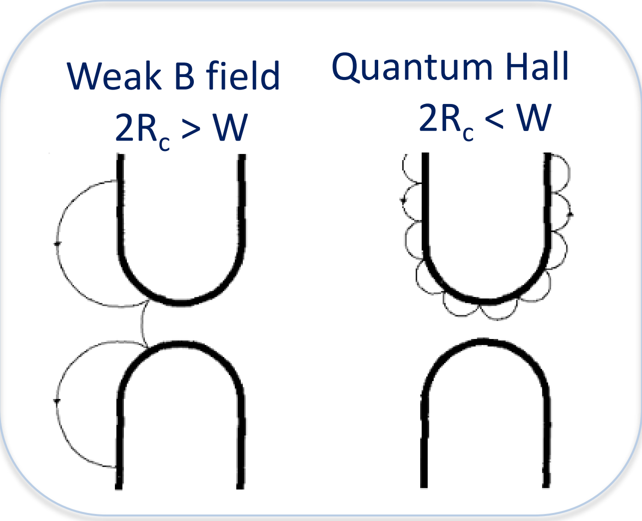
$2R_c$ = 154 nm

77 nm

51 nm

Zeeman spin splitting





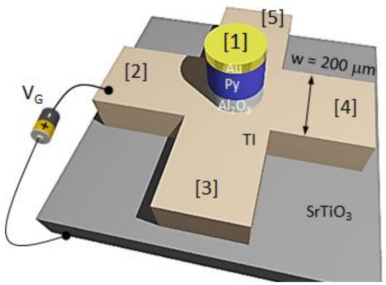
Weak B field
$2R_c > W$

Quantum Hall
$2R_c < W$

Cyclotron radius: $R_c \equiv \hbar k_F/eB$

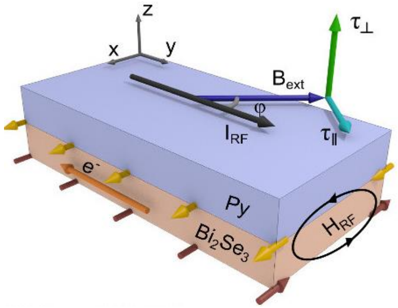
Lee *et al., in preparation*

Summary of the talk



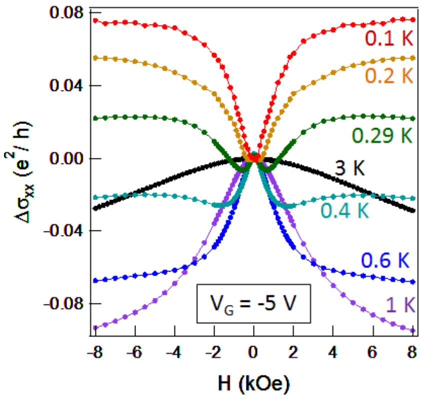
1. Current-induced spin polarization of topological surface state was electrically detected.

   Lee *et al.*, *Phys. Rev. B* **92**, 155312 (2015)



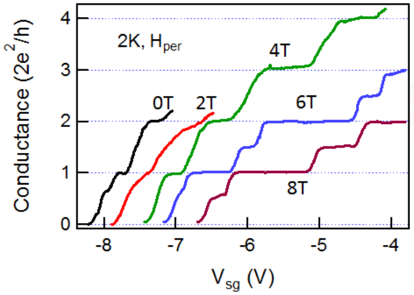
2. Efficient spin-charge conversion in topological insulators by spin transfer torque and spin pumping.

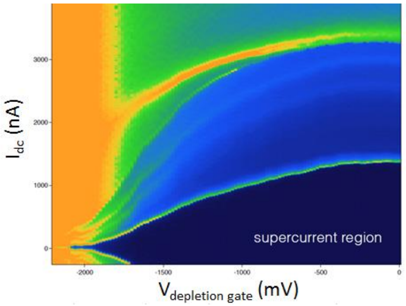
   Mellnik, Lee *et al.*, *Nature* **511**, 449 (2014)
   Jamali, Lee *et al.*, *Nano Lett.* **15**, 7126 (2015)
   Wang, Kally, Lee *et al.*, PRL **117**, 076601 (2016)



3. A magnetic gap with breaking time-reversal symmetry was evidenced in topological insulator/insulating FM hybrid system.

   Lee *et al. in preparation*





4. 1D transport and superconducting proximity effect in epi-Al/InAs quantum well were demonstrate.

   Lee *et al. in preparation*
   Shojaei *et al. in preparation*

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U of Tokyo

Seigo Tarucha, Sadashige Matsuo

Thank you for your attention!