Proximity-coupled Topological Magnetic Devices

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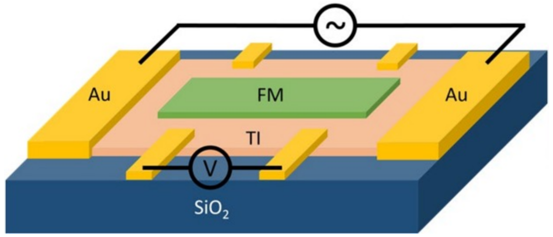

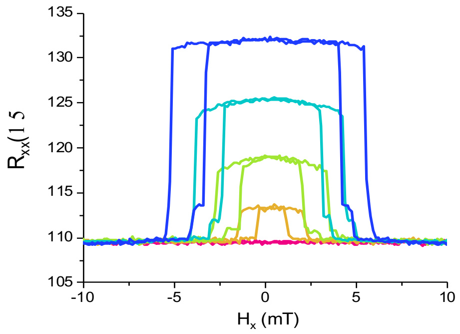

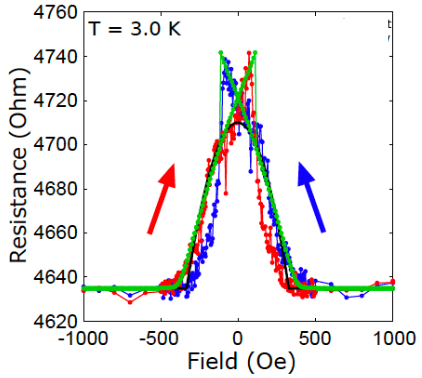

Collaborators and Acknowledgements


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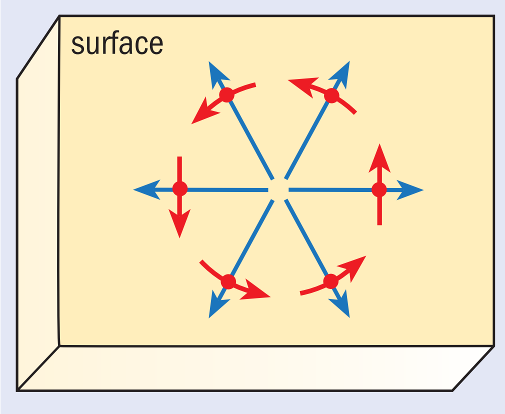
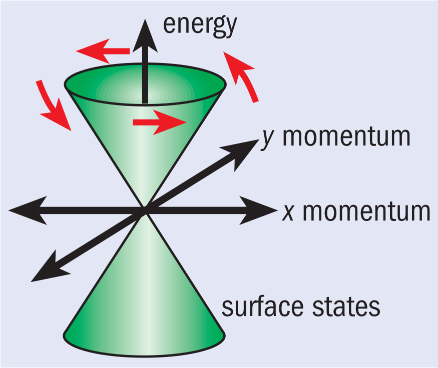
Proximity-coupled Topological Magnetic Devices

Outline

- Magnetic properties of TIs
- Magnetic TIs, QAHE
- TI-magnet heterostructure devices
- Bi_2Se_3/YIG devices – Surface State AMR
- Bi_2Se_3/[Co/Pt Multilayer] devices – spin valve effect

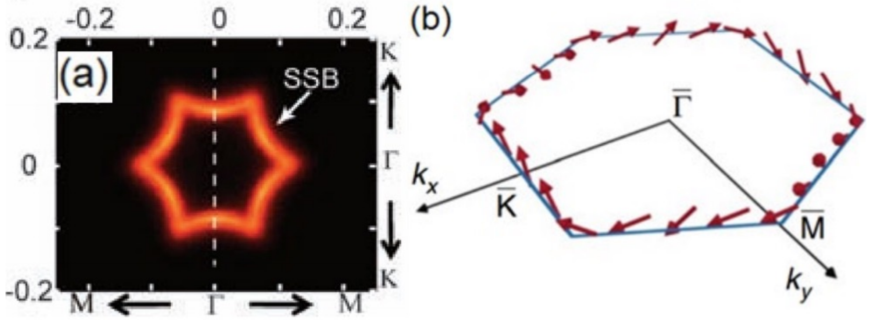
3D Topological Insulator Surface States





Kane, Moore, Phys. World 2011

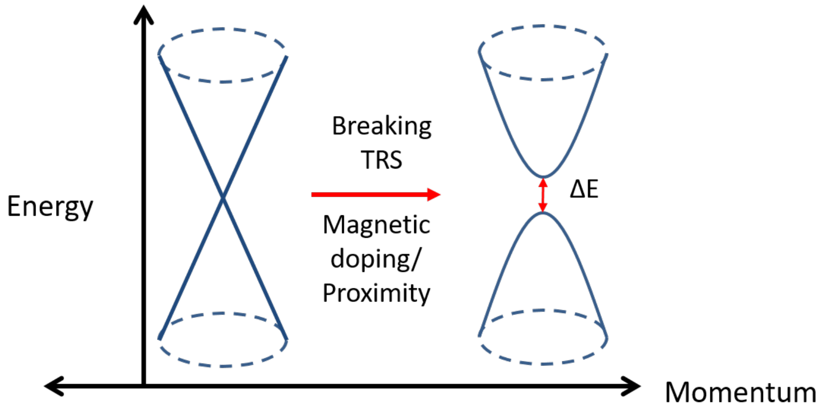
- Single Dirac point
- Spin momentum locking (helical surface states)
- Prohibited back scattering
- Hexagonal warping

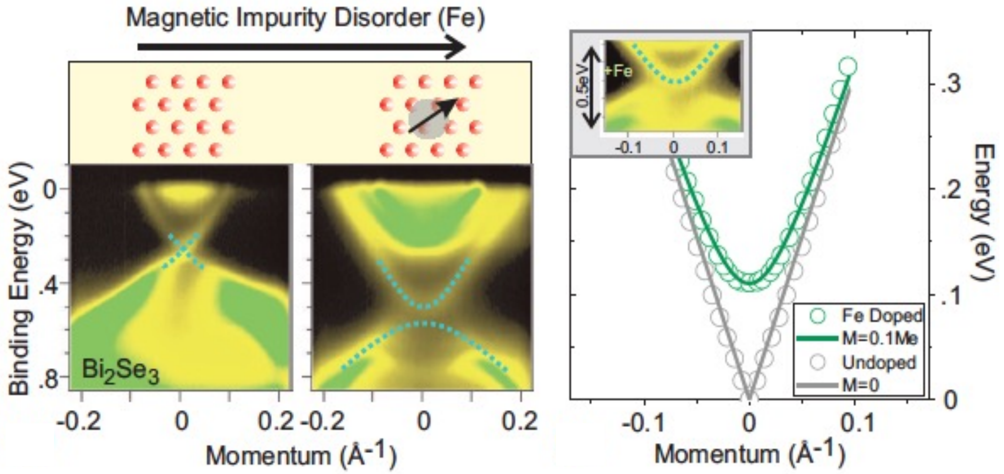


Hexagonal warping and spin momentum locking in TSS
PRL 103, 266801 (2009); Science 325.5937 (2009): 178- 181; Nature Physics 14.5 (2018): 495

3D TIs and Magnetism

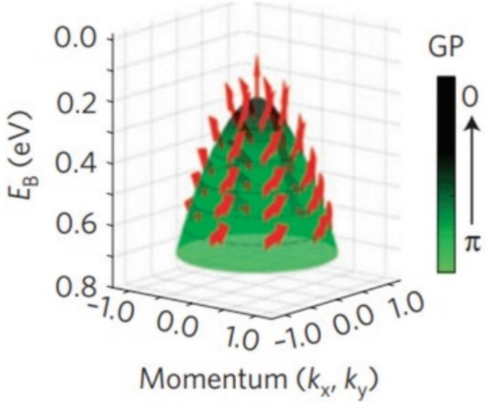
- Ferromagnetism in out-of-plane (OOP) direction breaks time reversal symmetry and lifts degeneracy to induce energy gap ΔE in Topological Surface State (TSS) Dirac point





Hseih et al., *Nature* **460**, 1101 (2009).
Xia et al., *Nature Physics* **5**, 398 (2009).
Wray et al., *Nature Physics* **6**, 855 (2010).

- Magnetic TSS has hedgehog spin texture

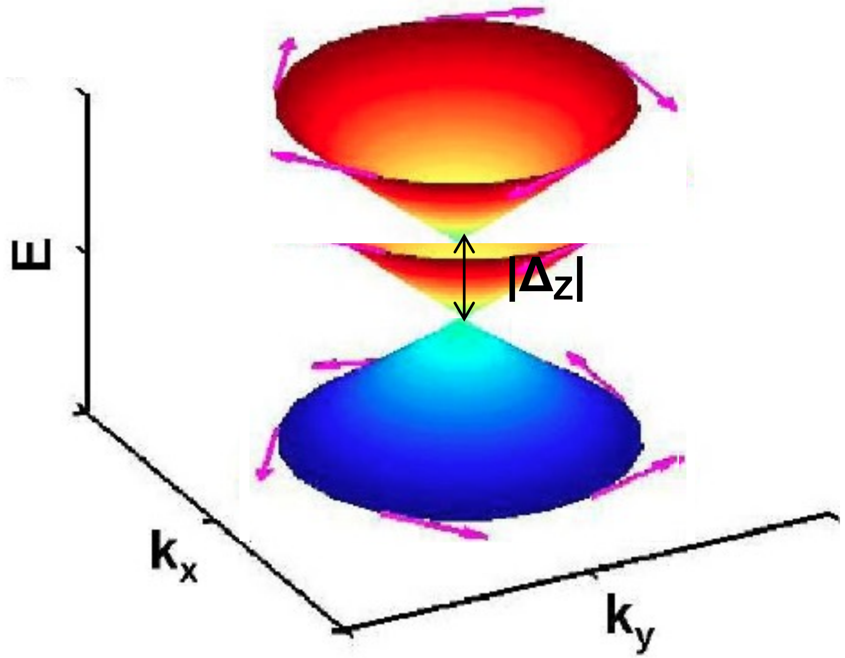


Hedgehog spin texture in magnetic TI
Nature Physics 8.8 (2012): 616

3D TIs and Magnetism

The magnetic properties of 3D topological insulators seem to have large effects, so let's consider the surface of a 3D TRI topological insulator…

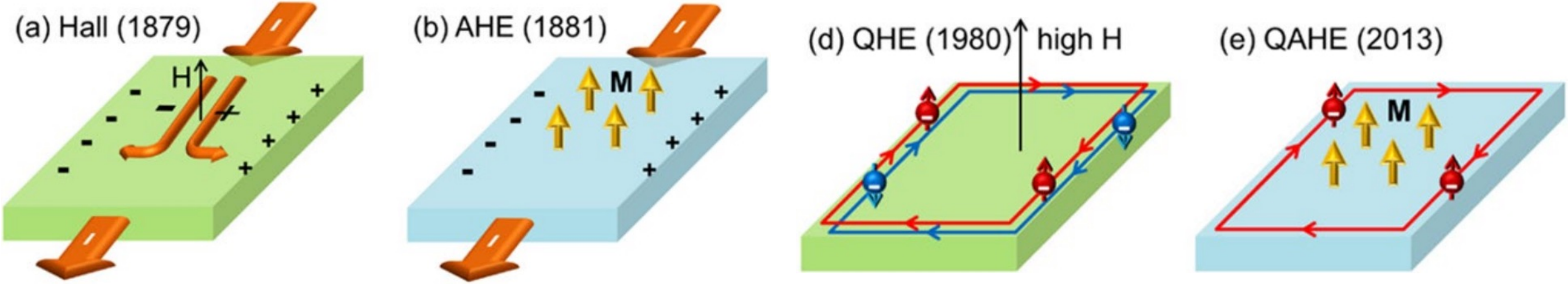
- The surface is spin-split everywhere except at the Dirac point where it is protected by time-reversal symmetry.
- Now add a Zeeman field with the magnetization direction pointed out of plane.
- Each gapped Dirac cone is known to contribute $\pm e^2/2h$



→ Connection between top and bottom surfaces, along the edge, is Chern insulator, with non-zero integer Hall conductance (chiral, e^2/h)

→ Quantum Anomalous Hall Effect (QAHE)

Quantum Anomalous Hall Effect

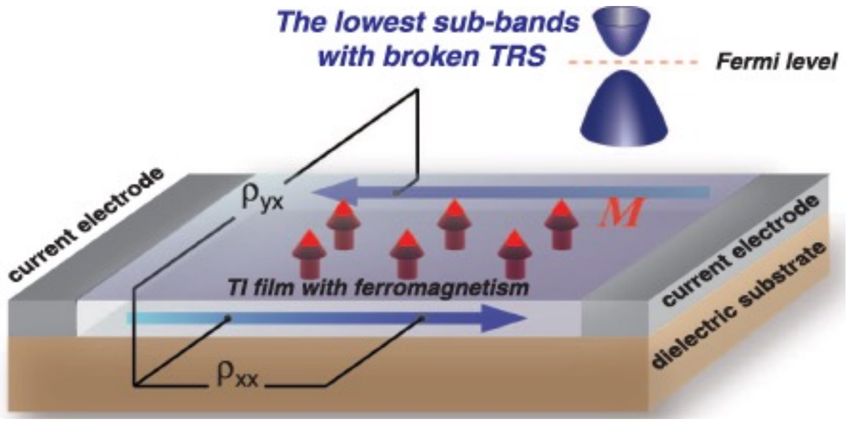


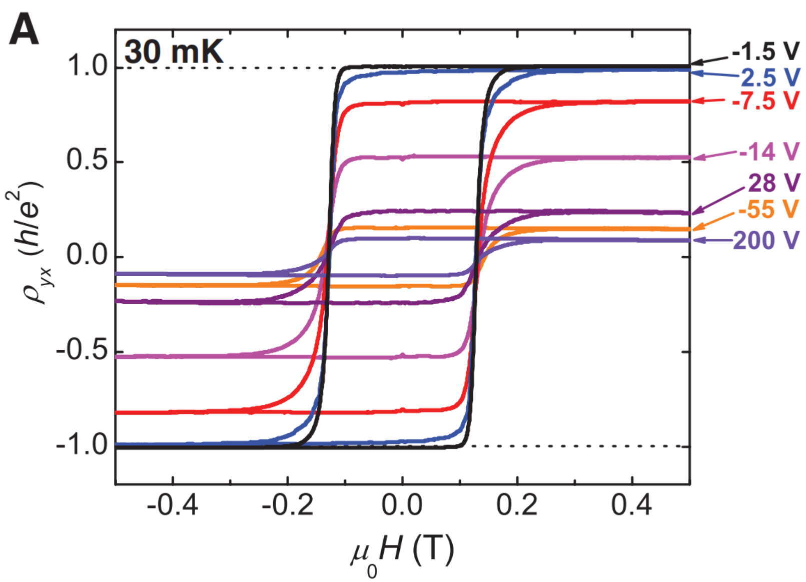
Adv. Phys. 64, 227 (2015)

- Quantization of Hall signal (quantum Hall)
  + Hall signal at zero field (anomalous Hall)
  = Quantized Hall resistance at zero field (QAHE)

Quantum Anomalous Hall Effect

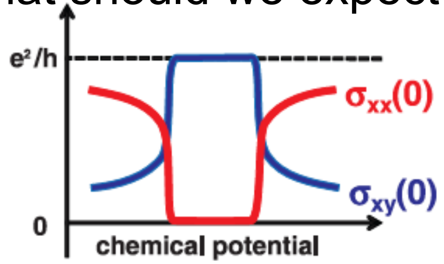
The addition of magnetic dopants or intrinsic magnetization causes a quantized Hall effect without an external magnetic field…





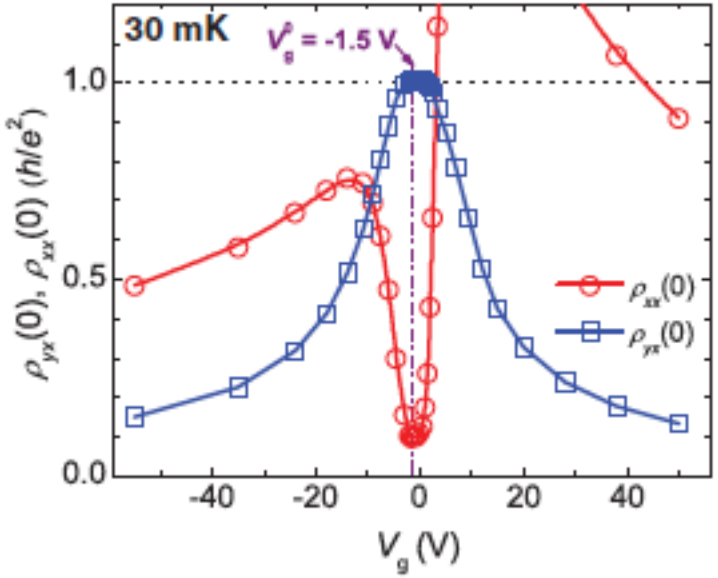
QAH effect in $Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

What should we expect?



And…

We get what we expect.



C. –Z. Chang et al. *Science* **340**, 167 (2013)

New results:
Deng, et al. *Science* 367, 895 (2020) – intrinsically magnetic MnBi2Te2
Li et al, Nature 600, 7890 (2021) – MoTe2/WSe2 moire heterostructure

Chern insulators and Axion insulators

Chern insulator; Quantum Anomalous Hall (QAH) insulator

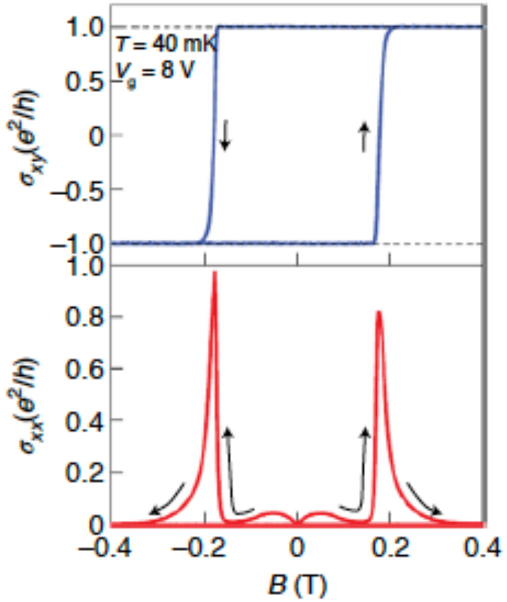
- Edge states on the side walls have the same chirality:

$$\sigma_{xy} = +\frac{1}{2}\frac{e^2}{h} + \frac{1}{2}\frac{e^2}{h} = \frac{e^2}{h}$$

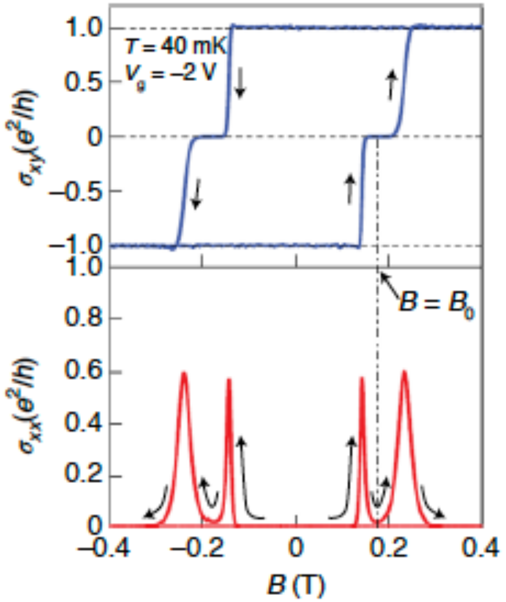
Axion insulator

- Edge states cancel each other: $\sigma_{xy} = +\frac{1}{2}\frac{e^2}{h} - \frac{1}{2}\frac{e^2}{h} = 0$

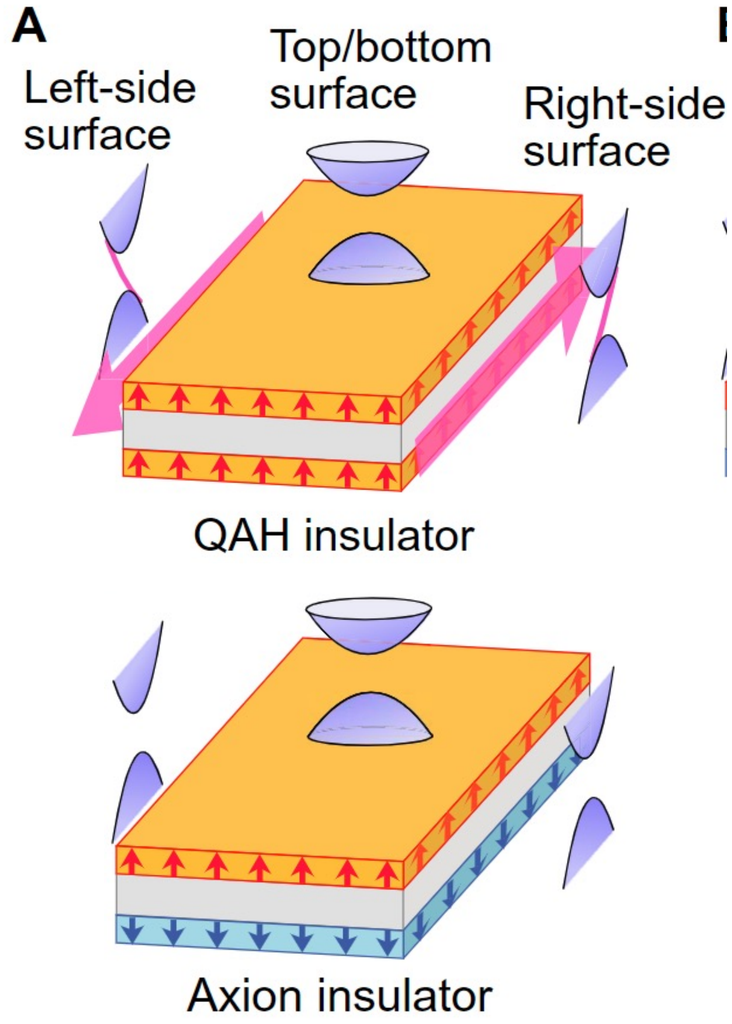
QAHE (Cr-doped $(Bi,Sb)_2Te_3$



Modulation doped for AFM top and bottom surfaces → axion insulator



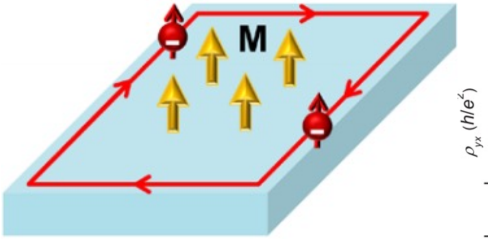
Nat. Mat., 16, 516 (2017)

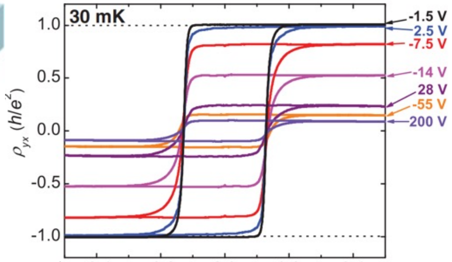


Also observed via electric field control, layer control, intrinsic TI

Magnetically doped TIs:

- Enabled first measurement of quantum anomalous Hall and axion effect … BUT
- Low Curie temperature T_c ~ 15
- Inhomogeneous magnetization



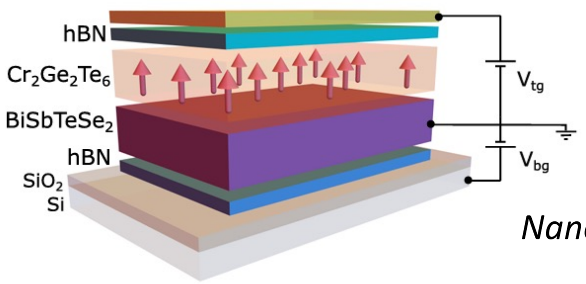


Quantum anomalous Hall effect in Cr doped TI
Science 340.6129 (2013): 167-170

Solution:
Proximity-magnetized TI heterostructures

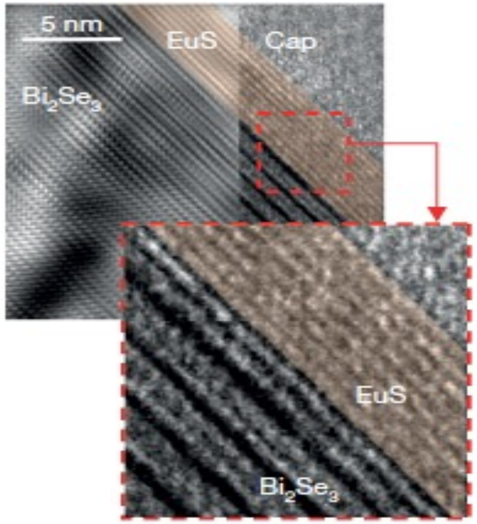
Topological-Magnetic Heterostructures (TI/FM)

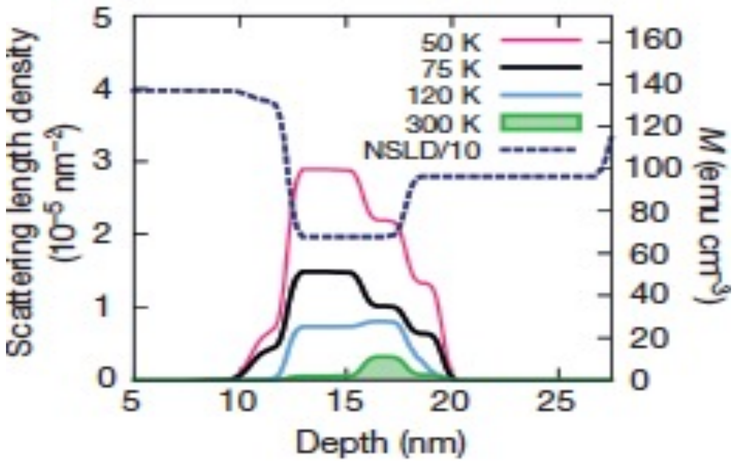
- Exchange coupling can induce proximity magnetization on the surface



Nano Lett. 17, 7166 (2022)

- Ferromagnetic proximity coupling can persist well-above room temperature:

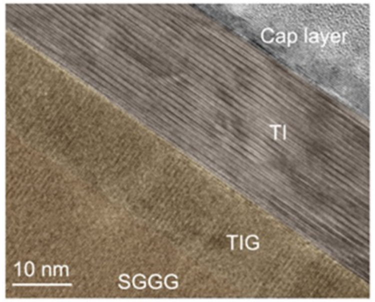


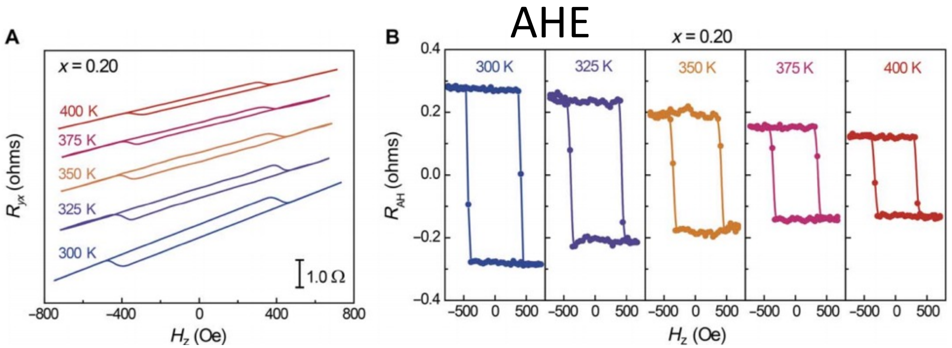


Neutron scattering

EuS alone non-magnetic above 50K (Effect of trivial interface states?)

F. Katmis et al. *Nature* **533**, 513 (2016)



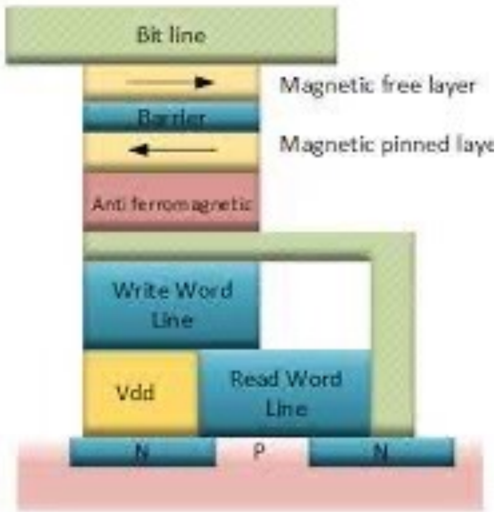


Transport signatures from TI alone

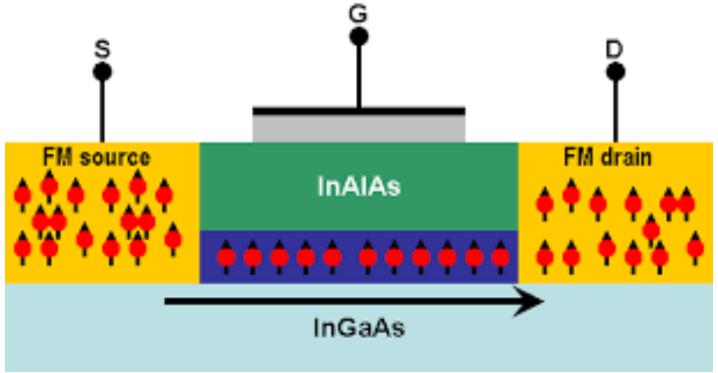
Tang, C., et al. *Science Advances, 3*(6). (2017)

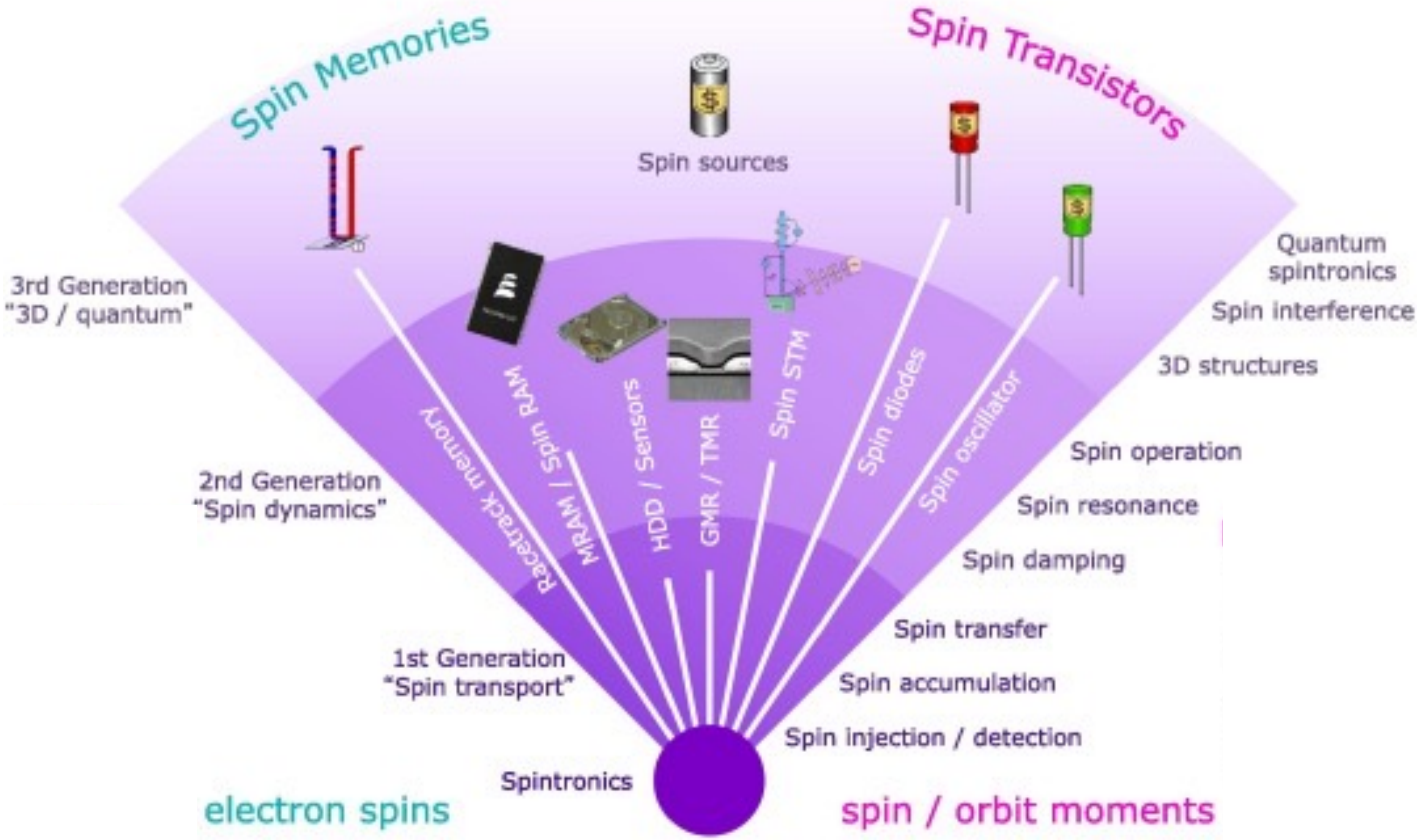
Magnetic multilayer devices relevant to “Spintronics”

MRAM



Spin FET





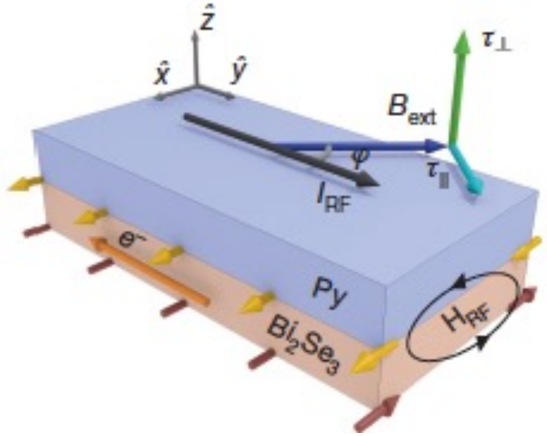
Jour. Mag. & Mag. Materials, 509, 166711 (2020)

Large Spin-Transfer Torque in TIs

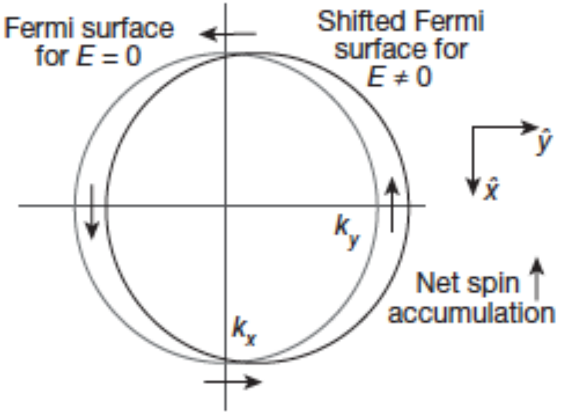
Many spintronic devices require using spin to modify orientation of magnetic layers, i.e., strong spin transfer torque (STT)

→ TIs have unusually large STT

Measure a 3D topological insulator with permalloy on the surface.



- Because of spin-momentum locking, by generating a current in a topological insulator surface, one automatically obtains a spin current.



- The spin current then generates a torque on the magnetization.

$$\frac{d\hat{m}}{dt} = -\gamma\hat{m} \times (\vec{B}_{ext} - \mu_0 M_{eff} m_z \hat{z}) + \alpha\hat{m} \times \frac{d\hat{m}}{dt} + \gamma\tau_\parallel \frac{\hat{m} \times (\hat{x} \times \hat{m})}{|\hat{x} \times \hat{m}|} + \gamma\tau_\perp \frac{\hat{x} \times \hat{m}}{|\hat{x} \times \hat{m}|}$$

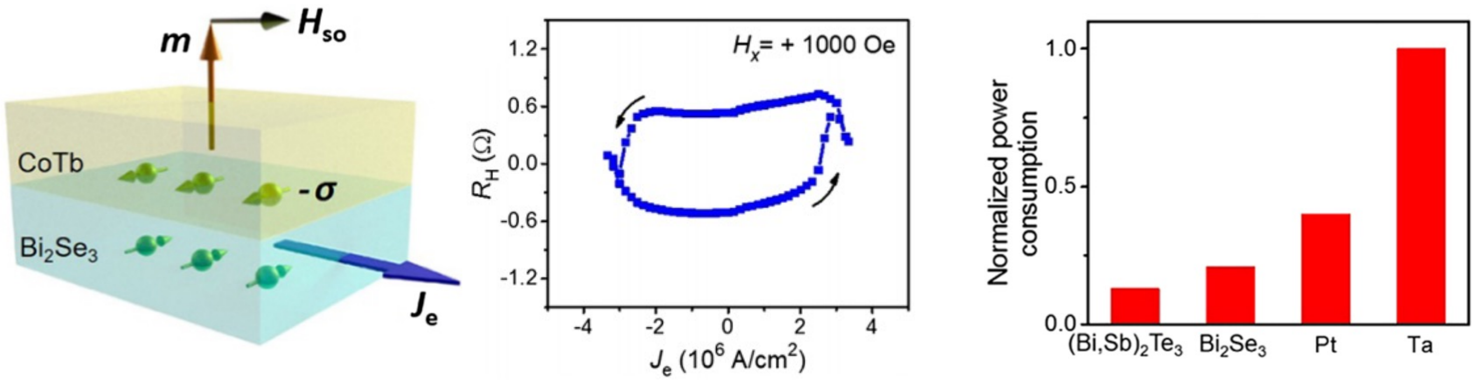
- The action of the topological surface currents produces a larger spin-torque effect on the permalloy than other comparable materials.

Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
$\theta_\parallel$	2.0–3.5	0.08	0.15	0.24	0.3
$\sigma_{S,\parallel}$	1.1–2.0	3.4	0.8	—	1.8

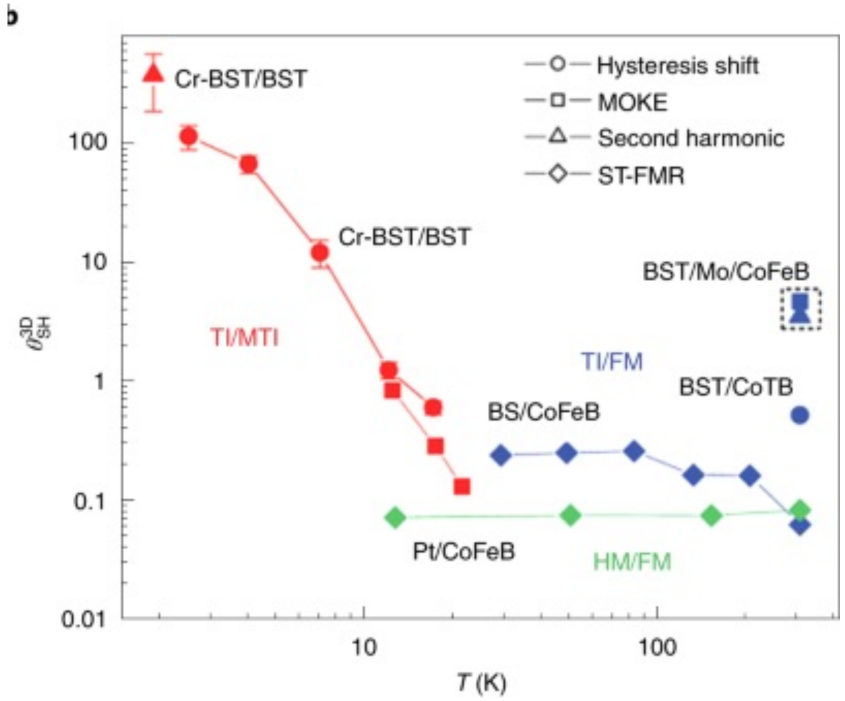
A. R. Mellnik, et al. *Nature* **511**, 449 (2014).

Topological-Magnetic Heterostructure Devices

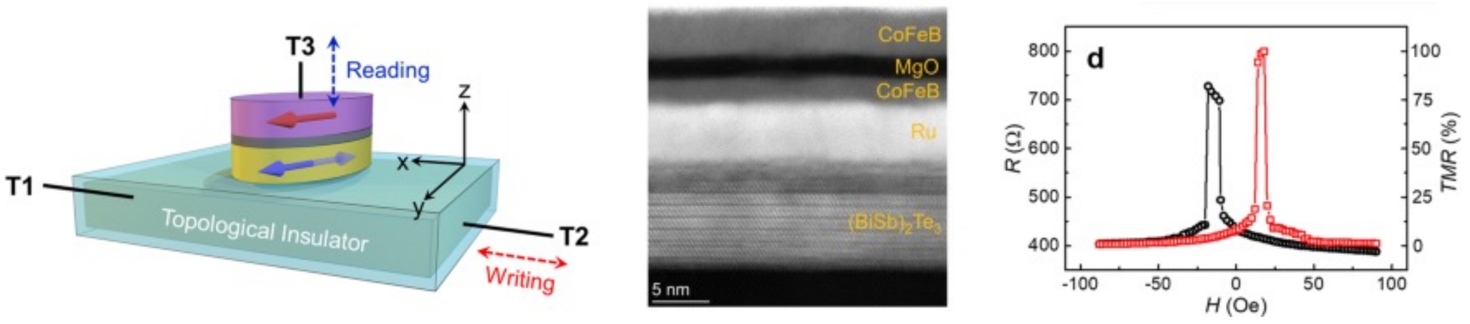
High TI/FM device potential for spin pumping, current induced magnetization switching, spin-charge conversion



Magnetization reversal in CoTb using spin orbit torque from TI
PRL 119.7 (2017): 077702



Adv. Mater. **32**, 1907661 (2020).



Magnetic memory driven by topological insulators
Nature Comm., 12, 6251 (2021)

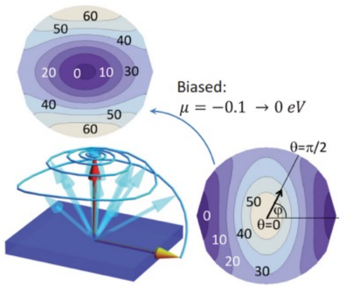
Lots of potential!

Still challenges to switch perpendicular magnetization, integrate with CMOS

New Proximity-Magnetized Topological Devices Possible

Electrically controlled magnetization in ferromagnet-topological insulator heterostructures

Yuriy G. Semenov, Xiaopeng Duan, and Ki Wook Kim*
Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27695-7911, USA
(Received 23 July 2012; published 15 October 2012)

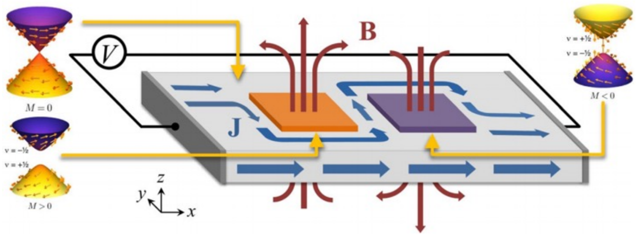


REVIEW ARTICLE
https://doi.org/10.1038/s41567-018-0064-5
nature physics
Corrected: Publisher Correction

Topological antiferromagnetic spintronics

Libor Šmejkal[1,2,3]*, Yuriy Mokrousov[4], Binghai Yan[5] and Allan H. MacDonald[6]

Topological Inductor

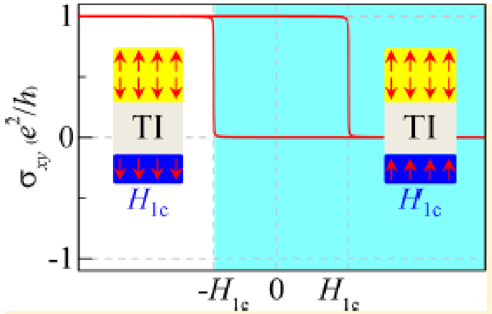


Philip, T. M., & Gilbert, M. *Scientific reports*, *7*(1), 6736.

Axion Insulator State in a Ferromagnet/Topological Insulator/Antiferromagnet Heterostructure

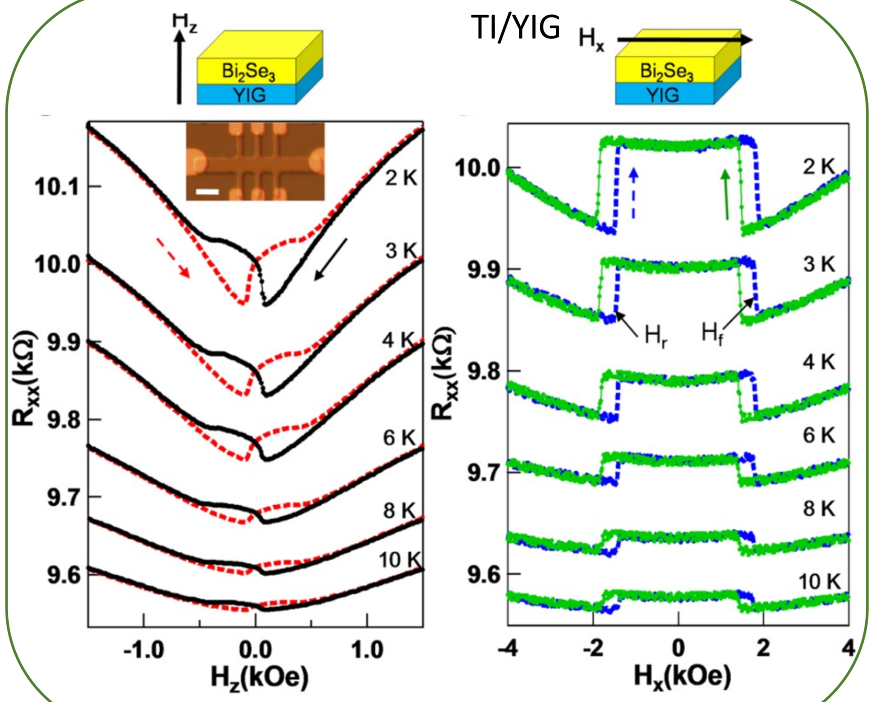
Yusheng Hou† and Ruqian Wu*,†

FMI/TI/AFMI
$MnBi_2Se_4/Bi_2Se_3/MnBi_2Se_5$



Open Questions:
-What are signatures of proximity-magnetized topological surface states?
-What controls the magnetoresistance in topological-magnetic devices?

Magnetic proximity effects in TIs evident in transport

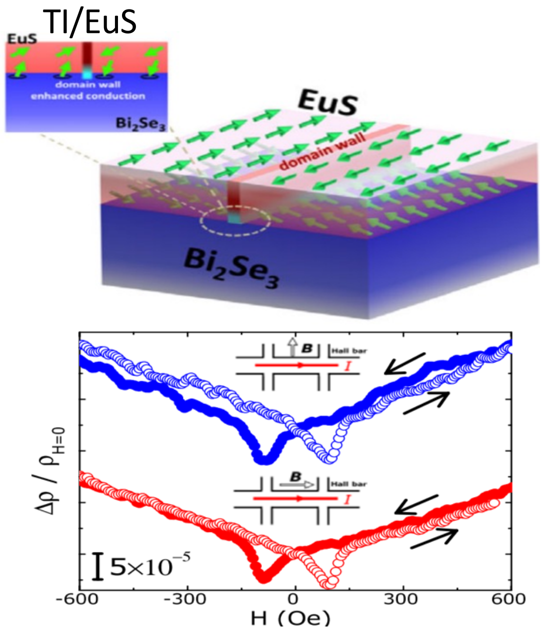


M. Lang, et al. Nano Letters **14**, 3459 (2014)

Bi_2Se_3/YIG bilayer

Abrupt MR switching corresponding to the magnetization switching of YIG

- Interface magnetism cants out of plane
- Domains of gapped and gapless surface states
- Increased scattering off domain walls → increased R



Wei, P., et al. PRL 110(18) (2013)

Bi_2Se_3/EuS bilayer

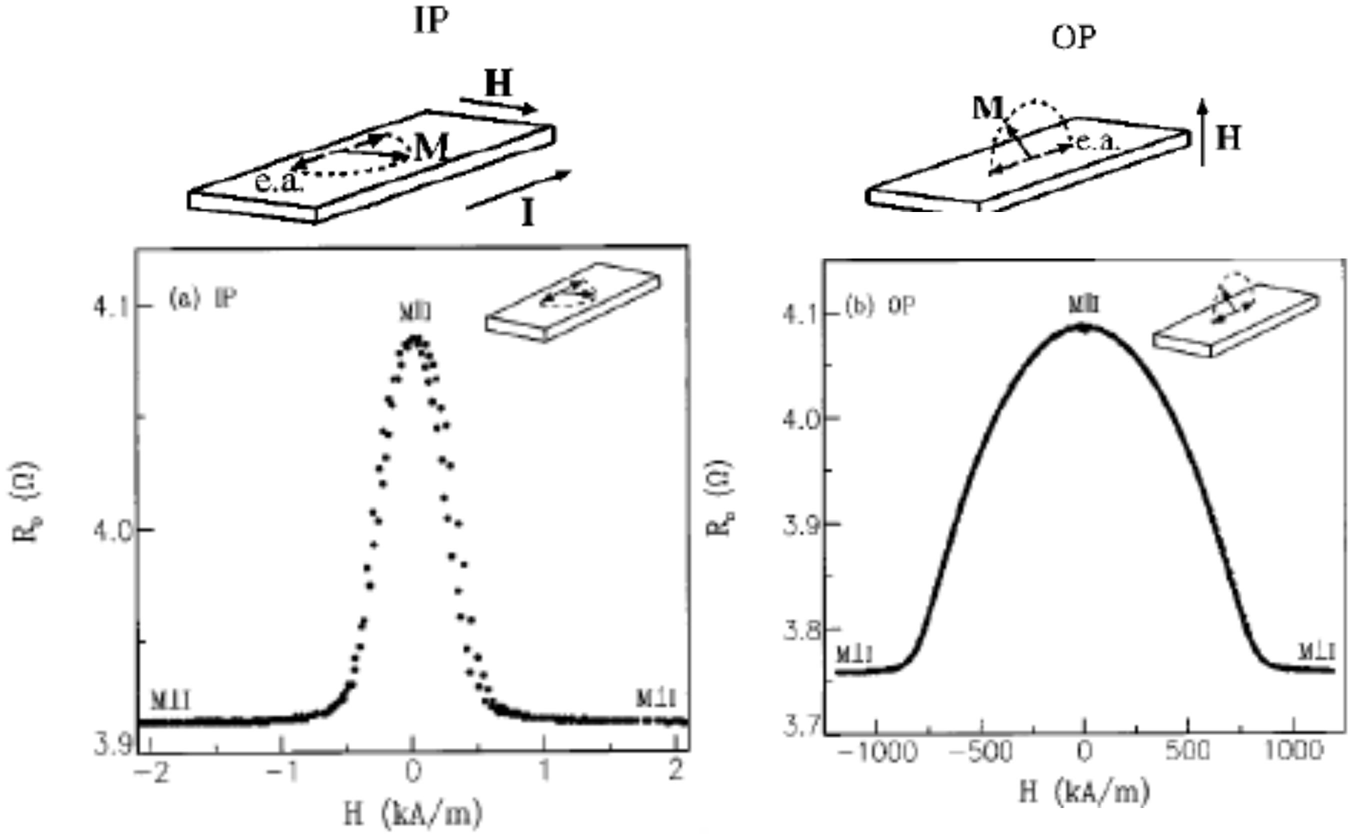
Smooth MR dip

- Interface magnetism cants out of plane
- Dips appear below 4K (note small scale)
- Chiral conduction on domain walls leads to resistance dips

No clear understanding of transport, interface effects

Anisotropic magnetoresistance (AMR) should be observed in ferromagnets as M rotates …

- Resistance depends on the angle between the magnetization and the current
- Originates from spin-orbit coupling.
- High resistance when **M** is parallel to **I**.
- Low resistance when **M** is perpendicular to **I**.



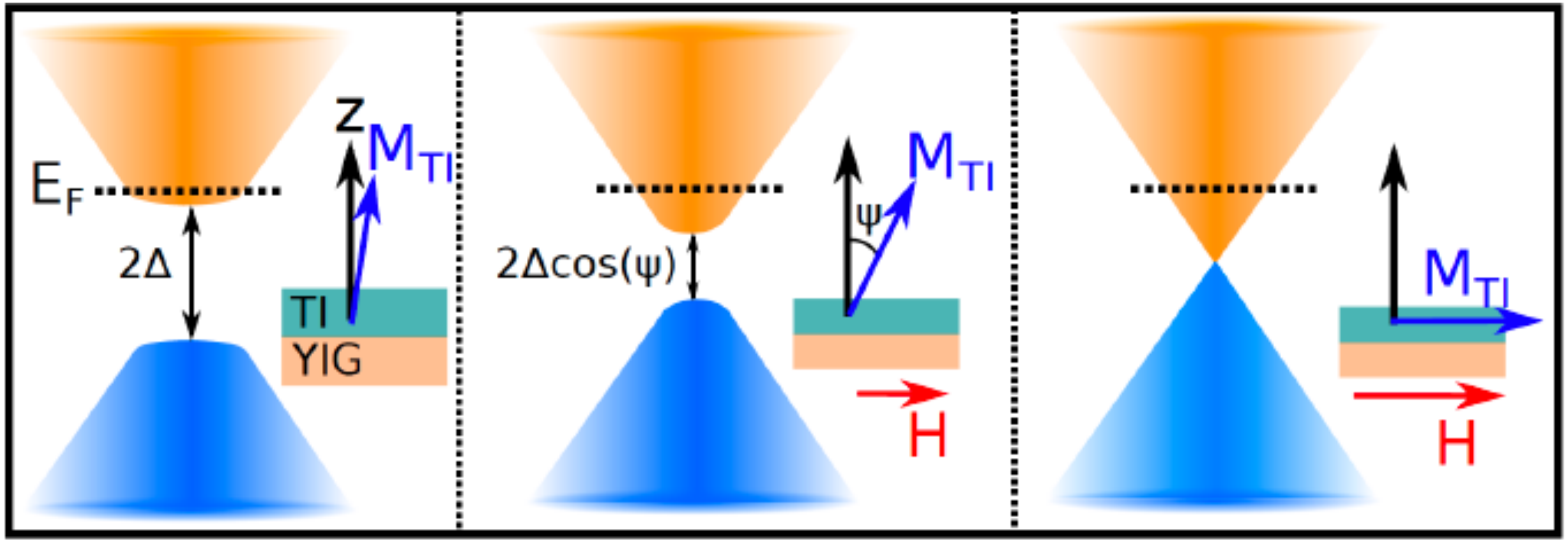
M initially parallel to I, rotated to perpendicular

*Rijks et al. PRB 1997

Proximity AMR should appear in a topological insulator

TI magnetization initially out-of-plane, then rotated by in-plane magnetic field

Tuning of TSS gap and magnetoresistance modeled by Chiba et al, PRB 95, 094428 (2017)



High resistance

Low resistance

$$\rho_{xx} \sim \frac{1+\xi^2\cos\psi^2}{1-\xi^2\cos\psi^2}, \quad \xi = \frac{\zeta}{\sqrt{1+\zeta^2\cos\psi^2}}$$

$$\zeta = \Delta/E_F$$

Unconventional AMR:

Due to SS gap, not related to orientation of I

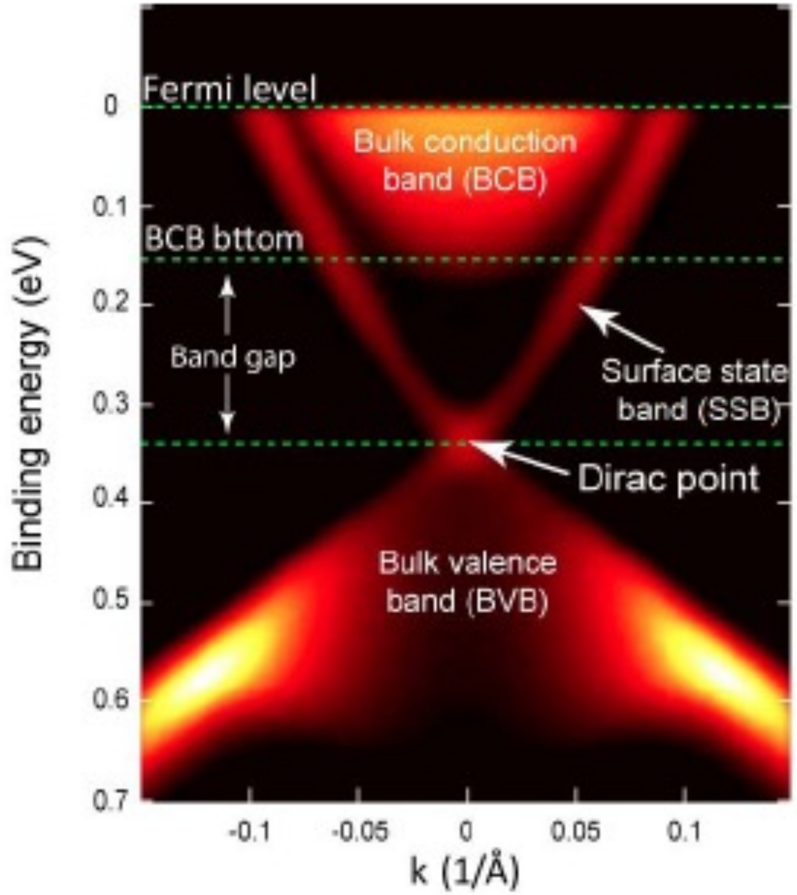
- High R when M_{TI} out of plane
- AMR independent of in-plane angle

For our experiments, we use exfoliated flakes of the 3D Topological Insulator Bi_2Se_3

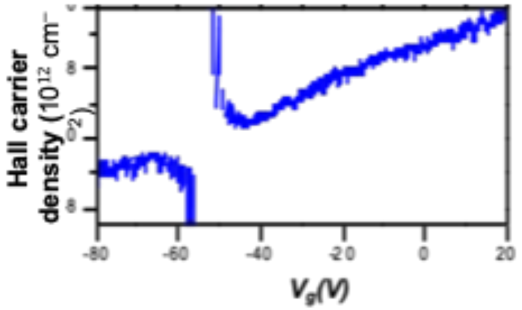
- Dirac surface bandstructure and the topologically protected states evident.
- Gap between the bulk valence band and bulk conduction band is 0.35 eV.
- Topologically protected states are evident at room temperature
- Spin-resolved ARPES → spin-momentum locked surface states

D. Hseih et al., Nature **452**, 970 (2008).
H. Zhang et al., Nat. Phys. **5**, 438 (2009).

Angle resolved photoemission (ARPES) on Bi_2Se_3.



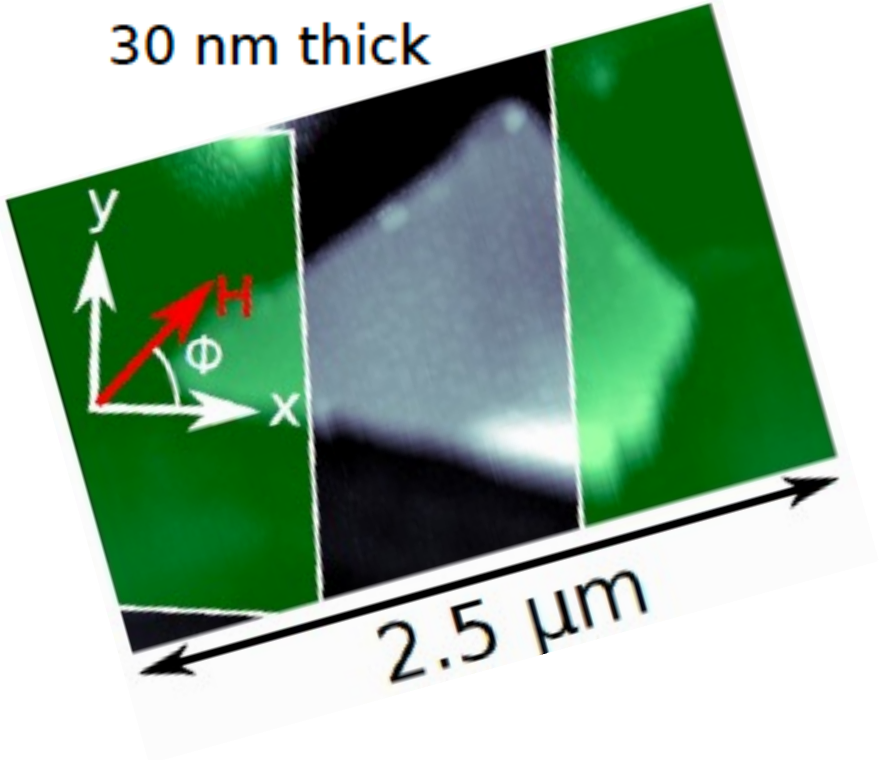
- Our samples have measured carrier density of 5 x 10^{17} (consistent with Fermi energy in or near bandgap – see J. G. Analytis et al., PRB **81**, 205407 (2010)).

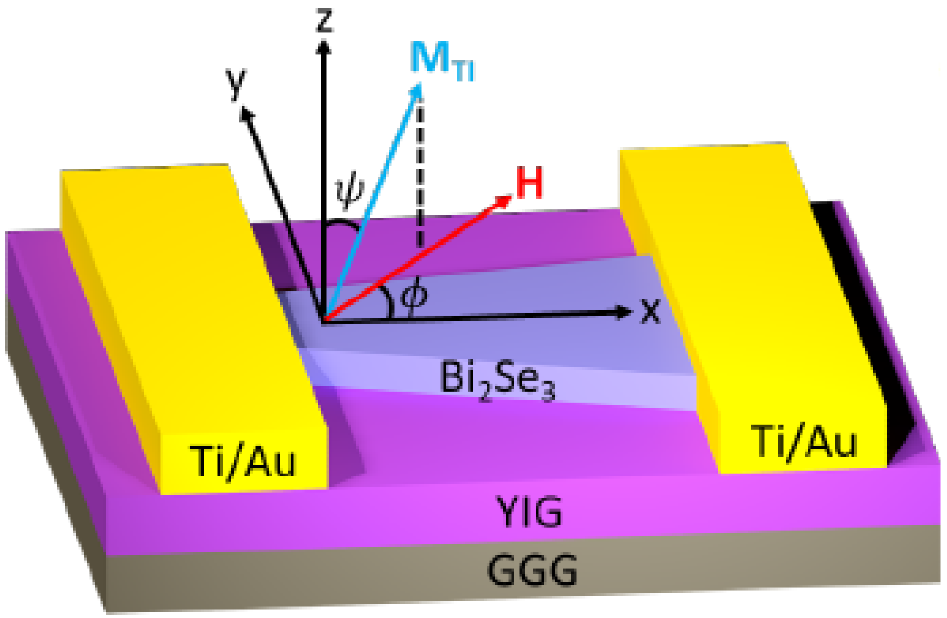


- Thin flakes exfoliated from bulk crystal using scotch tape method
- Exfoliated flakes may avoid surface reconstruction evident in some MBE-grown structures

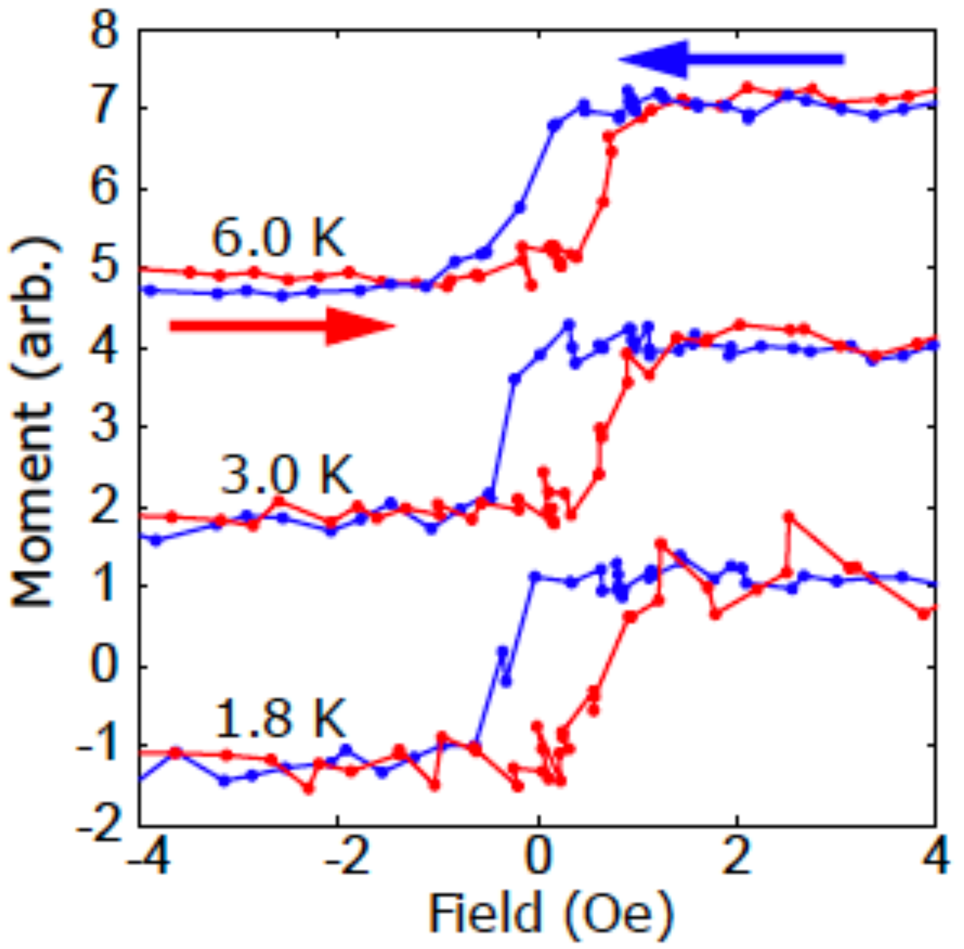
Bi_2Se_3 flakes exfoliated onto a thin film of YIG (Yttrium Iron Garnet) ….

- The YIG film is 25 nm thick and was prepared via sputtering.
- The Bi_2Se_3 samples are targeted to be between 15-60 nm.





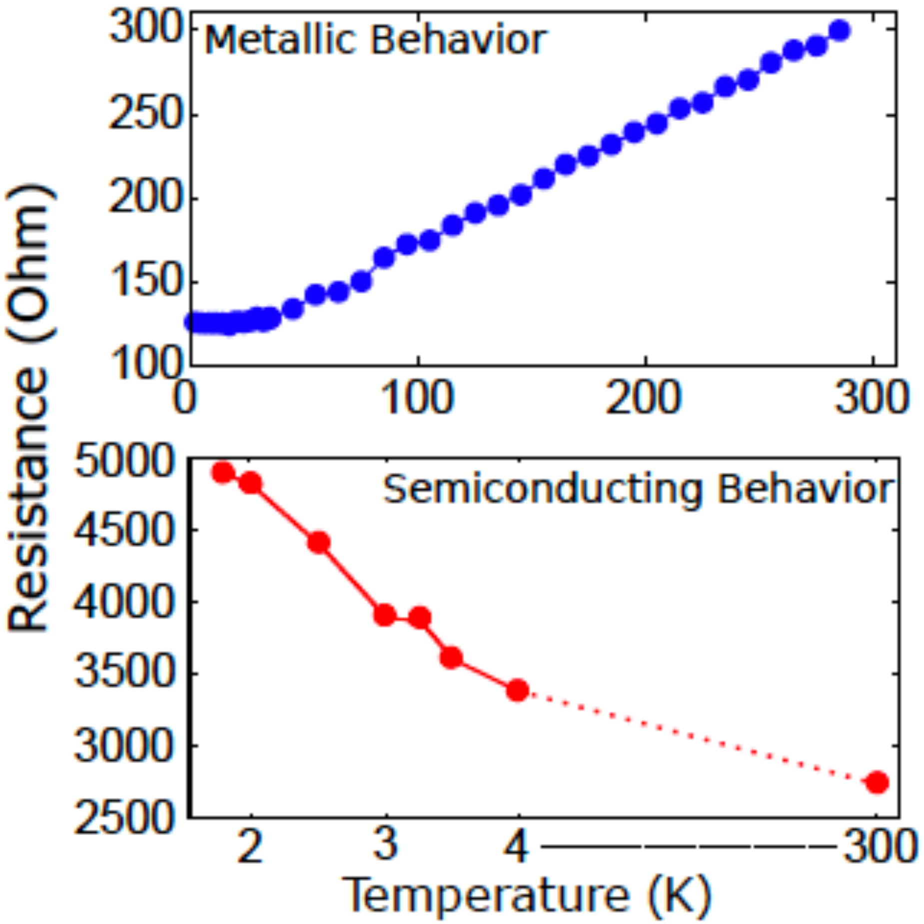
YIG behaves as an in-plane ferromagnet with 2 Oe coercive field from 1.8K to 300K



Characterizing the Bi_2Se_3

Exfoliation leaves variable flake sizes and thicknesses along with resistivities

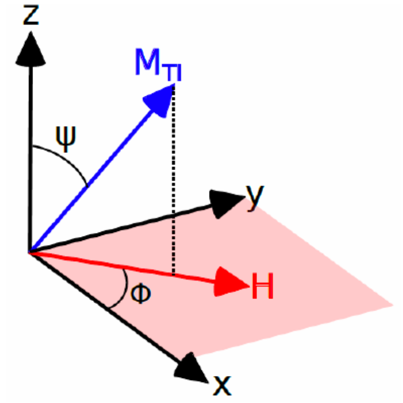
Proximity magnetization evident in semiconducting devices (associated with surface state conduction)

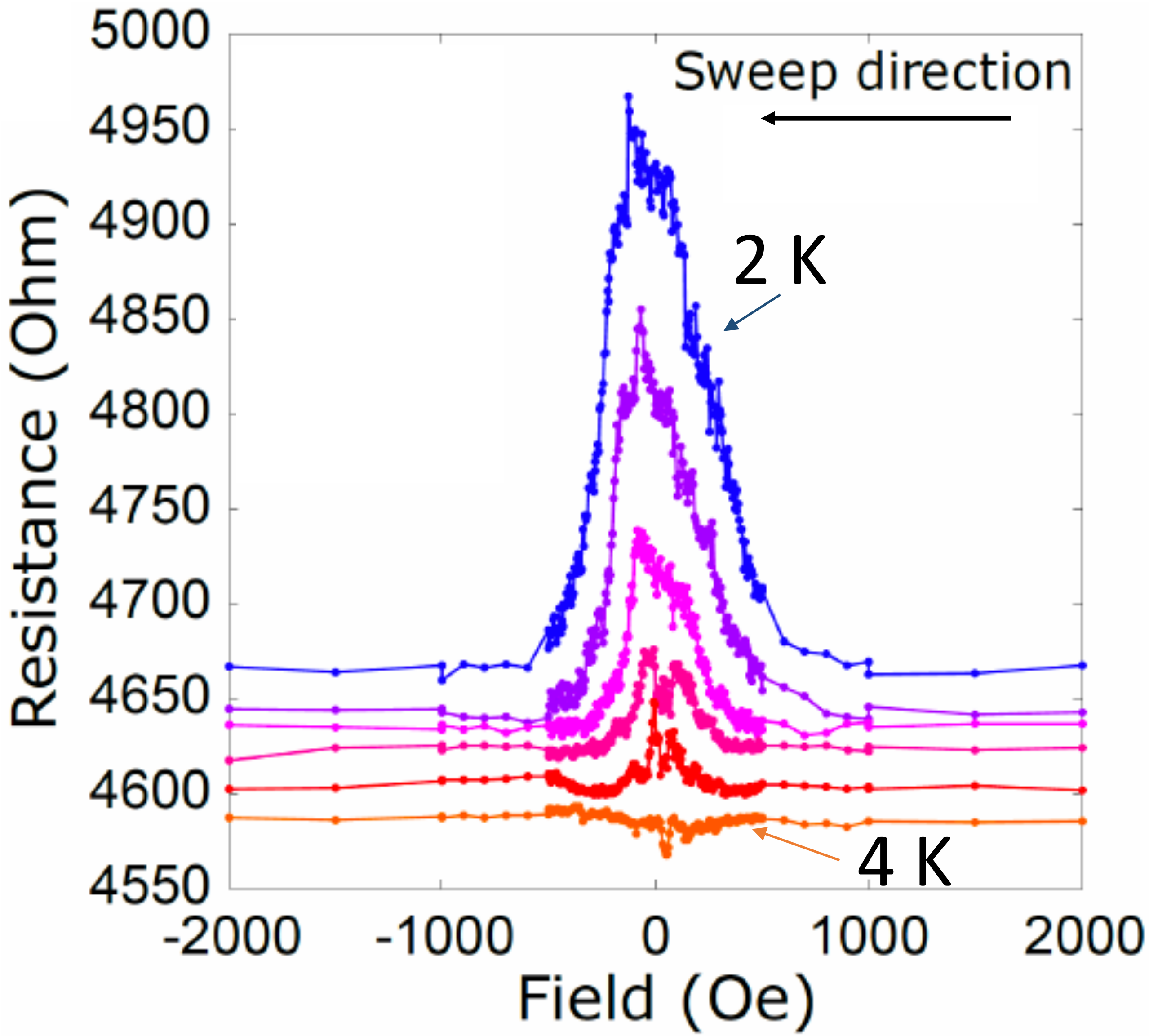


No apparent ferromagnetic effects are observed. Weak anti-localization effects are seen

Ferromagnetic effects occur in samples that show an increase in resistance as T is lowered.

Large AMR Peak in YIG/ Bi_2Se_3

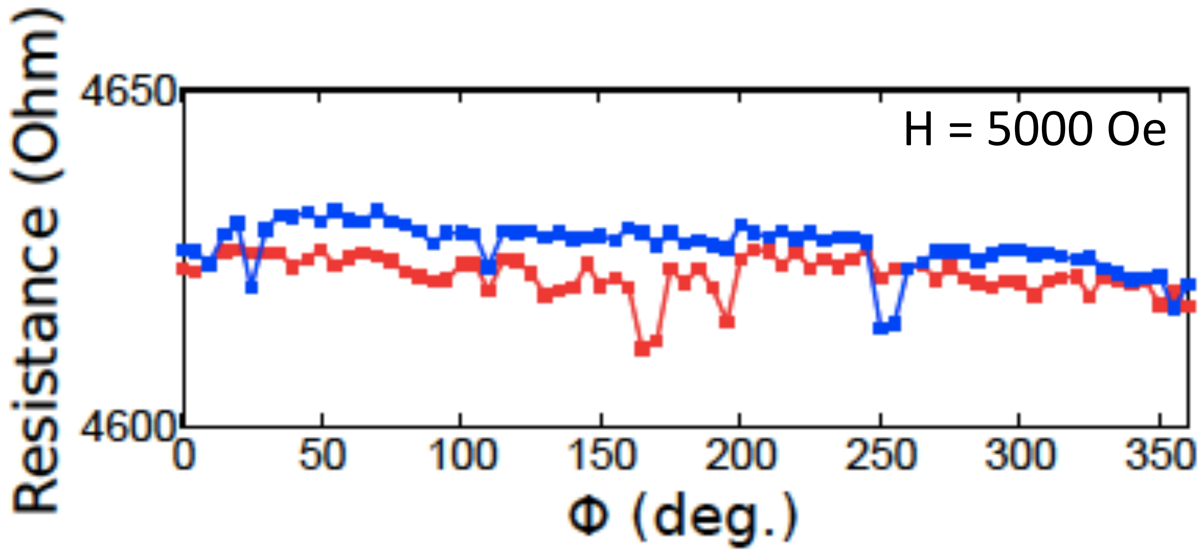


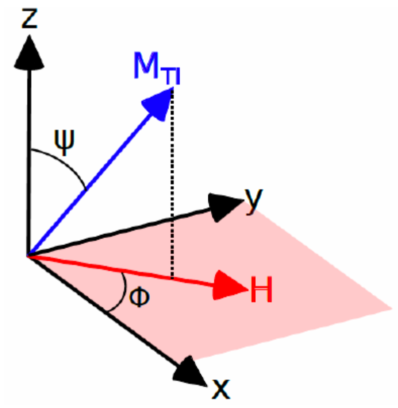


In-plane B-field at ϕ = 90 degrees to current

- **AMR peak of 6.5%**
- Onset at low T
- Field scale much larger than YIG switching

MR of YIG/TI: In-plane Angle Dependence

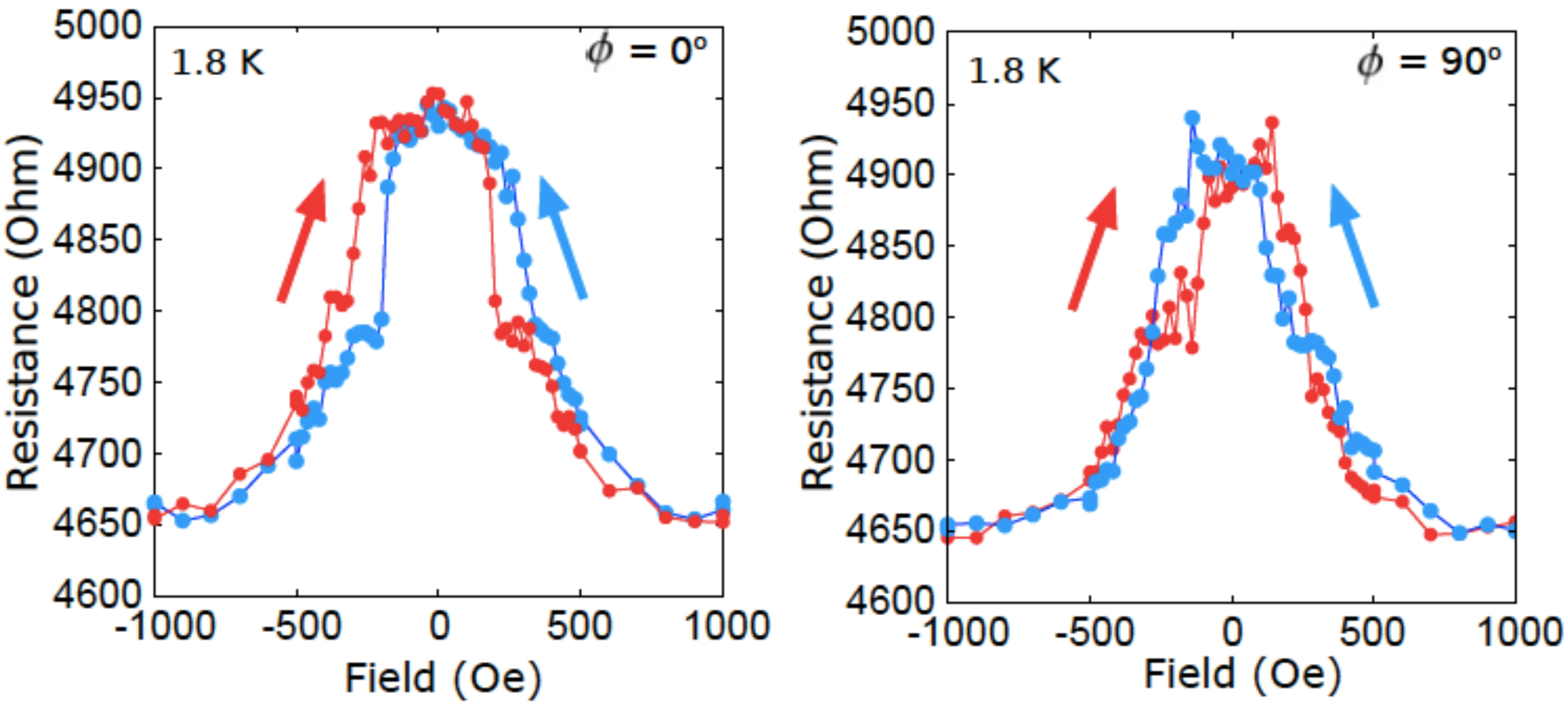


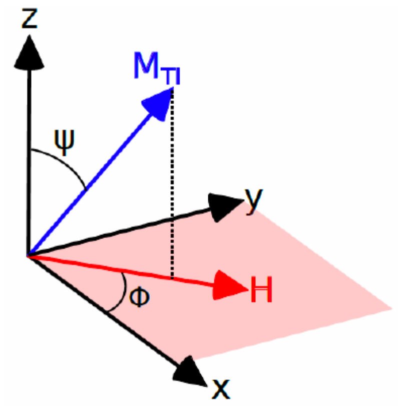


Unlike conventional AMR, peak doesn't depend on relative direction of H and I

(expect $\cos^2\phi$ for conventional AMR)

MR of YIG/TI: In-plane Angle Dependence



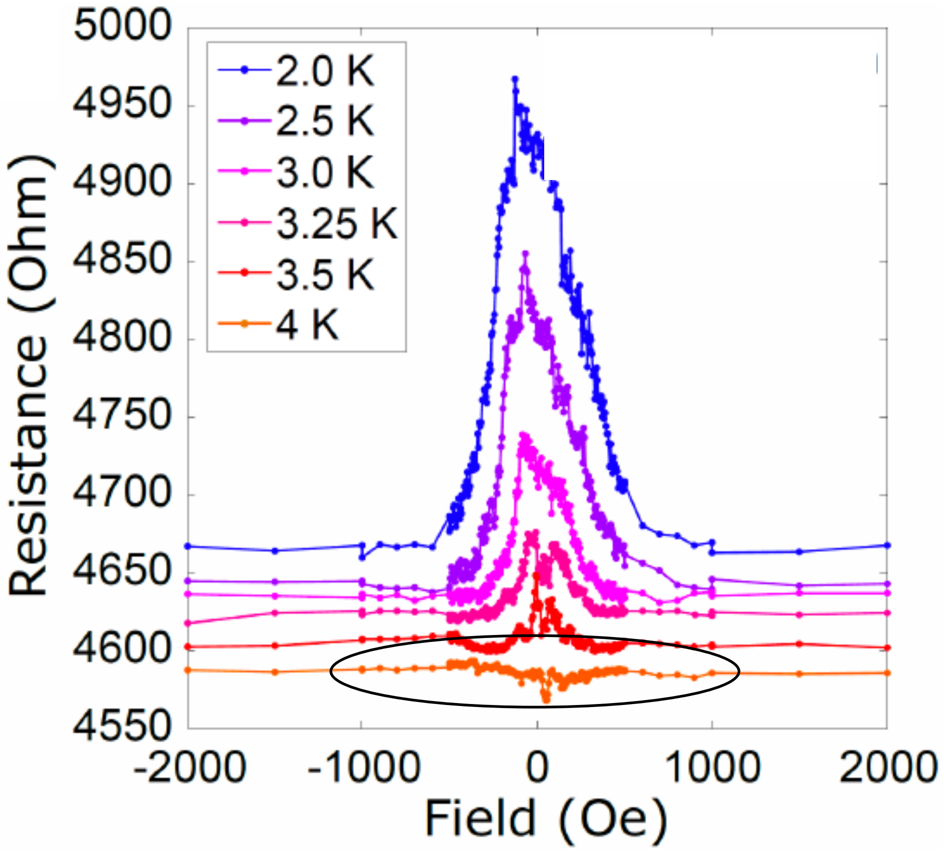


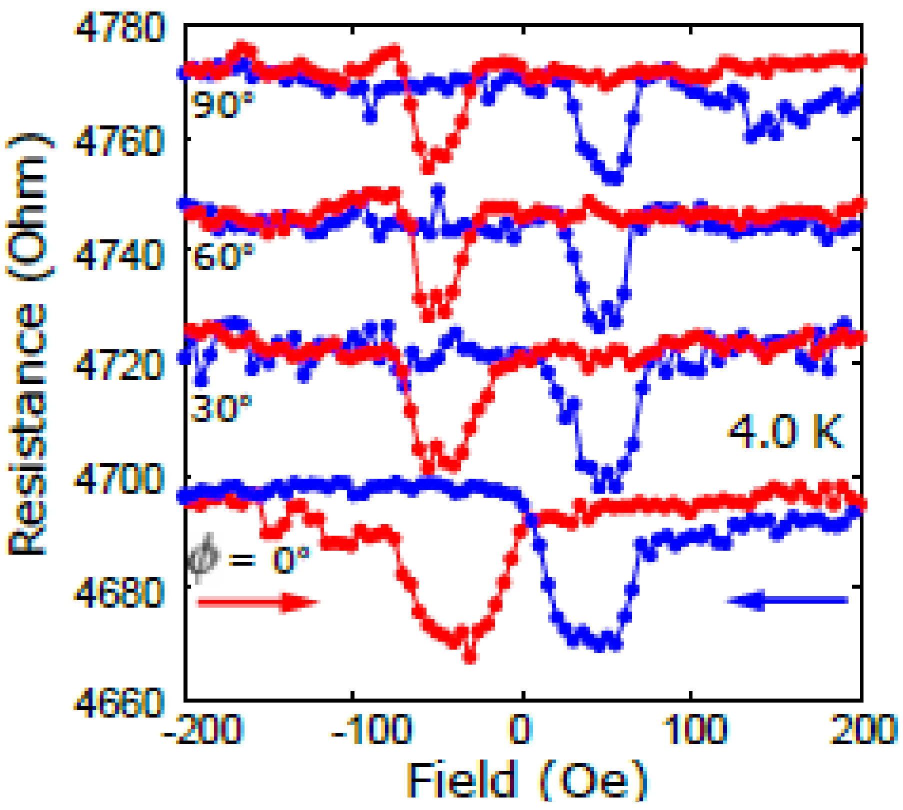
Unlike conventional AMR, peak doesn't depend on relative direction of H and I

Hysteresis consistent with FM interface effect

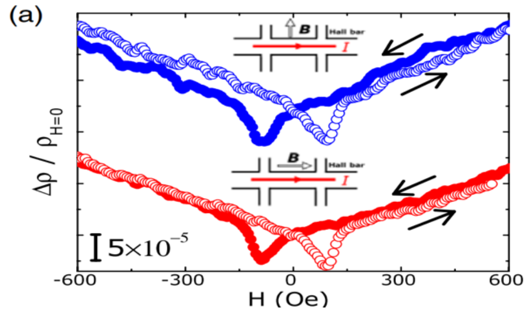
Behavior consistent with coherent rotation of surface state's perpendicular magnetization

Small dips appear at higher temperature





Small dips at 4K similar to Wei et al (domain wall origin?)



Modeling of MR data

Use simple free energy model:

$$F = -HM_{TI}\sin\psi + 2\pi M_{TI}^2\cos^2\psi - K_u\cos^2\psi$$

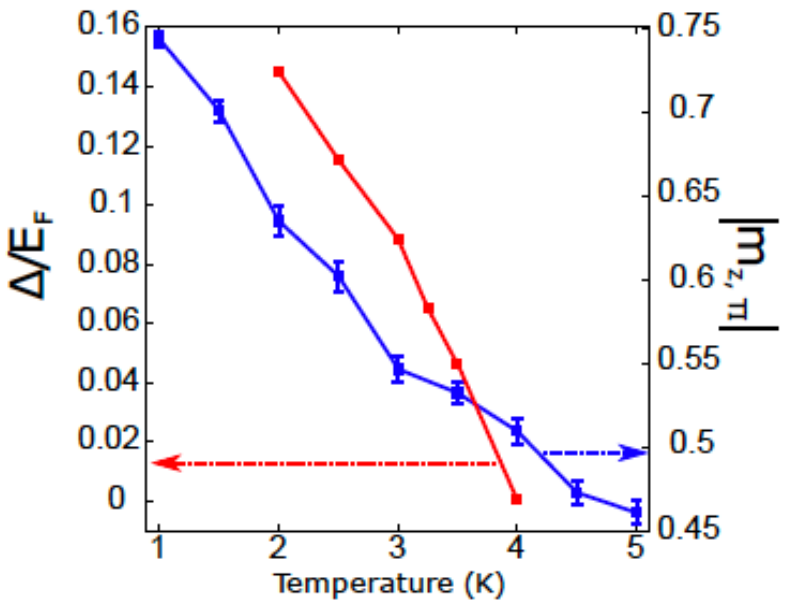
H-M_{TI} alignment (Zeeman)

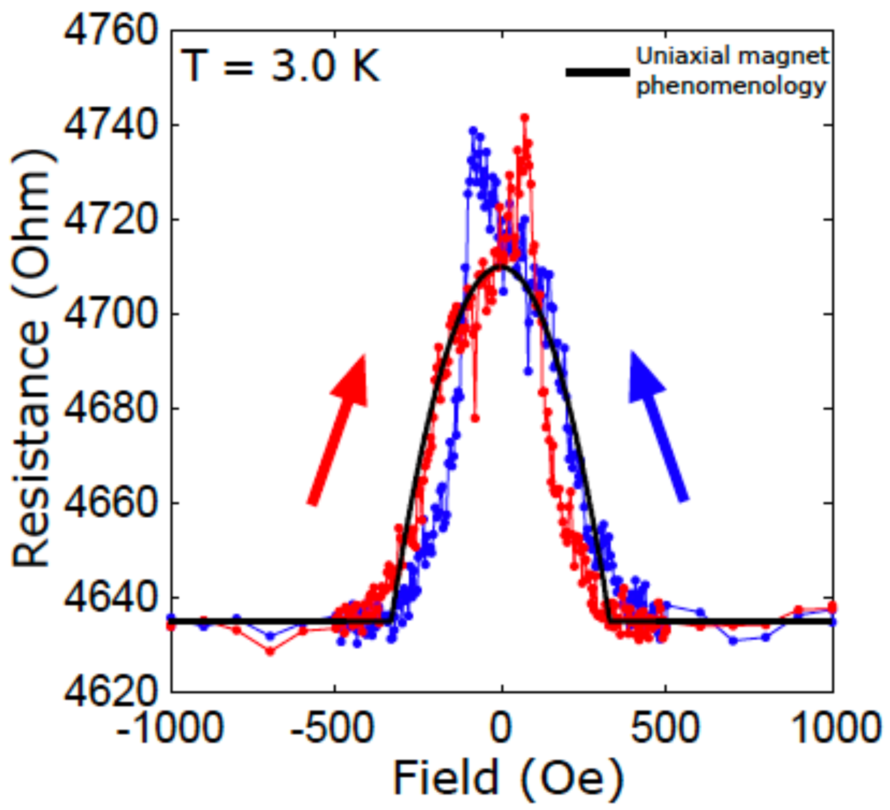
Shape anisotropy (in-plane)

Uniaxial anisotropy (TI PMA)

$$\rho_{xx} \sim \frac{1+\xi^2\cos\psi^2}{1-\xi^2\cos\psi^2}, \quad \xi = \frac{\zeta}{\sqrt{1+\zeta^2\cos\psi^2}}$$

$$\zeta = \Delta/E_F$$





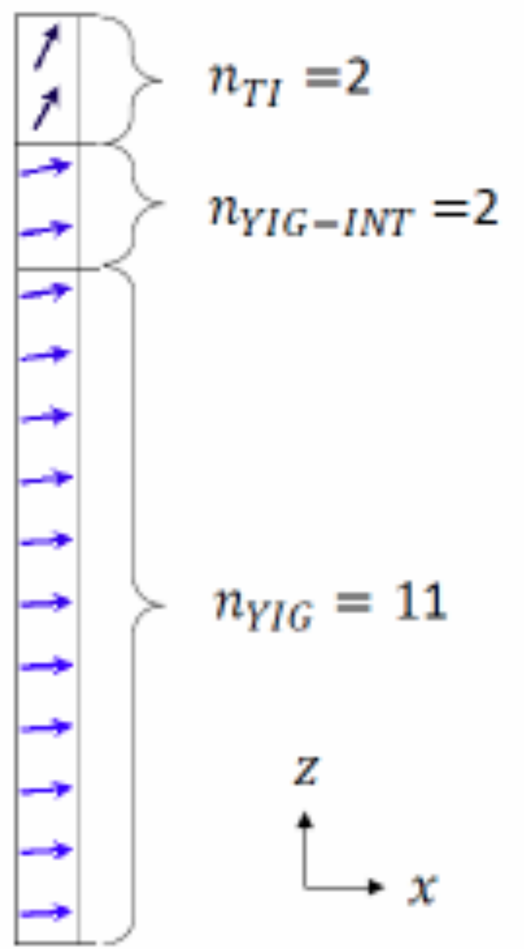
Simple model misses some features, but allows gap energy to be extracted

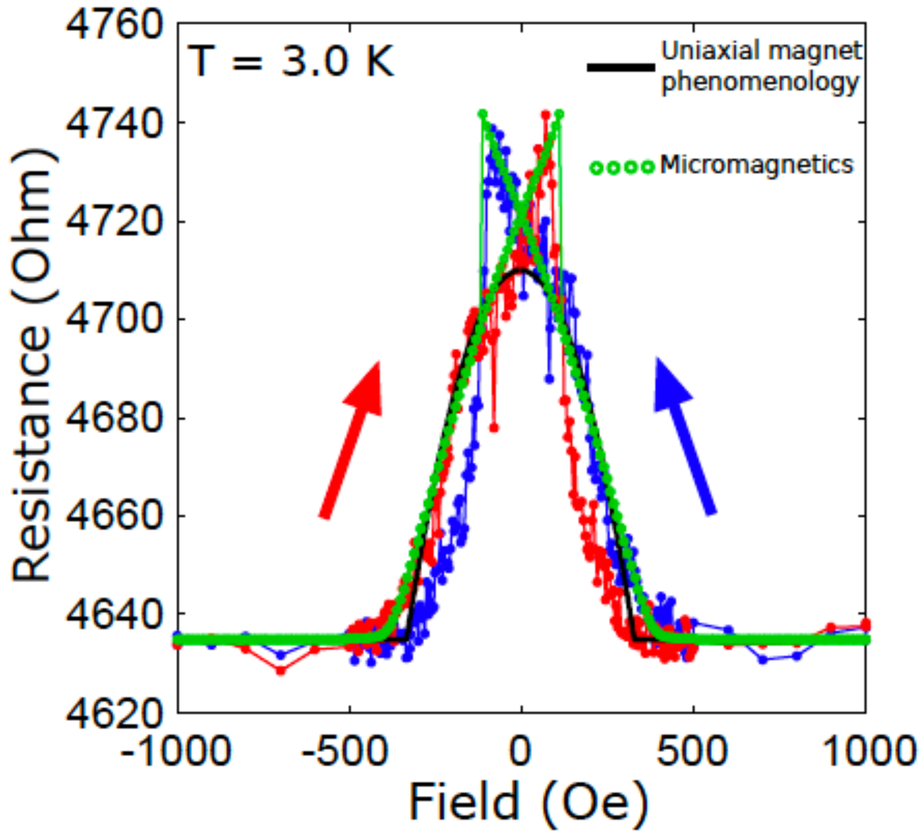
Modeling of MR data

Micromagnetics simulations capture additional features …

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} - \gamma \frac{\alpha}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{eff})$$

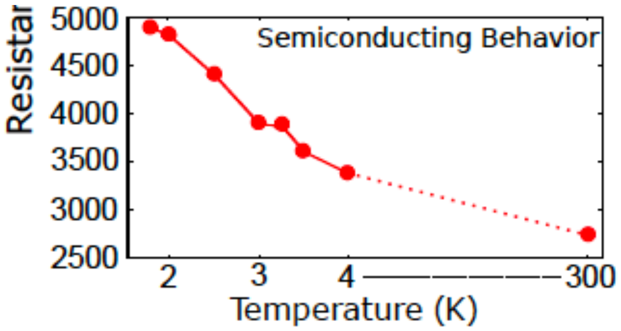
torque damping





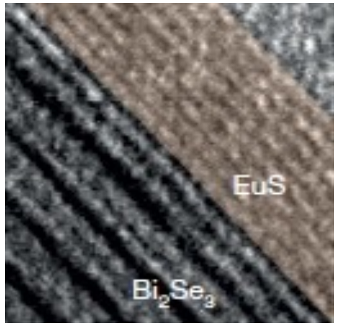
Fit is much better! Sharp hysteretic peaks due to pinned YIG-TI interface switching

Surface states seem to dominate bulk contributions



- Semiconducting behavior consistent with surface-dominated regime

- Measured carrier density of 5 x 10^{17} consistent with Fermi energy in or near bandgap



- Magnetic proximity effects likely extend < 3 nm into TI (See F. Katmis et al. *Nature* **533**, 513 (2016))

- Previous measurements show magnetotransport sensitive to surface rather than bulk


nature physics ARTICLES
https://doi.org/10.1038/s41567-017-0029-y

Bilinear magnetoelectric resistance as a probe of three-dimensional spin texture in topological surface states

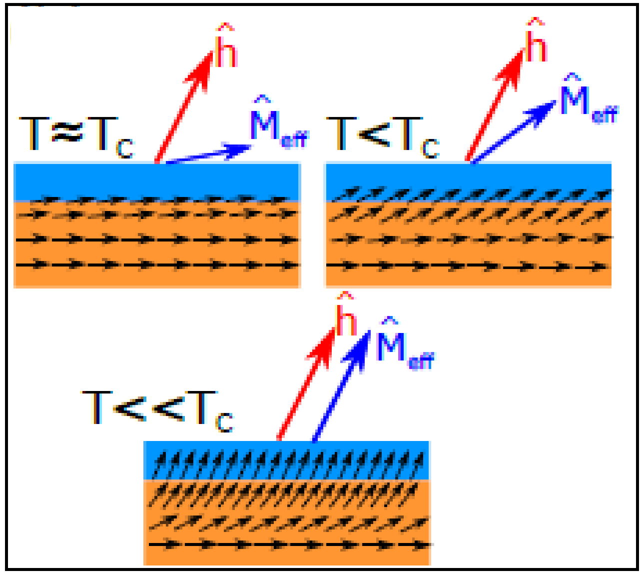
Pan He[1,4], Steven S.-L. Zhang[2,3,4], Dapeng Zhu[1], Yang Liu[1], Yi Wang[1], Jiawei Yu[1], Giovanni Vignale[2] and Hyunsoo Yang[1*]

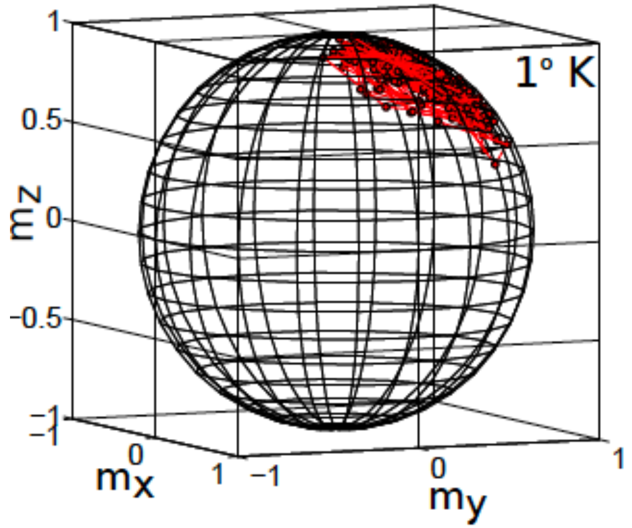
Our experiments and simulations most consistent with surface state AMR

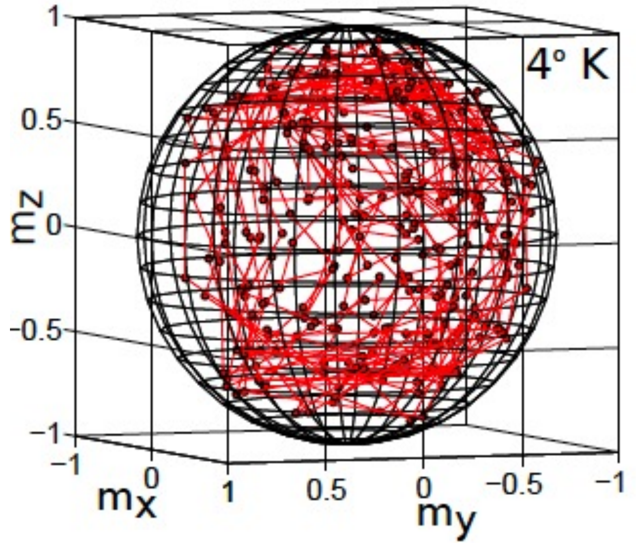
Thermal fluctuations

Finite temperature may lead to magnetization fluctuations

- Thermal fluctuations are incorporated as a white noise in the micromagnetics as a random force.
- Below 1K there appears to be magnetic order but around 4K the magnetic order is lost.

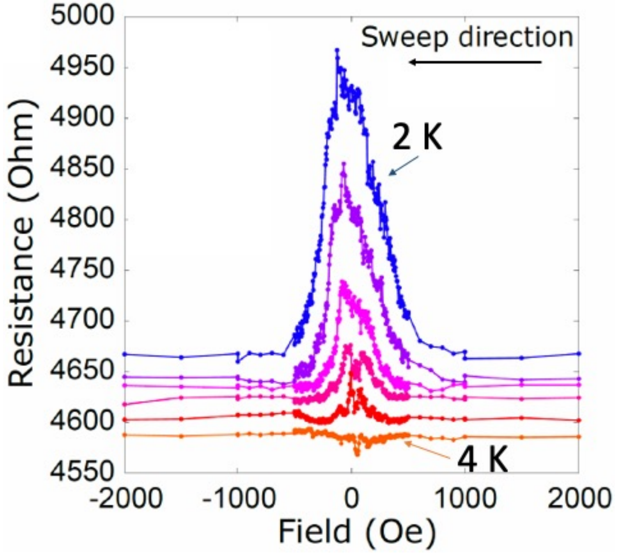


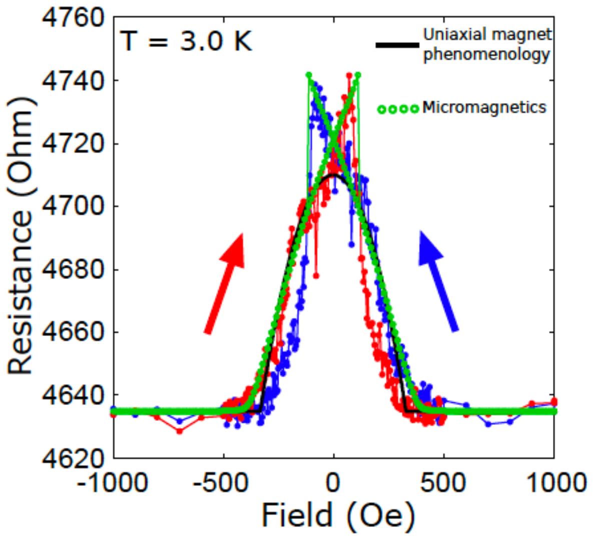




MR of YIG/TI: Take-Aways

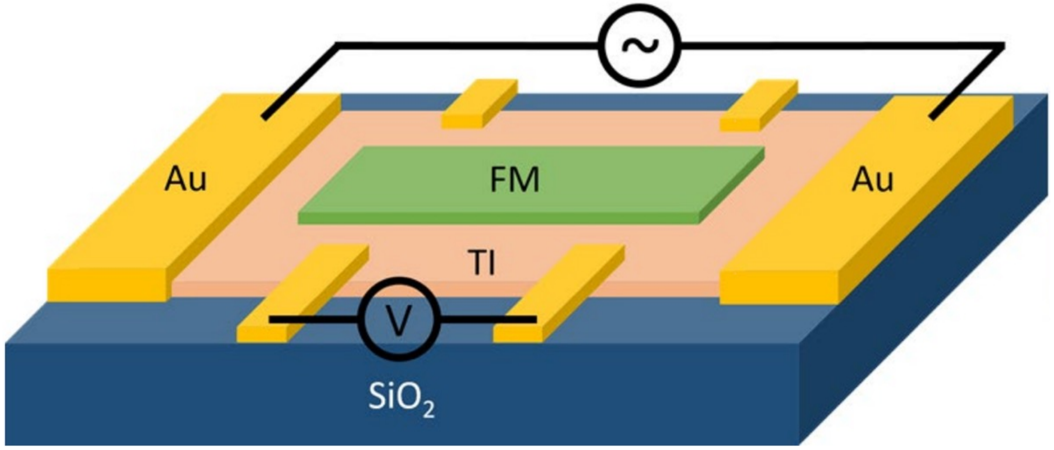
- Clear evidence of proximity magnetization between TI flakes and YIG
- Evidence of competing anisotropies between YIG (IP) and TI (OOP), where TI magnetization rotates coherently with in-plane field, creating new type of strong AMR peak
- Consistent with gapped TI surface state with PMA at remanence

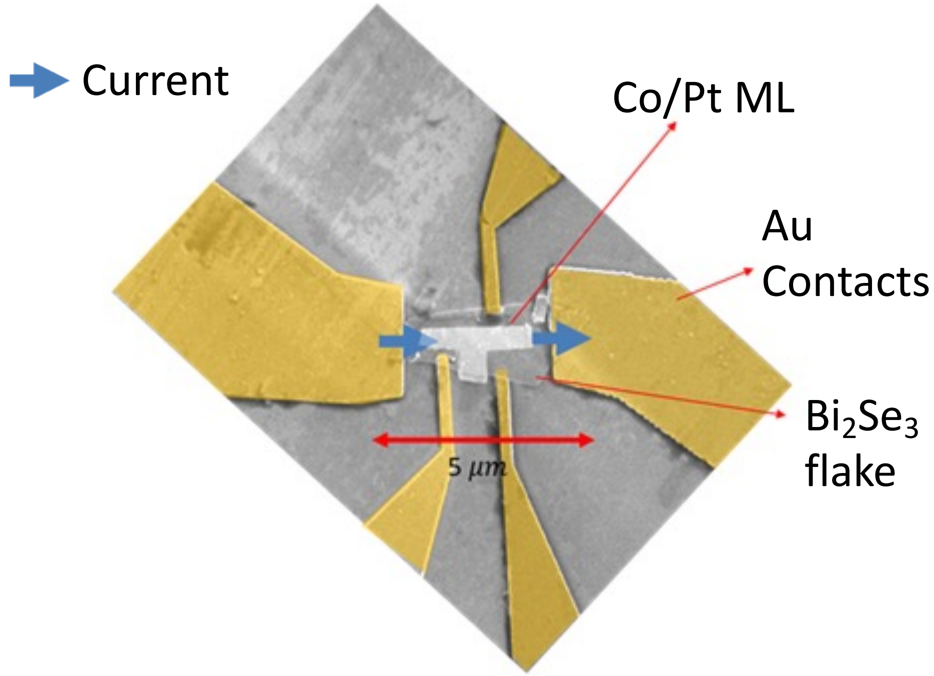




Can we observe similar effects for a TI on a FM metal having different anisotropy?

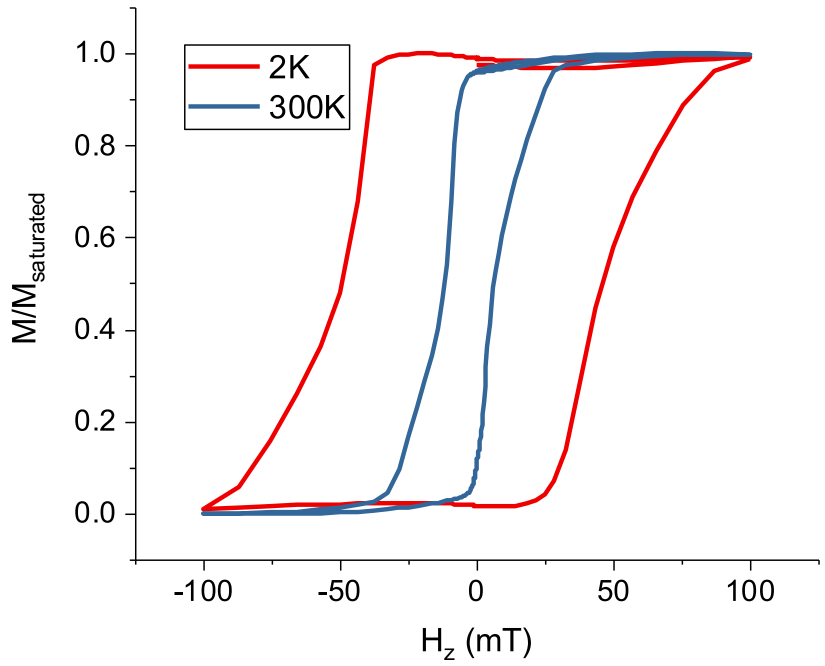
We fabricate Co/Pt multilayers on top of exfoliated 20 - 30nm thick Bi_2Se_3 flakes on SiO_2 substrates…

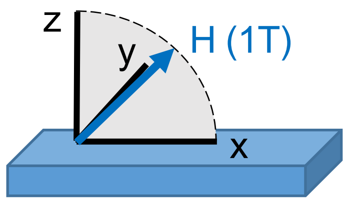


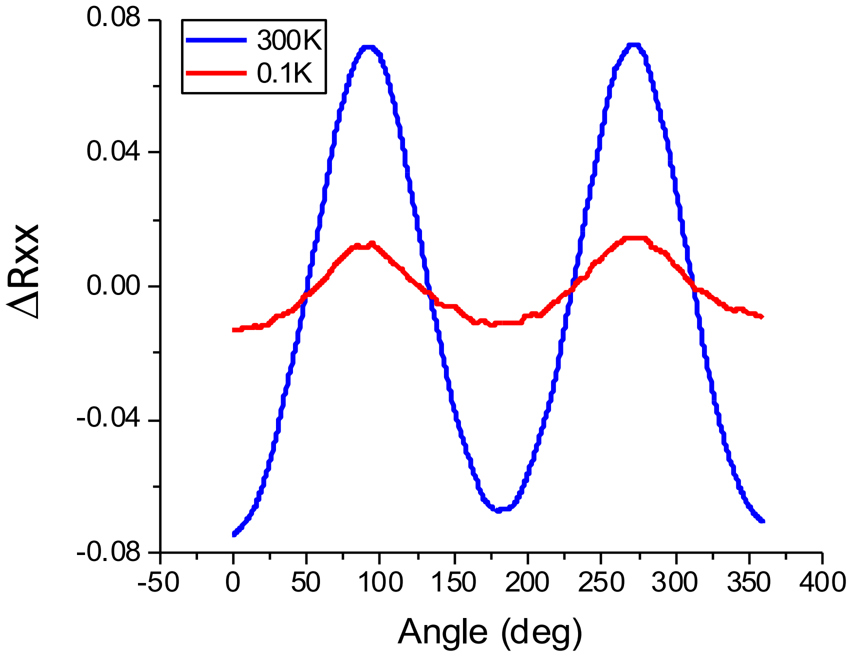


Characterization of Co/Pt multilayers

$Pt_{seed}(5nm)/[Co(0.3)/Pt(1)]_8/Pt_{cap}(1)$







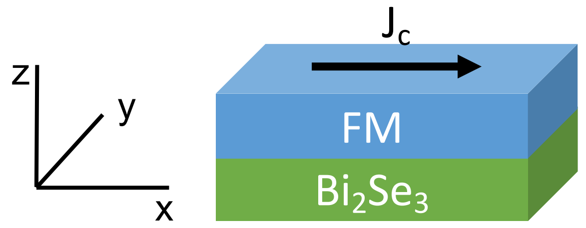
Strong out-of-plane perpendicular magnetic anisotropy
H_s ~ 25-100mT

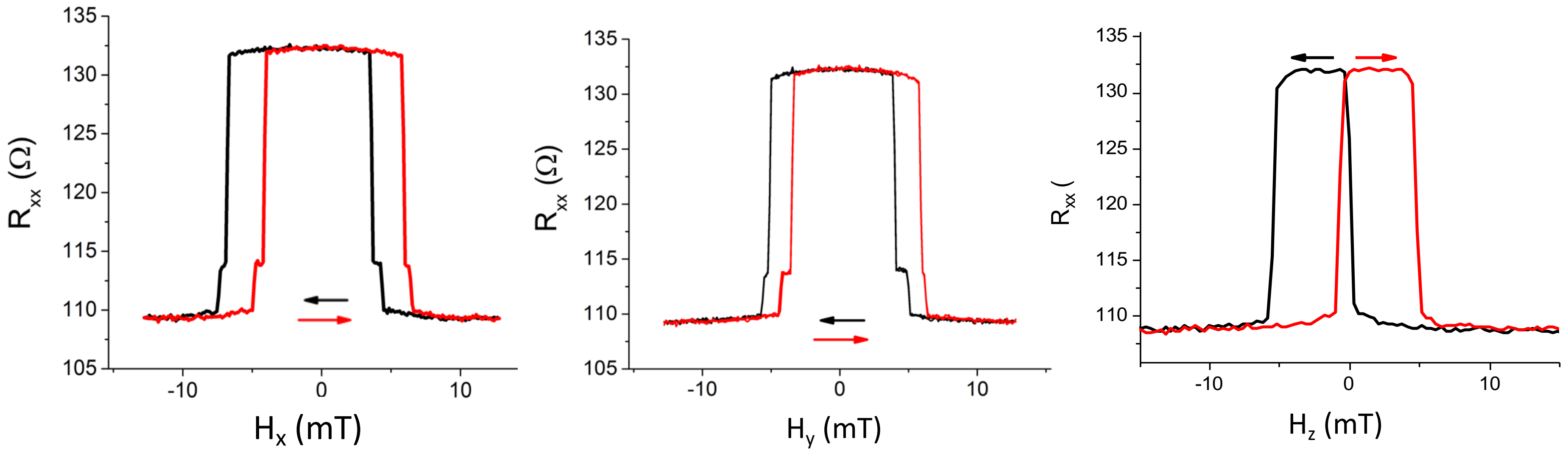
Typical AMR at both 0.1K and 300K (<1% of the MR).

Magnetoresistance BiSe/CoPt

We measure the magnetoresistance on a 26nm thick flake with a Co/Pt multilayer sputtered on top…

T = 100mK

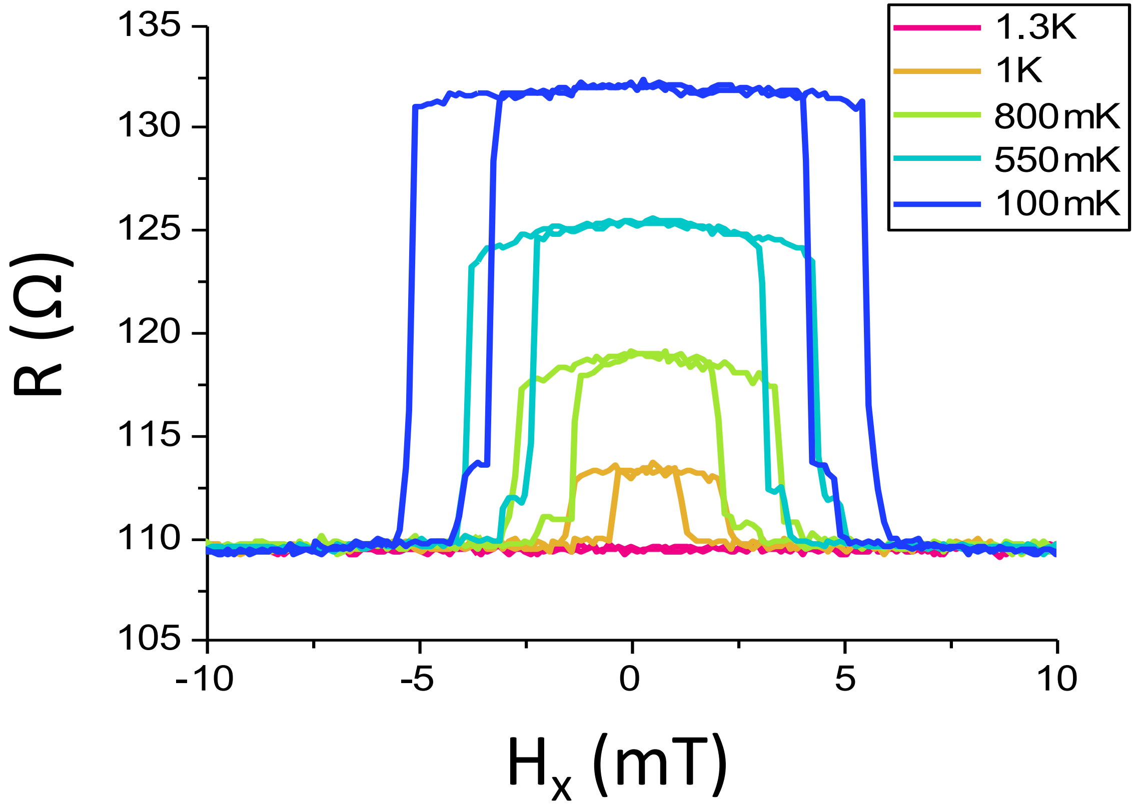




We observe more than a 20% change in the magnetoresistance.

Magnetoresistance BiSe/CoPt: Temperature Dependence

The MR effect becomes narrower in field and smaller in magnitude as the temperature is increased.

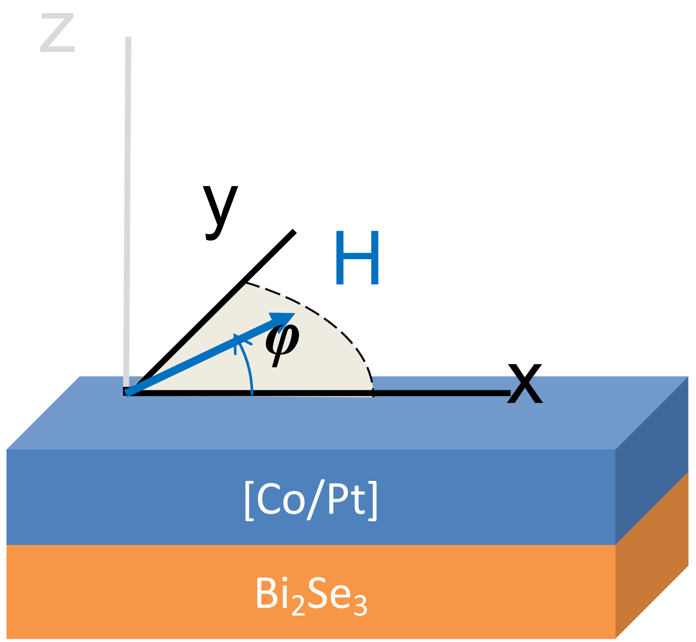


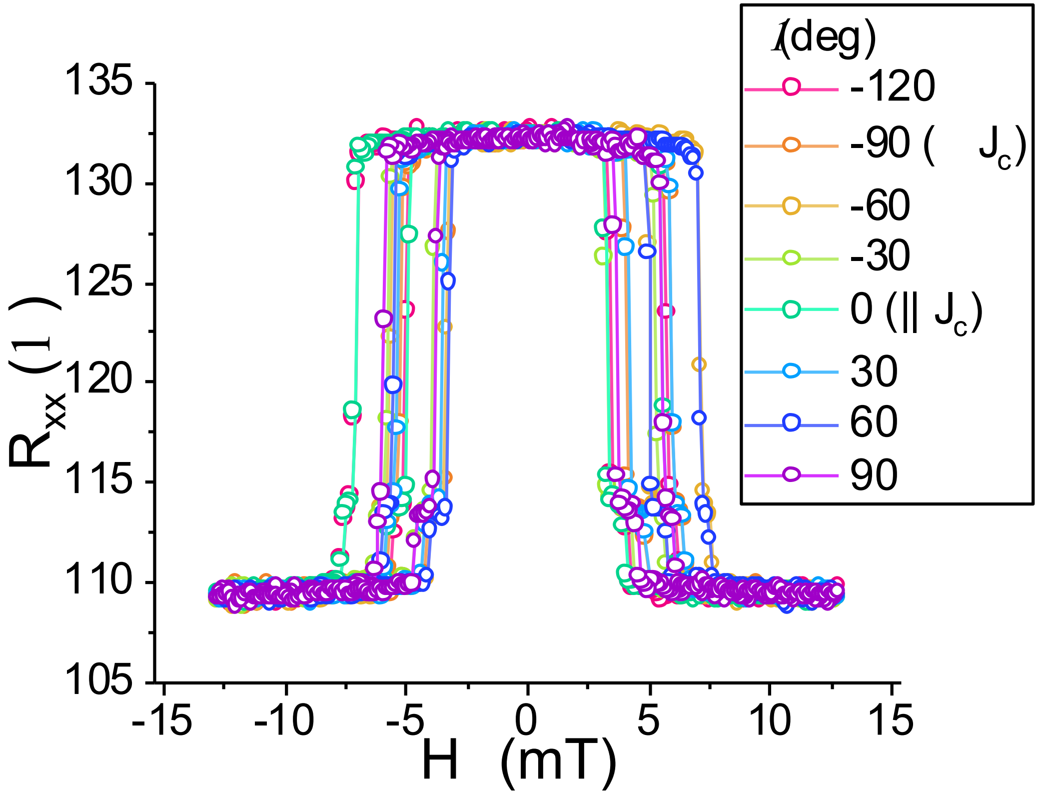
Strong evidence effects due to BiSe (not CoPt);

- Temperature dependence
- AMR peaks for both x and y in-plane field sweeps (should vary as $\cos^2$ for CoPt)
- Magnetic switching field much smaller than for Co/Pt (~300 Oe at 2K)
- Signal magnitude is much greater than Co/Pt AMR

Field Sweeps at Varying In-Plane Angle

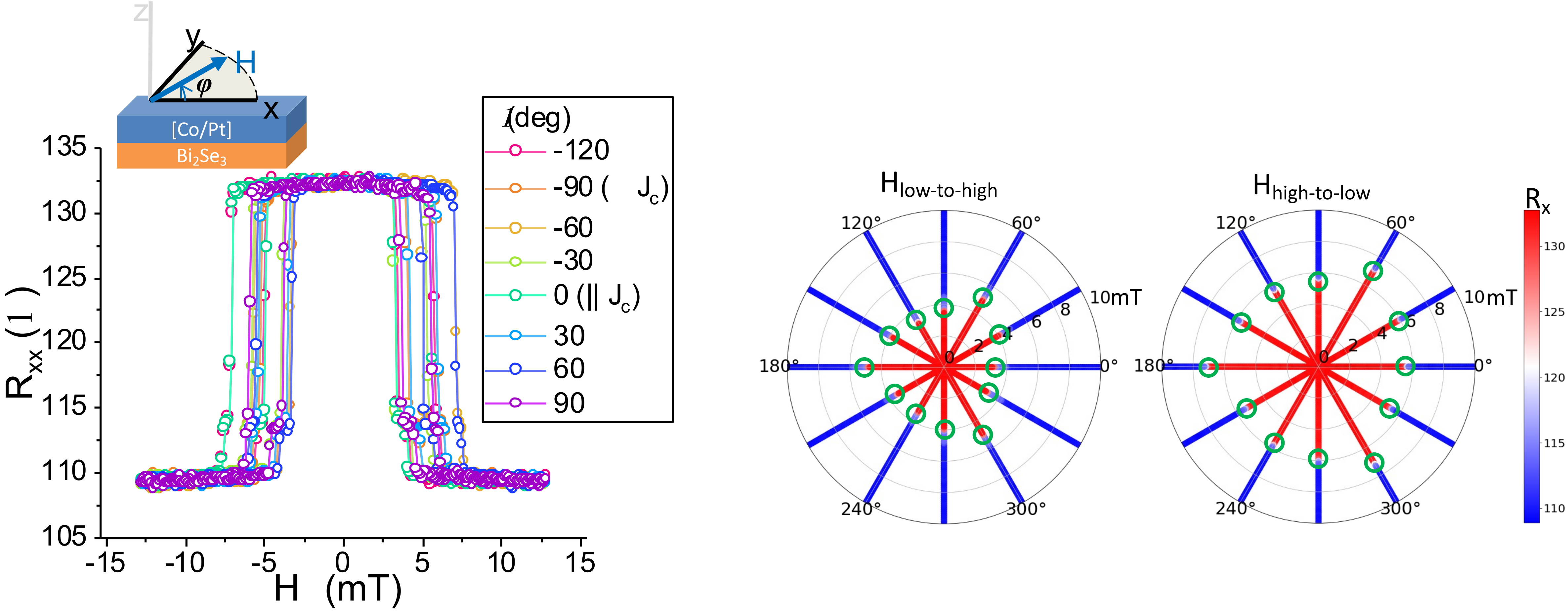
- MR magnitude has no dependence on IP angle ϕ





Field Sweeps at Varying In-Plane Angle

- MR magnitude has no dependence on IP angle ϕ
- Variation in $H_{low\text{-}to\text{-}high}$ and $H_{high\text{-}to\text{-}low}$ reveals repetition of maximum switching fields every 120 deg in ϕ



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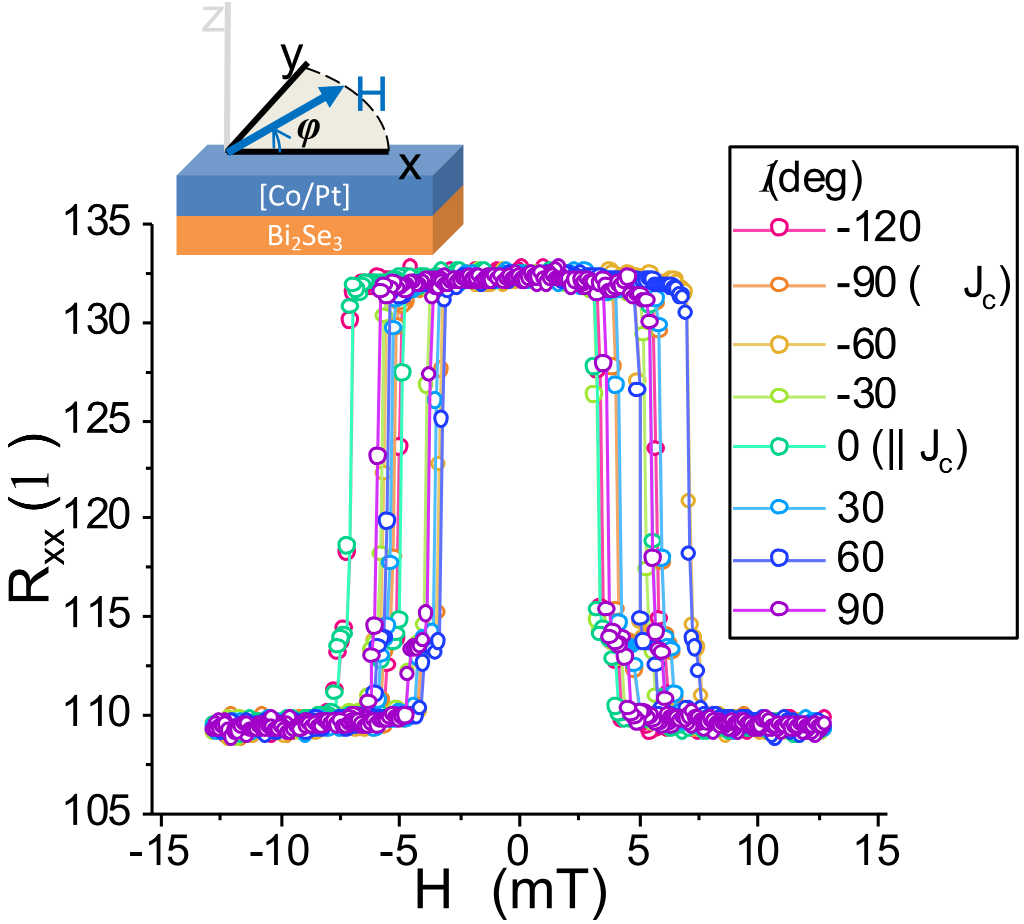
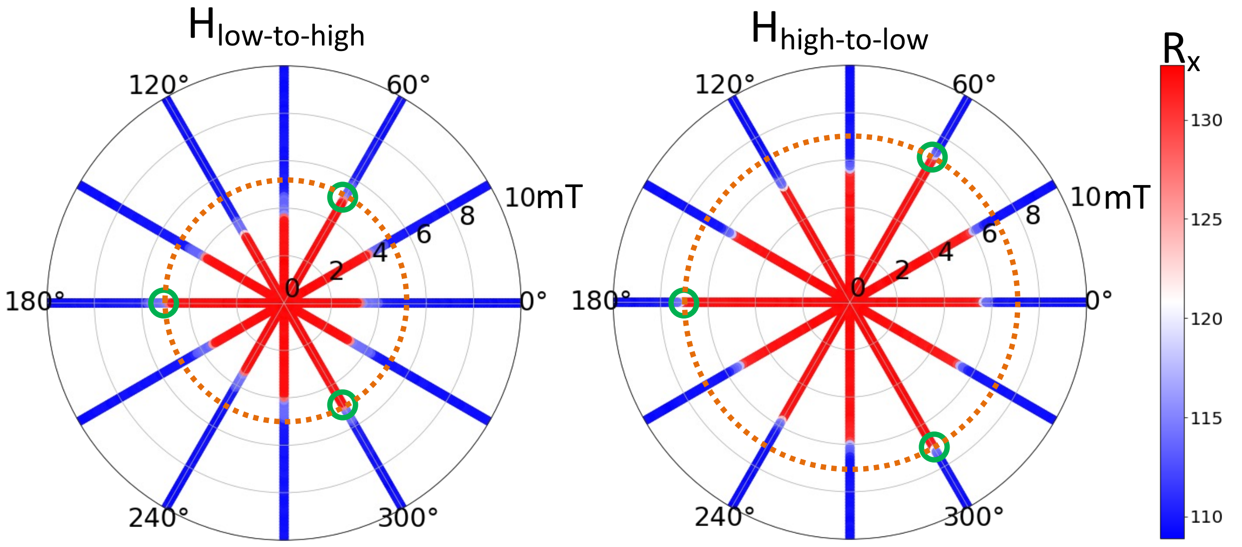
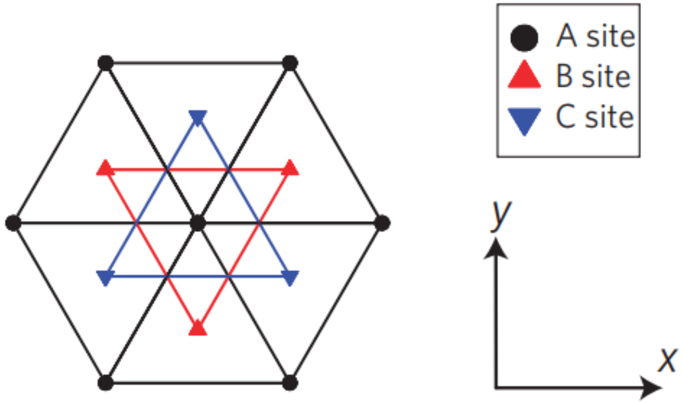


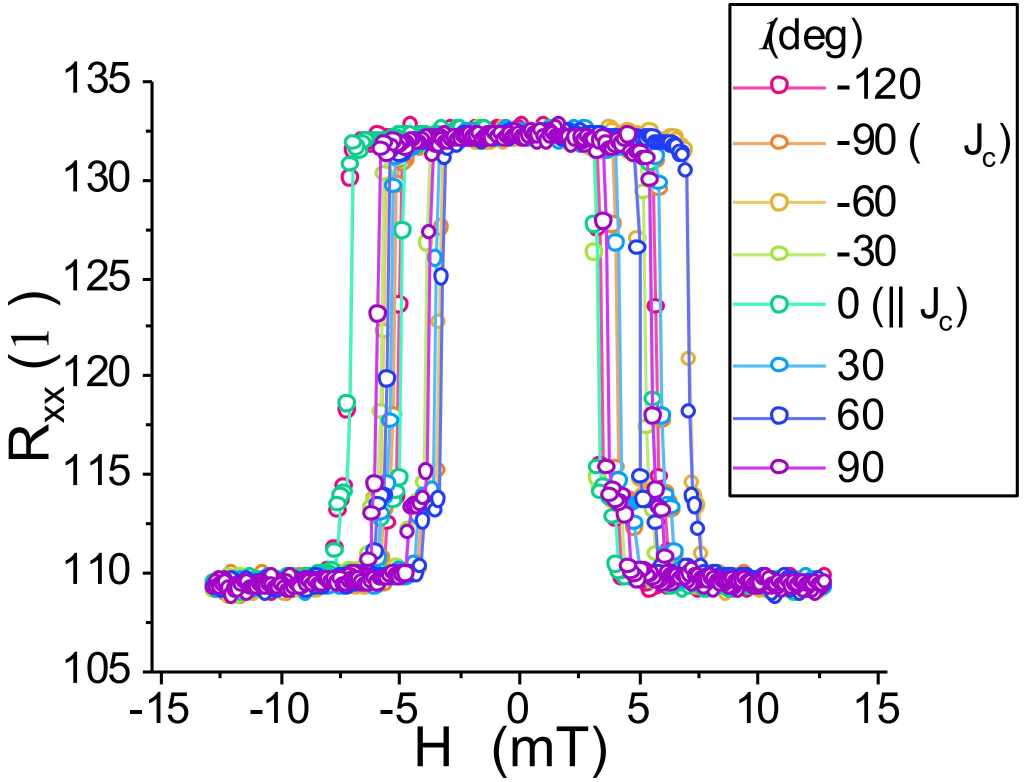


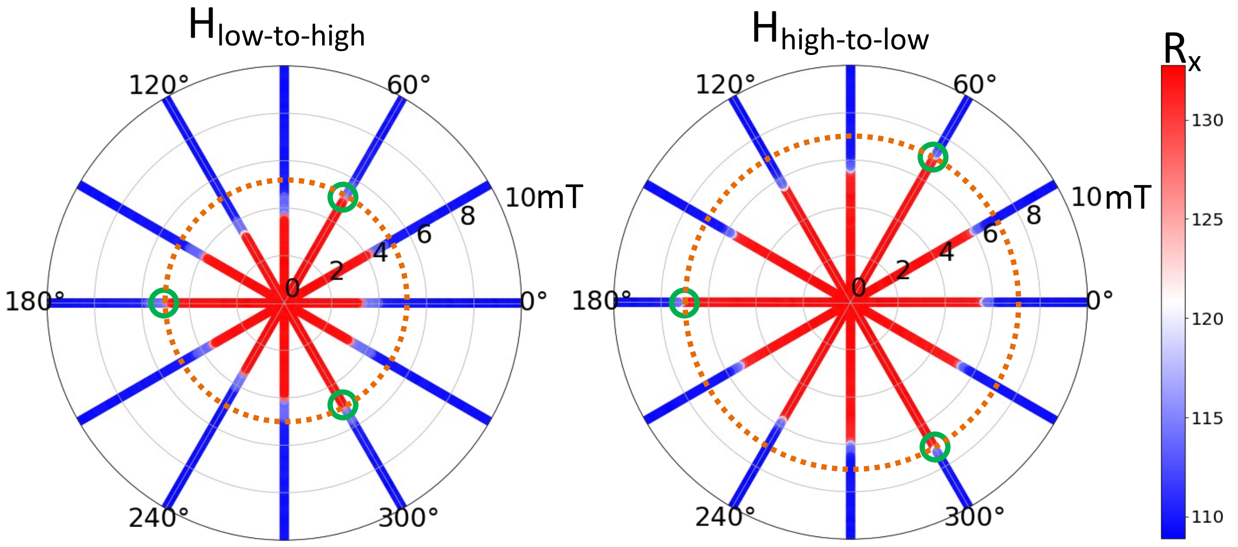
Field Sweeps at Varying In-Plane Angle

- MR magnitude has no dependence on IP angle ϕ
- Variation in $H_{low\text{-}to\text{-}high}$ and $H_{high\text{-}to\text{-}low}$ reveals repetition of maximum switching fields every 120 deg in ϕ
- Likely due to the crystal symmetry of Bi_2Se_3



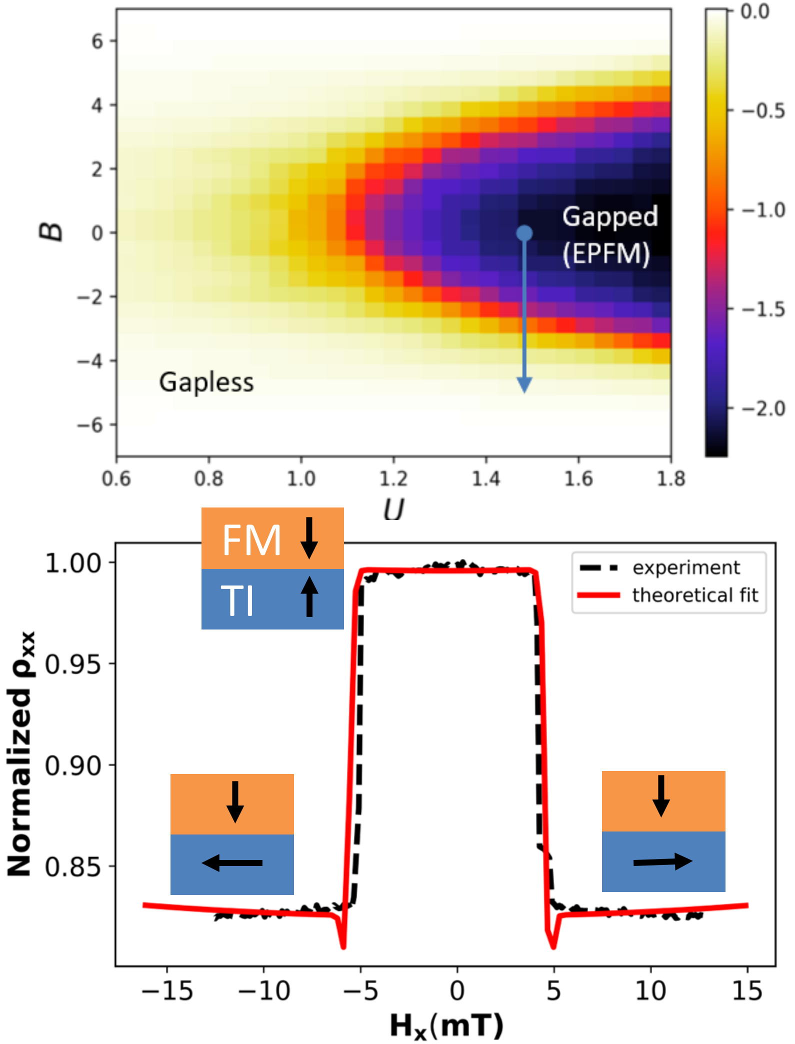
Crystal structure of Bi_2Se_3
Nature physics 5.6 (2009): 438





Theoretical Model

- MR observed in TI/FM insulators was attributed to domain wall effect. However, this explanation does not suit our results because of the difference in switching field of FM and MR.
- Four band model of TI/FM heterostructure explains the square MR behavior
- The competition between Zeeman energy and Coulomb-like coupling drives the phase transition between gapped/ungapped TSS
- OOP spin texture in gapped TSS gives rise to high MR state. As Zeeman coupling to an external field becomes larger, TSS becomes gapless and leads to low MR state



OOP spin component in TI surface as a function of external field B and coupling coefficient *U* (top) and corresponding MR fit using the model (bottom). Courtesy of Bora Basa

Conclusions

TI surface states can show prominent switching effects in transport, when coupled to ferromagnetic metals and insulators … but only at low temperatures

TI-magnetic heterostructures have significant promise in spin-torque/magnetic memory devices

Need better control over coupling to surface states, decreasing disorder, integrating with CMOS