Spin-orbit torques based on topological spin texture and magnon

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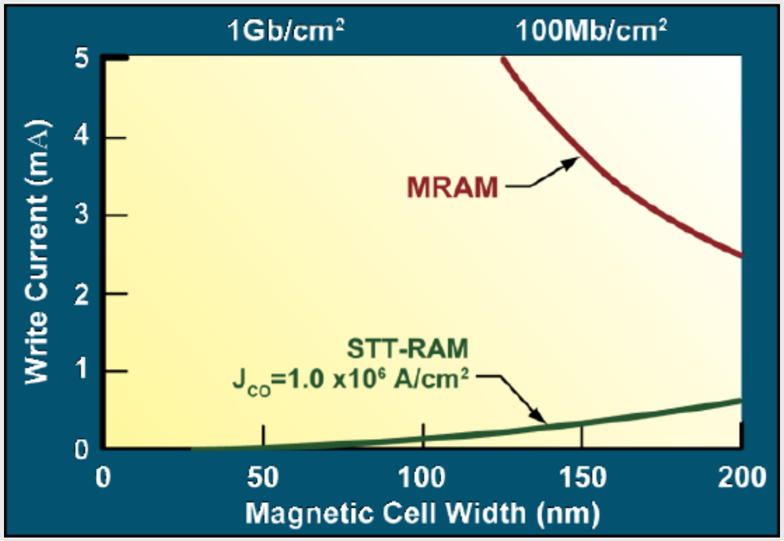
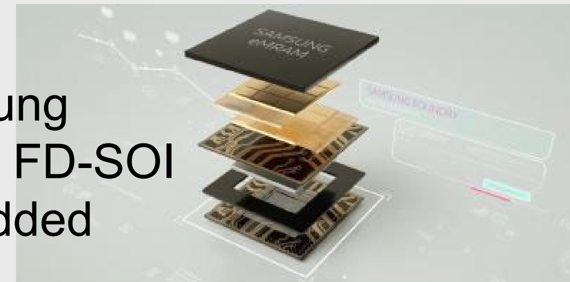
Spin transfer torque (STT) MRAM

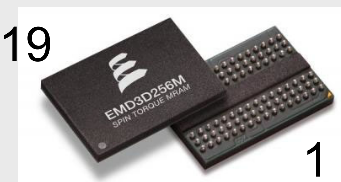


-Samsung, GF, TSMC, IBM, TDK, Hynix, Sony, Avalanche, Toshiba, Intel, Qualcomm…

2019
Samsung
28 nm FD-SOI
embedded



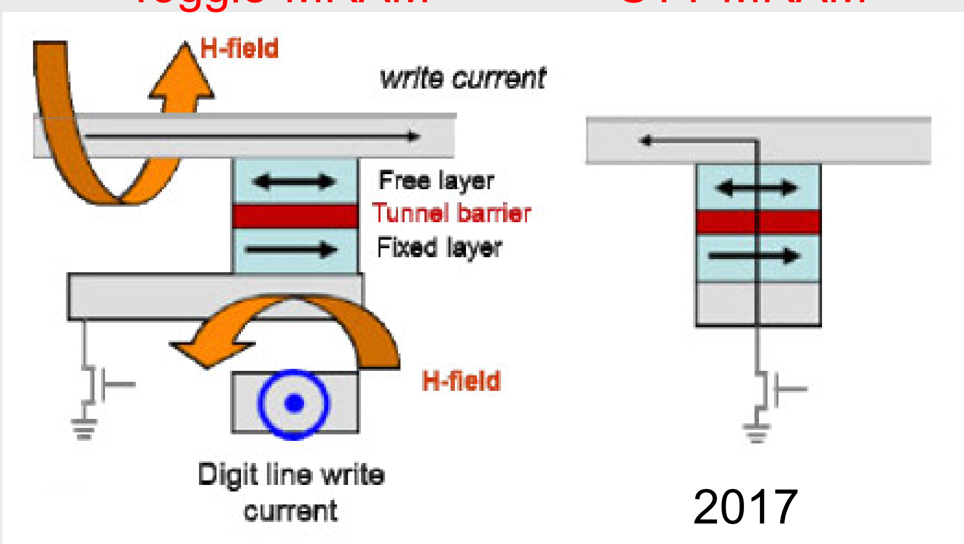
2019



1 Gb

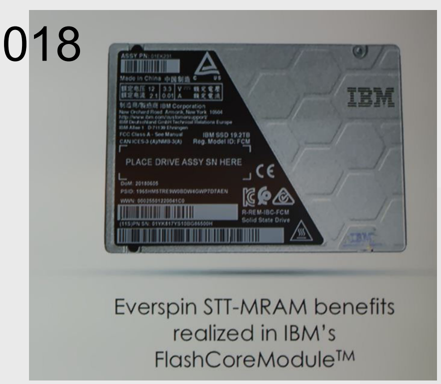
Everspin with GlobalFoundries

Toggle-MRAM STT-MRAM

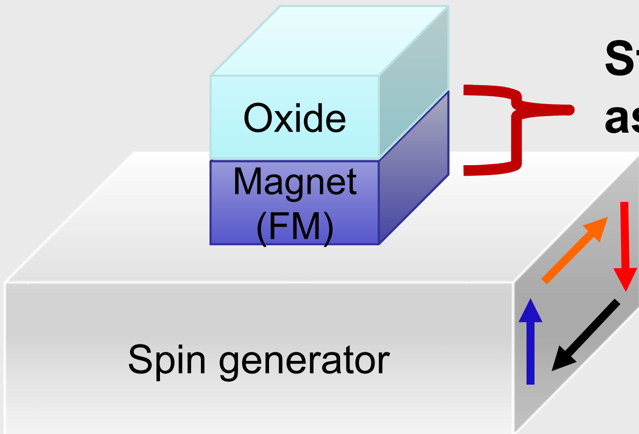


16 Mb 256 Mb

2018



Spin-orbit torque magnetization switching



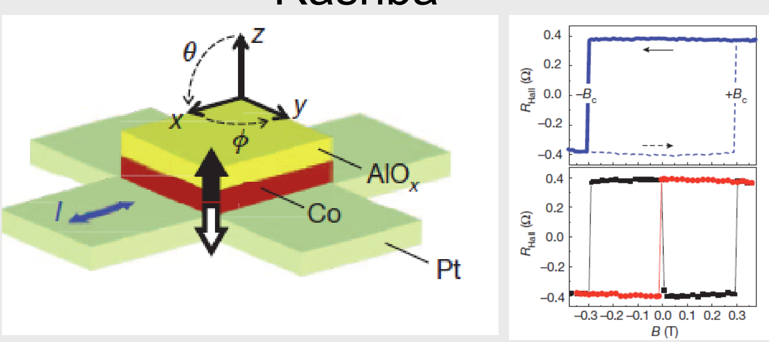
Strong Rashba field arises from asymmetric interfaces

Spin Hall effect arises from HM

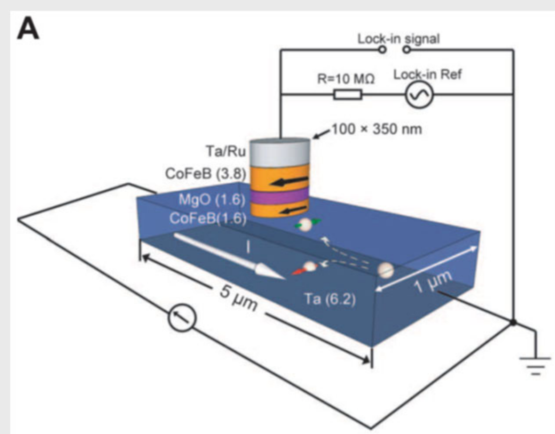
In-plane currents can switch the magnetization.

Spin-orbit torque has paved a novel way to manipulate the magnetization.

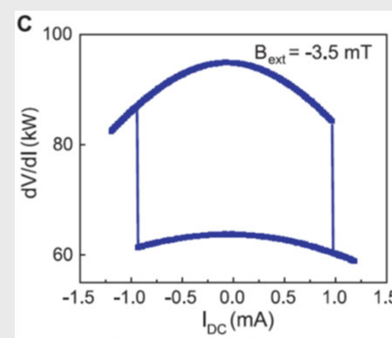
Rashba



Nature **476**, 189 (2011)

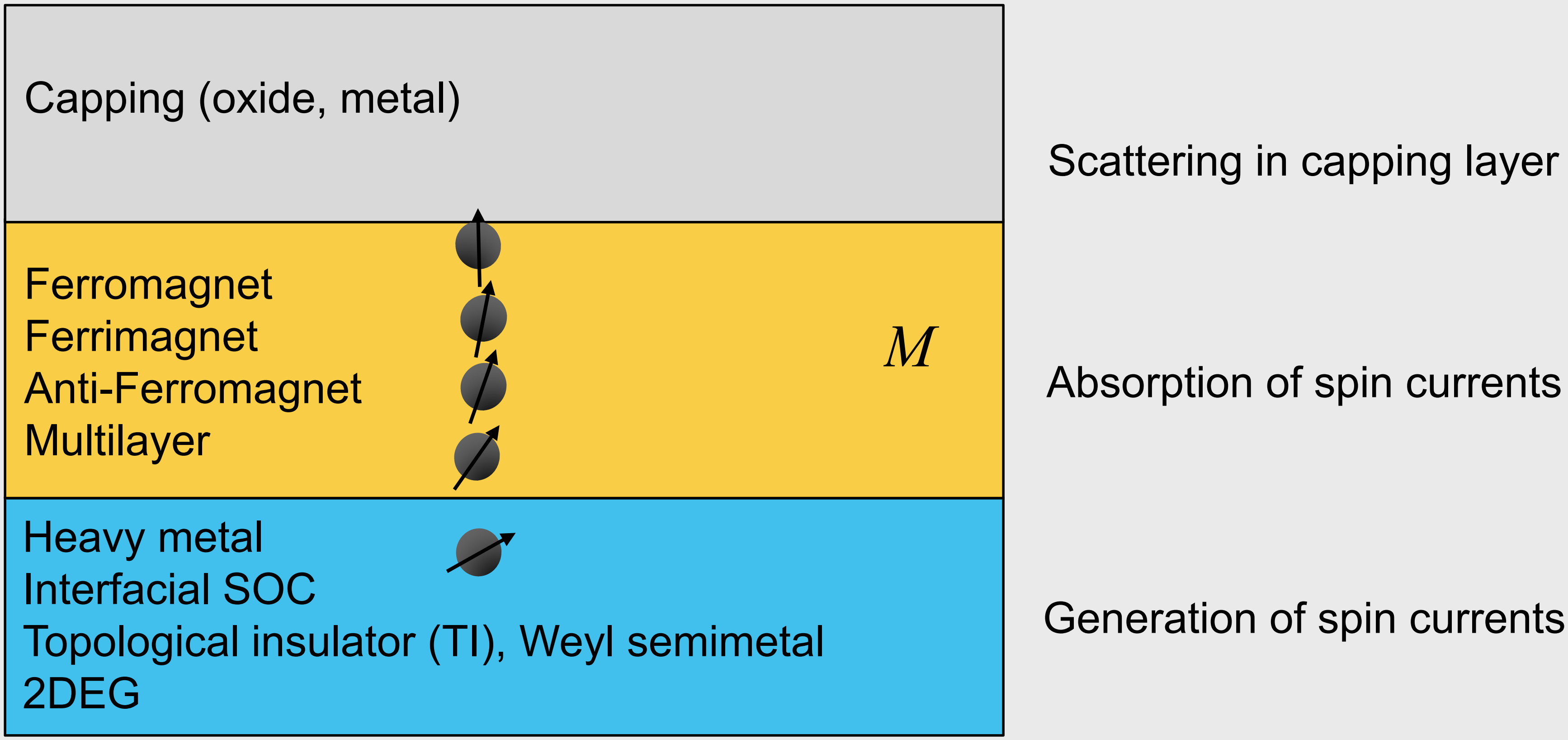


Spin Hall



Science **336**, 556 (2012)

Spin orbit torque (SOT) engineering



Goal is to achieve a low switching current and power.
Search for large effective spin Hall angle (θ_{SH}) or fields (H_L and H_T)

Review: *Appl. Phys. Rev.* **5**, 031107 (2018)

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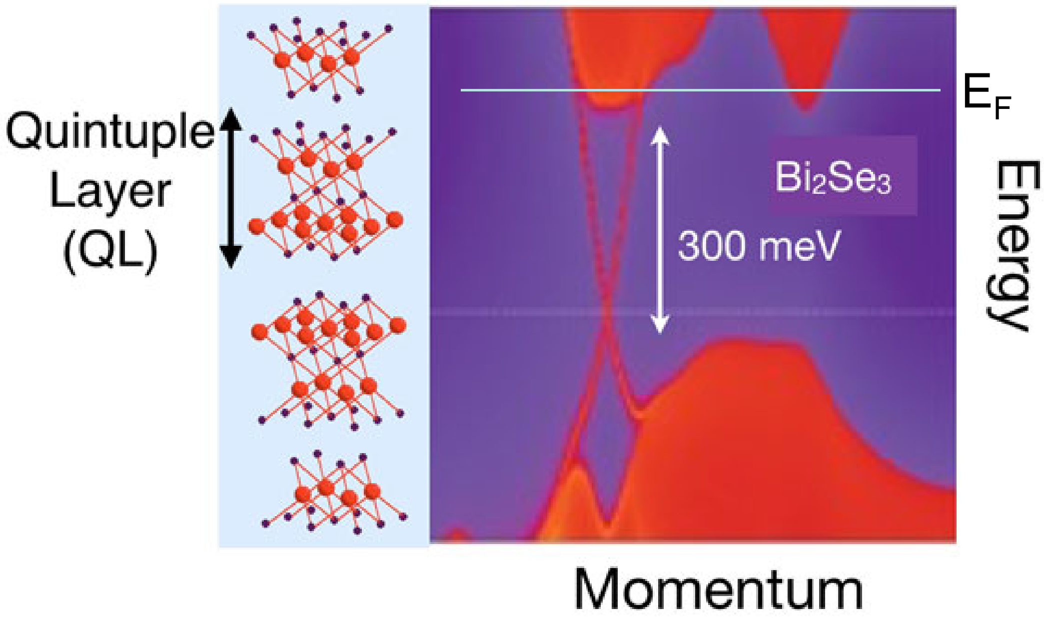
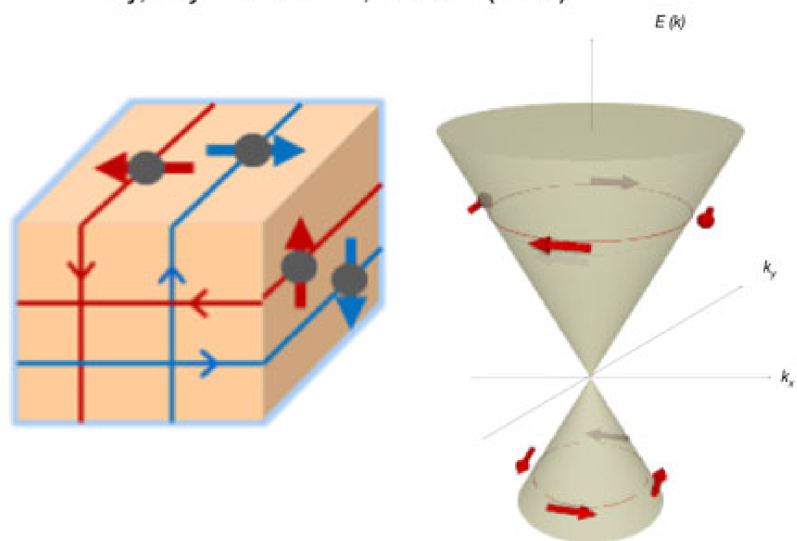
3D topological insulators (TIs)



H. Zhang, C.-X. Liu, *et al.*, *Nature Physics* **5**, 438 (2009)

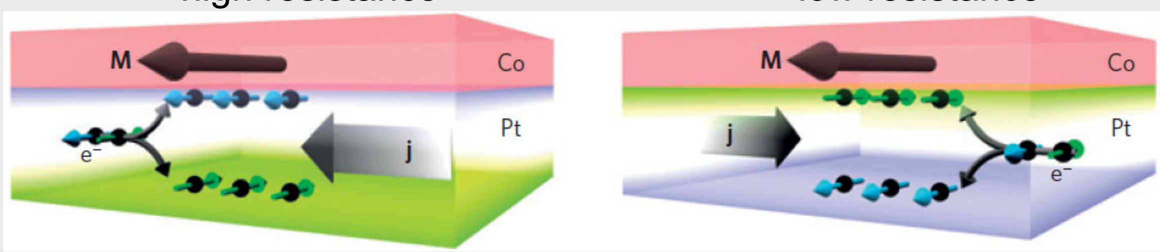
Fu & Kane, *Phys. Rev. B* **76**, 045302 (2007)
Moore & Balents, *Phys. Rev. B* **75**, 121306(R) (2007)
Roy, *Phys. Rev. B* **79**, 195321 (2009)



- ❑ Spin polarized surface states
- ❑ Spin-momentum locking → giant spin Hall angle?

UMR in ferromagnet/normal metal bilayers

❖ Unidirectional magnetoresistance (UMR): Longitudinal resistance changes when either the current or the magnetization direction is switched, i.e., $R_{xx}(-\boldsymbol{j}) \neq R_{xx}(+\boldsymbol{j})$.



Pt/Co & Ta/Co - Avci *et al.*, Nat. Phys. **11**, 570 (2015)

$$R(I) = R(0) + R'(0)I + \cdots$$

Current-dependent (nonlinear) resistance

$I = I_0 \sin \omega t$ a.c. current

$$V(I) = IR(I) = R(0)I_0 \sin \omega t + R'(0)I_0^2 \sin^2 \omega t$$

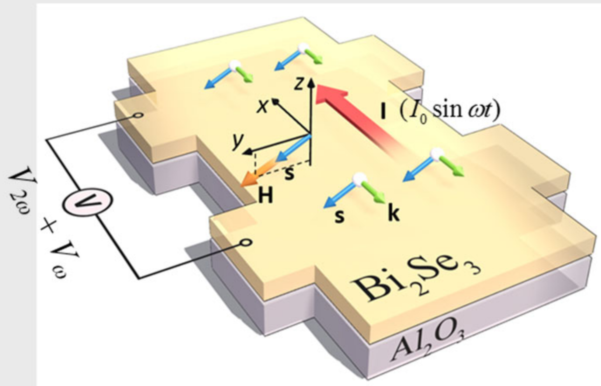
$$= R(0)I_0 \sin \omega t + \frac{1}{2}R'(0)I_0^2 + \frac{1}{2}R'(0)I_0^2 \sin(2\omega t - \pi/2),$$

$$R_{2\omega} = \frac{1}{2}R'(0)I_0$$

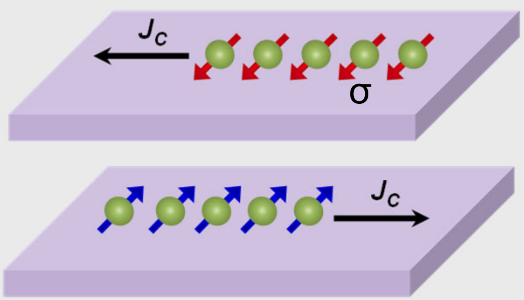
Second harmonic resistance

UMR requires a magnetic layer.

Observation of nonlinear MR in single layer Bi_2Se_3

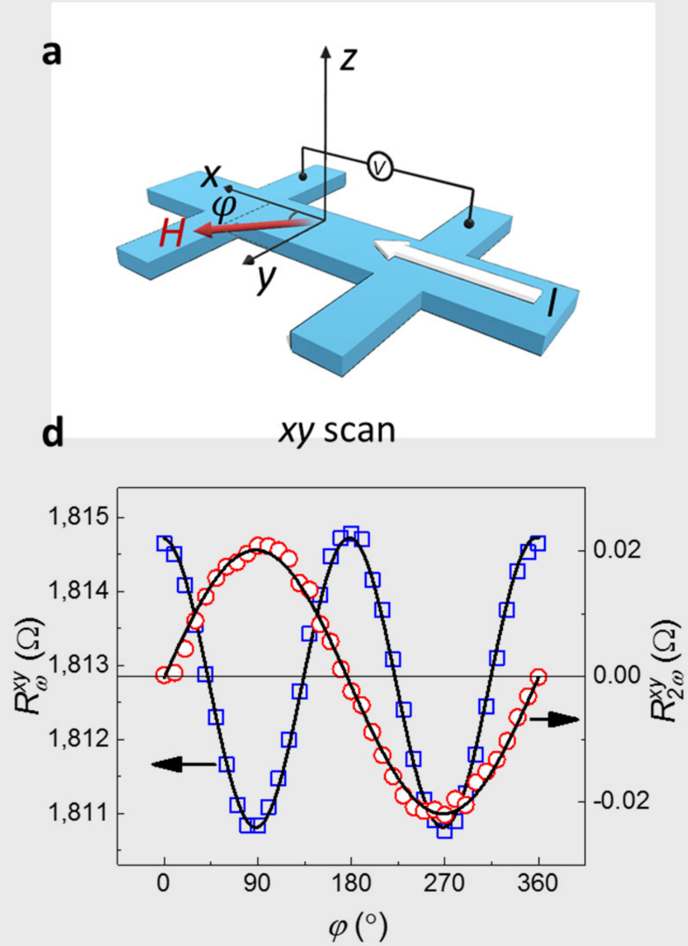


MBE grown Bi_2Se_3 (20 QL)/Al_2O_3 (0001)



$$R_{2\omega} \propto \boldsymbol{s} \cdot \boldsymbol{H}$$

A new spin-dependent nonlinear MR



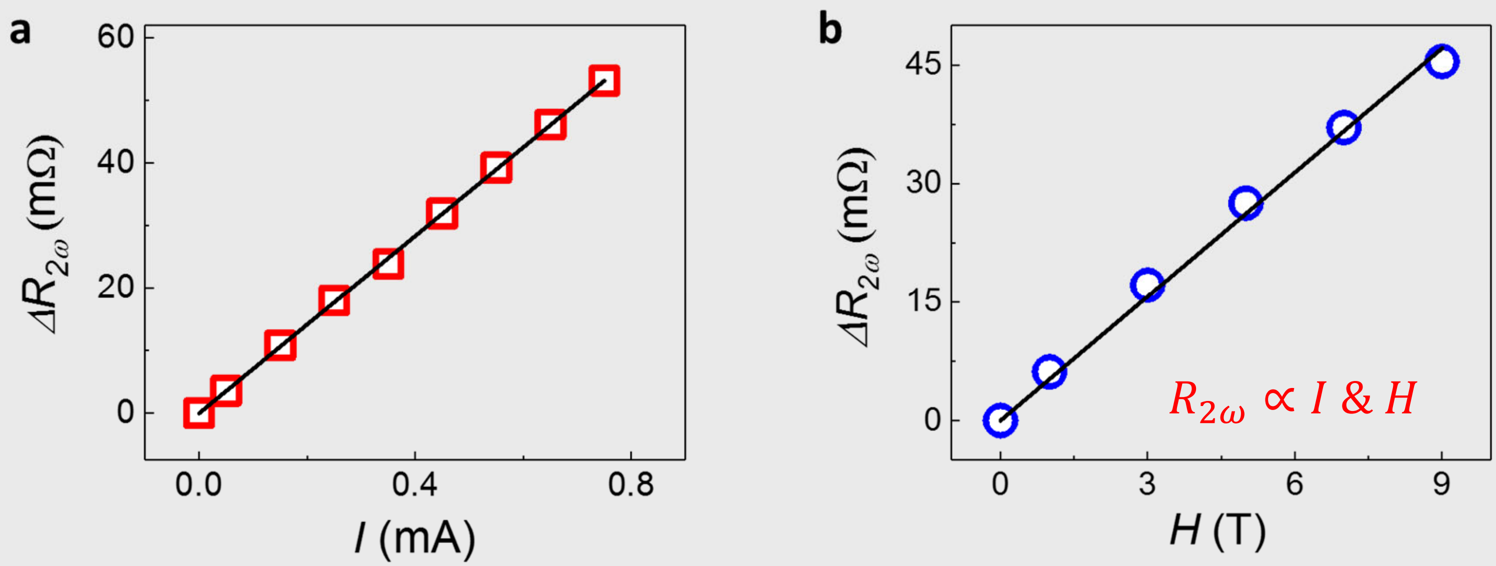
Blue curves:
$R_\omega(-\boldsymbol{H}) = R_\omega(\boldsymbol{H})$

Red curves:
$R_{2\omega}(-\boldsymbol{H}) = -R_{2\omega}(\boldsymbol{H})$

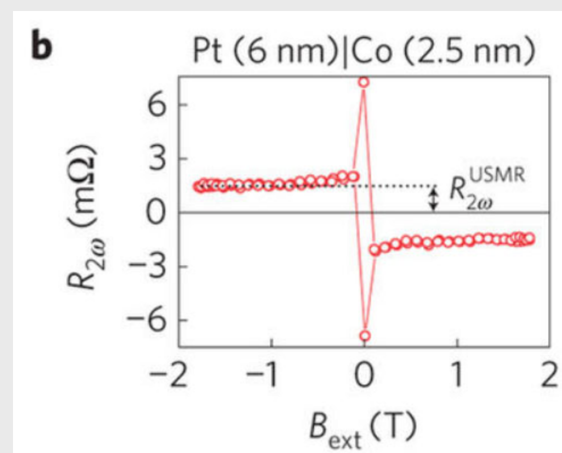
Nat. Phys. **14**, 495 (2018)

Bi_2Se_3 (20 QL, 125K, 9T, 0.55mA)

Bilinear magneto-electric resistance (BMR or BMER)



Bilinear magneto-electric resistance (BMR):
No need to have a magnetic layer.

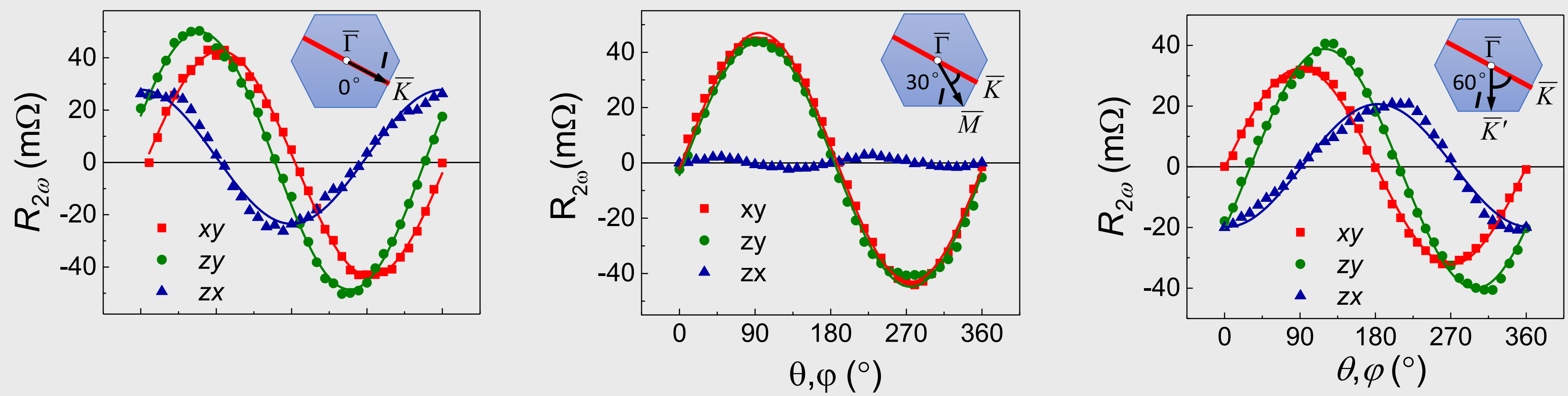


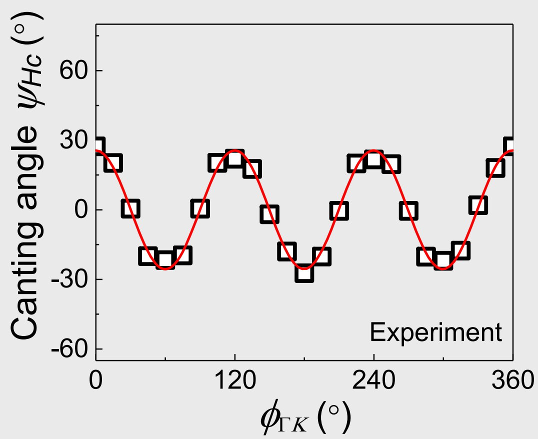
UMR: a magnetic layer is essential.

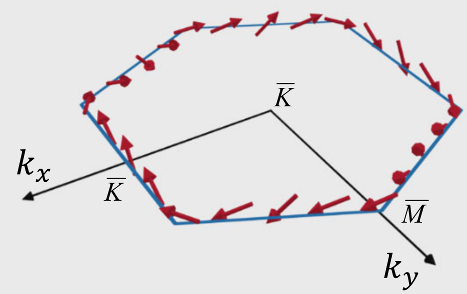
Avci *et al.*, Nat. Phys. **11**, 570 (2015)

Nat. Phys. **14**, 495 (2018)

BMR along different crystal directions





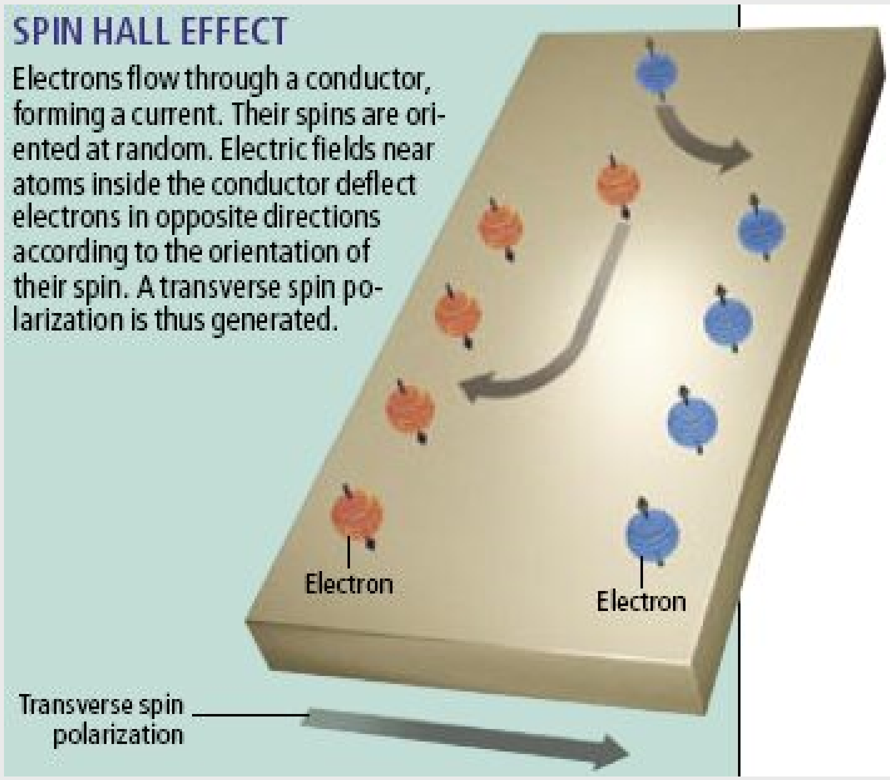


3D spin texture can be mapped along different crystalline directions.
Simple electrical transport based 3D spin texture detection.

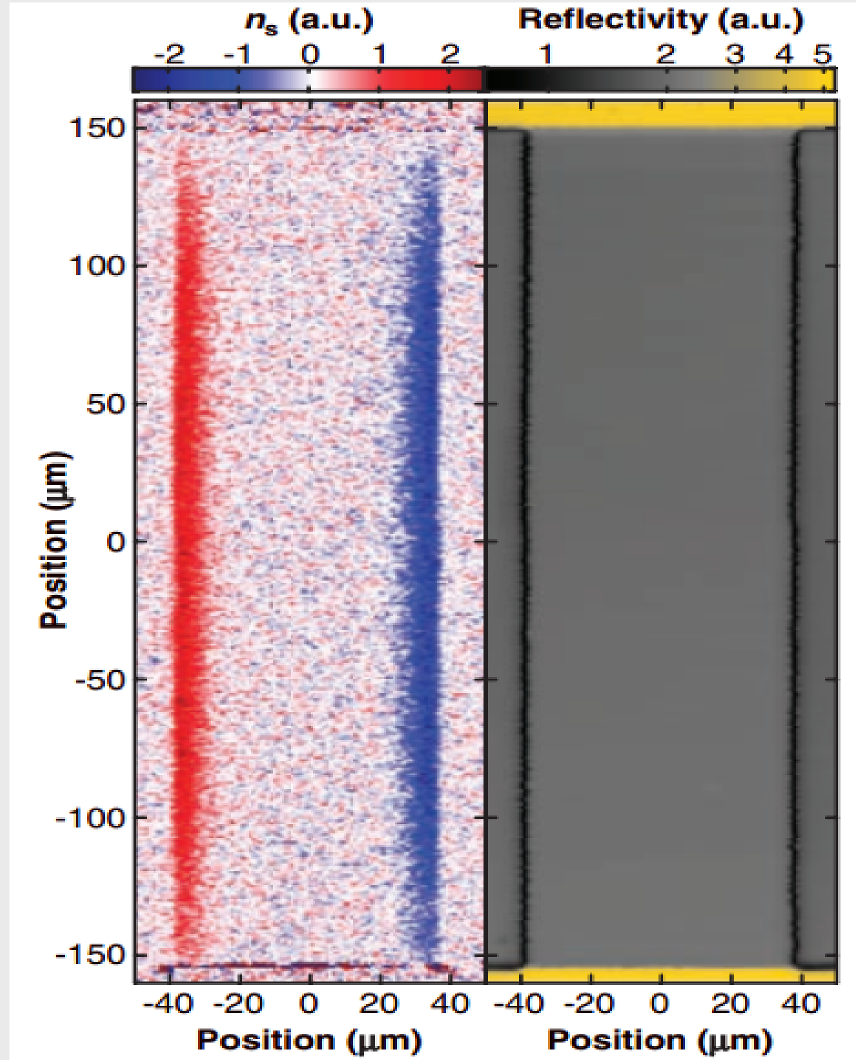
Nat. Phys. **14**, 495 (2018)

Imaging of spin Hall effect

Magneto optical Kerr imaging
GaAs, T = 30 K



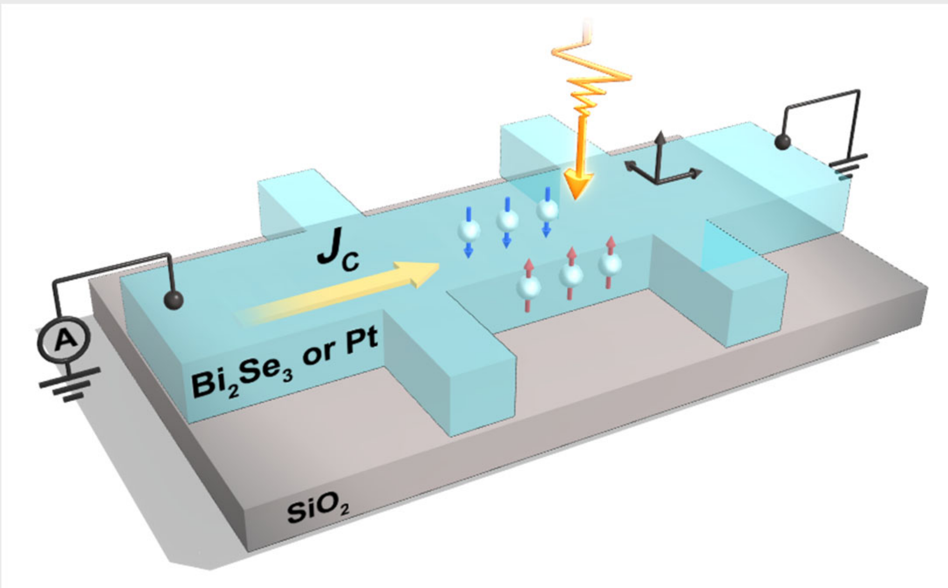
Y.K. Kato, Sci. Am. 2007



Science **306**, 1910 (2004)

Imaging is believing!
Easy for semiconductors, but difficult for metals.

Scanning photovoltage microscope with currents



- DC current is applied to induce spin accumulation.
- Circularly polarized light normally incidents on the sample.
- Magnetic circular dichroism (MCD).
- Photovoltages are detected by lock-in amp (chopper for laser).
- Piezo sample stage enables mapping.

- $V_{photovoltage} = V_{RCP} - V_{LCP}$

RCP light excites spin up electron, while LCP light excites spin down electron.

- $V_{photovoltage} > 0$ → local spin direction is spin down.
- $V_{photovoltage} < 0$ → local spin direction is spin up.

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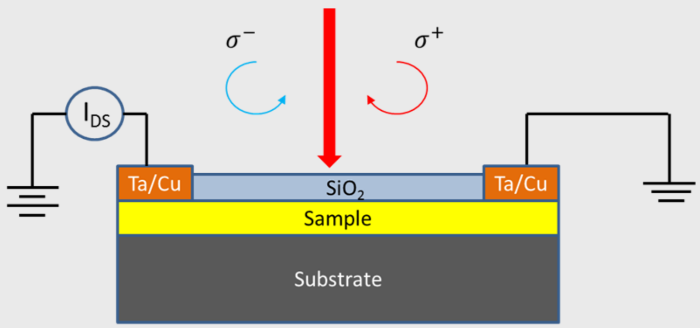
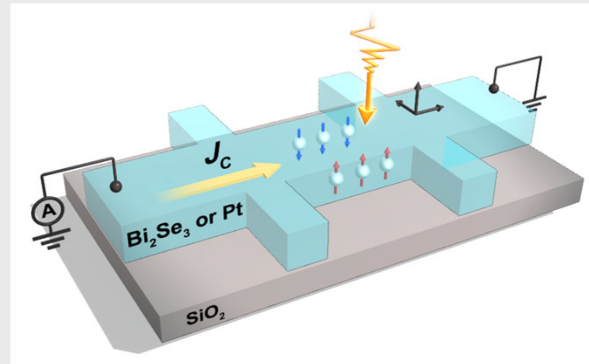
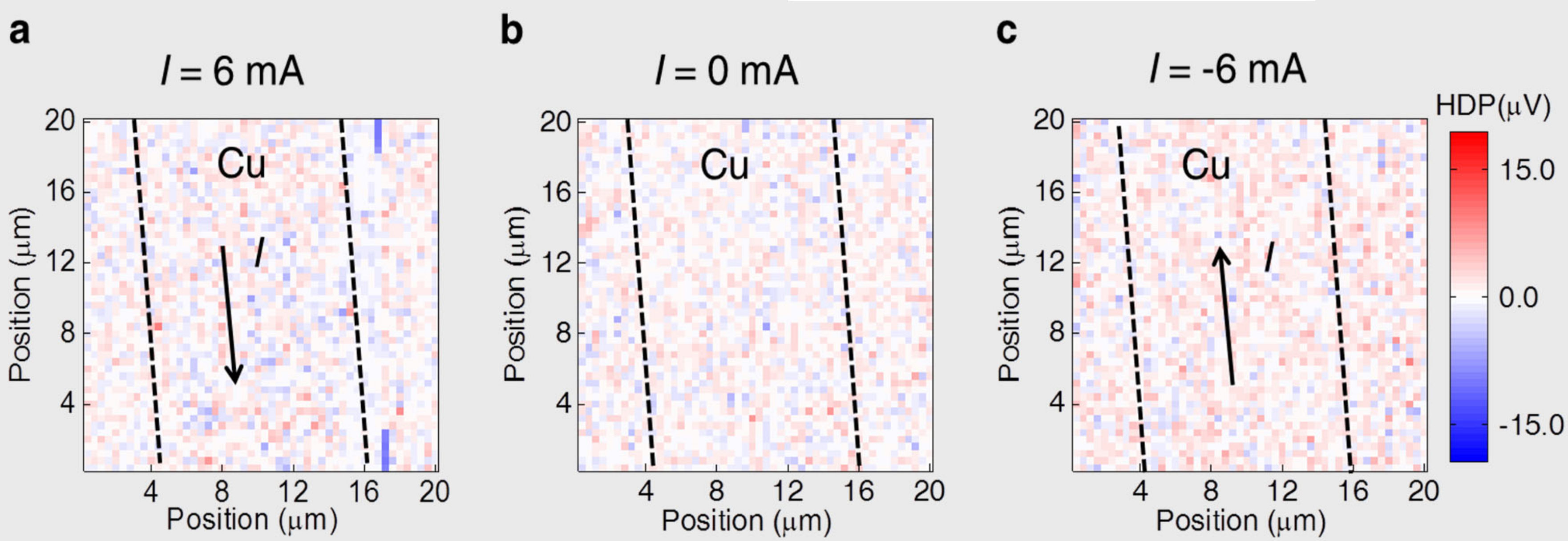
Nat. Comm. **9**, 2492 (2018); Adv. Opt. Mat. **4**, 1642 (2016)

Negligible spin accumulation in Cu





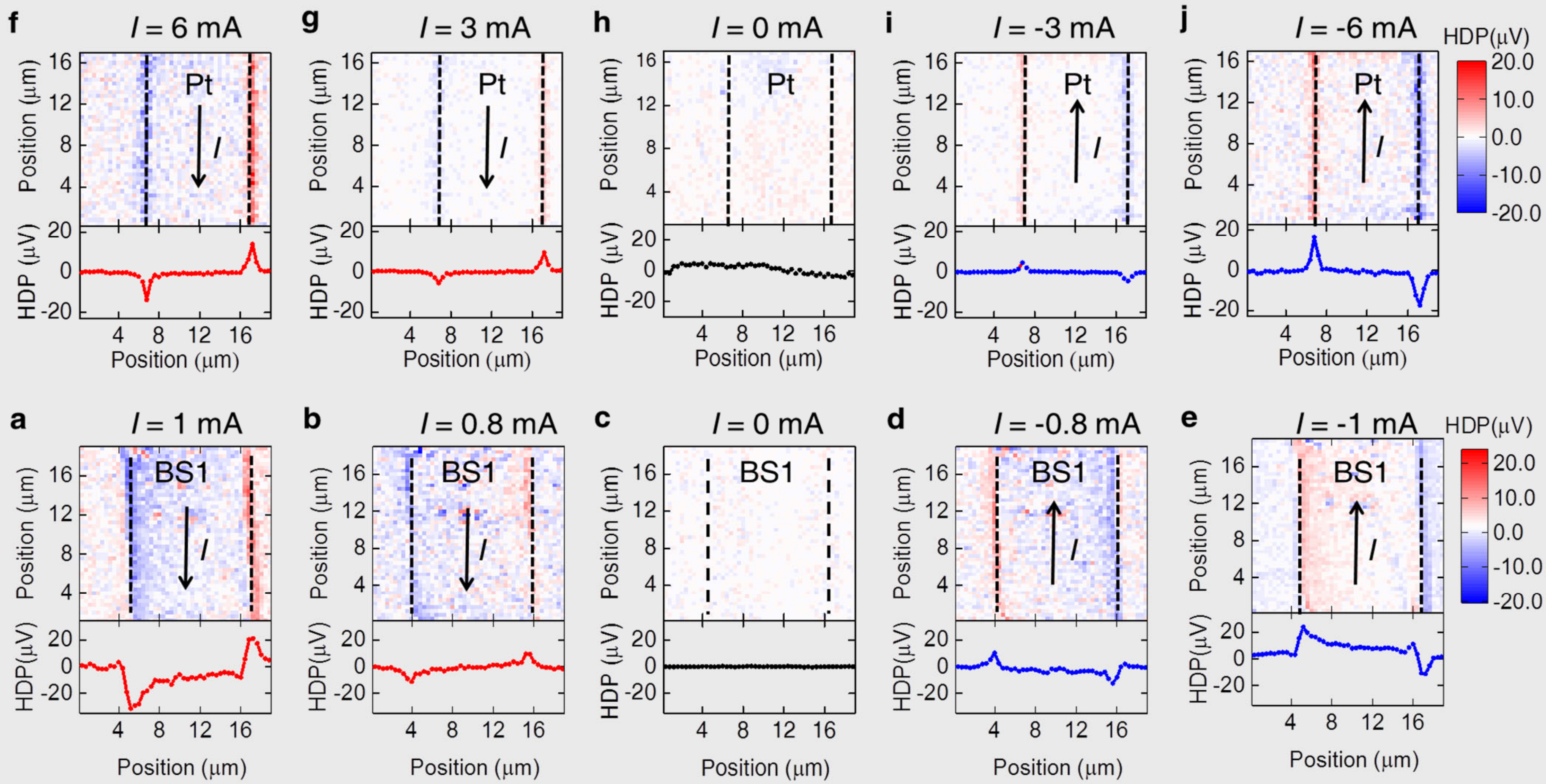


Bias dc current of 1 mA ~ 10^6 A cm^{-2}.

No signal regardless of currents.

Nat. Comm. **9**, 2492 (2018)

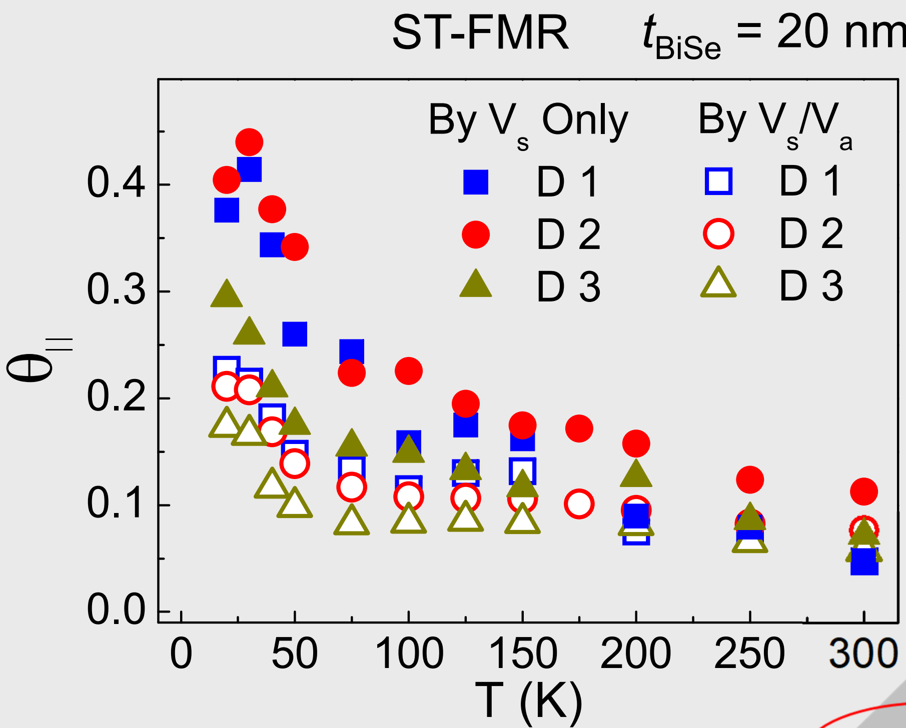
Accumulated spin imaging in Pt and Bi_2Se_3

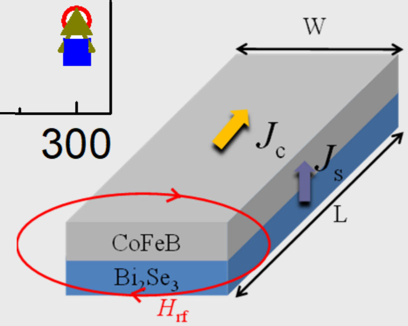


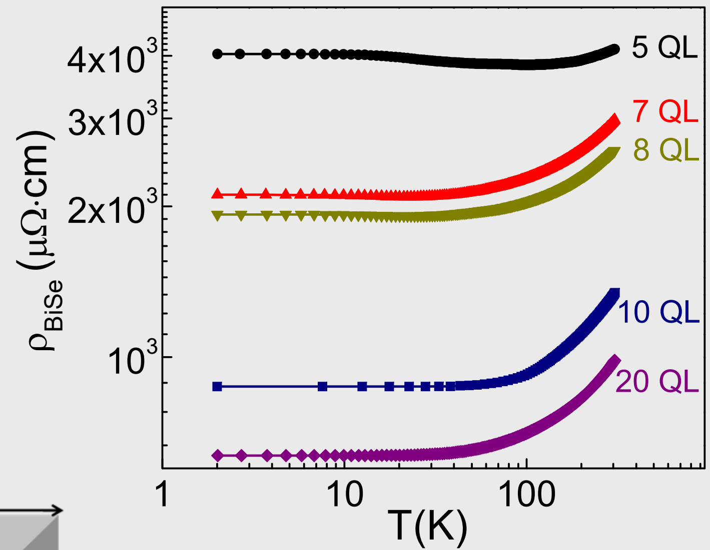
- Sign switches in opposite edges and with reversing currents.
- Both semiconductors and metals work.
- Can extract spin Hall angle and spin lifetime without a ferromagnet.

Nat. Comm. **9**, 2492 (2018)

Temperature dependent SOT efficiency in Bi_2Se_3







- Spin torque ferromagnetic resonance (ST-FMR) measurements.
- Cornell found θ = 2-3.5 at room temp [Nature 511, 449 (2014)]
- $\theta_{||}$ increase by 10 times at low temperature (upto ~ 0.42).
- Surface state dominant torques in Bi_2Se_3.

PRL **114**, 257202 (2015)

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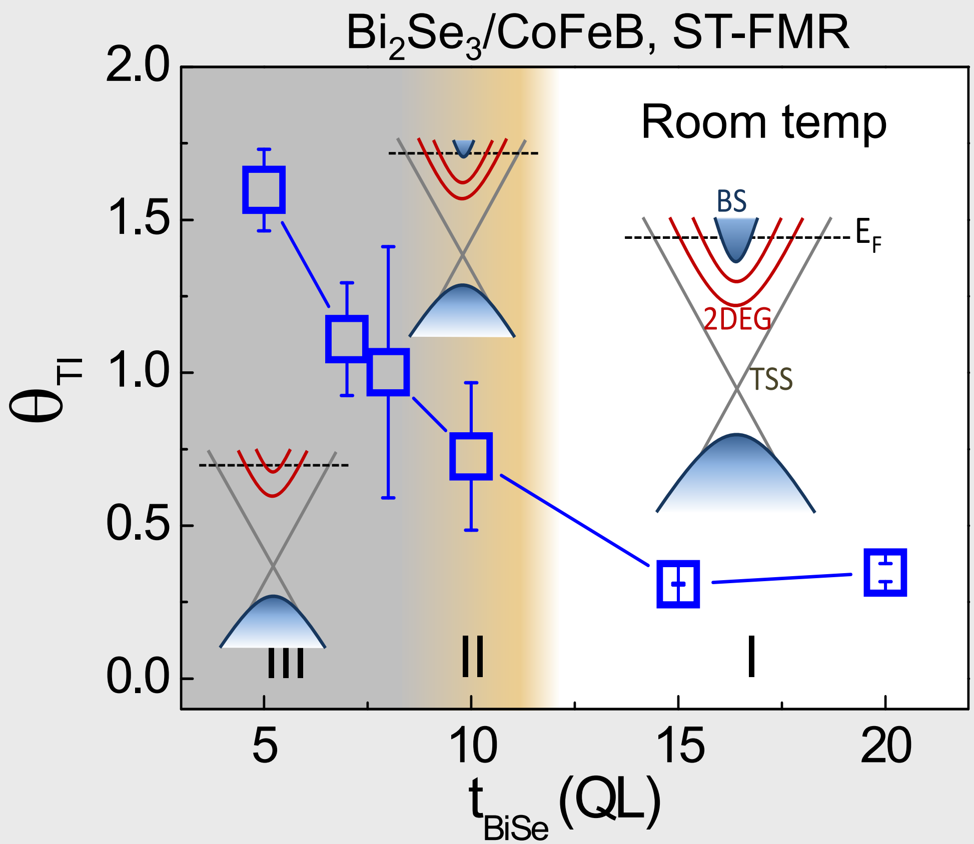
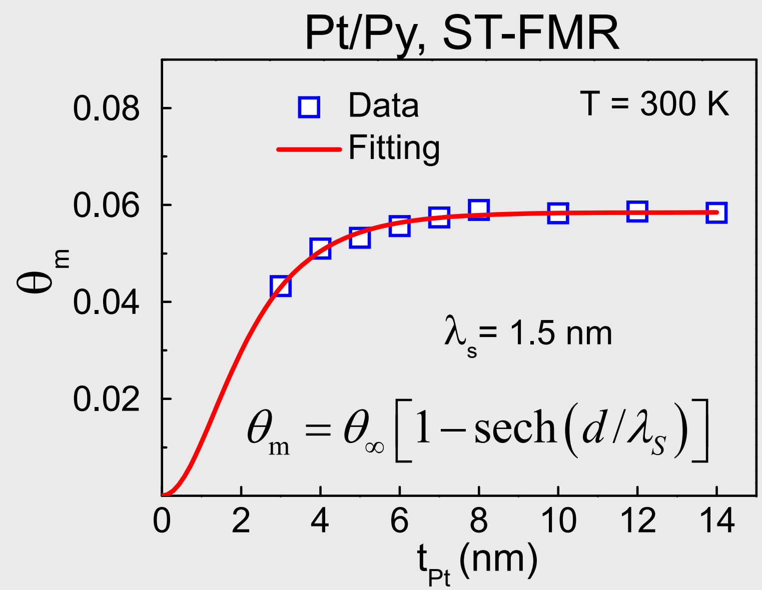
Thickness dependent spin torques in Bi_2Se_3/CoFeB





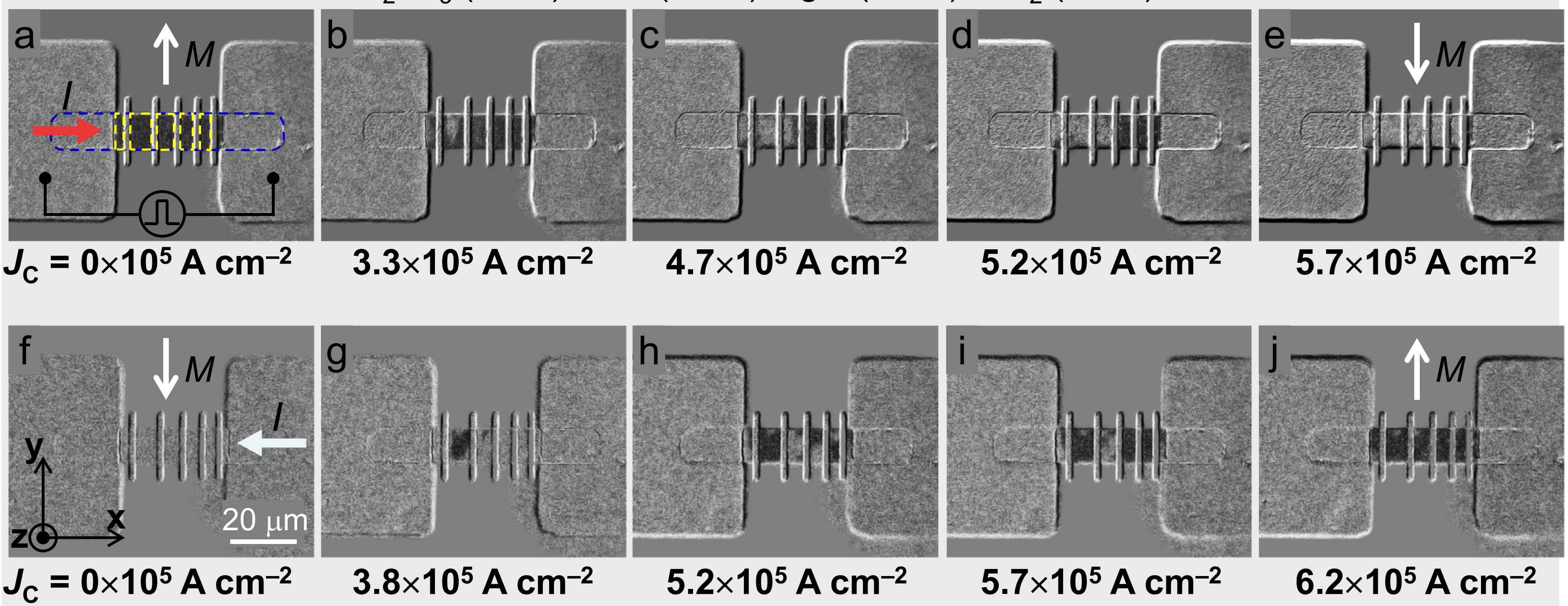
APL 105, 152412 (2014)

- Identify the optimum thickness range of Bi_2Se_3 to be 5–8 quintuple layers (QL) to maximize the spin torque effect.
- A giant SOT efficiency (θ_{TI}) of ~1–1.75 at room temperature.
- Surface dominant torques.

Nat. Comm. **8**, 1364 (2017)

Current induced magnetization switching in Bi_2Se_3/Py

Bi_2Se_3 (8 QL)/NiFe (6 nm)/MgO (1 nm)/SiO_2 (4 nm)



- TI magnetization switching reported in a Cr doped TI at 1.9 K with an external magnetic field [Nat. Mater. 13, 699 (2014)].
- Demonstrated magnetization switching of Bi_2Se_3/NiFe at room temp with a low critical current density (J_C~6×10^5 A/cm^2) and without a magnetic field.
- A giant $\theta_{TI} = 1.75$.

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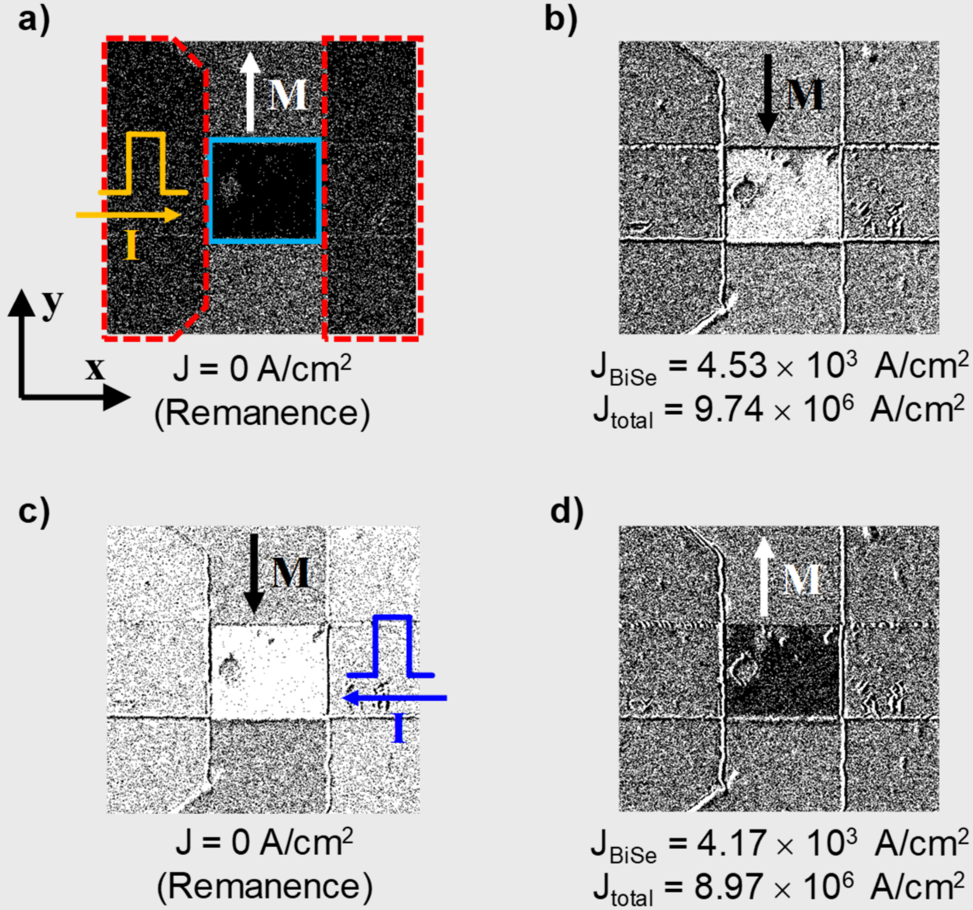
Nat. Comm. **8**, 1364 (2017)

Sputtered Bi_2Se_3

Si/SiO_2 sub/Bi_2Se_3 (t)/Py (6 nm)/SiO_2 (5 nm)



θ_{TI} = 45 for 10 nm

-Extremely large spin Hall angle, but large power consumption due to 100x resistivity

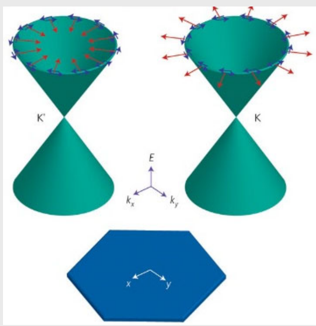
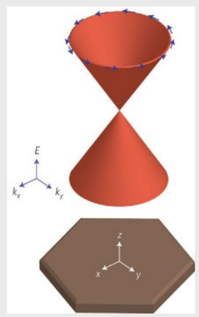
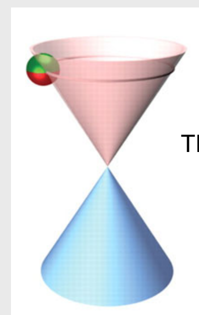
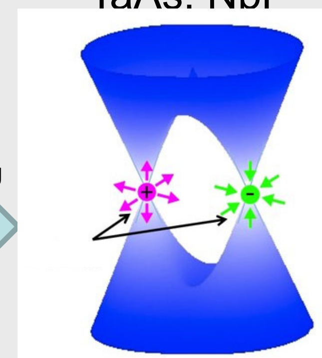
-Minnesota also reported sputtered Bi_2Se_3 (Nat. Mater. 17, 800 (2018))

θ = 18.6, $J_c = 4.3 \times 10^5$ A/cm^2

-What is the role of surface state? Does it exist?

J. Phys. D: Appl. Phys. **52**, 224001 (2019)

From Dirac to Weyl materials

	Dirac		Weyl
2D		3D	3D
2004	2009	2014	2015
Graphene	$Bi(Sb)_2Se(Te)_3$ $PbSn_{1-x}(Se/Te)_x$	$ZrTe_5$ Cd_3As_2, Na_3Bi	WTe_2, $MoTe_2$ TaAs, NbP
		 TRS or IS breaking	
Semimetal	Semimetallic surface Insulating bulk (~0.3 eV)	Semimetal (3D analogue of graphene)	**Semimetal**
Weak SOC	Strong SOC	Strong SOC	Strong SOC
Spin degenerate	Surface spin-momentum locking	Spin degenerate	**Spin-momentum locking**

❖ Intriguing spintronic properties

Nat. Phys. 7 8-10 (2011)
Science 349 613-617 (2015)
Nature 527 495-498 (2015)

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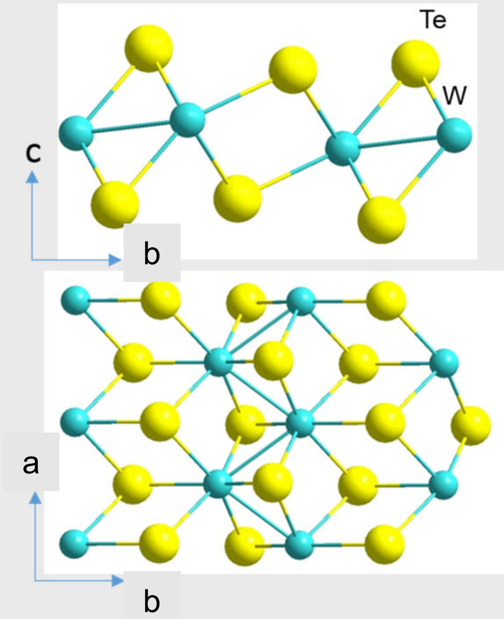
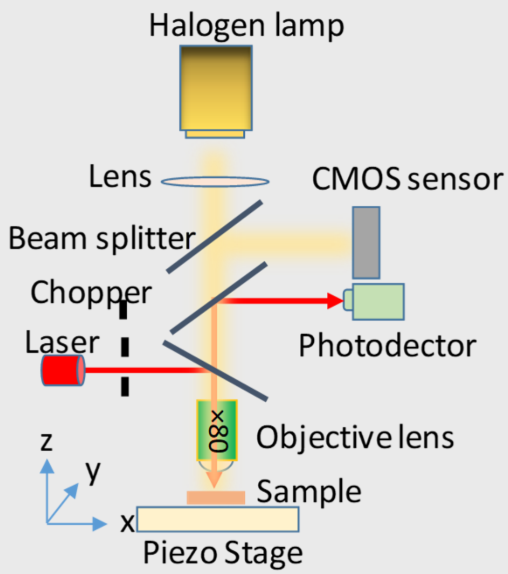
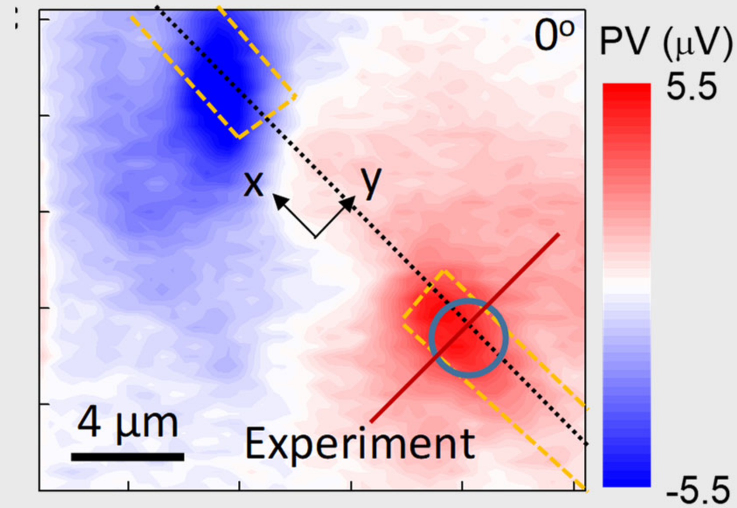
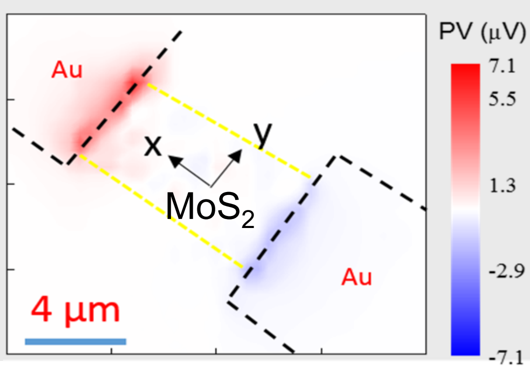
Anisotropic conductivity in WTe_2







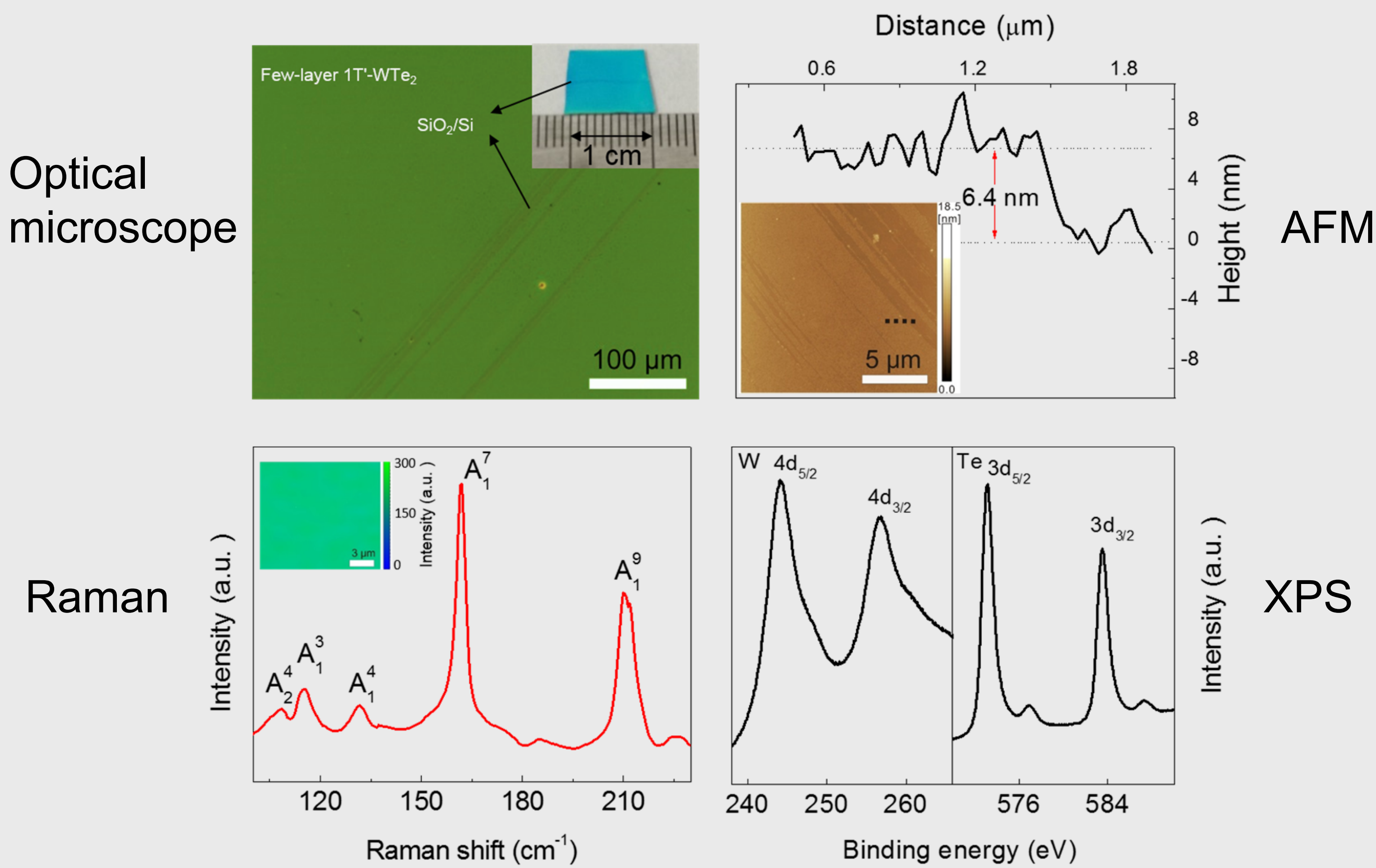
Photovoltage in the entire WTe_2 nanoflake → long carrier diffusion length (3.2 μm).
Anisotropic photocurrent distribution → anisotropic conductivity in *a*- and *b*-axis.
Elliptical Fermi surface.



Photovoltage signals only around the contacts.
Axisymmetric photovoltage response.
Circular Fermi surface.

Nano Lett. **19**, 2647 (2019)

CVD-grown 2D Weyl semimetal thin films

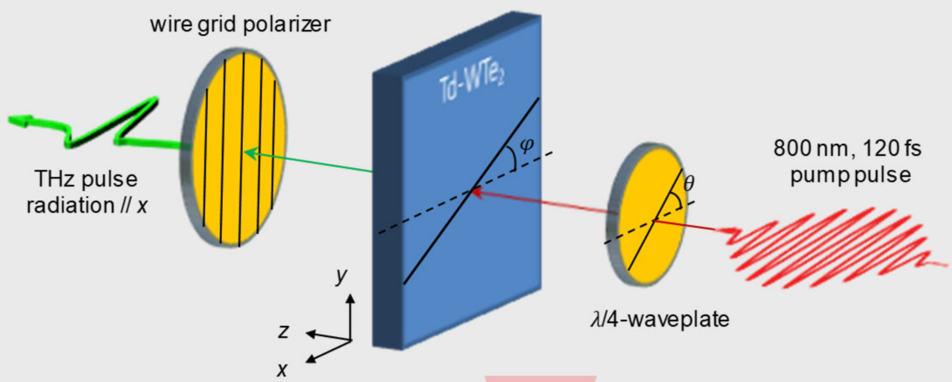


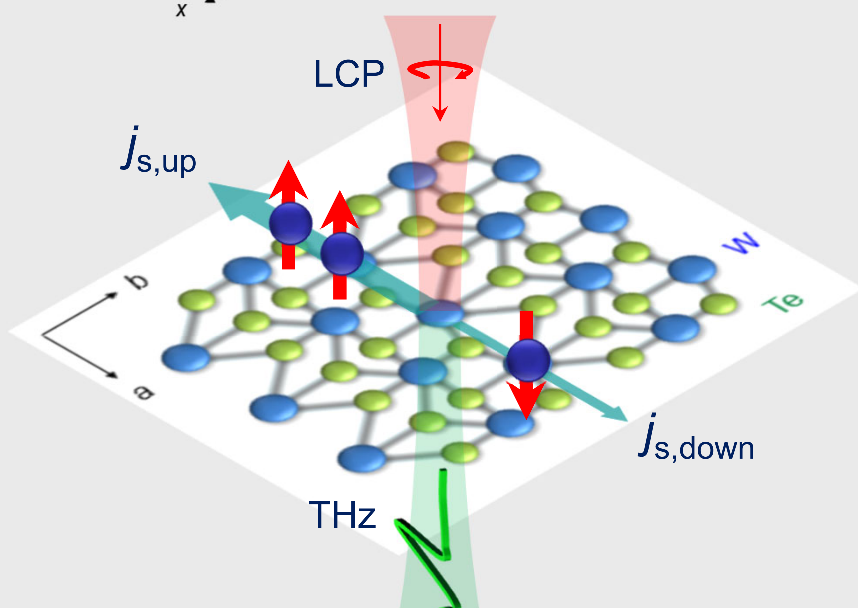
- Centimeter-scale few-layer WTe_2 and $MoTe_2$ thin films
- Semimetal (T_d) phase

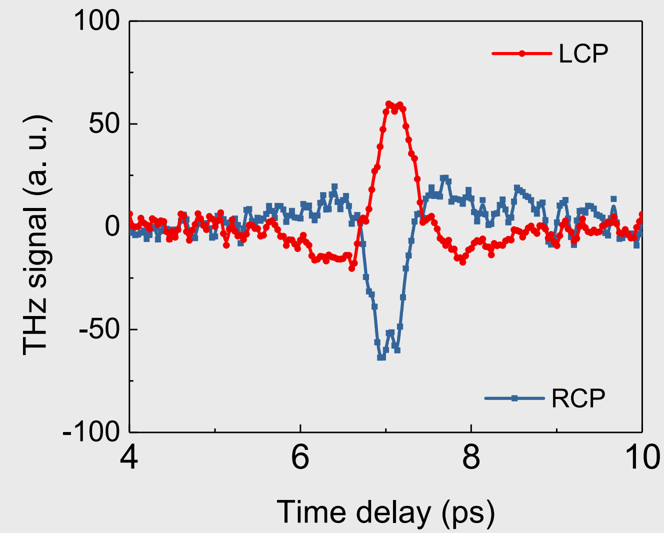
Adv. Sci. **5**, 1700912 (2018)

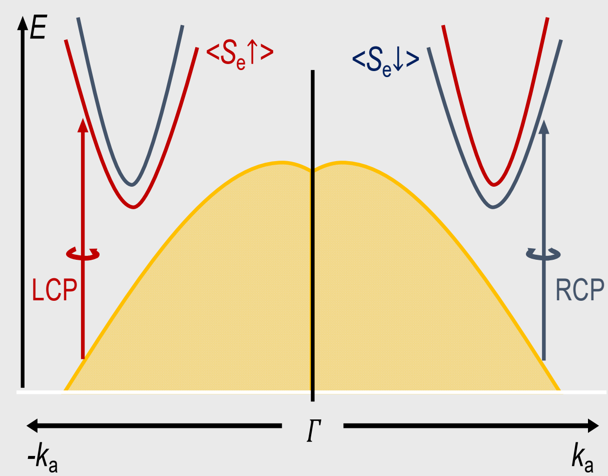
Anisotropic spin-photocurrent from CVD WTe_2

Circular photogalvanic effect (CPGE)









Anisotropic spin photocurrent is generated along the *a*-axis.
Indicates out-of-plane spin texture at room temperature.

ACS Nano **14**, 3539 (2020)

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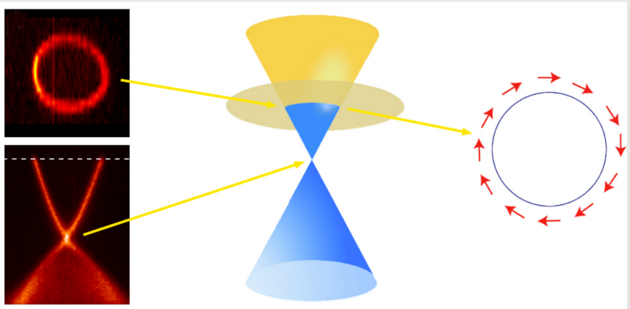
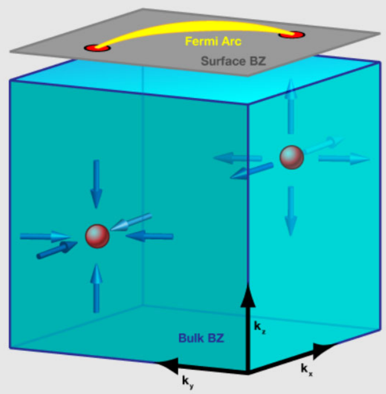
Surface + bulk effect in Weyl semimetal

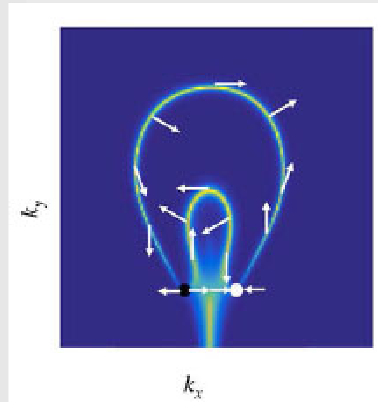
Topological insulator (TI):

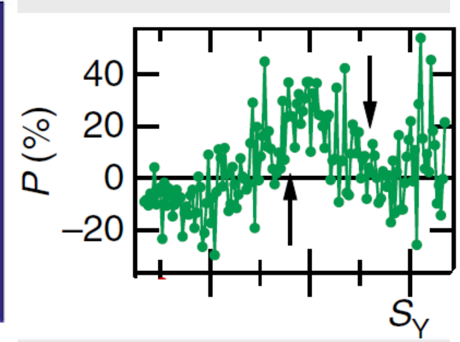


Conductive surface: spin-momentum locked surface states (P ~ 20-50%)

Weyl semimetal:







Conductive surface: SML Fermi arc states (P ~ 80%)

Conductive bulk: strong spin orbit coupling (P ~ 40%)

http://newscenter.lbl.gov/2012/05/14/
S. Xu, *et al.* Nat. Commun. **6,** 6870 (2015).

S. Xu, *et al.* Phys. Rev. Lett. **116,** 096801 (2016).
P. K. Das, *et al.* Nat. Commun. **7,** 10847 (2016).

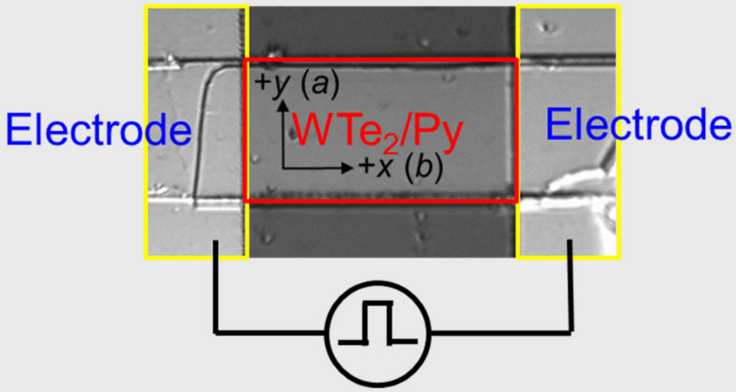
Td-WTe_2 : Weyl semimetal, strong Edelstein effect, good conductivity, 2D layered TMD material, less roughness than MBE grown TI such as Bi_2Se_3, etc.

Ideal material to achieve the spin orbit torque driven magnetization switching.

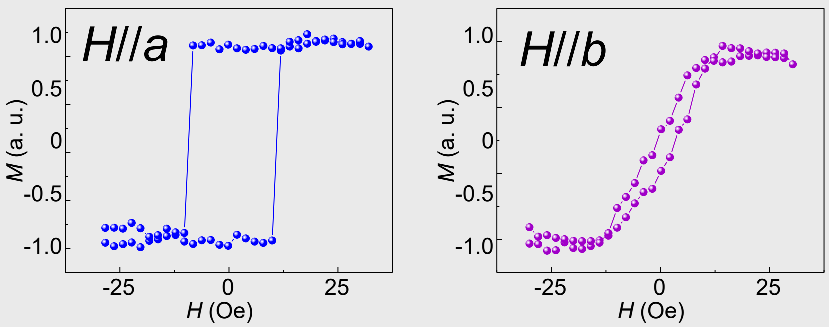
National University of Singapore

WTe$_2$ SOT driven magnetization switching

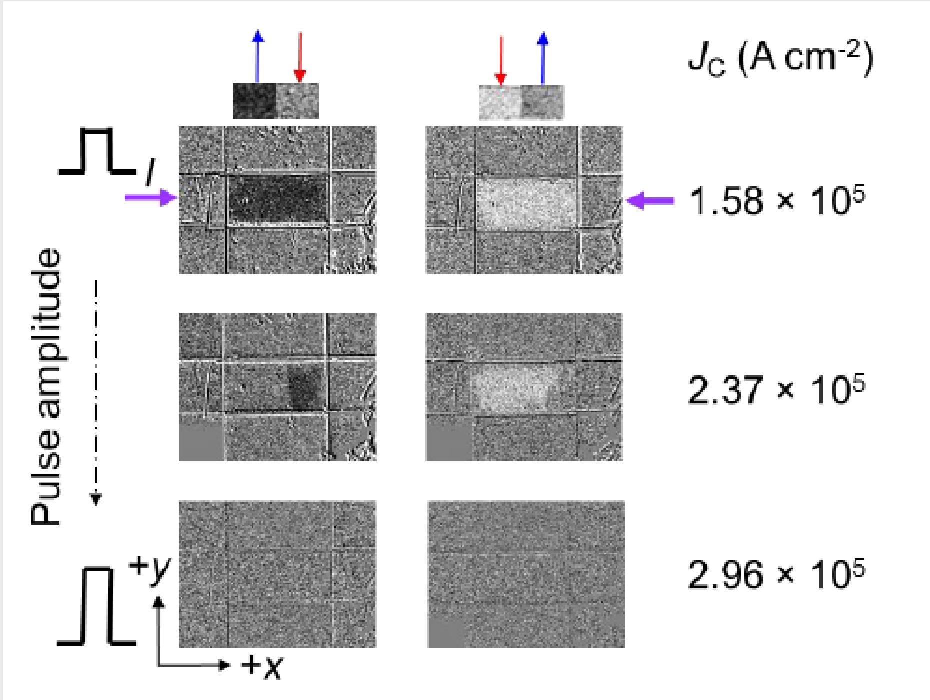
- Exfoliated WTe$_2$.
- Charge current is applied along the *b*-axis.
- Spin is polarized along the *a*-axis.



Hysteresis loops of the device



MOKE microscopy

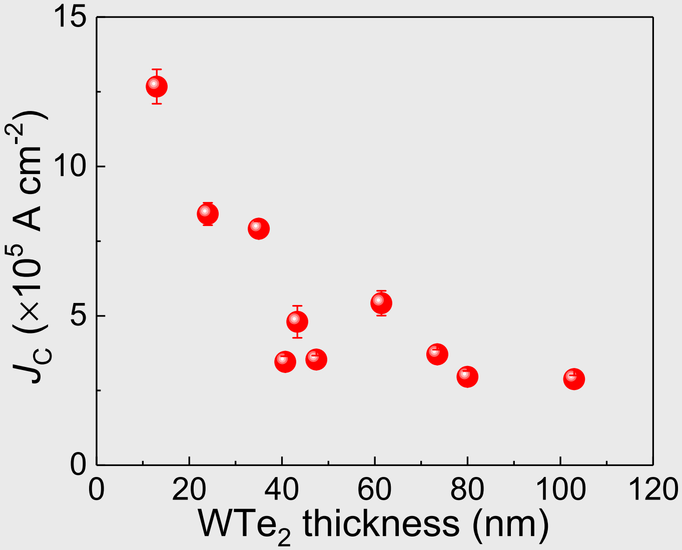


- Switching starts to happen at 1.58×10^5 A/cm^2
- Domain wall moves in the direction of J_C

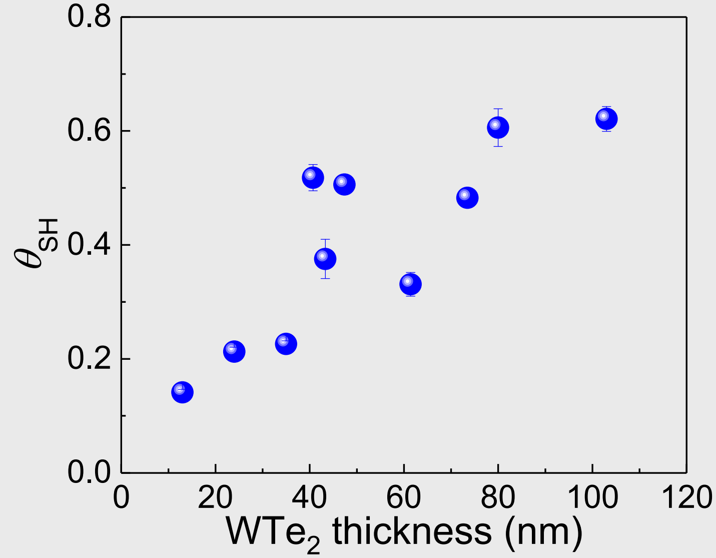
Nat. Nano. **14**, 945 (2019)

WTe_2 thickness dependent J_C and θ_{SH}

Switching current density J_C



Effective spin Hall angle θ_{SH}



- The J_C saturates at ~ 46 nm.
- J_C for WTe_2 is 1-2 orders smaller than Pt.
- θ_{SH} from switching is comparable with that from ST-FMR.

Anti-damping switch followed by domain wall propagation

$$J_{C0} = \frac{2e}{\hbar}\mu_0 M_S t\alpha(H_C + M_{eff}/2)/(J_S/J_C)$$

$$\frac{J_C}{J_{C0}} = 1 - \frac{K_B T}{K_{Py} V_N}\ln\frac{t_P}{t_0}$$

Nat. Nanotech. **11**, 621 (2016).
IEDM Technical Digest. IEEE International 459 (2005).

Spin efficiency increases with thickness → Significant bulk effect
20x smaller power than Bi_2Se_3 due to ρ_{WTe2}~580 μΩ·cm

Nat. Nano. **14**, 945 (2019)

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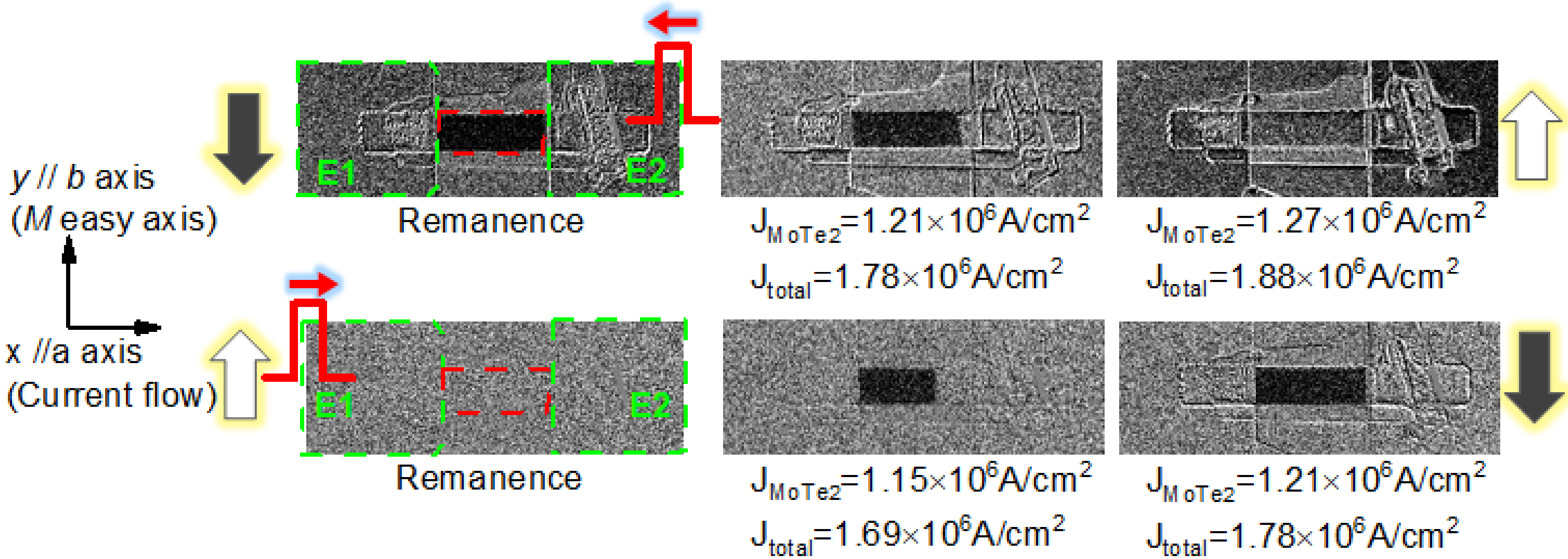
Scanning MOKE switching of $MoTe_2$/Py

1T′-$MoTe_2$ (83 nm)/Py (6 nm)



ST-FMR θ_{SH} = 0.27 from $MoTe_2$ (83 nm)/Py (6 nm)
Switching based θ_{SH} = 0.35 from $MoTe_2$ (66 nm)/Py (6 nm)
Resistivity of $MoTe_2$ ~ 542 μΩ·cm
Power (I^2R) = 12.7 mW

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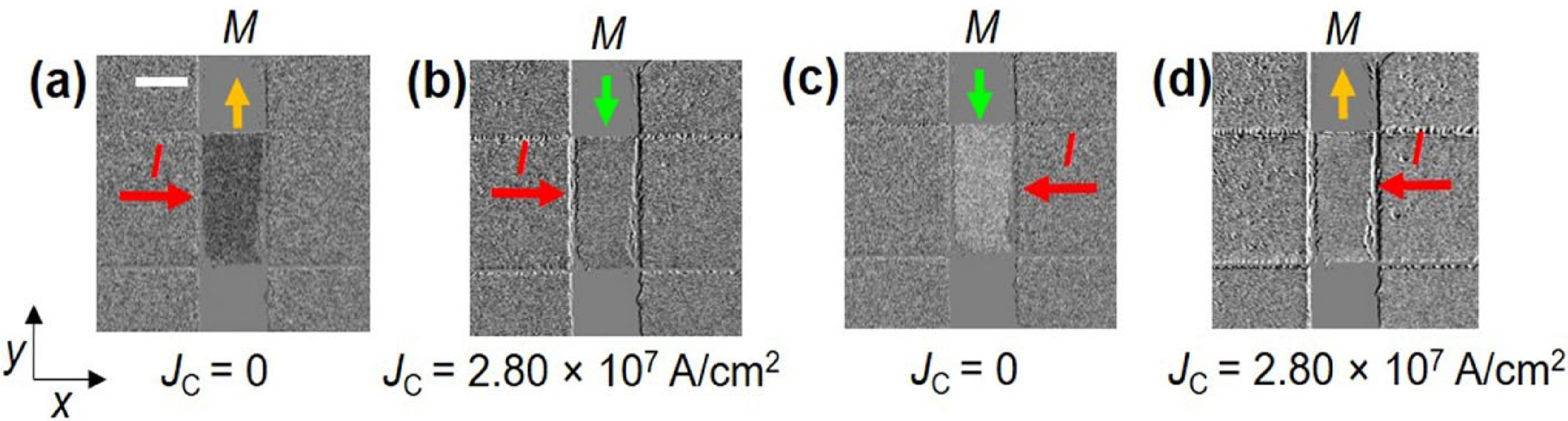
Adv. Mater. (2020) doi.org/10.1002/adma.202002799

Pt (6 nm)/Py (6 nm) control sample

Scanning MOKE switching



Py resistivity ~ 90 μΩ·cm
Pt resistivity ~ 22.7 μΩ·cm

Power (I^2R) = 33.7 mW

Adv. Mater. (2020) doi.org/10.1002/adma.202002799

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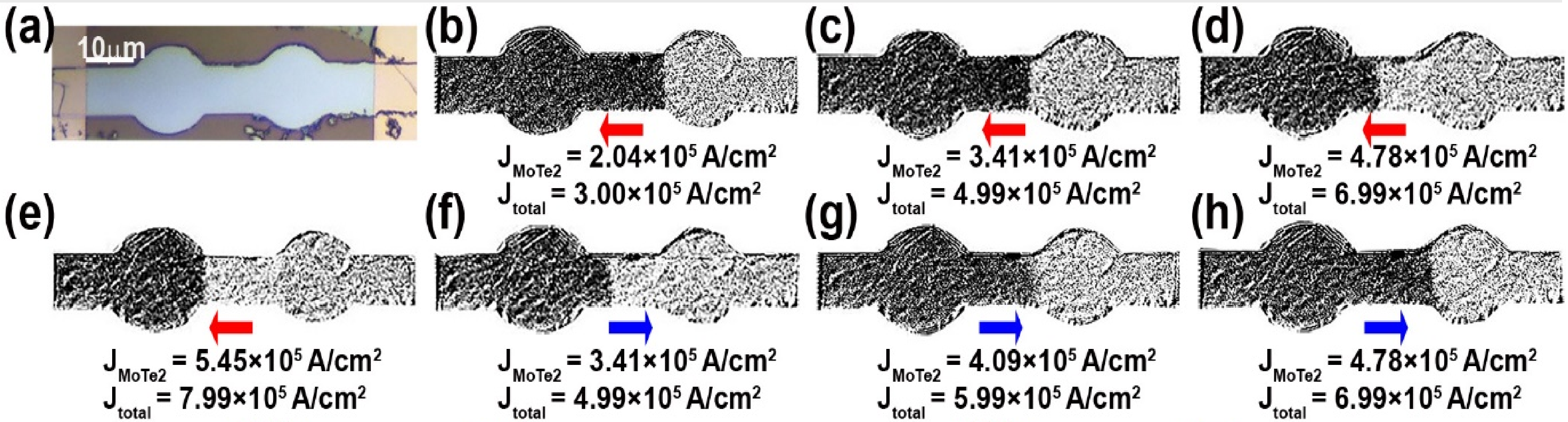
Dumbbell-patterned $MoTe_2$/Py switching device



Single domain wall (DW) can be pinned in anti-notch structure, Nano Lett. **18**, 4669 (2018).

DW stops at the neck part due to lower current density.

3x reduction of *J* compared to no domain wall case *J* = 1.32×10^6 A/cm^2.

One order smaller power (I^2R) = 1.74 mW compared to rectangular channel.

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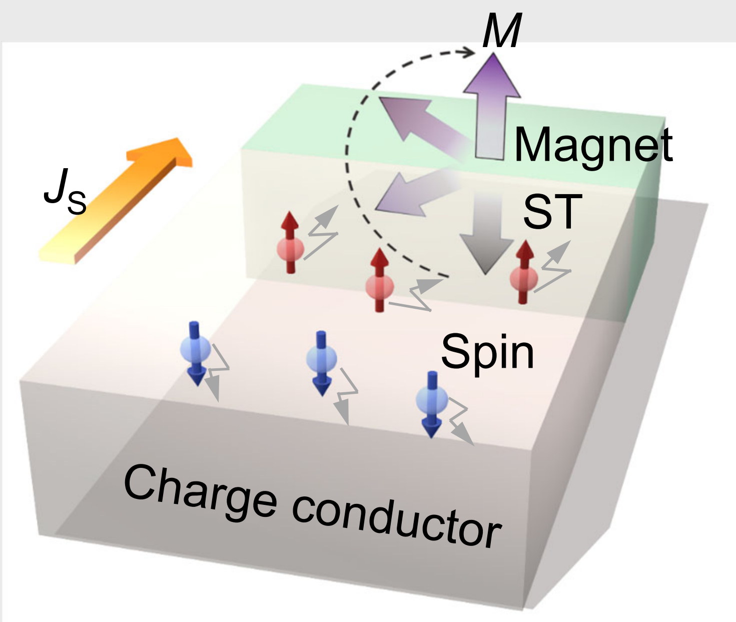
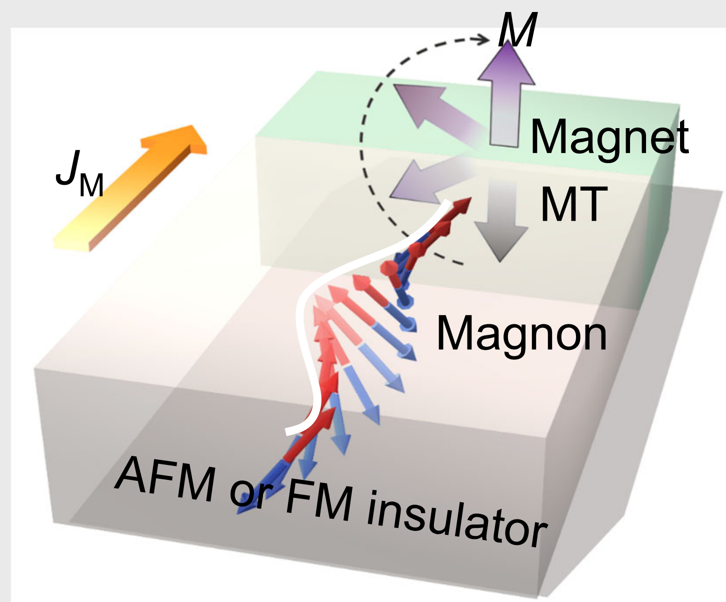
Adv. Mater. (2020) doi.org/10.1002/adma.202002799

Electrical spin torque and magnon torque

Electrical spin current & Electrical spin torque



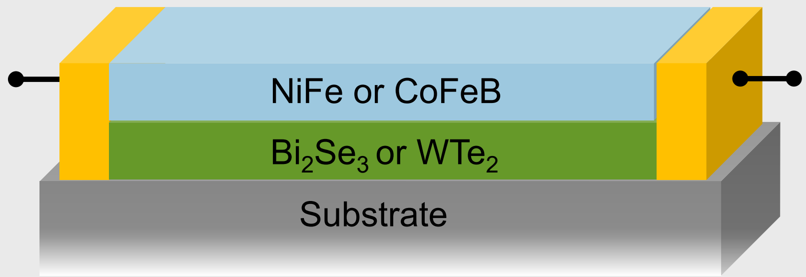
Magnon current & Magnon torque



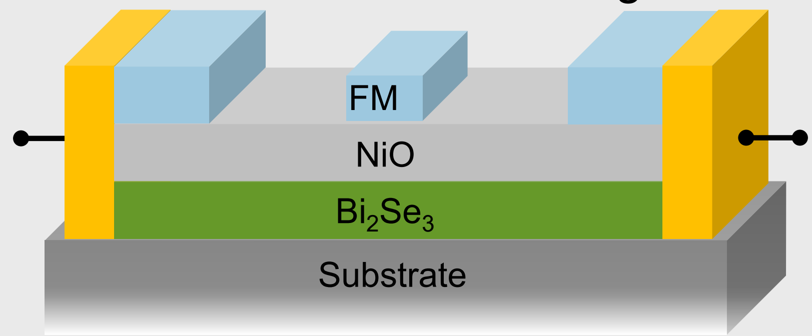
Science **366,** 1125 (2019)

Magnon driven magnetization switching

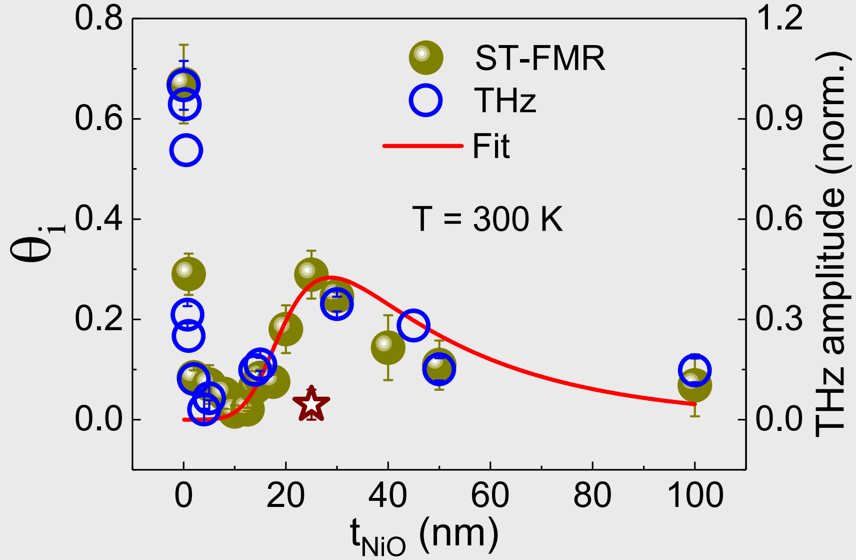
Current shunting thru FM



No current shunting

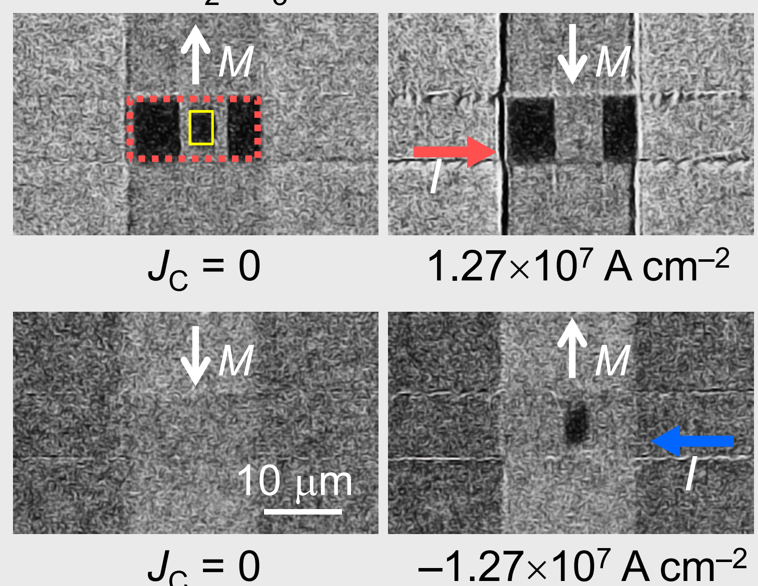


THz technique: Adv. Mat. **29**, 1603031 (2017)



Magnon diffusion length ~ 30 nm

Bi$_2$Se$_3$/NiO 25 nm/NiFe



Science **366**, 1125 (2019)

Summary

- Spin orbit technologies
  - Magnetic memory switching
  - Topological insulators (surface dominant with large ρ)
  - Weyl semimetals (surface + bulk, less ρ)
  - Magnon torques (no current shunting)

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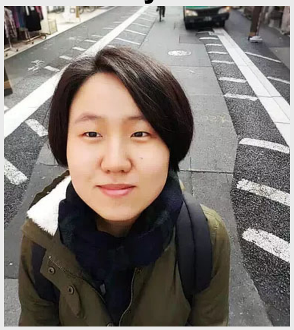

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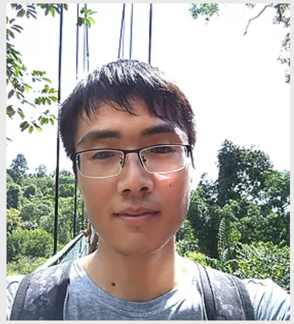

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