Exotic spin-orbit torques from topological materials and ferrimagnets

Hyunsoo Yang

Department of Electrical and Computer Engineering
National University of Singapore

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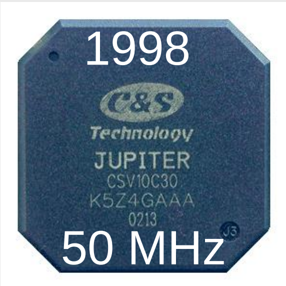
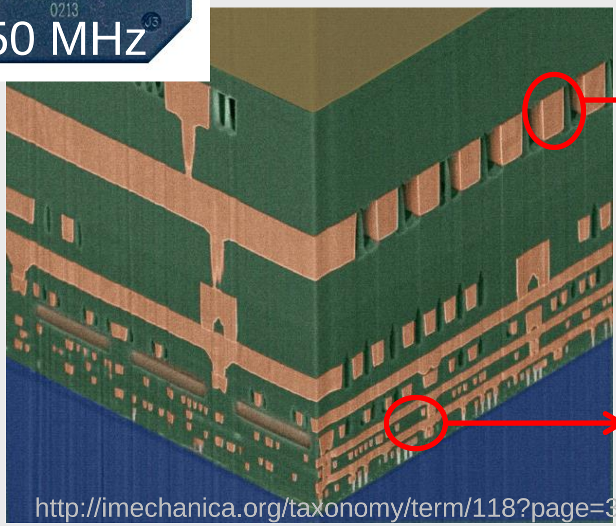
National University of Singapore

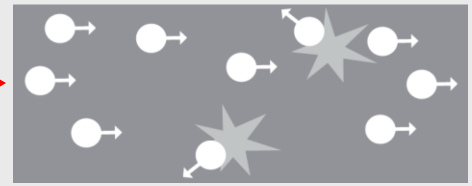
Charge electronics → Spin electronics





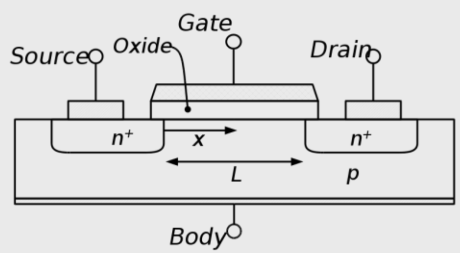
Information transfer

= electron transfer

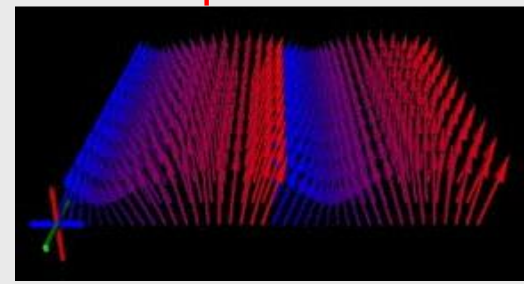


Information processing

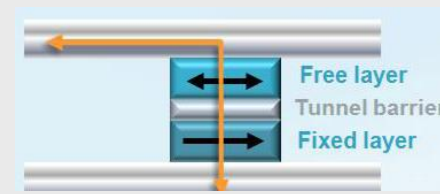
= processing electron flow



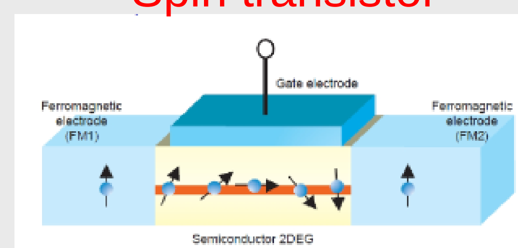
Spin wave



MTJ memory



Spin transistor



Charge transfer and processing energy loss is huge
→ All spin electronics

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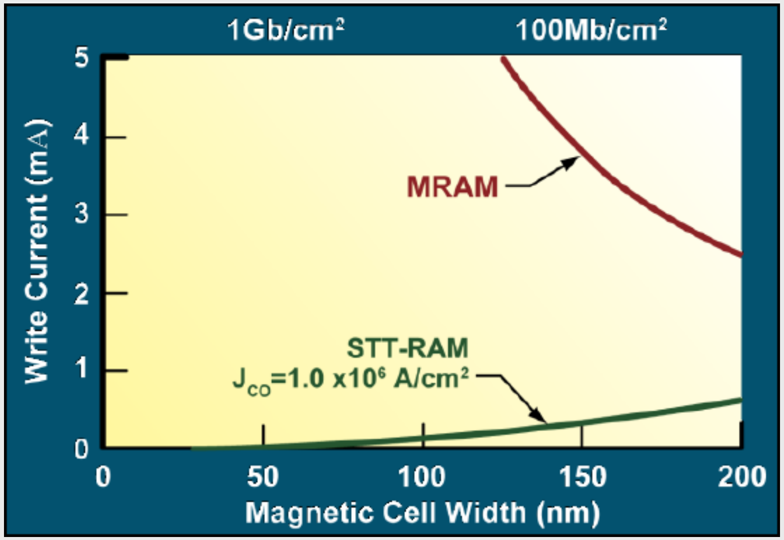
Spin torque MRAM

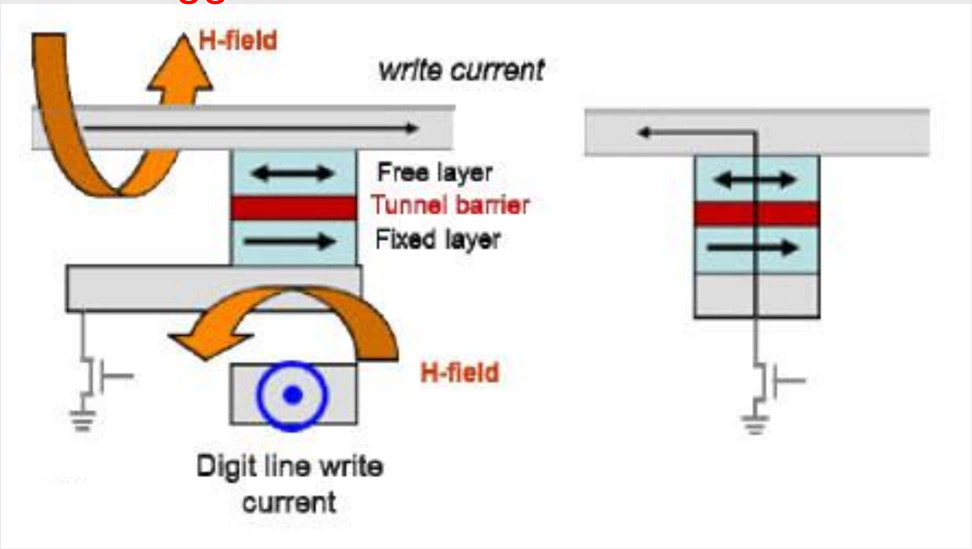


-Present STT-MRAM (Everspin) uses 90 nm node
-GF started to use 40, 28, 14 nm node
-TSMC, IBM, Samsung, TDK, Hynix, Sony, Avalanche, Toshiba, Intel, Qualcomm…

2019 March
Samsung
28 nm FD-SOI
embedded

Toggle-MRAM

STT-MRAM

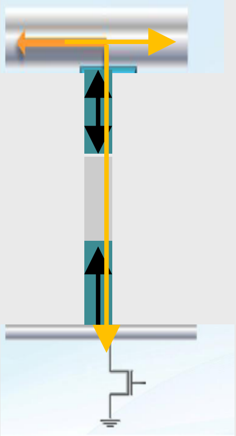


16 Mb

256 Mb

Everspin with GlobalFoundries

SOT-MRAM

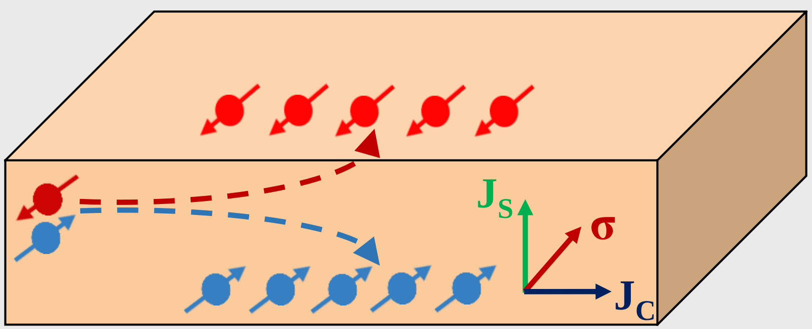


Spin Hall and Inverse Spin Galvanic effects

Spin Hall effect

- Spin orbit coupling in the bulk of non-magnet.
- Can be from intrinsic or extrinsic (impurities).
- Quantified by spin Hall angle (SHA or θ_{sh})

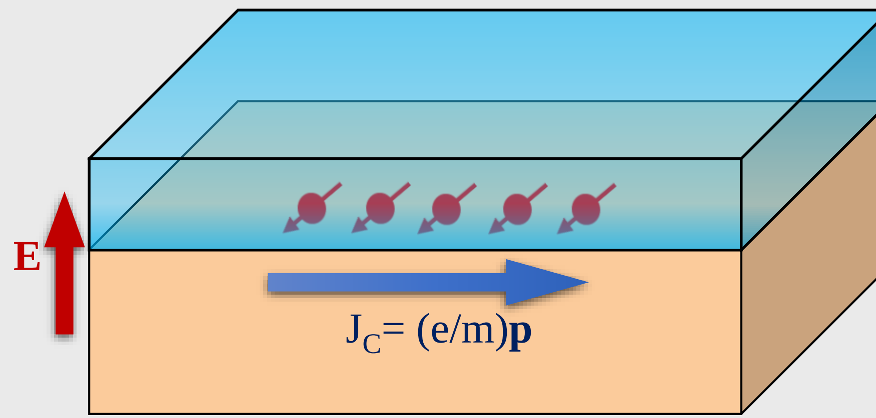
$$\vec{j_s} \propto \theta_{sh} \left(\vec{j_c} \times \vec{\sigma} \right)$$



Rashba-Edelstein effect

- Structures with broken inversion symmetry
- Interfacial spin orbit coupling.
- Depends on the nature of the interface.
- Quantified by Rashba coefficient (∝ magnitude of **E=-∇V**)

$$\hat{H}_{so} = \xi \hat{\boldsymbol{\sigma}} \cdot \left(\nabla V \times \hat{\mathrm{p}} \right)$$

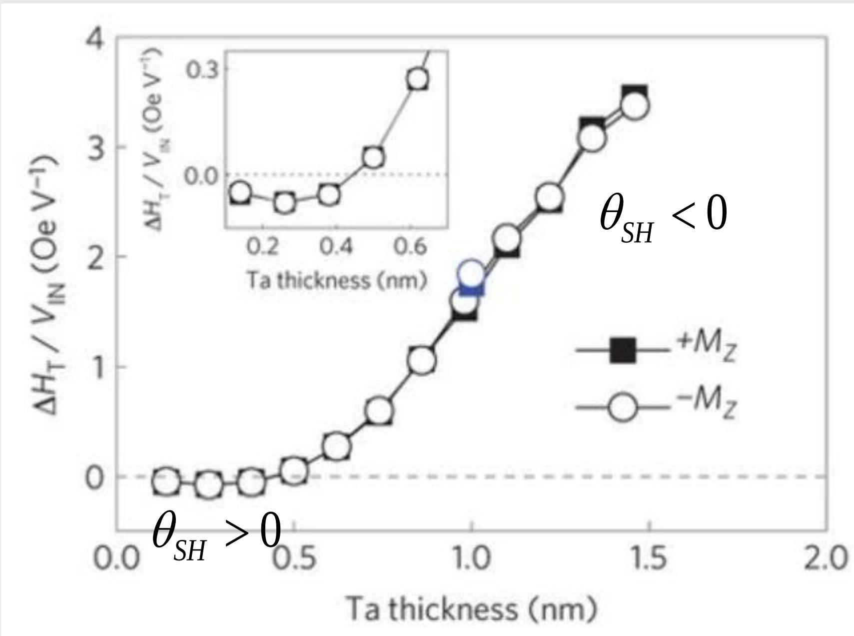


Is spin accumulation direction the same for both cases?

Theory: D'yakanov and Perel (1971), Hirsch (1999), Edelstein (2000), Zhang (2000), Murakami, Nagaosa, Zhang (2003), Sinova *et al.* (2004),…Manchon and Zhang (2008).
Experiments: (semiconductors) Ganichev *et al.* (2002), Kato *et al.* (2004), Wunderlich *et al.* (2005) (metals) Valenzuela and Tinkham (2006), Saitoh *et al.* (2006), Kimura *et al.* (2007).

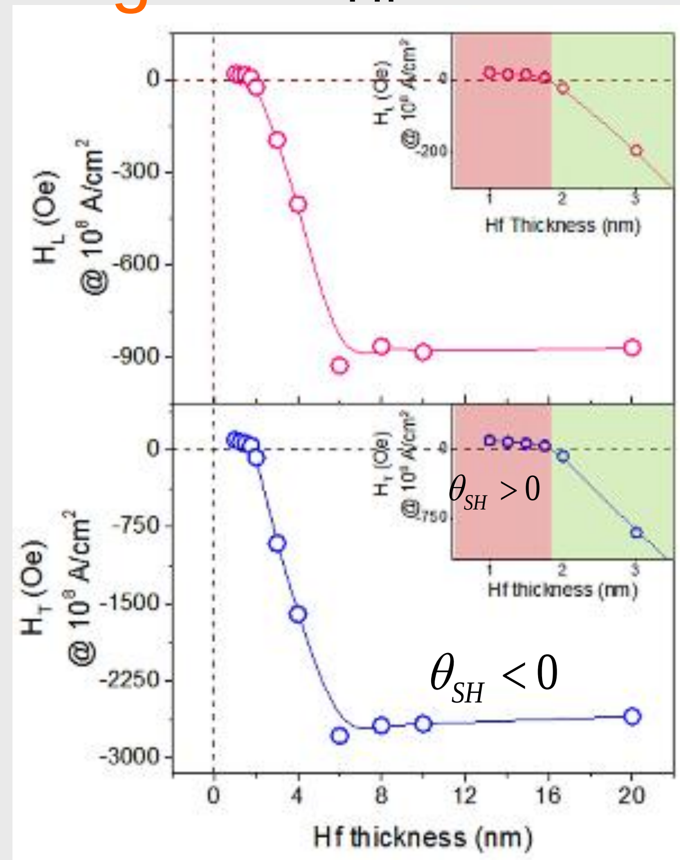
Sign change of effective spin Hall angle

Ta



Nature Mater. 12, 240 (2013)

Hf



Appl. Phys. Lett. 108, 202406 (2016)

- The SOT polarity is a function of heavy metal thickness
- Thick regime: spin Hall dominant
- Thin regime: interfacial spin-orbit with opposite sign to spin Hall

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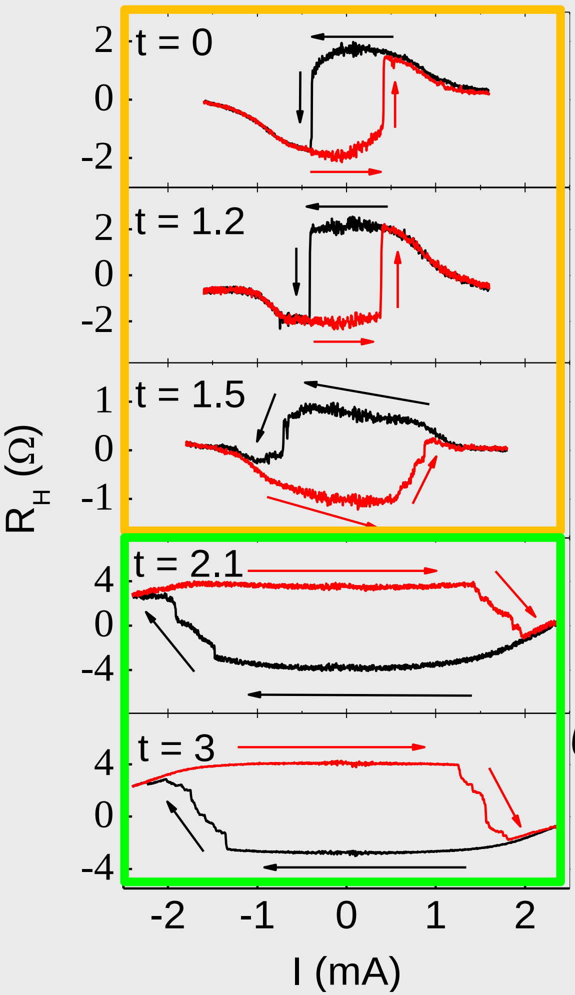
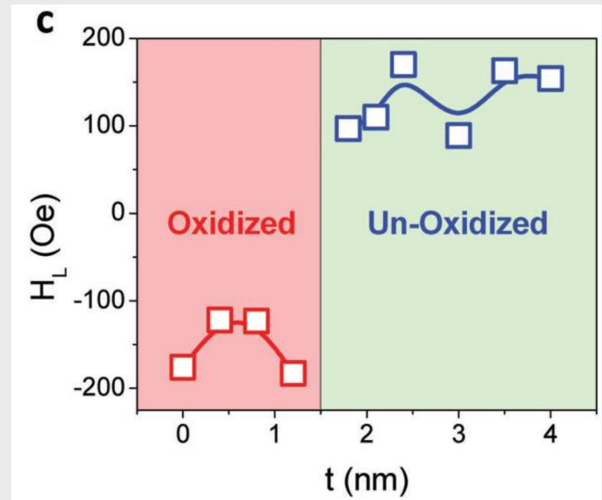
Is the sign of θ_{SH} fixed for a given material?

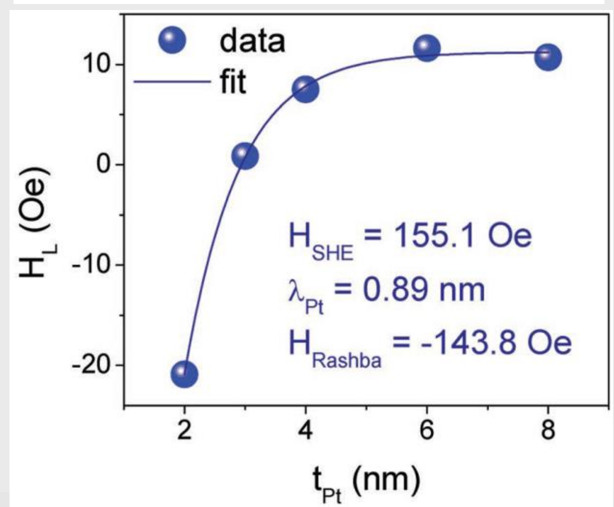
Reverse switching polarity by oxygen engineering

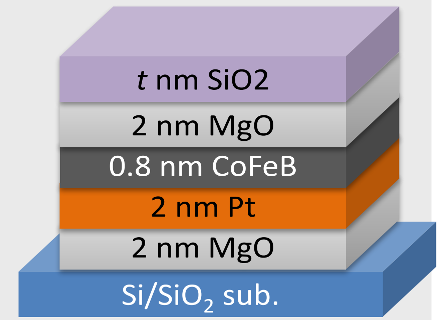


$\theta_{SH} < 0$

$\theta_{SH} > 0$







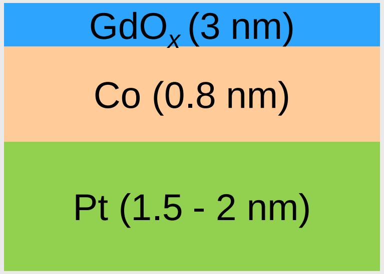
-Sign of spin Hall angle changes across a transition thickness of SiO_2 (*t* = 1.5 nm)

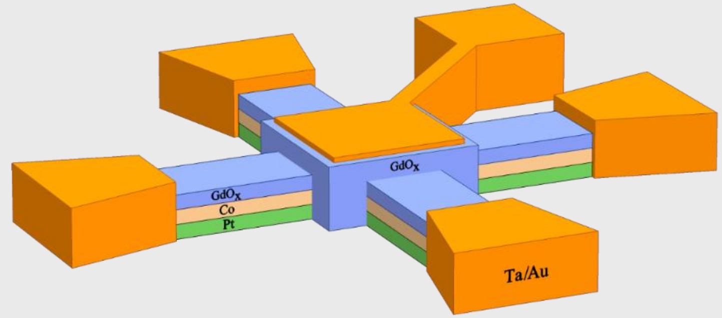
-Cannot be understood by spin Hall physics → suggest the role of interface

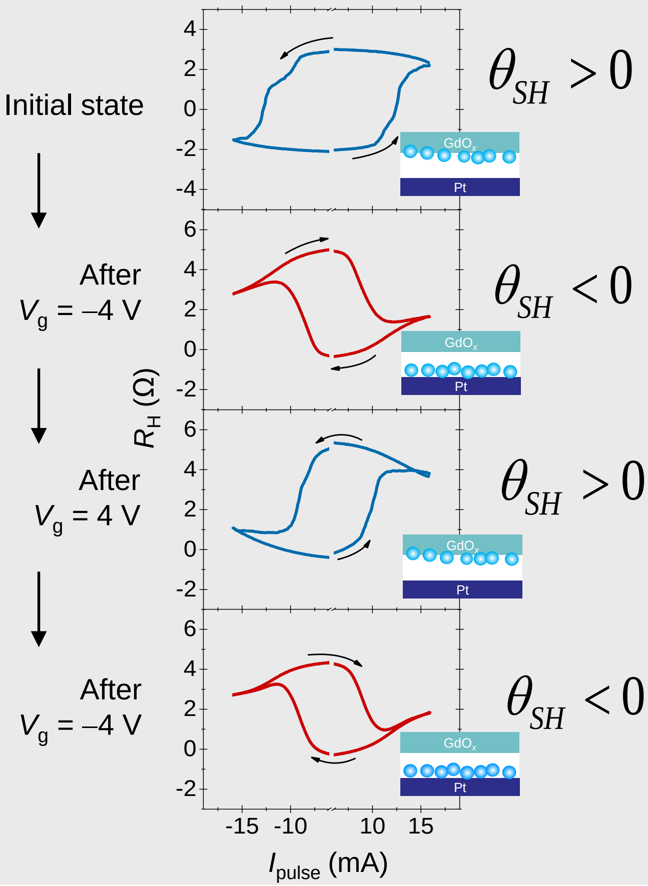
Nat. Nano. **10**, 333 (2015)

Adv. Mat. **30**, 1705699 (2018)

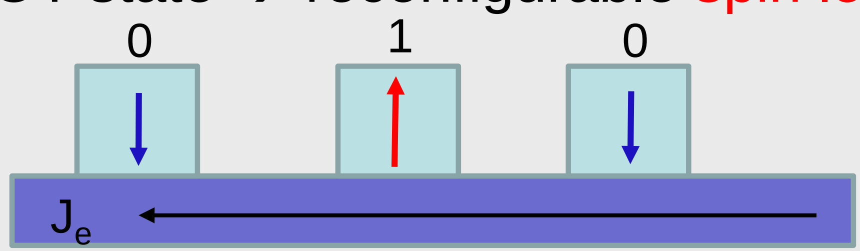
Electric-field control of effective spin Hall sign







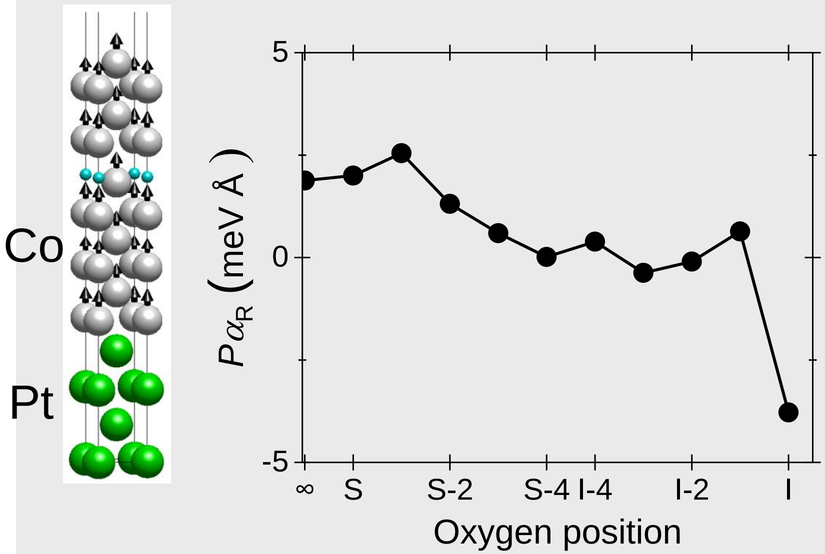
- Competition b/w bulk spin Hall vs. interfacial SOC with opposite sign
- Device can switch to either up or down depending on its programmed SOT state → reconfigurable spin logic

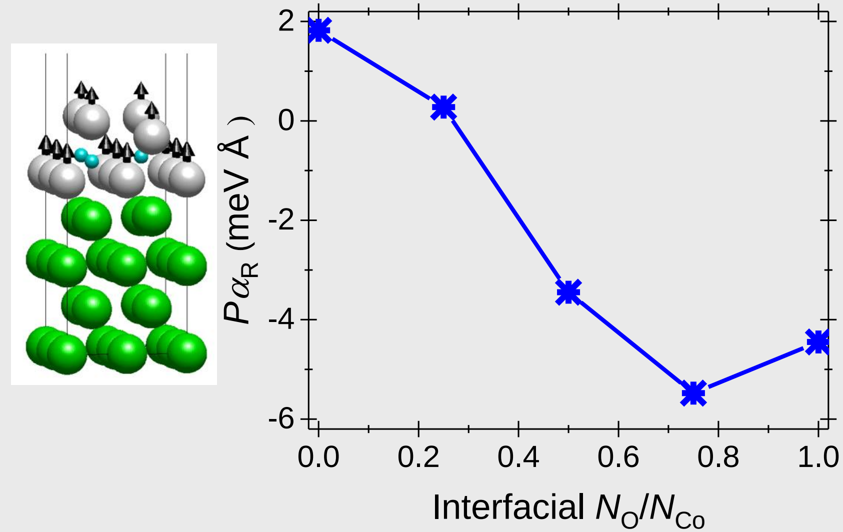


Nat. Commun. **10**, 248 (2019)

First principle calculations

First principle calculations performed in Prof. Nicholas Kioussis's group, *California State University.*

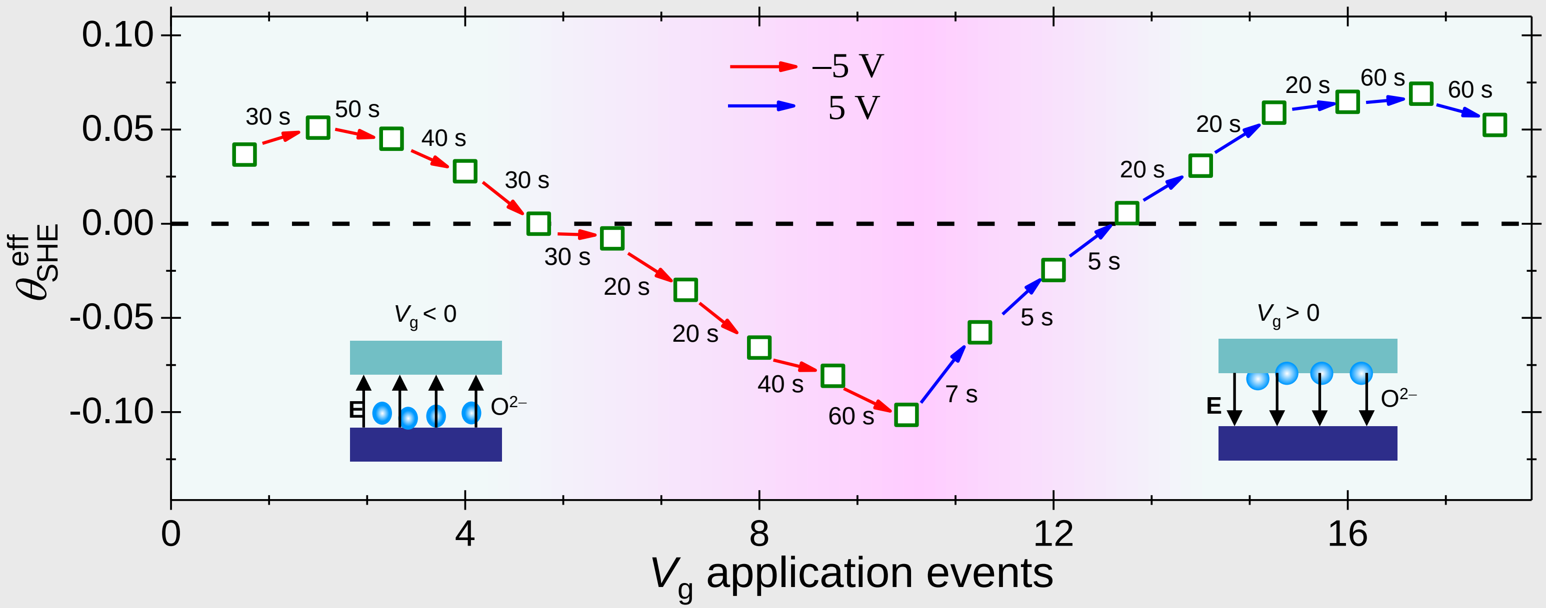




- The effective Rashba parameter ($P\alpha_R$) changes sign as oxygen is filled at the Pt/Co interface.
- The spin accumulation direction changes sign when the negative effective Rashba torque exceeds the spin Hall torque.
- Effective Rashba coefficient changes its sign for 30% oxidization.

Nat. Commun. **10**, 248 (2019)

Gradual modulation of SOTs

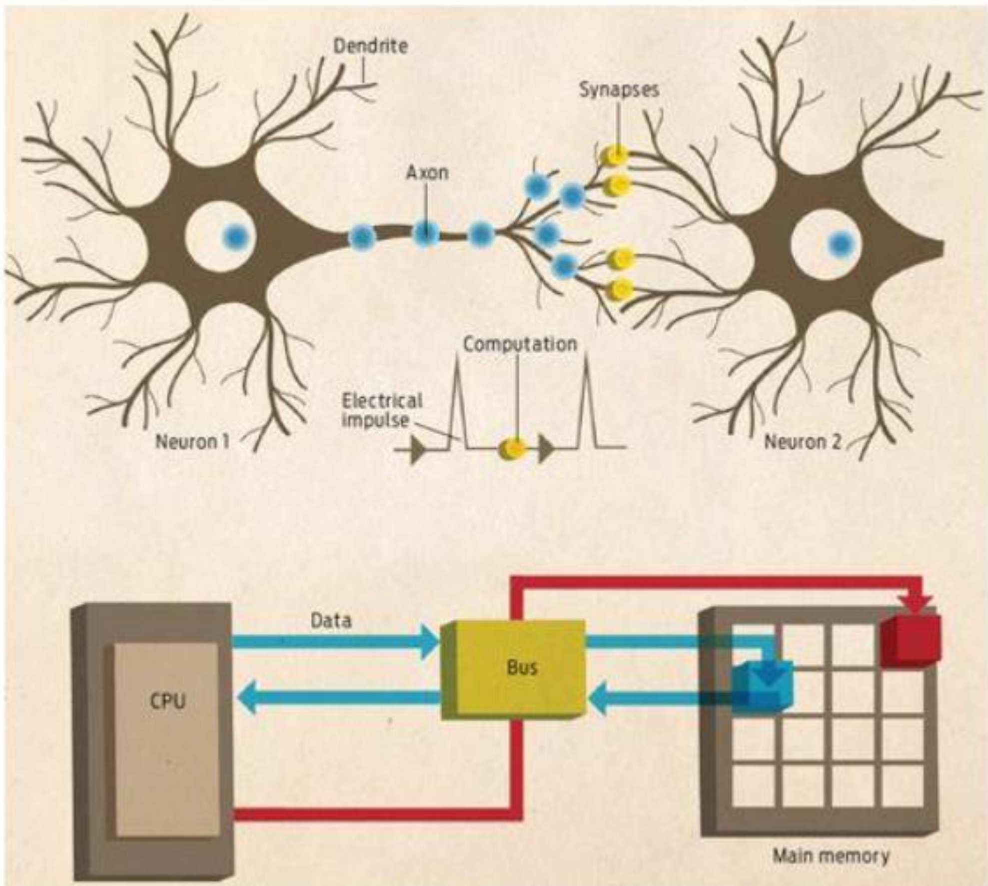


- Application of V_g pulses on a Pt (1.5 nm)/Co (0.8 nm) device.
- Thin gate oxide results in modulation at room temperature.
- The sign of effective spin Hall angle of the material can be changed using electric-field.
- Gradual modulation of SOTs can be applied to neuromorphic devices.

Phys. Rev. Appl. **11**, 054065 (2019), Nat. Commun. **10**, 248 (2019)

Neuromorphic Computation

Even the simplest brain is superior to a super computer, the secret: ARCHITECTURE!



From: Versace, M. & Chandler, B. The brain of a new machine. *Spectrum, IEEE* (2010).

Human brain:

- 10^6 neurons / cm^2
- 10^{10} synapses / cm^2
- 2 mW / cm^2

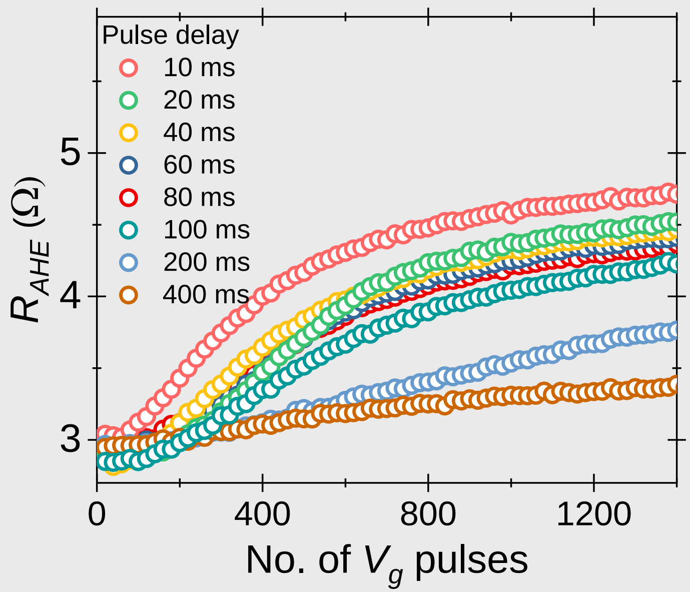
Total power consumption: 20 Watts

Memristors:

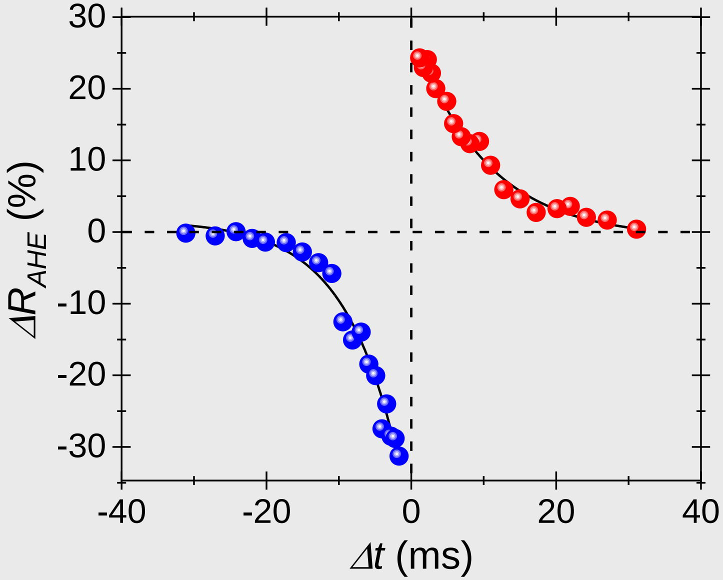
- Cheap
- Power efficient
- Small

Spike temporal dependence

Spike-rate dependence



Spike-timing dependence plasticity



- Frequent stimulation results in larger modulation of weight.
- The magnetic synapse follows the STDP curve.
- Closely spaced pre- and post-synaptic spikes results in larger weight modulation.

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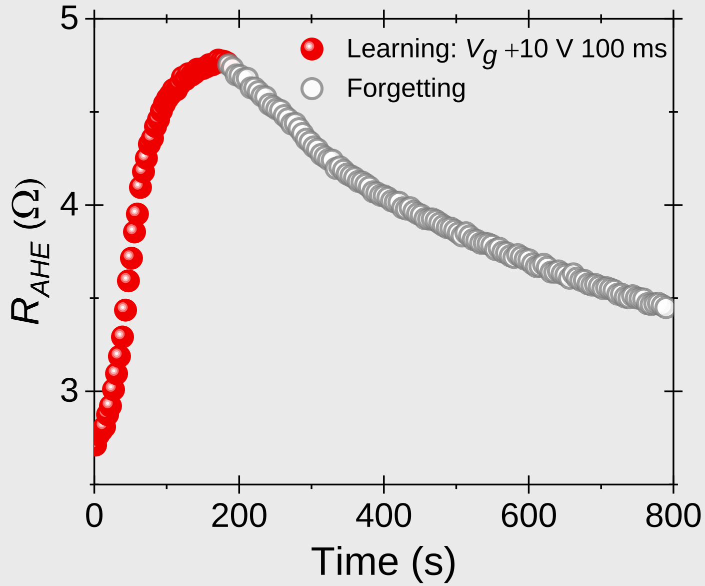
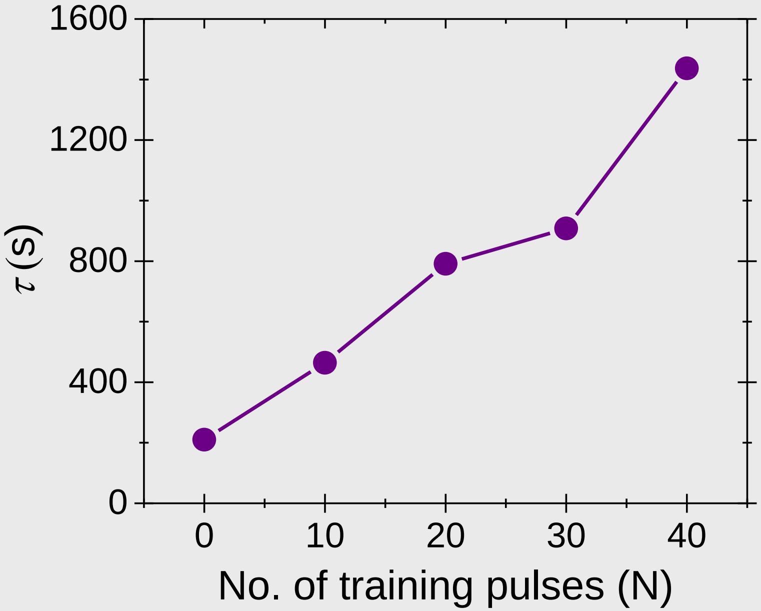
Phys. Rev. Appl. **11**, 054065 (2019)

Learning, forgetting & training

Learning & forgetting



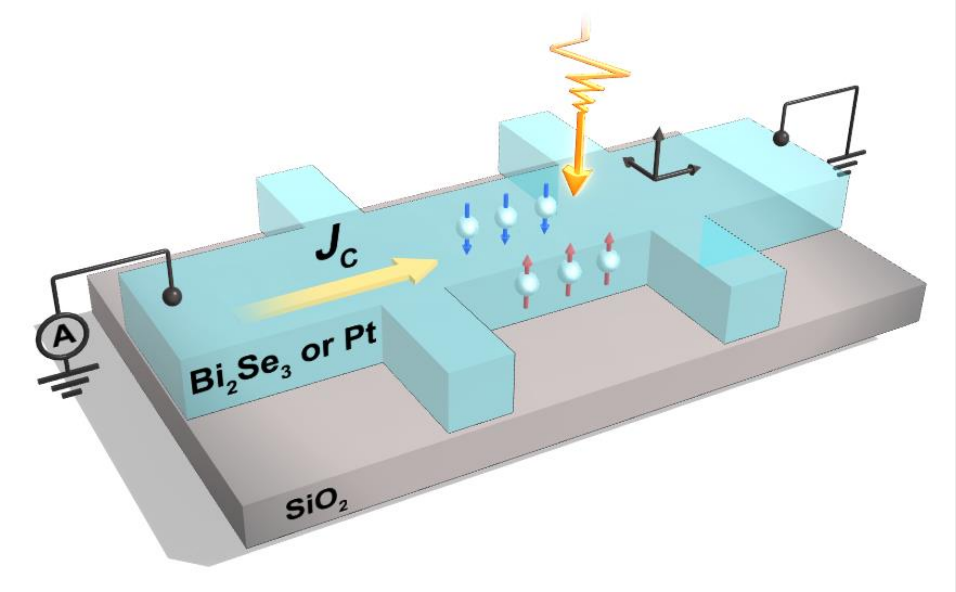
Training



- After removing the stimulation the weight starts decreasing again similar to forgetting behavior of human brain.
- With increasing number of training pulses the forgetting rate decreases.

Phys. Rev. Appl. **11**, 054065 (2019)

Scanning photovoltage microscope with currents



- ❖ DC current is applied to induce spin accumulation.
- ❖ Circularly polarized light normally incidents on the sample.
- ❖ Magnetic circular dichroism.
- ❖ Photovoltages are detected by lock-in amp.
- ❖ 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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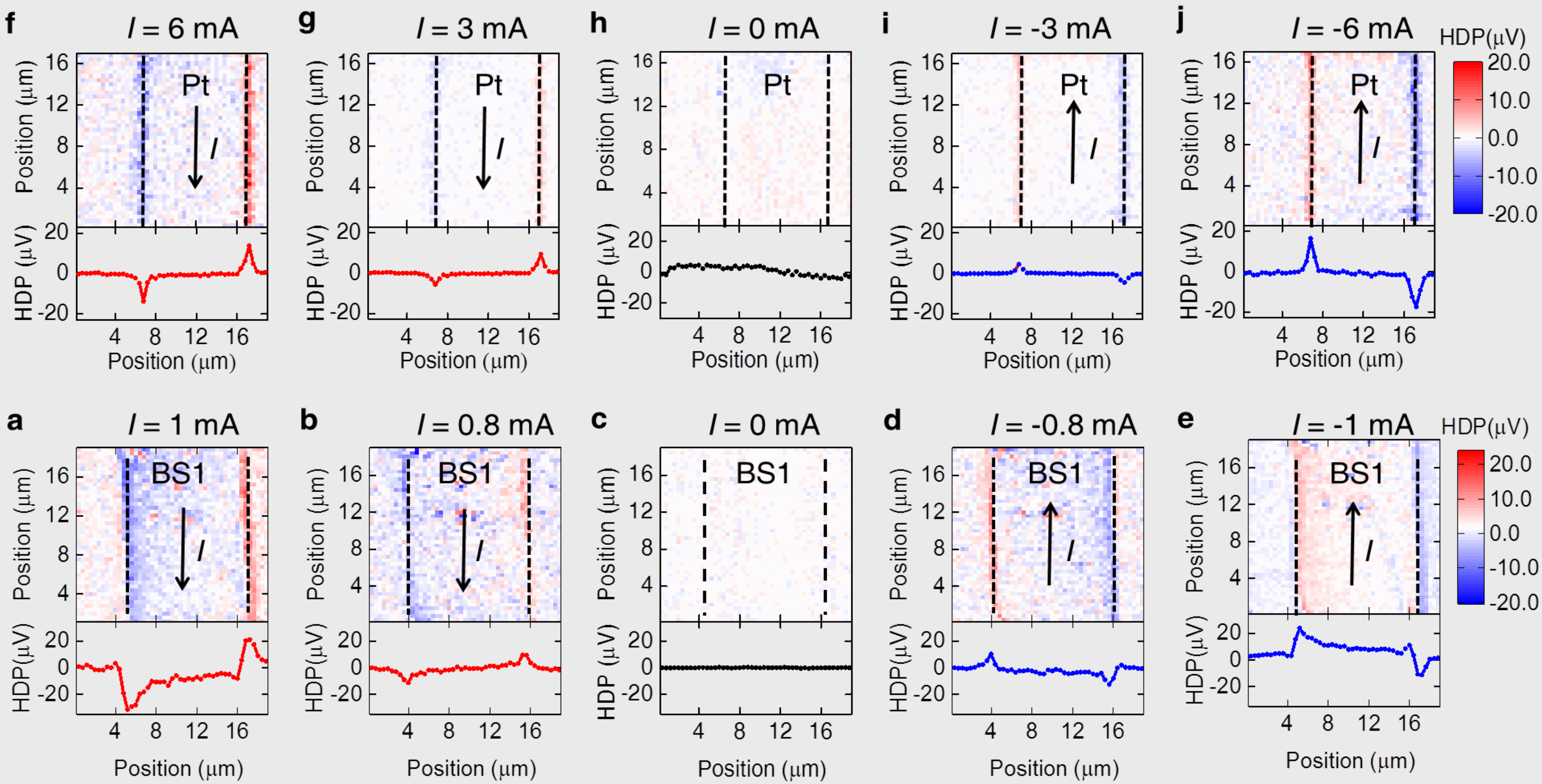
Nat. Comm. **9**, 2492 (2018); Adv. Opt. Mat. **4**, 1642 (2016)

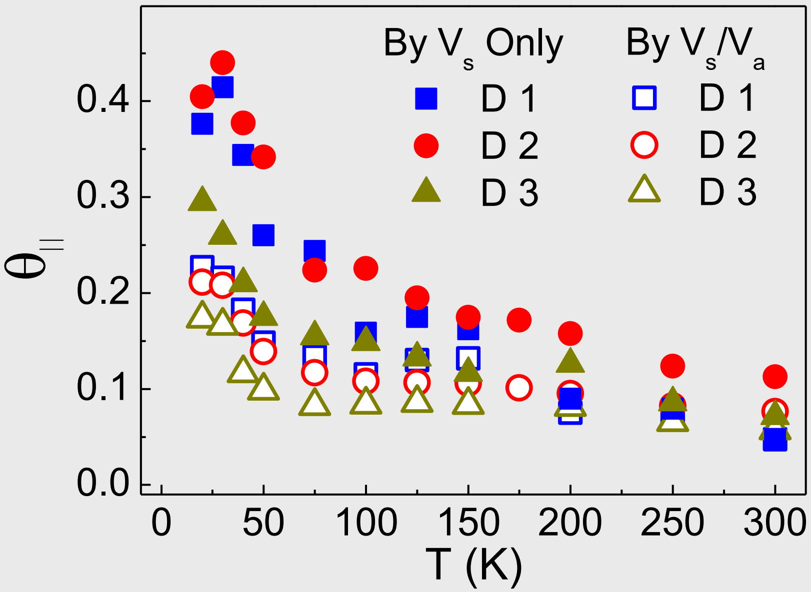
Accumulated spin imaging in Pt and Bi_2Se_3

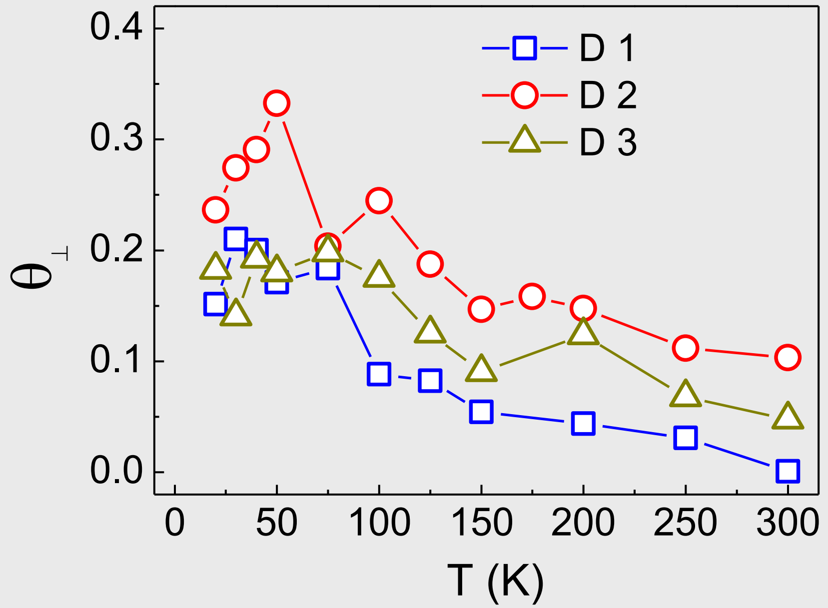


- ❖ Sign switches in opposite edges and with reversing currents.
- ❖ Both semiconductors and metals work.
- ❖ Can extract spin Hall angle and spin lifetime without a ferromagnet.

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

In-plane and out-of-plane SOT efficiency in Bi_2Se_3





- $\theta_{||}$ increase by 10 times at low temperature (upto **~ 0.42**).
- $\theta_{\perp}$ has the same order of magnitude compared to $\theta_{||}$.
- Origin of the observed spin-orbit torques is topological surface states in Bi_2Se_3.
- Hexagonal warping in the TSS of Bi_2Se_3 can account for $\theta_{\perp}$.

PRL **114**, 257202 (2015)

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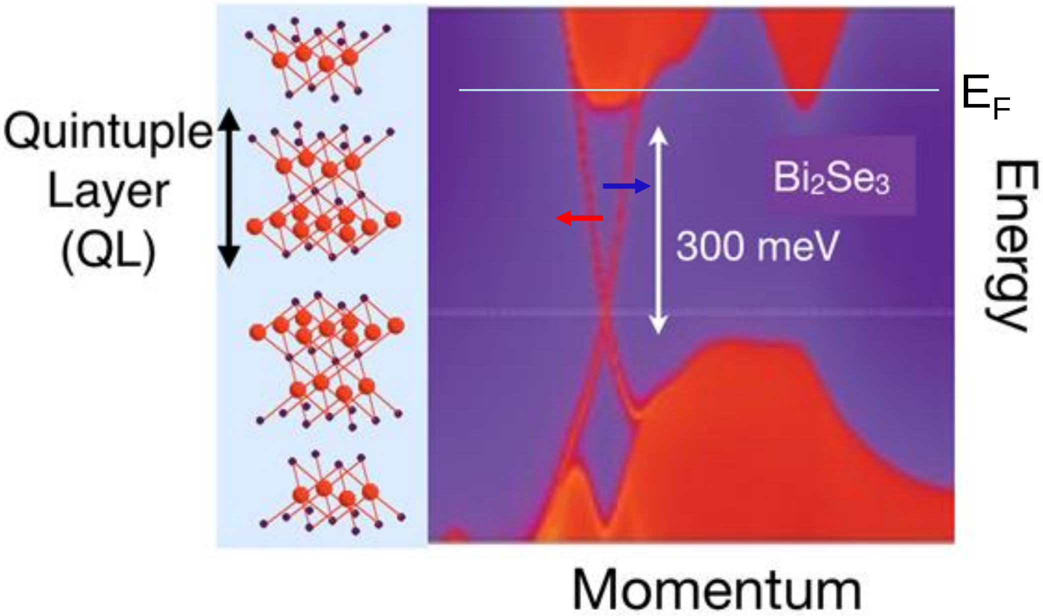
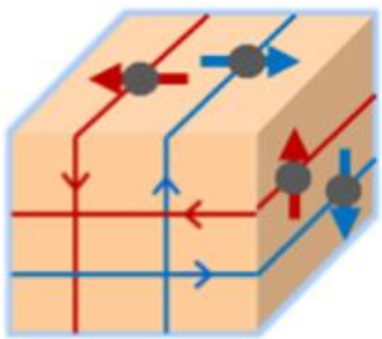
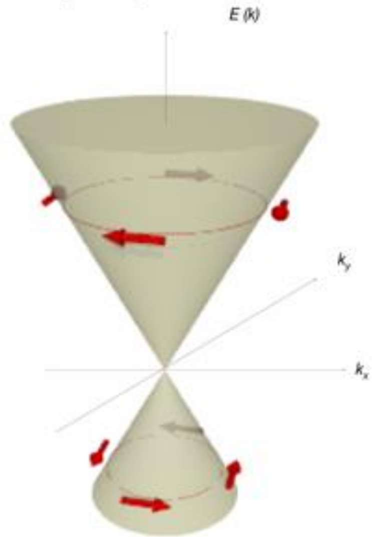
3D topological insulators (TIs)



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)

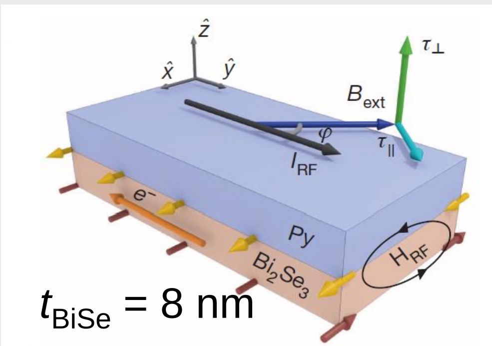




- ❑ Spin polarized surface currents
- ❑ Spin-momentum locking → giant spin Hall angle?

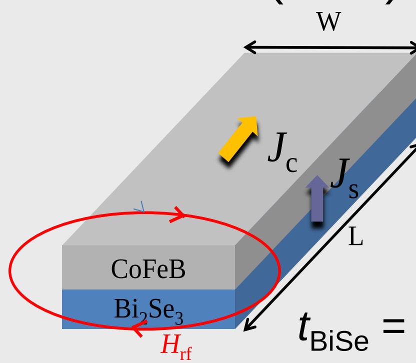
Exotic spin Hall angles from topological insulators

spin Hall angle (θ_{SH}) = 2~3.5
ST-FMR (Cornell)



Nature **511**, 449 (2014)

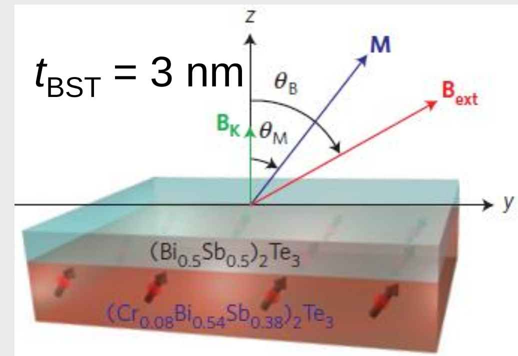
θ_{SH} = 0.42 (low temp)
ST-FMR (NUS)



t_{BiSe} = 20 nm

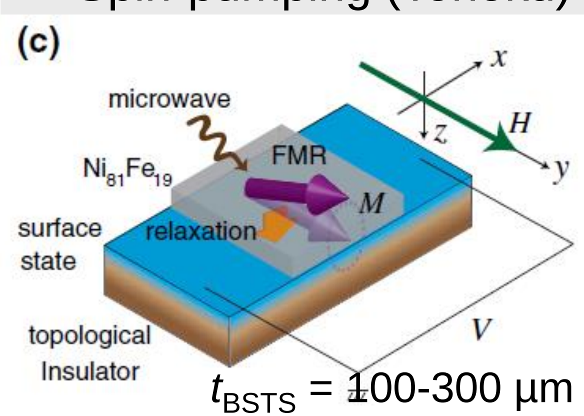
PRL **114**, 257202 (2015)

θ_{SH} = 140-425 (low temp)
spin-orbit switching (UCLA)



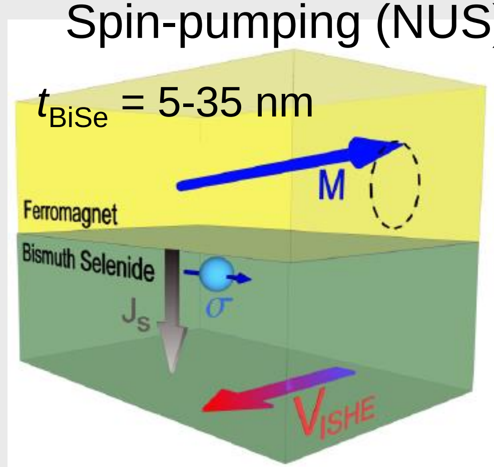
Nat. Mater. **13**, 699 (2014)

θ_{SH} ~ 1 × 10^{-4}
Spin-pumping (Tohoku)



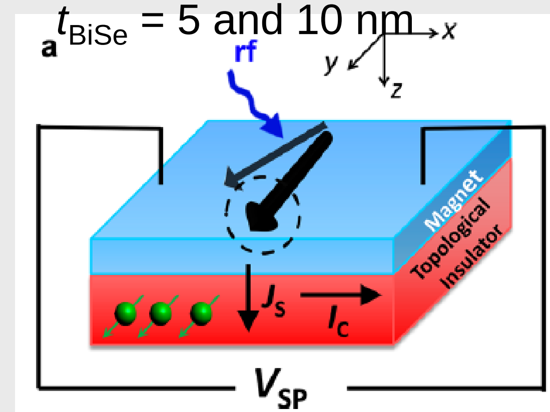
PRL **113**, 196601 (2014)

θ_{SH} = 0.01
Spin-pumping (NUS)

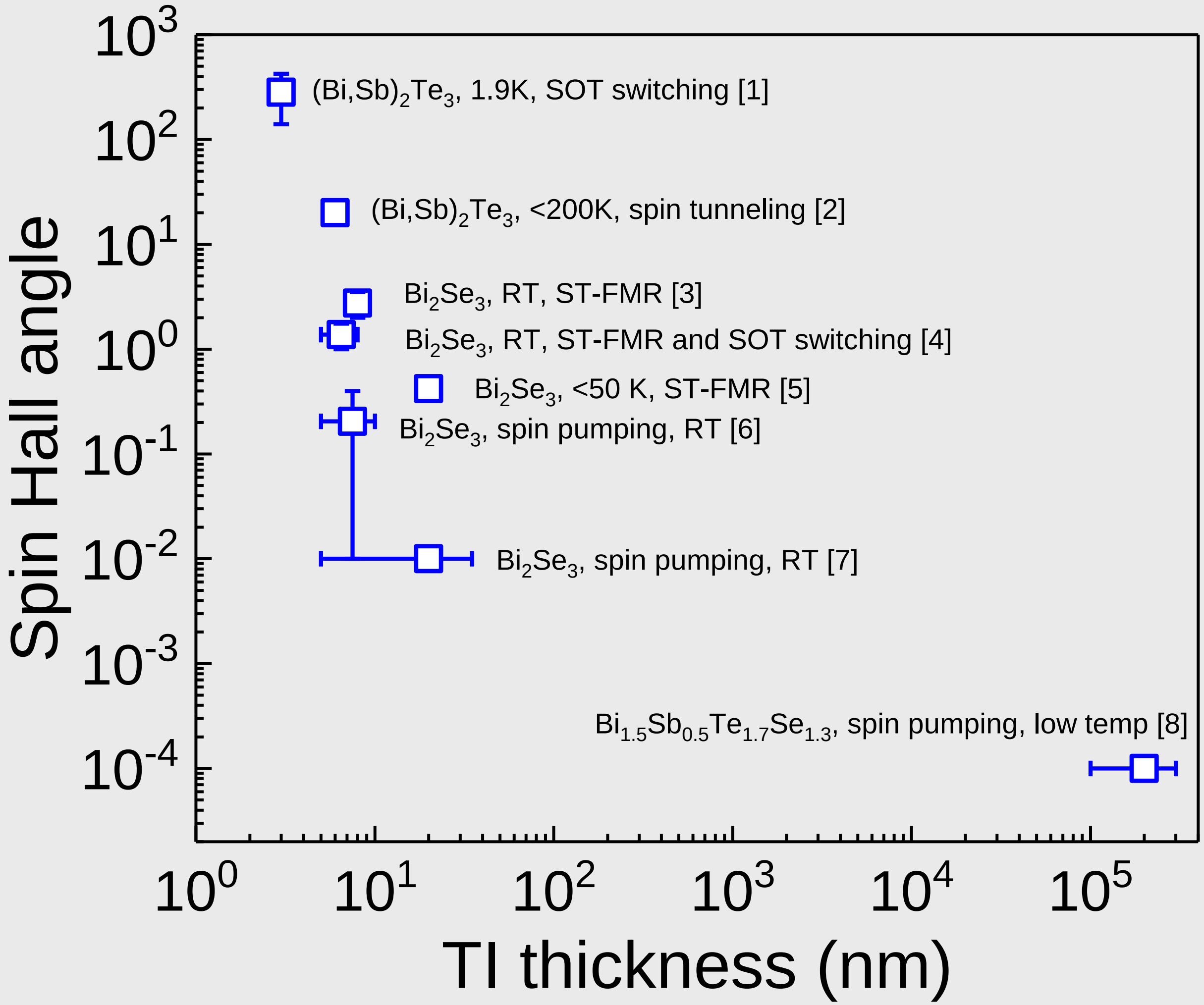


PRB **90**, 094403 (2014)

θ_{SH} = 0.01-0.4
Spin-pumping (Minnesota)



Nano Lett **15**, 7126 (2015)



- TI is not a good insulator.
- E_F is pinned in conduction band.
- Current shunting thru bulk reduces the efficiency!

[1] Nat. Mater. **13**, 699 (2014)
[2] PRB **91** 235437 (2015)
[3] Nature **511**, 449 (2014)
[4] Nat. Commun. **8** 1364 (2017)
[5] PRL **114**, 257202 (2015)
[6] PRB **90**, 094403 (2014)
[7] Nano Lett **15**, 7126 (2015)
[8] PRL **113**, 196601 (2014)

Review: J. Phys. D: Appl. Phys. **51**, 273002 (2018)

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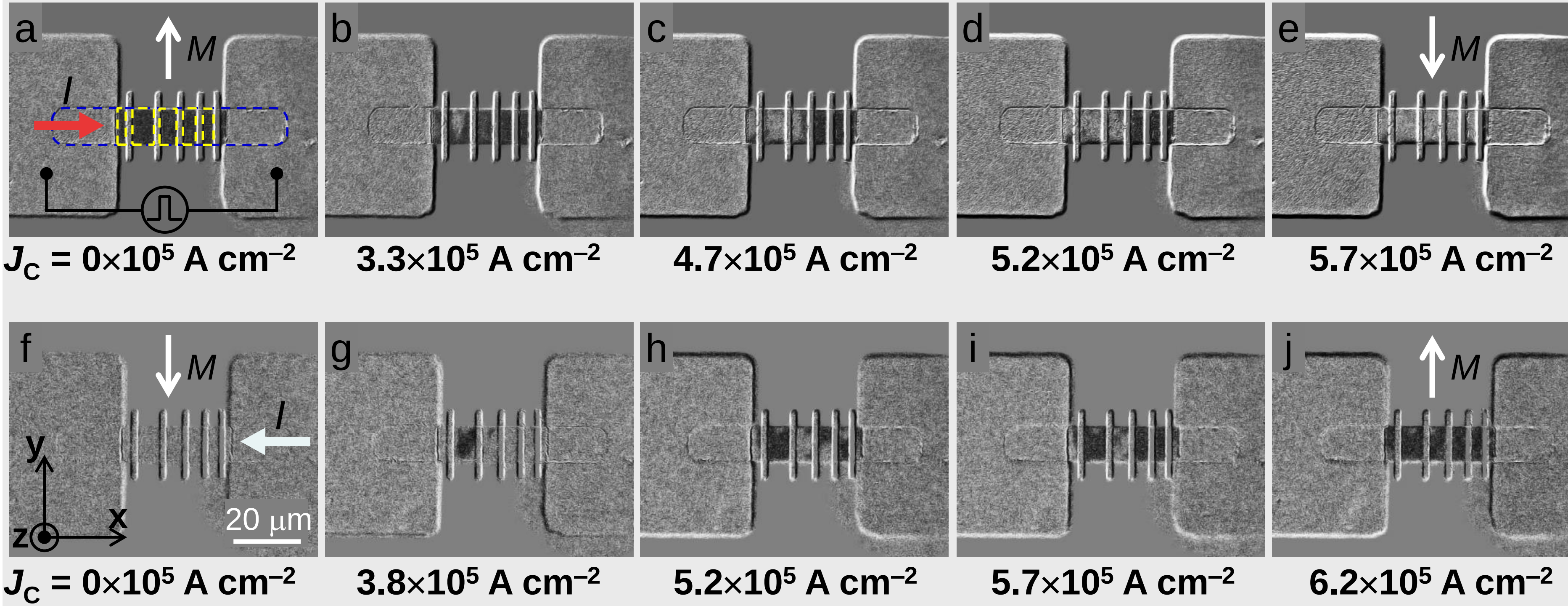
Current induced magnetization switching in Bi_2Se_3/Py

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 $\theta_{TI} = 1.75$.

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

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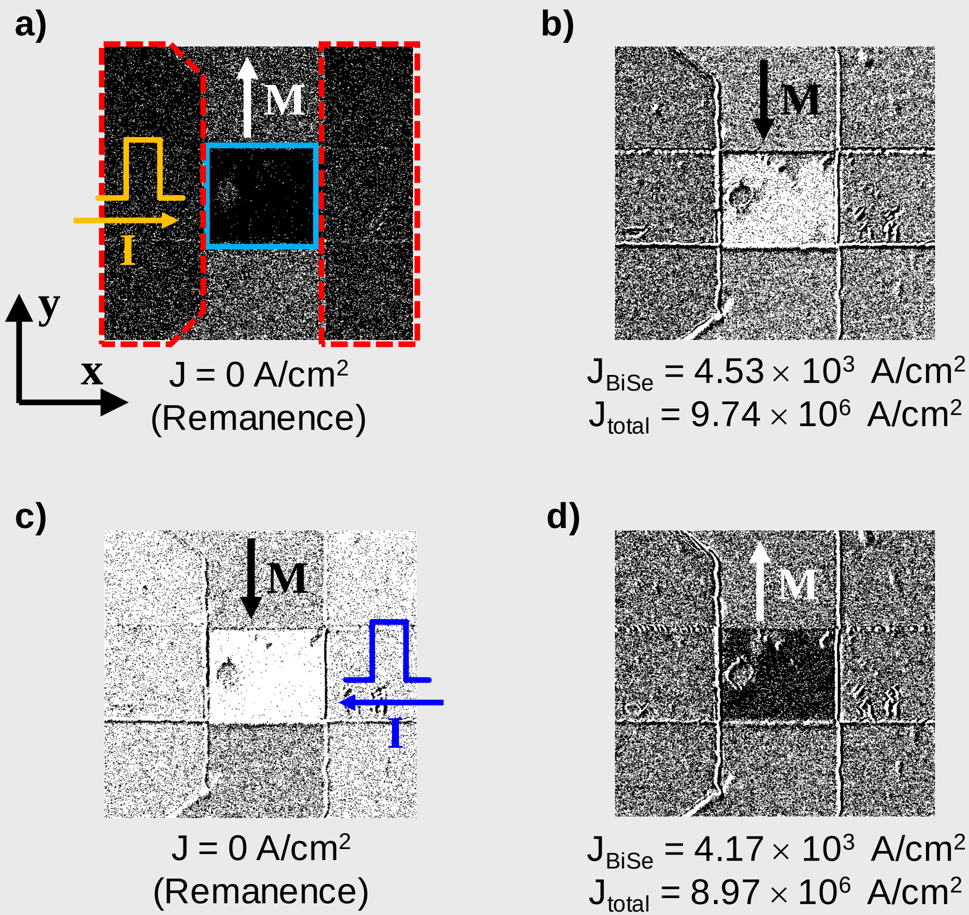
Sputtered Bi_2Se_3

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 large resistivity

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

$\theta = 18.6$, $J_c = 4.3 \times 10^5$ A cm^{-2}

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

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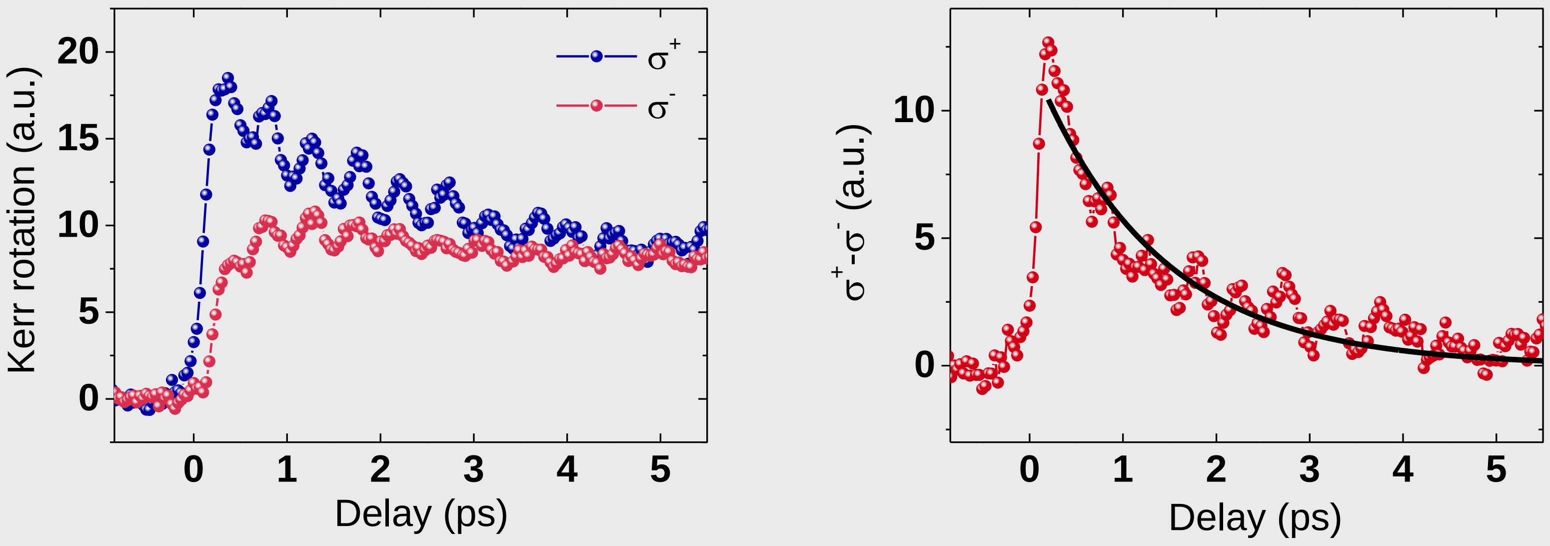
Spin relaxation time in Bi_2Se_3

Time-resolved magneto optical Kerr effect



- Signal sensitive to bulk due to large penetration depth of light
- Oscillation frequency is 2.13 THz from coherent vibrations of the A_{1g} longitudinal optical phonons of Bi_2Se_3
- Exponentially decay with a characteristic time of 1.3 ps

Adv. Opt. Mat. **4**, 1642 (2016)

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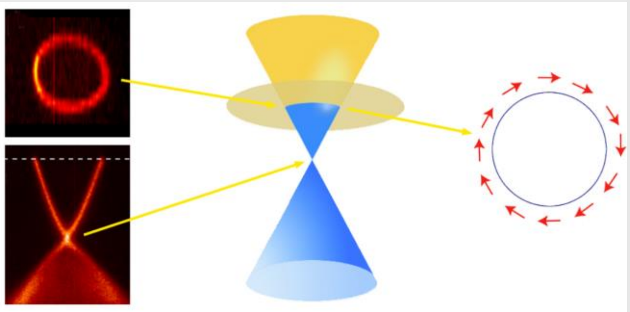
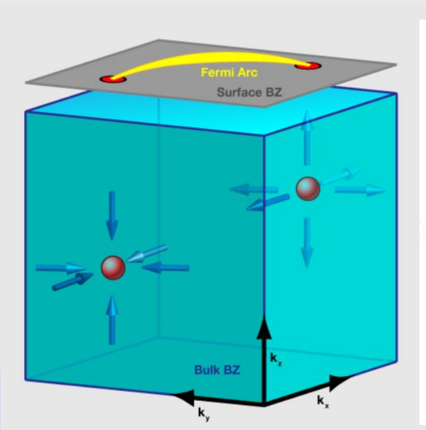
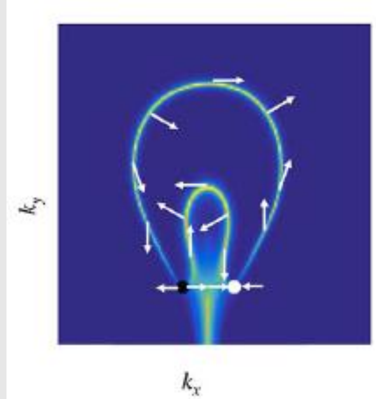
Weyl semimetal background

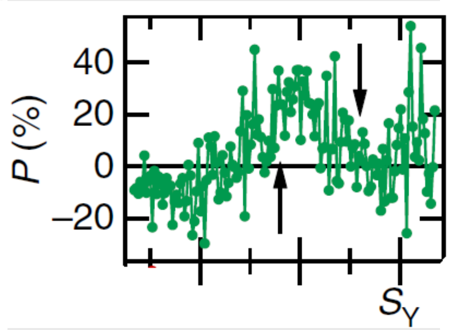
Topological insulator (TI):



Weyl semimetal:







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

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

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

S. Xu, *et al.* Nat. Commun. **6,** 6870 (2015)

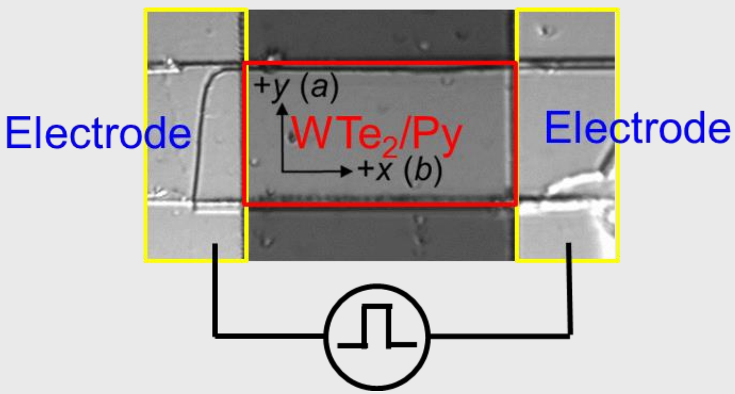
S. Xu, *et al.* Phys. Rev. Lett. **116,** 096801 (2016)
P. K. Das, *et al.* Nat. Commun. **7,** 10847 (2016)

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.

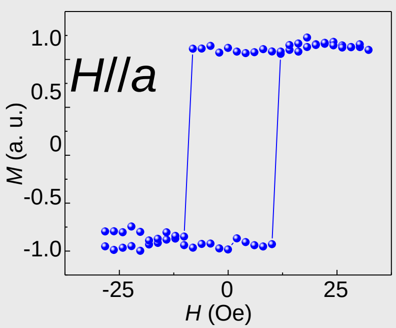
Ideal material to achieve the spin orbit torque driven magnetization switching.

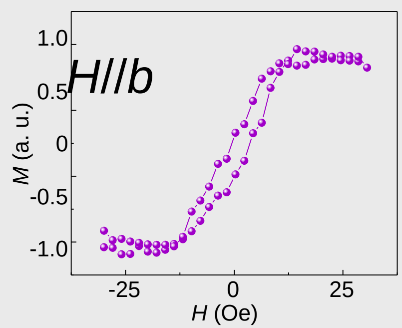
SOT driven magnetization switching-*I* along *b*-axis

- Charge current is applied in the *b*-axis.
- Spin current is generated along the *a*-axis.

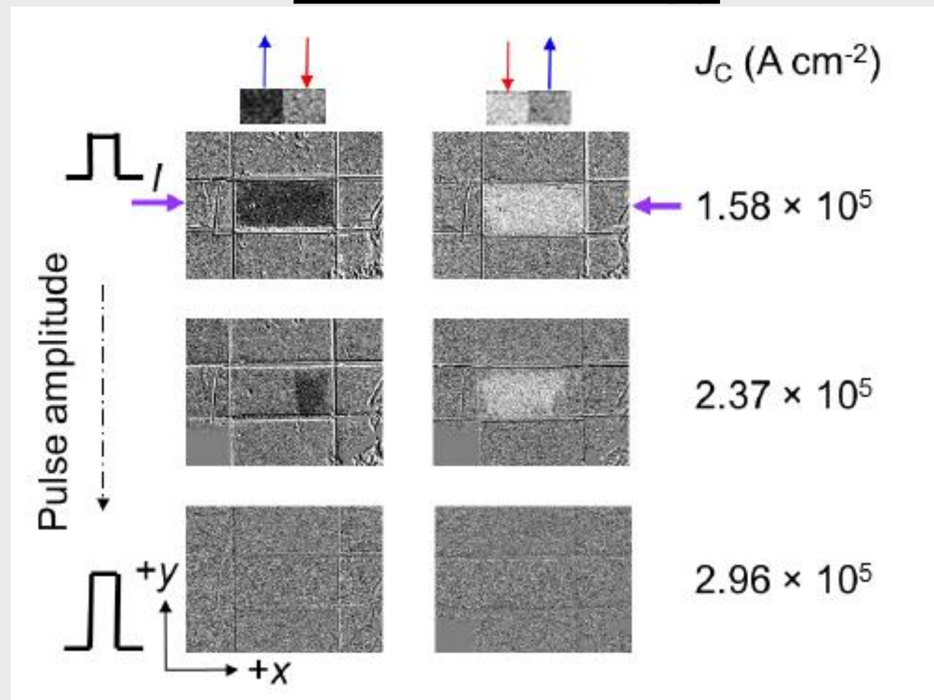


Hysteresis loops of the device





MOKE microscopy



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

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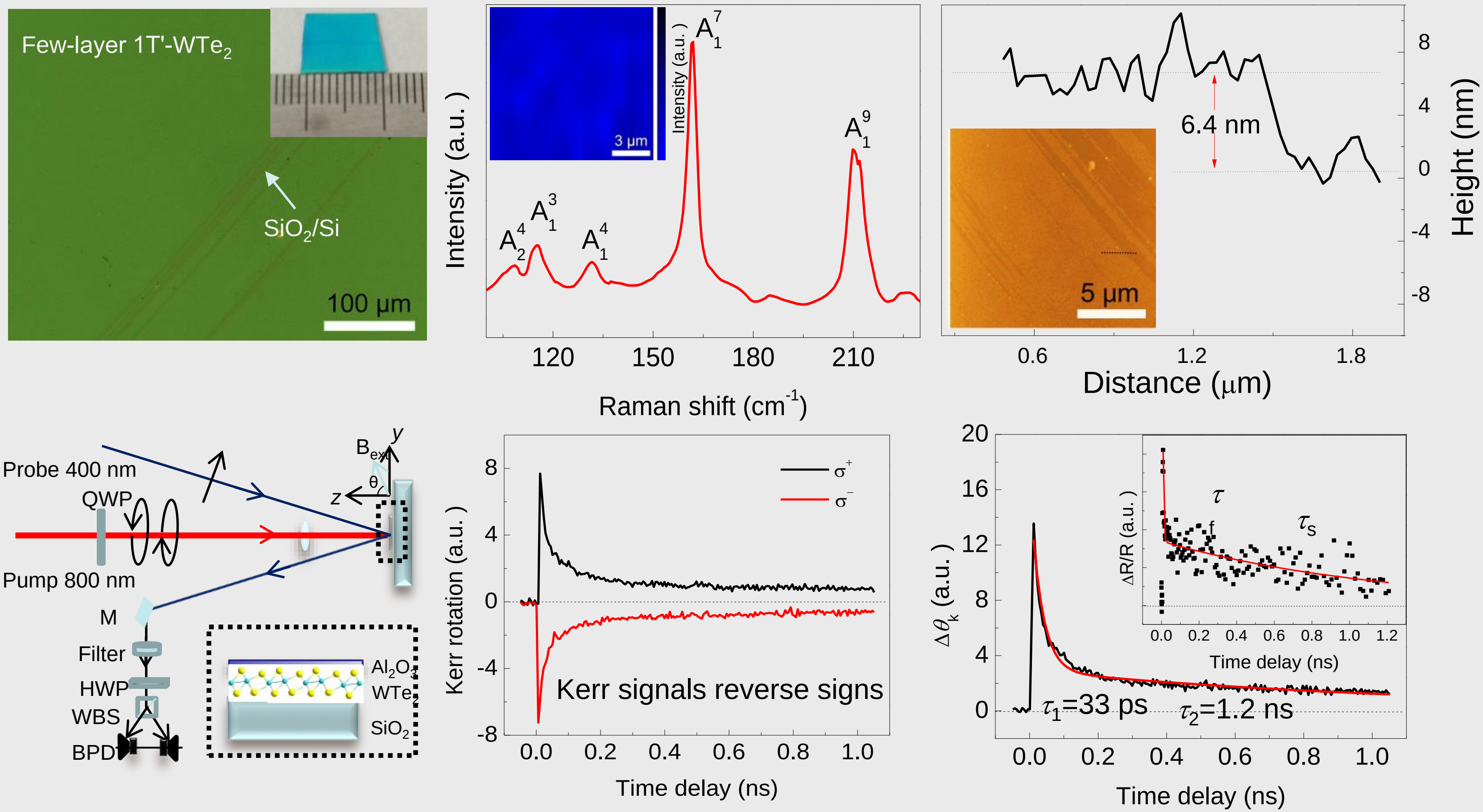
Nat. Nano. **14**, 945 (2019)

Room-temperature nanosecond spin relaxation



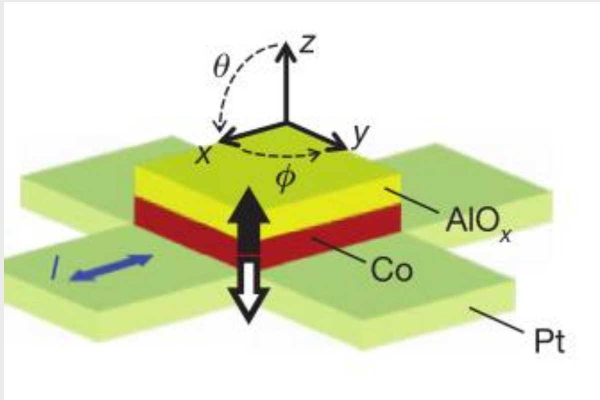
- Centimeter-scale, chemical vapor deposition (CVD)-grown few-layer 1T'-W(Mo)Te_2
- Room-temperature 1.2 ns spin relaxation

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

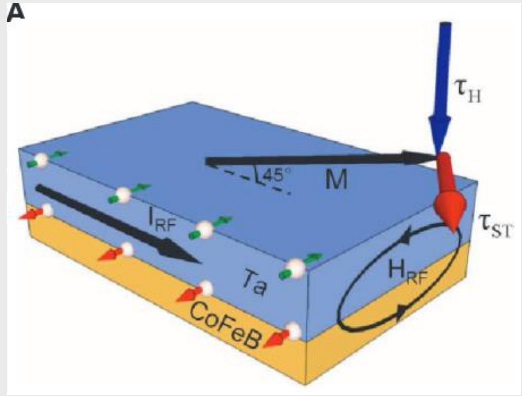
Spin orbit torque in various magnets

Antiferromagnet

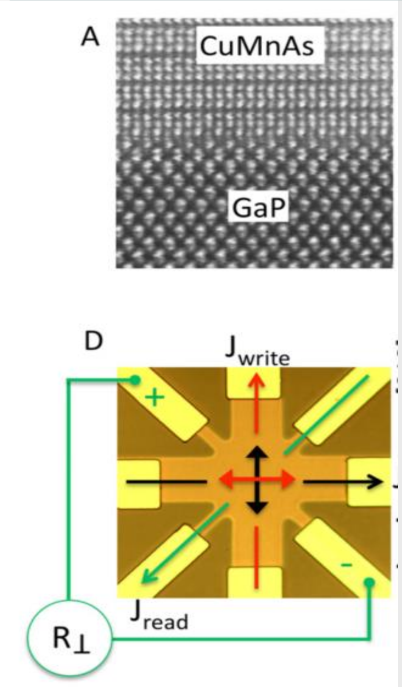
Ferromagnet



Nature **476**, 189 (2011)



Science **336**, 555 (2012)



Science **351**, 587 (2016)

$1/t_{FM}$ dependence of spin torque (surface torque)
→ Limitation on FM thickness
→ Thermal stability issue

90 degree rotation
Not compatible with MTJs
Small MR → slow reading

How about a **multilayer** or **ferrimagnet (FIM)**?
-Easy perpendicular anisotropy, enough magnetic volume

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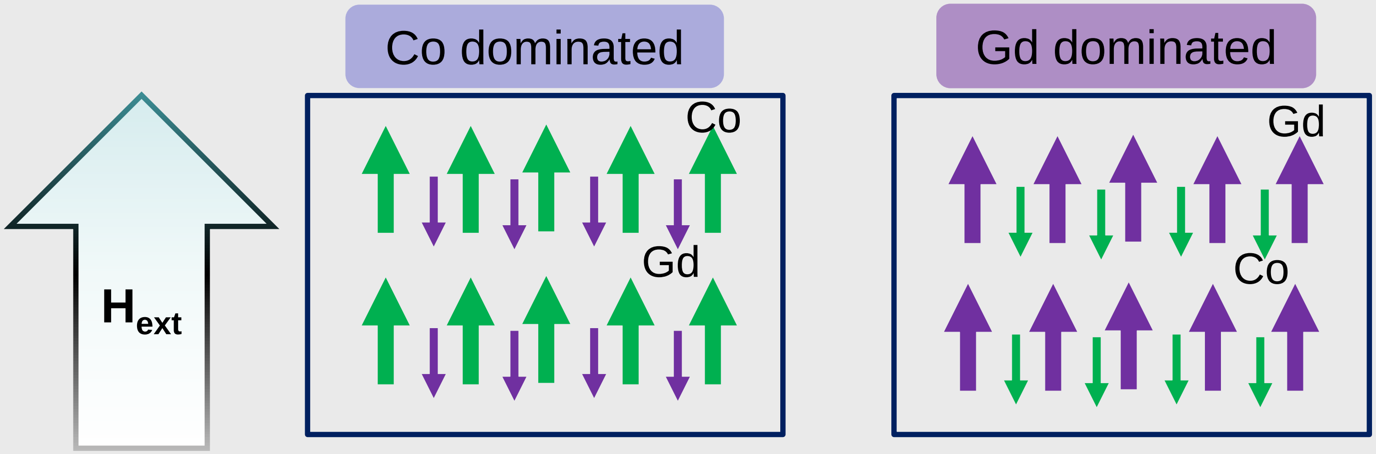
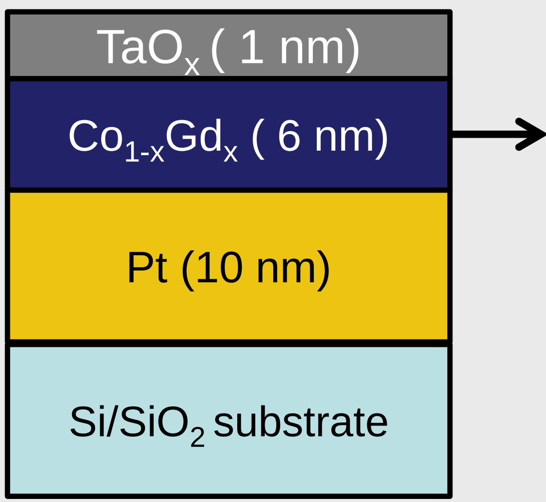
SOT in ferrimagnet : CoGd

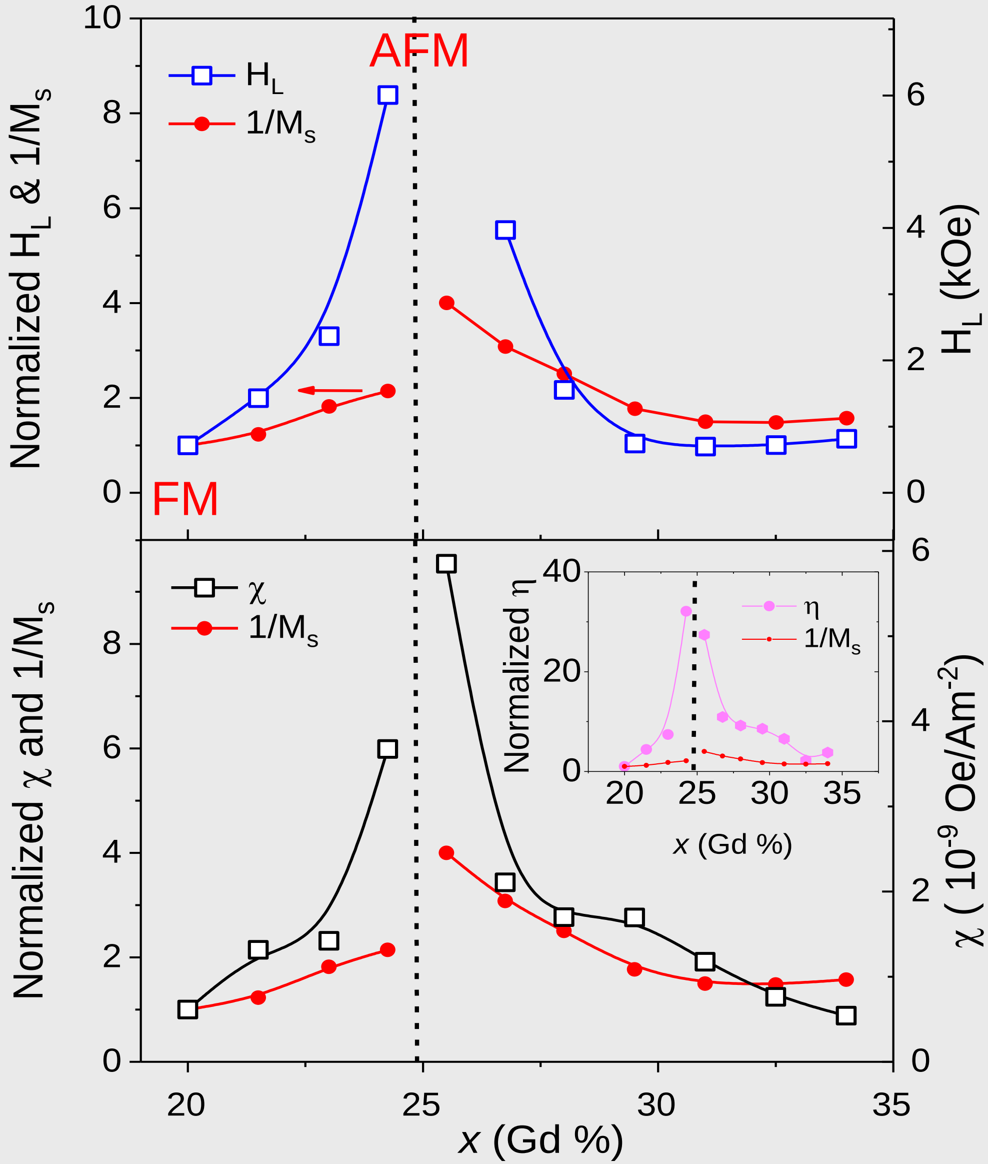




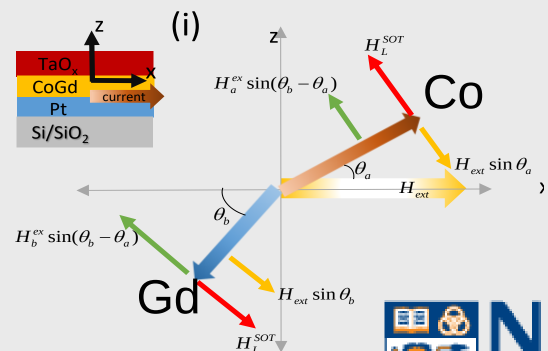
- Films deposited with varying Co and Gd compositions.
- CoGd has bulk PMA.
- Thermally stable thick magnetic layer is grown.

Phys. Rev. Lett. **118**, 167201 (2017)

Anomalous scaling of SOT in ferrimagnets



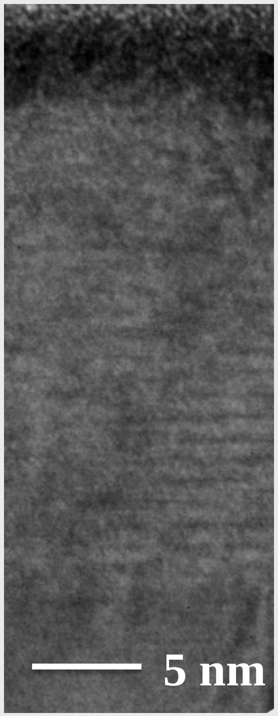
- Switching efficiency ($\chi = H_p / J_s$), H_L and $1/M_s$ are normalized with respect to their respective values for $Co_{80}Gd_{20}$.
- Exceptional and disproportionate (to $1/M_S$) change of η and H_L cannot be explained by existing SOT understanding.
- 10 times increase in θ_{SH} due to negative exchange coupling



Phys. Rev. Lett. **118**, 167201 (2017)

Multilayer: structural asymmetry can be added up

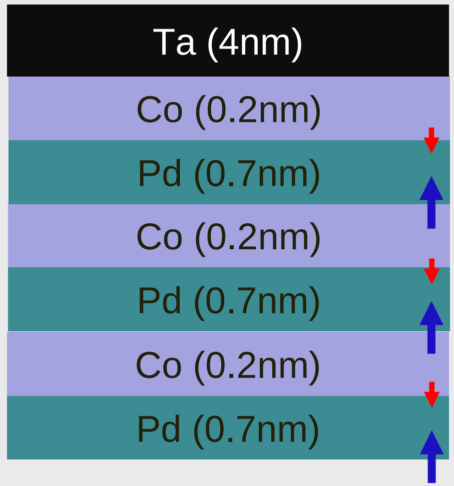
TEM



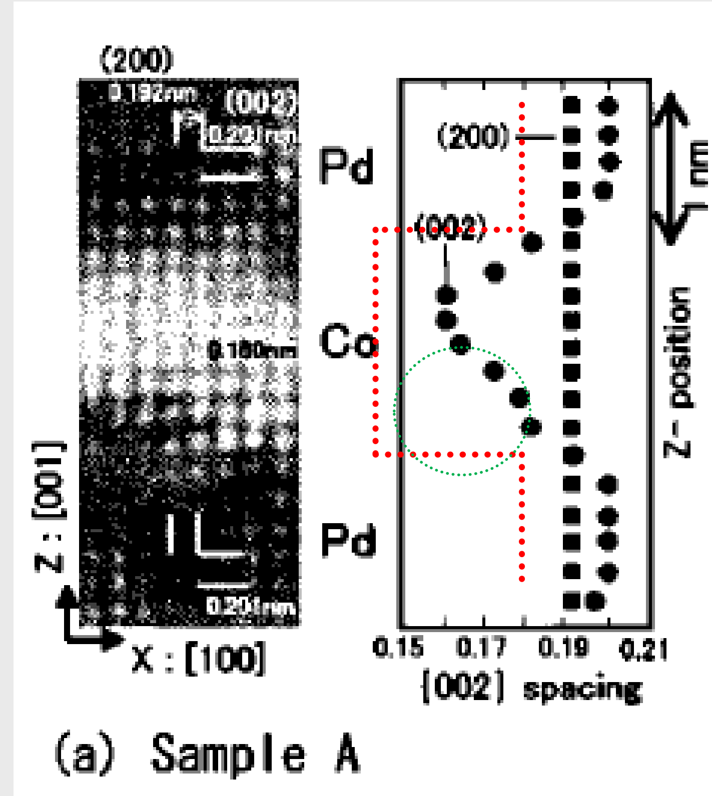
Ta (4 nm)

Co (0.2 nm)/
Pd (0.7 nm)/
multilayer
(22 times)

Ru



$$\theta_{SH} = 4$$



Maesaka, IEEE Trans. Magn. 38, 2676 (2002)
Kim, PRB 53, 11114 (1996)

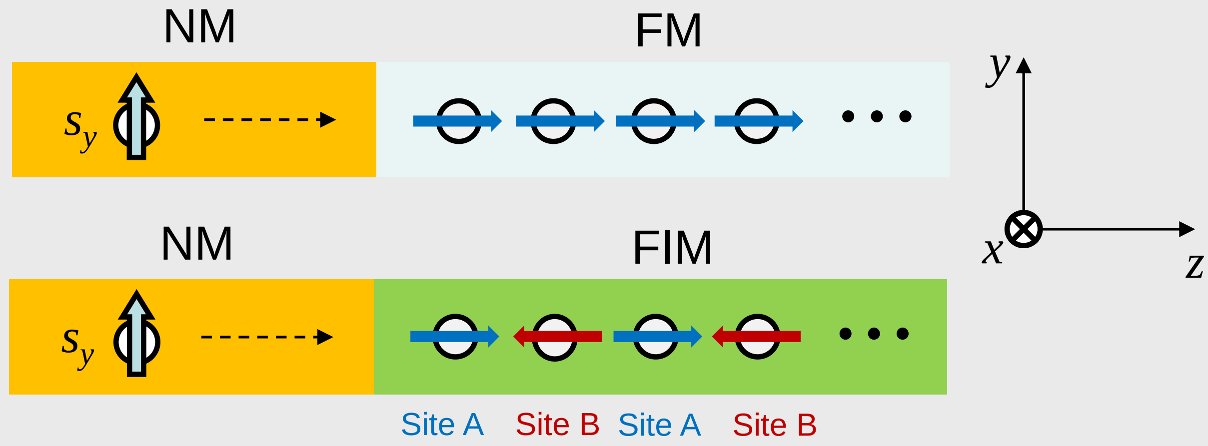
-Two successive Co/Pd and Pd/Co interfaces are structurally dissimilar.

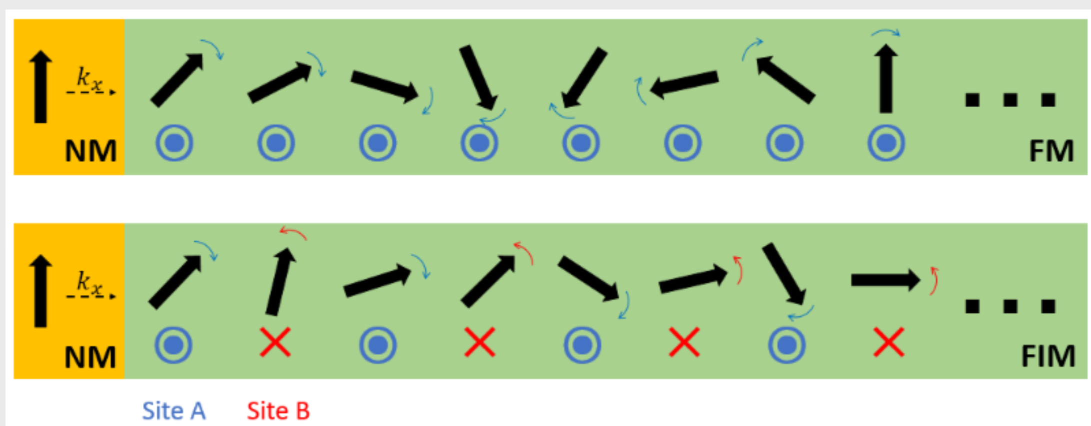
-Lattice mismatch (9%) between Pd and Co → Strain engineering

-This distortion is 30% stronger for Co/Pd than for Pd/Co interfaces

Phys. Rev. Lett. **111**, 246602 (2013)

Ferromagnet vs. ferrimagnet

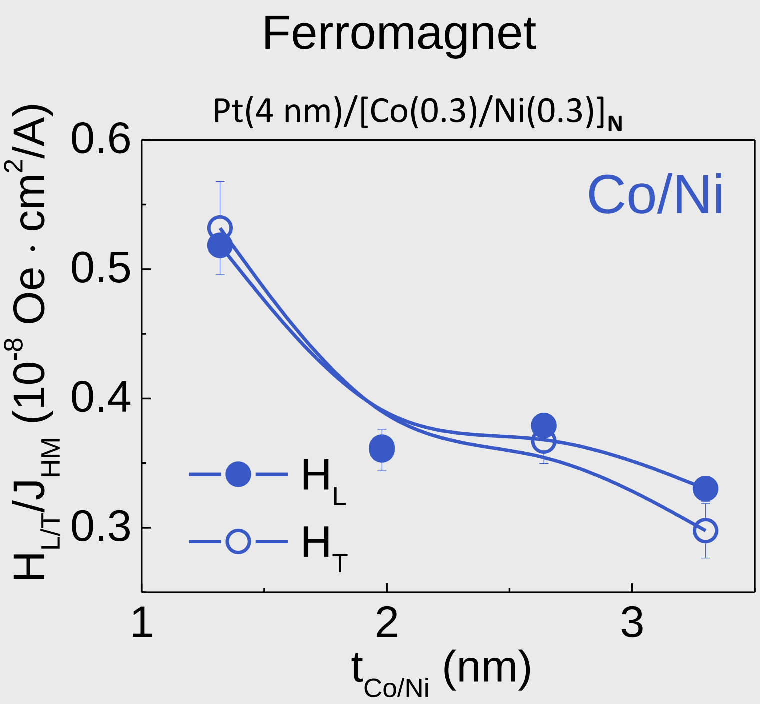


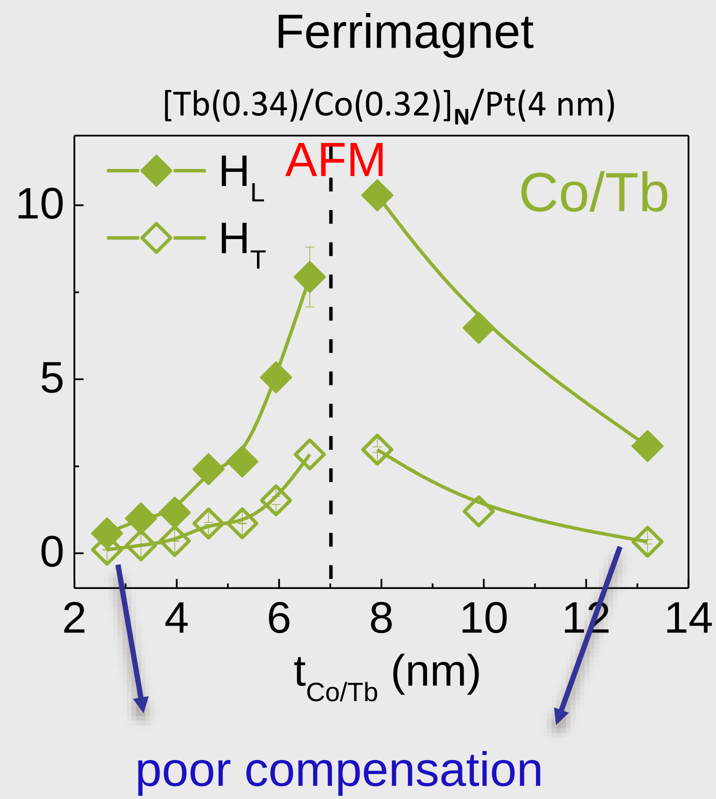


Alternating exchange fields in ferrimagnet (FIM) on an atomic scale
→ much less spin dephasing → long spin coherence length
→ Bulk-like torque in FIM (20 times enhanced SOT compared to FM)

Nat. Mater. **18**, 29 (2019)

SOT effective fields



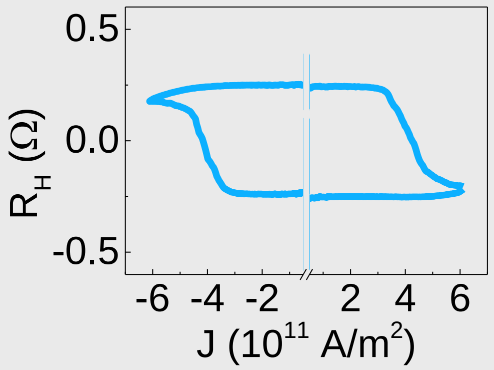


$$H_L = \frac{\hbar}{2e}\frac{J_{HM}}{M_S t_{FM}}\theta_{HM}\left[1-\text{sech}\left(\frac{t_{HM}}{\lambda_{HM}}\right)\right]$$

- FM Co/Ni: $t_{Co/Ni}$ ↑ → **SOT** ↓.
- FIM Co/Tb: SOT **diverges** at **compensation**.
- SOT in FIM is **~20 times larger** than that in FM.
- SOT in FIM shows **bulk-like-torque** characteristic.

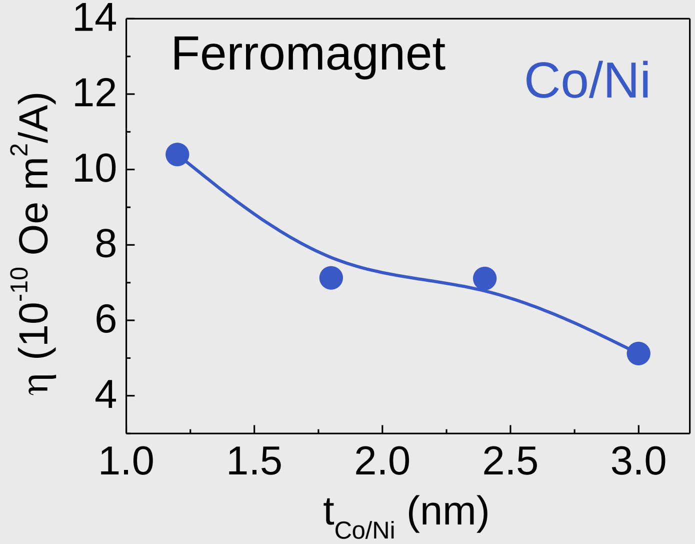
Nat. Mater. **18**, 29 (2019)

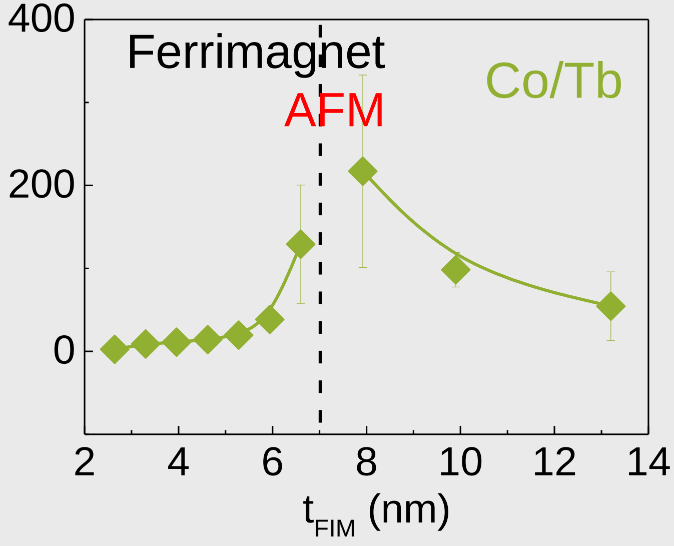
SOT current induced switching efficiency



Most switching through DW nucleation and propagation

SOT switching efficiency: $\eta = H_P / J_W$





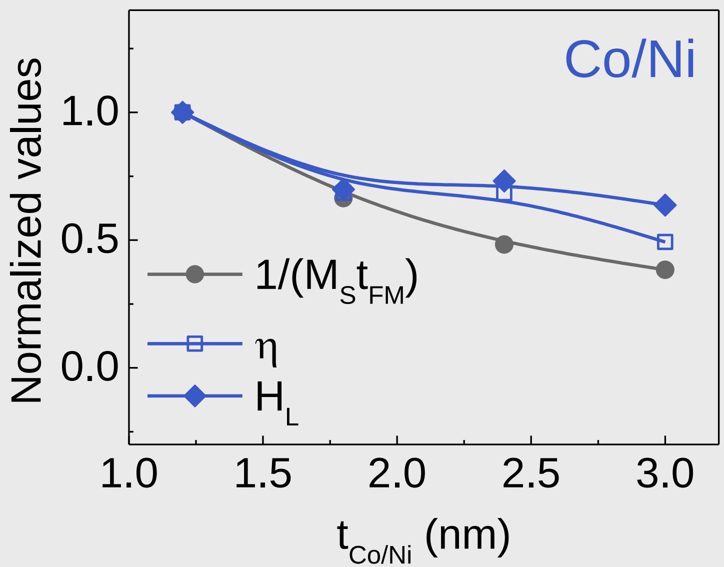
- η is in line with that of SOT effective fields, decreasing for FM and **diverging** at **compensation.**
- In FIM system, η is ~**20 times higher** than FM system.

Nat. Mater. **18**, 29 (2019)

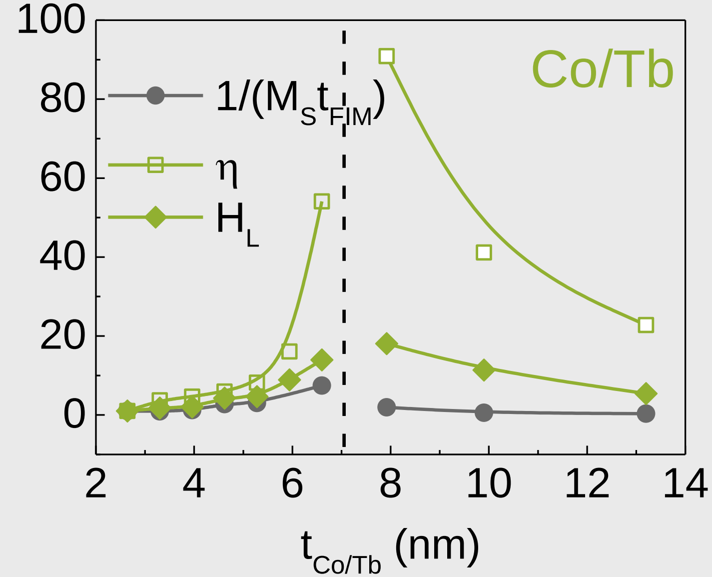
M_S & $t_{FM/FIM}$ effect?

$$H_L = \frac{\hbar}{2e}\frac{J_{HM}}{M_S t_{FM}}\theta_{HM}\left[1-\mathrm{sech}\left(\frac{t_{HM}}{\lambda_{HM}}\right)\right] \rightarrow \eta, H_L \propto 1/\left(M_S t\right)$$

Ferromagnet



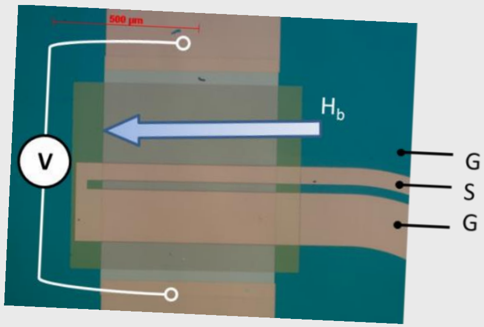
Ferrimagnet

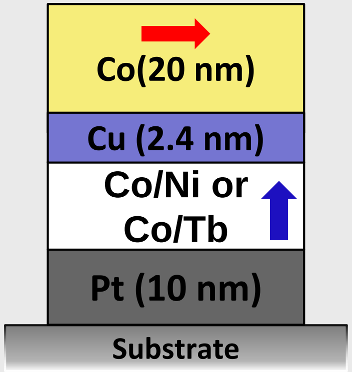


Surprisingly in FIM, the scaling trend of η and H_L **contradicts** SOT governing equation.

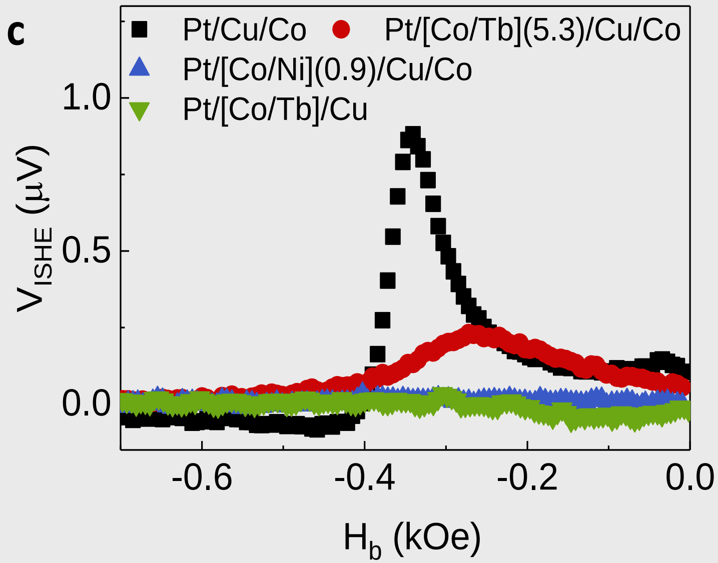
Nat. Mater. **18**, 29 (2019)

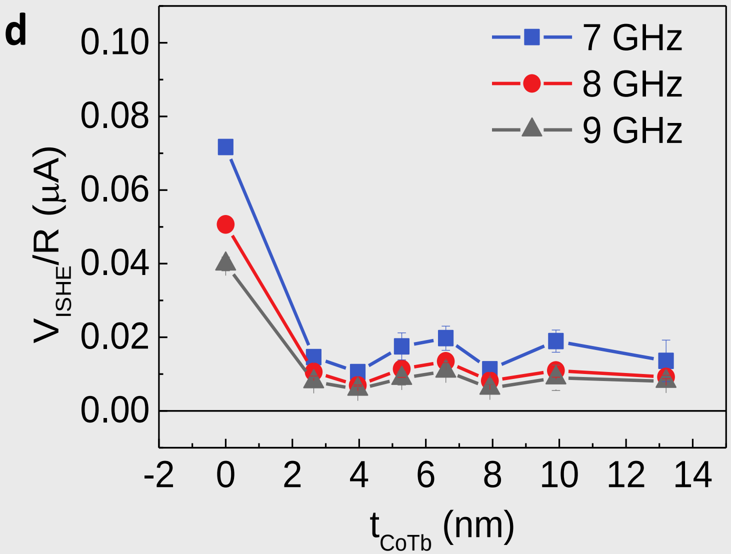
Spin pumping in a ferrimagnet





-If spin coherence length is long, a transverse spin current passes through the Co/Ni or Co/Tb layer.
-V_{ISHE} is generated.





Spin dephasing length in Co/Tb > 13 nm
Spin dephasing in FM is 1.2 nm (PRL 117, 217206 (2016))

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Nat. Mater. **18**, 29 (2019)

Summary

- Spin orbit technologies
  - Oxygen modulation in HM/FM interface can switch spin Hall sign → neuromorphic devices
  - Spin accumulation imaging (www.tuotuot.com)
  - Weyl semimetal spin sources
  - Ferrimagnetic spintronics

Bulk-like