Spintronics Research at Cornell
(with some questions for you)

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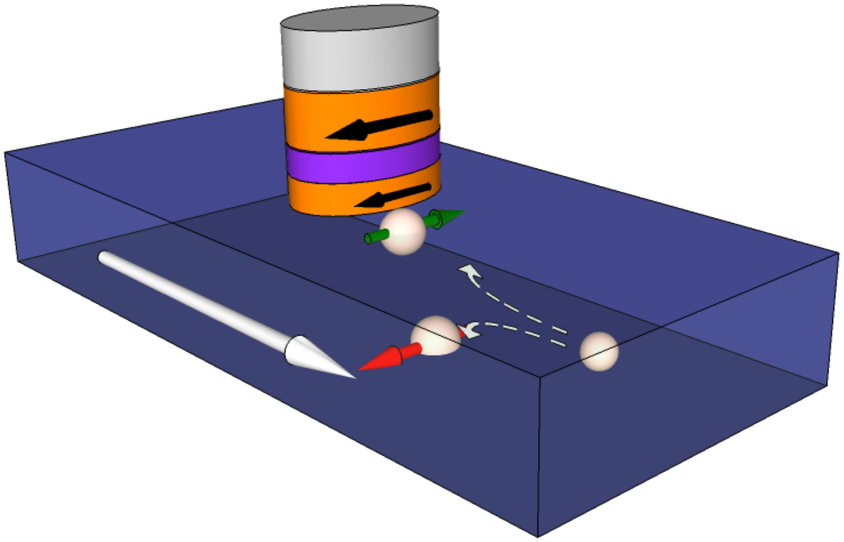


KIC Kavli Institute at Cornell
Cornell Center for Materials Research
NSF
DARPA
CNF Cornell NanoScale Science and Technology Facility

This is an Exciting Time in Spintronics

Very strong effects (certain to be useful/important)

- high TMR tunnel junctions
- spin transfer torque
- interface anisotropy
- exchange bias with AFs
- spin Hall effect
- voltage-controlled magnetic anisotropy
- Dzyaloshinskii-Moriya interaction (DMI)
- spin pumping

Very interesting physics (could be useful/important)

- strain/spin coupling
- multiferroics
- optical manipulation
- thermal spin currents
- Rashba effect

Possibilities of new physics or applications using previously-unutilized families of materials

- topological insulators
- insulating ferro- or ferrimagnets
- antiferromagnets
- atomic-membrane materials
- half-metals

Outline

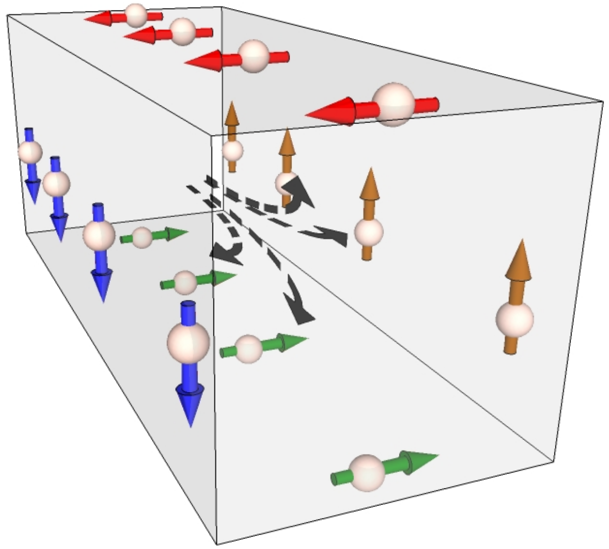
- How to make accurate measurements of current-induced torques? (separate discussions of torques with the symmetries of the spin Hall torque and the Rashba effect)

- Useful things you can do with spin torque from the spin Hall effect (+ voltage controlled magnetic anisotropy, in some cases)

- Current-induced torques arising from topological insulators

- If time, preliminary data (and questions) concerning antiferromagnetic spintronics and the use of atomic-membrane materials as tunnel barriers

Spin Hall Effect (SHE)



In heavy metals, spin-orbit coupling can deflect electrons laterally in directions that depend upon their spin orientation.

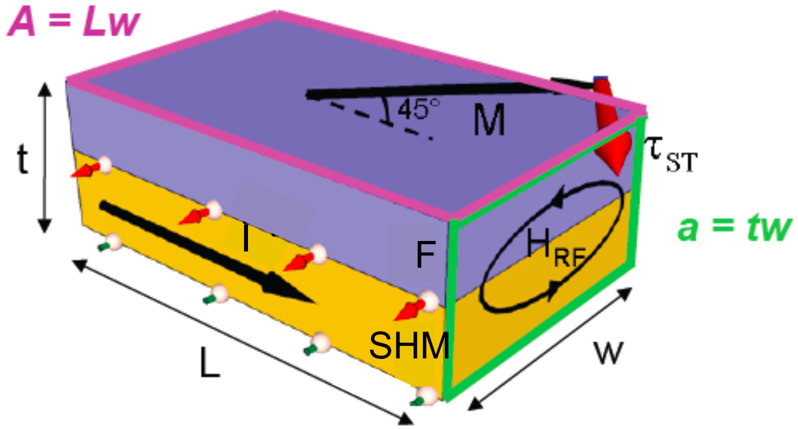
Result: a spin current transverse to the charge current.

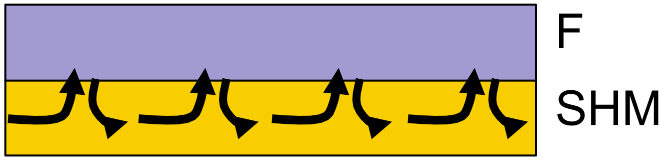
Spin Hall Ratio $$\theta_{SH} = \frac{J_S / (\hbar / 2)}{J_C / e}$$

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

The Spin Hall Effect Can Generate Much More Efficient Spin Torques than Simple Spin Filtering

In conventional spin torque devices using spin polarized currents, the efficiency of the torque can never exceed 1 unit of $\hbar/2$ per *e* of current





The efficiency of spin torque due to the Spin Hall Effect is (in units of $\hbar/2$ per *e*)

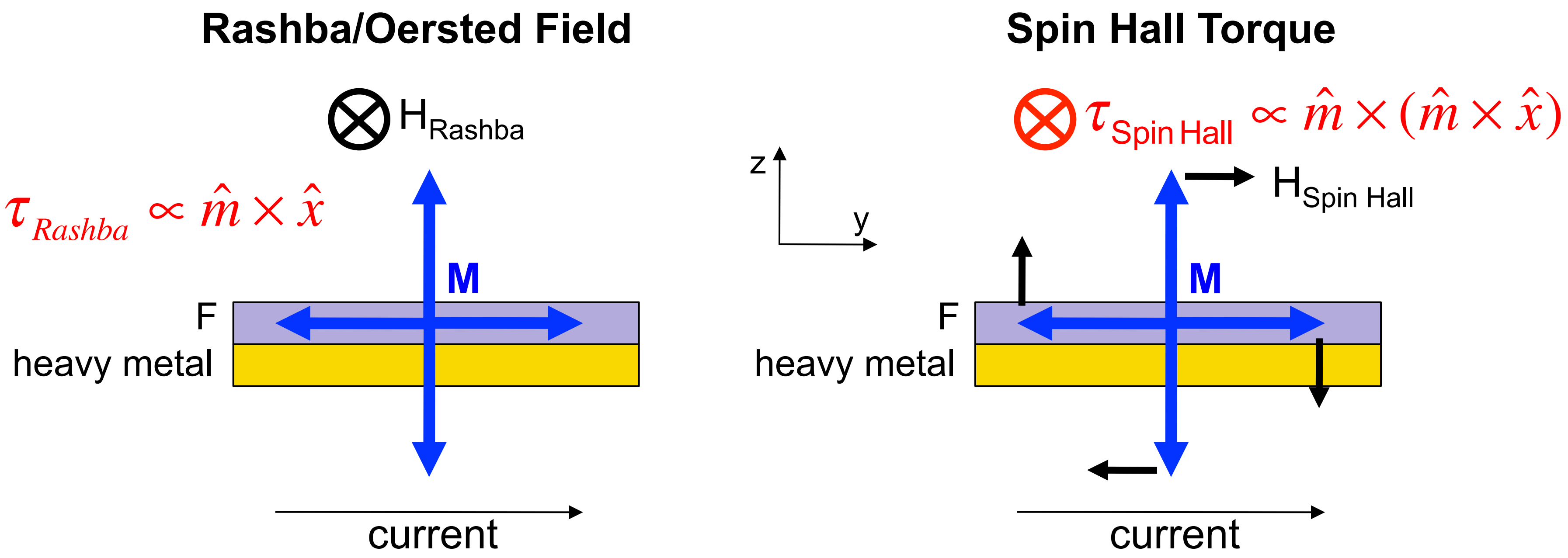
$$\frac{I_S}{I} = \frac{J_S A}{J_C a} = \theta_{SH}\frac{A}{a} = \theta_{SH}\frac{L}{t}$$

L ~ 50-100 nm
t ~ 2 nm

For θ_{SH} = 0.30 or more, I_S/I can be > 10 !

With the spin Hall effect, the traversal of one electron through the sample can transfer much more than $\hbar/2$ angular momentum to a magnet, since it can interact with the magnet many times.

Current-Induced Torques with Rashba/Oersted versus Spin Hall Symmetry



Rashba Symmetry: Effective field is in fixed direction, no anti-damping.
Spin Hall Symmetry: Spin torque is in fixed direction, equivalent field rotates, can give anti-damping.

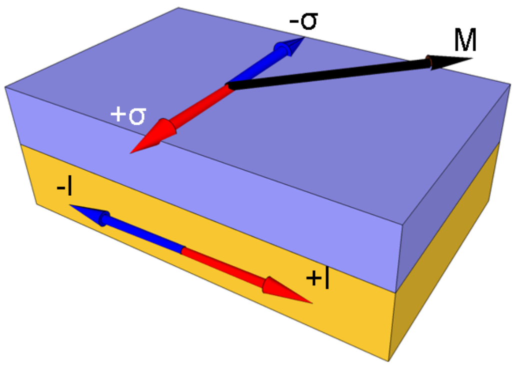
Magnetic manipulation by Rashba torque generally requires $\tau_{\text{Rashba}} \propto H_{\text{anis}}$

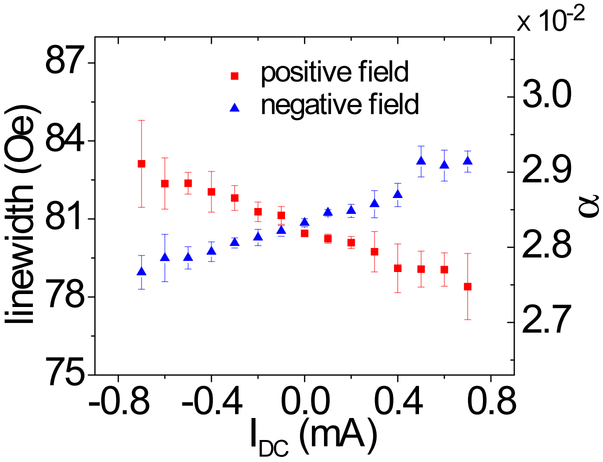
Magnetic manipulation by antidamping can happen when $\tau_{\text{Spin Hall}} \propto \alpha H_{\text{anis}}$ with α ~ 0.01, so the spin Hall symmetry is more important for applications.

Techniques for Measuring the Spin Torque from the Spin Hall Effect

These seem to be converging on reasonably consistent results for effective spin Hall angles if used carefully.

Current-dependence of FMR linewidth (K. Ando et al. PRL **101**, 036601 (2008))





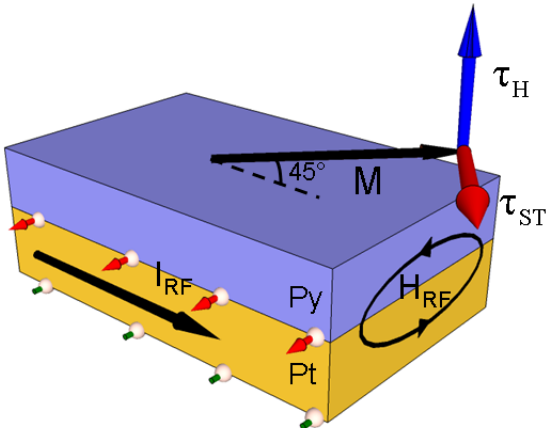
DC or non-resonant AC current-induced magnetization tilting, measured using anomalous Hall effect (L.-Q. Liu et al., PRL **109**, 096602 (2012), J. Kim et al., Nature Mater. **12**, 240 (2013), K. Garello et al., Nature Nanotech. **8**, 587 (2013), S. Emori et al. Nature Mater. **12**, 611 (2013))

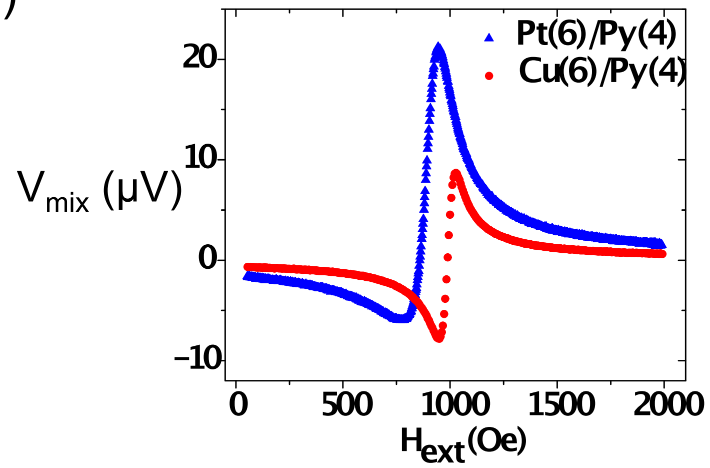
Need to be careful of both nonuniform magnetic states when perpendicular anisotropy is weak and also heating effects.

(Technique first used for Rashba field by Pi et al., APL **97**, 162507 (2010))

Techniques for Measuring the Spin Torque from the Spin Hall Effect

Spin-torque FMR amplitudes, resonant AC current drive with AMR-based readout (L.-Q. Liu et al., PRL **106**, 036601 (2011))





Spin Hall torque → in plane torque τ_{ST} → symmetric resonance

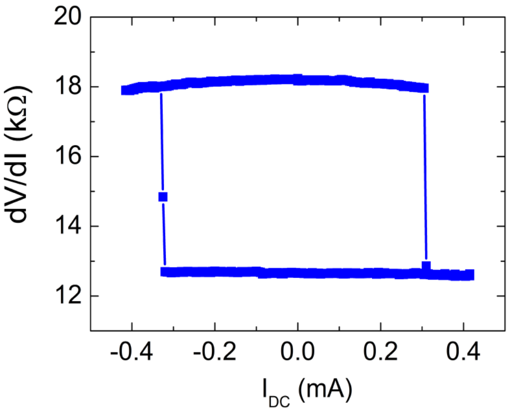
Oersted/Rashba → perpendicular torque τ_H → antisymmetric

Cautions:

- Don't assume the perpendicular torque is due only to the Oersted field.
- Spin-pumping + ISHE can alter the results when the ferromagnet is very thin and the spin Hall metal has low resistivity compared to the ferromagnet.

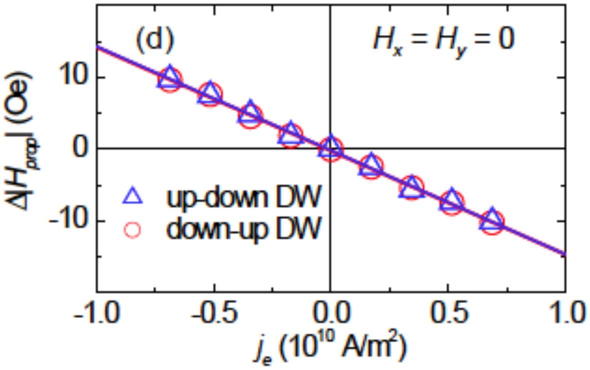
Techniques for Measuring the Spin Torque from the Spin Hall Effect

Critical currents for magnetic switching driven by the spin Hall effect
(L. Q. Liu et al., Science **336**, 555 (2012)

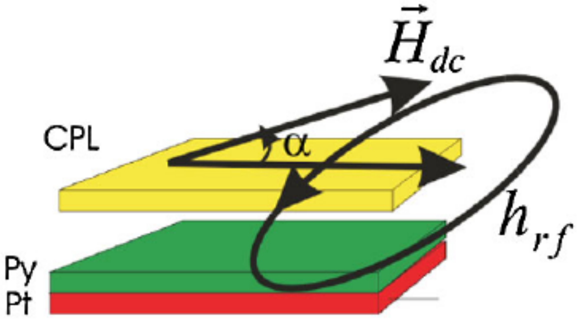


$$J_c \approx \frac{2e}{\hbar}\frac{\alpha}{\theta_{SH}} M_S t_F \left(H + \frac{M_{eff}}{2\mu_0} \right)$$

Equivalent field for current-driven domain wall motion
(S. Emori et al. arxiv/1308.1432)



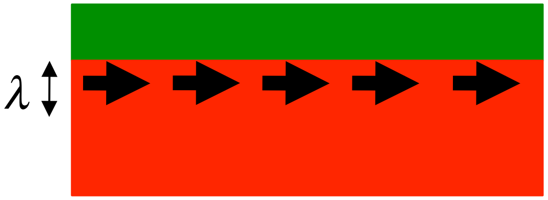
Measuring θ_{SH} Using Spin Pumping + Inverse SHE (Argonne Group and others)



O. Mosendz et al.
PRL **104**, 046601 (2010),
PRB **82**, 214403 (2010)
θ_{SH} ~ 0.013 for Pt
(compared to our value of 0.07)

Magnetically-excited Py precession produces DC voltage :

Symmetric resonance component due to spin pumping signal + ISHE
Antisymmetric component due to AMR



J_C is generated in a surface layer

$$\theta_{SH} \propto \frac{V_{symmetric}}{\lambda}$$

Mosendz et al. originally assumed
λ = 10 nm.
Better agreement with λ ~ 1.5 nm.

Still disagreement about θ_{SH} for Ta.

I suggest care is needed in accounting for spin backflow.

Need to measure $G_{\uparrow\downarrow}^{eff}$ and λ to know θ_{SH}.

In spin pumping,

$$G_{\uparrow\downarrow}^{eff} = G_{\uparrow\downarrow}^{bare}\left(\frac{\sigma/\lambda}{G_{\uparrow\downarrow}^{bare} + \sigma/\lambda}\right) \approx \sigma/\lambda \ll G_{\uparrow\downarrow}^{bare} \quad \text{for Ta}$$

Should We Be Accounting for Spin Backflow (in the opposite direction) in Spin Torque Experiments?

We have assumed for simplicity that all of the transverse spin current generated by the spin Hall effect is absorbed by the ferromagnet. Our value of θ_{SH} is really a lower bound for the value within the heavy metal.

In analogy with the theory of spin pumping, one might expect the fraction of the spin current absorbed by the ferromagnet to be

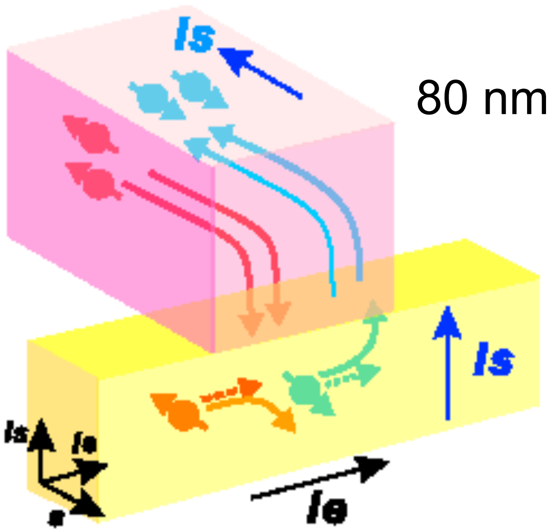
$$\frac{G_{\uparrow\downarrow}^{bare}}{G_{\uparrow\downarrow}^{bare} + (\sigma / \lambda)} \leq 1$$

where $G_{\uparrow\downarrow}^{bare}$ is the bare mixing conductance and σ / λ is the effective spin conductance of the spin Hall metal.

These parameters can be measured using spin pumping experiments. For β-Ta and β-W, σ is so small that I expect small corrections. However, for Pt our value for θ_{SH} may be significantly lower than the true intrinsic value.

$\sigma_{Pt} / \lambda \approx 8 \times 10^{19}\ \mathrm{m}^{-2}$ $\sigma_{\beta-Ta} / \lambda \approx 1 \times 10^{19}\ \mathrm{m}^{-2}$ $\sigma_{\beta-W} / \lambda \approx 0.7 \times 10^{19}\ \mathrm{m}^{-2}$

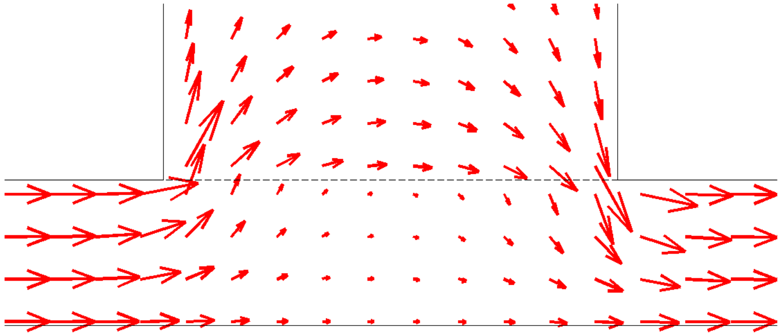
Method of Kimura et al.: Lateral Spin Diffusion



80 nm thick Cu

4 nm thick Pt

100 nm junction width

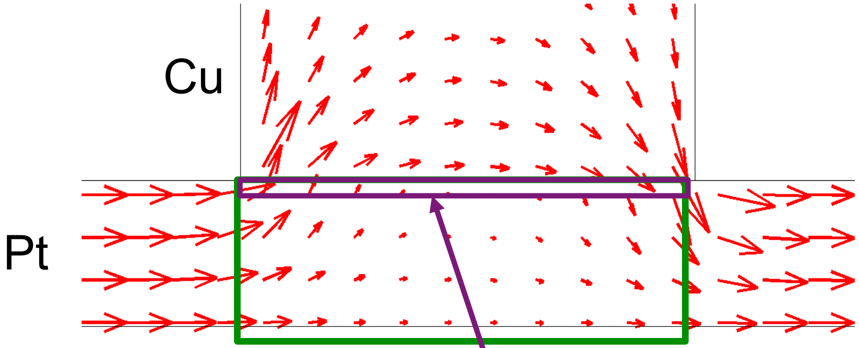


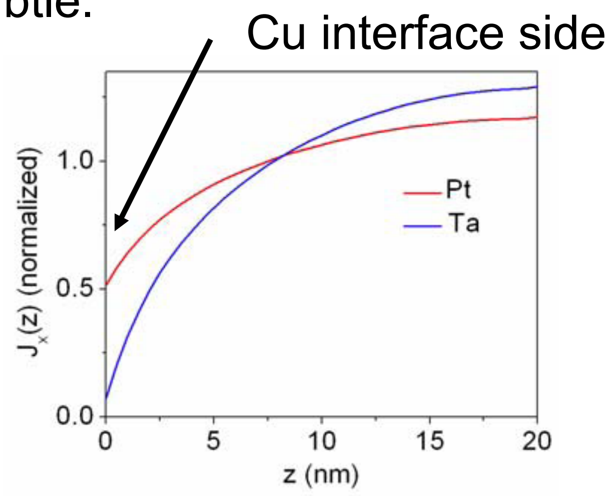
T. Kimura et al.
PRL **98**, 156601 (2007)
θ_{SH} ~ 0.0037 for Pt
(later revised)

The Cu shunts most of the charge current, so the charge current density in the Pt was much smaller than assumed.

Method of Kimura et al.: Lateral Spin Diffusion

Correcting for this shunting is surprisingly subtle.





The 1-d model correction employed by Otani group effectively averages the lateral component of the charge current density over the whole thickness of the Pt.

But really, only the region within a spin diffusion length of the Cu should matter.

The 1-d correction produces large errors for spin Hall metals with high resistivities and short spin diffusion lengths.

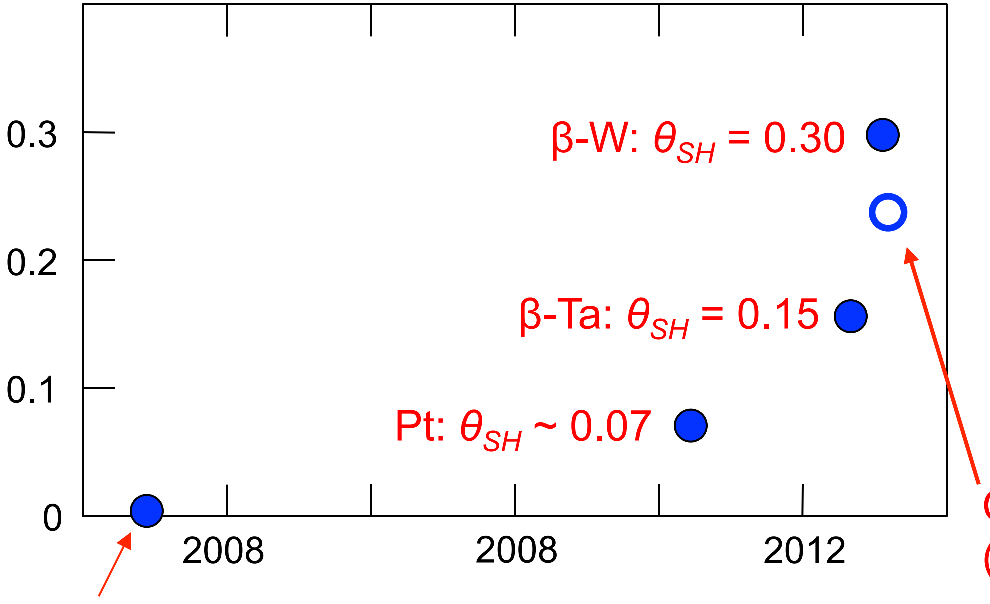
Otani group is now using full 3-d modeling, but the results depend on the transparency of the interface which is difficult to measure.

Measured Effective Spin Hall Angles, Results to Date

(no spin backflow corrections included)

$$\left|\theta_{SH}\right| = \frac{J_S}{J_C}$$

(dimensionless)



β-W: θ_{SH} = 0.30

β-Ta: θ_{SH} = 0.15

Pt: θ_{SH} ~ 0.07

Cu(Bi): θ_{SH} = 0.24 (Otani group)

first claim for Pt: θ_{SH} = 0.0037 (Kimura et al.), later revised

Our values confirmed by multiple techniques:

- ST-FMR amplitude
- ST-FMR linewidth vs. I
- Tilting of M by DC current
- Critical currents for switching

Liu et al., Phys. Rev. Lett. **106**, 036601 (2011)
Liu et al., Science **336**, 55 (2012)
Pai et al., Appl. Phys. Lett. **101**, 122404 (2012)

How Do These Values Compare to ab Initio Theory?

We don’t have apples-to-apples comparisons yet.
Tanaka et al. (Phys. Rev. B 77, 165117 (2008)) calculated intrinsic spin Hall conductivities for Ta and W, but for bcc, not the high-resistivity β structures, and the predictions depend on a quasiparticle damping rate parameter.

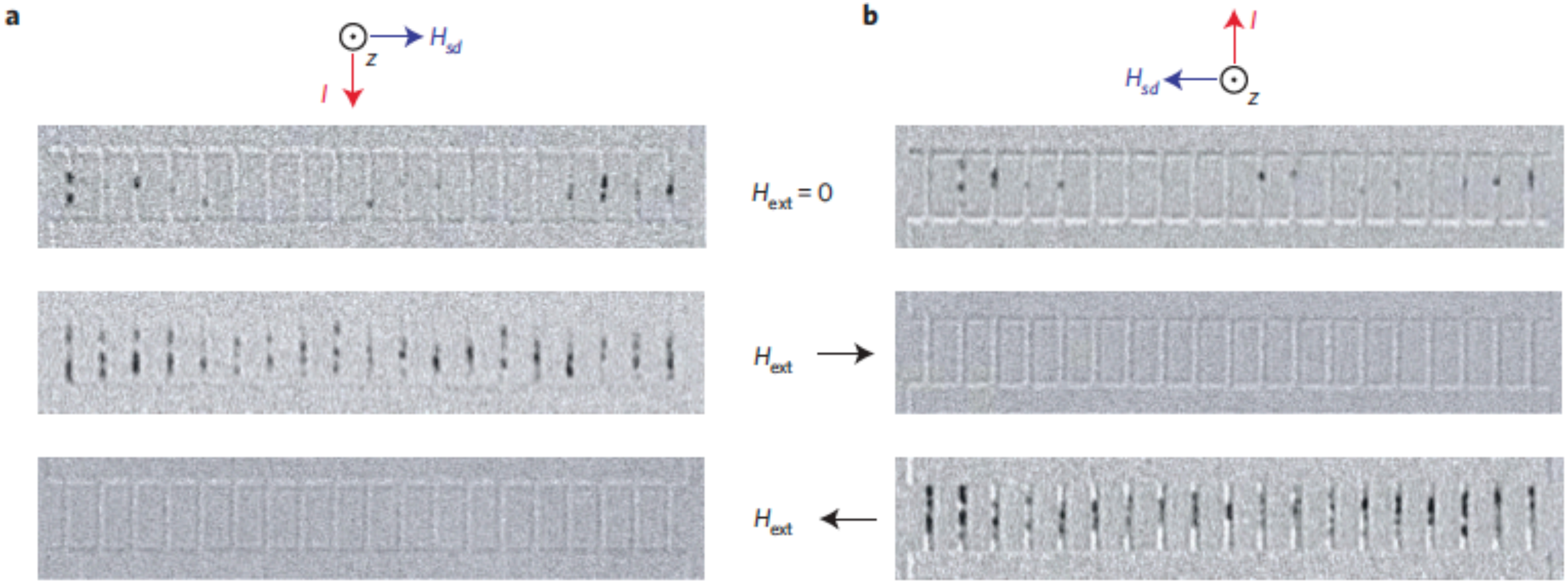
Spin Hall conductivities = $\theta_{SH}\sigma$

		Measured		Tanaka et al.
Pt		$3.4 \times 10^3\ (\Omega\mathrm{cm})^{-1}$		$1 \times 10^3\ (\Omega\mathrm{cm})^{-1}$
Ta	(β form)	$-0.8 \times 10^3\ (\Omega\mathrm{cm})^{-1}$	(bcc)	$-0.06 \times 10^3\ (\Omega\mathrm{cm})^{-1}$
β-W	(β form)	$-1.8 \times 10^3\ (\Omega\mathrm{cm})^{-1}$	(bcc)	$-0.07 \times 10^3\ (\Omega\mathrm{cm})^{-1}$

Still very early days in terms of achieving quantitative understanding.

Current-Induced Effective Fields with Rashba Symmetry?

First experimental suggestion, Miron et al., Nature Mater. **9**, 230 (2010).



Inferred H_{eff} = 1.0 T at j = 10^8 A/cm^2, which is a huge effective field (60x the spin Hall strength!)

Contradicted later by direct measurements (Liu et al., PRL **109**, 096602 (2012), Emori et al., Nature Mater. **12**, 611 (2013)) including new measurements by the original group (Garello et al. Nature Nanotech. **8**, 587 (2013).

But the effective Rashba field is not necessarily zero.

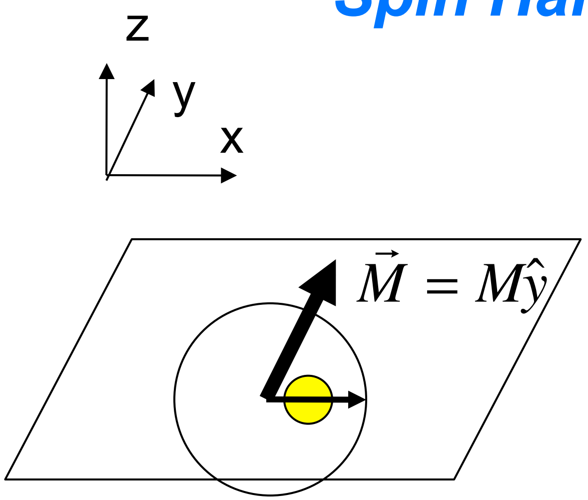
Current-Induced Effective Fields with Rashba Symmetry?

Recent measurements seem to indicate that the effective Rashba field is negligible for ferromagnetic layers thicker than 3-4 nm, but can grow to be comparable to or somewhat larger than the equivalent spin Hall field for very thin ferromagnets.

(Fan et al., Nature Comm. **4**:1799 (2013), Kim et al., Nature Mater. **12**, 240 (2013), Garello et al., Nature Nanotech. **8**, 587 (2013), Emori et al., Nature Mater. **12**, 611 (2013))

Simple possible explanation:
A short dwell time for spins that enter the ferromagnet.

Spin Hall Effect + Finite Spin Dwell Times



If a spin enters a magnet with a spin orientation

$$\vec{s}_{initial} = \hat{x}$$

and precesses for a time t_f before leaving the magnet or undergoing spin flip, its final orientation is

$$\vec{s}_{final} = \cos(\omega t_f)\hat{x} + \sin(\omega t_f)\,\hat{z}.$$

The spin transfer torque on the magnet is

$$\vec{\tau} = \vec{s}_{initial} - \vec{s}_{final}$$

$$\vec{\tau} = \left(1 - \cos(\omega t_f)\right)\hat{x} - \sin(\omega t_f)\hat{z}.$$

Averaging over an exponential distribution of lifetimes with an average $t_{d:}$

In-plane torque

$$\tau_x = \left[\frac{(\omega t_d)^2}{(\omega t_d)^2 + 1}\right]$$

Out-of-plane torque

$$\tau_z = -\left[\frac{\omega t_d}{(\omega t_d)^2 + 1}\right]$$

$$\left|\frac{\tau_z}{\tau_x}\right| = \frac{1}{\omega \tau_d}$$

Corresponds to an effective imaginary part of the bare mixing conductance.

Z. Li et al., PRL **100**, 246602 (2008)

Mechanism?: Bulk spin Hall in the Heavy Metal vs. Rashba in the Ferromagnet vs. Interface Effects?

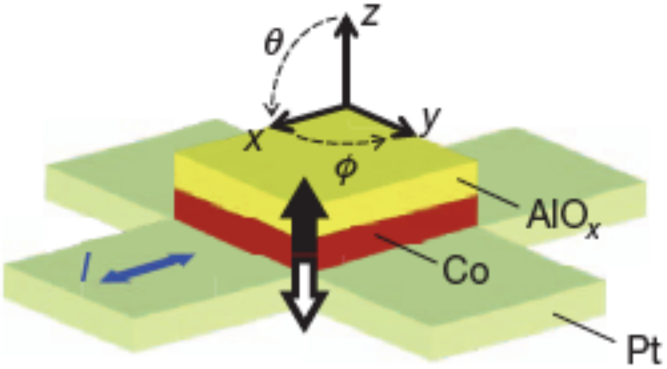
If there is a short dwell time in the ferromagnet, it is not possible to distinguish between different mechanisms based on symmetry alone, but they can be distinguished via other experimental tests.

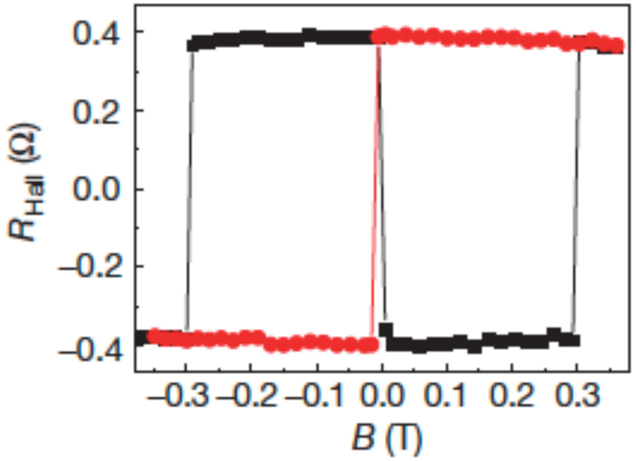
- Insert spacer layer between the heavy metal and the ferromagnet (Fan et al., Nature Comm. **4**:1799 (2013), Cornell group)
- Dependence on thickness of the ferromagnet
- Do different ferromagnets yield the same value of θ_{SH}?

Switching of Magnets with Perpendicular Anisotropy Using In-Plane Current

First observation: Pt/Co/AlO$_x$ multilayer, I. Miron, P. Gambardella, et al.

Nature **476**, 189 (2011)



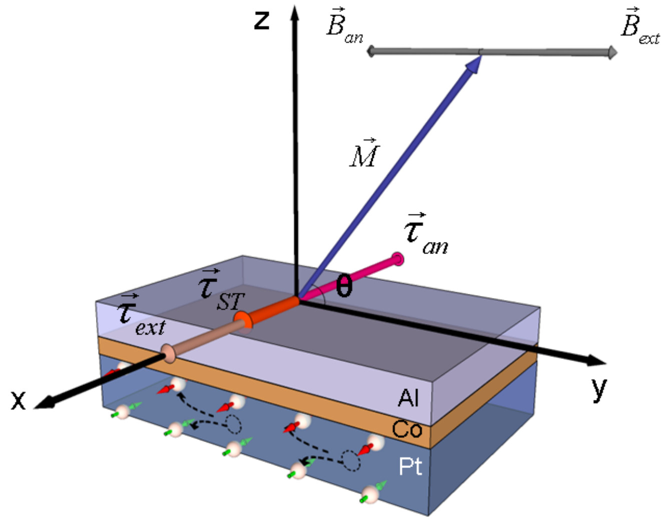


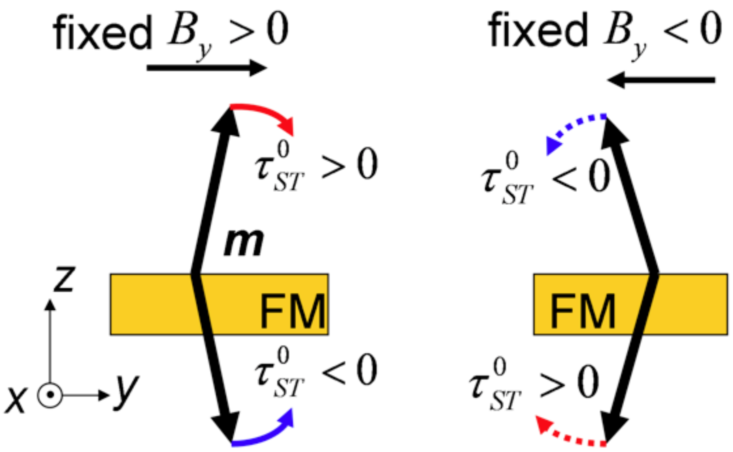
Miron et al.’s proposed explanation: Spin-orbit-induced out-of-plane Rashba field within the Co layer.

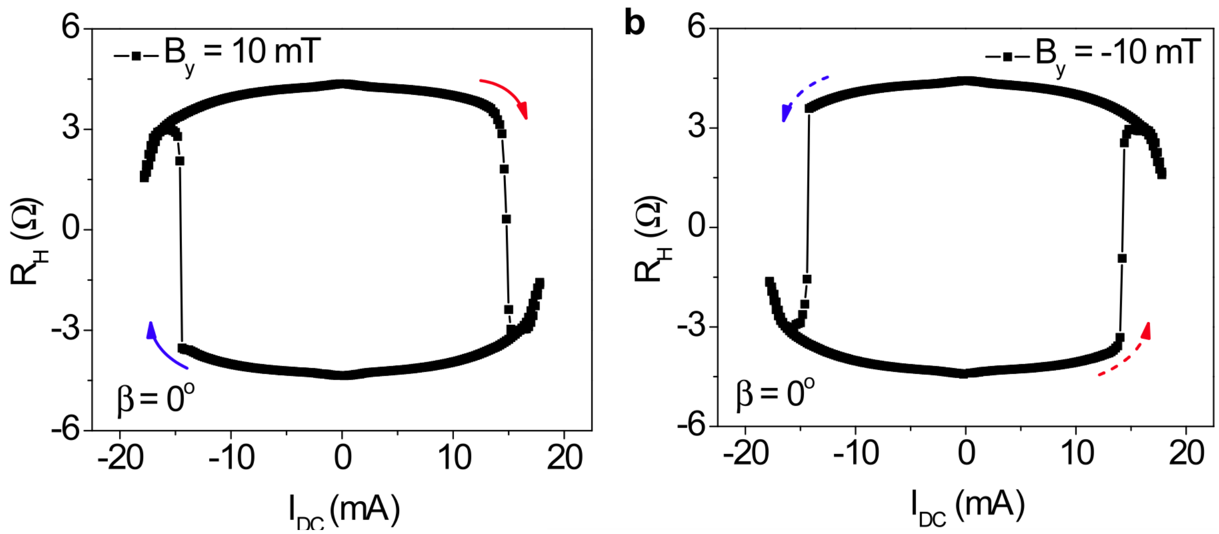
We argue: This switching can be explained quantitatively by the SHE from the Pt, and direct measurements do not show a very strong conventional in-plane Rashba field.

L. Q. Liu et al. *PRL* **109**, 096602 (2012).

SHE Switching of a Perpendicularly Magnetized Ferromagnet (Macrospin Cartoon)







J_s/J_c ratio from switching agrees with ST-FMR.

Liu et al., PRL **109**, 096602 (2012)

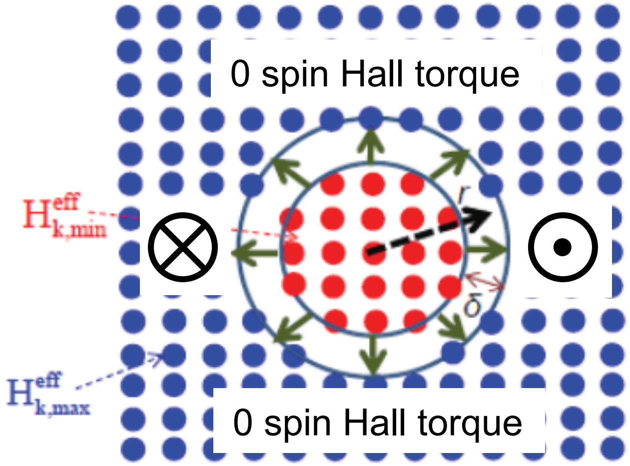
SHE Switching of a Perpendicularly Magnetized Ferromagnet (More Realistic Picture)

The perpendicularly-magnetized samples that have been studied are large, and reversal actually occurs by nucleation of domains + domain wall motion.

The spin Hall torque acts primarily to drive domain wall motion.

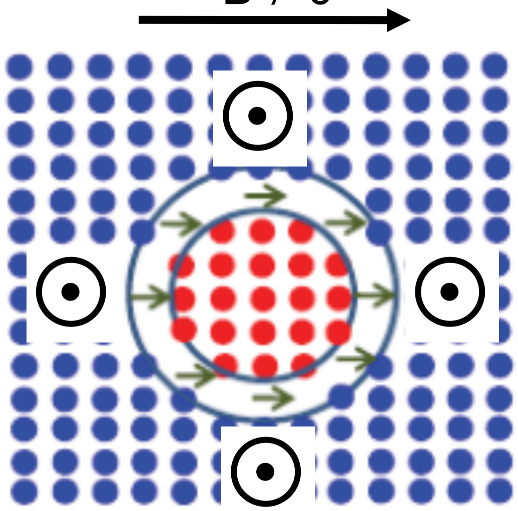
The in-plane magnetic field seems to act to overcome the DMI, aligning spins in the domain wall. This allows the spin Hall torque to expand or contract domains.

B = 0



Domain may shift, but not expand

B ≠ 0

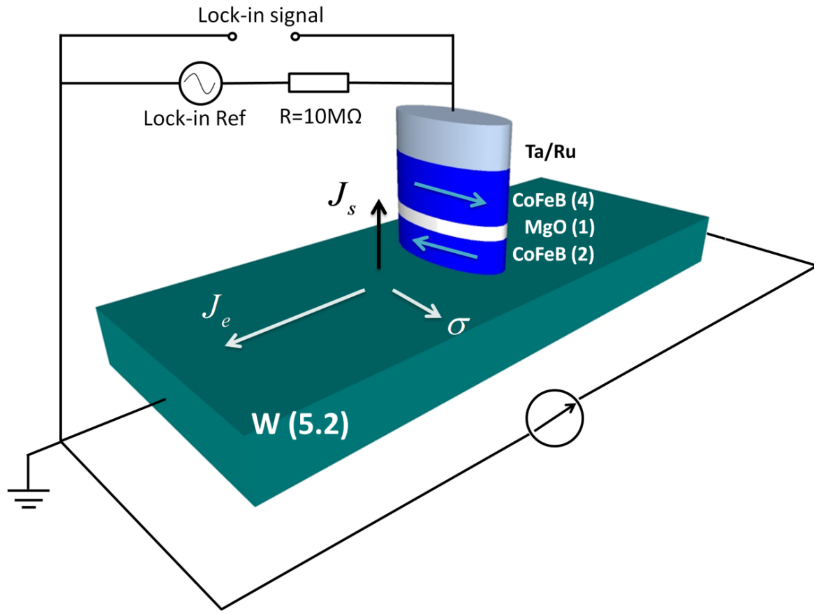


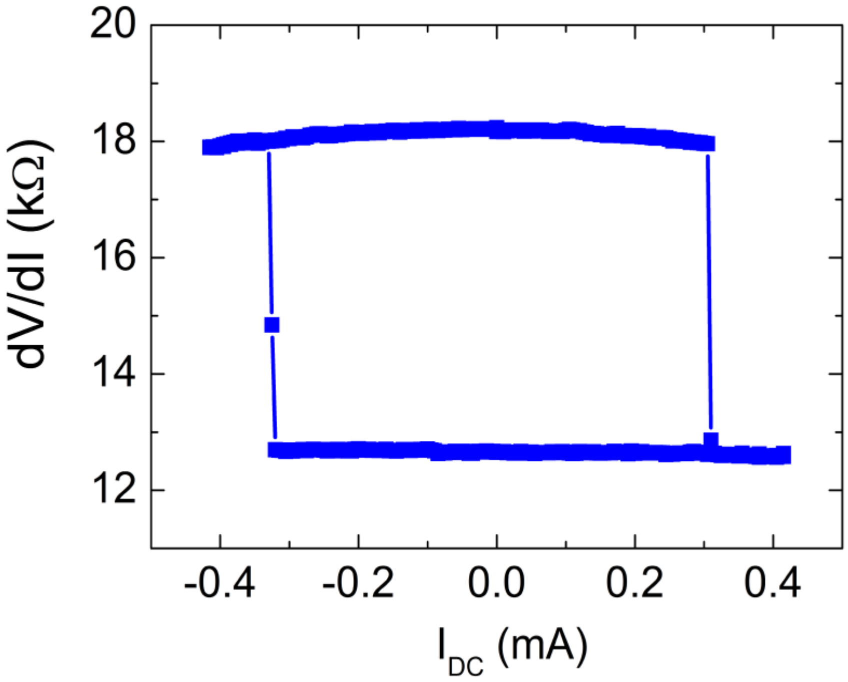
Domain will expand

Red = up, blue = down

O.-J. Lee et al., preprint

Switching of In-Plane-Polarized Magnetic Memory Devices Using Spin Hall Torque





β-W strip 1.2 μm wide

MTJ 80 × 300 nm^2

Geometry & magnetic anisotropy not yet optimized

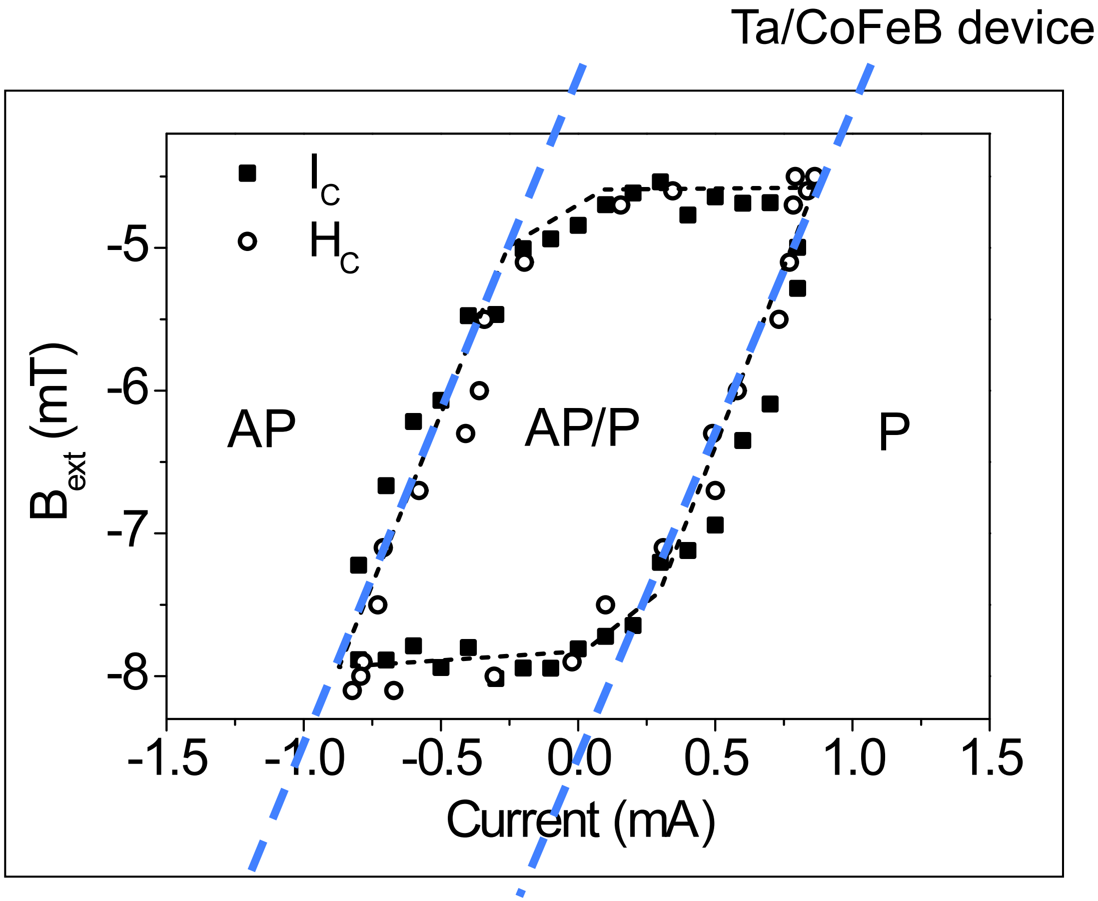
Critical current is in quantitative agreement with expectations for anti-damping switching with θ_{SH} = 0.3.

With controlled perpendicular magnetic anisotropy, I_c should scale well below 50 μA.

Expect $$J_c \approx \frac{2e}{\hbar}\frac{\alpha}{\theta_{SH}} M_S t_F \left(H + \frac{M_{eff}}{2\mu_0} \right)$$

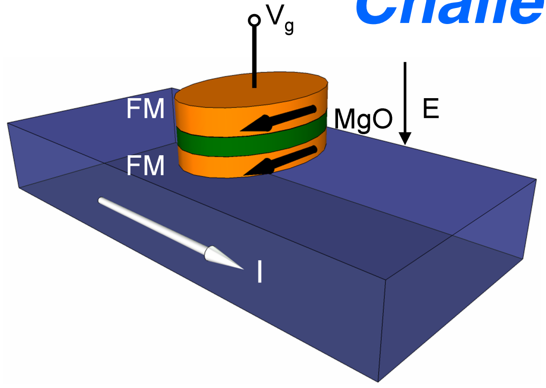
Liu et al., Science **336**, 55 (2012)
Pai et al., Appl. Phys. Lett. **101**, 122404 (2012)

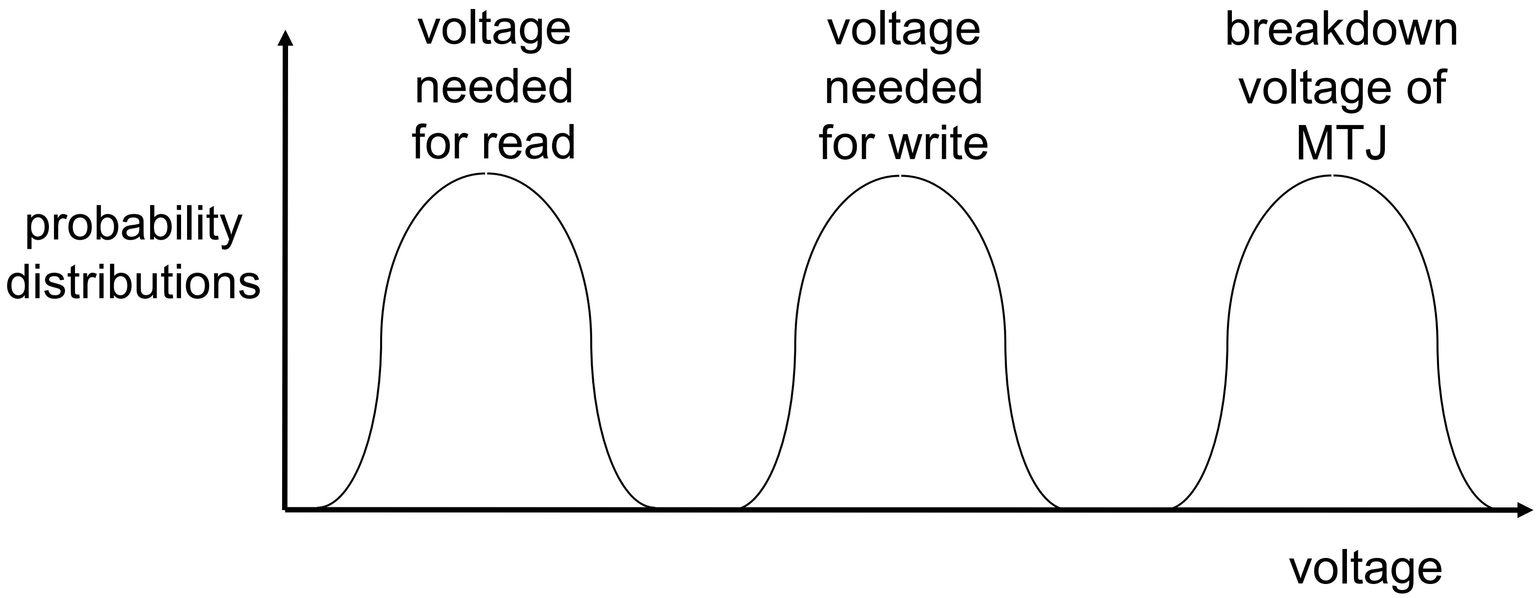
Switching Phase Diagram Indicates Spin Torque Switching



Consistent with anti-damping spin torque mechanism,
not an effective field mechanism

Spin Hall Torque Devices Solve Reliability Challenges As Well as Improving Efficiency

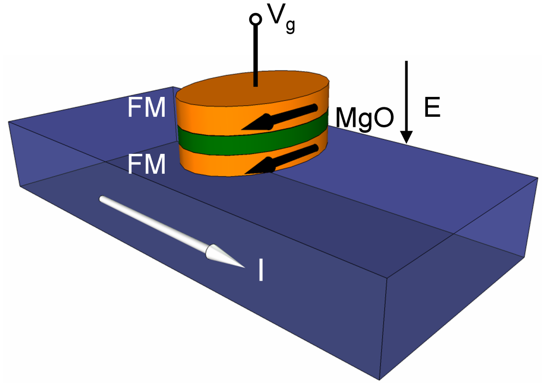




Therefore, no problem with read disturbs or tunnel-barrier breakdown.

New Engineering Possibilities: Gated Switching with the Spin Hall Torque

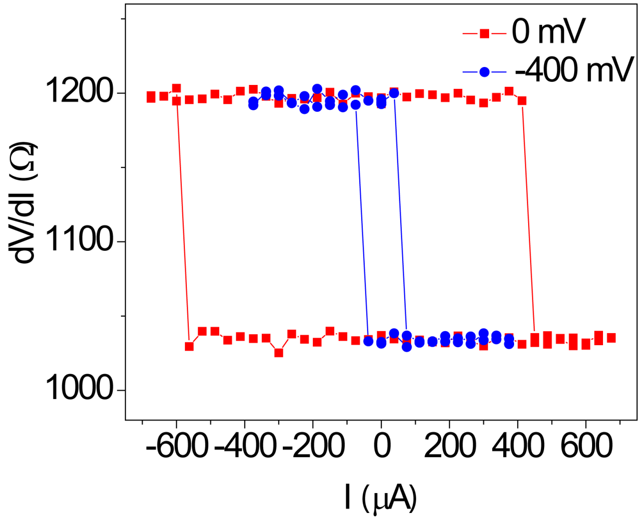
L. Liu et al., arXiv:1209.0962



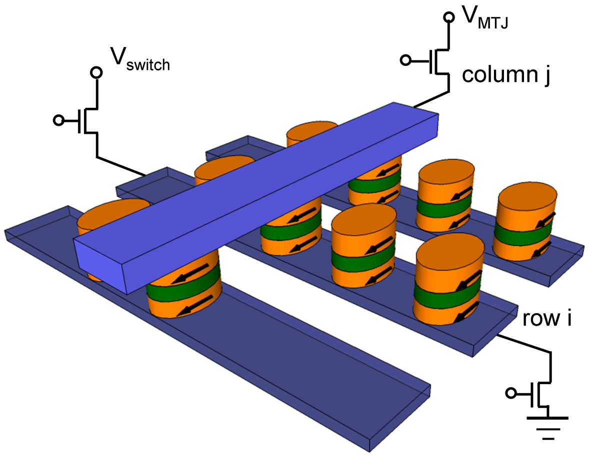
Voltage controlled magnetic anisotropy – by applying strong electric field to the surface of a very thin ferromagnet, can tune M_{eff} (e.g., Maruyama et al. Nature Nanotech. (2009)).

$$J_c \approx \frac{2e}{\hbar}\frac{\alpha}{\theta_{SH}} M_S t_F \left(H + \frac{\enclose{circle}{M_{eff}}}{2\mu_0} \right)$$

Can use in combination with the Spin Hall Torque to reduce the critical current for switching and enable a dense new architecture for memory.



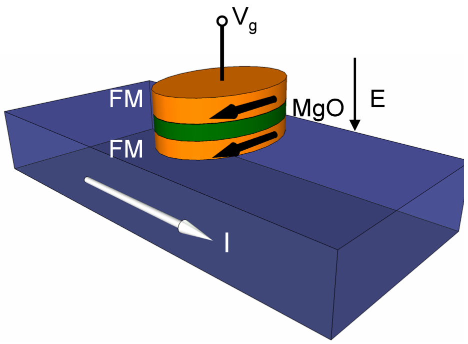
Big further reductions in switching currents and energy

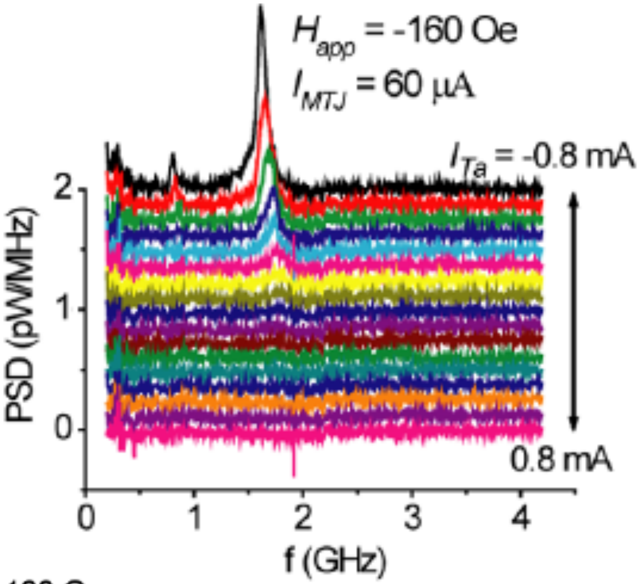


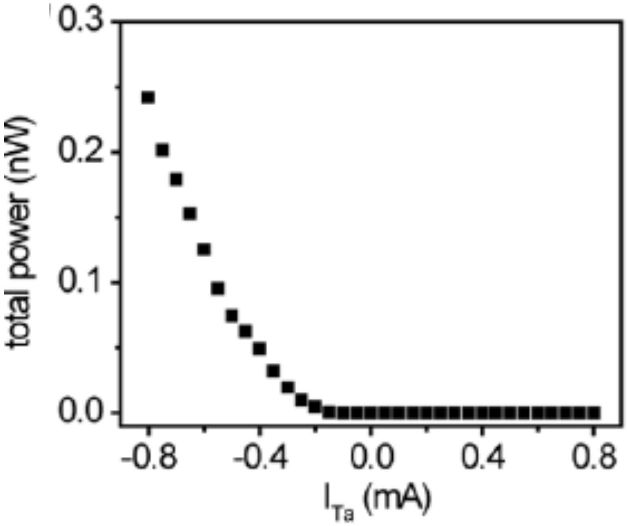
Bit selection in maximum-density crosspoint memory architecture

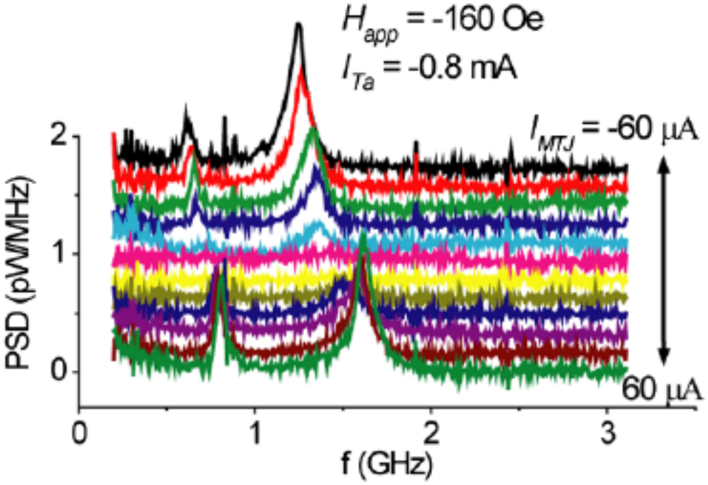
Magnetic Nano-Oscillators Driven by the SHE Torque

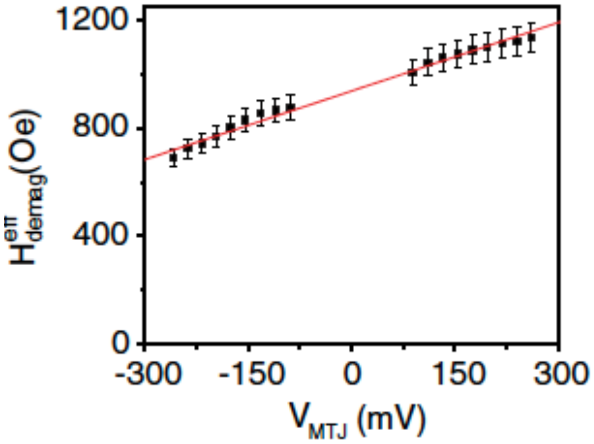
Liu et al., PRL **109**, 186602 (2012)











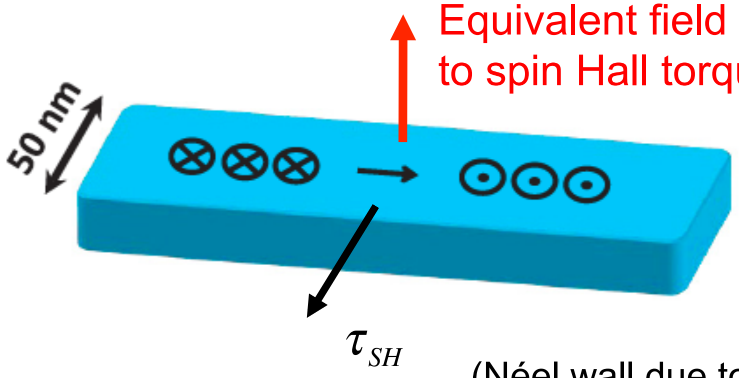
A bias across the MTJ tunes the frequency

Oscillations in YIG driven by the SHE torque observed by Kajiwara et al., Nature **464**, 262 (2010)
Oscillations in metallic ferromagnet observed independently by Demidov et al., Nature Mater. **11**, 1028 (2012)

Spin Hall Manipulation of Magnetic Domain Walls

A. Thiaville et al., Europhys. Lett. **100**, 57002 (2012)
P. P. J. Haazen et al., Nature Mater. **12**, 299 (2013)
A.V. Khvalkovskiy et al., Phys. Rev. B **87**, 020402(R) (2013)
S. Emori et al., Nature Mater. **12**, 611 (2013)
K. S. Ryu et al., Natue Nanotech. **8**, 527 (2013)

Spin Hall effect allows efficient manipulation of Néel walls in samples with perpendicular magnetic anisotropy.



Equivalent field corresponding to spin Hall torque

(Néel wall due to Dzyaloshinskii-Moriya interaction)

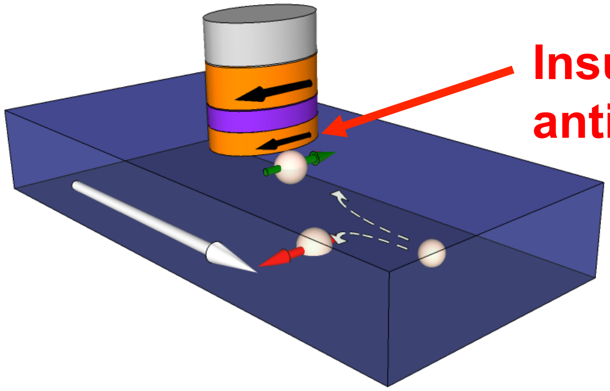
Can explain the observations of Miron et al. (Nature Mater. **9**, 230 (2010)) of unusually fast domain wall movement against the direction of current flow.

(picture adapted from Khvalkovskiy et al.)

Topics Under Development

The SHE can provide the ability to manipulate ferromagnetic or antiferromagnetic **insulators**:

- 100x lower intrinsic energy loss rates than magnetic metals
  (however, similar damping due to spin pumping?)
- internal fields in AFs that can give 100-1000x faster dynamics



Insulating ferromagnet or antiferromagnet?

Potentially much more energy efficient and faster devices

Kajiwara et al., Nature **464**, 262 (2010); many recent experiments on spin pumping from YIG and current-induced tuning of damping in YIG

Open Questions (Please Help)

What materials might provide even more efficient spin Hall torque manipulation of magnetic devices? Ideally, want:

- Large spin Hall angle
- Short spin diffusion length
- Little additional damping (due to spin pumping) for an adjacent ferromagnet
- Large spin mixing conductance for magnetic interface
- Low resistivities

What mechanism(s) (intrinsic or extrinsic) are the most promising for large spin Hall effects?

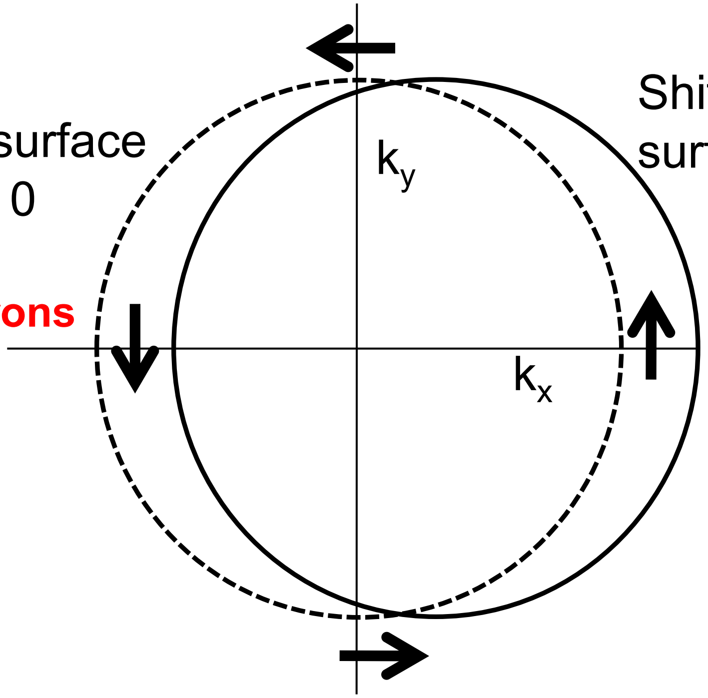
To what extent are the spin Hall angle, spin diffusion length, spin-pumped damping, spin mixing conductance, interface anisotropy, resistivity, and VCMA, coupled, and to what extent can they be tuned independently?

When might proximity-induced magnetic moments matter?

Are there differences in spin torque applied at insulating interfaces, compared to metallic ferromagnets, or does one parameter ($G_{\uparrow\downarrow}$) describe everything?

A Possible Mechanism for Generating Spin Torques Using Topological Insulator Surface States

Edelstein Effect



Fermi surface
for V = 0

Shifted Fermi
surface for V ≠ 0

Fewer down electrons

More up electrons

No net change in the in-plane net spin current, but charge flow should generate a non-equilibrium spin accumulation at the surface. If these spins couple to an adjacent ferromagnet, they could apply a strong spin transfer torque.

near Dirac point: Garate and Franz, PRL **104**, 146802 (2010).
away from Dirac point: Burkov and Hawthorn, PRL **105**, 066802 (2010); Culcer et al., PRB **82**, 155457 (2010); Pesin and MacDonald, Nature Mater. **11**, 409 (2012).

The Correct Way to Investigate This


insulating ferromagnet

topological insulator

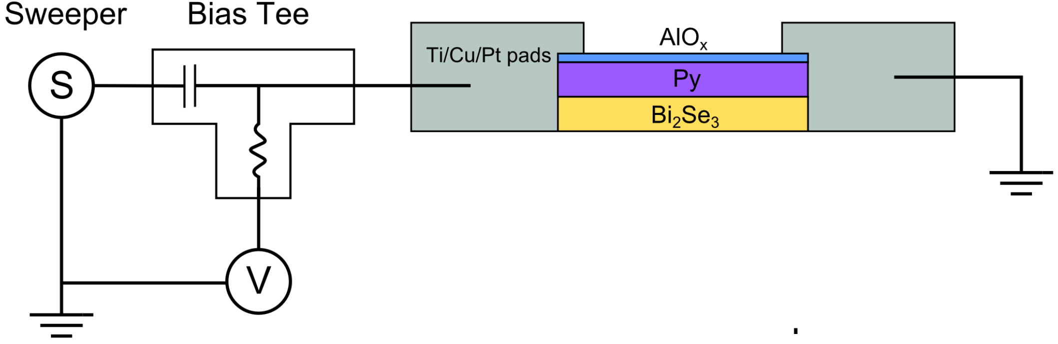
Use bilayer of a topological insulator with an <u>insulating</u> ferromagnet.

A metallic ferromagnet will shunt the TI and may change its conductivity so it is hard to estimate the current flowing in the TI.

We are working to grow insulating ferromagnets on Bi_2Se_3 and vice versa, but we can't do this quite yet.

In the mean time, we tried a quick-and-dirty experiment with metallic permalloy.

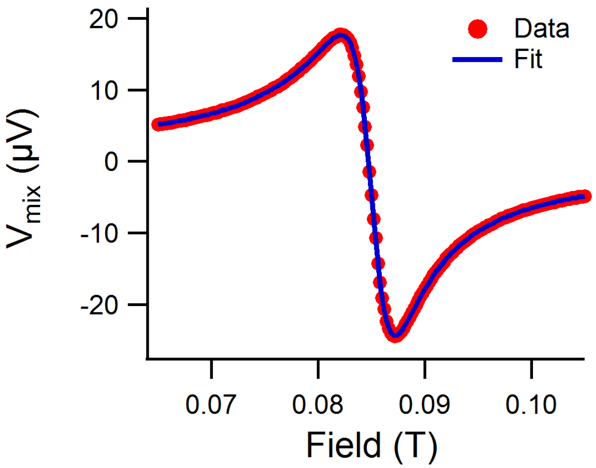
ST-FMR Measurement of Spin Torque from Bi$_2$Se$_3$

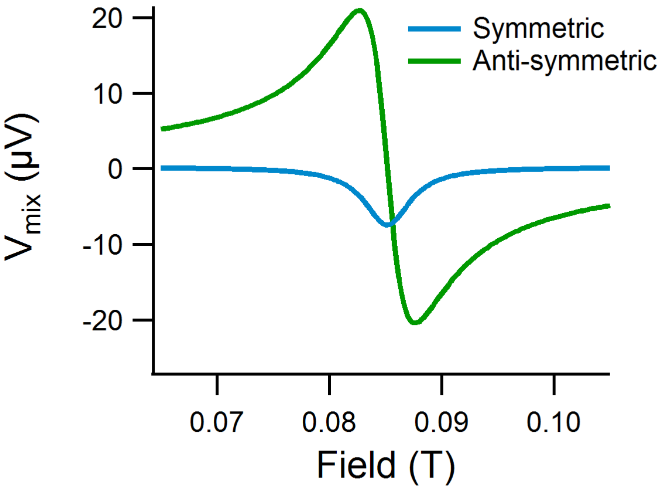


ρ_{Bi2Se3} = 1.5 mΩ cm

ρ_{Py} = 45 μΩ cm

(factor of about 30 diff.)

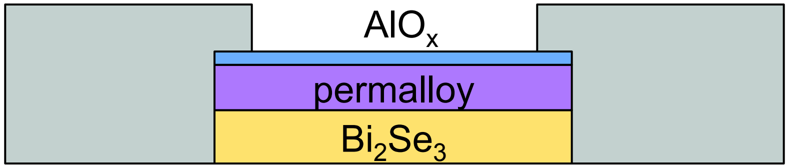




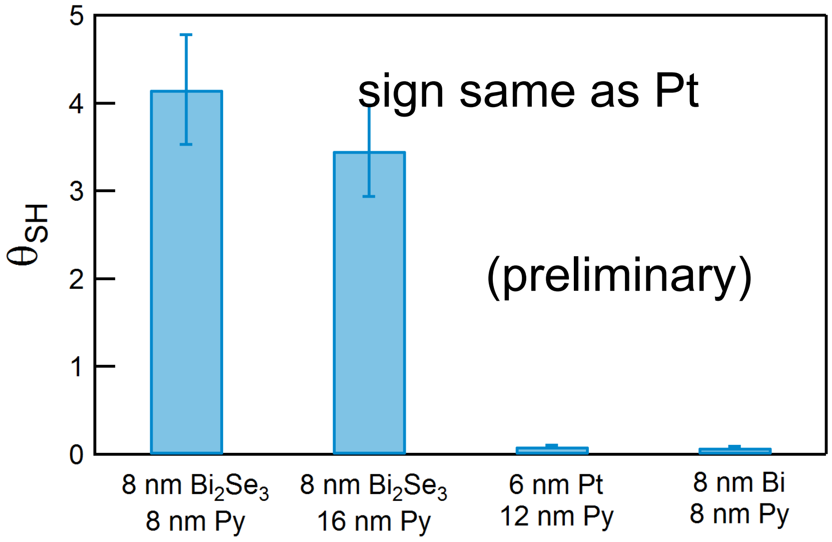
By fitting we can determine both the in-plane (like Spin Hall) and out-of-plane (like Rashba) components of current-induced spin torque.

The current dependence of the damping provides a consistent independent measure of the in-plane (like spin Hall) torque.

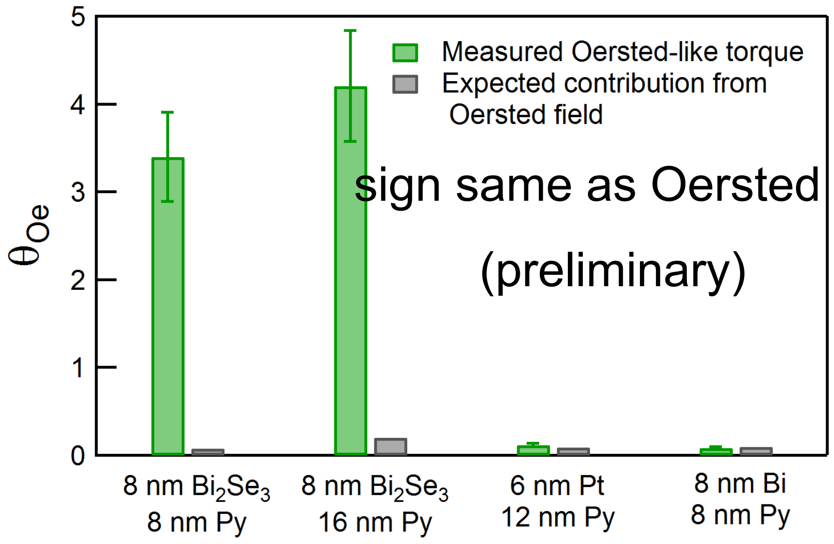
Helical Surface States as Sources for Spin Hall Torque?



In-Plane Spin Torque



Out of Plane Spin Torque



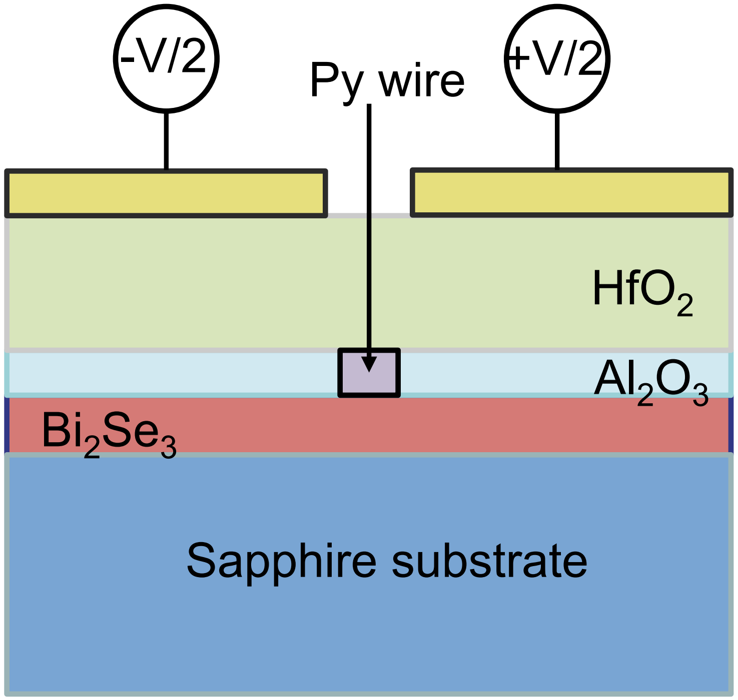
Very large spin Hall angles, for both components of torque

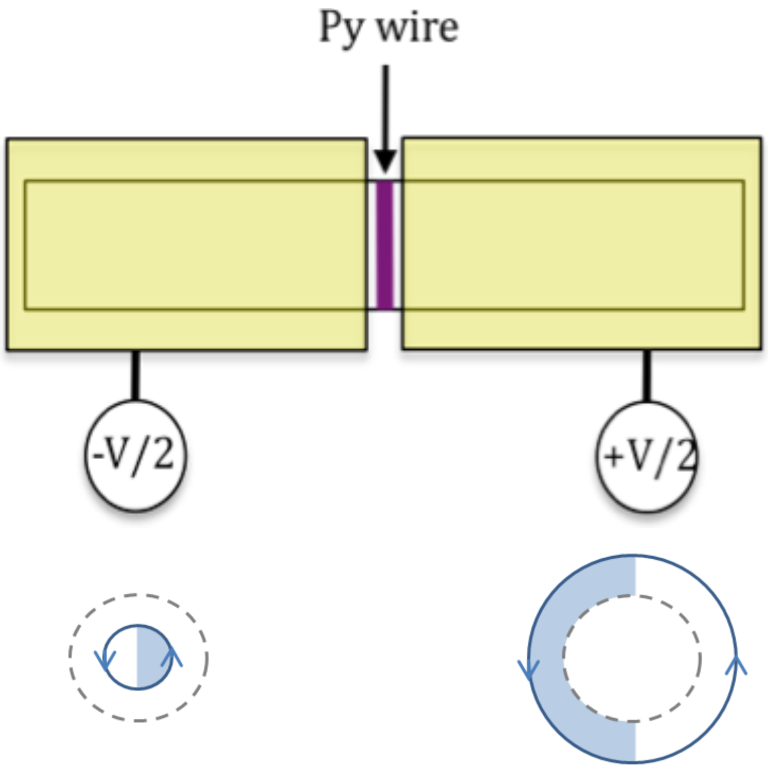
(in qualitative agreement with calculations by Fischer, Vaezi, Manchon, and Kim, arXiv:1305.1328)

But right now we don’t have proof to distinguish surface and bulk mechanisms.

Spin Torque from In-Plane Spin Currents in TIs?

(suggested by Charlie Kane)



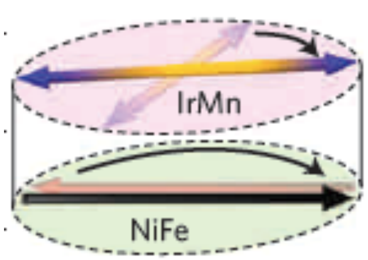


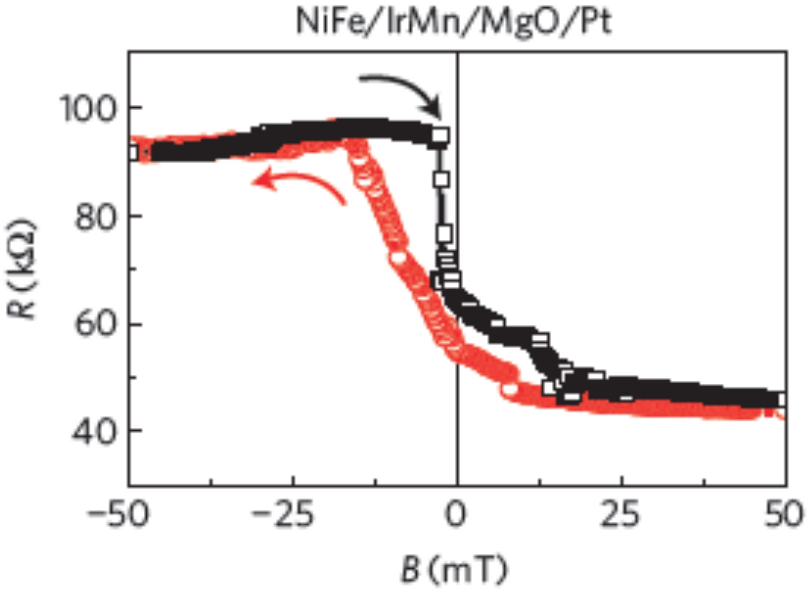
Idea: spatial gradient in chemical potential should induce a net spin current on the permalloy, giving a spin torque.

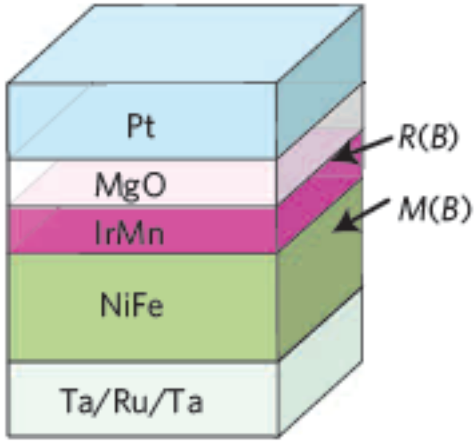
Question: For DC gate voltages, these should be equilibrium spin currents, so they should not be able to transfer energy to produce anti-damping. Is there a fundamental difference between the interactions of a ferromagnet with equilibrium and non-equilibrium spin currents?

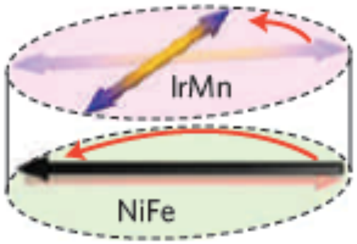
Antiferromagnetic Spintronics

Jungwirth group (Nature Mater. **10**, 347 (2011)):







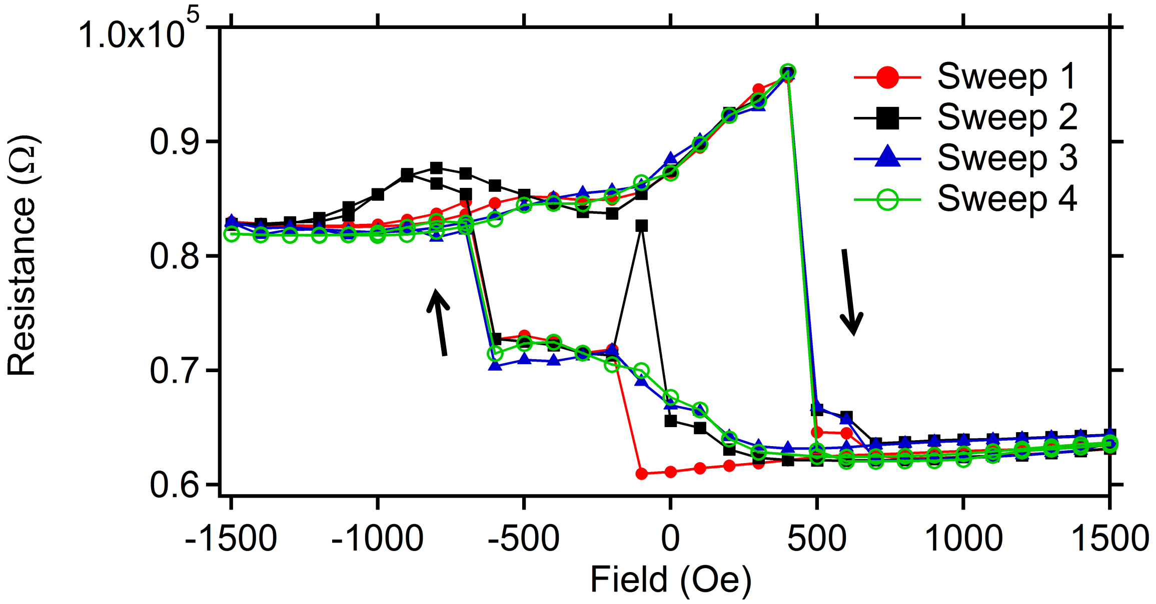


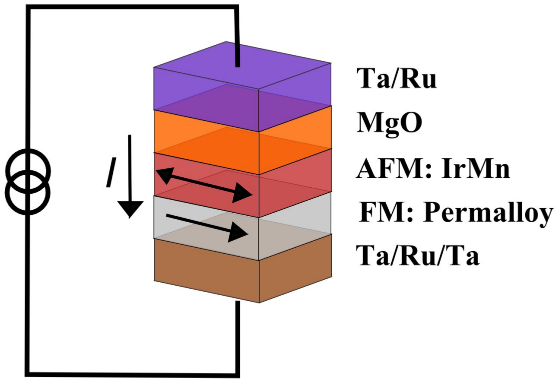
Very large (sometimes > 100%) magnetoresistance due to exchange-bias-induced rotation of moments in a tunnel-junction electrode made from antiferromagnetic IrMn.

Large effects are present only at low temperature.

Antiferromagnetic Spintronics

We can reproduce the effects seen by the Jungwirth group.





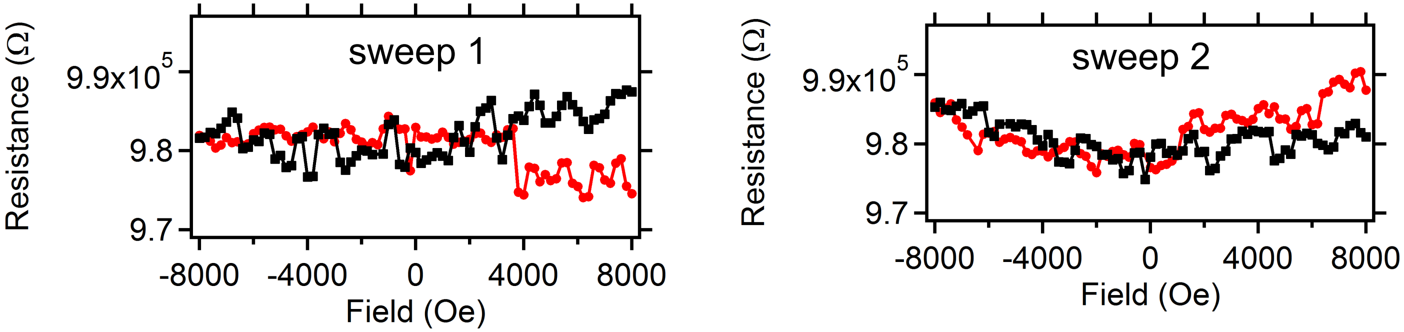
60 % MR at 4.2 K in a 9 x 3 μm^2 device, field in-plane

However, the existence of the effect has odd statistics for such a huge signal, and repeated scans in the same device show unexpected variations.

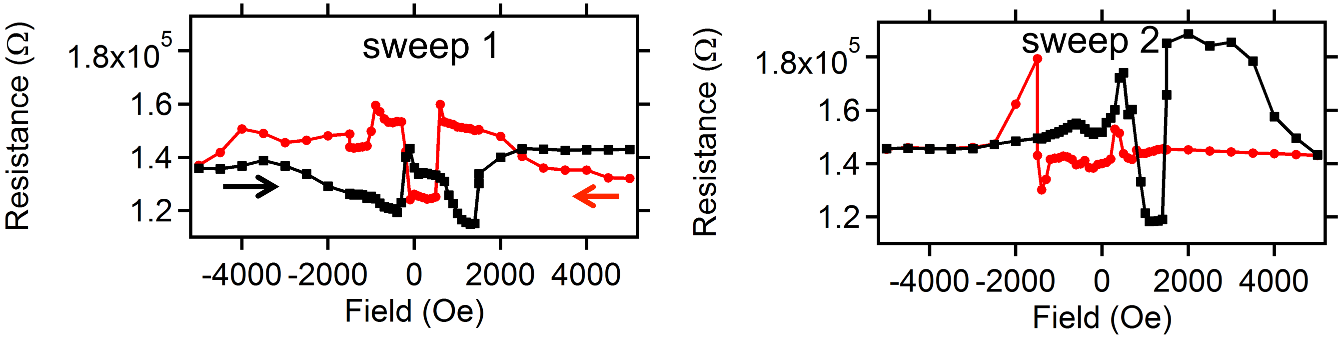
Antiferromagnetic Spintronics

Fewer than 10% of identically-prepared devices show large MR.

Most devices have scans like this (5 x 3 μm^2 device at 4.2 K):

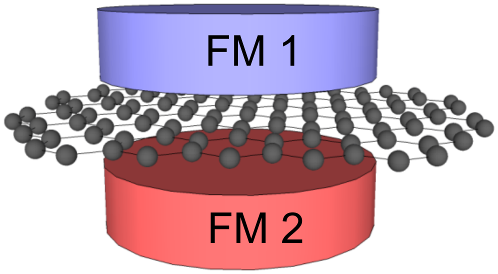


Others: (different 9 x 3 μm^2 device at 4.2 K)



Signals dominated by weak spots in tunnel barrier? Effects of strain? Why so strongly temperature dependent?

Graphene as a Tunnel Barrier for MTJs

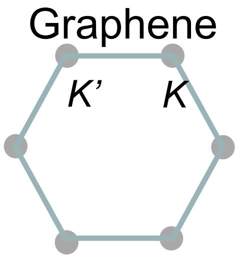


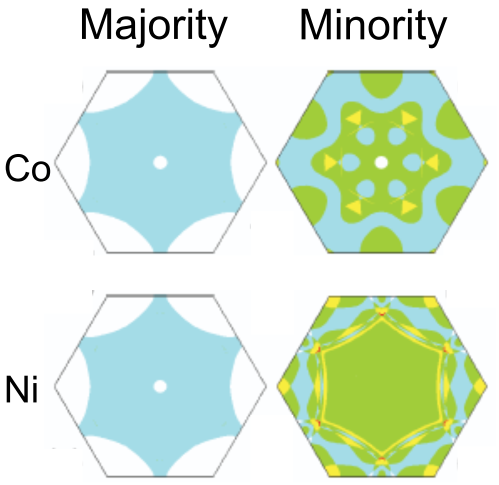
Potentially pinhole-free tunnel barrier 1 atom thick

Low RA product?

Predictions of large TMR for multi-layer graphene

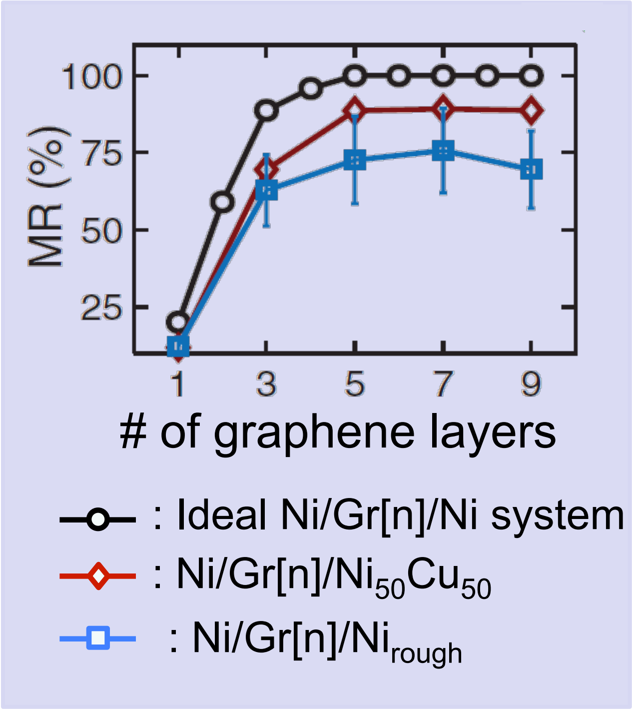
Predictions: V. M. Karpan,et al., PRL **99**, 176602 (2007)





Projected Fermi surfaces

spin filtering: minority transport should dominate near K, K' points

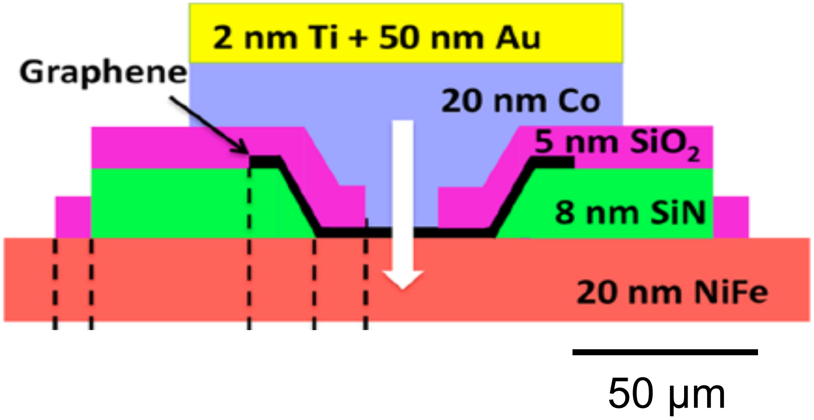


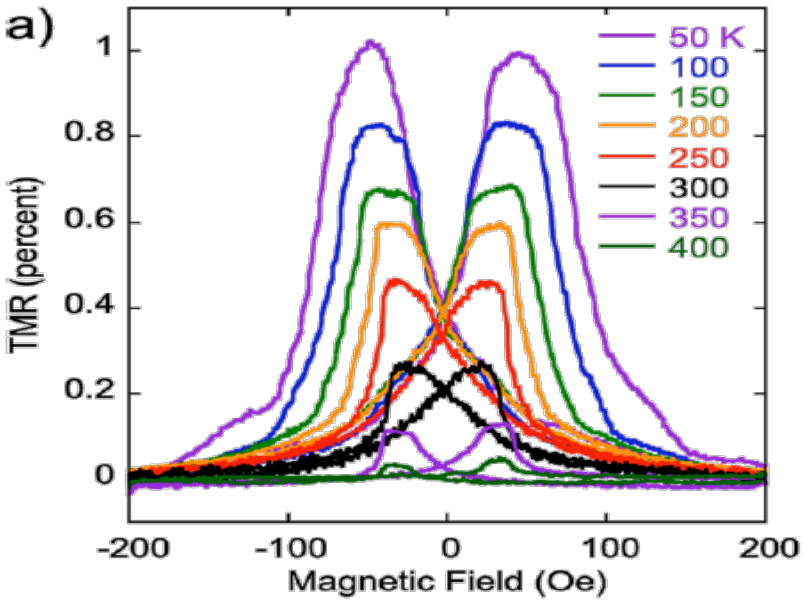
Graphene as a Tunnel Barrier for MTJs

Previous studies:

Mohiuddin et al., IEEE Trans. Magn. **44**, 2624 (2008), (Geim group)
E. Cobas et al., Nano Lett. **12**, 3000 (2012) (Jonker group)

In the previous work, one magnetic electrodes was always exposed to air (and sometimes immersed in water) to transfer graphene onto it.



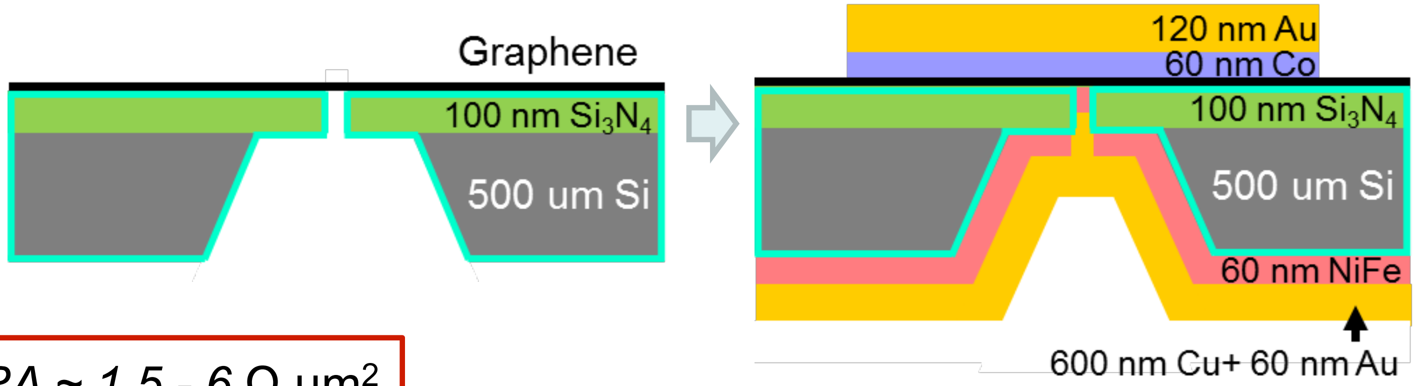


TMR: 2.0 % at 4K
0.3 % at room temperature

RA~35,000 -100,000 Ω μm^2 *vs.* 1.5 nm MgO: 10-100 Ω μm^2

Graphene as a Tunnel Barrier for MTJs

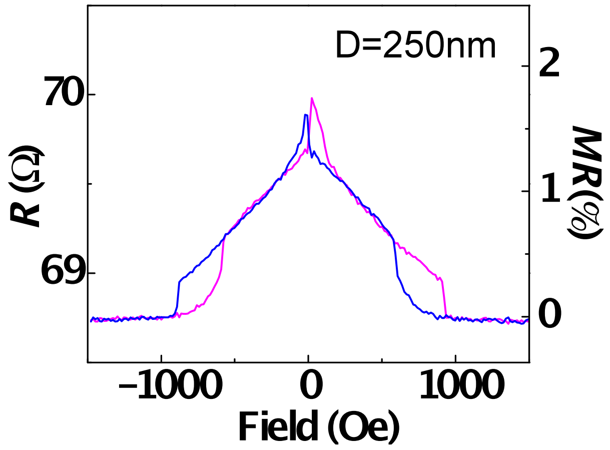
We have fabricated MTJ devices from single-layer graphene without exposing the magnetic electrodes to air – We make suspended graphene membranes and then deposit metal on either side.



RA ~ 1.5 - 6 Ω μm²

Bias and temperature dependence indicate tunneling

Simmons-Brinkman model fits: barrier height ~ 90 meV, width ~ 1 nm



Magnetoresistance is still small
1.5 - 3.5% at 4.2 K
Strong antiferromagnetic coupling

We have hope of making multilayer graphene barriers.

Summary

- Several techniques can now allow consistent quantitative measurements of spin torque due to the spin Hall effect.

- The spin Hall effect can be strong -- generating spin torques with efficiencies much greater than 1 $\hbar/2$ per *e*.

- θ_{SH} ~ 0.3 for β-W, 0.15 for β-Ta. What materials will maximize θ_{SH}?

- Spin torque from the SHE can switch both perpendicularly-polarized and in-plane-polarized magnets, drive steady-state oscillations of in-plane-polarized magnets, and move magnetic domain walls.

- Spin torques arising from topological insulators might be very efficient.

- Work underway on antiferromagnetic spintronics and atomic-layer tunnel barriers.

KIC Kavli Institute at Cornell
NSF
Cornell Center for Materials Research
DARPA
CNF Cornell NanoScale Science and Technology Facility