Electrical Generation of Spin Currents

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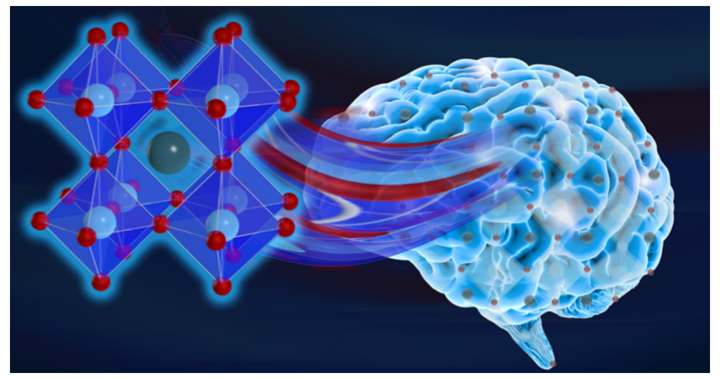
Funding: U.S. DEPARTMENT OF ENERGY Office of Science

Energy Frontiers Research Center



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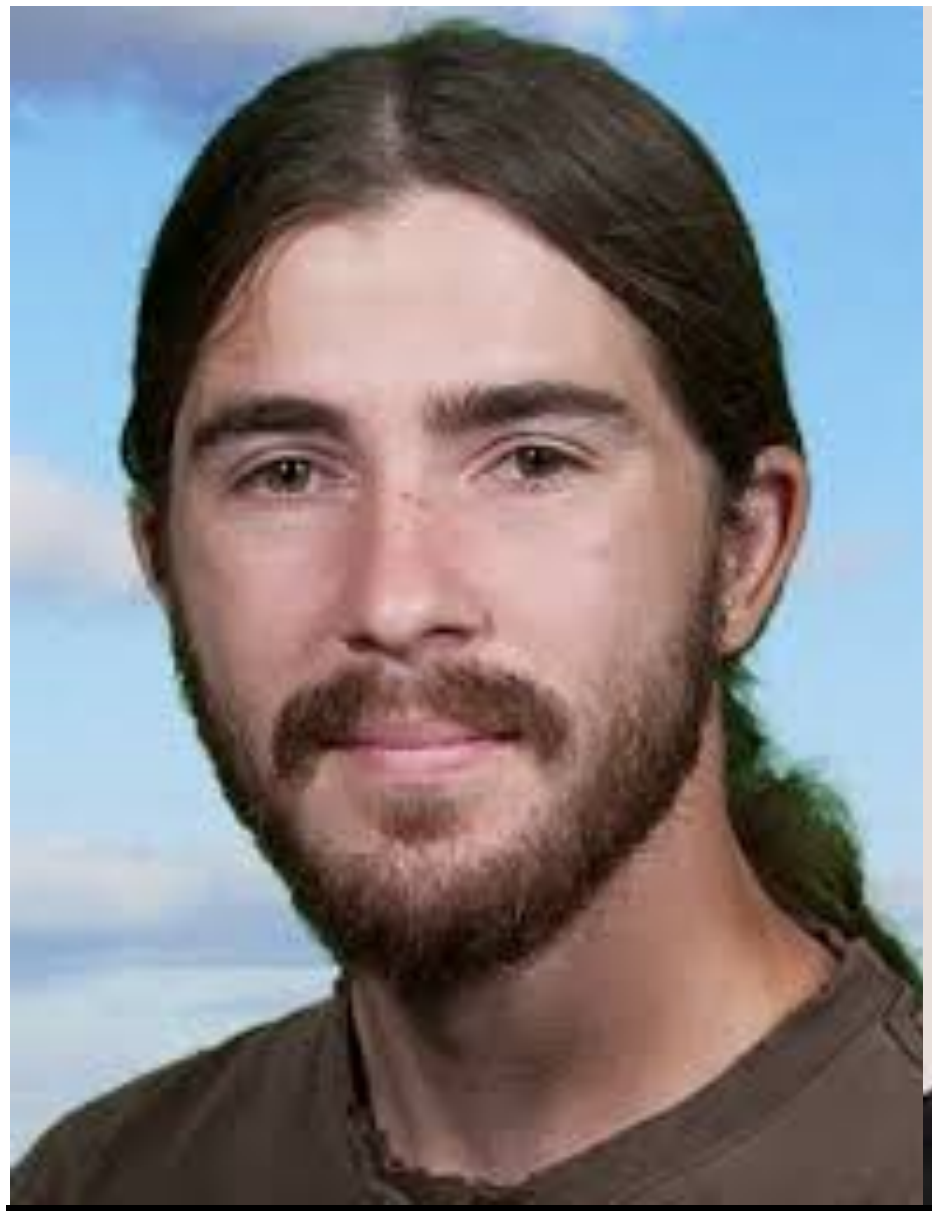
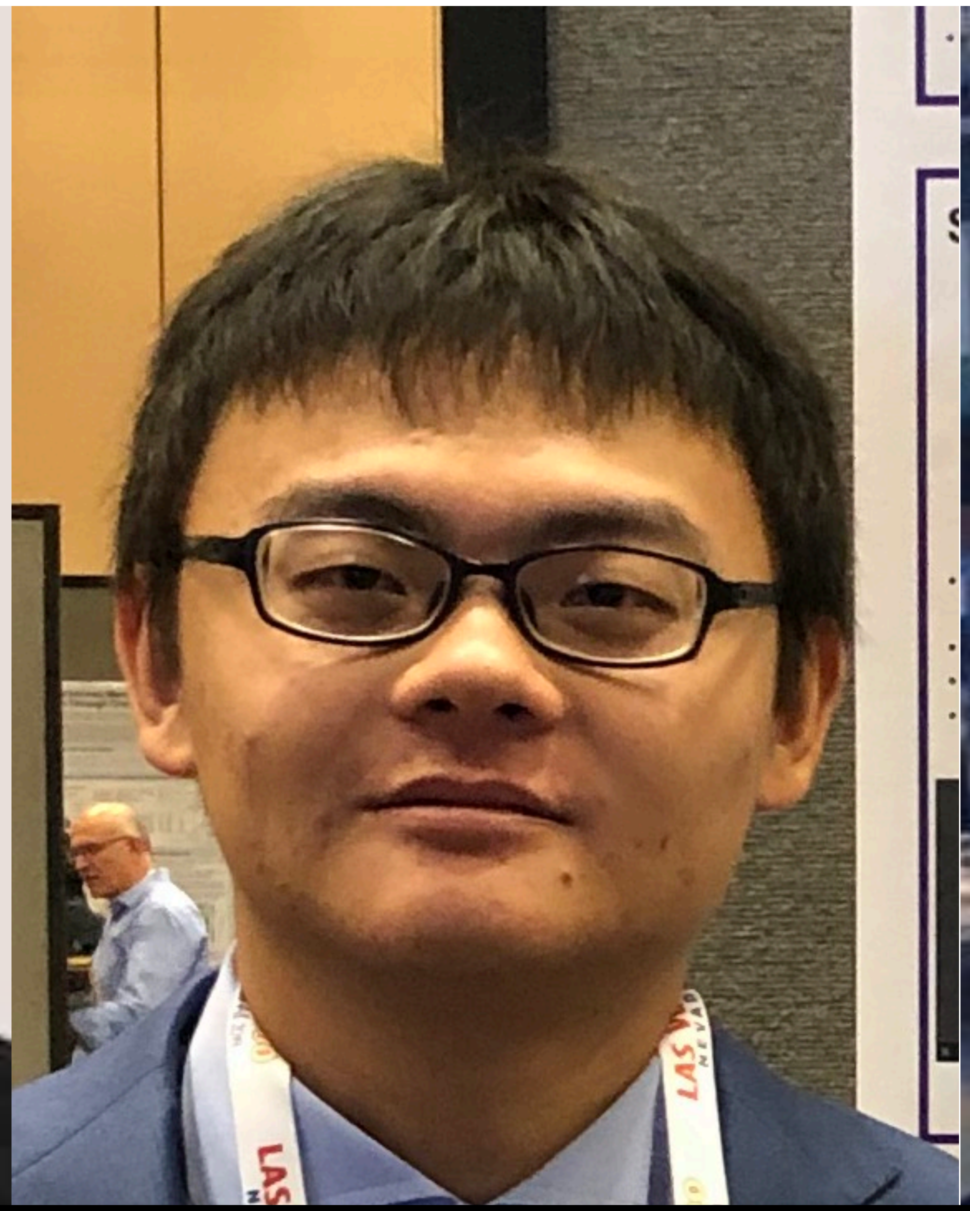
SPICE-SPIN+X Seminar: June 16th, 2021

Electrical Generation of Spin Currents



Chris Safranski, IBM

Jonathan Sun, IBM



Jun-Wen Xu, NYU

Haowen Ren, NYU

Laura Rehm, NYU

C. Safranski *et al.,* PRL **124**, 197204 (2020)

L. Rehm *et al.*, APL **115**, 182404 (2019)
L. Rehm *et al.,* PR Appl. **15**, 034088 (2021)

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Electrical Generation of Spin Currents

Outline

- Introduction: Spin torques and spin-orbit torques
- Charge-to-spin conversion efficiency in switching perpendicular magnetic tunnel junction nanopillars
- Planar Hall effect spin torques

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- **Introduction: Spin torques and spin-orbit torques**
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- Planar Hall effect spin torques

Prediction of Spin-Transfer Torques

2013 Oliver E. Buckley Prize

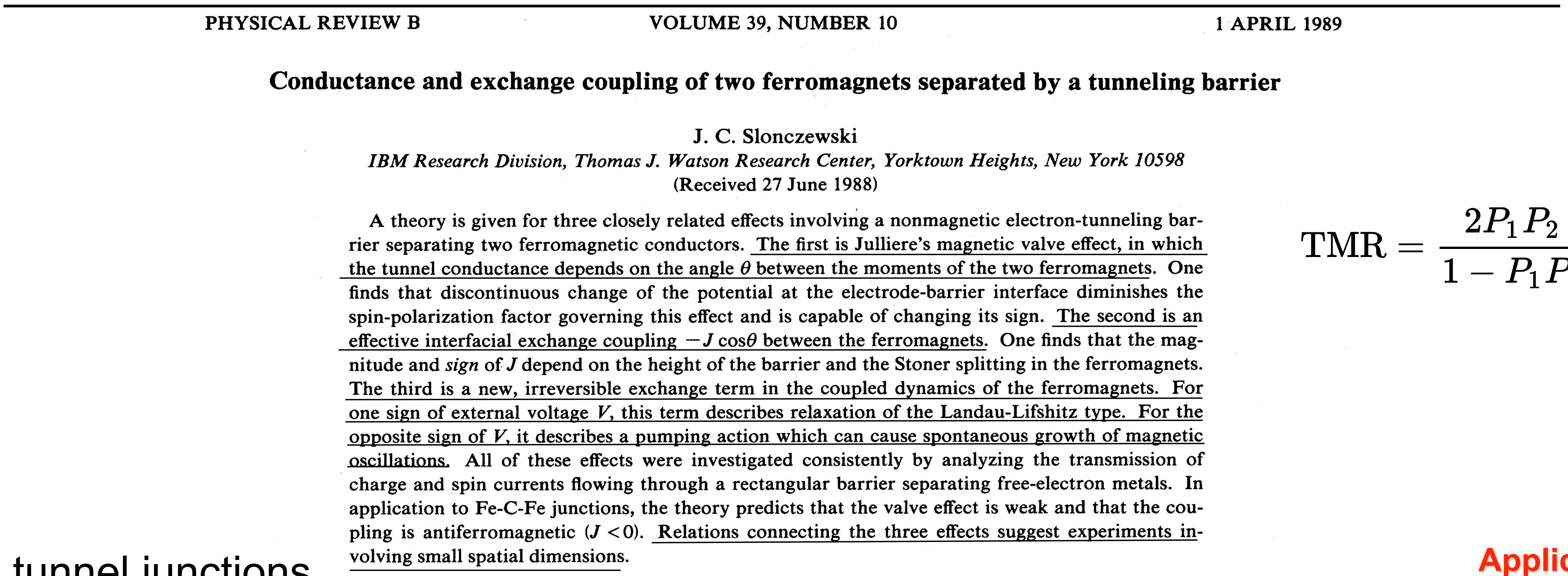
John Slonczewski

Luc Berger

Citation:
“For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures.”

Foundational papers:
J. C. Slonczewski, Phys. Rev. B. **39**, 6996 (1989)
J. C. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

Prediction of Spin-Transfer Torques



PHYSICAL REVIEW B VOLUME 39, NUMBER 10 1 APRIL 1989

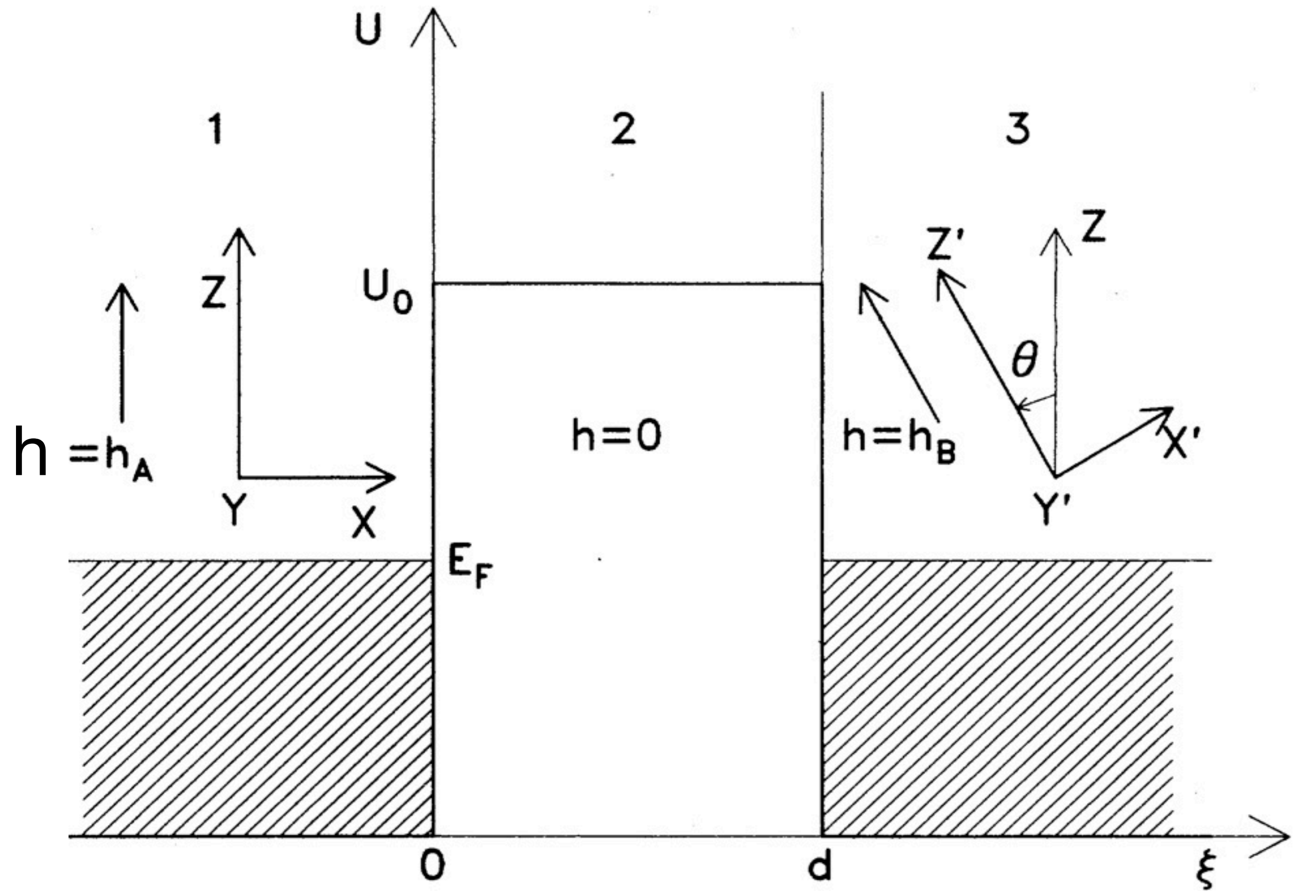
Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier

J. C. Slonczewski
IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 27 June 1988)

A theory is given for three closely related effects involving a nonmagnetic electron-tunneling barrier separating two ferromagnetic conductors. The first is Julliere's magnetic valve effect, in which the tunnel conductance depends on the angle θ between the moments of the two ferromagnets. One finds that discontinuous change of the potential at the electrode-barrier interface diminishes the spin-polarization factor governing this effect and is capable of changing its sign. The second is an effective interfacial exchange coupling $-J\cos\theta$ between the ferromagnets. One finds that the magnitude and *sign* of J depend on the height of the barrier and the Stoner splitting in the ferromagnets. The third is a new, irreversible exchange term in the coupled dynamics of the ferromagnets. For one sign of external voltage V, this term describes relaxation of the Landau-Lifshitz type. For the opposite sign of V, it describes a pumping action which can cause spontaneous growth of magnetic oscillations. All of these effects were investigated consistently by analyzing the transmission of charge and spin currents flowing through a rectangular barrier separating free-electron metals. In application to Fe-C-Fe junctions, the theory predicts that the valve effect is weak and that the coupling is antiferromagnetic ($J<0$). Relations connecting the three effects suggest experiments involving small spatial dimensions.

$$\mathrm{TMR} = \frac{2P_1P_2}{1-P_1P_2}$$

In magnetic tunnel junctions



Applications: New types of MRAM

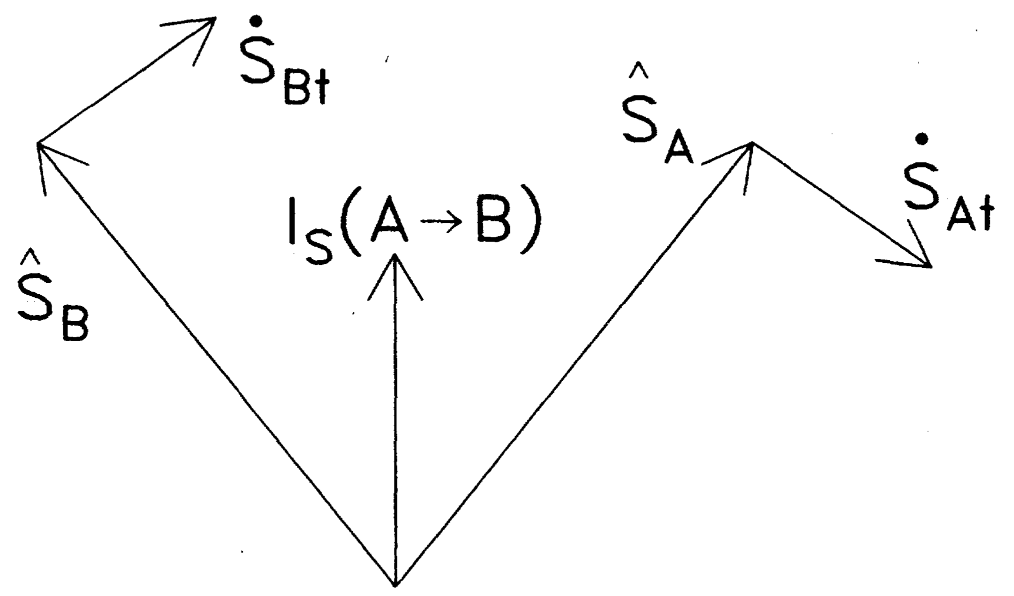
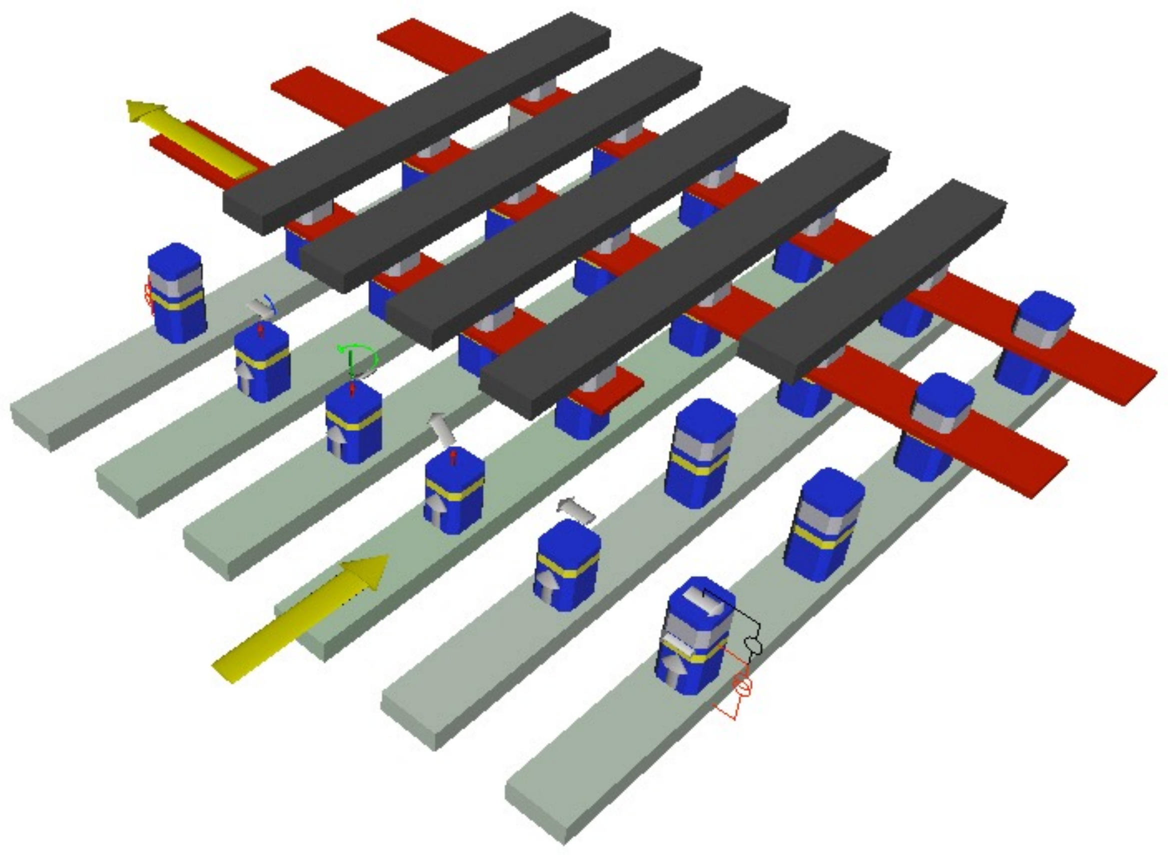


FIG. 6. Scheme of spin-vector dynamics due to the tra verse terms of dissipative exchange coupling induced by external voltage across the barrier.



In magnetic metallic multilayers

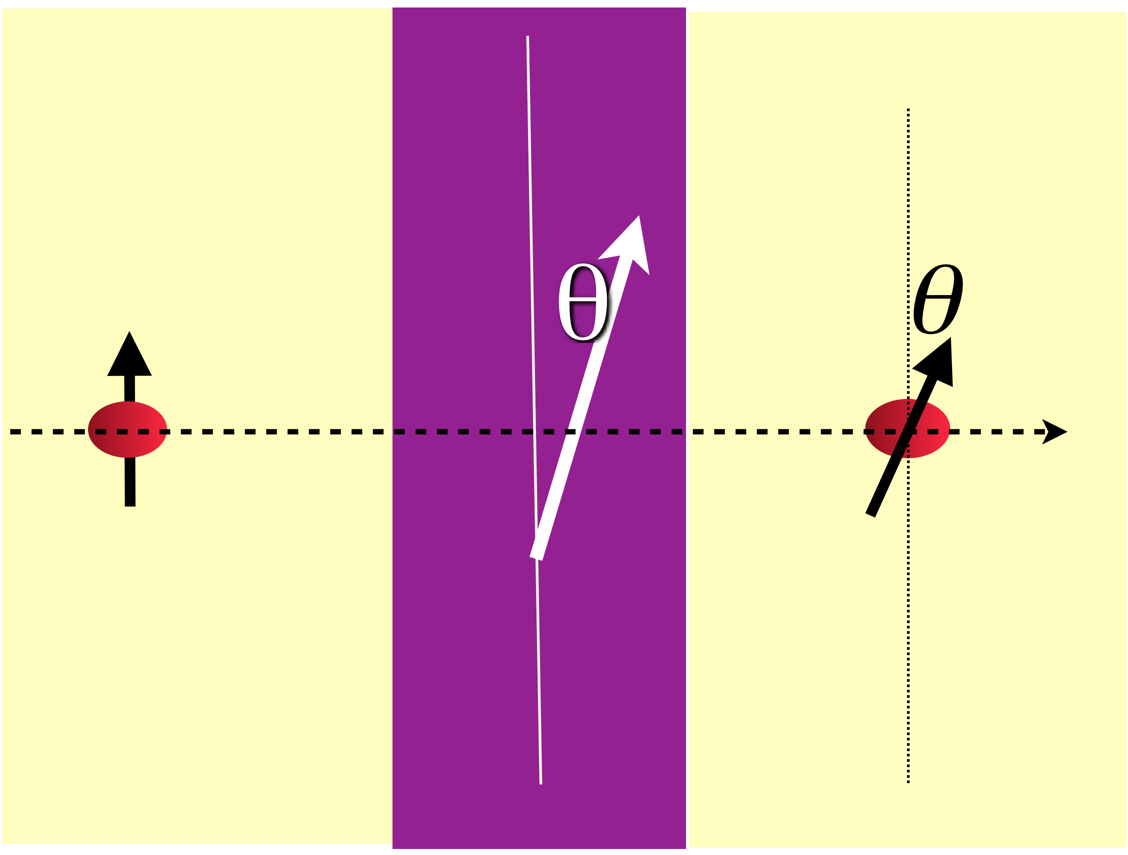
J. C. Sloncewski, JMMM **159**, L1-L7 (1996)
L. Berger, PRB **54**, 9353 (1996)

Applications: Magnetic Random Access Memory, STT-MRAM

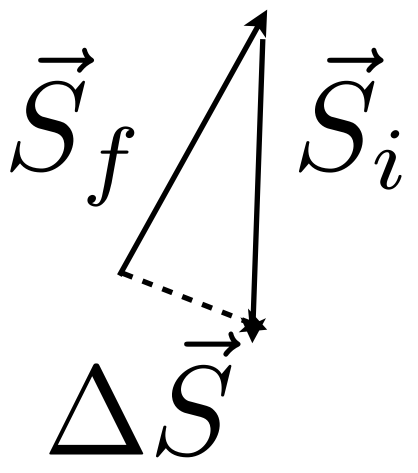
Nature Nanotechnology, March 2015
Spin-transfer-torque memory

Basic Physics of Spin Transfer

Based on conservation of angular momentum



$$\frac{d\vec{S}_{\text{int}}}{dt} \rightarrow \vec{\tau}$$



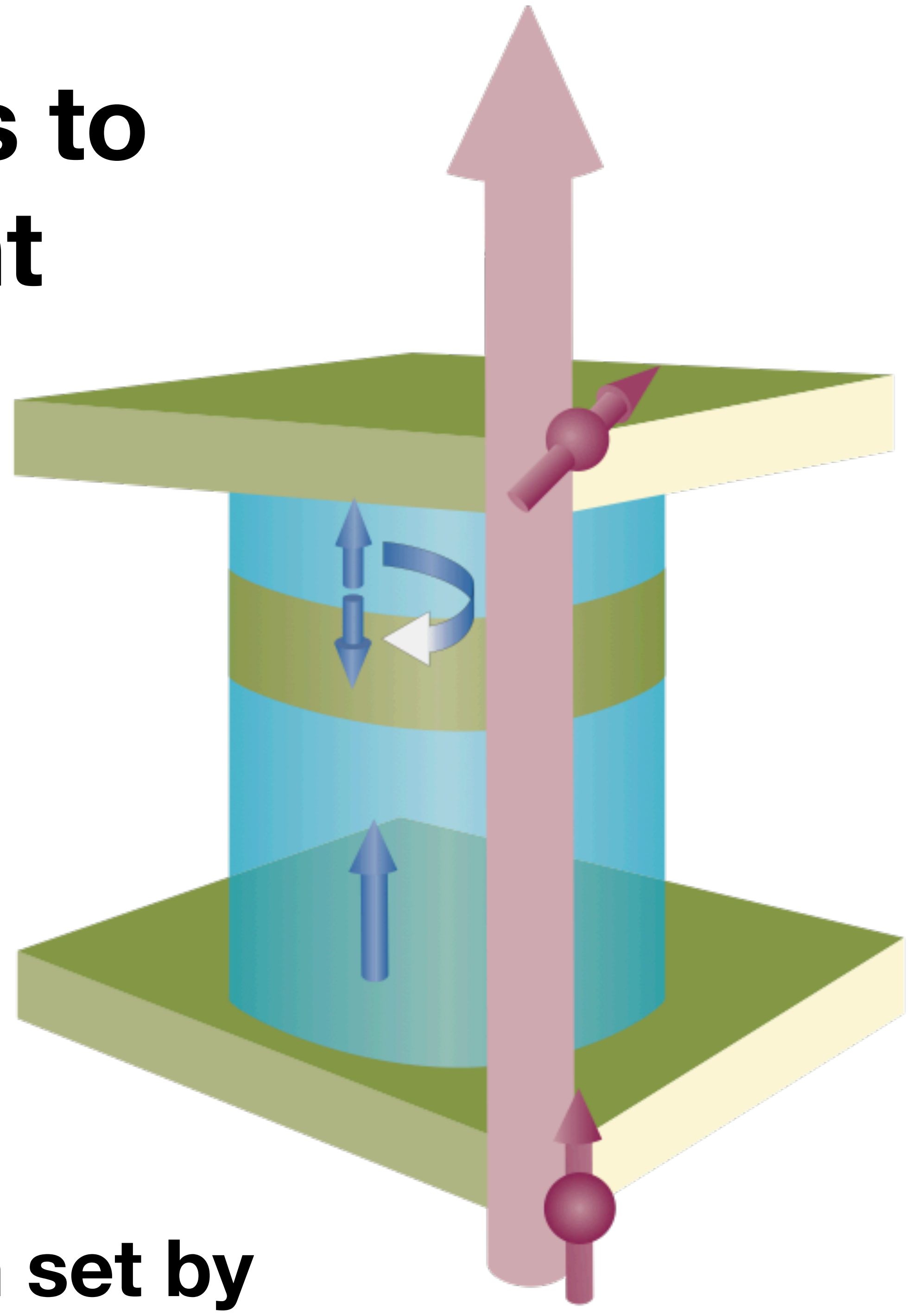
$$\left|\frac{d\vec{S}_{\text{int}}}{dt}\right| = \frac{\hbar}{2e} I P \sin\theta$$

$$\underbrace{\frac{1}{\gamma}\frac{d\vec{M}}{dt}}_{\text{magnetization}} + \underbrace{\frac{d\vec{S}_{\text{int}}}{dt}}_{\text{itinerant charge}} = 0$$

- Reference layer ‘sets’ spin-polarization of current
- Enables readout of magnetization state through the tunnel magnetoresistance (TMR), giant magnetoresistance (GMR), or anisotropic magnetoresistance (AMR) effects

Charge Current to Spin Current Conversion

Ferromagnetic layers to polarize the current

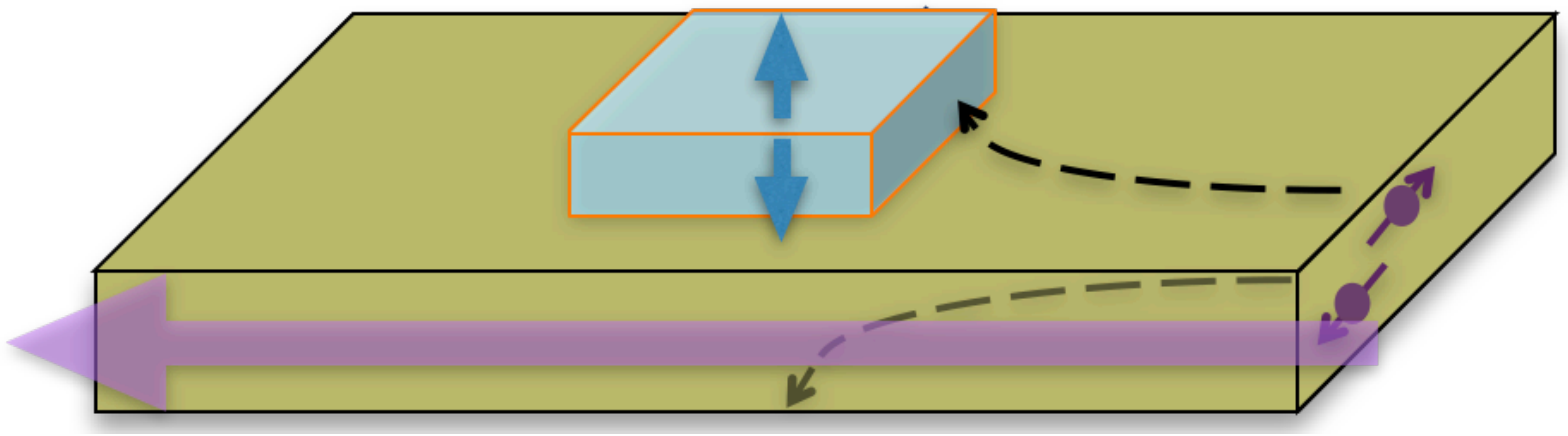


Spin-polarization direction set by reference layer magnetization direction

Spin torque foundational theory papers:

J. C. Slonczewski, Phys. Rev. B. **39**, 6996 (1989)
J. C. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

Spin-orbit torques



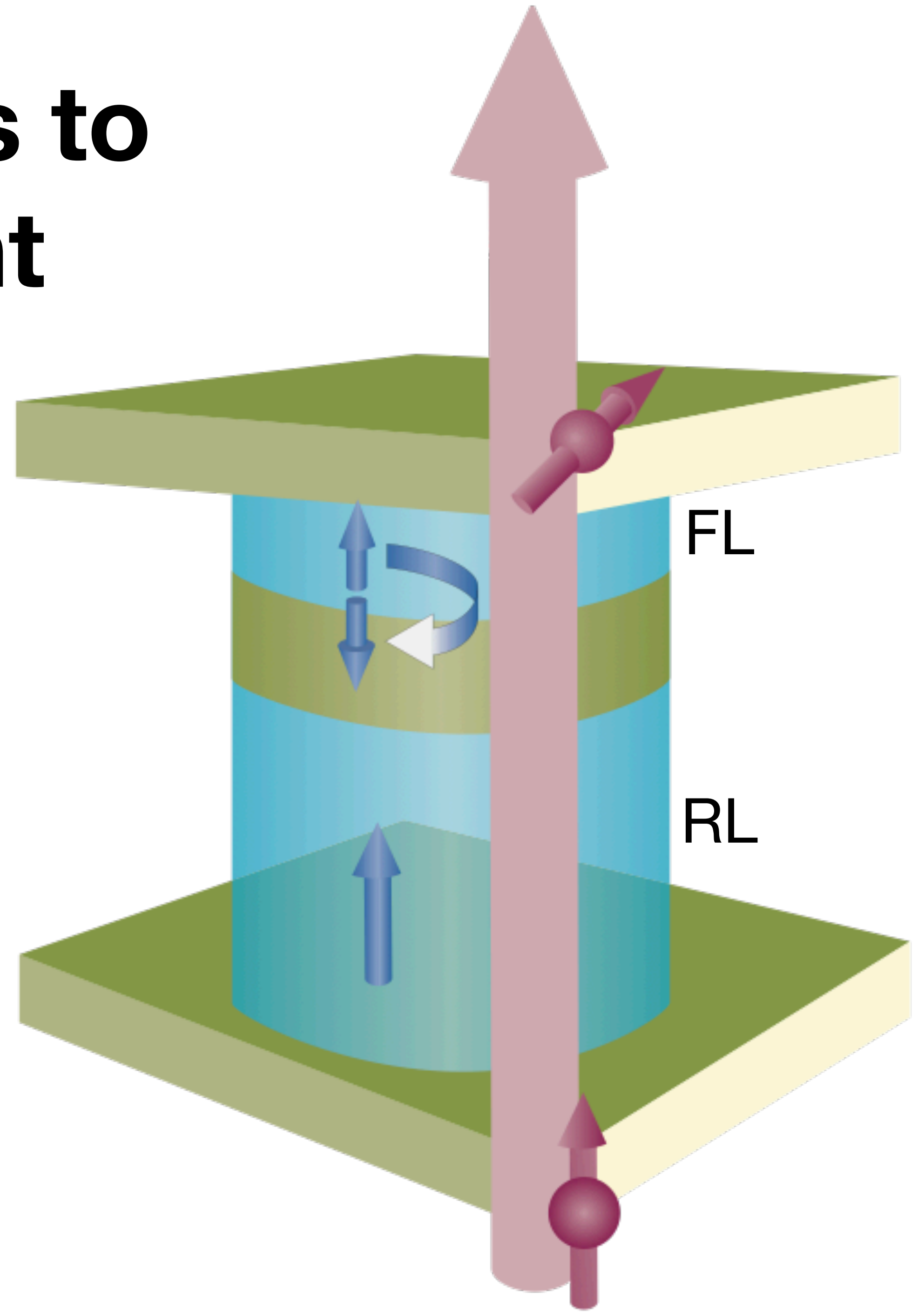
Spin-polarization direction set by layer geometry and current flow direction

Heavy metals/Ferromagnet bilayers
M. Miron *et al.*, Nature Materials 2010
L. Liu *et al.,* Science 2012

Review article: J. Sinova *et al.*, Spin Hall Effects, RMP **87**, 1213 (2015)

Charge Current to Spin Current Conversion

Ferromagnetic layers to polarize the current



$$\frac{\text{spin-current density}}{\text{charge current density}} \quad J_s/J_c \simeq P$$

$$I_s/I_c \simeq P$$

spin current is $\hbar J_s/(2e)$

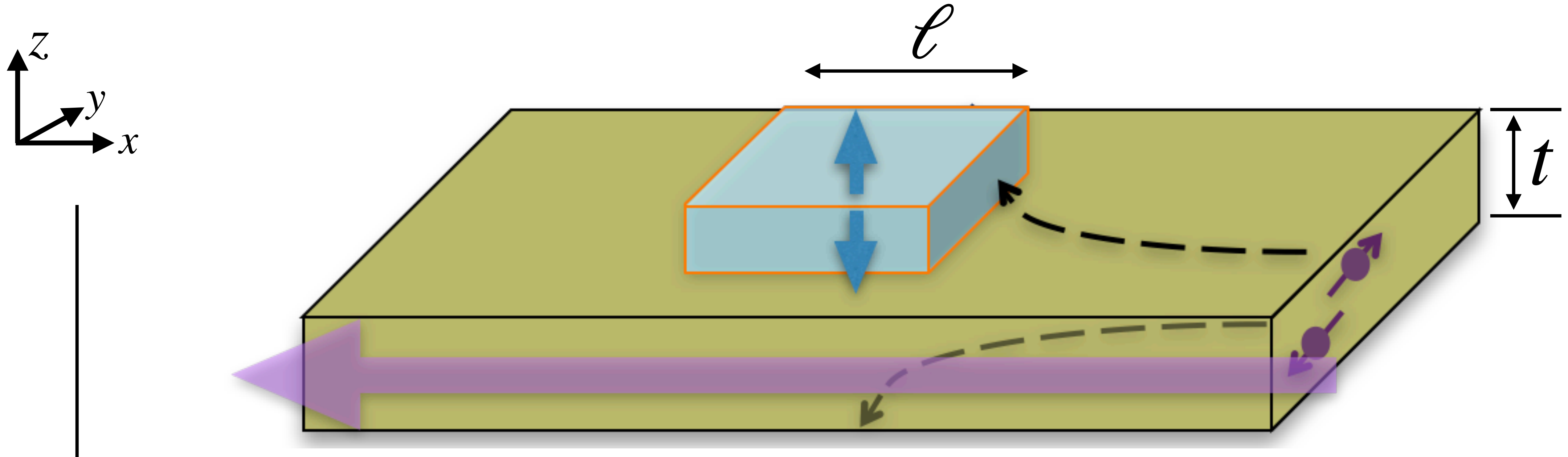
$$\mathbf{Q} \sim \hat{m}_{\mathrm{RL}} \otimes \hat{z}$$

Polarization ⊗ Flow direction

Spin torque foundational theory papers:

J. C. Slonczewski, Phys. Rev. B. **39**, 6996 (1989)
J. C. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

Spin-orbit torques



$$J_s/J_c = \theta_{\mathrm{SH}}$$

$$I_s/I_c \simeq \theta_{\mathrm{SH}}(\ell/t)$$

$$\mathbf{Q} = \frac{-\hbar}{2\mathbf{e}}\xi\sigma_{\mathrm{SHE}}(\hat{z}\times\mathbf{E})\otimes\hat{z}$$

Polarization ⊗ Flow direction

Heavy metals/Ferromagnet bilayers
M. Miron *et al.*, Nature Materials 2010
L. Liu *et al.*, Science 2012

Review article: J. Sinova *et al.*, Spin Hall Effects, RMP **87**, 1213 (2015)

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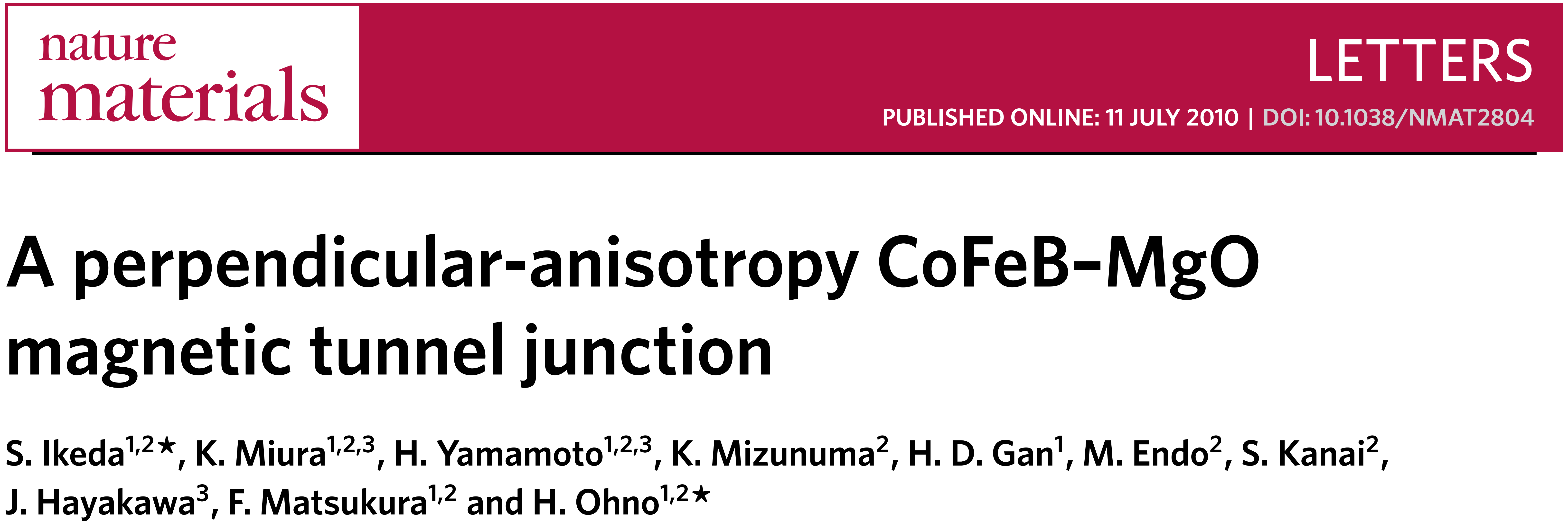


nature materials

LETTERS

A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction

S. Ikeda[1,2]★, K. Miura[1,2,3], H. Yamamoto[1,2,3], K. Mizunuma[2], H. D. Gan[1], M. Endo[2], S. Kanai[2], J. Hayakawa[3], F. Matsukura[1,2] and H. Ohno[1,2]★

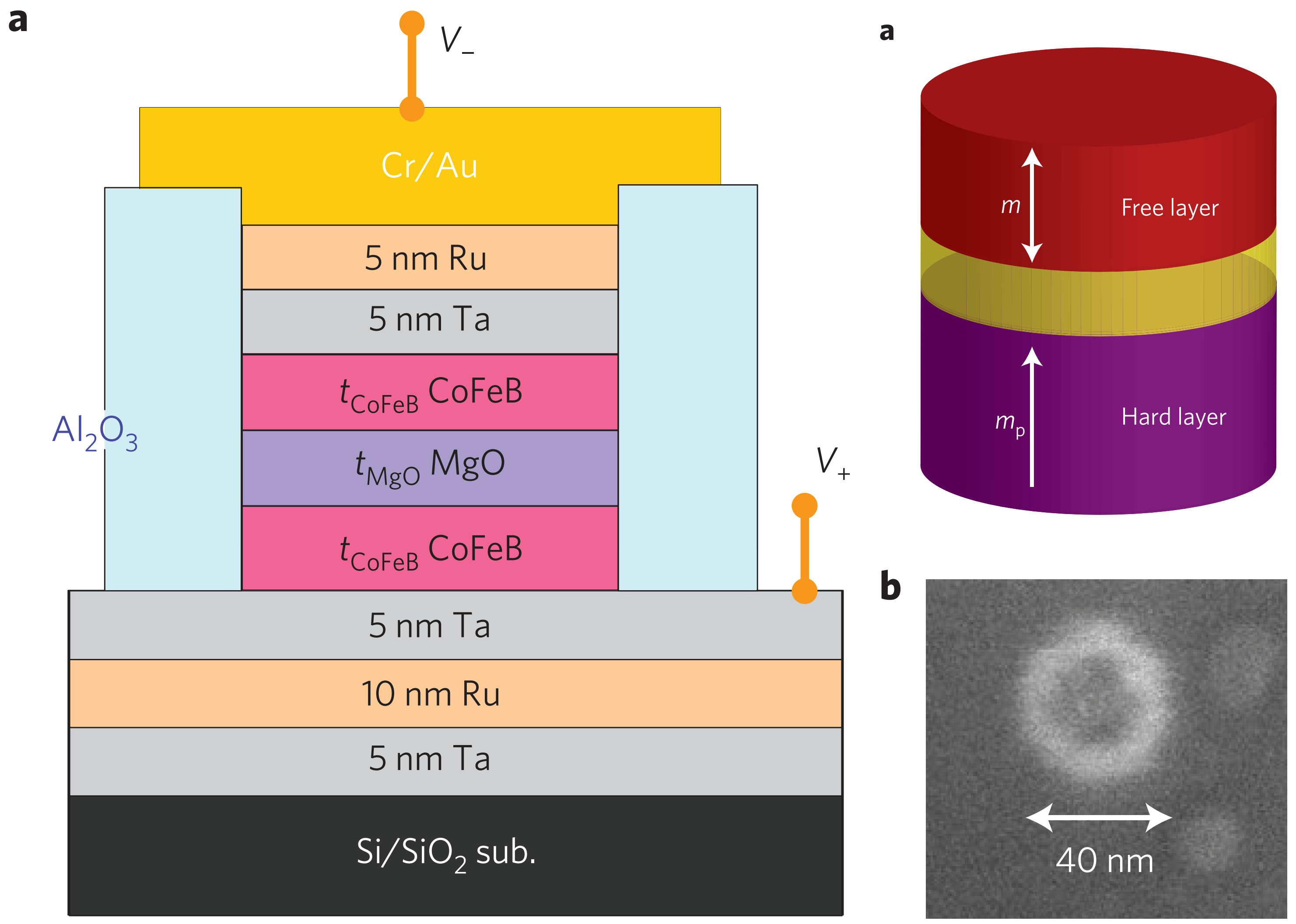
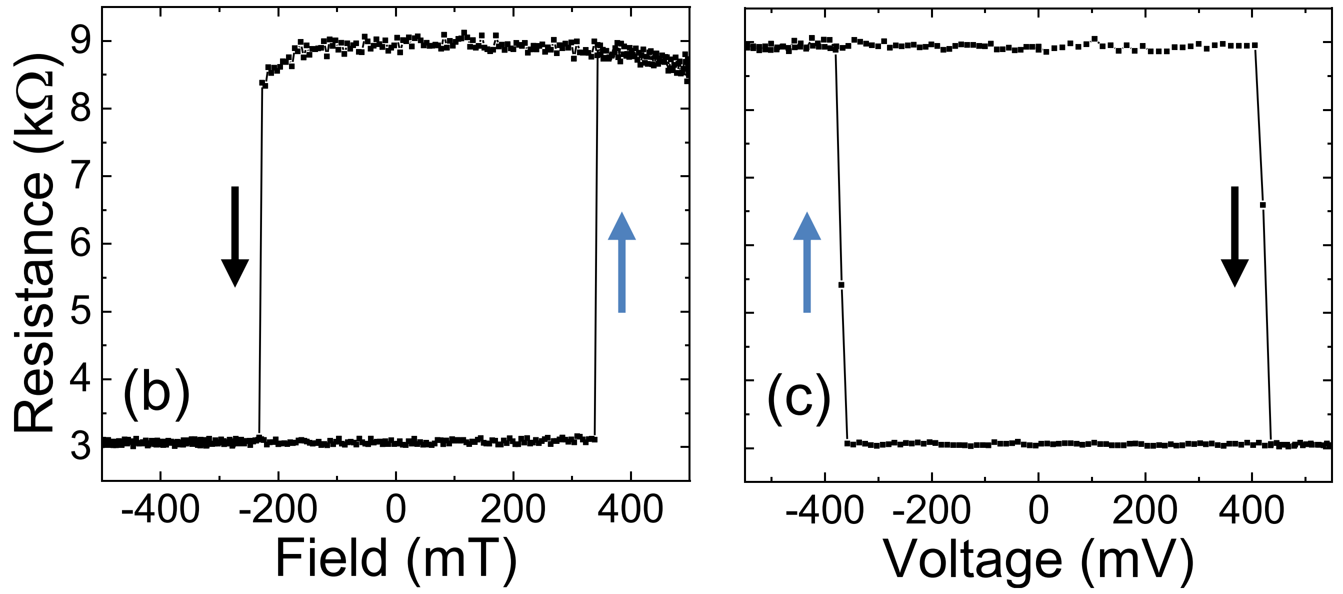


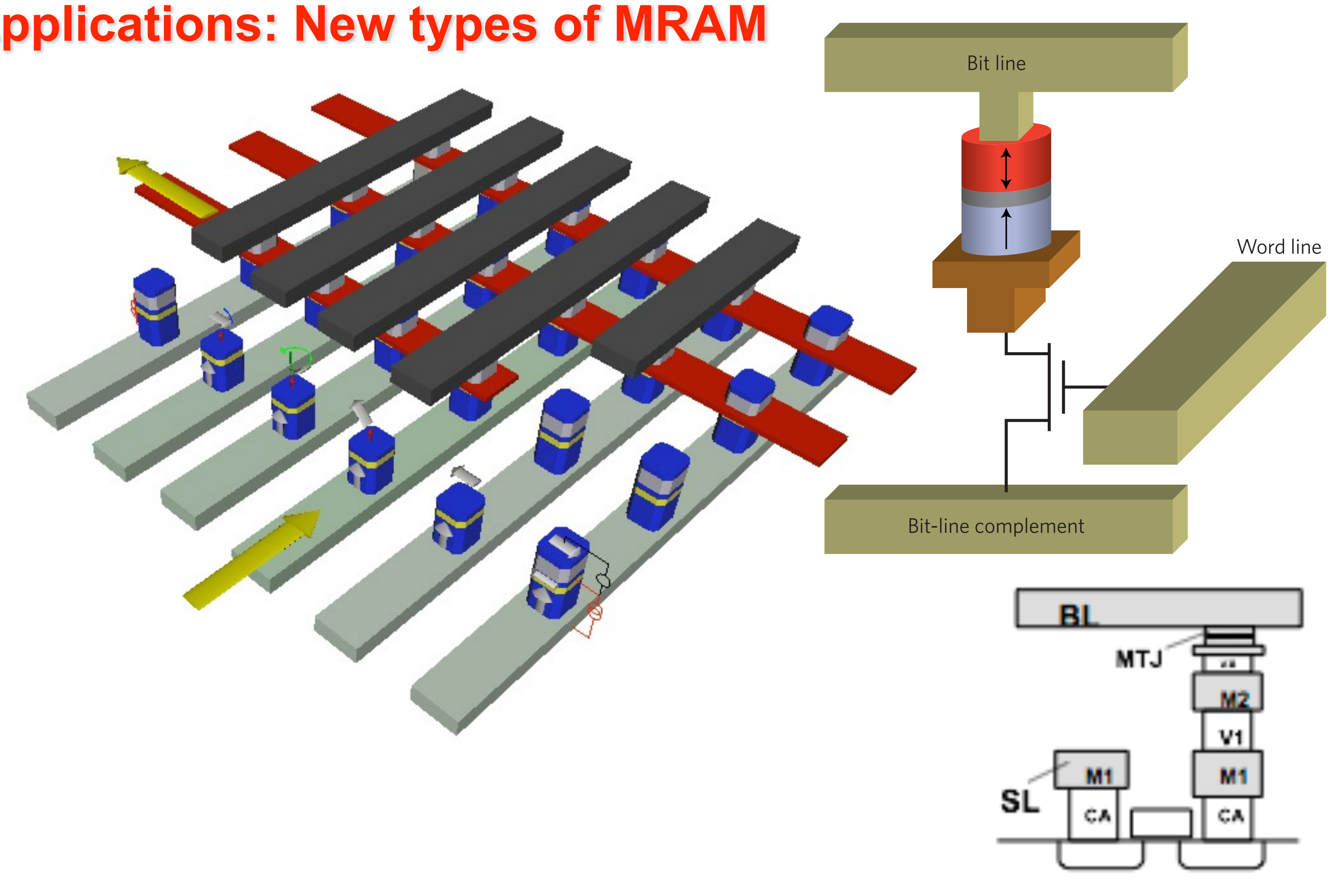
Figure 1 | MTJ structure. a, Schematic of an MTJ device for TMR and CIMS measurements. **b**, Top view of an MTJ pillar taken by scanning electron microscope.



Field induced free layer switching

Current-induced switching

Applications: New types of MRAM

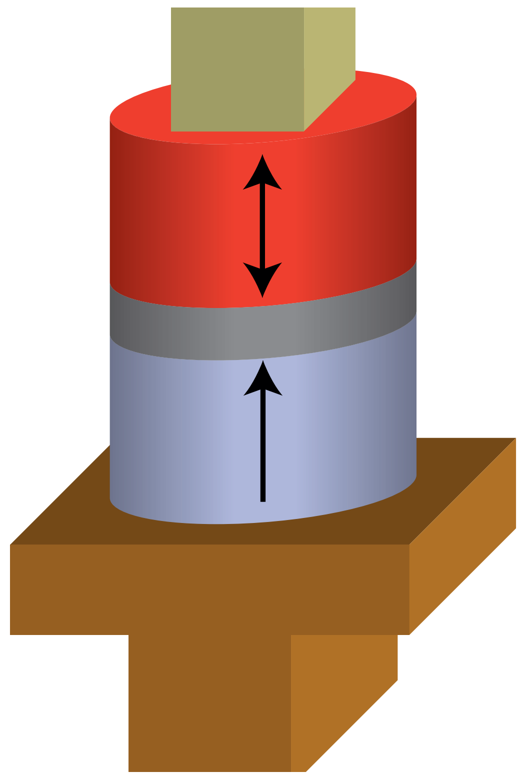


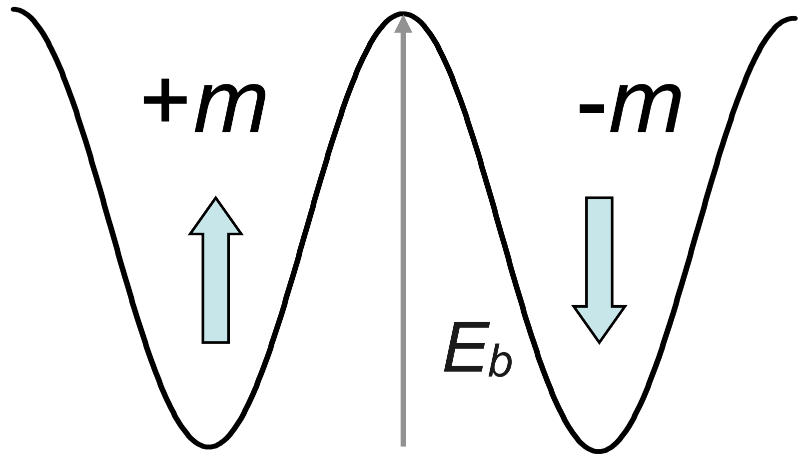
R. Beach *et al.*, IEDM 2008

Also, D.C. Worledge *et al.*, Applied Physics Letter **98**, 022501 (2011)

Perspective: A. D. Kent, Perpendicular all the way, Nature Materials **9**, 699 (2010)

Magnetic Tunnel Junction Nanopillars



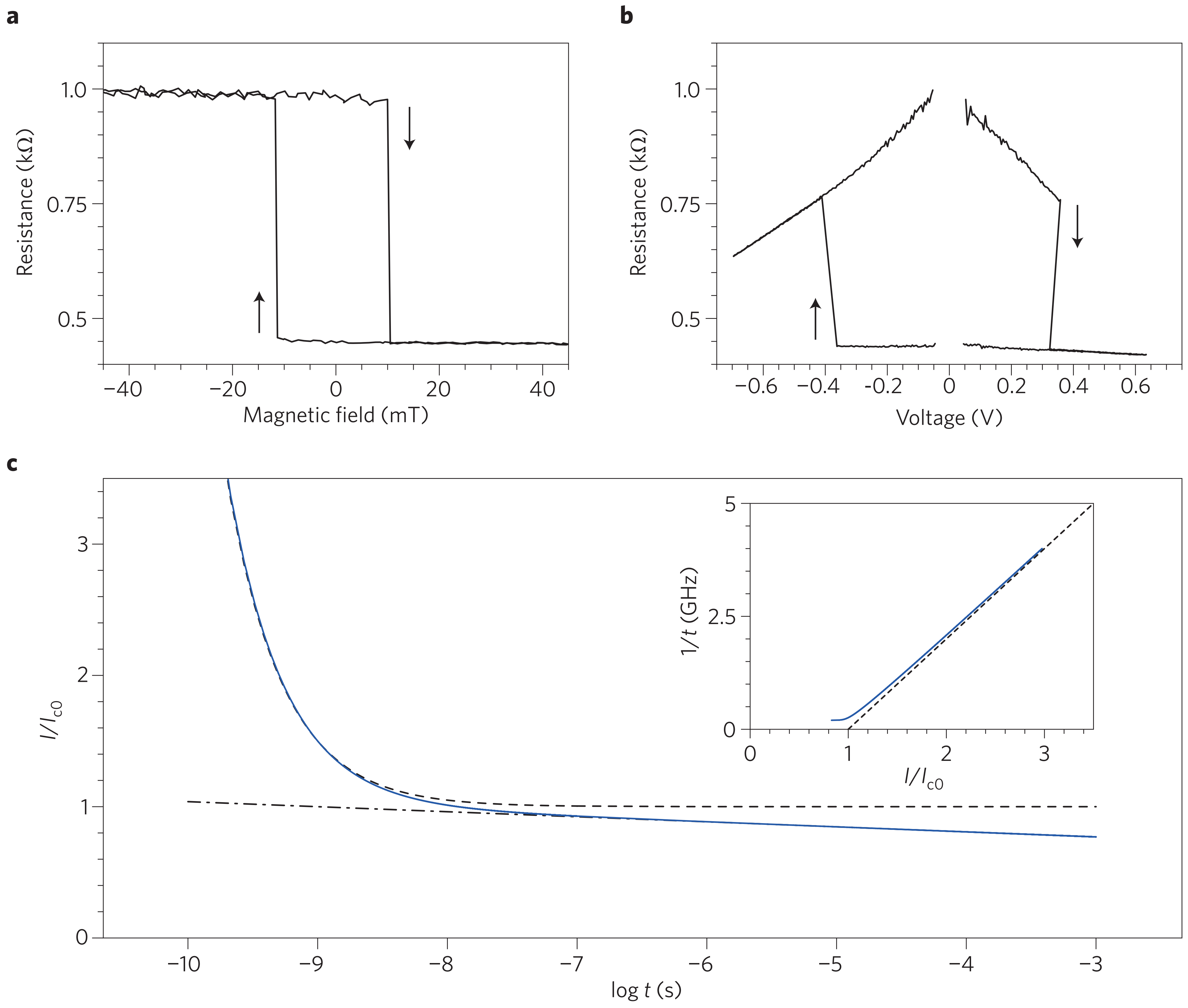


$$E_b/(kT) \gtrsim 60$$

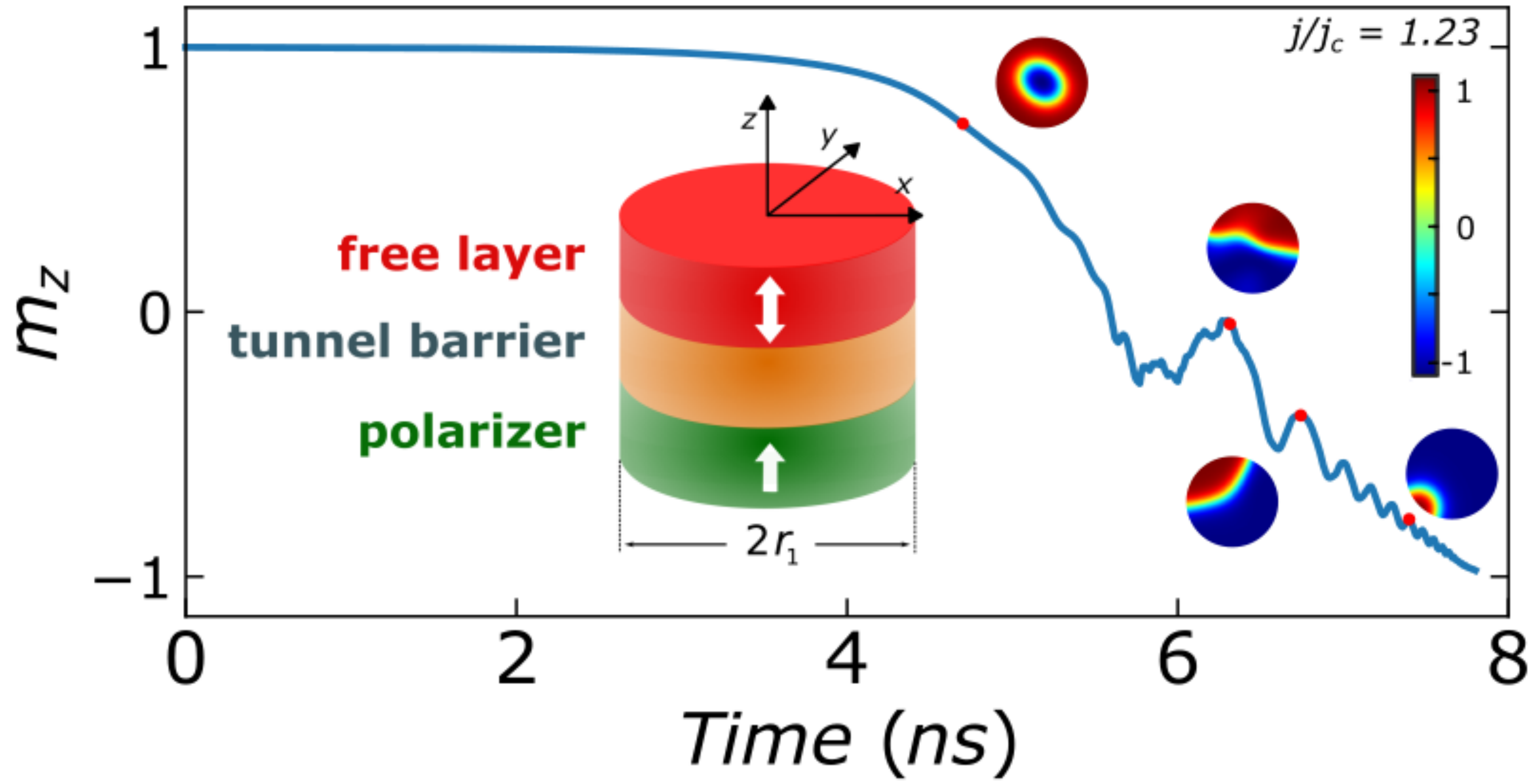
$$\boxed{V_c = \alpha\frac{4e}{\hbar}\left(\frac{1+P^2}{P}\right)\frac{E_b}{G_P}}$$

J. C. Slonczewski, PRB **71**, 024411 (2005)

J. C. Slonczewski & J. Z. Sun, JMMM **310**, 169 (2007)



Micromagnetic simulations



N. Statuto *et al.*, PRB **103**, 014409 (2021)

P. Bouquin *et al.*, APL **113**, 222408 (2018)

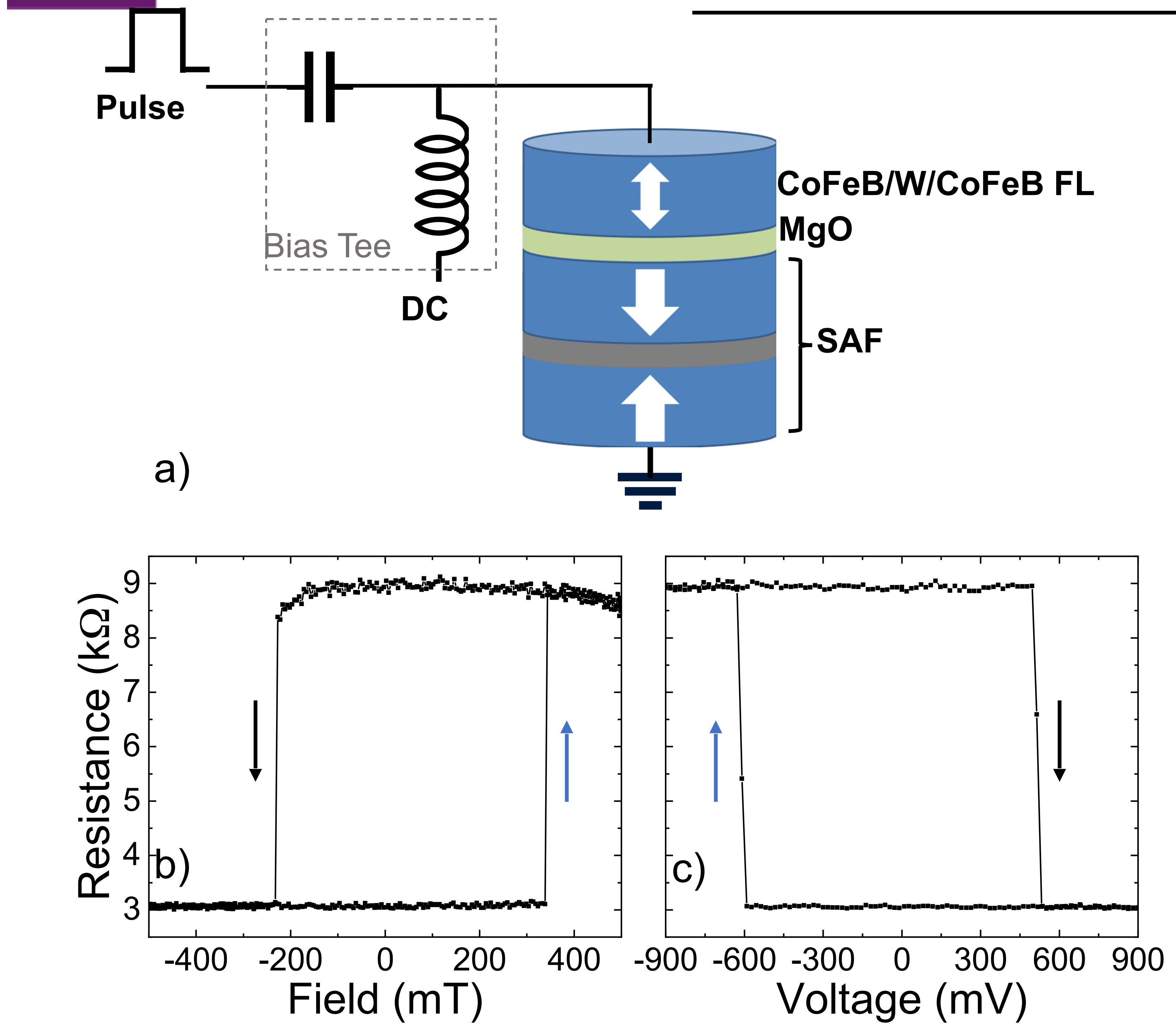
I. Volvach *et al.*, APL **116**, 192408 (2020)

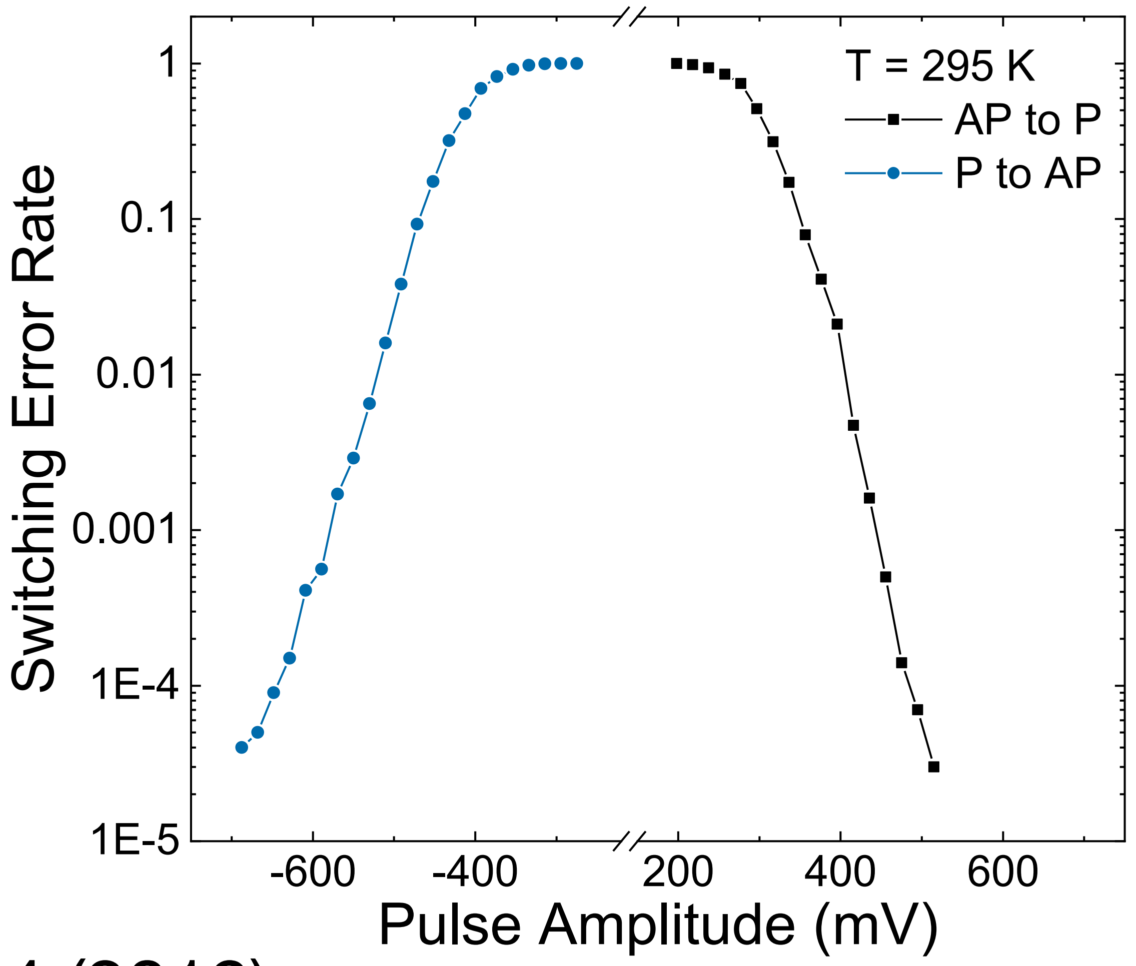
J. B. Mohammadi *et al.*, APL **118**, 132407 (2021)

A. D. Kent and D. C. Worledge, “A new spin on magnetic memories,” Nature Nanotechnology **10**, 187 (2015)

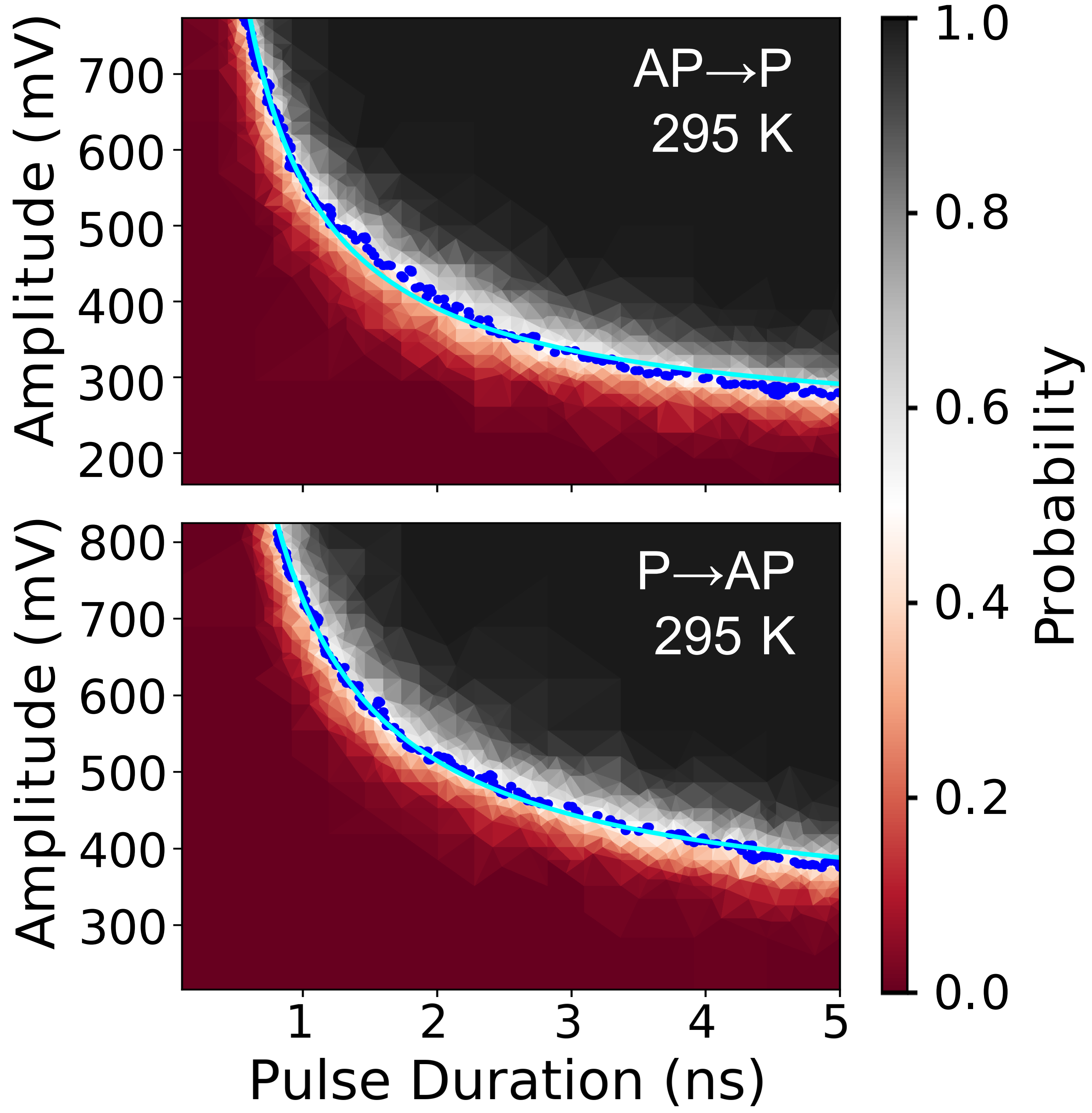
H. Liu *et al.,* "Dynamics of spin torque switching in all-perpendicular spin valve nanopillars," JMMM **358**, 233 (2014)

High Speed Magnetization Switching





40 nm diameter nanopillar



Laura Rehm *et al.*, Appl. Phys. Lett. **115**, 182404 (2019)
Laura Rehm *et al.*, Phys. Rev. Appl. **15**, 034088 (2021)

For pulse duration τ_0 the **spin-charge conversion efficiency** in a macrospin model:

$$\boxed{\frac{N_s}{N_c} = \frac{(m_{\mathrm{FL}}/\mu_B)}{(I_c\tau_0/e)} \simeq 0.23}$$

$$\frac{N_s}{N_c} = \frac{P}{(1+P^2)\ln(4\sqrt{\pi\Delta})} \simeq 0.11$$

$$P = \sqrt{m_r/(2+m_r)}$$

$$\Delta = E_b/(k_B T)$$

critical number of transmitted charges N_c

$$\frac{1}{\tau} = \frac{1}{\tau_0}\left(\frac{I - I_c}{I_c}\right)$$

$$\underset{eN_c}{\tau_0 I_c} = \underset{eN}{I\tau} - \underset{\text{dissipation}}{I_c\tau} \longrightarrow I_c \simeq 100\ \mu\mathrm{A}$$

Write energy: $\lesssim 250\ \mathrm{fJ}$

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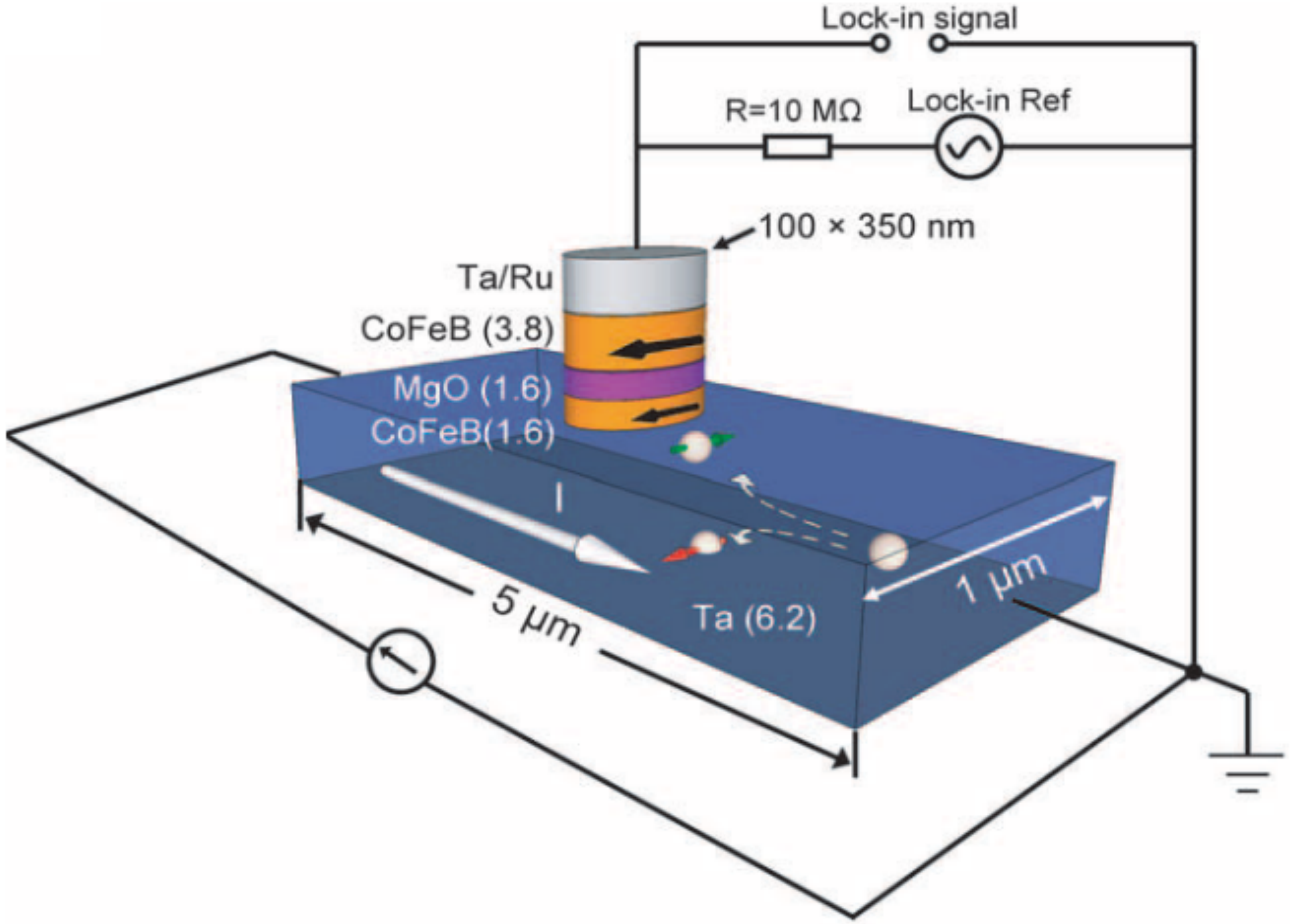
Spin Orbit Torques

- Separating read/write paths can
  - Allow separate optimization of read/write channels
  - Increase barrier longevity
  - Eliminate reference layer switching instabilities

- Spin Hall and Rashba effects can be used to generate spin current.

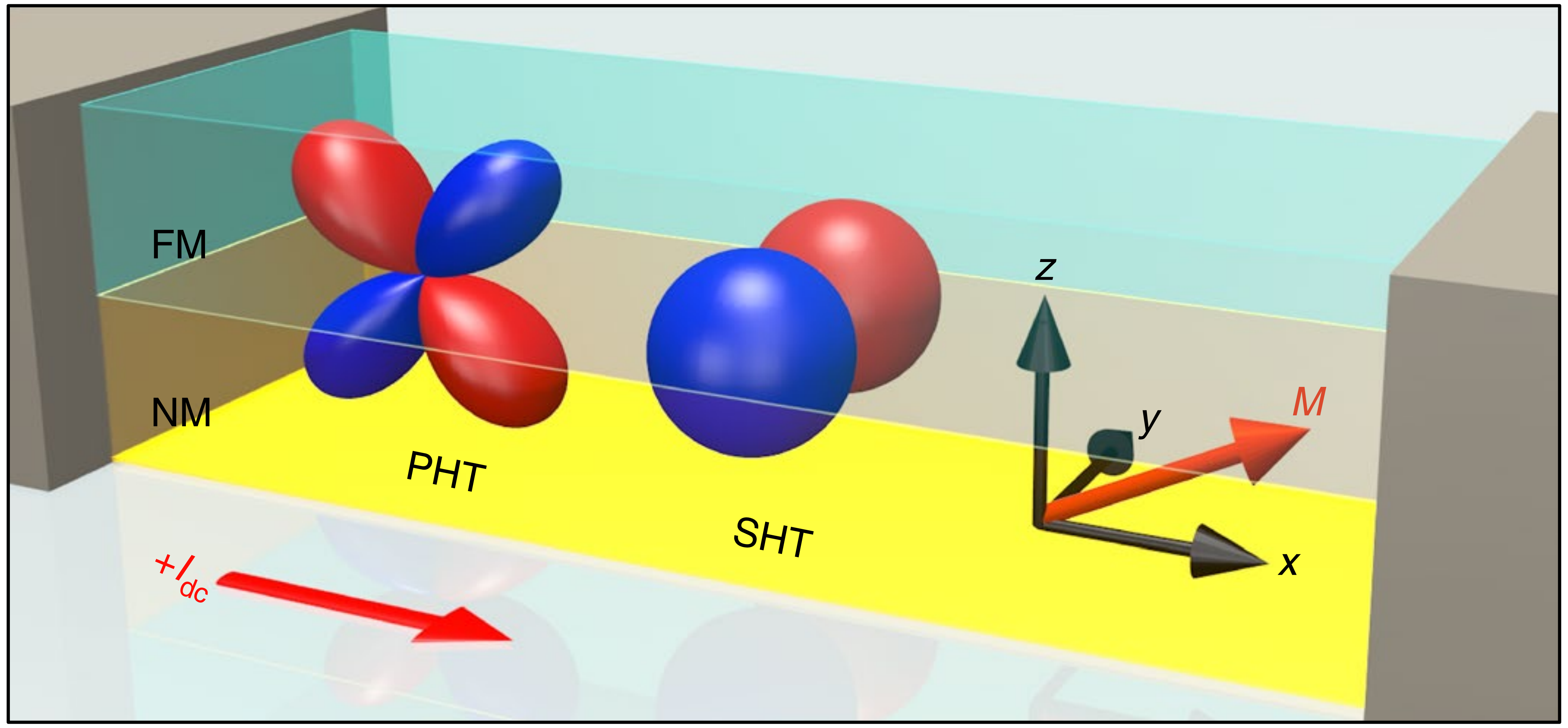


L. Liu *et al.*, "Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum." Science **336**, 6081 (2012)

I. M. Miron *et al.* "Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer," Nature Materials **9**, 230(2010)

Spin Currents Set By Magnetization

Symmetry of antidamping spin torques:



Blue=antidamping
Red=damping

From C. Safranski, E. A. Montoya & I. N. Krivorotov, Nature Nanotechnology **14**, 27 (2019)

Charge-to-spin conversion

- Spin-orbit coupling in non-magnetic materials (e.g. by Spin-Hall, Rashba and in TIs) leads to spin-polarization in the interface plane. (Exception are materials with low crystalline symmetries, e.g. TMDs.)
  - These are ideal for switching *in-plane* magnetized element

$$I_c \simeq \frac{\alpha}{P}\frac{4e}{\hbar}E_b(1+D), \qquad D = \frac{M_{\mathrm{eff}}}{H_k}$$

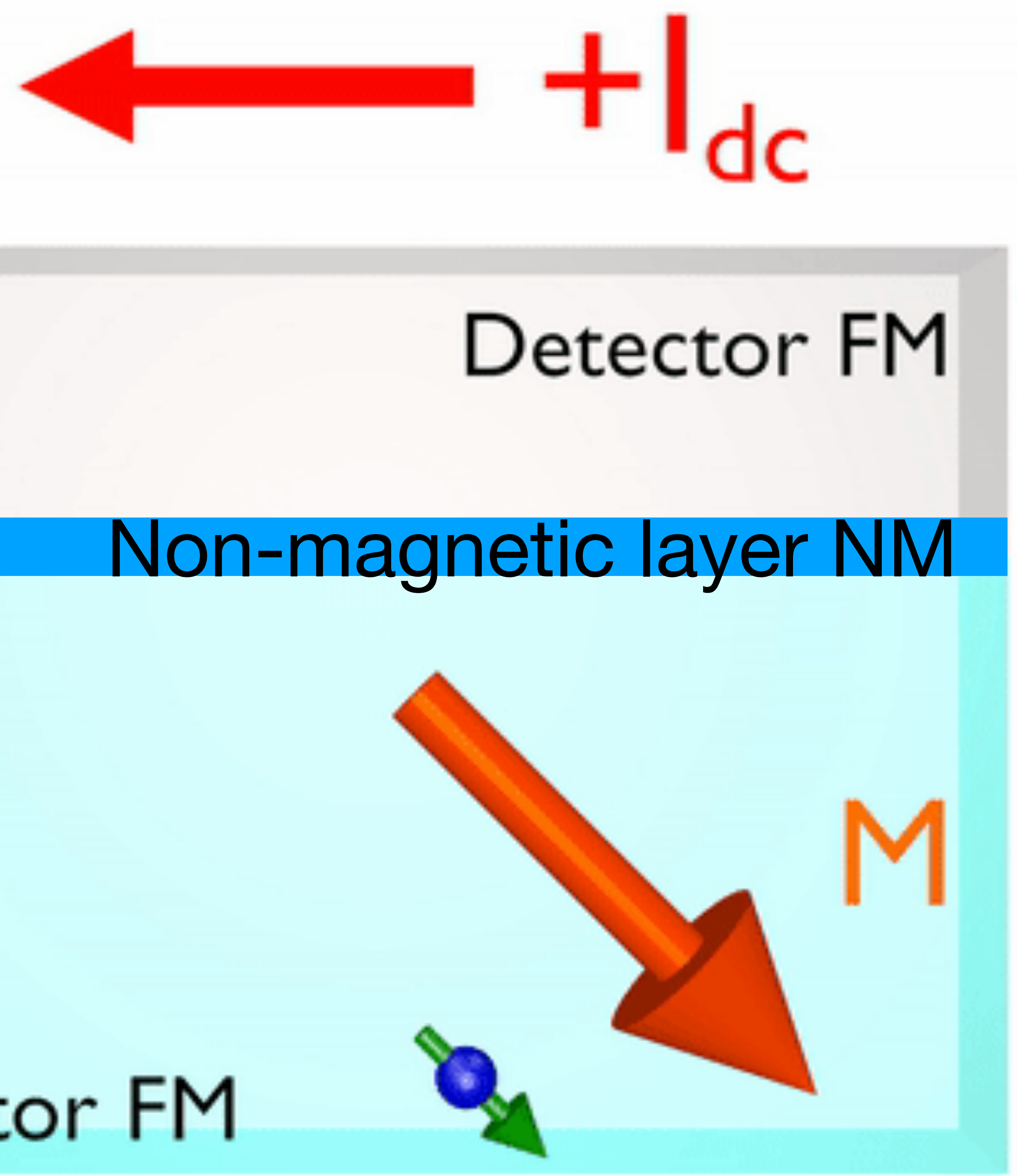
- A goal of spintronics is to covert a charge current into a spin current with a **controlled spin polarization** that can exert torques on an adjacent magnetic layer and switch **perpendicularly magnetized elements**

Planar Hall Driven Spin Current

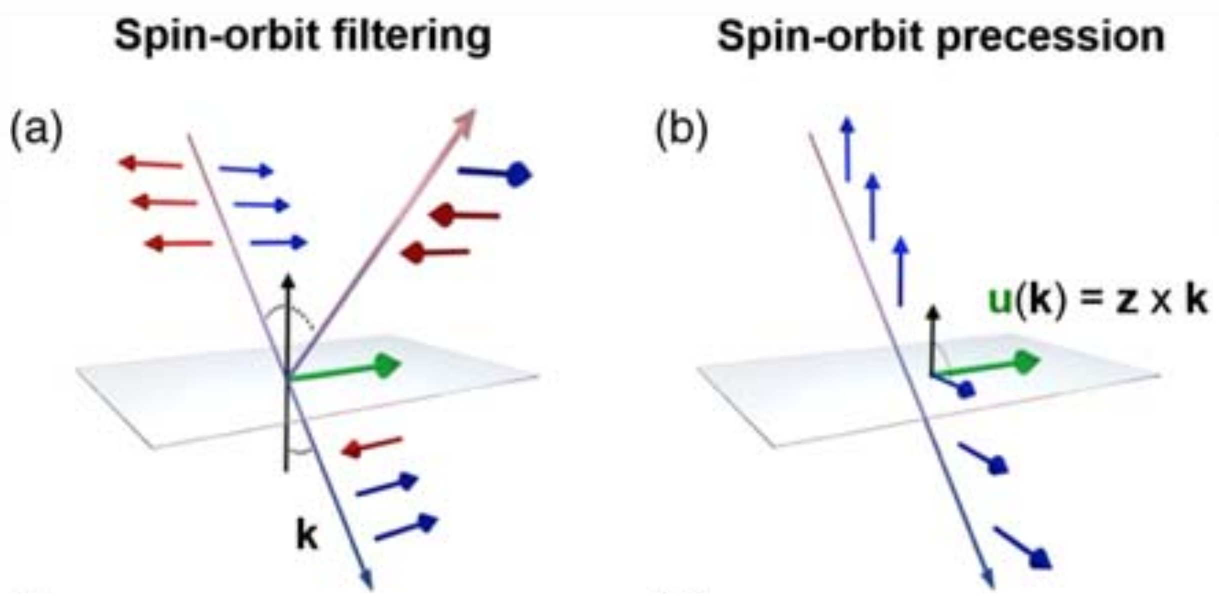
$$\mathbf{J}_\mathrm{s} = \eta \frac{\hbar}{2e} (\hat{m} \cdot \mathbf{J}_\mathrm{dc})\, \hat{m}$$

- Spin current needs to be injected into nearby FM
- Thus only the z component of current is important

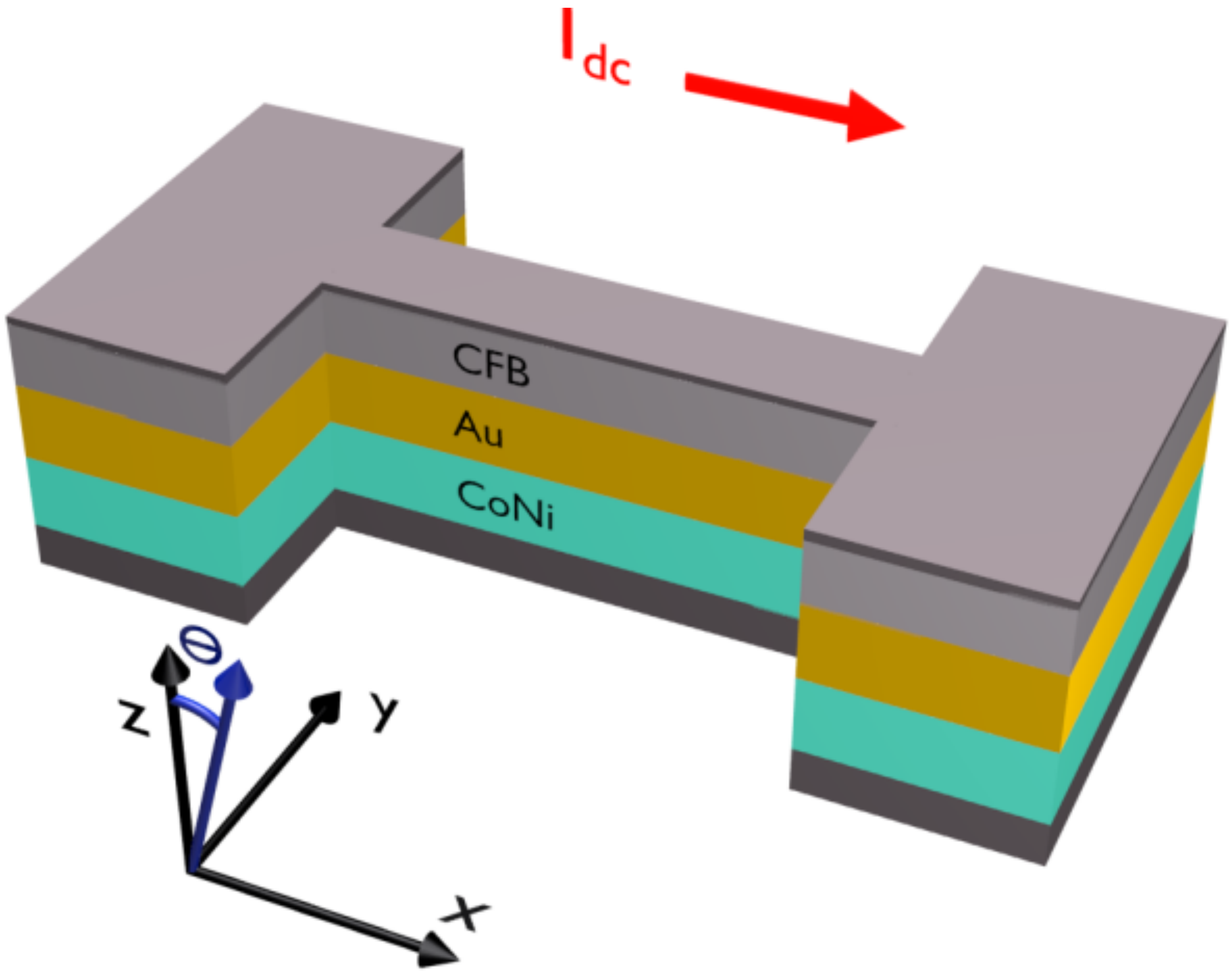
$$J_{sz} = \eta \frac{\hbar}{2e} (\hat{m} \cdot \hat{x})(\hat{m} \cdot \hat{z}) J_{dc} = \eta \frac{\hbar}{2e} \cos\theta \sin\theta$$



T. Taniguchi, J. Grollier & M. Stiles, PR Applied **3**, 044001 (2015)
K. D. Belashchenko *et al*., PR Materials **3**, 011401 (2019) & PRB **101**, 020407 (2020)
V. P. Amin, J. Zemen & M. D. Stiles. Interface-generated spin currents. PRL 121, 136805 (2018)
V. P. Amin, P. M. Haney & M. D. Stiles, "Interfacial spin-orbit torques," arXiv:2008.01182



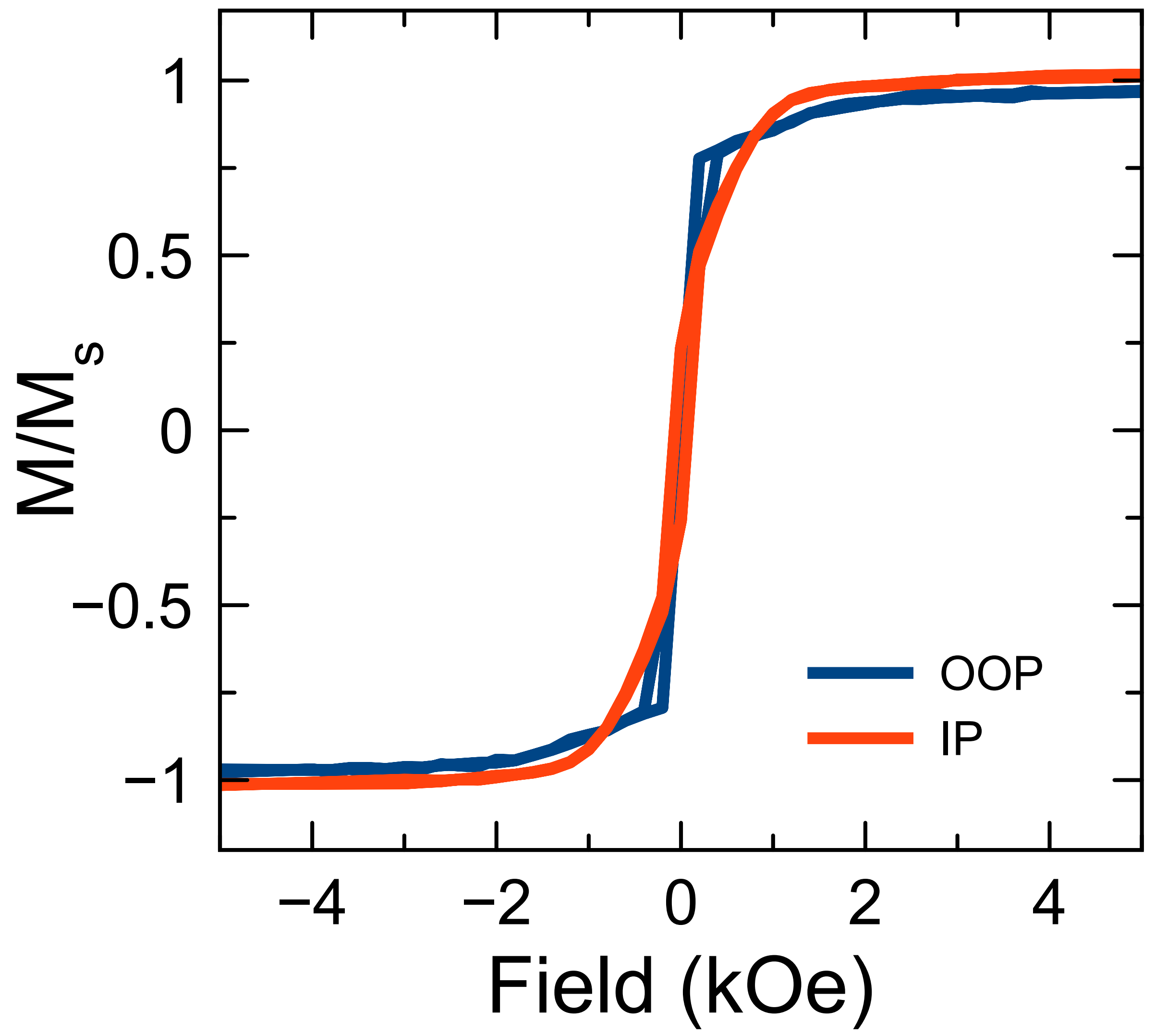
Patterned Samples



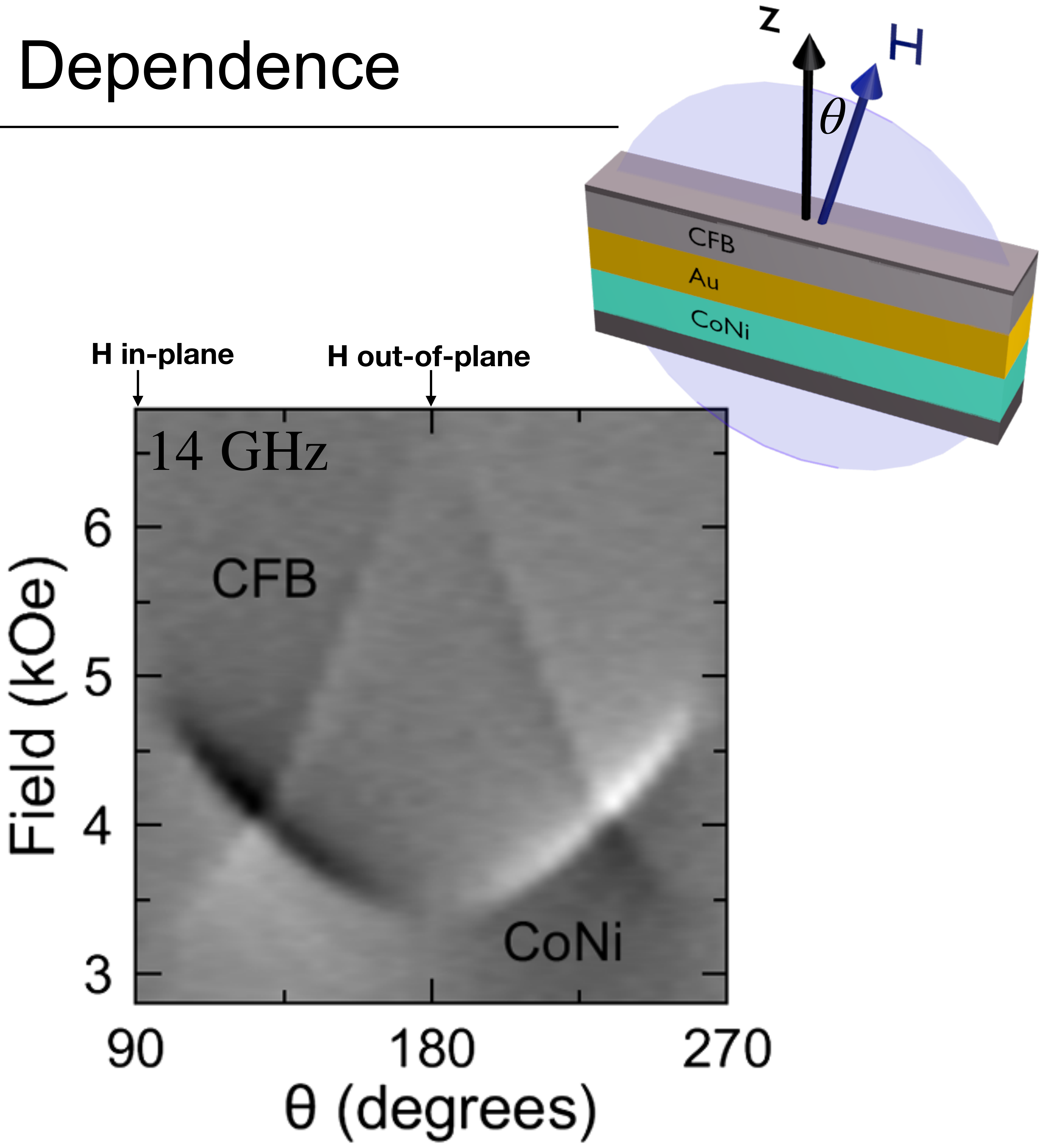
- 400 nm x 3 µm bridges

SiO_2/Ta(3)/Pt(3)/[Co(0.65)/Ni(0.98)]x2/Co(0.65)/Au(3)/CoFeB(1.5)/Ta(3)

- CoNi has large AMR and is grown with perpendicular anisotropy
- CoFeB has small AMR and is grown to be weakly in-plane
- A ~0.1 Tesla field can saturate both layers



ST-FMR Angular Dependence



- Angular dependence of resonance field with *f*=14 GHz drive can identify the layer's modes.

$$\left(\frac{\omega}{\gamma}\right)^2 = \mu_0^2(H - M_{\mathrm{eff}}\cos 2\theta)(H - M_{\mathrm{eff}}\cos^2\theta)$$

$$M_{\mathrm{eff}} = M_s - H_p$$

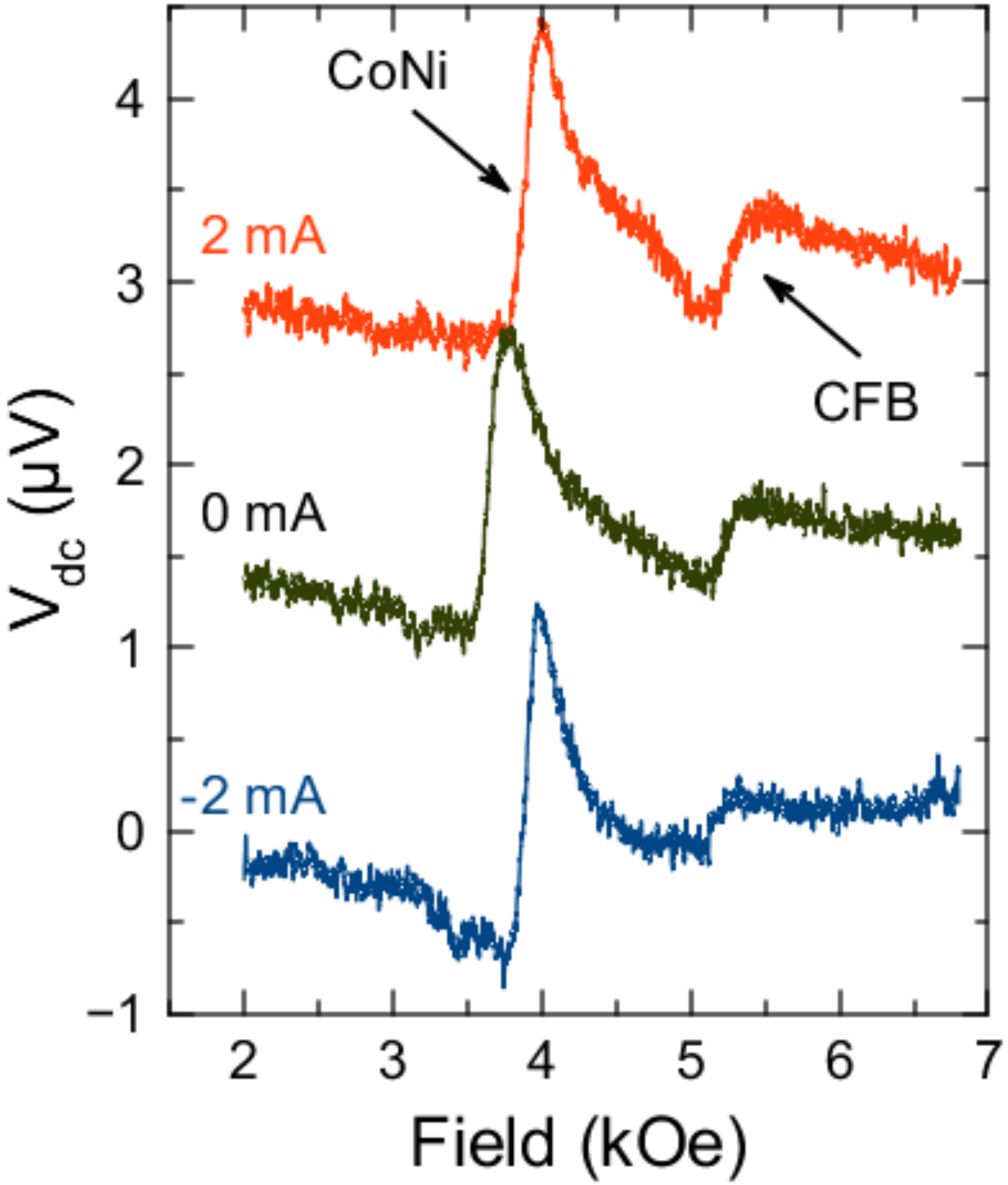
- CoNi has out-of-plane anisotropy ($M_{\mathrm{eff}} < 0$):
  H_{res} large for H in-plane
- CFB has in-plane anisotropy ($M_{\mathrm{eff}} > 0$):
  H_{res} large for H out-of-plane

ST-FMR Bias Dependence

- We work at high enough frequency so that the applied fields saturate both FM's magnetizations parallel to the applied field.
- Application of DC current changes the resonances linewidths

$$\Delta H = \Delta H_0 + 2\alpha\frac{\omega}{\gamma} + \frac{\hbar}{e}\frac{\eta}{M_s t_{\mathrm{FM}}}\frac{I_{dc}}{w t_{\mathrm{tot}}}\cos\theta\sin\theta$$

f = 14 GHz, θ = 330 degrees

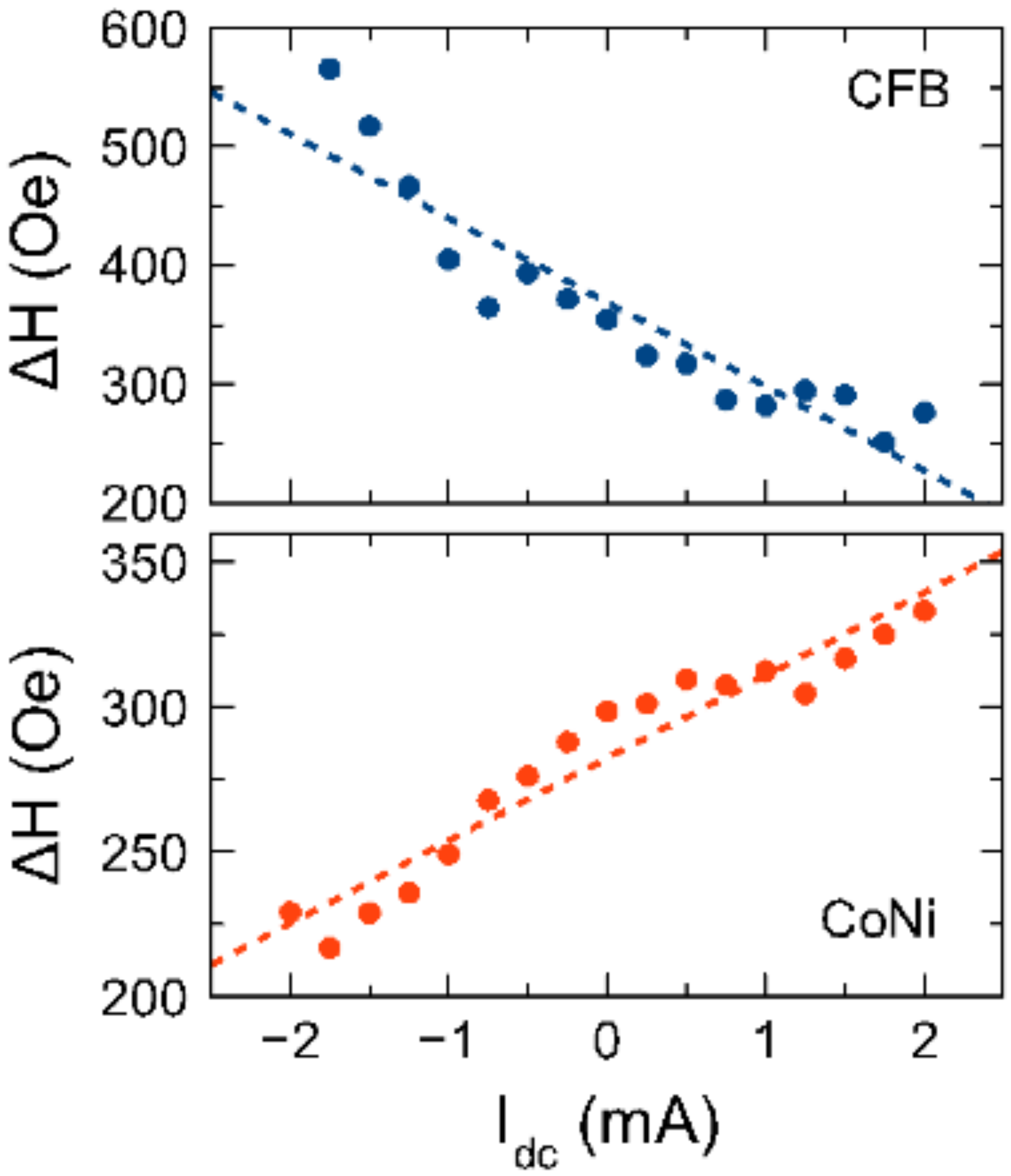


Linewidth vs Bias

- Observe linear modulation of resonance linewidth for both layers.
- The slope is proportional to the charge to spin conversion efficiency

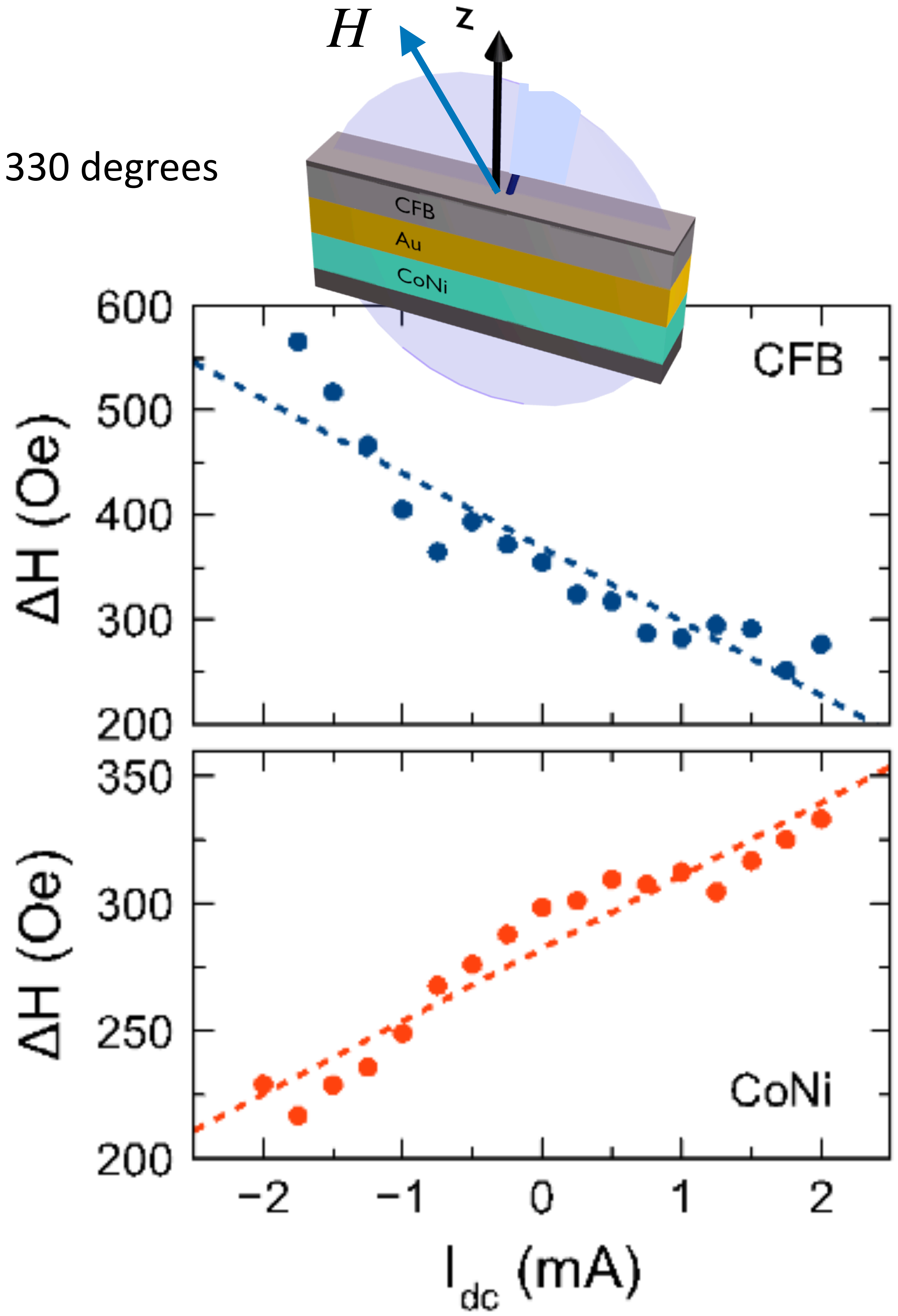
$$\frac{d\Delta H}{dI_{\mathrm{dc}}} = \frac{\hbar}{e}\frac{\eta}{M_s\, t_{\mathrm{FM}}}\frac{\cos\theta\sin\theta}{w t_{\mathrm{tot}}}$$

f = 14 GHz, θ = 330 degrees

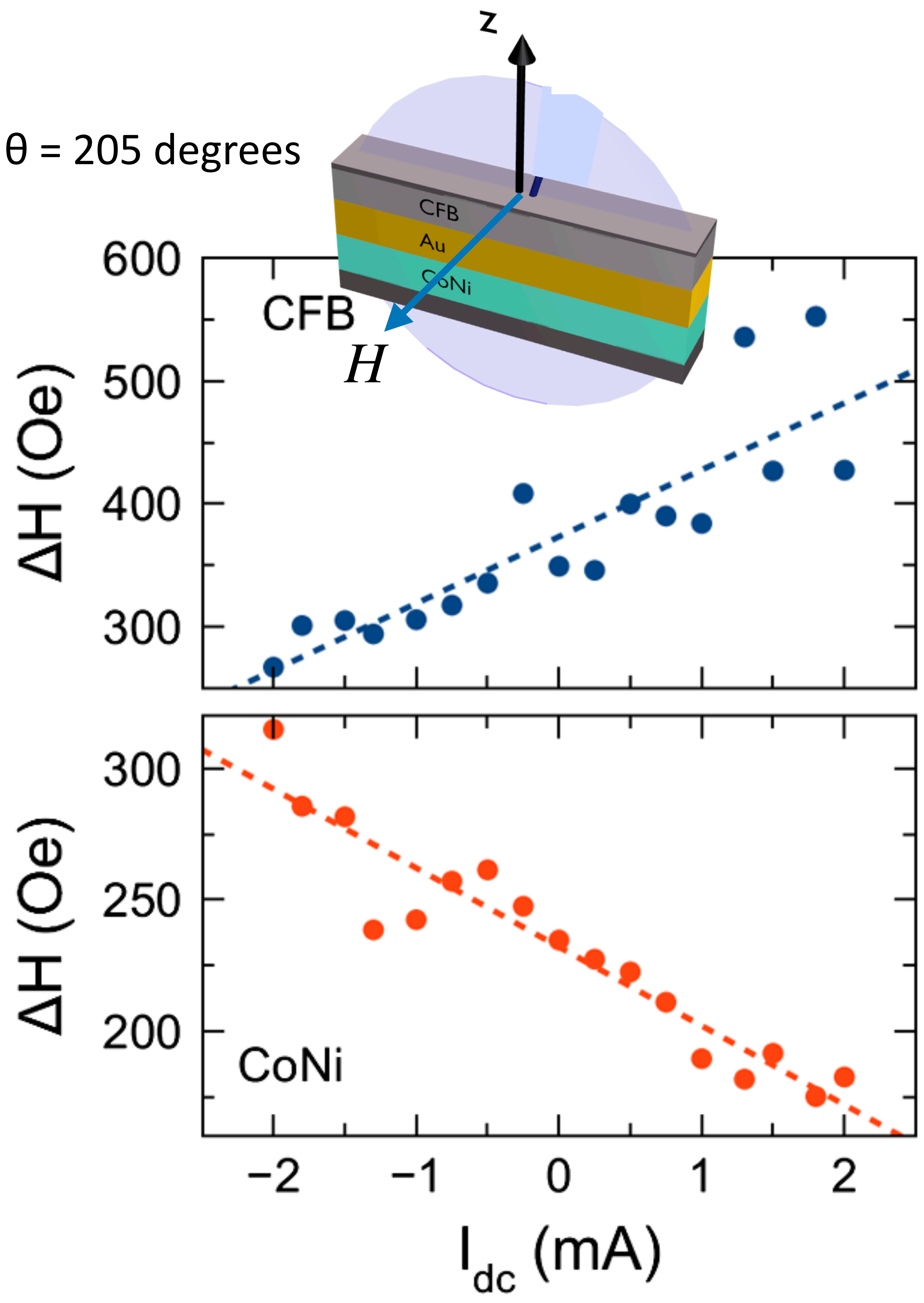


Linewidth vs Bias

θ = 330 degrees



θ = 205 degrees



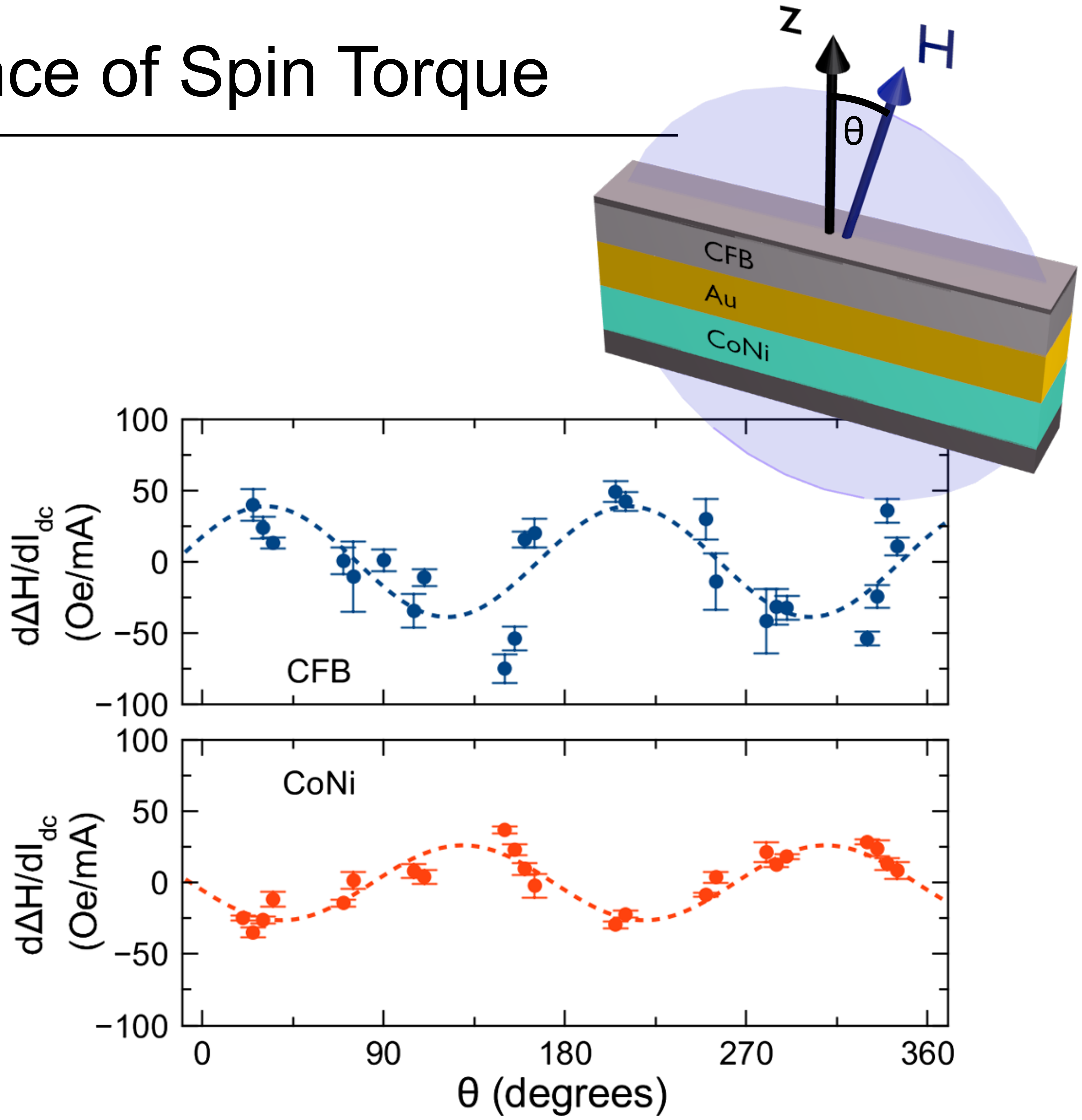
- Changing the z component of the field changes the sign of the spin-torques

Angular Dependence of Spin Torque

- Slope of linewidth vs bias follows expected angular dependence:

$$\frac{d\Delta H}{dI_{dc}} = \frac{\hbar}{e}\frac{\eta}{M_s t_{FM}}\frac{\cos\theta\sin\theta}{w t_{\mathrm{tot}}}$$

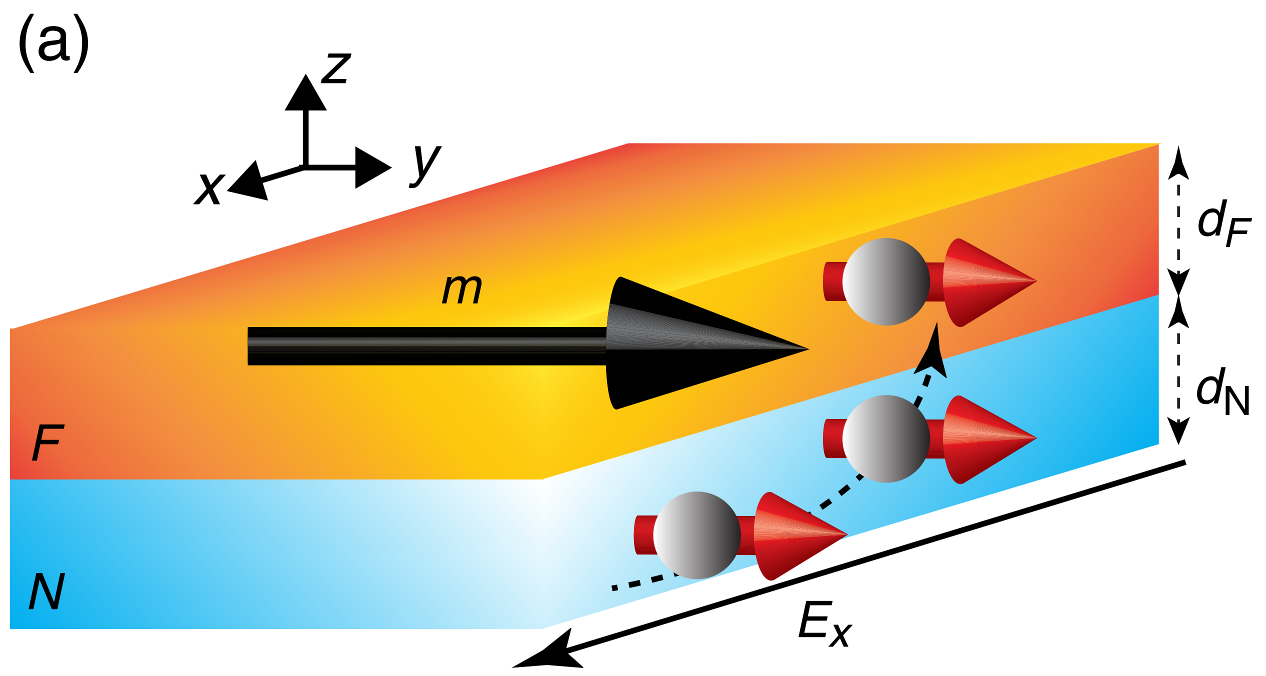
- Overall charge to spin conversion efficiency:
  - CFB $\eta = 0.05$
  - CoNi $\eta = 0.09$
- Similar conversion efficiency as spin Hall effect in materials like Pt.



C. Safranski, J. Z. Sun, J-W. Xu and ADK, PRL **124**, 197204 (2020)

Spin Currents Set By Magnetization

Spin Hall effect in non-magnetic metals



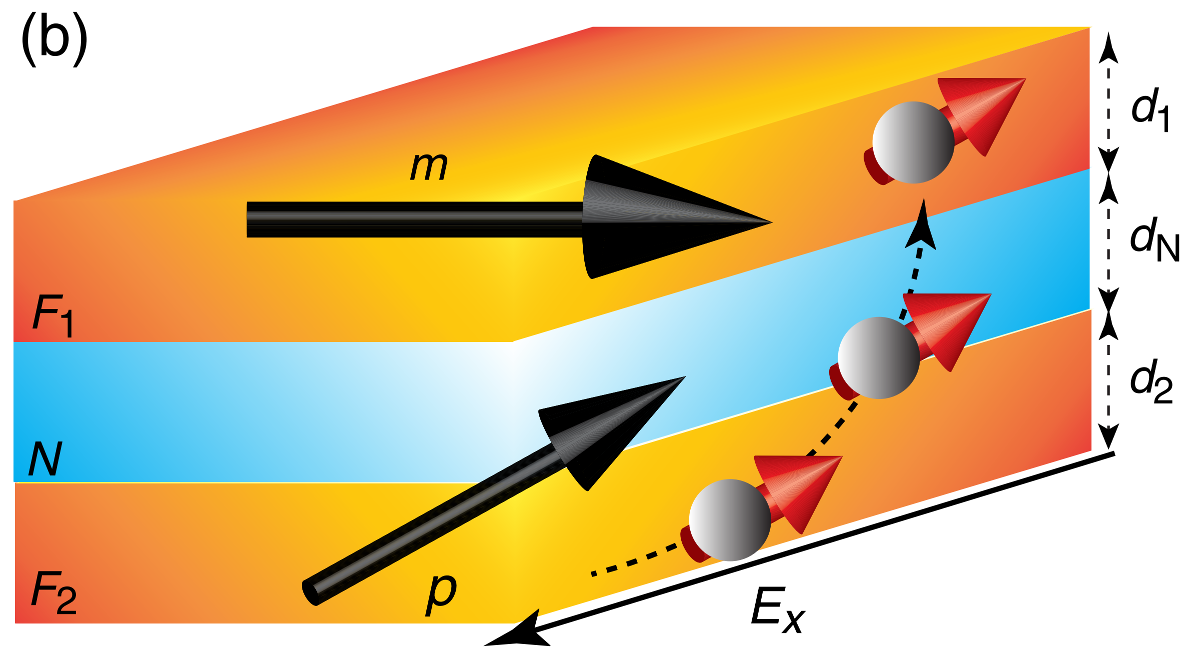
Spin Hall Effect

$$\mathbf{Q} = \frac{-\hbar}{\mathbf{2e}}\xi\sigma_{\mathrm{SHE}}(\hat{z}\times\mathbf{E})\otimes\hat{z}$$

Polarization ⊗ Flow direction

Polarization and flow direction set by geometry

Spin Orbit Interaction in magnetic metals



Anomalous Hall Effect

$$\mathbf{Q} = \frac{-\hbar}{2e}\zeta\sigma_{\mathrm{AH}}\mathbf{m}\otimes\mathbf{m}\times\mathbf{E}$$

Flow perpendicular to m and E

Planar Hall Effect

$$\mathbf{Q} = \frac{-\hbar}{2e}\eta\sigma_{\mathrm{AMR}}\mathbf{m}\otimes\mathbf{m}(\mathbf{m}\cdot\mathbf{E})$$

Flow parallel to m

✓

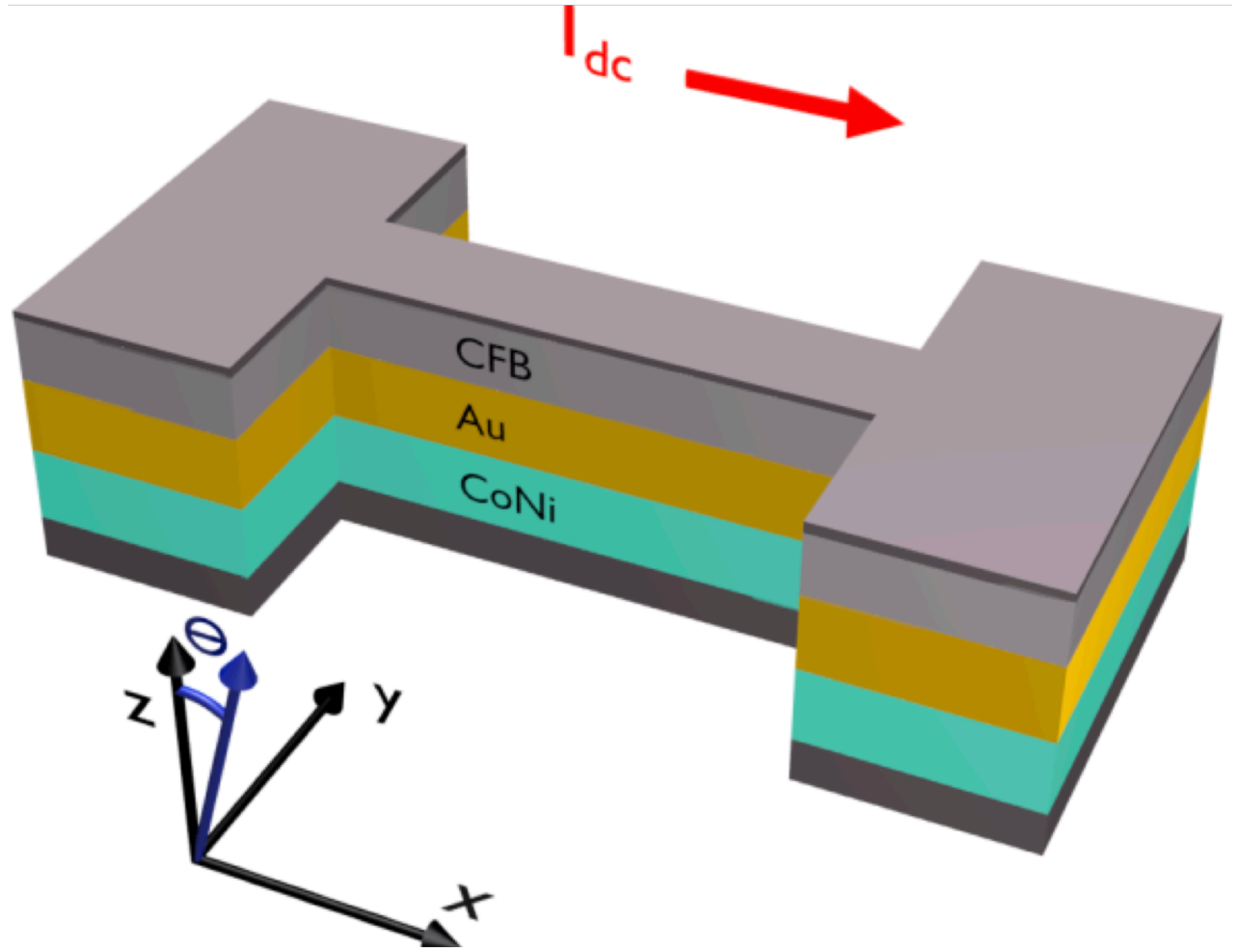
Polarization and flow direction set by magnetization!

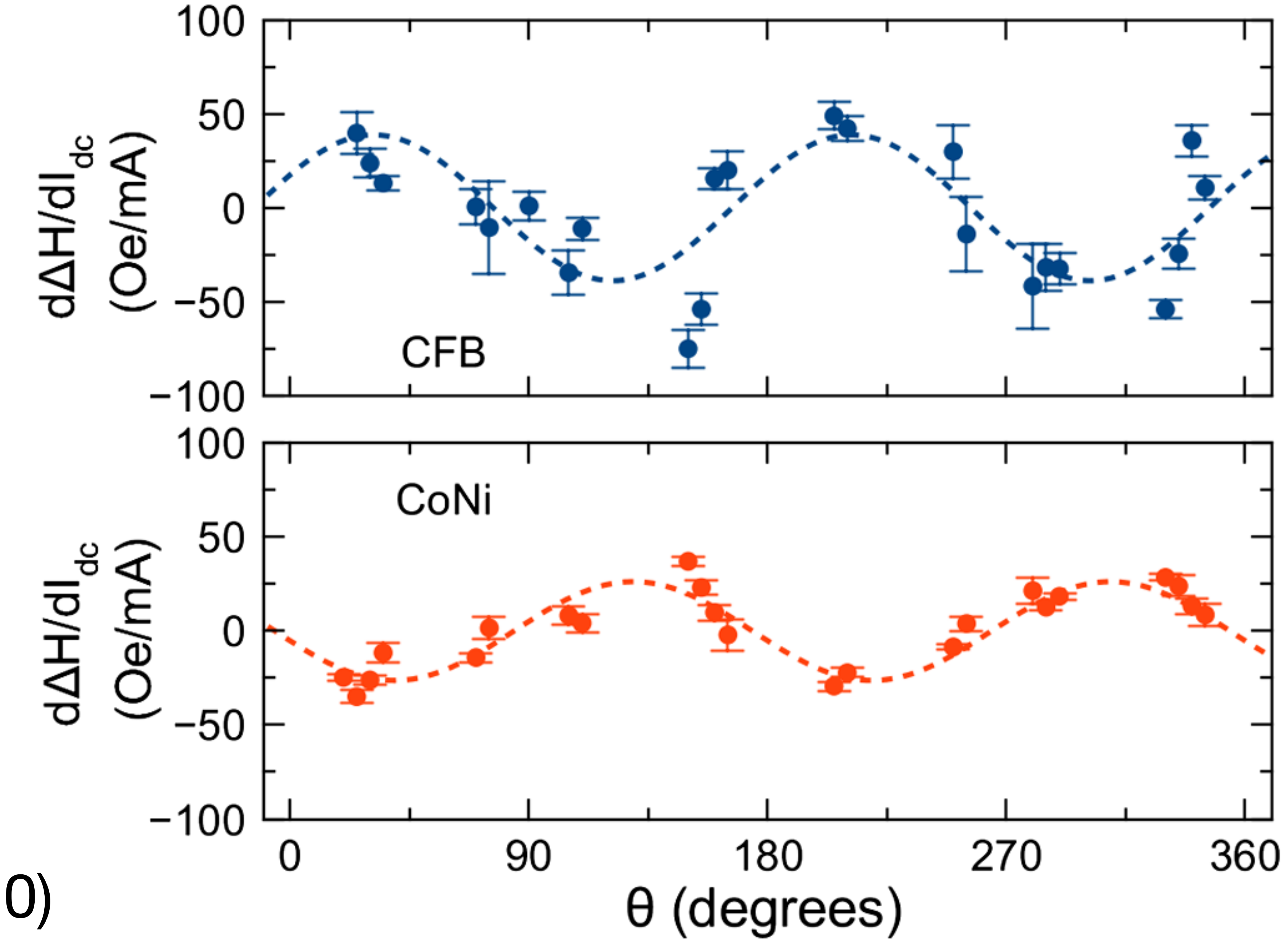
Figures from T. Taniguchi *et al*., PR Applied **3**, 044001 (2015)

Angular Symmetry

Spin Charge Effect	Spin Polarization	Spin Flow Direction	Symmetry Under Field Reversal*
Spin Hall	$\hat{y}$	$\hat{z}$	Odd
Anomalous Hall	$\mathbf{m}$	$\mathbf{m} \times \hat{x}$	Odd
Planar Hall	$\mathbf{m}$	$\mathbf{m}(\mathbf{m} \cdot \hat{\mathbf{x}})$	Even
Spin Seebeck	$\mathbf{m}$	$\hat{z}$	Even

*Symmetry of anti-damping torque under field reversal with fixed current direction





C. Safranski, J. Z. Sun, J-W Xu and ADK, PRL **124**, 197204 (2020)

Electrical generation of spin currents

Summary

- Spin torque switching in perpendicular MTJ nanopillars
  - -Charge-to-spin conversion efficiency can be 0.23 for switching!

- Spin orbit torques with planar Hall effect symmetry have been observed in CoNi multilayers
  - -Charge-to-spin conversion efficiency (~0.05) is on par with the Spin Hall effect in Pt.
  - -The spin polarization can be partially out-of-plane, making the PHE a candidate for deterministic switching of perpendicularly magnetized MTJs

https://www.spintalks.org/talks/safranski

PRL **124**, 197204 (2020)

L. Rehm *et al.*, APL **115**, 182404 (2019)
L. Rehm *et al.,* PR Appl. **15**, 034088 (2021)

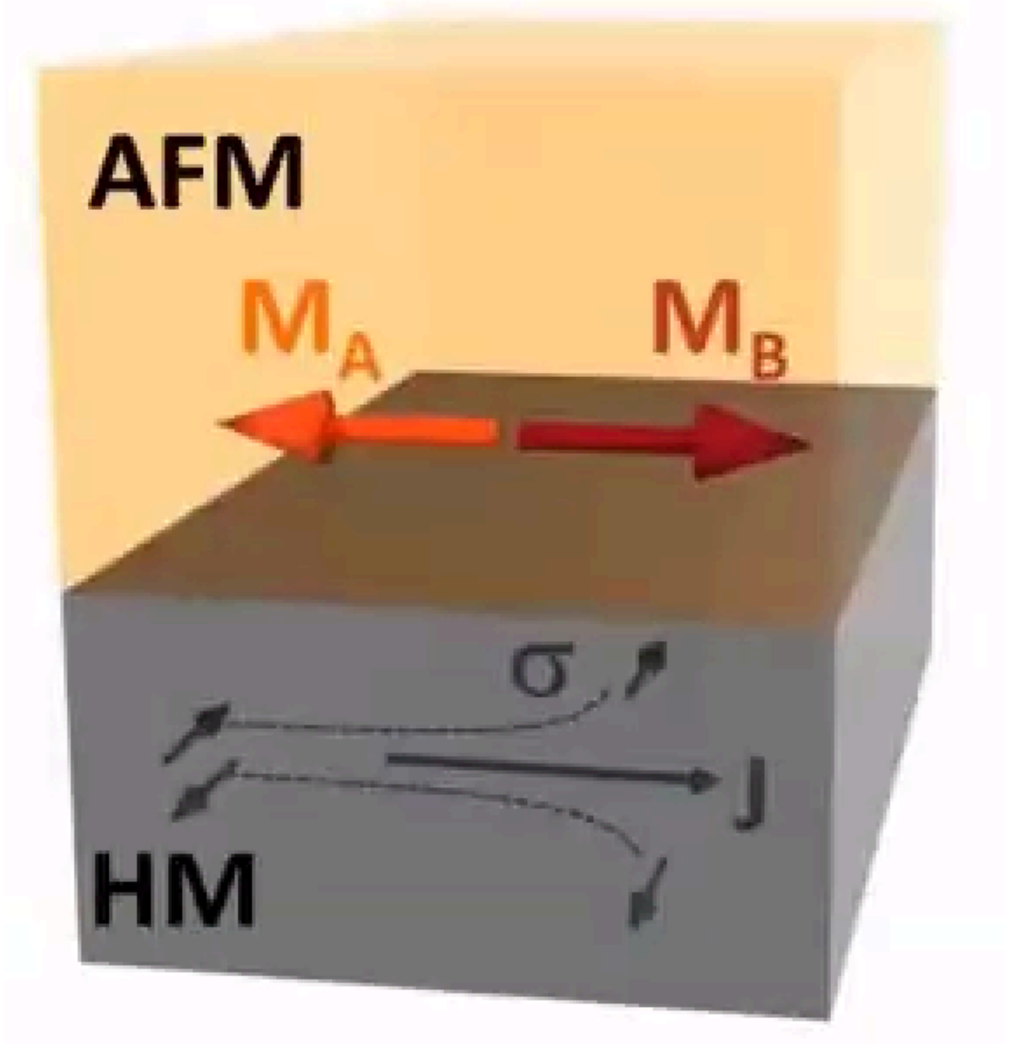
Kent Group

January 2020

http://www.physics.nyu.edu/kentlab/

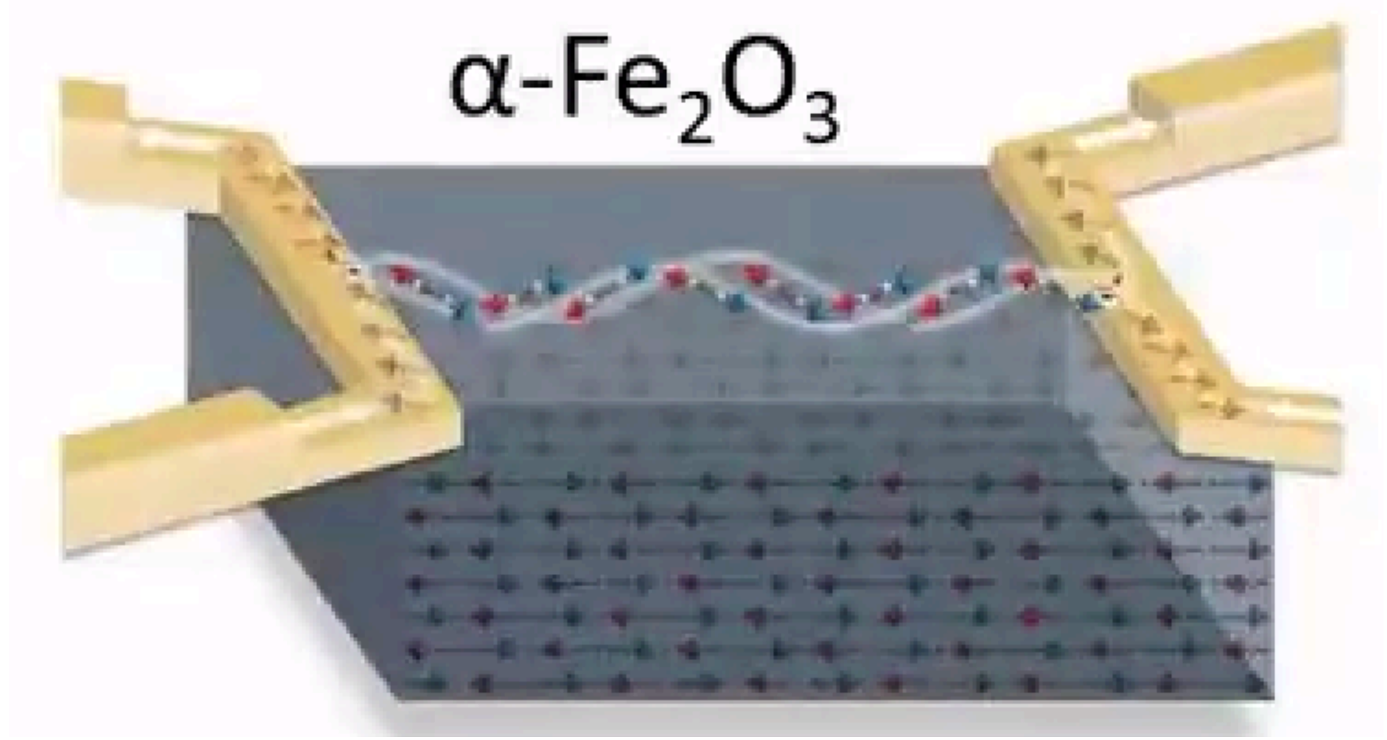
POSTDOCTORAL POSITION: ANTIFERROMAGNETIC SPINTRONICS @ NYU

Description: A postdoctoral position is available in Prof. Andrew Kent's research group in the Center for Quantum Phenomena of the Department of Physics. The research focus is on antiferromagnetic spintronics, specifically spin-transport phenomena in thin films of antiferromagnetic insulators and at their interfaces with heavy metals, ferrimagnets and ferromagnets. The successful candidate will work within a multi-university and national lab team with expertise in thin film materials, magnetic imaging, measurement, nanofabrication and modeling. Experience with electronic transport and magnetic measurements, magnetic imaging (e.g. x-ray), thin film deposition, nanofabrication and magnetic characterization methods is desirable. Good communication, writing and interpersonal skills are essential.

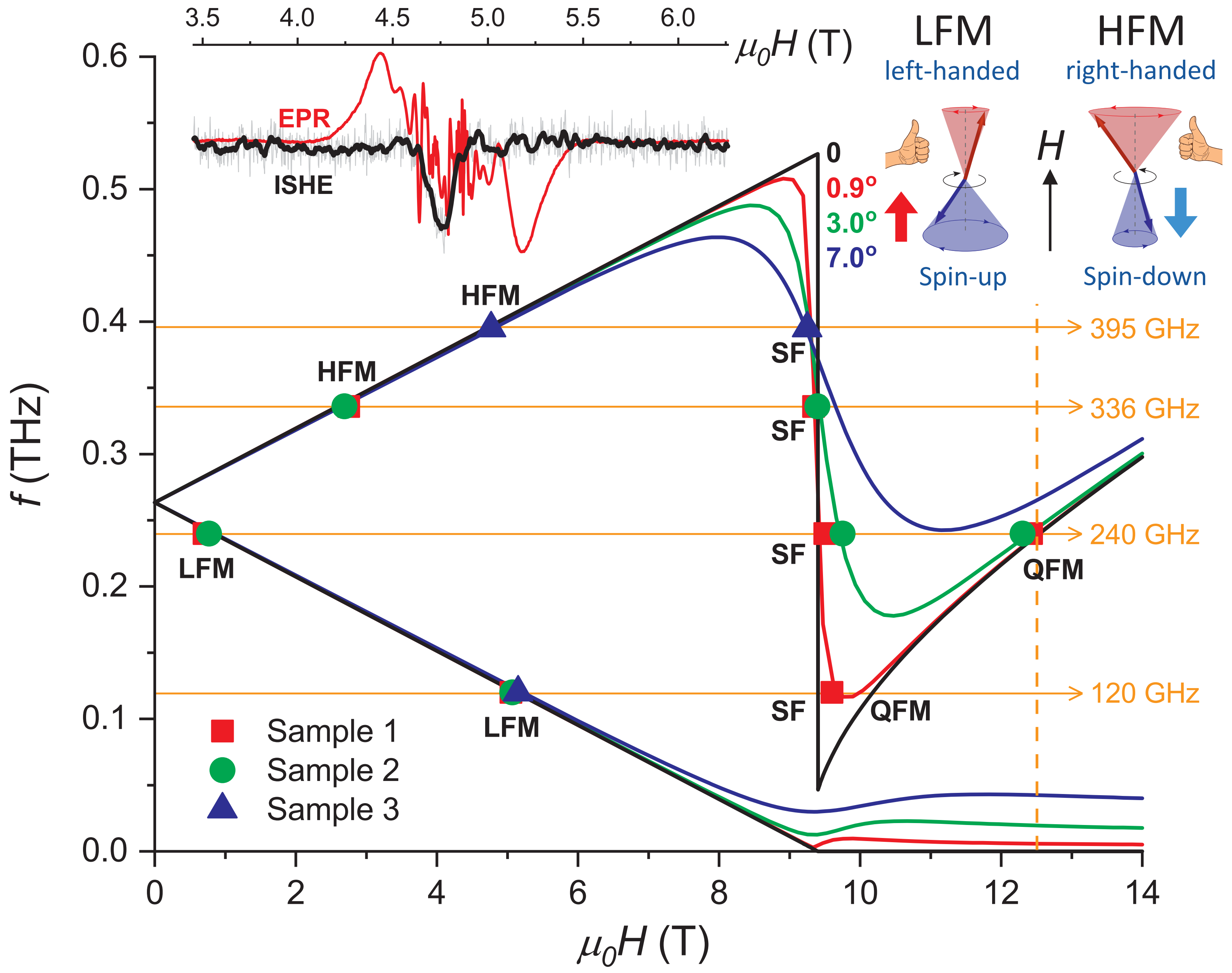


Email: andy.kent@nyu.edu

Posted: NYU Physics/Interfolio websites soon



R. Lebrun et al., Nature **561**, 222 (2018)



P. Vaidya et al., Science **268**, 160 (2020)

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-NYU: Gabriel Chaves and Dan Stein

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-UC Santa Cruz: David Lederman

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