Optical studies of current-induced magnetization

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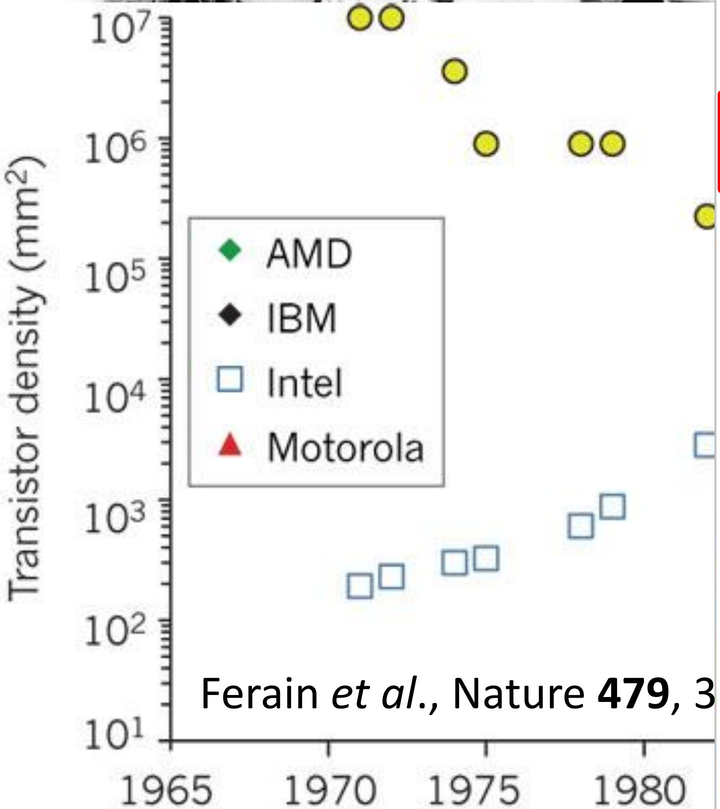
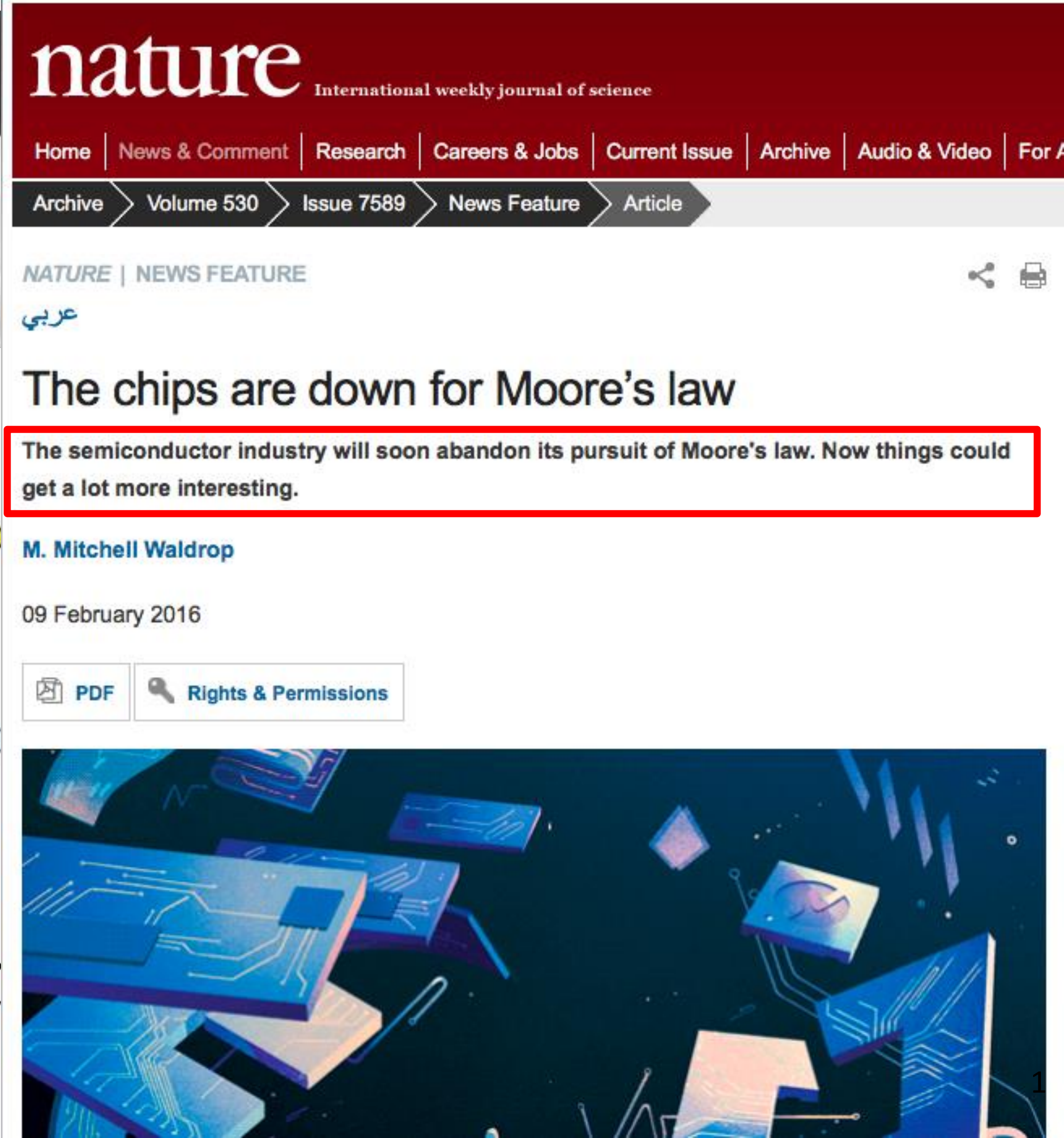
PHYS403, December 5, 2017

The scaling of electronics



Ferain *et al.*, Nature **479**, 3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NATURE | NEWS FEATURE

عربي

The chips are down for Moore's law

The semiconductor industry will soon abandon its pursuit of Moore's law. Now things could get a lot more interesting.

M. Mitchell Waldrop

09 February 2016

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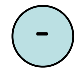
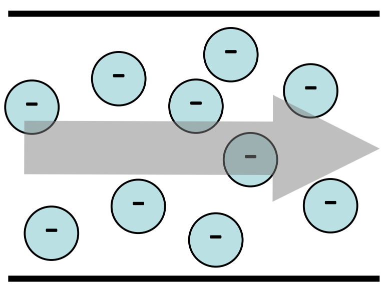
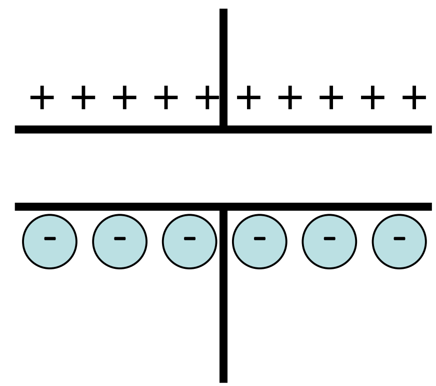
Electronics: charge of electron



Transfer information



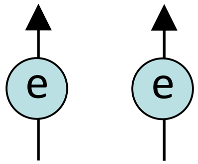
Store information



Miniaturization: Heat dissipation

Leakage

Spin of electron and magnetism



Electron spin

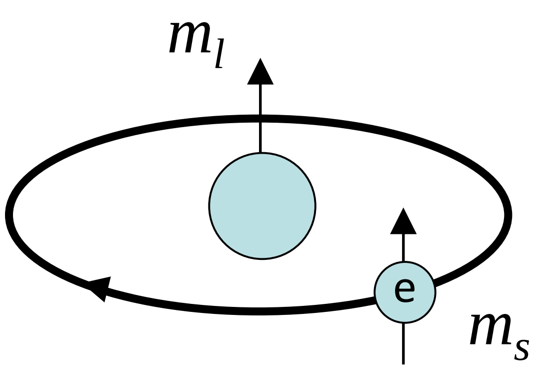
Projection of angular momentum

$$s = \pm \frac{\hbar}{2}$$

Spin magnetic dipole moment

$$\boldsymbol{\mu}_s = -g_s \mu_B \frac{\mathbf{S}}{\hbar}.$$ with g ~ 2

Orbital magnetic dipole moment



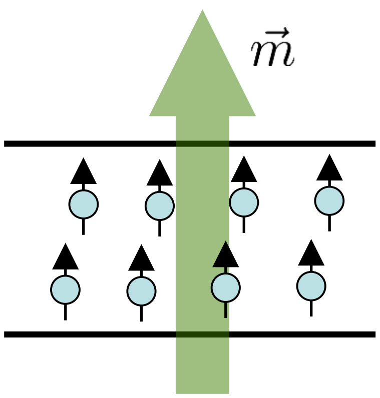
→ magnetization

Exchange interaction

Tends to keep the spins parallel

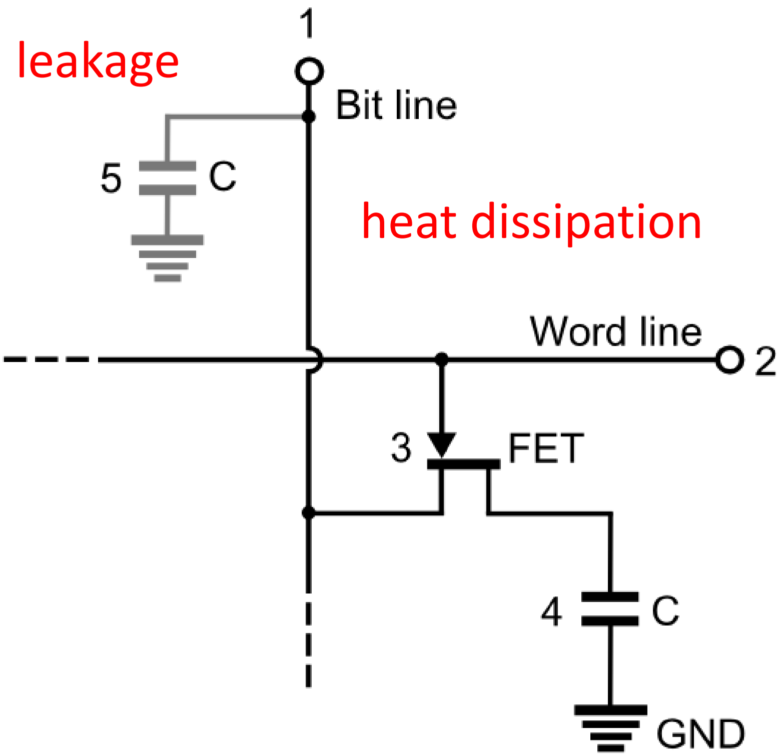
"magnetization" $\vec{m}$ = magnetic moment per unit volume

$m = \mu/V$

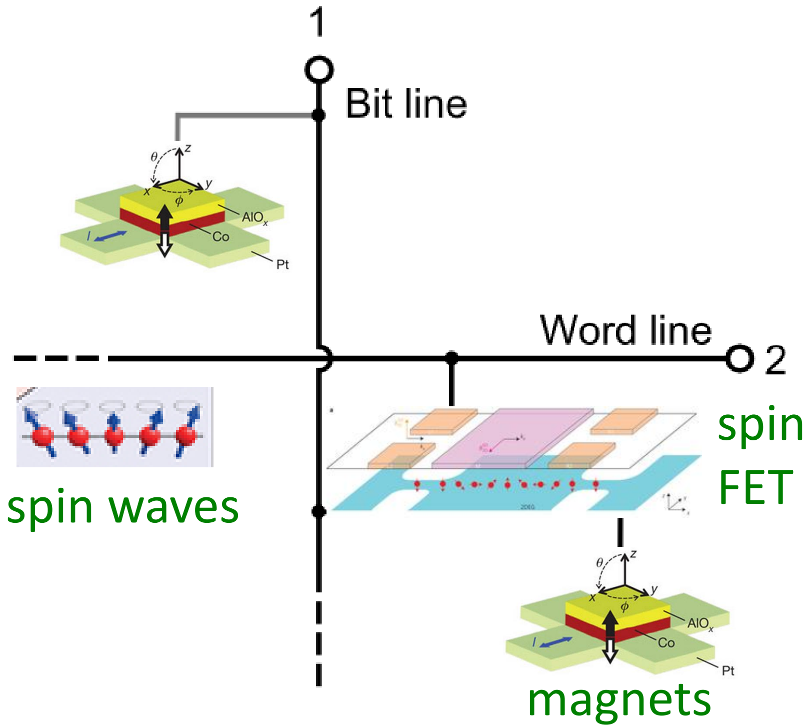


Charge vs. Spin

Electronic integrated circuit



Spintronic integrated circuit

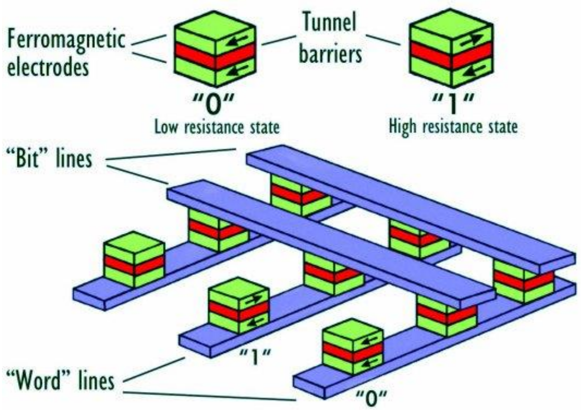


Miron IM, *et. al.* Nature **476**, 189 (2011).
Chumak *et al.*, Nat. Phys. 11, 453 (2015).
Chuang *et al.*, Nat. Nano. 10, 35 (2015).

Spintronics

- Use **magnetization** to control **current**
  - Giant magnetoresistance 1988
  - Used in read heads since 1997
- Use **current** to control **magnetization**
  - Tunneling magnetoresistance 1975
  - Magnetic random access memory 1995
- But challenges remain
  - High-efficiency control of magnetization with current at the nanoscale

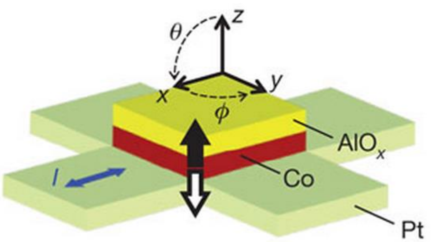

Fert and Grünberg, 2007



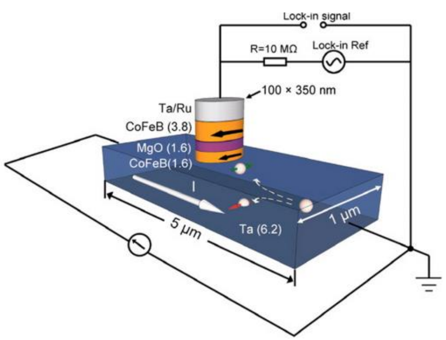
Fert, Rev. Mod. Phys. **80**, 1517 (2008).

Current-induced magnetization in bilayers

Magnetization switching

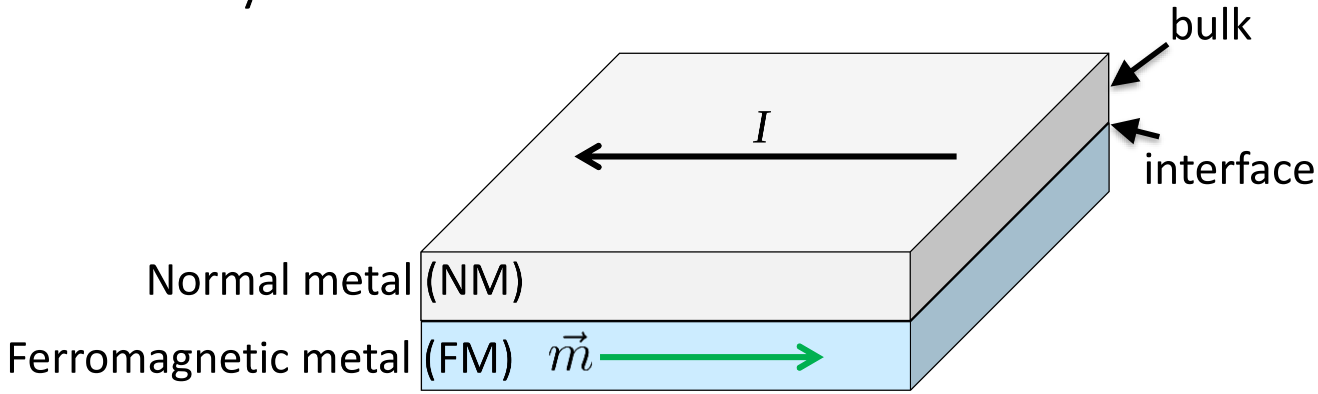


Miron IM, *et. al.* Nature **476**, 189 (2011).



Liu L, *et. al.* Science **336**, 555 (2012).

- Normal metal (NM) / ferromagnetic metal (FM) bilayer



- Mechanism controversial: two proposed
  - Spin Hall effect – bulk of NM
    Liu *et al.*, Science **336**, 555 (2012).
  - Rashba effect – FM/NM interface
    Miron *et al.*, Nat. Mater. **9**, 230 (2010).

- Signatures to distinguish proposed
  Haney *et al.*, Phys. Rev. B **87**, 174411 (2013).

Current-induced magnetization in bilayers

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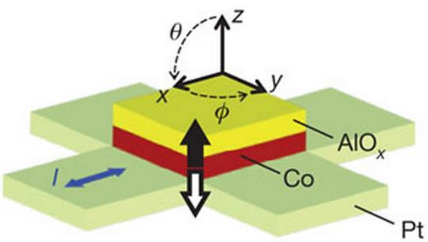
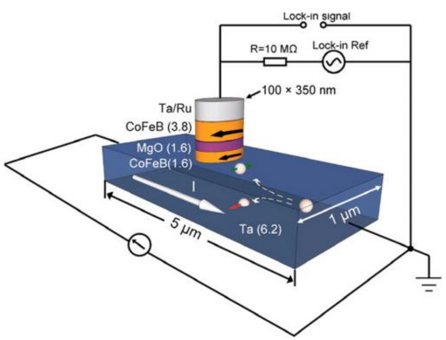
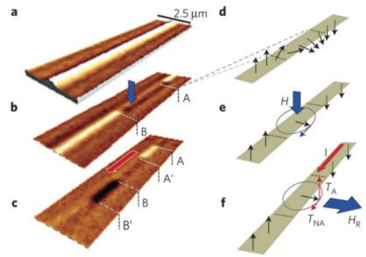


Miron IM, *et. al.* Nature **476**, 189 (2011).

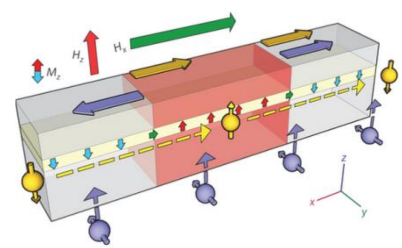


Liu L, *et. al.* Science **336**, 555 (2012).

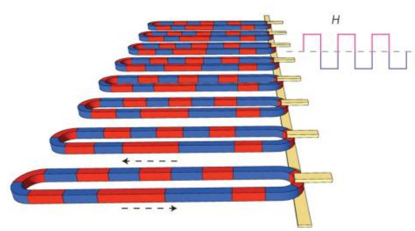
Domain interaction



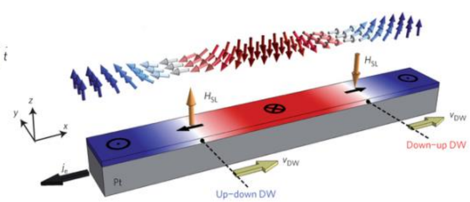
Miron IM, *et. al.* Nature Materials (2011)



Haazen PPJ, *et. al.* Nature Materials (2013)

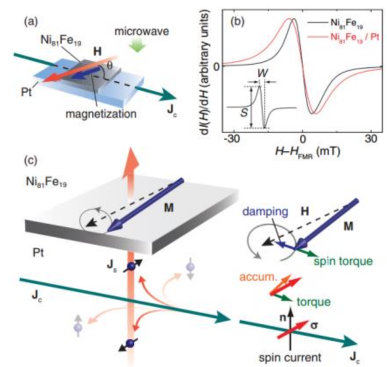


Franken JH, *et. al.* Nature Nanotechnology (2012)

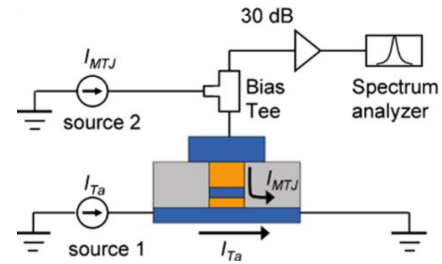


Emori S, *et al.* Nature Materials (2013)

Dynamics manipulation



Ando K, *et. al.* PRL (2008)



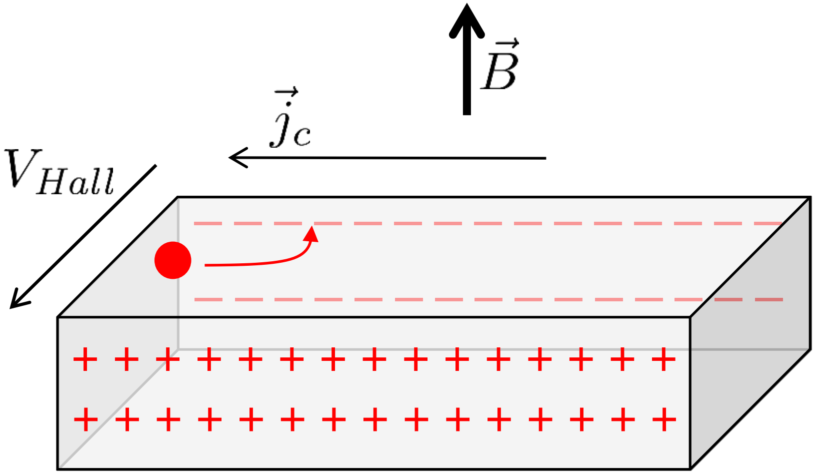
Liu L, *et. al.* PRL (2012)

Motivation

Investigate mechanisms of current-induced magnetization in normal metal / ferromagnetic metal bilayers

Develop a sensitive optical technique to measure current-induced magnetization

Spin Hall Effect

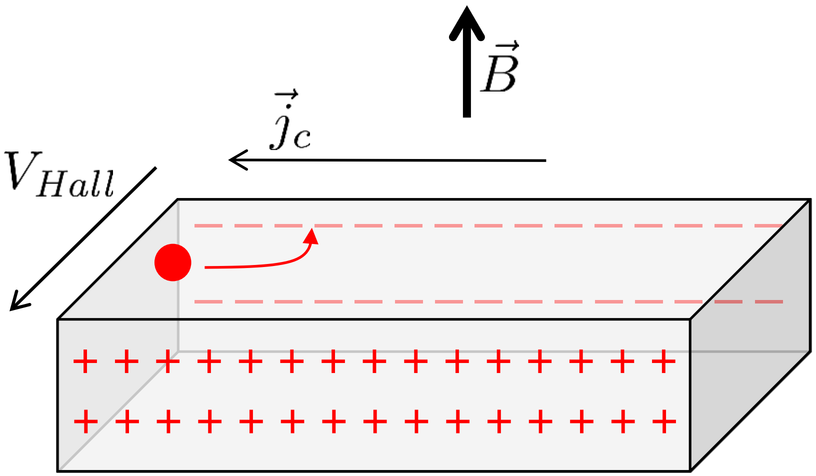


Hall Effect

- Electrons flowing through a normal metal are diverted by external magnetic field
- Produce a voltage difference

$$V_{Hall} = R_H \vec{B} \times \vec{j}_c$$

Spin Hall Effect



Hall Effect

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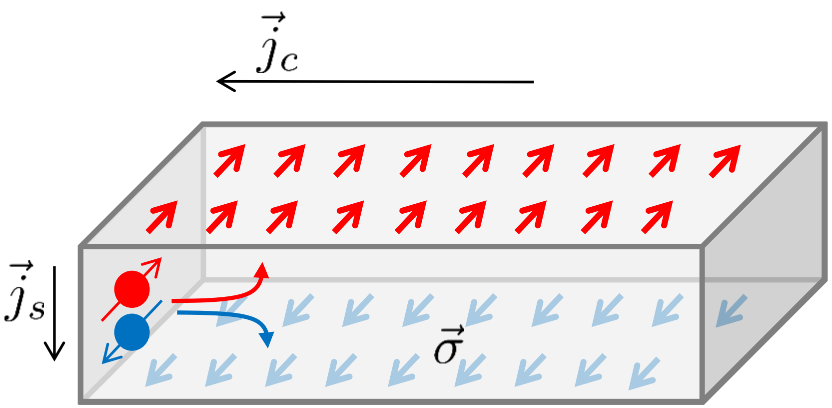


Spin Hall Effect

- Electrons with spin up and down travel differently due to spin-orbit interaction
- Spin accumulation occurs at the top and bottom of the normal metal

unit spin vector

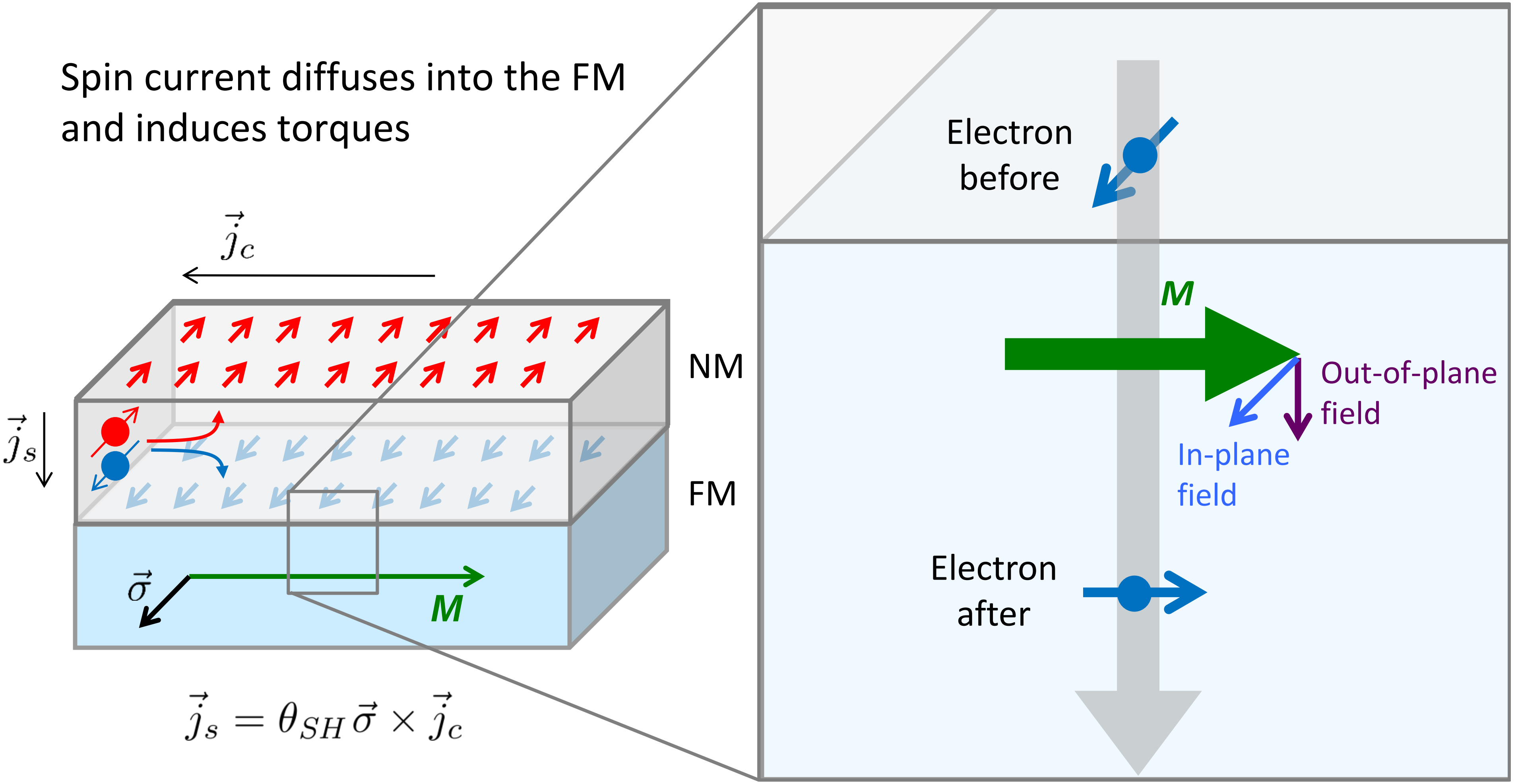
$$\vec{j}_s = \theta_{SH} \vec{\sigma} \times \vec{j}_c$$

spin current → $\vec{j}_s$; ← charge current ($\vec{j}_c$); ↑ "spin Hall angle" (θ_{SH})

D'yakonov & Perel', JETP Lett. **13**, 467 (1971).
Hirsch, Phys. Rev. Lett. **83**, 1834 (1999).

Current-induced magnetization: Spin Hall Effect

Spin current diffuses into the FM and induces torques

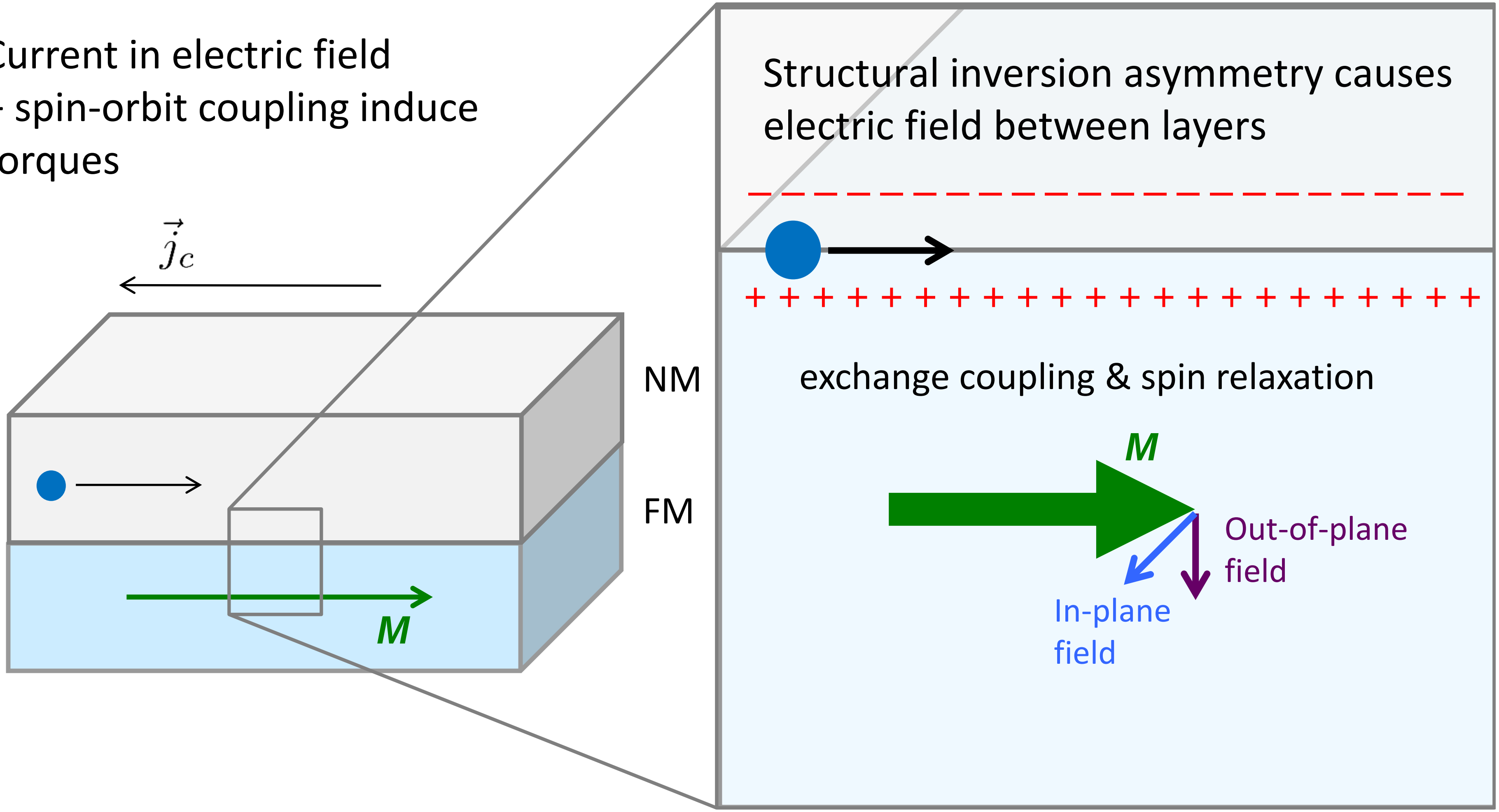


$$\vec{j}_s = \theta_{SH} \vec{\sigma} \times \vec{j}_c$$

Hirsch, Phys. Rev. Lett. **83**, 1834 (1999).

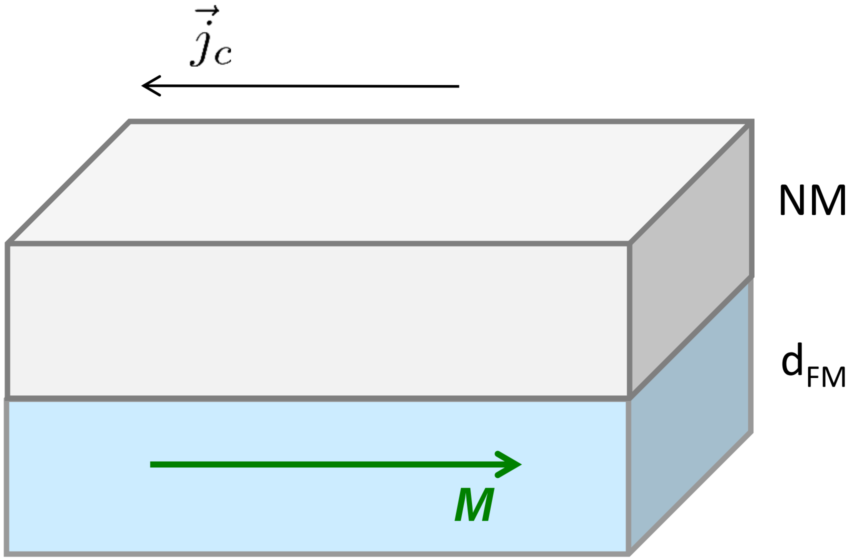
Current-induced magnetization: Rashba Effect

Current in electric field
+ spin-orbit coupling induce
torques



Manchon *et al.*, Phys. Rev B **79**, 094422 (2009).

Theory: distinguishing spin Hall & Rashba

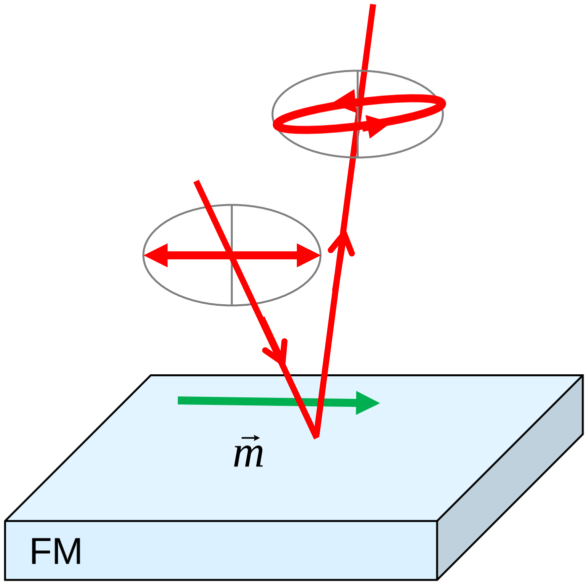


- Vary thickness of FM layer d_{FM}
- Spin Hall effect:
  - Out-of-plane field is proportional to $1/d_{FM}$
- Rashba effect:
  - Out-of-plane field decreases much faster than $1/d_{FM}$

Haney *et al.*, Phys. Rev. B **87**, 174411 (2013).

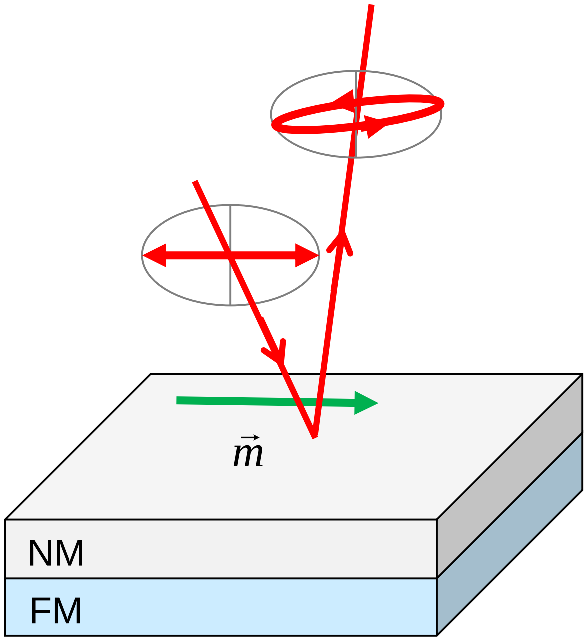
How? Magneto-optic Kerr effect

- Rotation and change of polarization state of light reflected from magnetic material



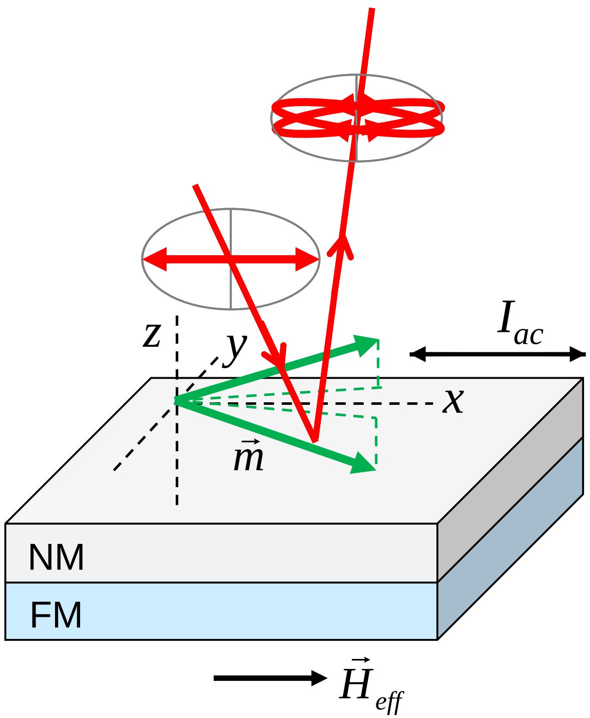
- Due to anisotropic permittivity (off-diagonal components of dielectric tensor ε): the speed of light varies according to its orientation

Optical studies of current-induced magnetization



Optical studies of current-induced magnetization

AC current generates oscillating change in magnetization



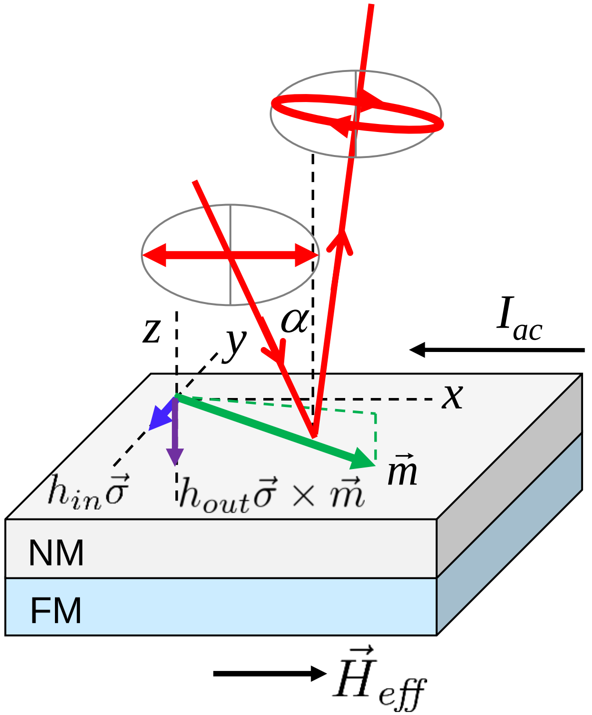
Change in polarization proportional to magnetization change

Advantages of optical technique:

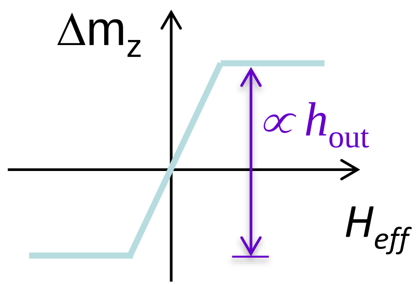
- Detects to first order in magnetization change, vs. 2nd order for electrical measurement techniques
- Non-contact, no artifacts from thermal or frequency-dependent rectification effects
- No need to go to high frequency
- Thin films can be measured
- All vector components of the magnetization can be measured simultaneously

Optical studies of current-induced magnetization

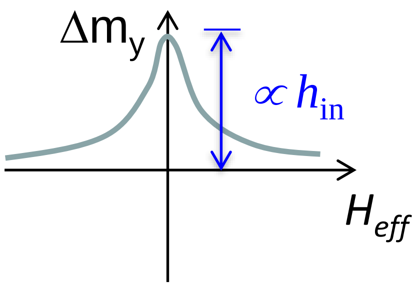
MOKE signal $\propto \Delta m_y \tan\alpha + \Delta m_z$



- Signal for normal incidence light:



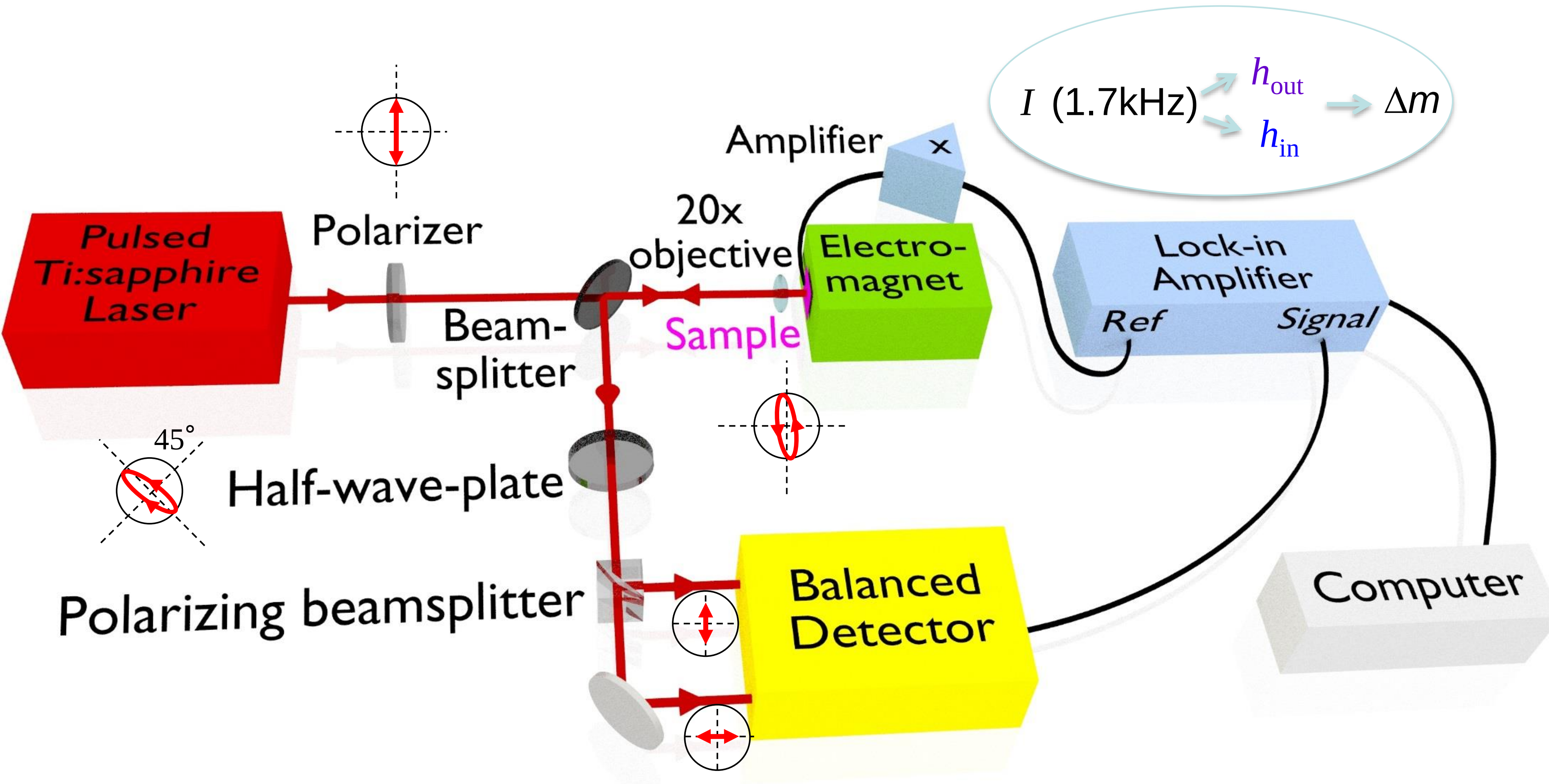
- Signal for oblique incidence light:



- If spin Hall dominates, h_{out} versus FM thickness scales as $1/d_{FM}$

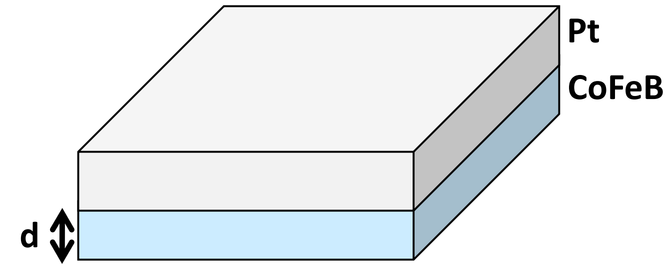
Haney *et al.*, Phys. Rev. B **87**, 174411 (2013).

Experimental setup

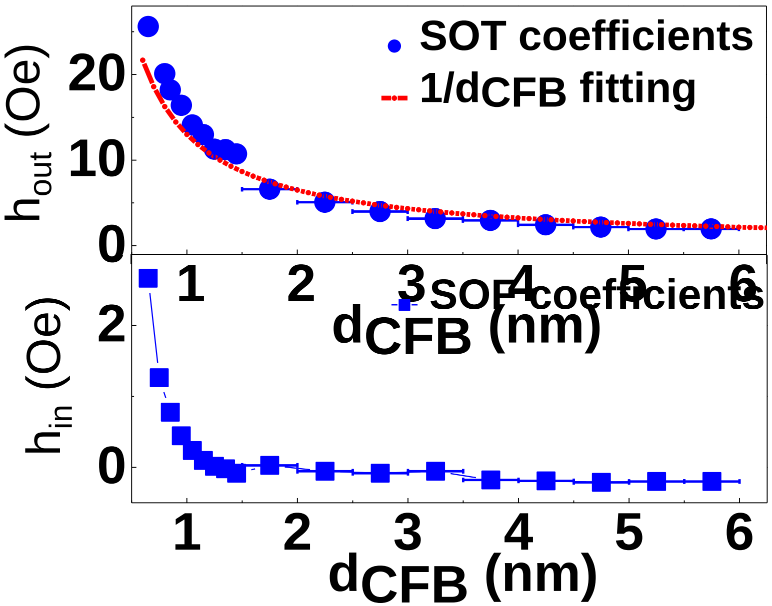


Experimental results: varying FM thickness

Varied thickness of $Co_{40}Fe_{40}B_{20}$ from 0.65 - 5.75nm



Ti(1nm)/CoFeB/Pt(5nm)

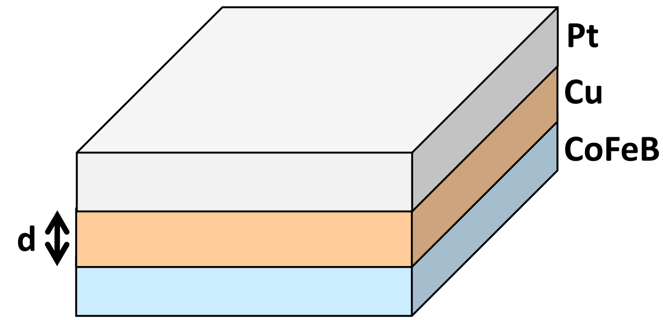


- h_{out} vs. FM thickness has 1/d dependence
- Implication: the dominant mechanism of spin-orbit torque in this bilayer is the bulk spin Hall effect*
- In-plane torque changes for thicknesses < 1nm → some kind of interface effect
- To be conclusive, must quantify the interface effect separately from the bulk effect

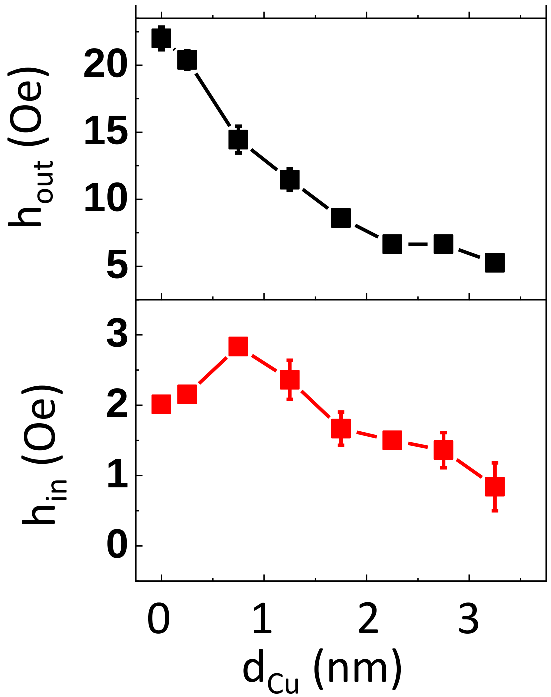
*Haney, et al., Phys. Rev. B **87**, 174411 (2013).

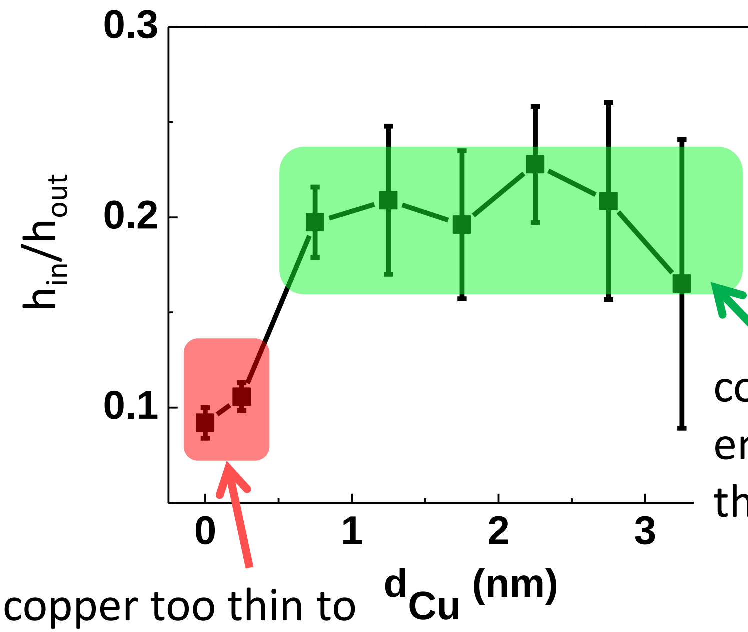
Experimental results: adding a spacer layer

- To test for interface effects, added copper layer
- Varied thickness of copper from 0-3.25nm



Ti(1)/CoFeB(0.7)/Cu/Pt(5nm)





copper is thick enough to remove the interface effect

copper too thin to form continuous film → interface effect

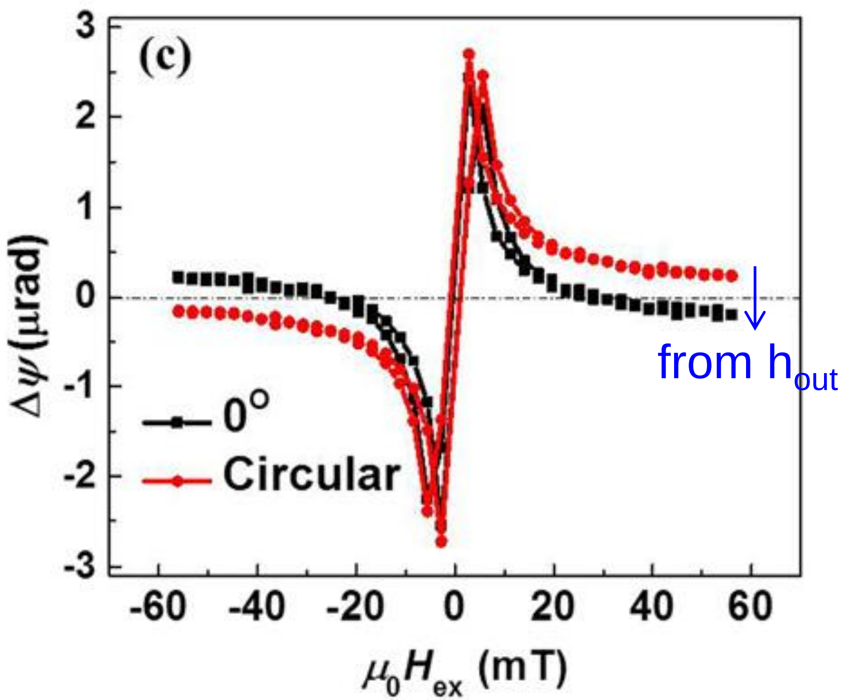
Spin Hall dominates but there is an interface effect

X. Fan, et al., Nat. Commun. **5**, 3042 (2014).

Quadratic magneto-optic Kerr effect

- Measuring in-plane field is possible without oblique incidence
- For normal incidence circularly polarized light, signal is proportional to $m_x m_y$

Jana H et al., Physica Status Solidi (b) **250**, 2194 (2013)

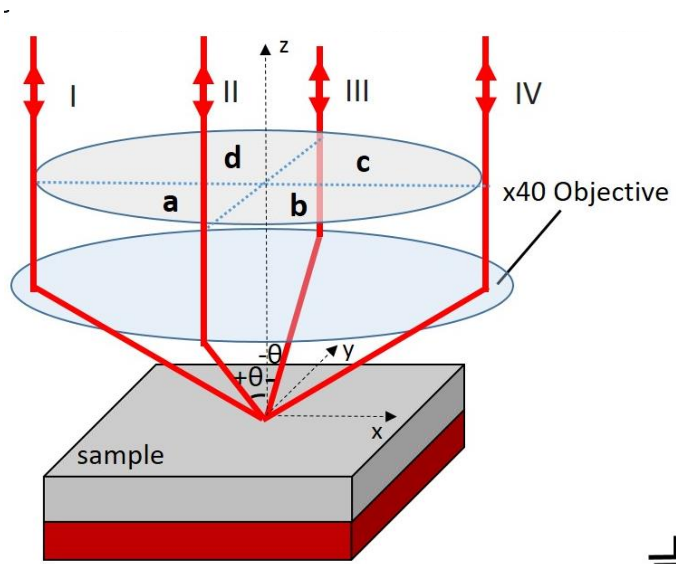


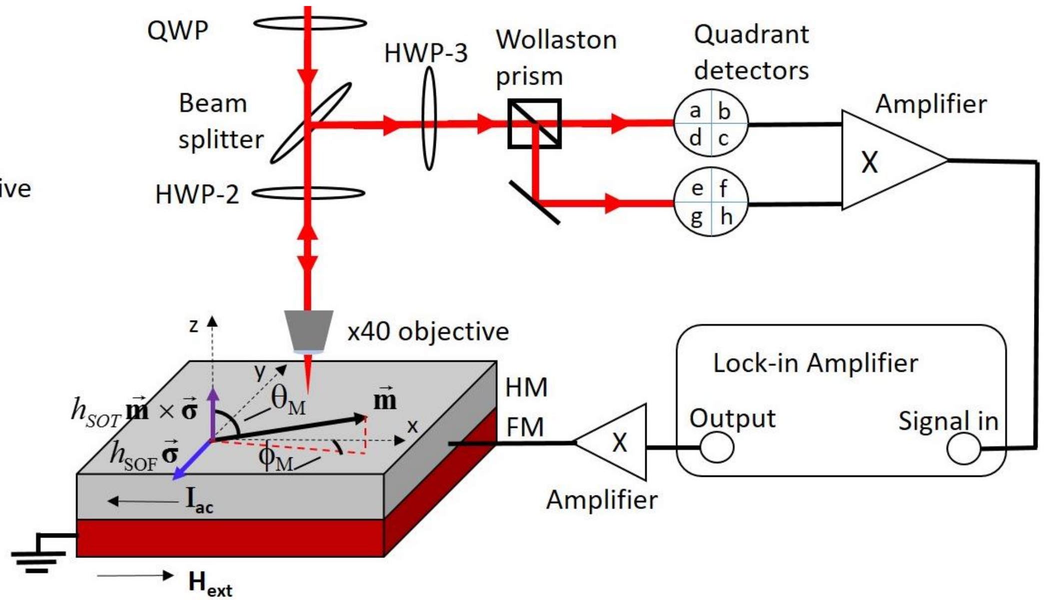
Can measure both out-of-plane and in-plane field using same experimental geometry

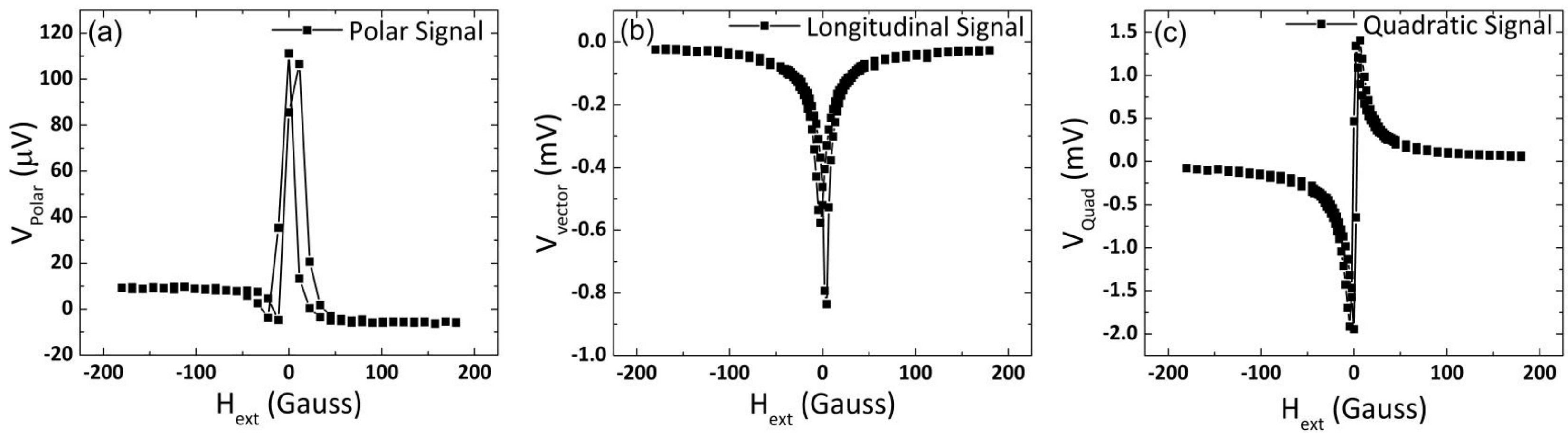
But $\eta_{Polar} : \eta_{Quadratic} \approx 50 : 1$

Fan *et al.*, Appl. Phys. Lett. **109**, 122406 (2016)

Vector magneto-optic Kerr effect



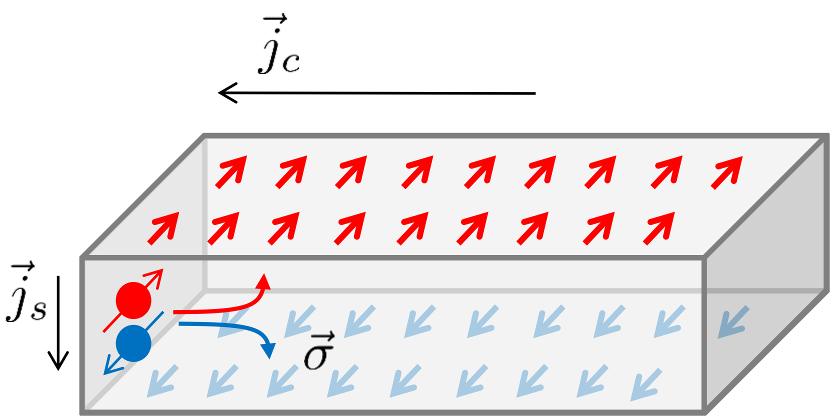




Celik *et al.*, in preparation

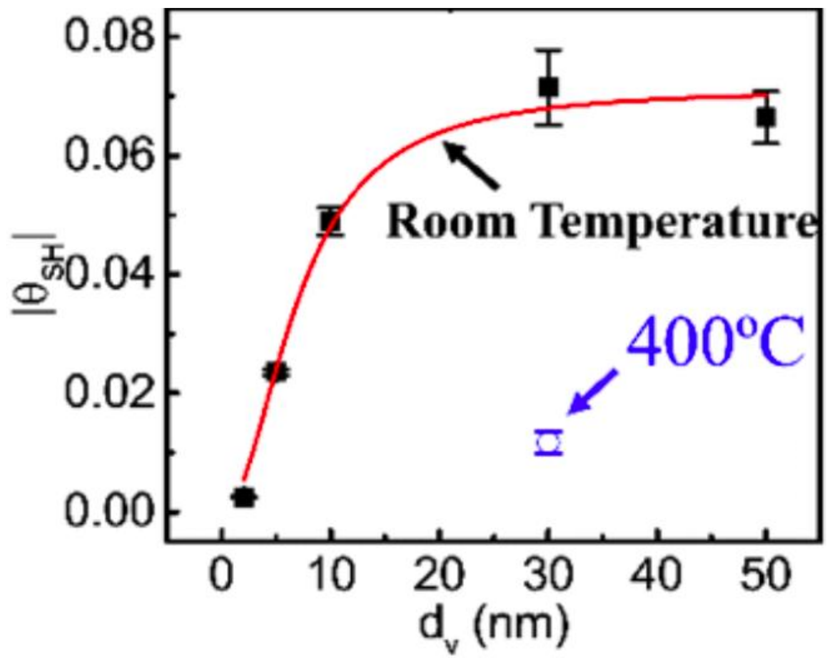
Spin Hall Effect of Vanadium

- Spin orbit coupling proportional to Z^4 → expect heavier metals to exhibit larger spin Hall effect*
- Recent results** indicate vanadium (3d light transition metal) may have spin Hall effect comparable to Platinum
- Confirmed using MOKE & found dependence on crystal symmetry



$$j_s = \theta_{SH} \vec{\sigma} \times \vec{j}_c$$

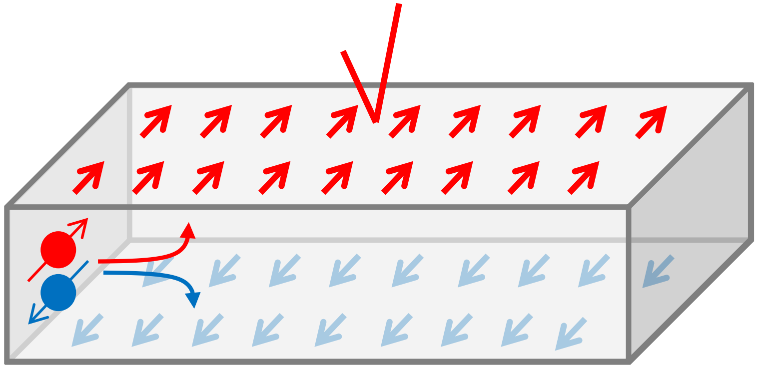
Hirsch, Phys. Rev. Lett. **83**, 1834 (1999).
*Sarma *et al.*, Proc. Indian Acad. Sci. **90**, 19 (1981).
Wang *et al.*, Phys. Rev. Lett. **112, 197201 (2014).



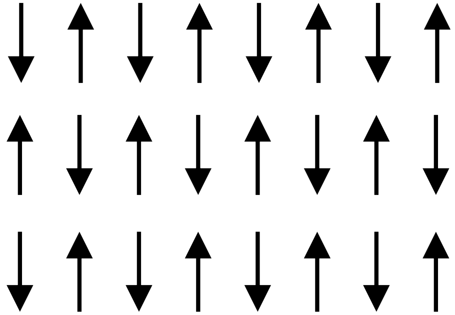
Wang *et al.*, Sci. Reports, in press.

Current and future work

- Measuring the spin accumulation directly



- Spin-orbit-interaction induced phenomena in antiferromagnets
  - Net zero magnetism: secure and robust information storage
  - Fast dynamics: high processing speeds



Thank you!

Mr. Wenrui Wang
UIUC

Ms. Halise Celik
U. Delaware

Prof. John Xiao
U. Delaware

Prof. Xin Fan
U. Denver

Prof. Dan Ralph
Cornell

EPSCoR DEPARTMENT of ENERGY

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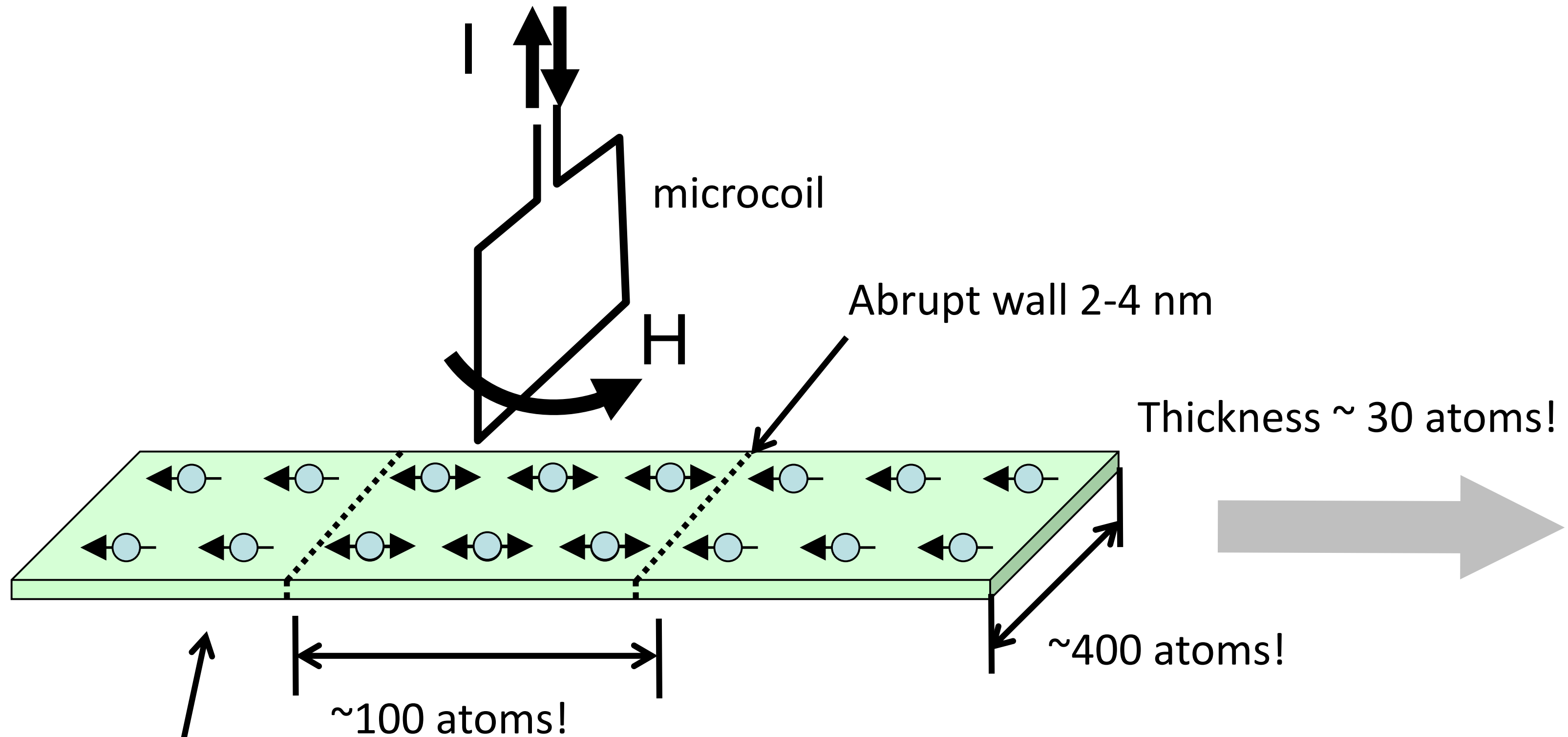
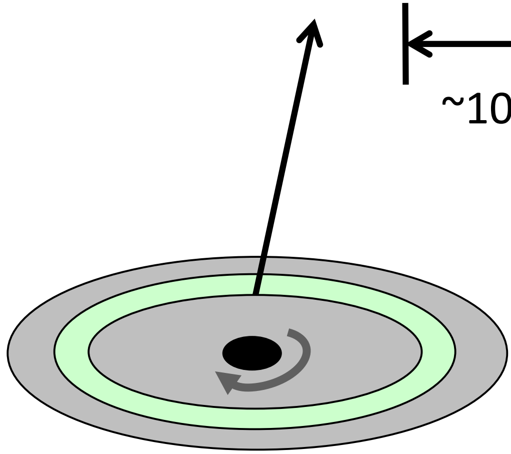
Magnetic storage





- Nanoscience but not electronics
- Nonvolatile but energy inefficient
- Reading and writing not scalable
- Can we read & write in other ways?

adapted from Chappert 2006