Spin Hall and Rashba effects in magnetic bilayers

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NIST National Institute of Standards and Technology • U.S. Department of Commerce

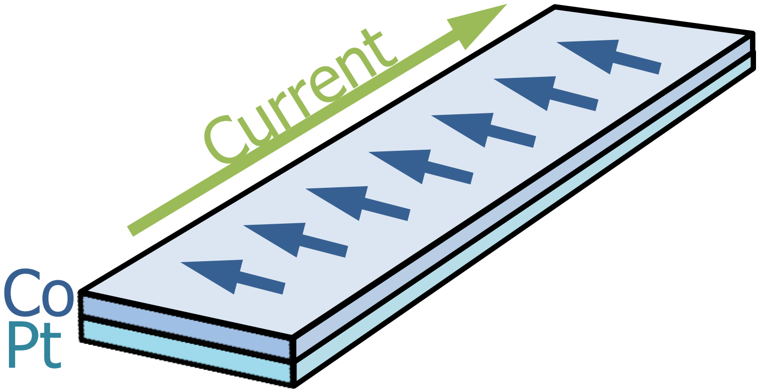
Overview

Experimental Phenomena

- Current induced domain wall motion
  - Efficient
  - Opposite electron flow
- Efficient Magnetic Reversal
- Quasi-static measurements of torque
  - Confusing thickness dependence

Theoretical Approaches

- First Principles calculations
- Semiclassical Transport
  - Drift Diffusion
  - **Boltzmann Equation**
- Magnetization dynamics
  - One dimensional models
  - Micromagnetics



Physical Processes

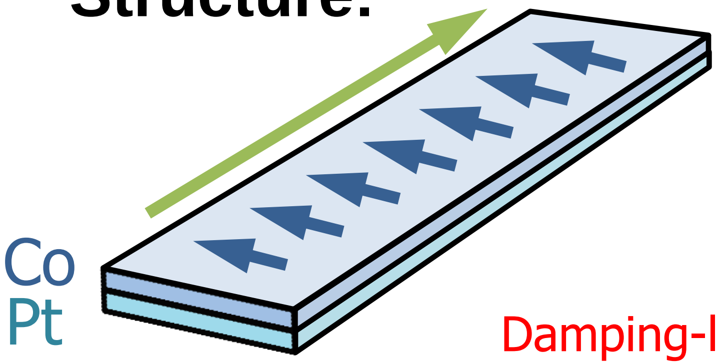
- Current induced torque in ferromagnet
  - Adiabatic spin transfer torque
  - Non-adiabatic spin transfer torque
- Interfacial spin orbit coupling
  - Current-independent Dzyaloshinskii-Moriya interaction
  - **Current dependent**
    - **Damping-like torque**
    - **Field-like torque**

Uncertainties

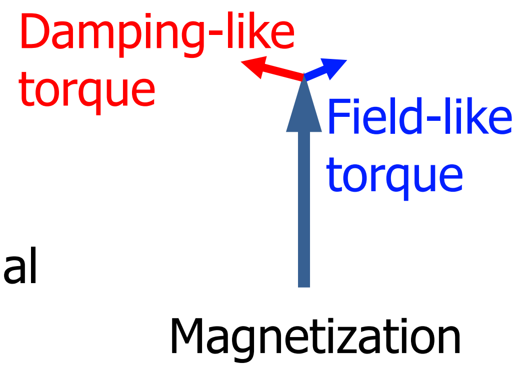
- Uncharacterized disorder
- Unknown physical parameters
- Complicated dynamics
- Competing processes

Current-dependent torques, independent of gradients

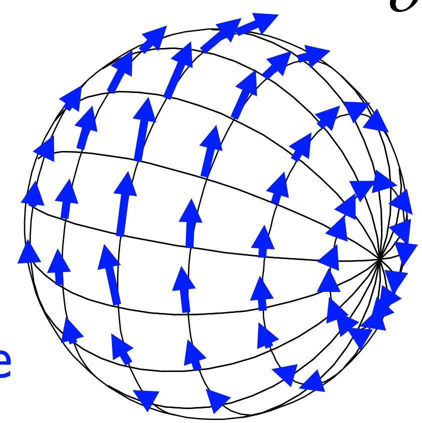
Structure:



Torques:

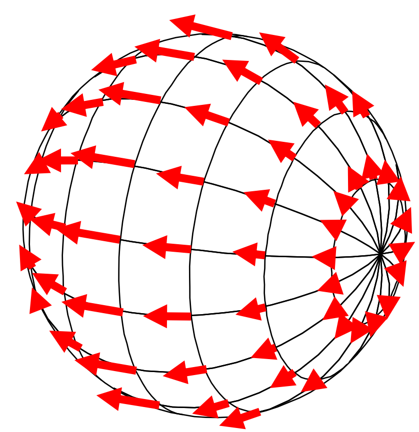


$$\delta(z) v_s' \tau_f \, \mathbf{M} \times \left(\hat{\mathbf{j}} \times \hat{\mathbf{n}} \right)$$

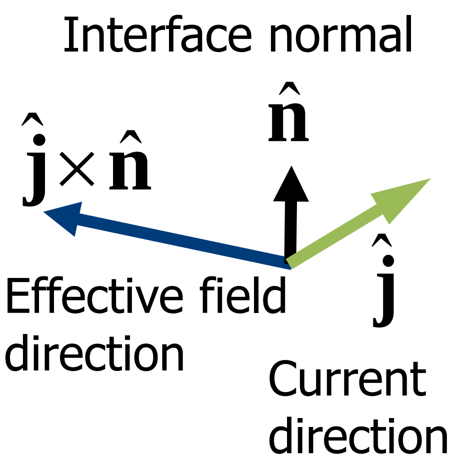


$$v_s' = \frac{g \mu_B}{2 e M_s} j_{NM}$$

$$\delta(z) v_s' \tau_d \, \mathbf{M} \times \left(\hat{\mathbf{M}} \times \left(\hat{\mathbf{j}} \times \hat{\mathbf{n}} \right) \right)$$



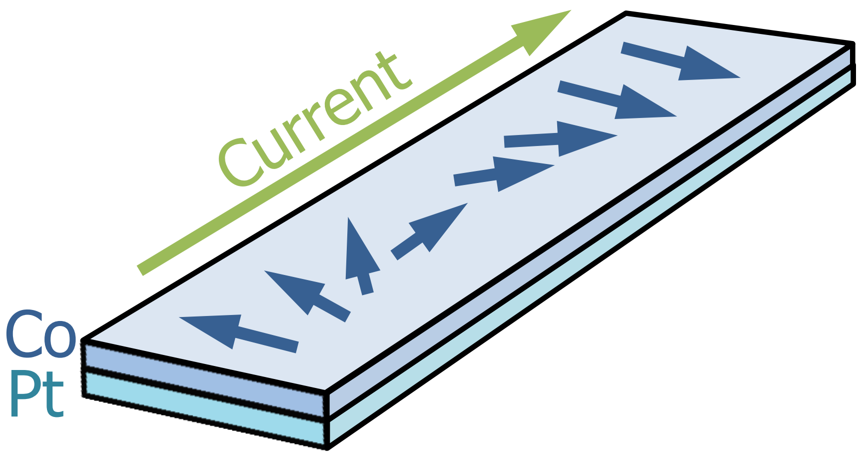
Directions:

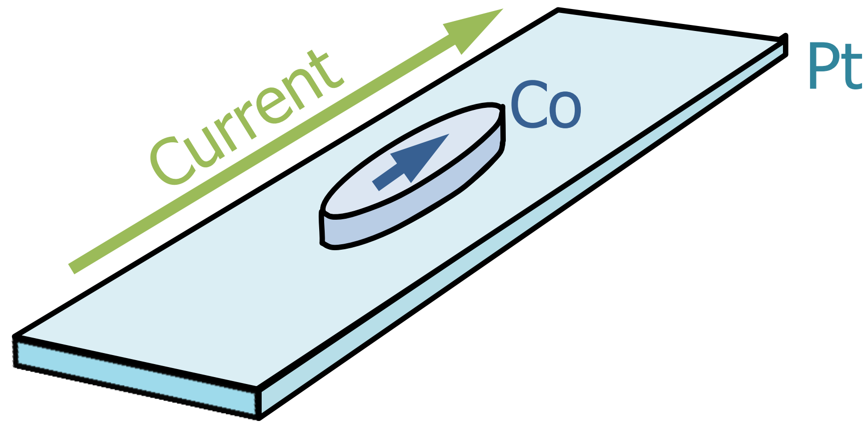


Simple system – bilayer thin film wire

Torque from current flow through a magnetization pattern

Dzyaloshinskii-Moriya interaction



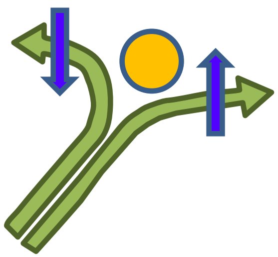


Torque from interfacial spin orbit coupling

Torque from current flow
In adjacent layer
- Spin Hall effect
- Spin transfer torque

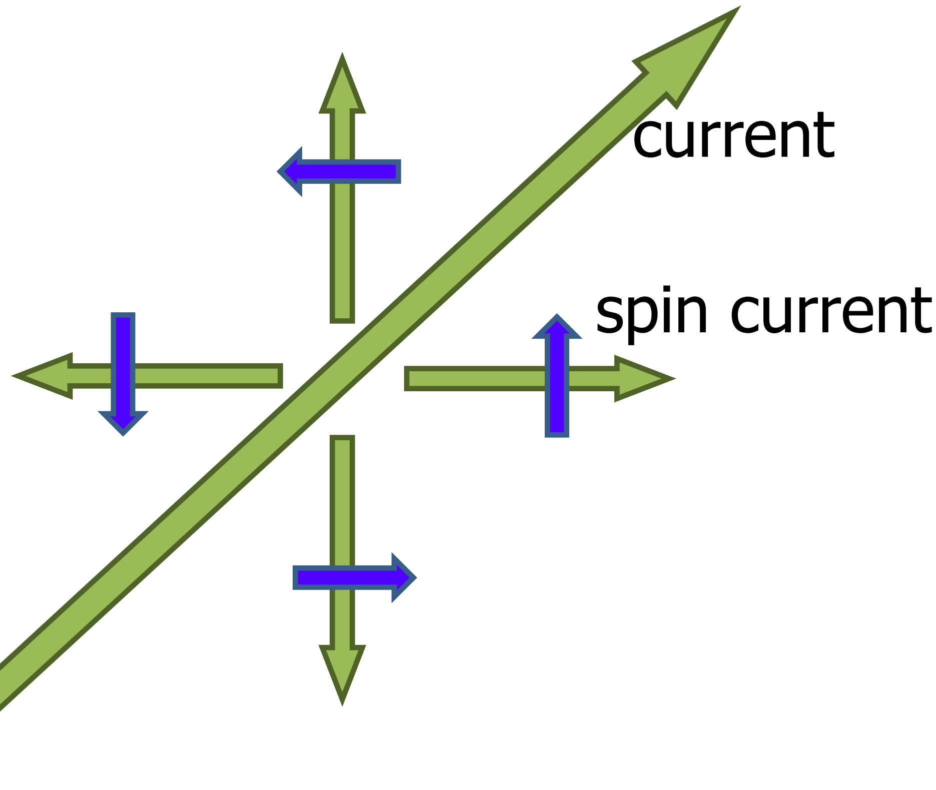
Spin Hall Effect – spin current due to spin-orbit interaction

Mott scattering



Spin Hall effect

D'yakonov and Perel' (1971), Hirsch (1999), Zhang (2000)

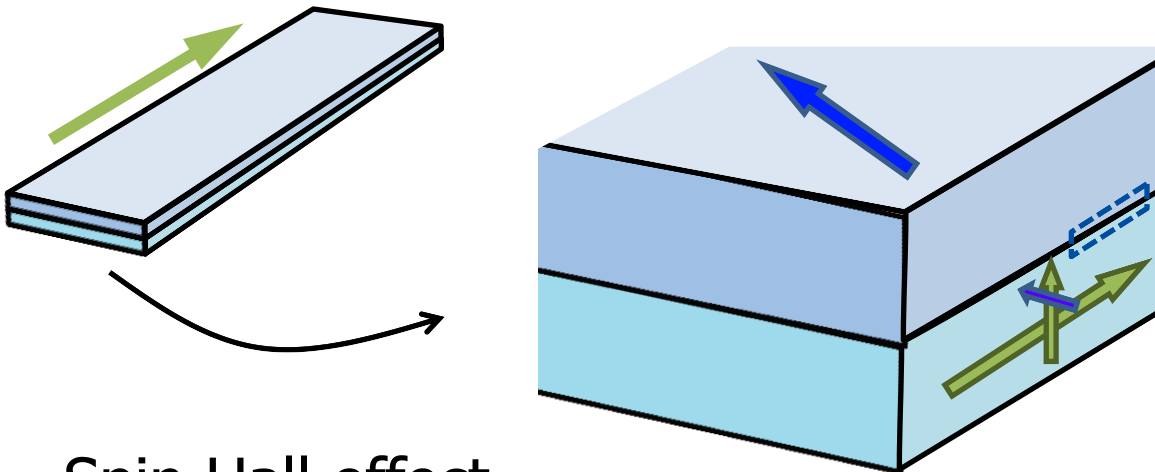


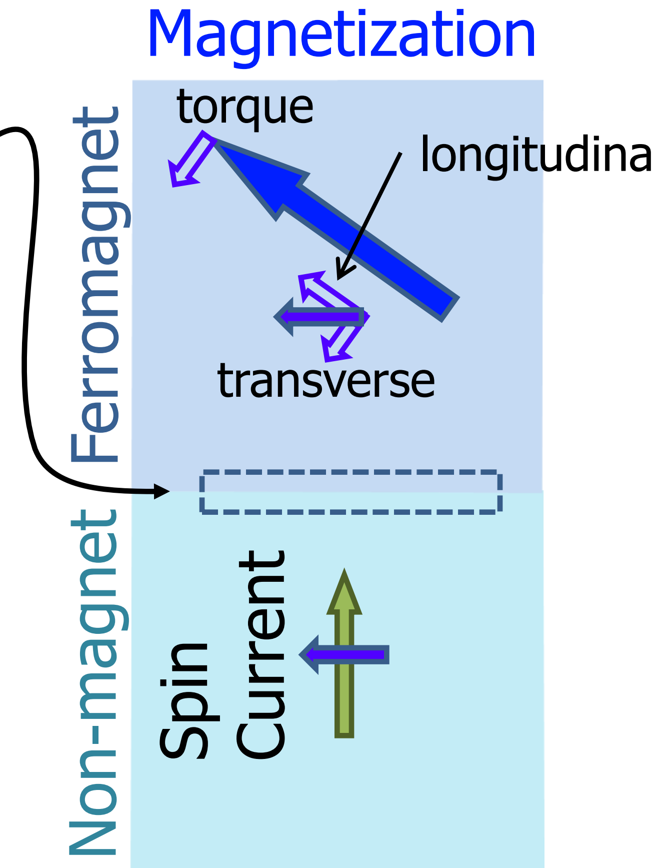
Spin asymmetry due to spin-orbit interaction

Intrinsic – spin-orbit coupling in the band structure

Extrinsic – spin-orbit coupling at defects

Model 1: Spin Hall Effect + Spin Transfer Torque

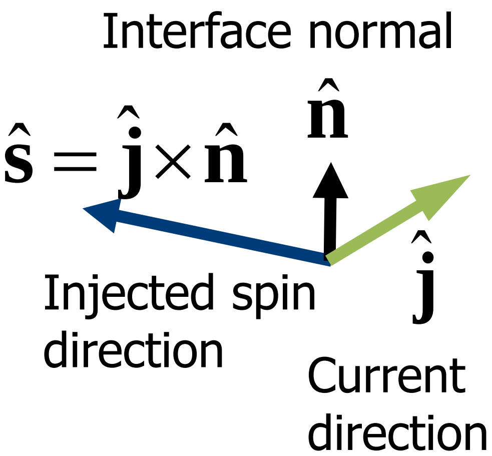


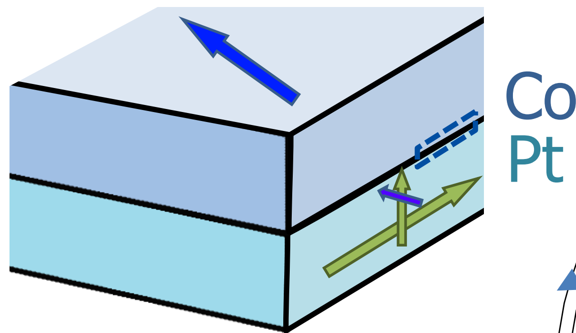


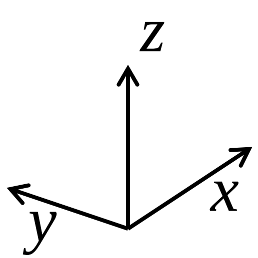
- Spin Hall effect
  ⇒Treat with drift diffusion.

- Spin Transfer Torque,
  Slonczewski, Berger (1996)
  ⇒ Treat with circuit theory or equivalent

Interfacial absorption of the transverse spin current
⇒ Effective (anti)damping due to spin transfer torque

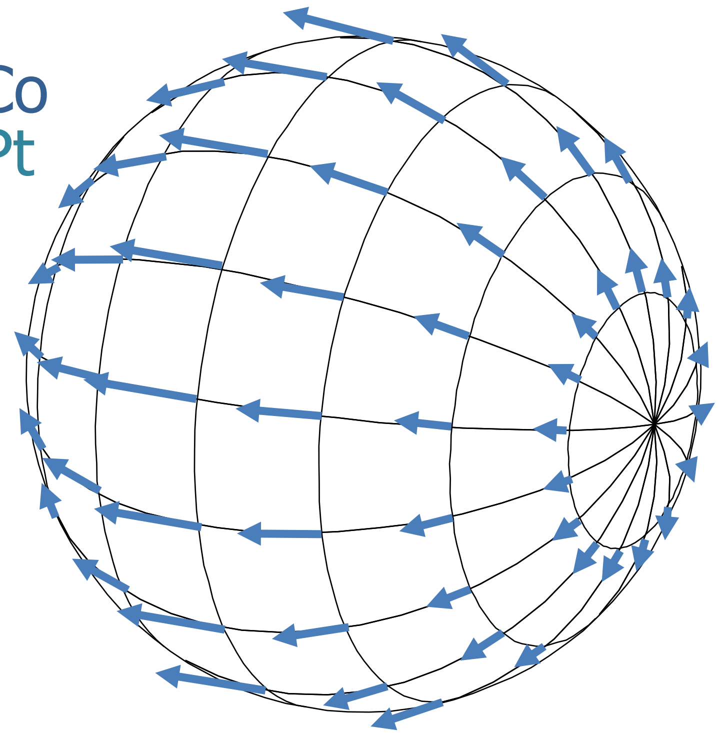






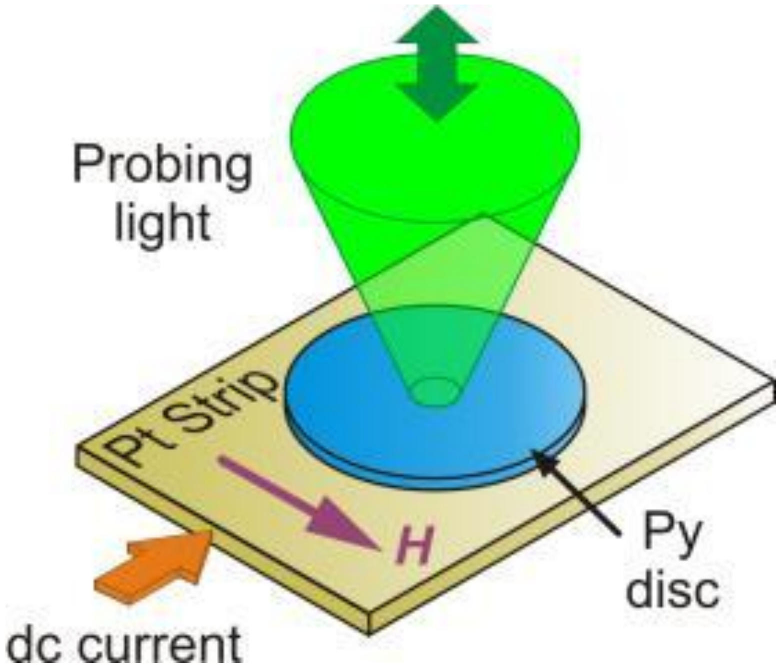
$$\mathbf{N} \sim \left[\hat{\mathbf{s}} - \hat{\mathbf{m}}\left(\hat{\mathbf{s}} \cdot \hat{\mathbf{m}}\right)\right]$$

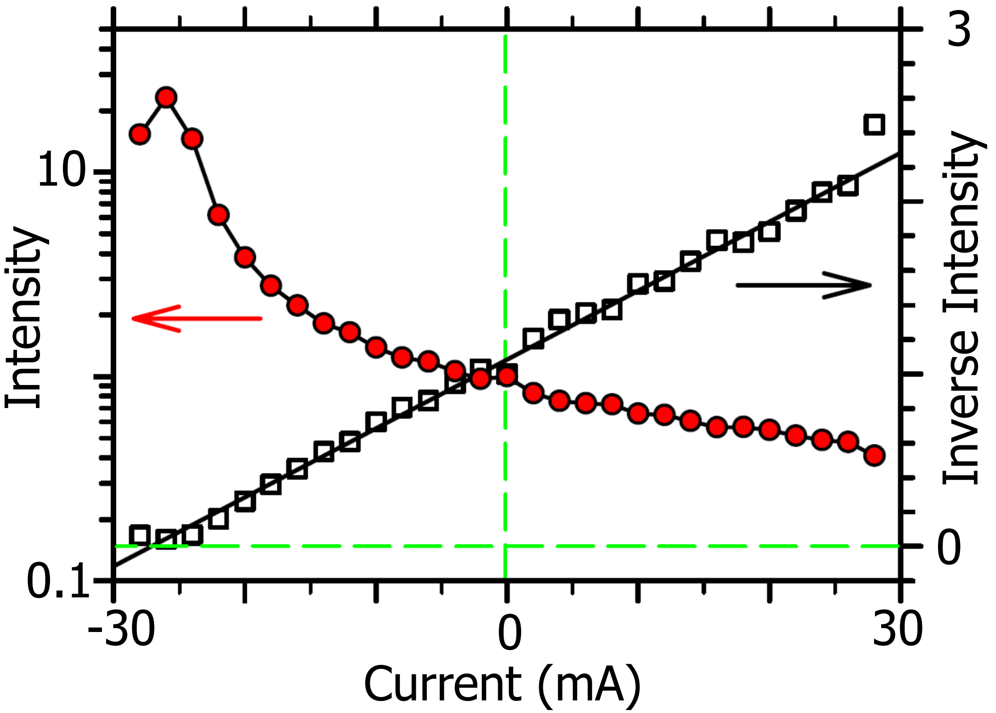
$$\underbrace{\hat{\mathbf{s}} - \hat{\mathbf{m}}\left(\hat{\mathbf{s}} \cdot \hat{\mathbf{m}}\right)}_{\hat{\mathbf{m}} \times \left(\hat{\mathbf{s}} \times \hat{\mathbf{m}}\right)}$$



Torque as a function of magnetization direction

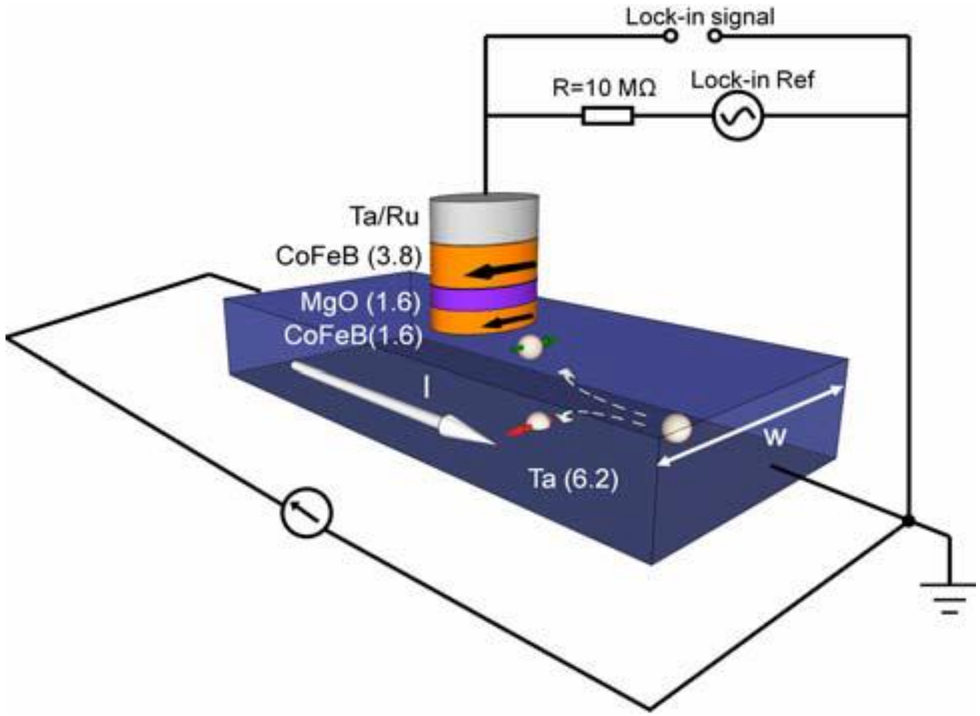
Modification of thermal spin wave amplitudes due to spin Hall effect spin transfer torque

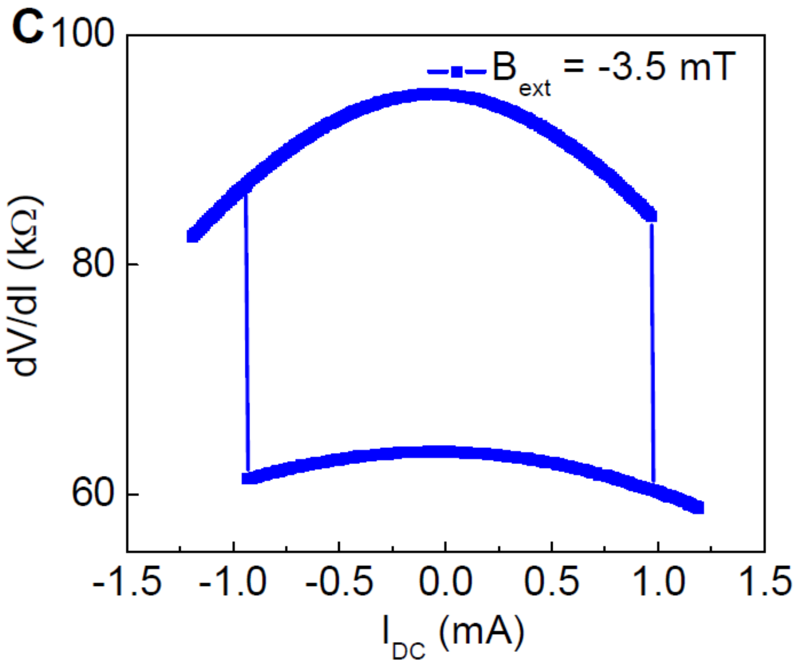




V. E. Demidov, S. Urazhdin, E. R. J. Edwards, M. D. Stiles, R. D. McMichael, and S. O. Demokritov, Phys. Rev. Lett. **107**, 107204 (2011)

Magnetization switching due to spin Hall effect spin transfer torque



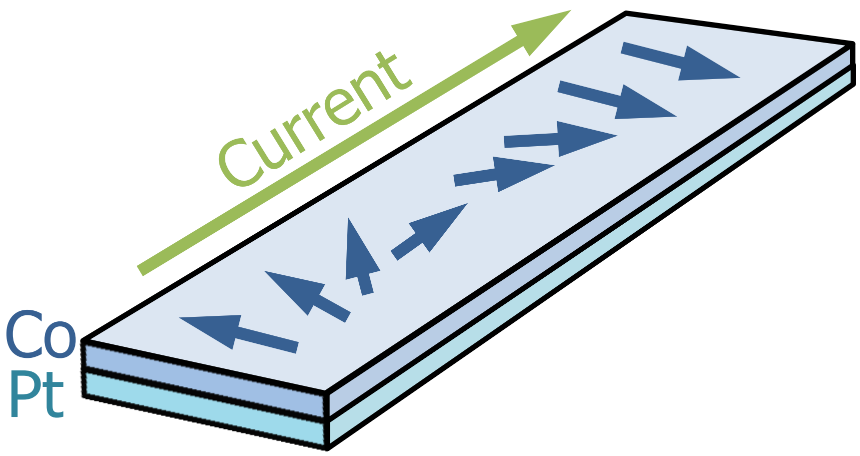


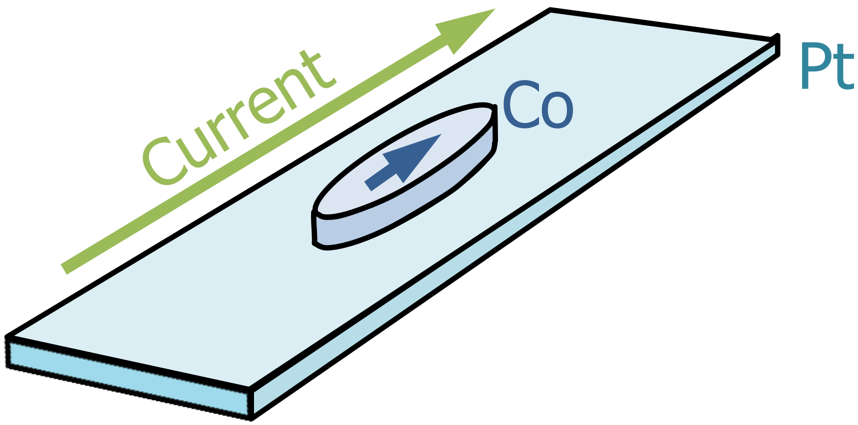
Spin torque switching with the giant spin Hall effect of tantalum
Luqiao Liu, Chi-Feng Pai, Y. Li, H. W. Tseng, D. C. Ralph and R. A. Buhrman,
Science 4 May 2012: 555-558

Simple system – bilayer thin film wire

Torque from current flow through a magnetization pattern

Dzyaloshinskii-Moriya interaction

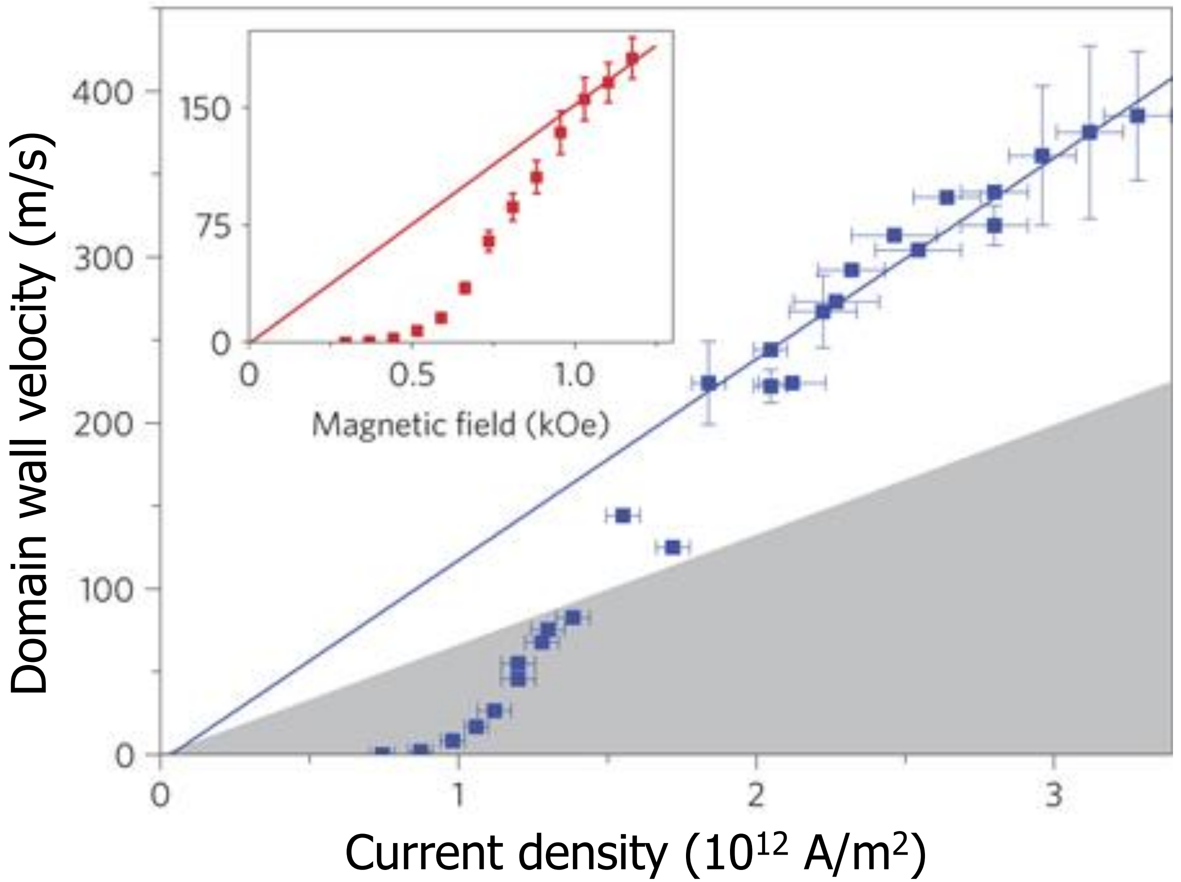




Torque from current flow
In adjacent layer
- Spin Hall effect
- Spin transfer torque

Torque from interfacial spin orbit coupling

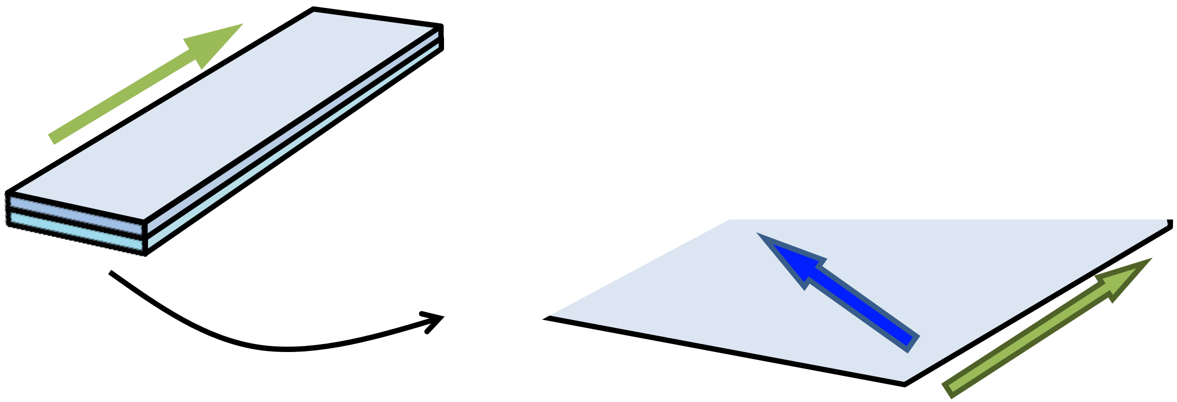
Domain wall motion in Pt/Co/MgO



Miron et al., Nature Materials **10**, 419 (2011)

- Velocity **twice** expected value
- Motion **against** electron flow
- Possibly explained by "field-like" torques (or Dzyaloshinskii-Moriya interaction)

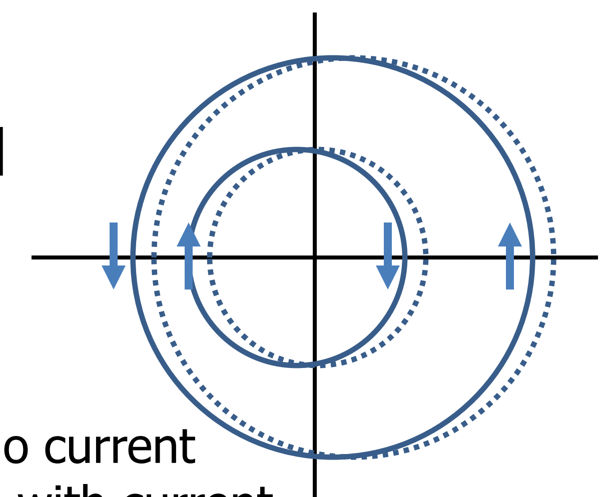
Model 2: 2d Rashba model



$$H = \frac{\hbar^2 k^2}{2m} + E_{ex}\sigma \cdot \mathbf{m} + \alpha\sigma \cdot \left(\mathbf{k} \times \hat{\mathbf{z}}\right)$$

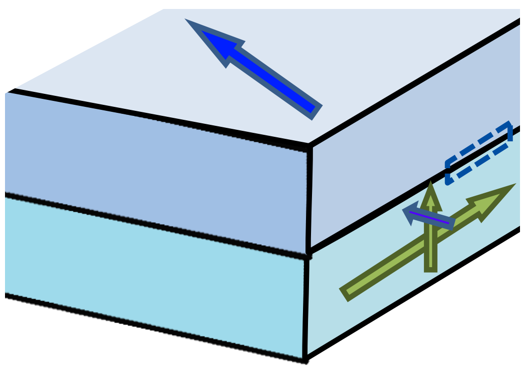
- Rashba interaction
  $\Rightarrow$Treat with Boltzmann equation.

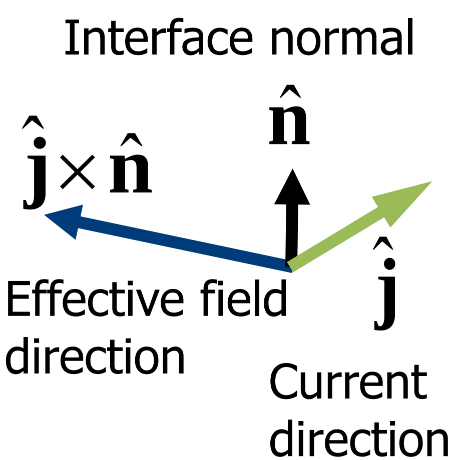
- Torque due to spin accumulation and exchange interaction.



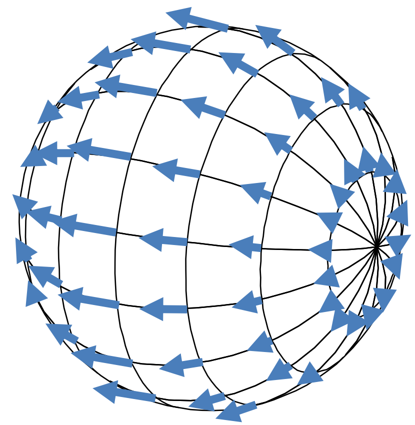
Solid – no current
Dotted – with current

Field-like torques

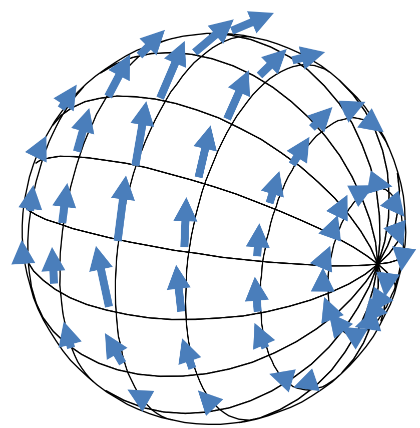




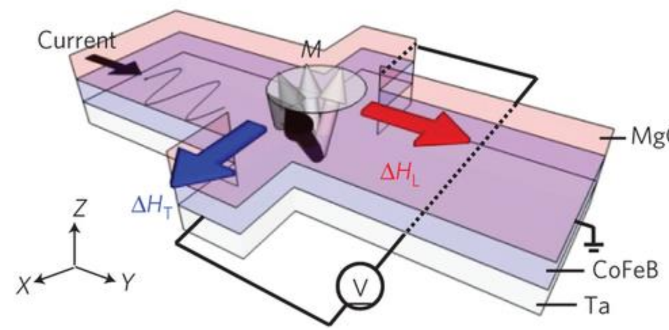
Damping-like



Field-like



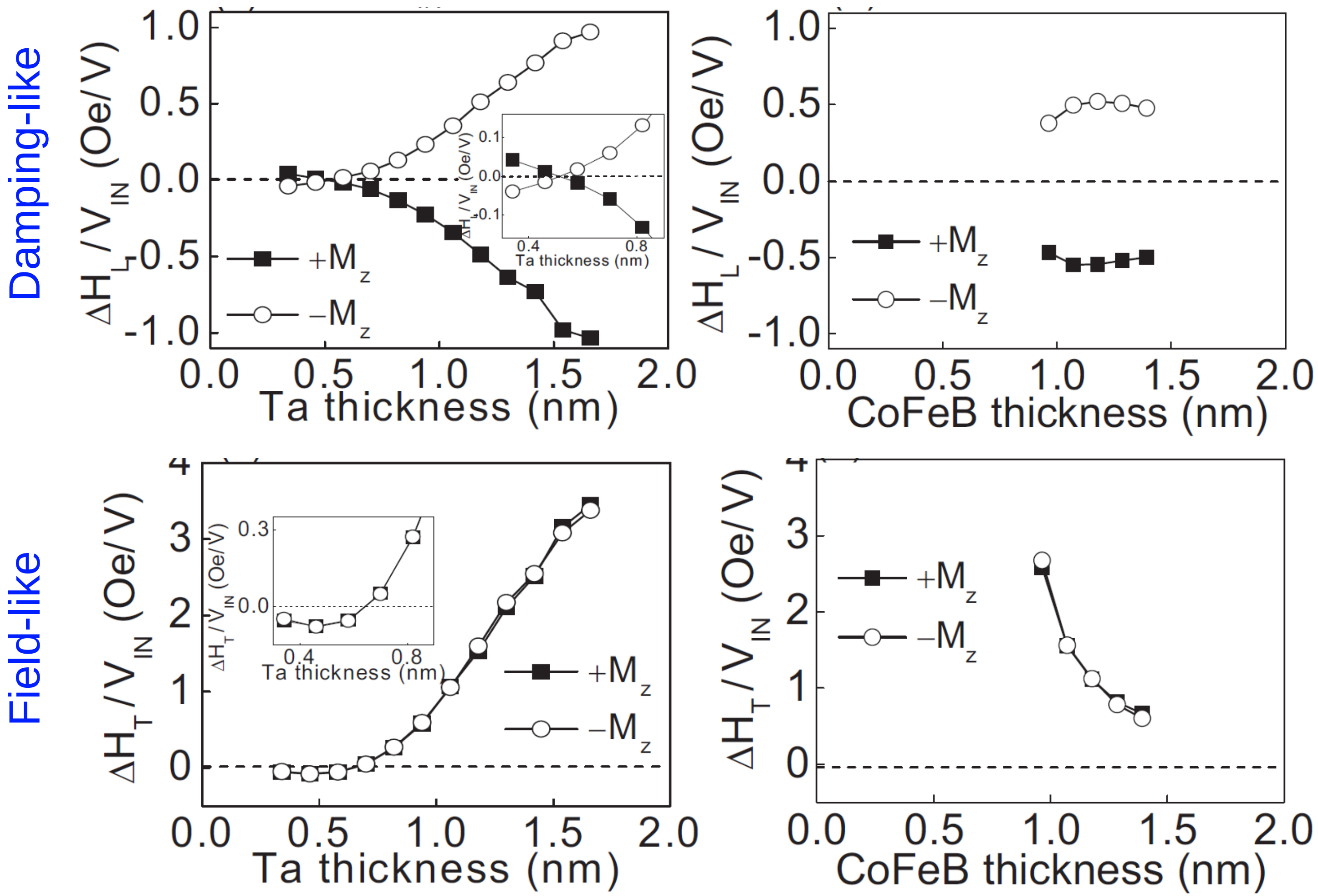
Direct measurement through small amplitude displacements



Kim et al., Nature Materials, **12**, 240 (2012)

Layer thickness dependence of the current induced effective field vector in Ta|CoFeB|MgO

J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, H. Ohno, Nature Materials (2012)



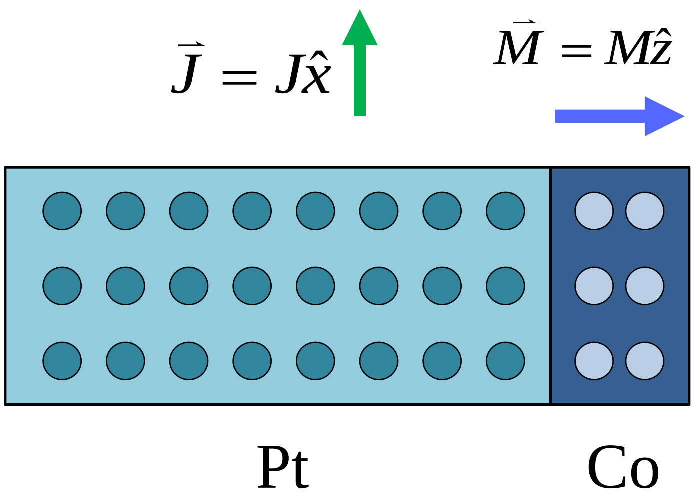
Why Semiclassical Calculations?

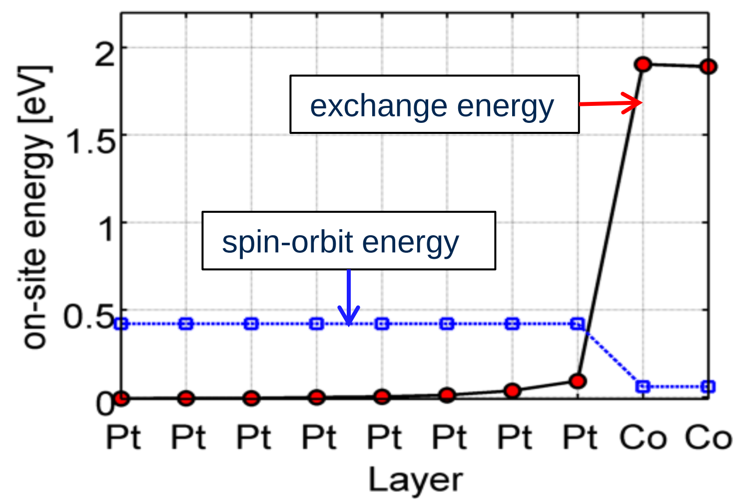
- Origin of most of what we know about transport.
- It's how people think.
- Easier and enables systematic studies.
- Structural details of system, necessary for first-principles are not known.

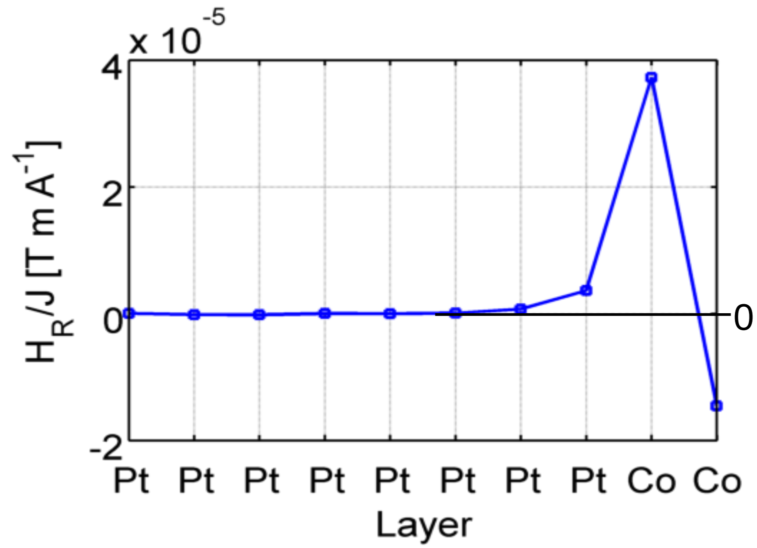
Why not?

- Can be difficult to be sure that all physics is included correctly.
- Not strictly valid for small thicknesses.

Rashba field due to influence of Pt spin-orbit coupling on Co electronic structure



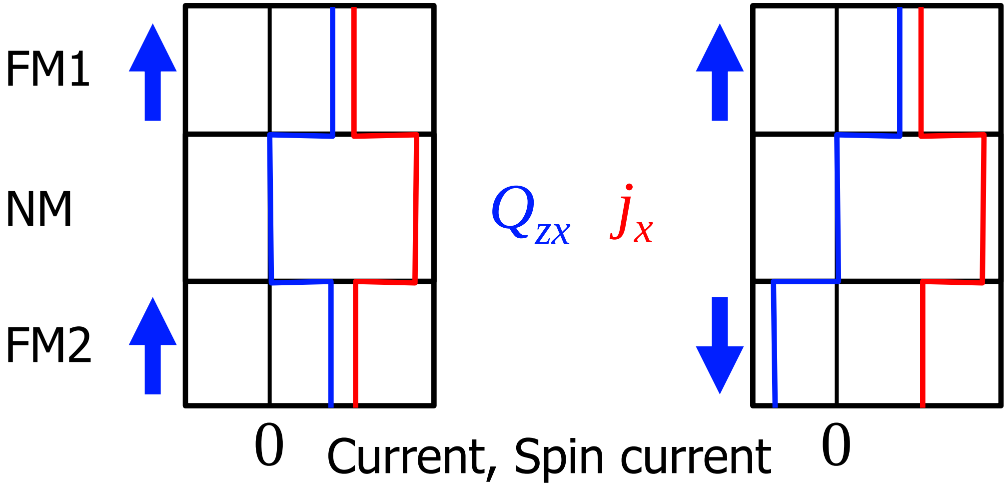


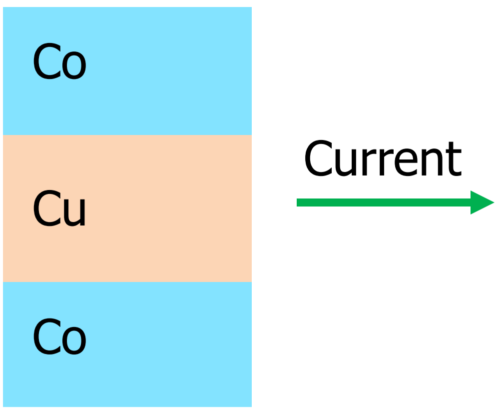


See also:
"Spin-orbit torques in Pt/Co films from first principles," Frank Freimuth, Stefan Blügel, Yuriy Mokrousov, arXiv:1305.4873

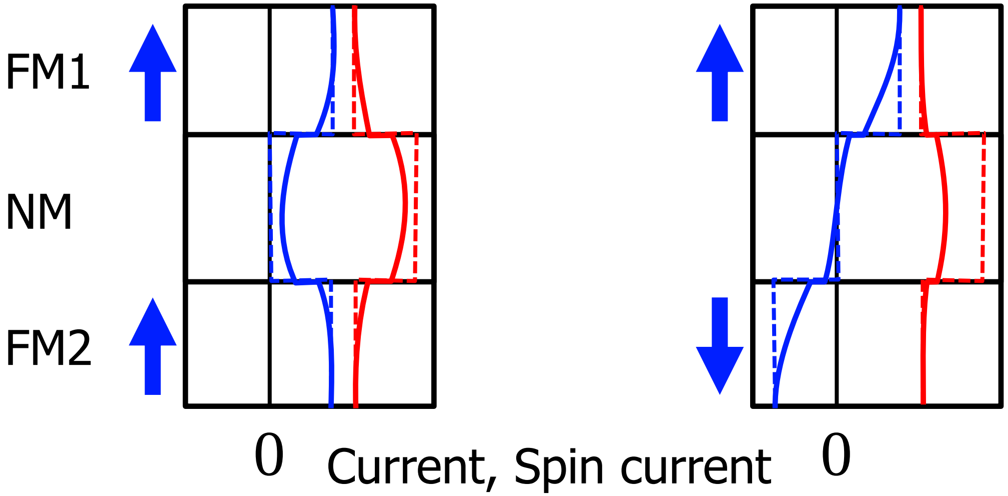
Why Boltzmann equation, why not drift-diffusion?

- Drift-diffusion equation gives no current-in-the-plane GMR.





- Boltzmann equation does (Camley & Barnas (1989)).



Electrons explicitly flowing in all directions allows spin flow between layers.

3d Boltzmann transport model (after Camley & Barnas)

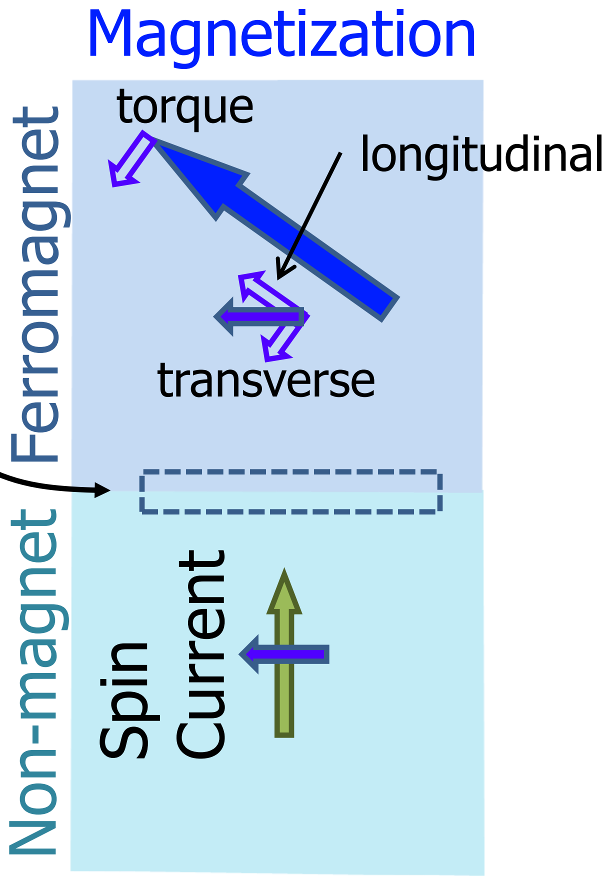
Simple model:

- Spherical Fermi surfaces
- Spin-dependent scattering
- Arbitrary spin direction
- "extrinsic" spin Hall effect
- Delta function interfacial potential

$$\delta(z)\left[u_0 + u_p \sigma \cdot \mathbf{m} + u_r \sigma \cdot (\mathbf{k} \times \hat{\mathbf{z}})\right]$$

Ignore Intrinsic contributions:

- Intrinsic spin Hall effect
- Interface contribution



More details of Boltzmann equation

- Linearized to Fermi surface.

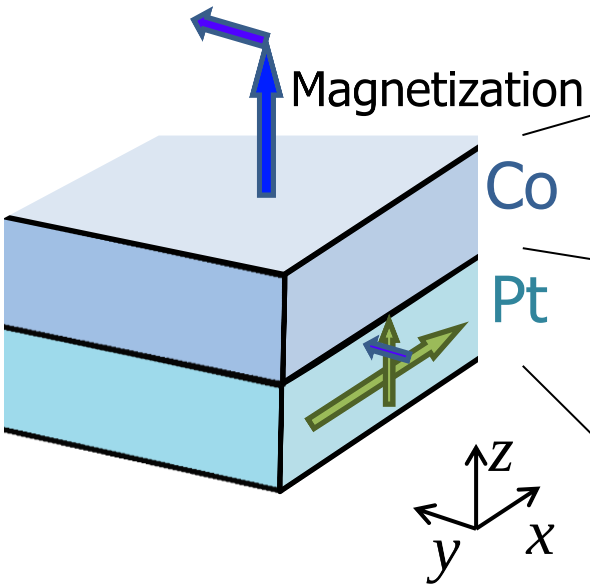
$$f(\mathbf{k}) \approx f_0(\varepsilon_{\mathbf{k}}) + g(\mathbf{K})\delta(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathrm{F}})$$

- "Matrix" Boltzmann equation – full spin coherence at each k point, but incoherent for different k's.

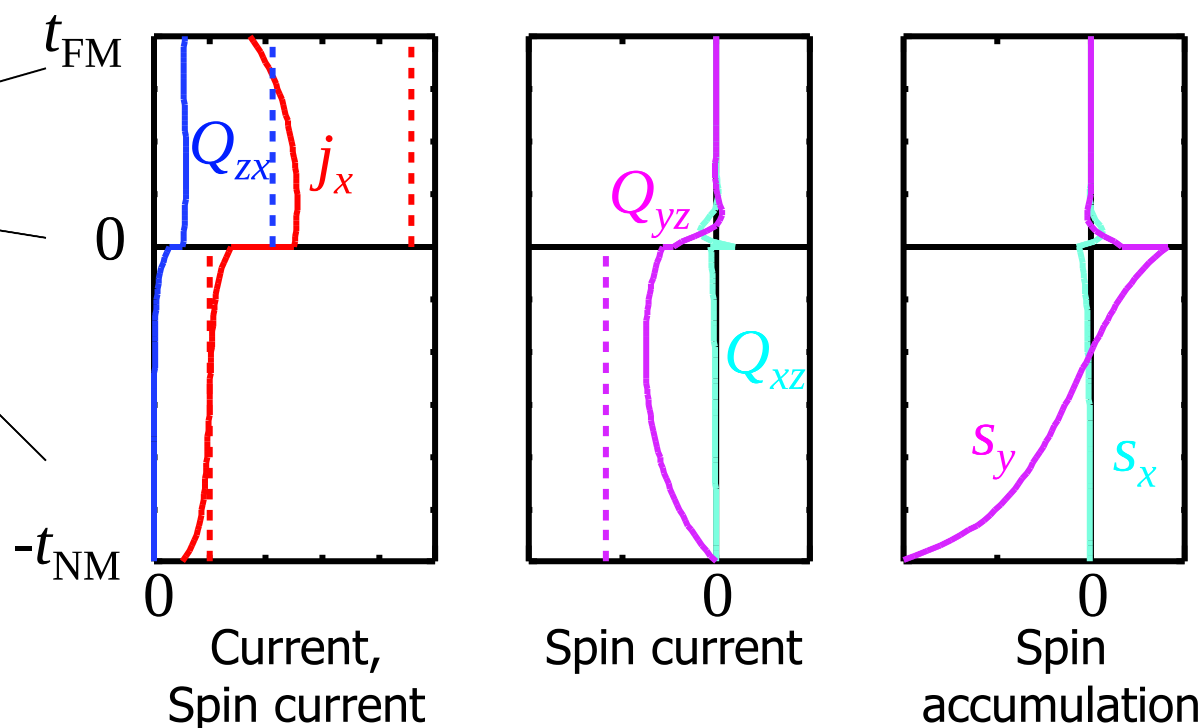
$$g \to \begin{pmatrix} g^{\uparrow\uparrow} & g^{\uparrow\downarrow} \\ g^{\downarrow\uparrow} & g^{\downarrow\downarrow} \end{pmatrix} = g_0 \mathrm{I} + \mathrm{g}_x \sigma_x + \mathrm{g}_y \sigma_y + \mathrm{g}_z \sigma_z$$

- Solve for arbitrary solution with 2d translational invariance.
- Join solutions between layers by matching with transmission and reflection coefficients.

Spin currents with bulk spin orbit coupling (no interfacial) ⇒ Predominantly damping-like torque

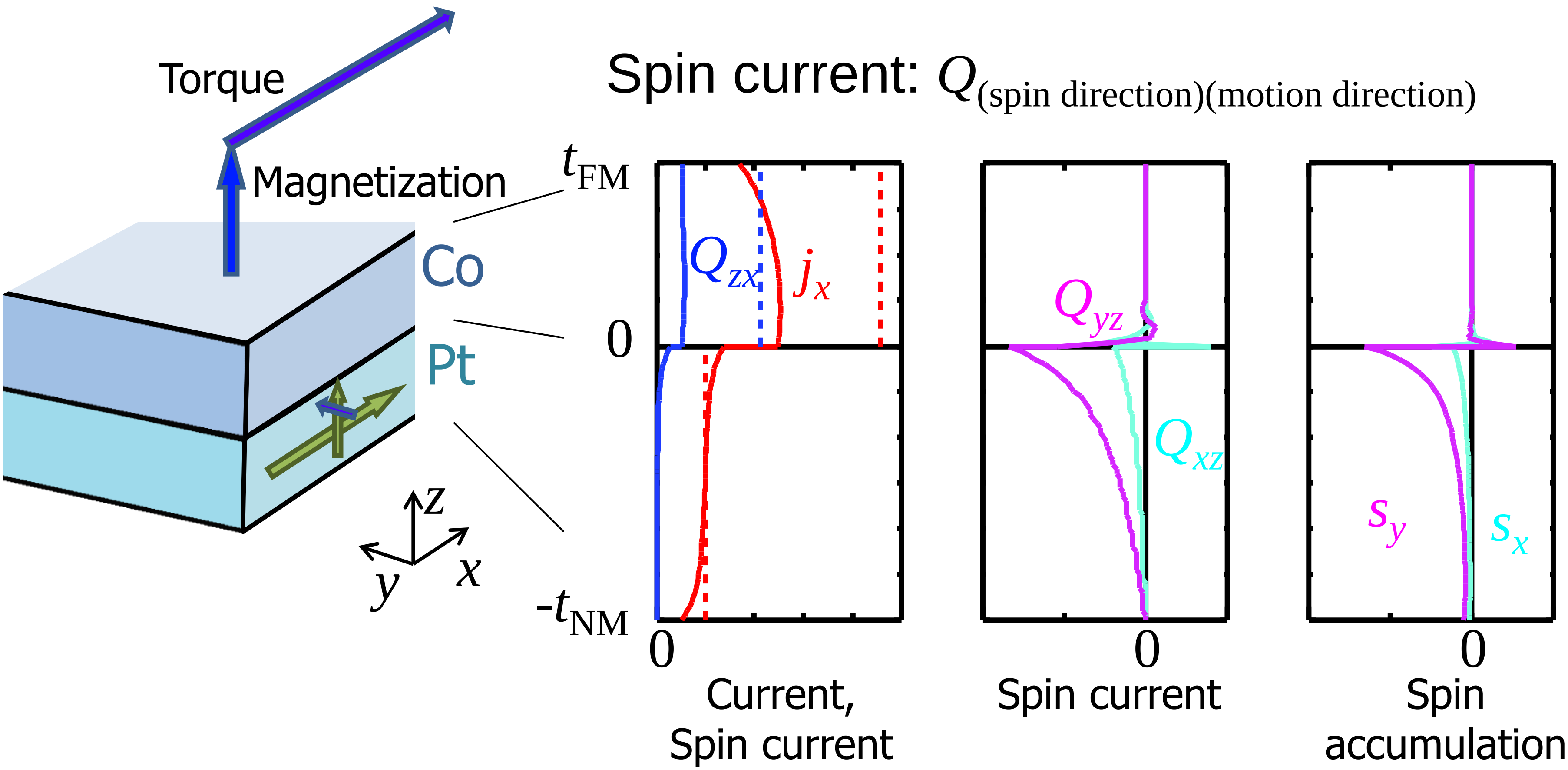


Spin current: $Q_{\text{(spin direction)(motion direction)}}$



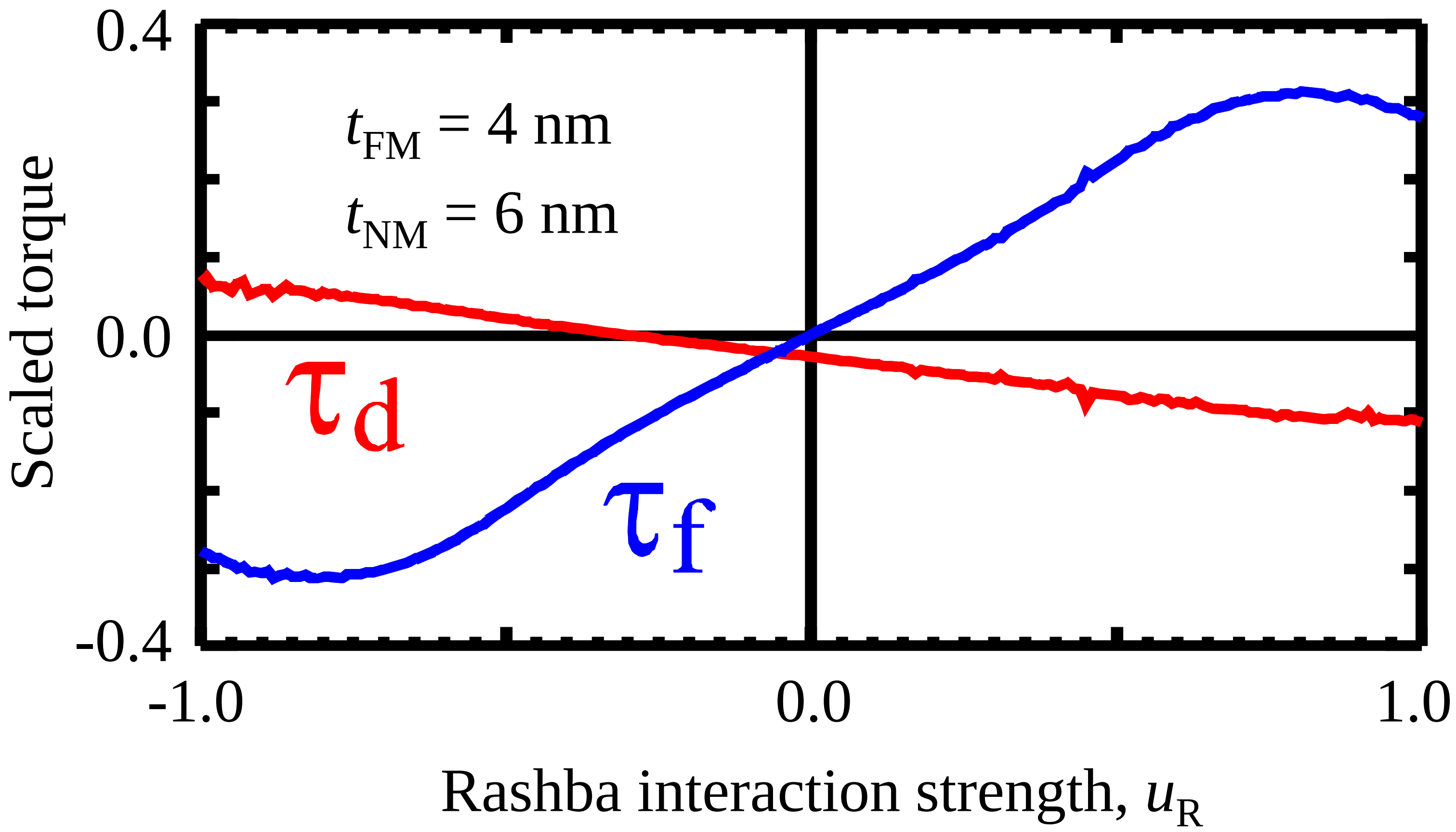
⇒ Torque differs quantitatively from $\dfrac{g\mu_{\text{B}}}{2M_{\text{s}}t_{\text{FM}}}\dfrac{j}{e}\theta_{\text{SH}}$

Spin currents with interfacial spin orbit coupling (no bulk) ⇒ Predominantly field-like torque

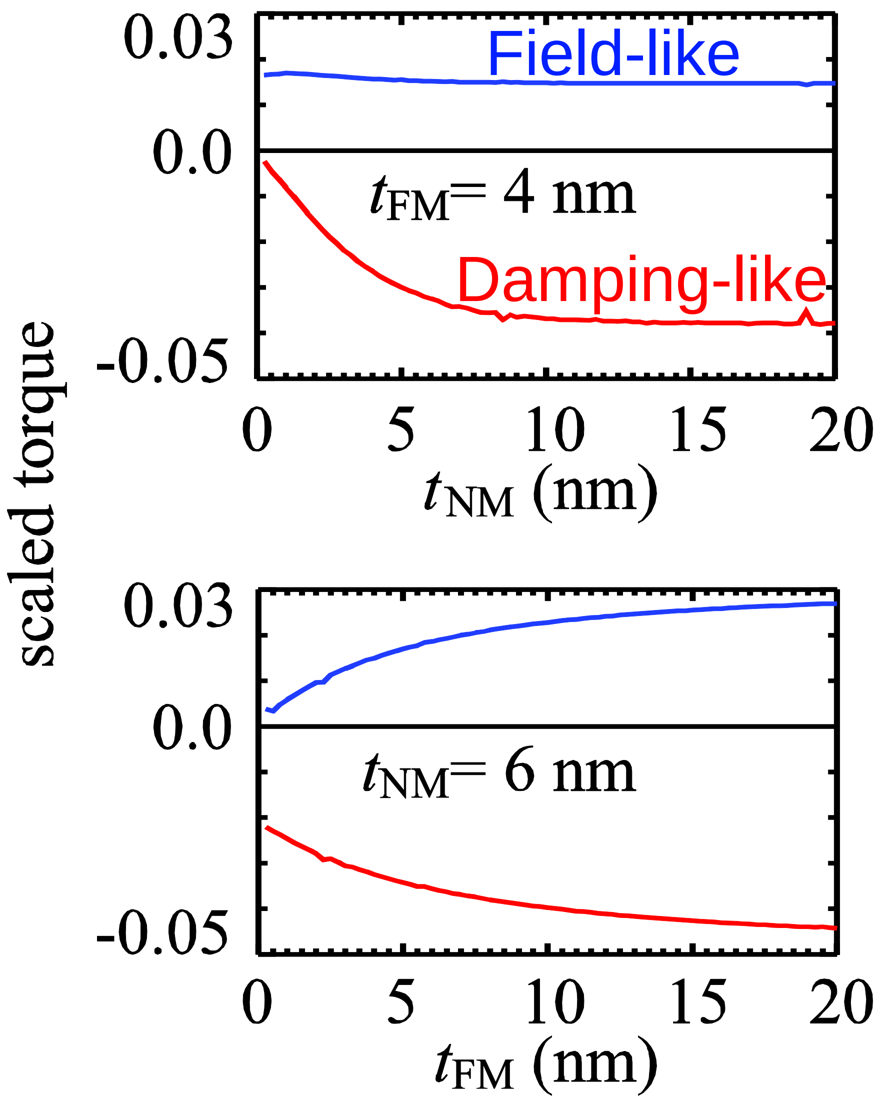


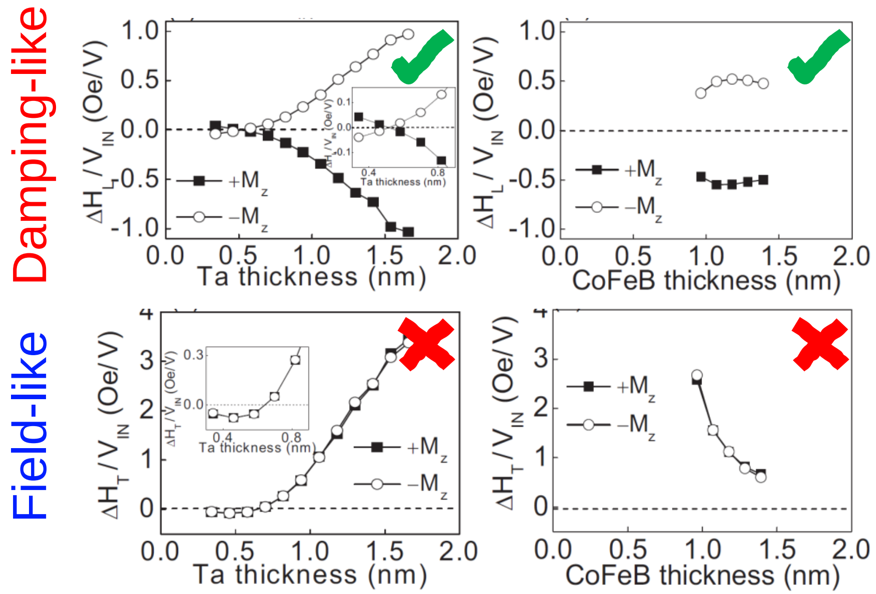
⇒ Torque driven by spin current injection from FM

Two mechanisms are largely independent



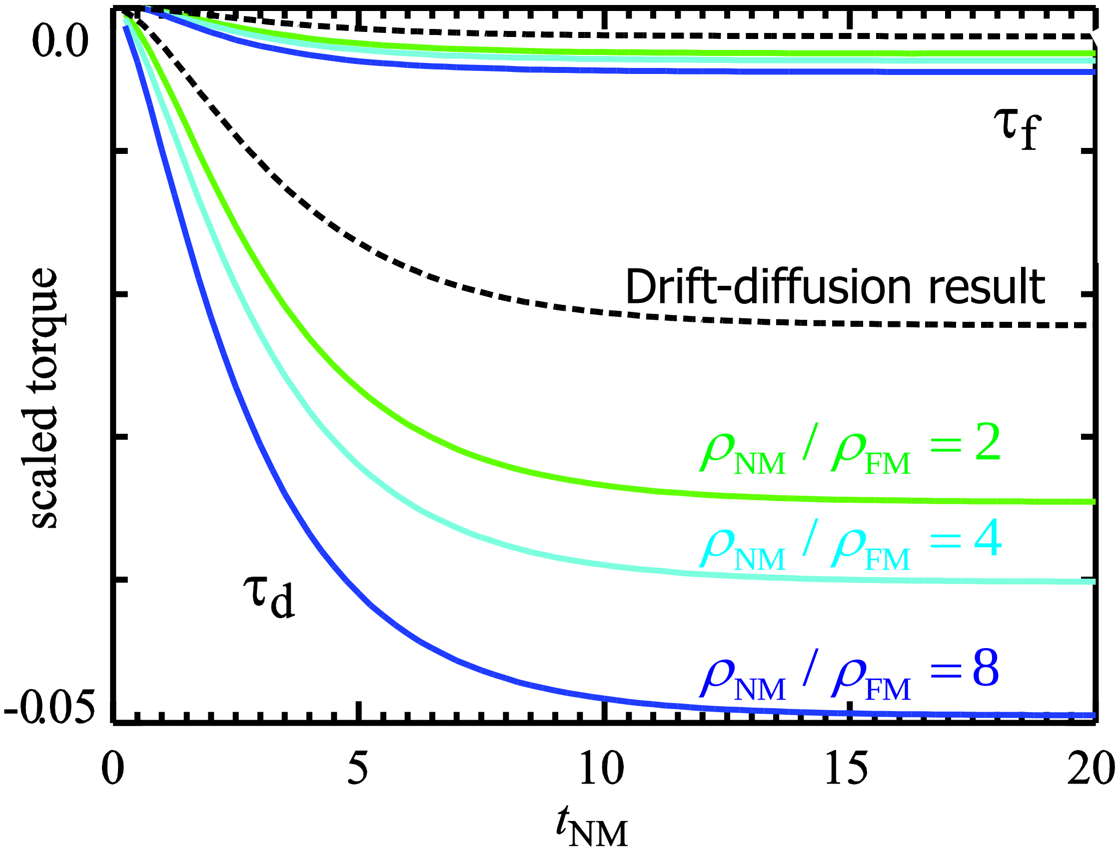
Thickness dependence

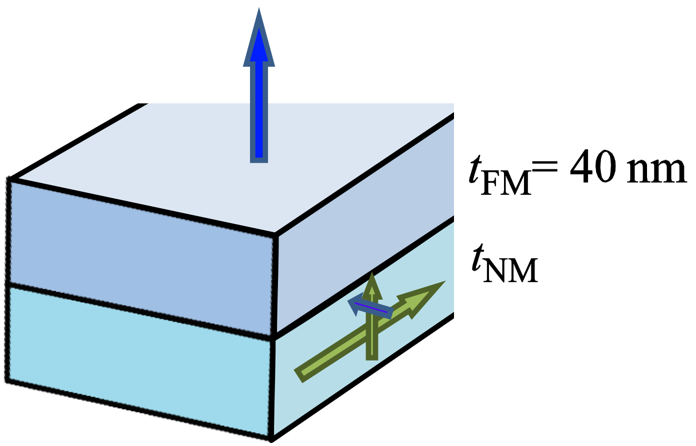




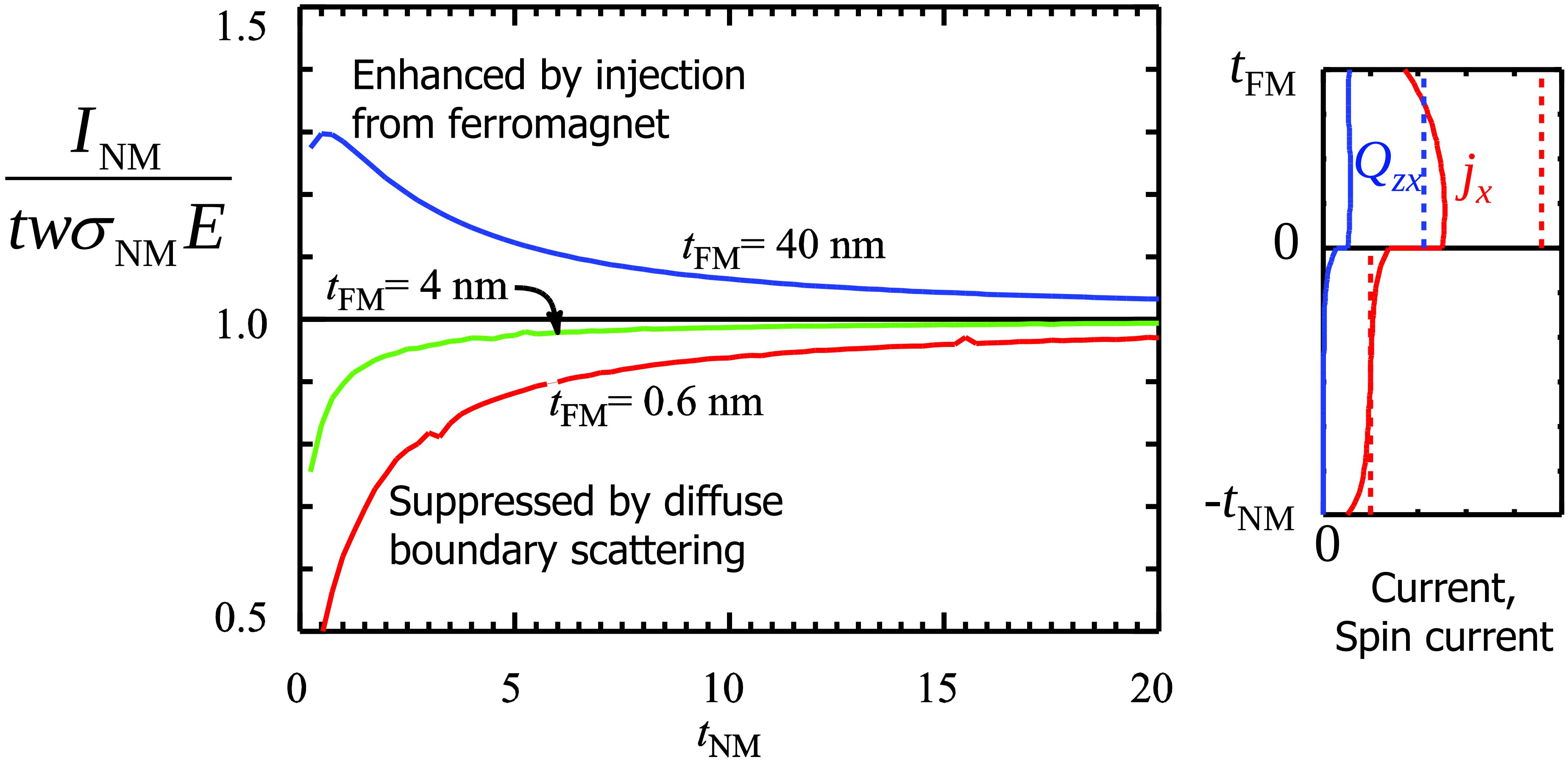
J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, H. Ohno, Nature Materials (2012)

When FM and NM resistivities are very different, the drift-diffusion approximation can be significantly off.





Current in NM layer may be very different than bulk value.



Boltzmann equation calculations of spin transfer torques in magnetic bilayers with strong spin orbit coupling

- Captures essential physics of
  - Spin Hall effect + spin transfer torque,
  - 2-d Rashba model.
- Two mechanisms are largely independent.
- Captures some but not all of the experimental behavior (thickness dependence).
- Drift-diffusion approximation can be quantitatively off.
- Current in NM layer may be very different than bulk value.

Papers: PRB 87, 174411 (2013) (arXiv:1301.4513)
See also: arXiv:1309.1356, arXiv:1308.3341, arXiv:1308.1198
Review articles on spin transfer torque: JMMM 320
More information at http://cnst.nist.gov