Domain Wall Motion in Magnetic Nanowires

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Robert McMichael – NIST
Michael Donahue – NIST

Keith Gilmore – LBL
Ion Garate – Yale
Allan MacDonald – UT Austin

Paul Haney – NIST

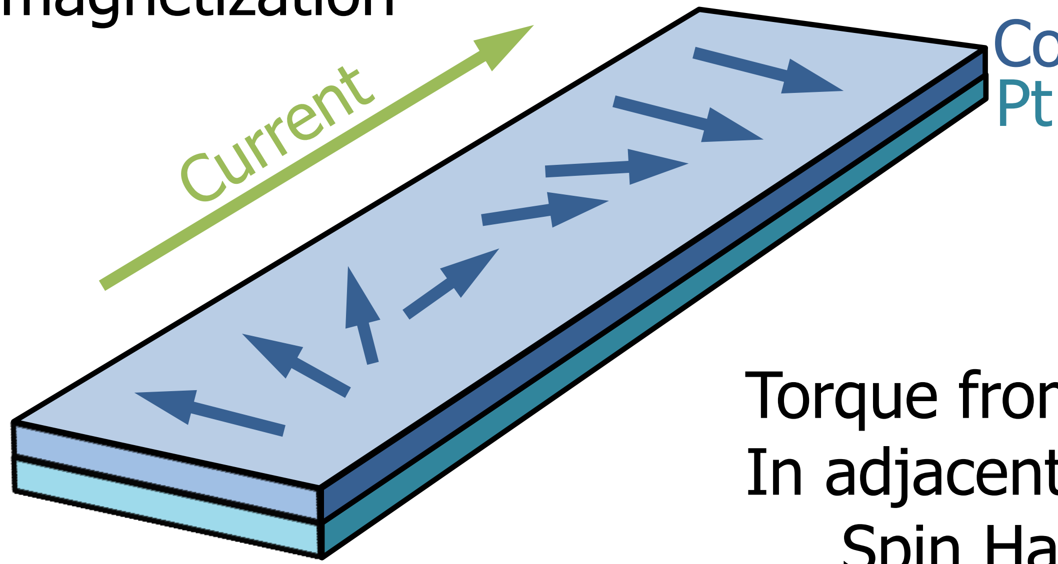
Christian Heiliger - Geissen

Vladimir Demidov – Muenster U
Sergei Demokritov – Muenster U
Sergei Urazhdin – Emory U

Kyung-Jin Lee – Korea U
Hyun-Woo Lee – Pohang U

Simple system – bilayer thin film wire

Torque from current flow through a magnetization pattern

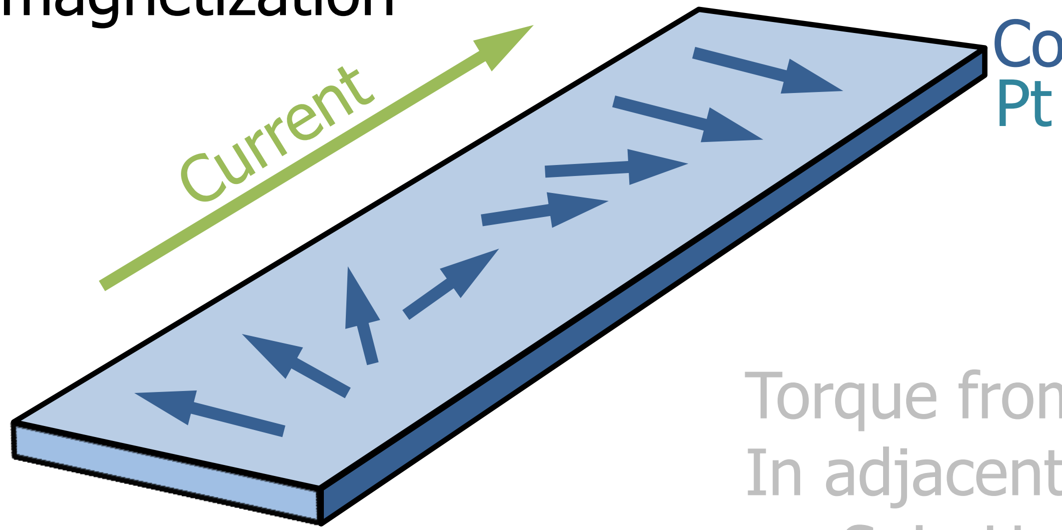


Torque from current flow
In adjacent layer
- Spin Hall effect
- Spin transfer torque

Torque from interfacial spin orbit coupling

Simple system – bilayer thin film wire

Torque from current flow through a magnetization pattern



Torque from current flow
In adjacent layer
- Spin Hall effect
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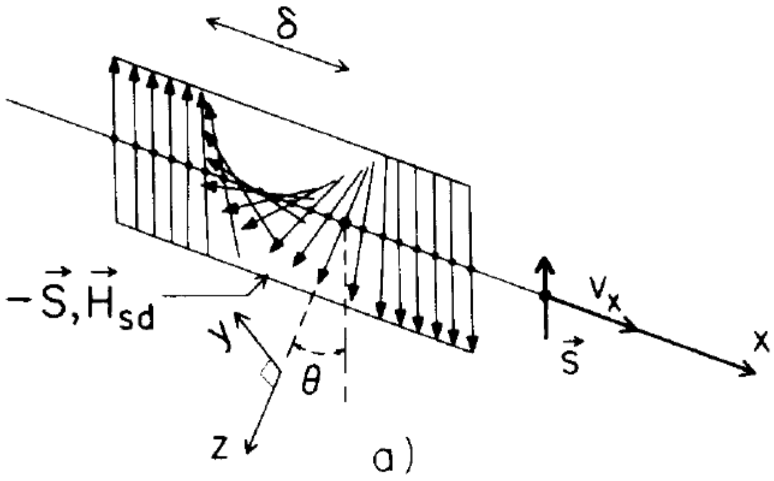
Torque from interfacial spin orbit coupling

Current Induced domain wall motion

Prediction

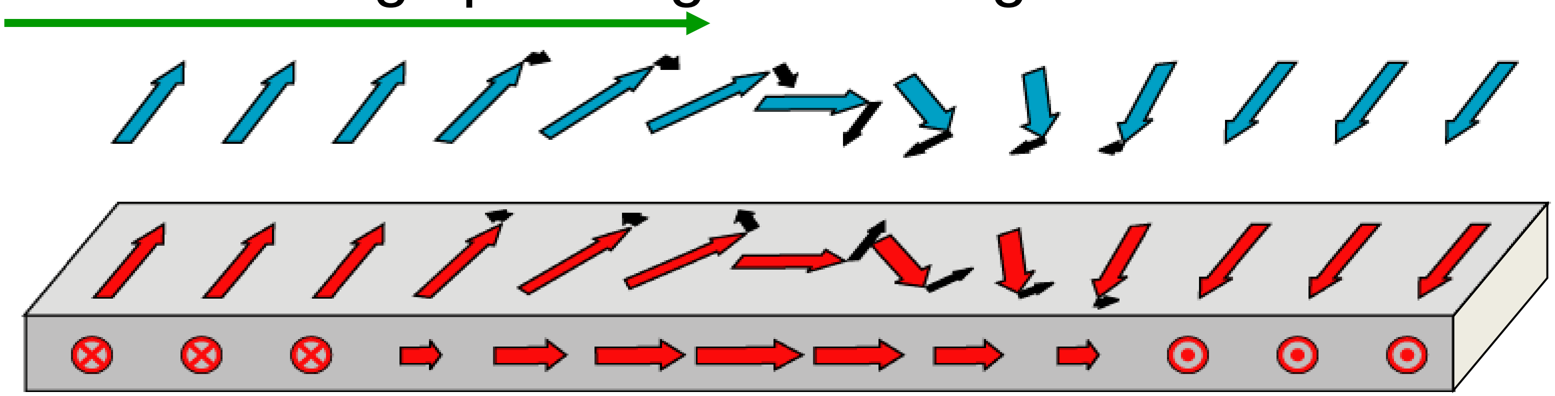


Exchange interaction between ferromagnetic domain wall and electric current in very thin metallic films
L. Berger, J. Appl. Phys. **55**, 1954 (1984)

Review articles: JMMM 320
p. 1272, Current-induced domain wall motion, Beach et al.
p. 1282, Theory of current-driven …, Tserkovnyak et al.

Slowly varying magnetization adiabatic spin transfer torque

when flowing spins align with magnetization:



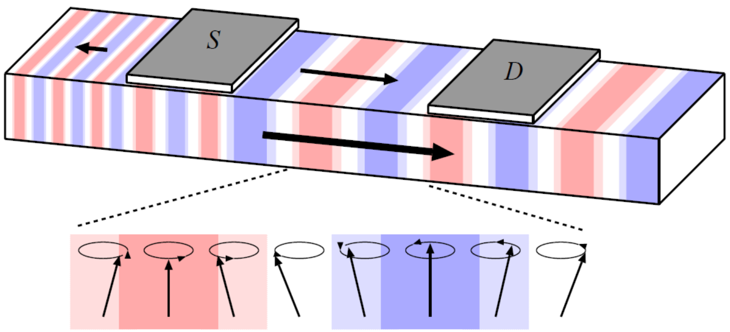
Conservation of angular momentum $\Rightarrow$ Reaction torque on magnetization

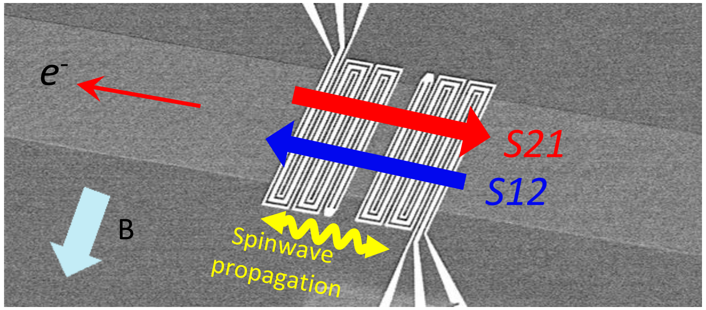
Wall translates

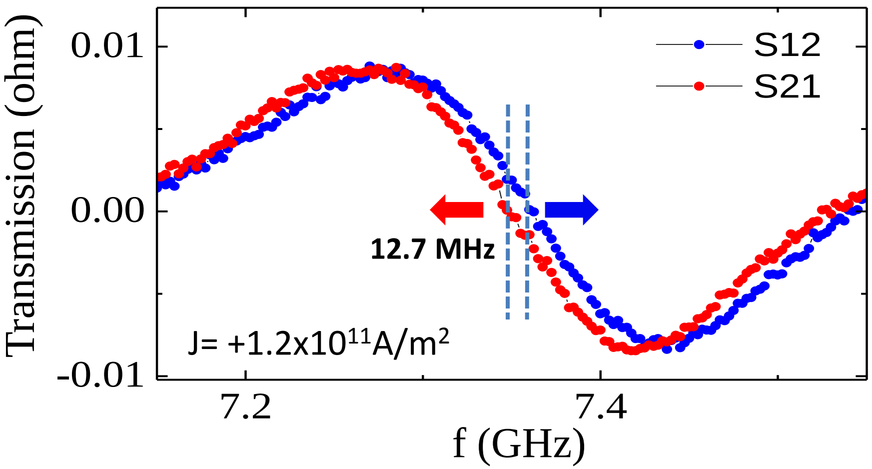
$$\mathbf{n}_{\mathrm{st}} = \frac{Pg\mu_{\mathrm{B}}}{e}\ \mathbf{j}\cdot\nabla\ \ \hat{\mathbf{m}}\ \ x$$

$$v_{\mathrm{s}} = \frac{-Pjg\mu_{\mathrm{B}}}{eM_{\mathrm{s}}}$$

Spin wave Doppler effect – measure spin transfer velocity v_s







S12: Spin wave propagating with electrons

S21: Spin wave propagating against electrons

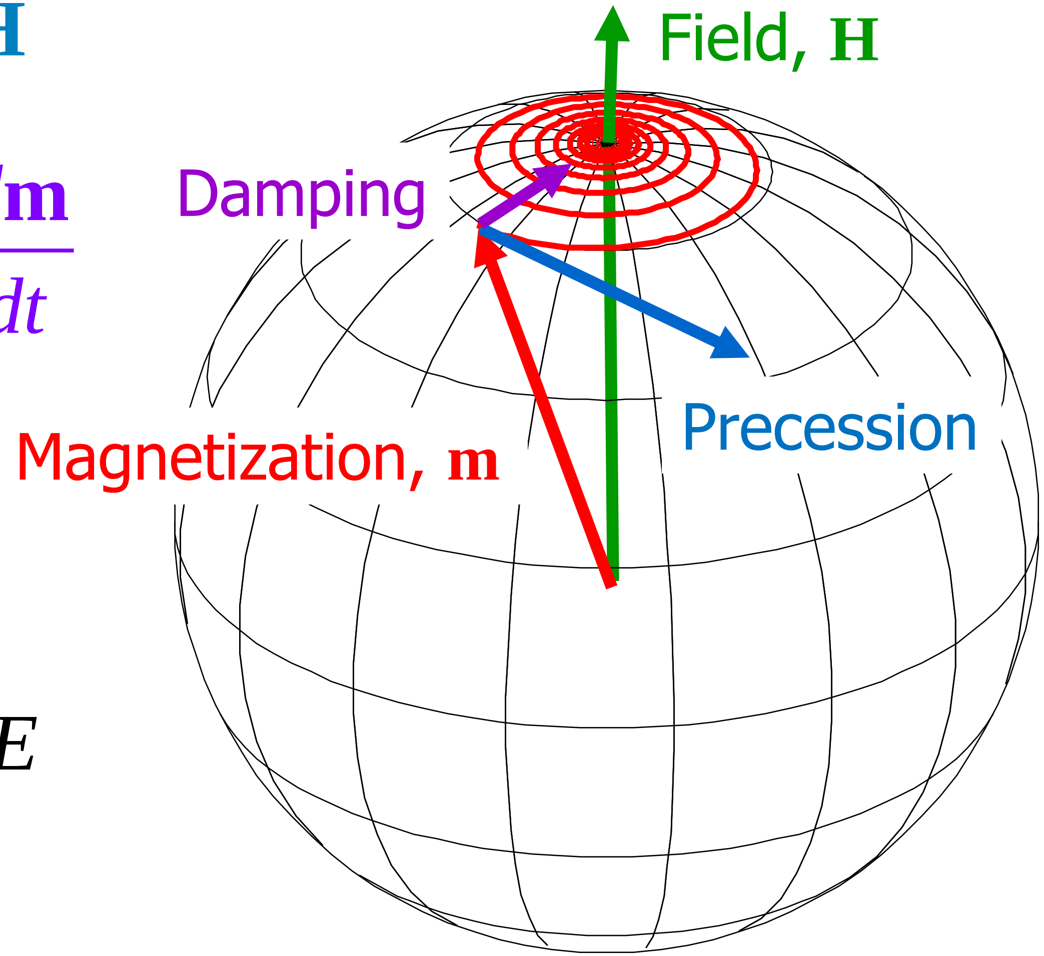
V. Vlaminck and M. Bailleul, Science, **322**, 410 (2008)

R. D. McMichael and M. D. Stiles, Science, **322**, 386 (2008)

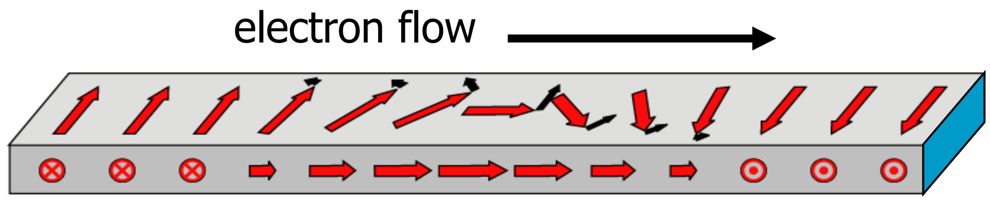
Dynamics – Landau-Lifshitz-Gilbert equation

$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \times \mathbf{H} + \alpha \hat{\mathbf{m}} \times \frac{d\mathbf{m}}{dt}$$

$$\mathbf{H} = -\frac{1}{\mu_0} \nabla_{\mathbf{m}} E$$



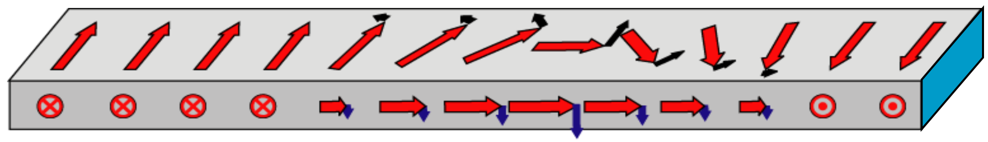
Importance of non-adiabatic torque



Adiabatic torque - translates wall

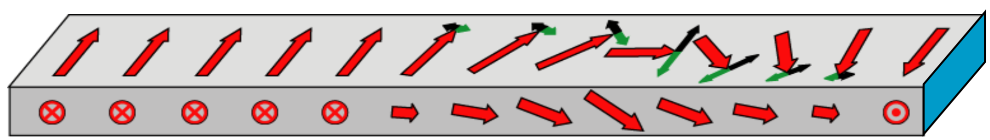
$$\dot{\mathbf{M}} = -(\mathbf{v}_s \cdot \nabla)\mathbf{M}$$

$$v_s = \frac{-Pg\mu_B j}{eM_s}$$



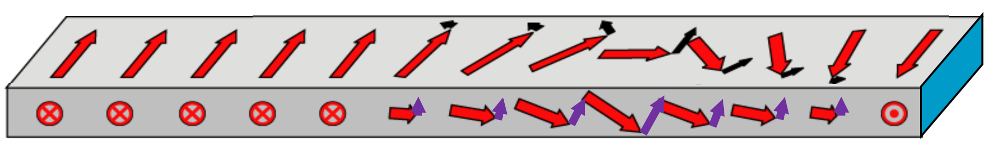
Gilbert damping torque - tilts wall out of plane

$$+\alpha \hat{\mathbf{M}} \times \dot{\mathbf{M}}$$



Magnetostatic torque compensates adiabatic torque - wall stops

$$-\mathbf{M} \times \gamma \mathbf{H}$$



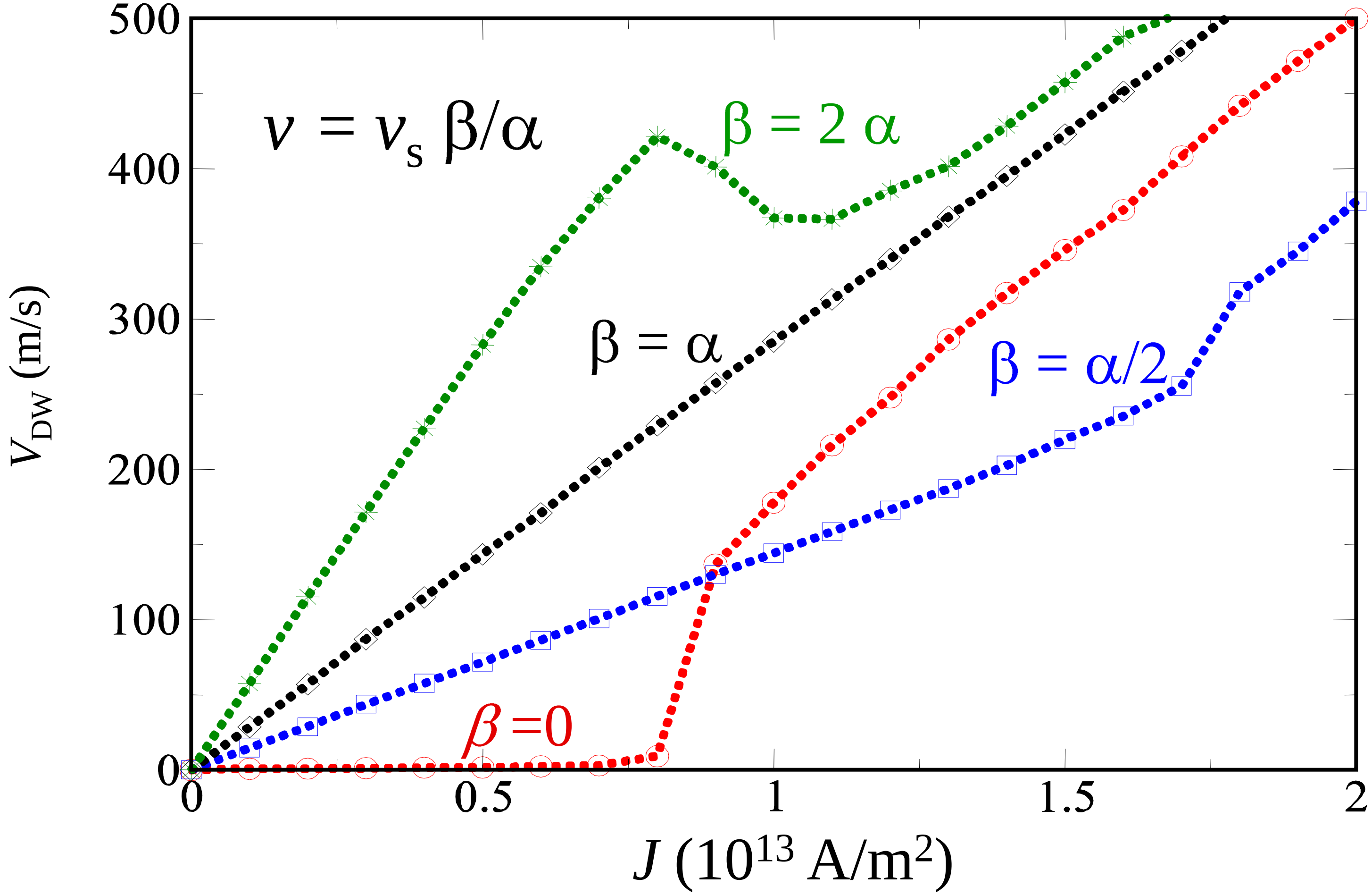
$$+\beta \hat{\mathbf{M}} \times (\mathbf{v}_s \cdot \nabla)\mathbf{M}$$

Non-adiabatic torque acts opposite to Gilbert damping

- reduces tilt, and allows continued motion -

$$v = v_s \beta/\alpha.$$

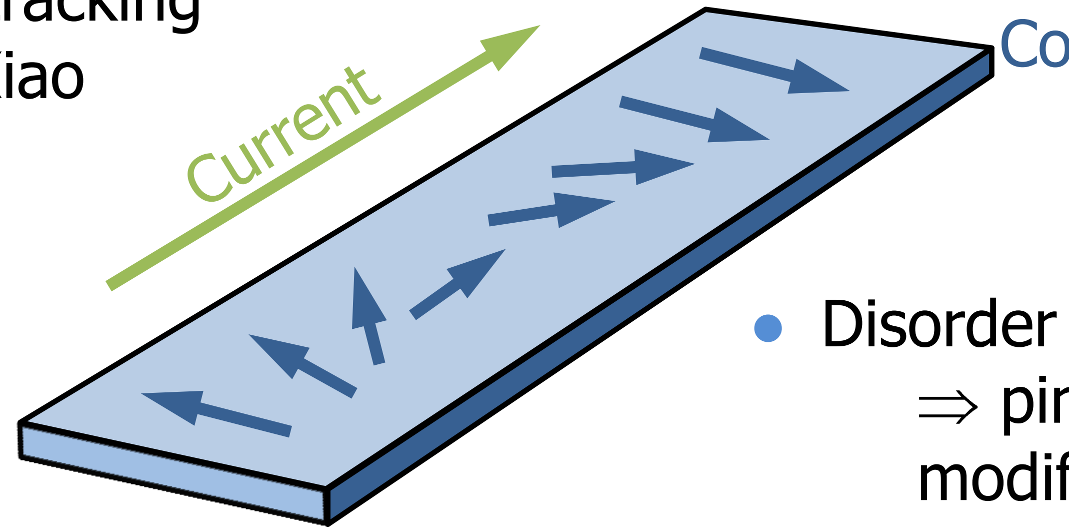
Variation of vortex wall motion with non-adiabatic spin transfer torque



Work done by Hongki Min

Aspects of current-induced domain wall motion

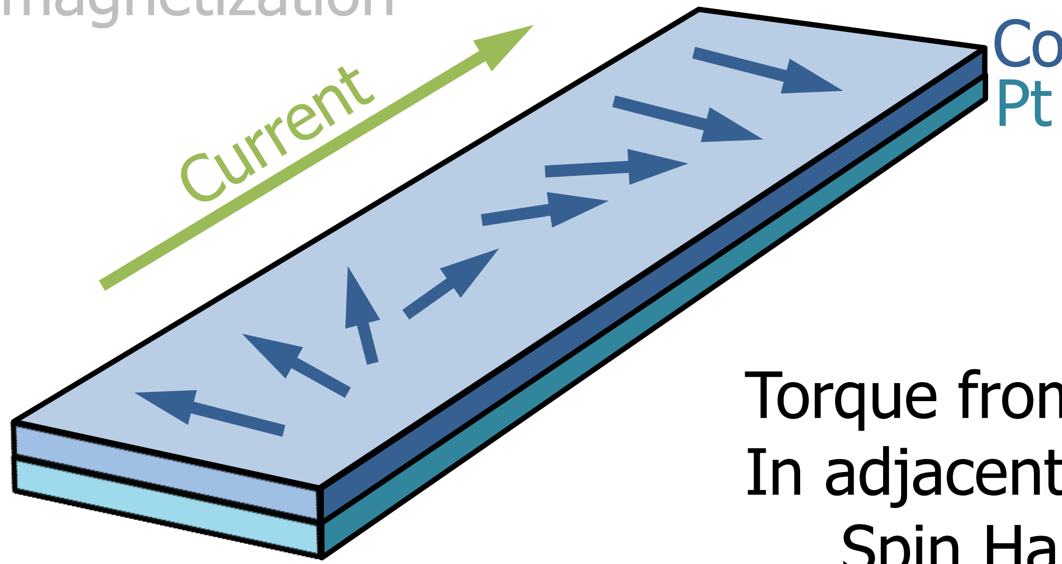
- Abrupt domain walls
  $\Rightarrow$ mistracking
  Jiang Xiao
- Calculation of α and β
  Keith Gilmore



- Disorder
  $\Rightarrow$ pinning,
  modified velocities
  Hongki Min
- Strong spin-orbit coupling in the FM
  $\Rightarrow$ lattice torques
  Paul Haney

Simple system – bilayer thin film wire

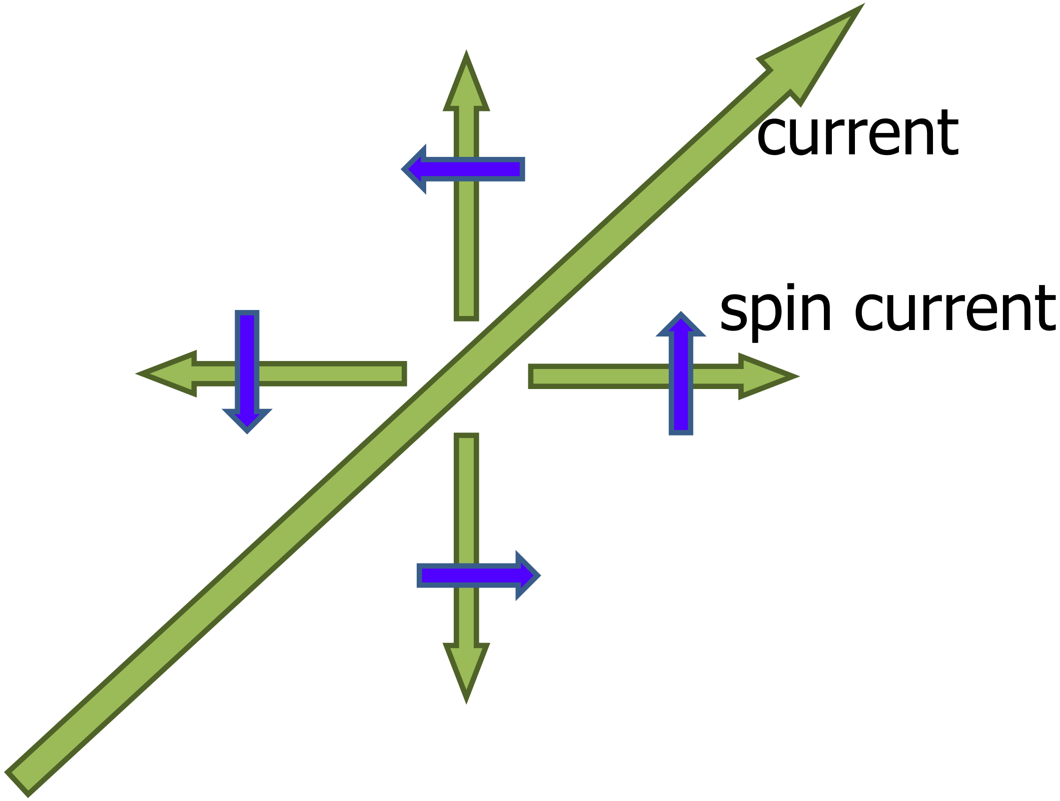
Torque from current flow through a magnetization pattern



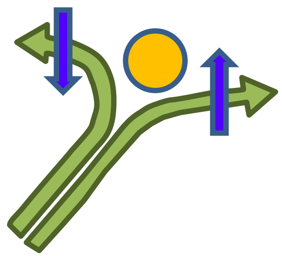
Torque from current flow
In adjacent layer
Spin Hall effect
Spin transfer torque

Torque from interfacial spin orbit coupling

Spin Hall Effect (Anomalous Hall Effect)

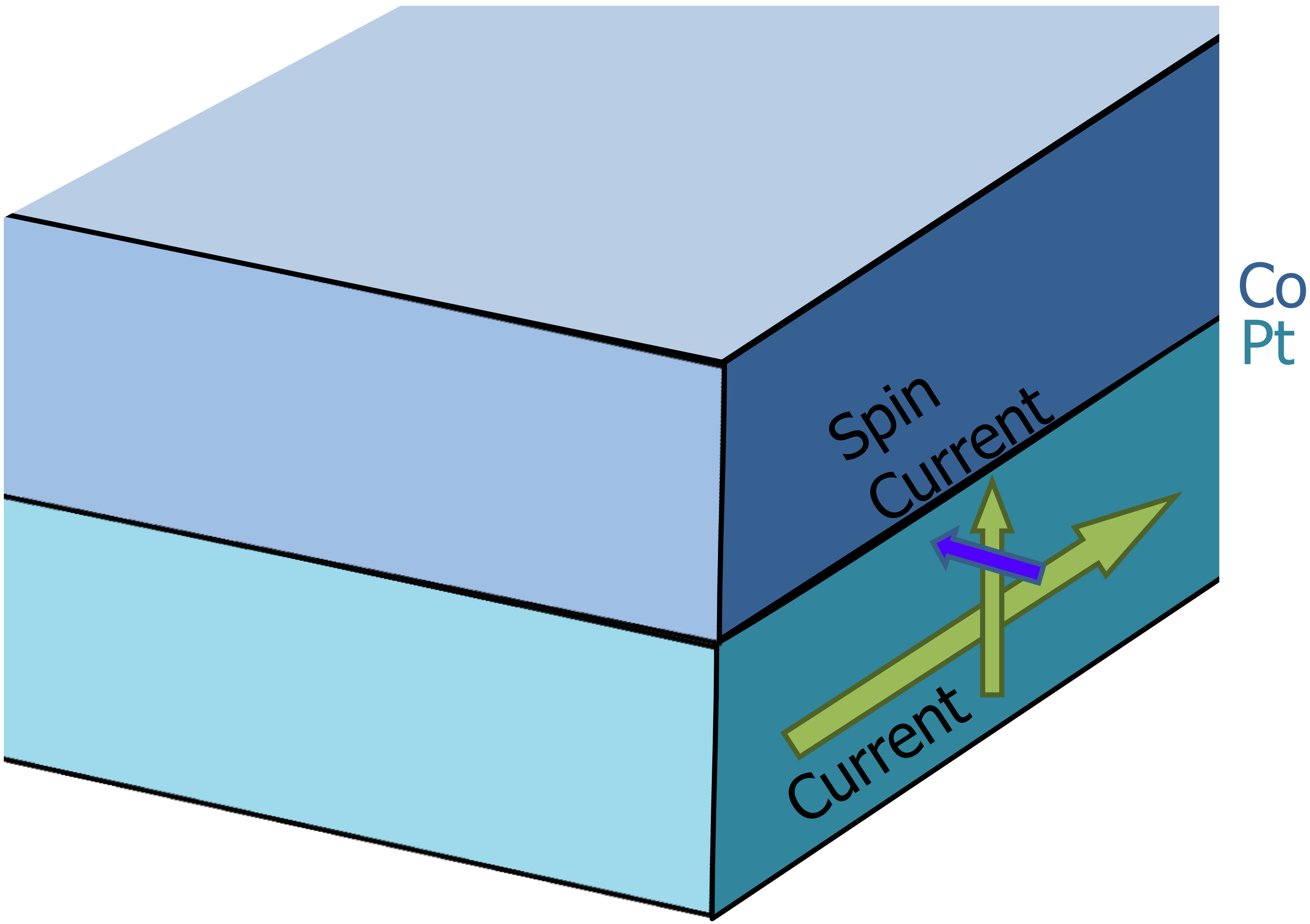


Extrinsic
(Mott scattering)



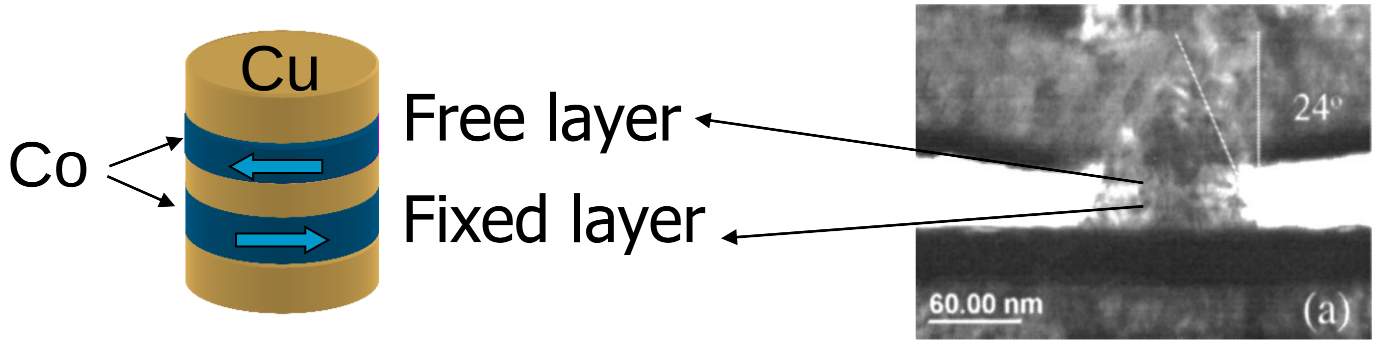
Intrinsic

Spin Hall effect in bilayer nanowire



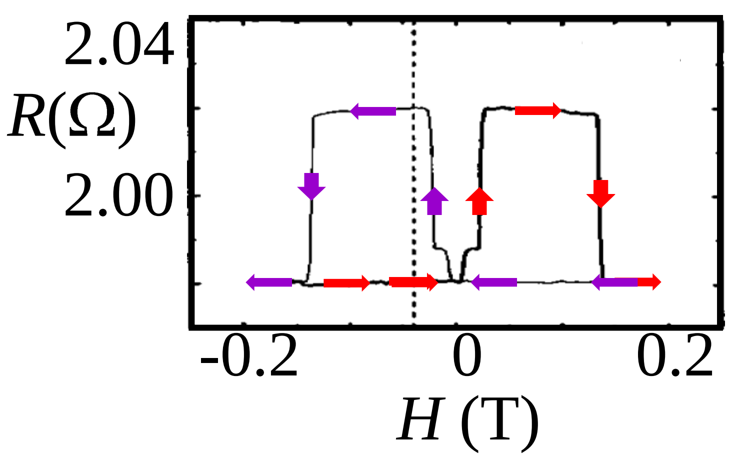
Spin transfer torques in magnetic multilayers

- Independent predictions in 1996 by J. C. Slonczewski and L. Berger
- Observation by Grenoble/Michigan State (1998) and Cornell (1999)

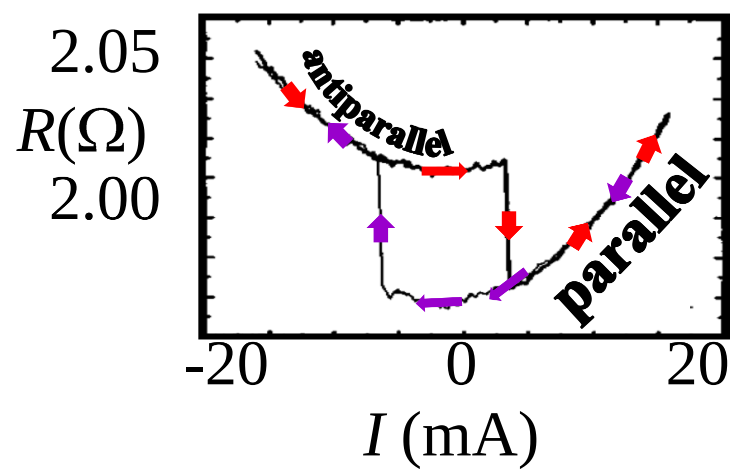


J. Z. Sun et al., JAP (2003)

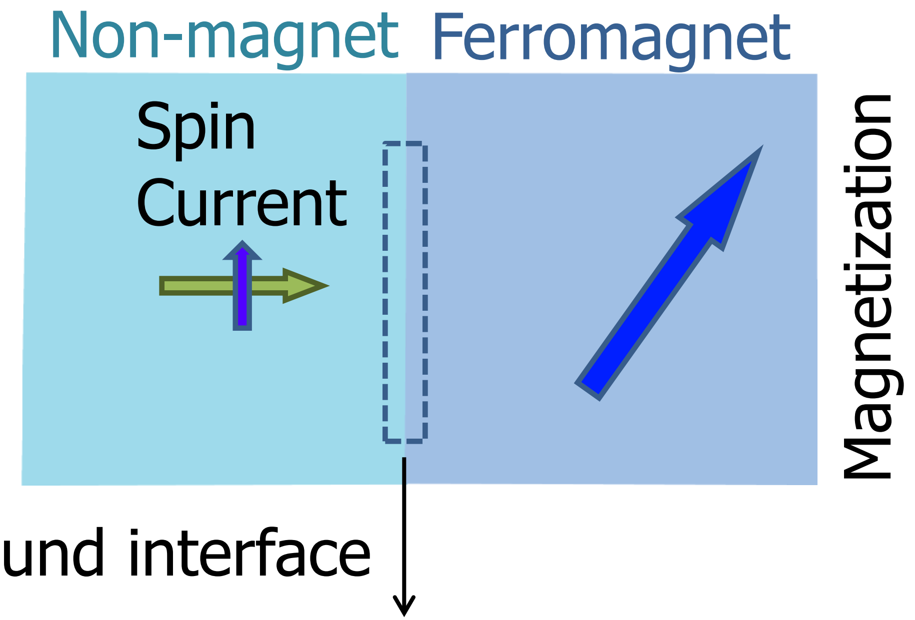
Giant Magnetoresistance



Current-Induced Switching



Interfacial absorption of the transverse spin current

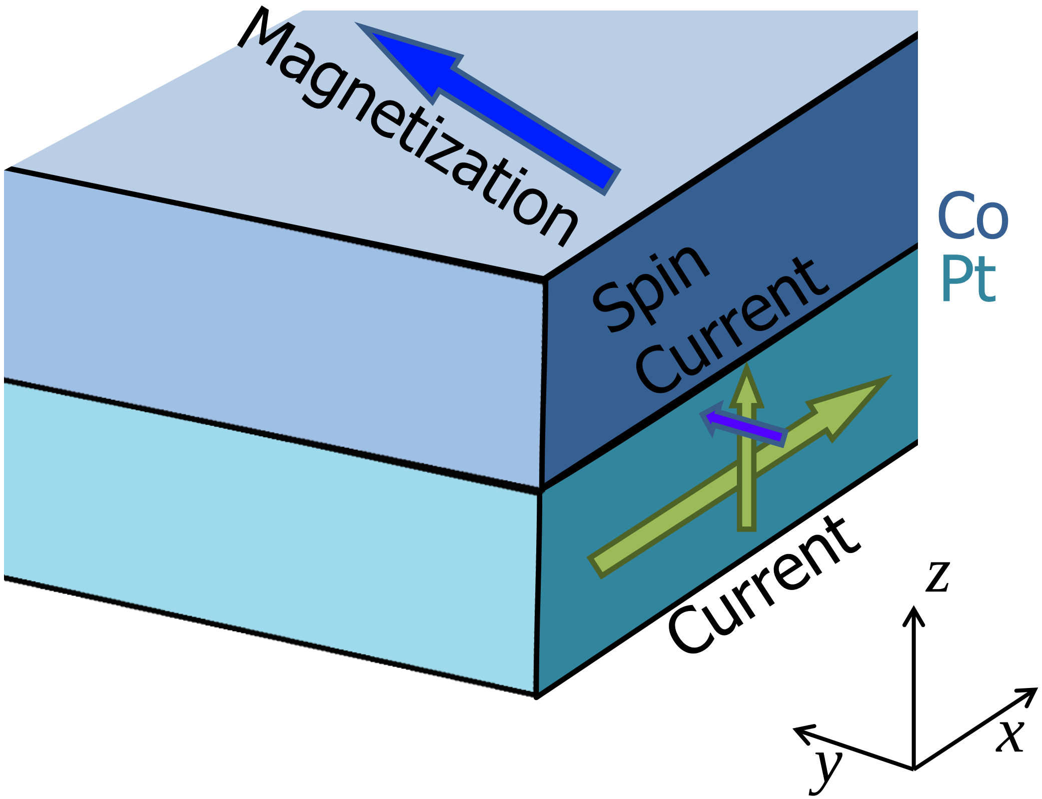


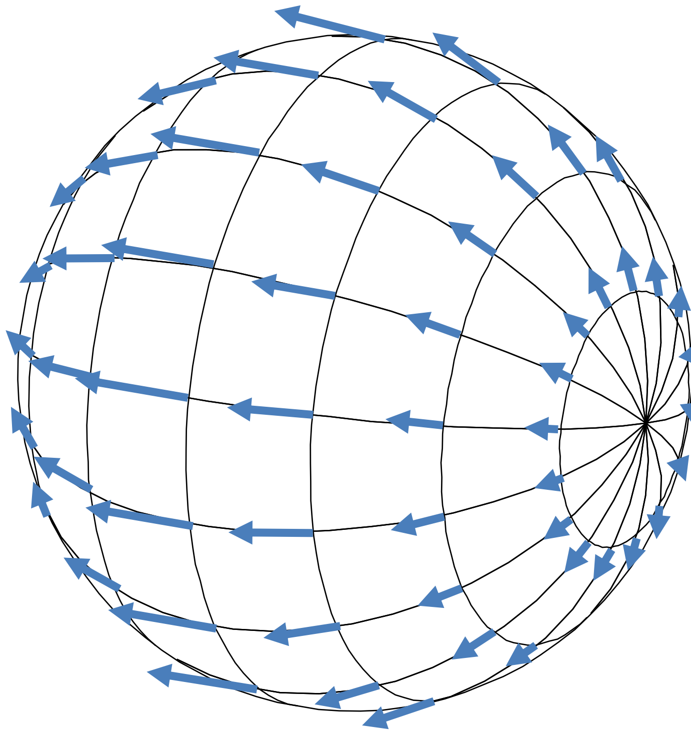
"pillbox" around interface

- Longitudinal spin current conserved
- Transverse spin current absorbed

Due to details of spin-dependent reflection

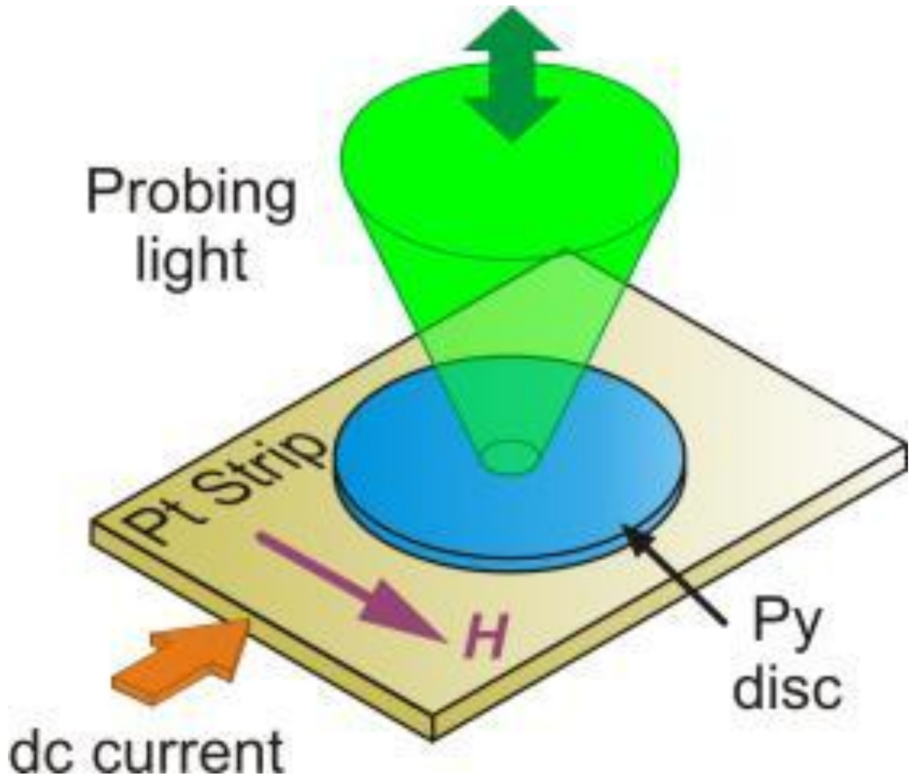
Effective (anti)damping due to spin transfer torque

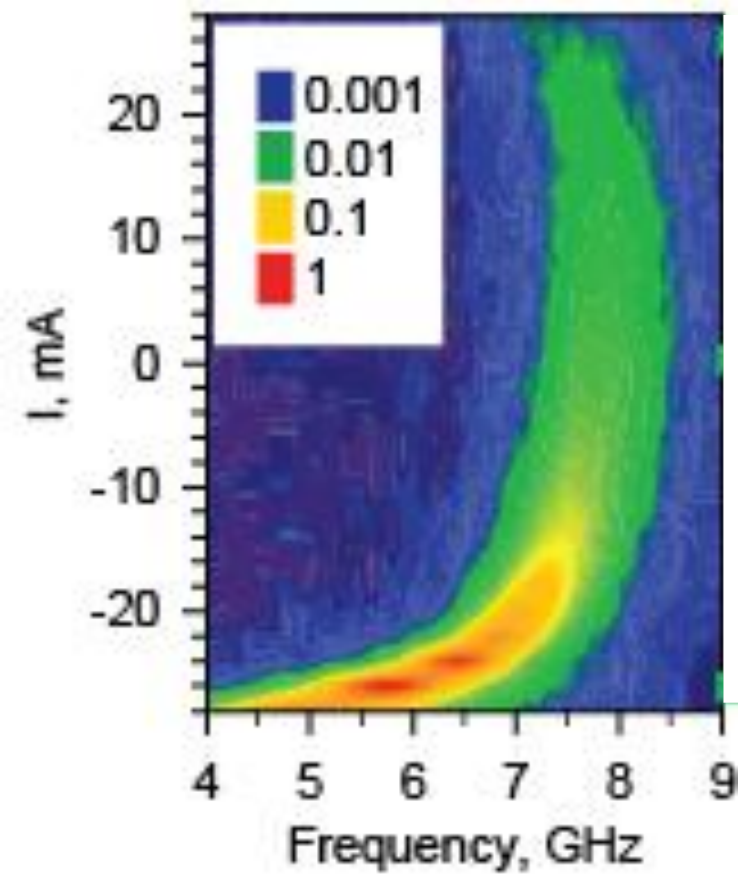




Torque as a function of magnetization direction

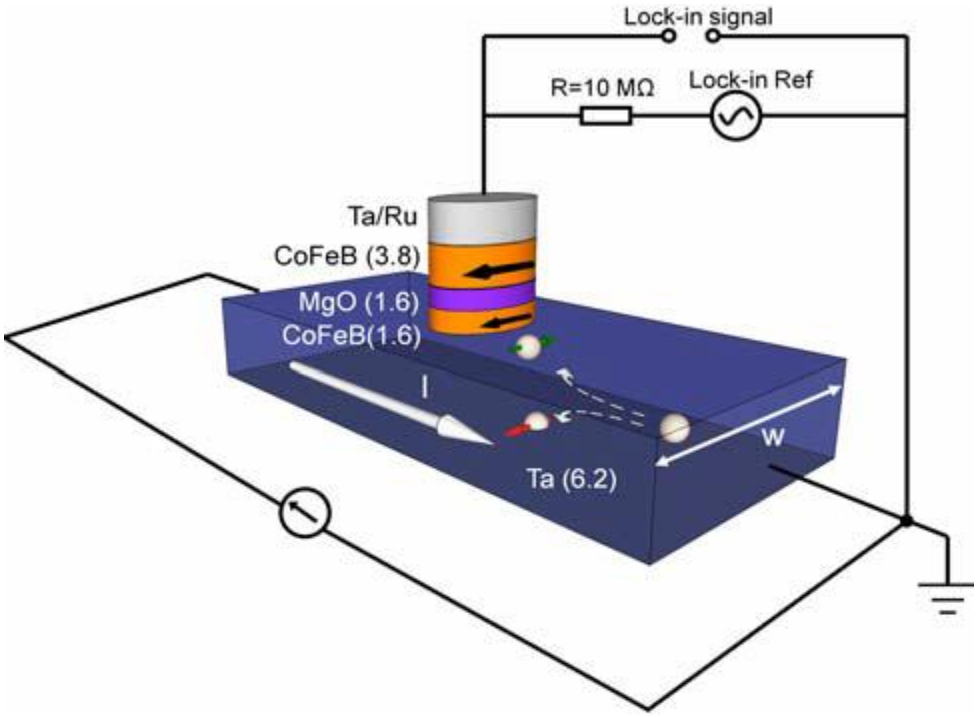
Modification of thermal spin wave amplitudes due to spin Hall effect spin transfer torque

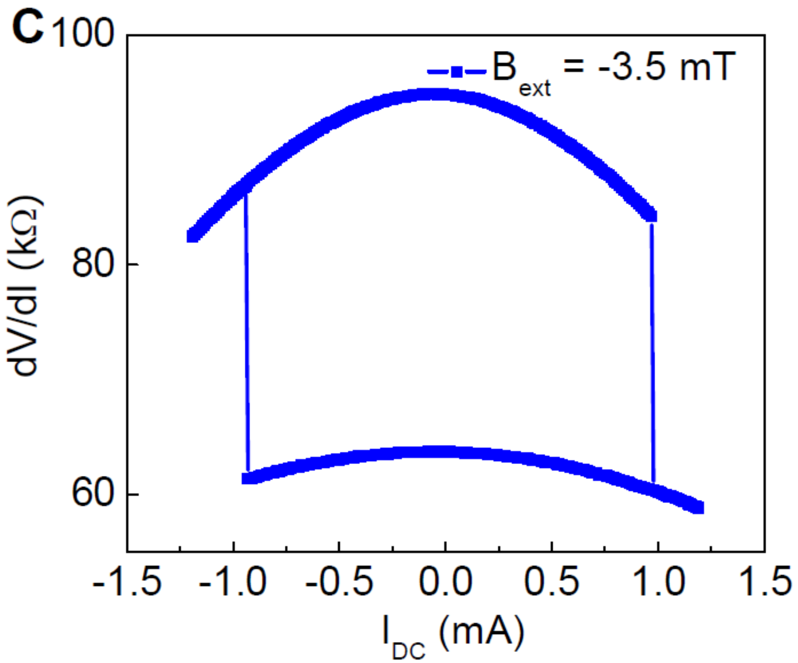




Work done by Vladimir Demidov

Magnetization switching due to spin Hall effect spin transfer torque

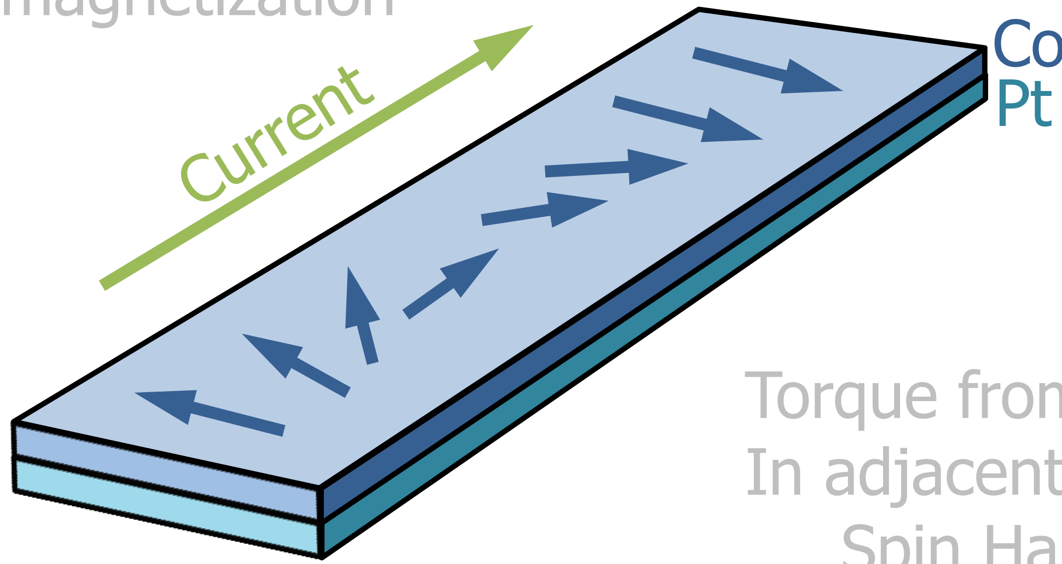




Spin torque switching with the giant spin Hall effect of tantalum
Luqiao Liu, Chi-Feng Pai, Y. Li, H. W. Tseng, D. C. Ralph and R. A. Buhrman
arXiv:1203.2875

Simple system – bilayer thin film wire

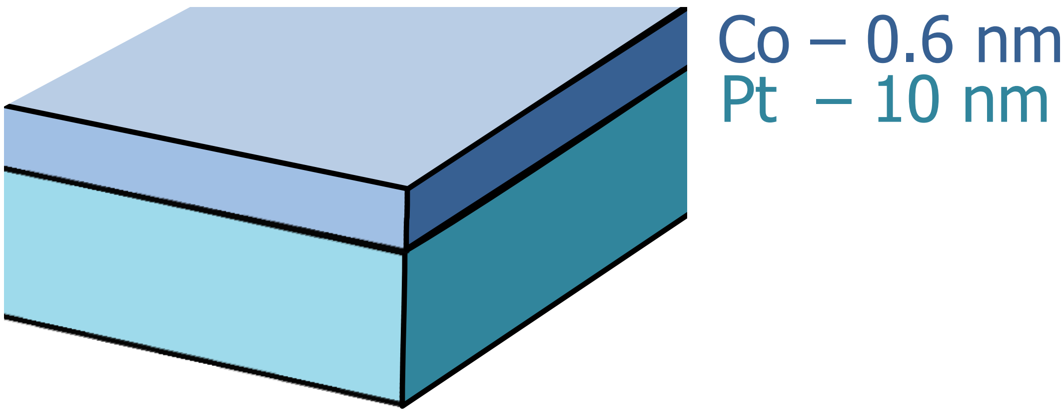
Torque from current flow through a magnetization pattern



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

Torque from interfacial spin orbit coupling

Is something more needed? (controversial)



I.M. Miron et al.,
Nature (2011),
Nature Materials (2011),
Nature Materials (2010)

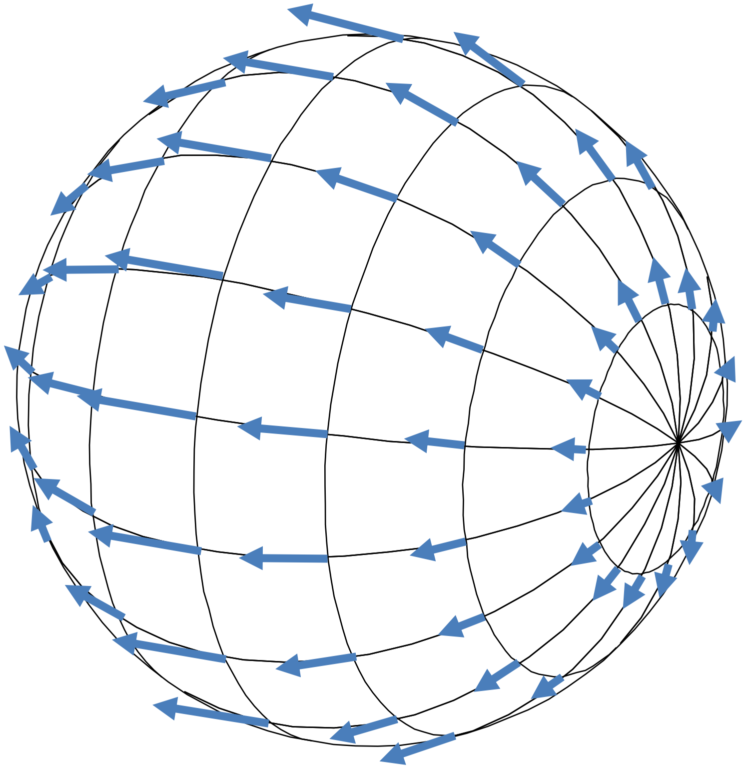
S.S.P. Parkin et al
(unpublished)

- Domain wall velocities much larger than expected
- Domain wall motion opposite electron flow
- …

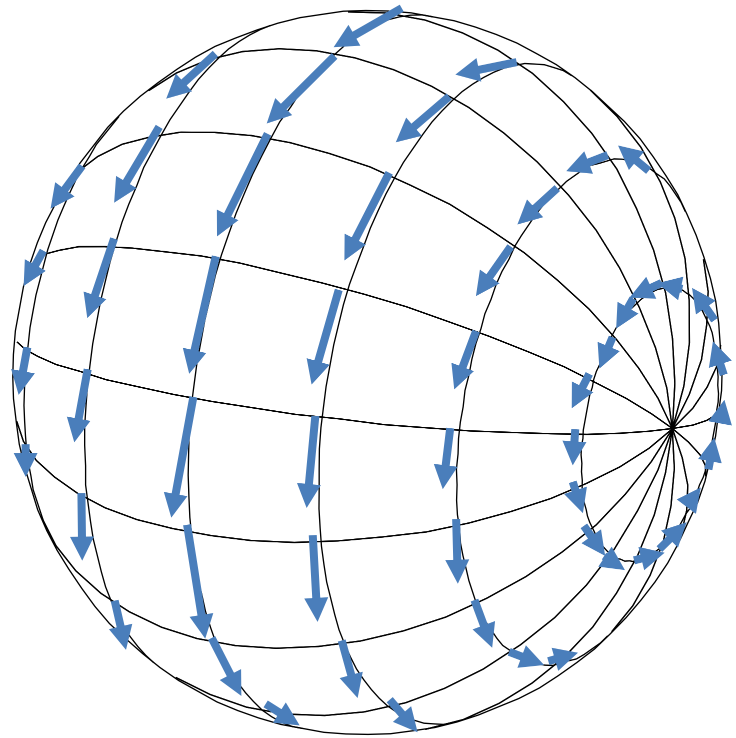
⇒ Interpretation – large “field-like” torque due to strong interfacial spin orbit coupling

Additional spin Hall spin transfer toques

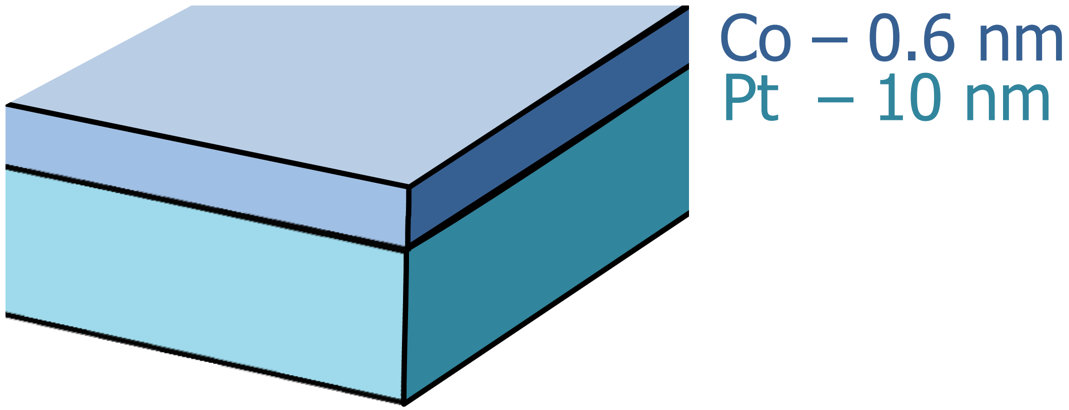
Damping-like



Field-like



Difficult problem – multipronged approach

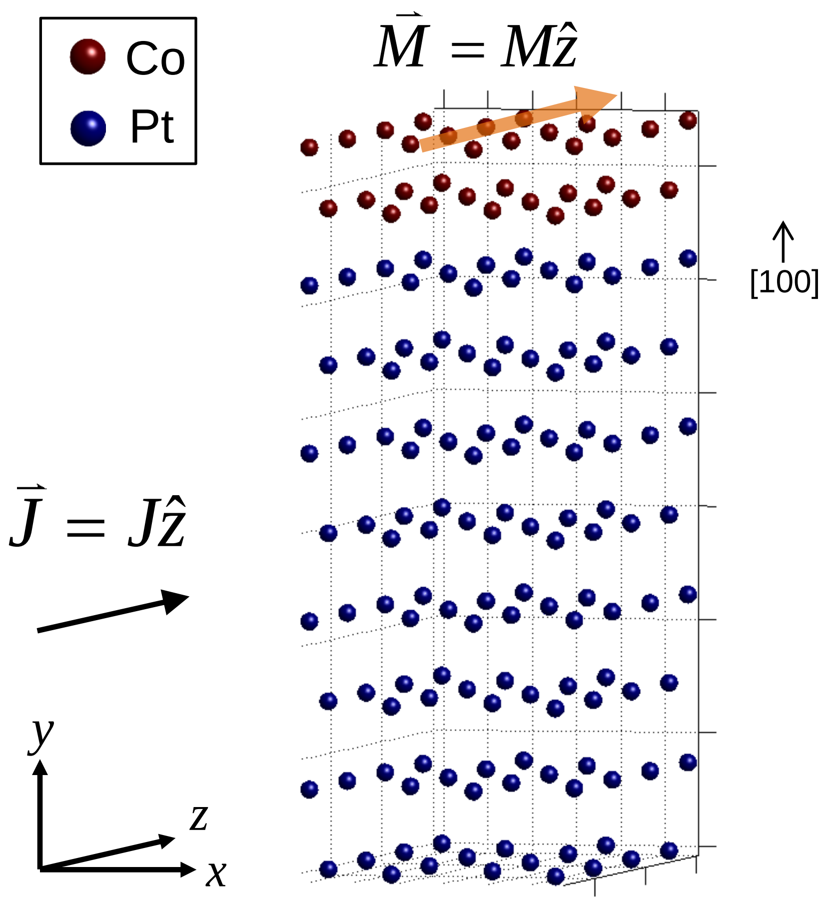


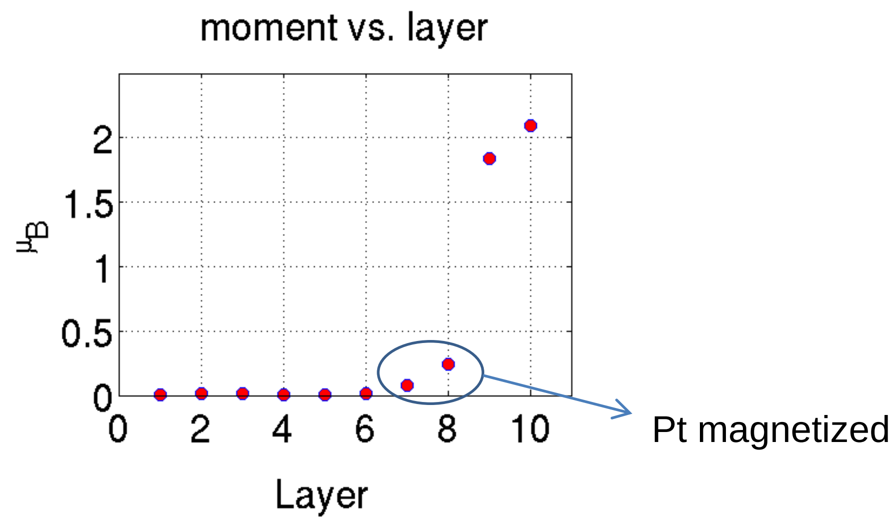
Electronic Structure
- To understand interface

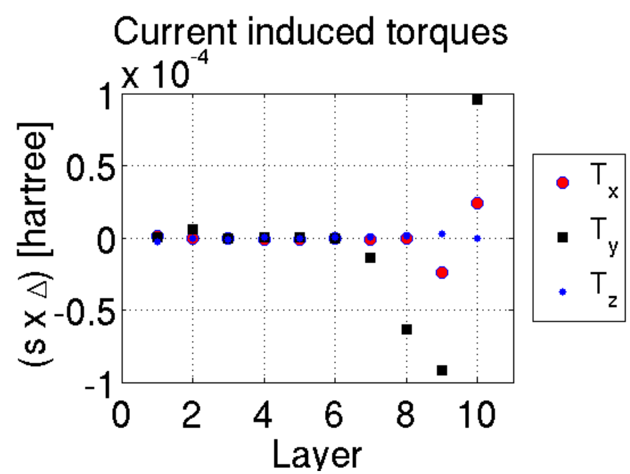
Semiclassical Transport
- To determine the torque

Micromagnetic simulations
- To determine what equations of motion can reproduce experiment

Modification of electronic structure at the interface







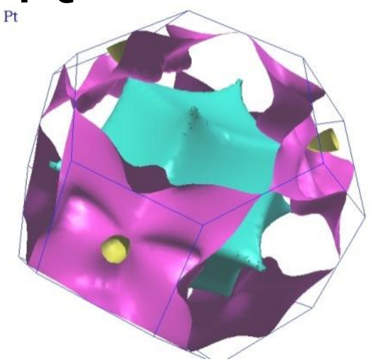
Periodic in x, and z-directions

Work in progress by Paul Haney

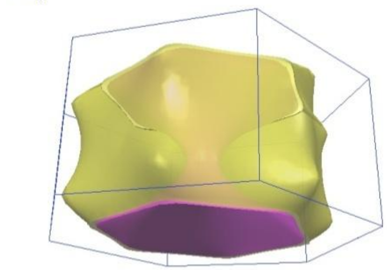
*Landauer (linear response) → no intrinsic from E-field contribution?

Crude model for semiclassical transport

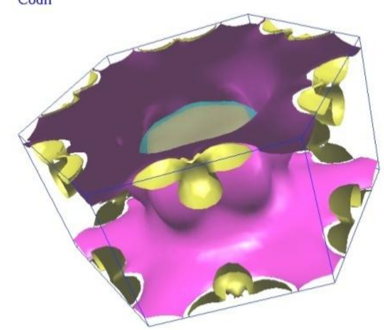
Pt



Co Majority



Co Minority

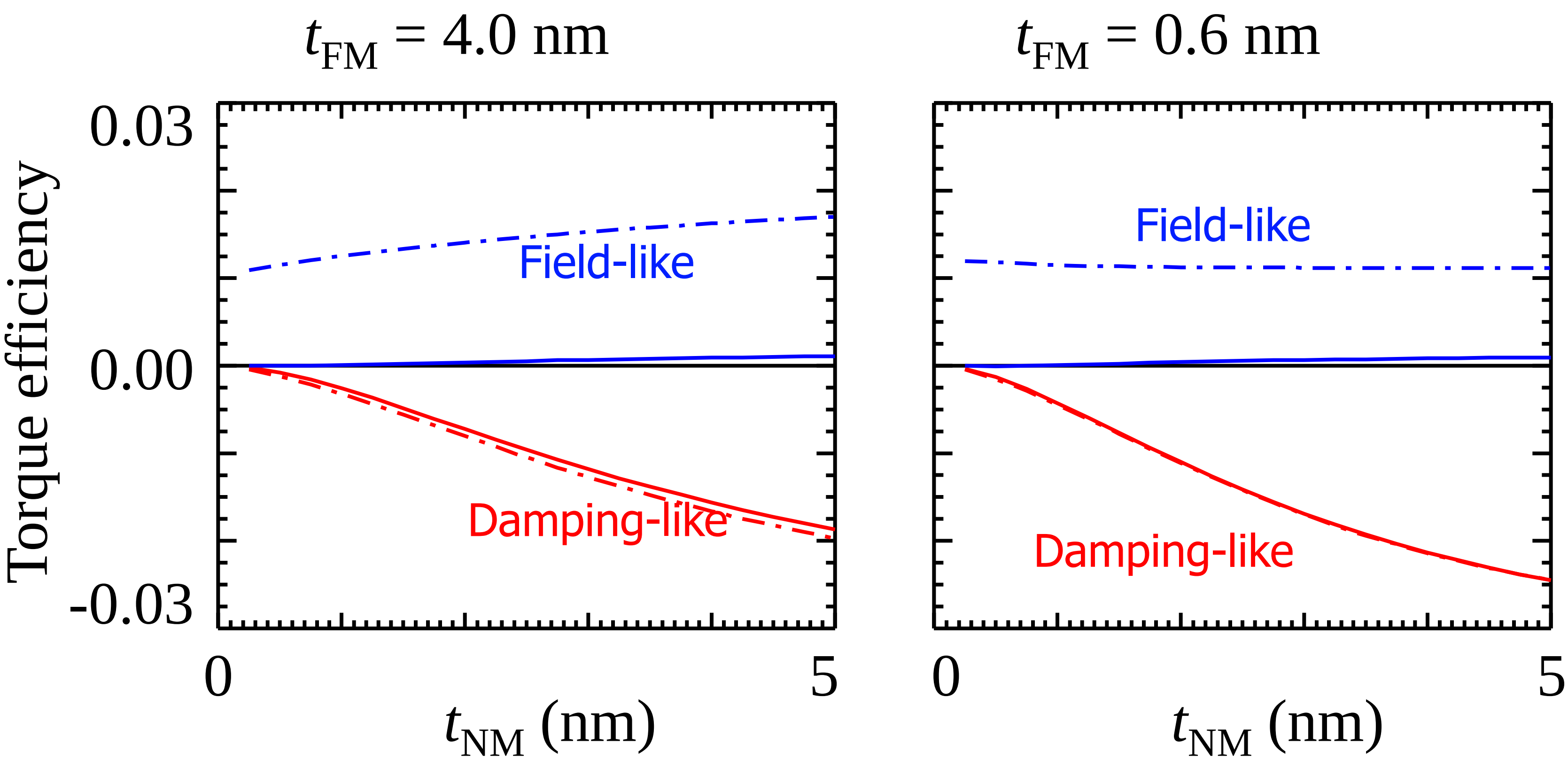


http://www.phys.ufl.edu/fermisurface/

- Boltzmann equation
- Spherical Fermi surfaces
- Spin-dependent scattering
- “extrinsic” spin Hall effect
- Delta function interfacial potential

$$g_0 + g_{\mathrm{p}}\sigma\cdot\mathbf{m} + g_{\mathrm{r}}\sigma\cdot \;\; \mathbf{k}\times\hat{\mathbf{z}} \quad \delta \;\; z$$

Boltzmann equation calculation of spin transport and torques in bilayer nanowires



Solid curves – no interfacial spin-orbit coupling
Dash-dot curves – with additional interfacial spin-orbit coupling (very asymmetric reflection amplitudes)

Equation of motion

$$\dot{\mathbf{M}} = -\gamma_{\mathbf{0}}\mathbf{M}\times \ \mathbf{H}_{\mathrm{ext}} + \mathbf{H}_{\mathrm{dipole}} + \mathbf{H}_{\mathrm{ani}} + \mathbf{H}_{\mathrm{ex}} \ + \alpha\hat{\mathbf{M}}\times\dot{\mathbf{M}}$$

"Standard" torques

Damping

$$+ v_{\mathrm{s}} \ \hat{\mathbf{j}}\cdot\nabla \ \mathbf{M} \quad - \quad \beta v_{\mathrm{s}}\hat{\mathbf{M}}\times \ \hat{\mathbf{j}}\cdot\nabla \ \mathbf{M}$$

Adiabatic spin transfer torque

Non-adiabatic spin transfer torque

$$+ \theta_{\mathrm{SH}} c_j \mathbf{M}\times \ \mathbf{M}\times \ \hat{\mathbf{j}}\times\hat{\mathbf{n}} \quad + \quad \beta'\theta_{\mathrm{SH}} c_j \mathbf{M}\times \ \hat{\mathbf{j}}\times\hat{\mathbf{n}}$$

Spin Hall spin transfer torques

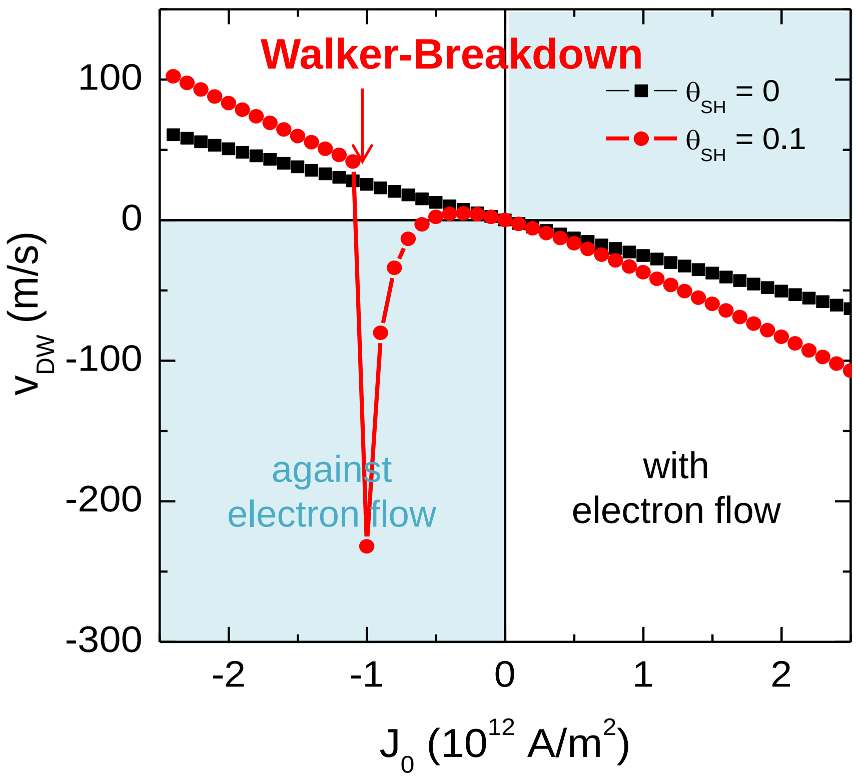
Damping-like

Field-like

Micromagnetic simulations with different current-induced torques

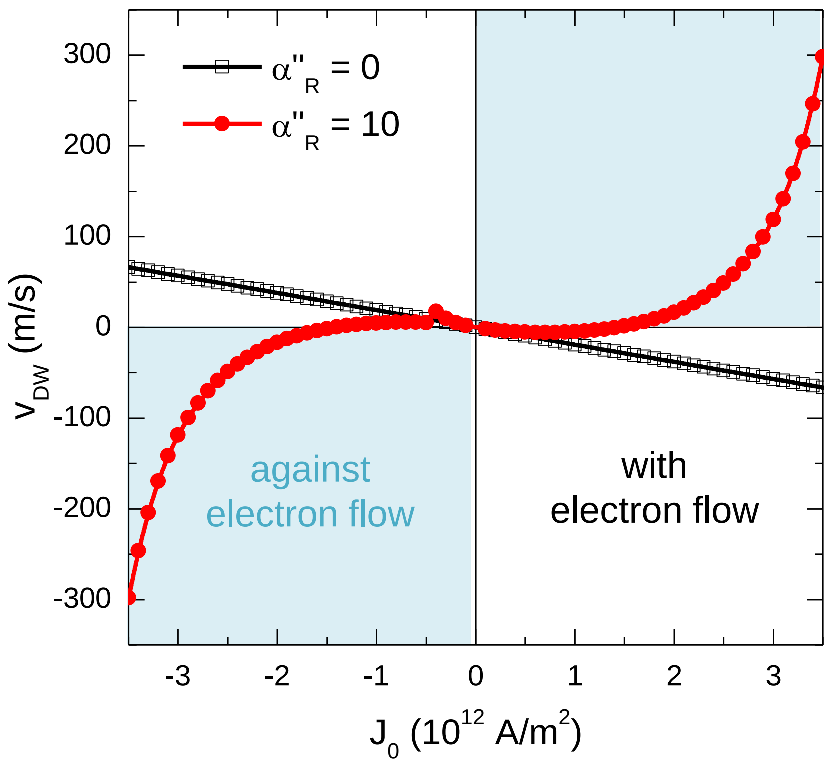
Only damping-like torque

NiFe (4 nm) | Pt (3 nm)



Damping-like torque + large field torque (4x)

Pt | Co (0.6 nm)



Work by Kyung-Jin Lee

Summary

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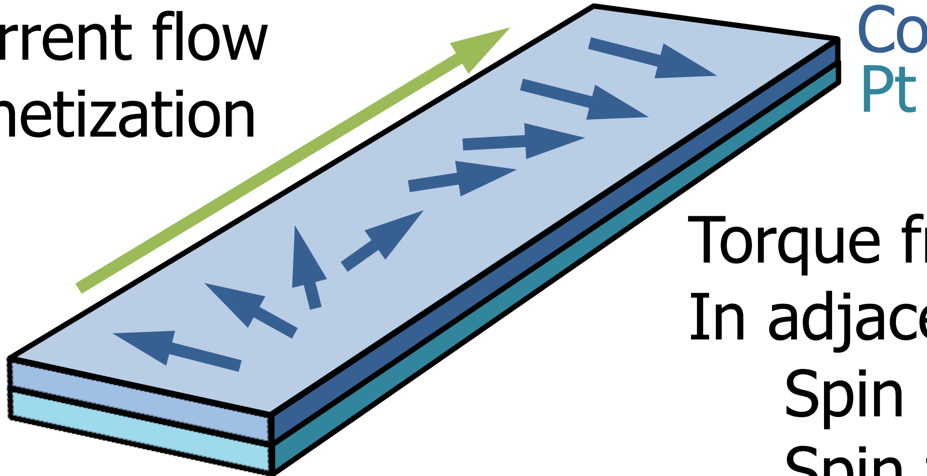

Torque from current flow
In adjacent layer
- Spin Hall effect
- Spin transfer torque

Torque from interfacial spin orbit coupling

More information at http://cnst.nist.gov

Review articles: JMMM 320
p. 1190, Spin transfer torques, Ralph & Stiles
p. 1272, Current-induced domain wall motion, Beach et al.
p. 1282, Theory of current-driven …, Tserkovnyak et al.
p. 1300, Current-induced torques …, Haney et al.