Domain Wall Motion in Magnetic Nanowires

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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

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Torque from interfacial spin orbit coupling
Exchange interaction between ferromagnetic domain wall and electric current in very thin metallic films

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

$$n_{st} = \frac{P g \mu_B}{e} j \cdot \nabla \hat{m} \ x$$

$$v_s = \frac{-P j g \mu_B}{e M_s}$$
Spin wave Doppler effect – measure spin transfer velocity $v_s$

$\begin{array}{c}
S12: \text{Spin wave propagating with electrons} \\
S21: \text{Spin wave propagating against electrons}
\end{array}$

Dynamics – Landau-Lifshitz-Gilbert equation

\[ \frac{dm}{dt} = -\gamma_0 m \times H \]

\[ + \alpha \hat{m} \times \frac{dm}{dt} \]

\[ H = \frac{1}{\mu_0} \nabla_m E \]
Importance of non-adiabatic torque

Magnetostatic torque compensates adiabatic torque - wall stops

\[ \dot{M} = - (v_s \cdot \nabla) M + \alpha \hat{M} \times \dot{M} - M \times \gamma H + \beta \hat{M} \times (v_s \cdot \nabla) M \]

v = v_s \beta/\alpha

Adiabatic torque - translates wall

Gilbert damping torque - tilts wall out of plane

Non-adiabatic torque acts opposite to Gilbert damping - reduces tilt, and allows continued motion -

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

\[ \nu = v_s \frac{\beta}{\alpha} \]

\[ \beta = 2\alpha \]

\[ \beta = \alpha \]

\[ \beta = \frac{\alpha}{2} \]

\[ \beta = 0 \]

Work done by Hongki Min
Aspects of current-induced domain wall motion

- Abrupt domain walls
  \(\Rightarrow\) mistracking
  Jiang Xiao

- Calculation of \(\alpha\) and \(\beta\)
  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 interfacial spin orbit coupling

Co
Pt

Torque from current flow in adjacent layer
Spin Hall effect
Spin transfer torque
Spin Hall Effect (Anomalous Hall Effect)

Extrinsic current (Mott scattering)

Intrinsic spin current

Intrinsic
Spin Hall effect in bilayer nanowire
Spin transfer torques in magnetic multilayers

- Independent predictions in 1996 by J. C. Slonczewski and L. Berger

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 interfacial spin orbit coupling
Is something more needed? (controversial)


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

Co – 0.6 nm
Pt – 10 nm
Modification of electronic structure at the interface

Periodic in $x$, and $z$-directions

$\mathbf{J} = J\hat{z}$

$\mathbf{M} = M\hat{z}$

*Landauer (linear response) $\rightarrow$ no intrinsic from E-field contribution?

Work in progress by Paul Haney
Crude model for semiclassical transport

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

\[ g_0 + g_p \sigma \cdot m + g_r \sigma \cdot k \times \hat{z} \delta z \]

http://www.phys.ufl.edu/fermisurface/
Boltzmann equation calculation of spin transport and torques in bilayer nanowires

$t_{\text{FM}} = 4.0 \text{ nm}$

$t_{\text{FM}} = 0.6 \text{ nm}$

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

\[ \dot{\mathbf{M}} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{ext}} + \mathbf{H}_{\text{dipole}} + \mathbf{H}_{\text{ani}} + \mathbf{H}_{\text{ex}} + \alpha \dot{\mathbf{M}} \times \dot{\mathbf{M}} \]

“Standard” torques

\[ + \nu_s \dot{\mathbf{j}} \cdot \nabla \mathbf{M} - \beta \nu_s \dot{\mathbf{M}} \times \dot{\mathbf{j}} \cdot \nabla \mathbf{M} \]

Adiabatic spin transfer torque

Non-adiabatic spin transfer torque

\[ + \theta_{\text{SH}} \gamma_j \mathbf{M} \times \mathbf{M} \times \dot{\mathbf{j}} \times \hat{n} + \beta' \theta_{\text{SH}} \gamma_j \mathbf{M} \times \dot{\mathbf{j}} \times \hat{n} \]

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)

Walker-Breakdown

against electron flow

with electron flow

$\theta_{SH} = 0$

$\theta_{SH} = 0.1$

$\alpha''_R = 0$

$\alpha''_R = 10$

Work by Kyung-Jin Lee
Summary

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


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p. 1282, Theory of current-driven ..., Tserkovnyak et al.
p. 1300, Current-induced torques ..., Haney et al.