Lecture 2: Spin Current Induced Magnetization Dynamics

Lecture 3: Quantum Spin Dynamics in Molecular Nanomagnets
Outline

I. Spin-Transport and Transfer Basics
   – Giant magnetoresistance (GMR)
   – Spin filtering and spin momentum transfer

II. Spin-Transfer Induced Magnetization Dynamics
    – Landau-Lifshitz-Gilbert dynamics and spin-torque
    – Current threshold for excitations and stability diagrams

III. Experiments
    – Point contacts, nanopillars
    – dc transport, noise, high frequency characteristics

IV. Spin-Transfer MRAM
    – Ultimate miniaturization of MRAM

V. Summary

References
Giant Magnetoresistance (GMR)

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Albert Fert

1/2 of the prize

France

Univ. Paris-Sud;
Unité Mixte de Physique
CNRS/THALES
Orsay, France

b. 1938

Peter Grünberg

1/2 of the prize

Germany

Forschungszentrum Jülich
Jülich, Germany

b. 1939

→ ‘Spintronics’= Spin + Transport + Electronics: control of current using the spin of electrons
Giant Magnetoresistance (GMR)

$H$

$GMR=5.4\%$ at $4.2\, K$
Magnetoresistance (MR) $\Delta R/R$

$Cu$

$Co$

$R_{spin-down} = R_{spin-up}$

$MR \approx 0$

$R_{spin-down} > R_{spin-up}$

$MR \sim 1\%$
The Two Channel Model of GMR

Spin-dependent scattering of conduction electrons & change of scattering rate with an external field.

Resistance

\[ R_{\text{parallel}} \ll R_{\text{anti-parallel}} \]

\[ \Delta \frac{R}{R} \sim 1-10\% \]
Spin Filtering by Ferromagnetic Layers

Parallel
low resistance state

Antiparallel
high resistance state

Ferromagnetic layers act spin polarizers and analyzers for an electric current!
**Key Idea!!!**

*If a magnetic layer acts as a spin-filter, then it must also experience a torque.*

\[ \tau \propto I \sin \theta \]

Slonczewski 1996 and Berger 1996

Seeds of the idea in Slonczewski 1988
Reversing the direction of the current changes the sign of the torque

\[ \tau \propto I \sin \theta \]
**Torques with Two Magnetic Layers**

**Electron flow (negative current)**

Spin currents moving to the right exert a torque favoring parallel alignment
(and a low resistance state)

**Electron flow (positive current)**

Spin currents moving to the left exert a torque favoring antiparallel alignment
(and a high resistance state)

**Spin-transfer is an interface effect:**

Transverse spin coherence length:

\[ \lambda_c = \frac{2\pi}{k_{f\uparrow} - k_{f\downarrow}} \]

Stiles and Zangwill, PRB 2002
Spin Transfer – A new method to manipulate nanomagnets

- Spin current induced switching, Coherent dynamic precession.

Charge current

Spin current

- “fixed” ferromagnet
- normal metal layer
- “free” ferromagnet

C. Oersted, 1819

J.C. Slonczewski, 1996

New Physics:

- Insight into spin transport: injection, diffusion and coherence
- Fundamentally new types of magnetic excitations
- Most of the theories are still untested
Dynamics: LLG+spin-torque (LLGS)

\[
\frac{d\hat{m}}{dt} = -\gamma\hat{m} \times \vec{H}_{\text{eff}} + \alpha\hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_J \hat{m} \times (\hat{m} \times \hat{m}_P) - [\hat{m}_P - (\hat{m} \cdot \hat{m}_P)\hat{m}]
\]

\[
a_J = \frac{\hbar P J}{2eM_s t}
\]

When the spin-torque exceeds the damping, instabilities can occur!

Also possible: \(b_J \hat{m} \times \hat{m}_P\)

‘Current-Induced Effective field’

\[
\vec{H}_{\text{eff}} = \vec{H} - 4\pi M_{\text{eff}} (\hat{m} \cdot \hat{z})\hat{z} + H_K (\hat{m} \cdot \hat{x})\hat{x}
\]
Spin-current amplifies the motion for currents greater than a critical value:

$$J_c = \frac{2e}{\hbar} \frac{\alpha}{P} M_s t (H + H_K + 2\pi M_{eff})$$

J. Z. Sun, PRB 2000
Stability Diagrams

✧ In-plane magnetization and field:

\[ J_c = \frac{2e}{\hbar} \frac{\alpha}{P} M_s t (H + H_K + 2\pi M_{\text{eff}}) \]

✧ Perpendicular magnetization and field:

\[ H > 4\pi M_{\text{eff}} \quad H_K \ll 4\pi M_{\text{eff}} \]

J. Z. Sun, PRB 2000; Bertotti et al., PRL 2005, Chen et al PRB 2006
Charge versus Spin Currents

In both cases there will be a current threshold at which the magnet will respond

**Charge current**: magnet responds to the magnetic field generated:

\[ B_c = \frac{\mu_o I_c}{2\pi r} \rightarrow I_c \sim r \]

**Spin Current**: there is a critical current density

\[ J_c = \frac{I_c}{\pi r^2} \rightarrow I_c \sim r^2 \]

In devices with radii less than \( R_{\text{min}} \):

The critical current due to the spin-current will be less than that due to the charge current

\[ R_{\text{min}} \approx 250 \text{ nm for Co} \]
Experiments on Spin-Transfer

Geometries
- Point contacts
- Nanopillars
- Nanowires
- Nanorings

Structures
- Spin-values
- Multilayers
- Tunnel junctions
- Single magnetic layers

Materials
- Metallic ferromagnets
- Magnetic semiconductors
- Metallic antiferromagnets
- Oxide ferromagnets

Phenomena
- Current induced switching & precession
- Current induced domain wall motion
Experiments on Spin-Transfer

Point-contacts

- Uniform precession of $M$

Pillars junctions

- Hysteretic Switching of $M$

$H$ $\uparrow$ $I$

$M \rightarrow M_P$

$Co$

Experiments on Spin-Transfer

M. Tsoi et al.; E.B. Myers et al.; Y. Ji et al., ...

J. A. Katine et al.; J. Grollier et al.; ...

1998

2000
Current-Induced Magnetization Reversal in High Magnetic Fields in Co/Cu/Co Nanopillars

B. Özyilmaz and A. D. Kent
Department of Physics, New York University, New York, New York 10003, USA

D. Monsma
Department of Physics, Harvard University, Cambridge, Massachusetts 02143, USA

J. Z. Sun, M. J. Rooks, and R. H. Koch
IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA
(Received 17 December 2002; published 8 August 2003)

Field applied perpendicular to the plane of the film
Microwave Oscillations of a Nanomagnet Driven by a Spin-Polarized Current

Kiselev et al., Nature 2003
Microwave Oscillations in Point Contact Geometries

Rippard et al. PRL 2004

Fig. 1. Spectrum of the emitted microwave signal for a spin torque nano-oscillator using a point contact structure.

Fig. 2. Cross-sectional sketch of a spin torque nano-oscillator. The two magnetic layers are labeled “active” and “fixed” by virtue of the differing thickness and magnetic moment of the two layers; a thin, low-moment layer has a lower threshold current for excitation of spin-torque-induced dynamics. The trilayer structure below the point contact is of large lateral extent, on the order of tens of micrometers. A magnetic field $H$ is usually applied at some angle $\theta$ when studying gigahertz excitations in such devices.

Theory on linewidth: Slavin 2007
Phase Locking of Two Spin-Torque Oscillators

Spin-Transfer Induced Precession

A nanomagnet oscillator

More recent experiments:  Krivorotov et al., Science 2005
Spin-Transfer Driven FMR

Measurement Principle

- Tulapurkar et al., Nature 2005
- Sankey et al., PRL 2006

Resonance:

\[ I(t) = I_0 \sin(\omega t) \]
\[ R(t) = \frac{\Delta R_0}{2} (1 - \hat{m}(t) \cdot \hat{m}_p) \]
\[ V_{\text{mix}}(f) \propto \frac{I_{\text{rf}}^2/\Delta_0}{1 + [(f - f_0)/\Delta_0]^2} \]
\[ \Delta_0 = \alpha f_0 \]

- Determine anisotropies and damping of nanometer scale magnetic elements
- Characterize the spin-transfer interaction near equilibrium
- Excite highly non-linear magnetization dynamics
Nanopillar Characteristics: DC

Perpendicular applied field

$\vec{H}$

$[0.4 \text{ nm Co}|0.8 \text{ nm Ni}] \times 3$

3.6 nm Co/Ni
10 nm Cu
12 nm Co

- High field $dV/dI$ shows current induced excitations of free layer at $\sim 8 \text{ mA}$
Spin-Transfer Driven FMR

Mode that disperses to higher field with increasing frequency:

- Mirrors the FMR mode on a film of the same composition
- Enables determination of the easy-plane anisotropy and g-factor of an individual nanomagnet
The resonance frequency is consistent with excitation of the lowest lying mode of the element--shifted from the uniform FMR mode due to finite size effects and dipole fields from other magnetic layers.

Slope: $\alpha = 0.036 \pm 0.003$ for the film; $0.033 \pm 0.003$ for the nanopillars

Intercept: $\Delta H_0 = 284 \pm 30$ Oe for the film; $24 \pm 15$ Oe for the nanopillars
Spin Transfer MRAM

- Spin-transfer interaction may enable the ultimate miniaturization of MRAM to limits set by thermal stability.
- Why? Means of switching very high anisotropy nanomagnets

\[ U = \frac{1}{2} H_k M_s V \geq 40k_B T \]

\[ I_c \simeq \frac{2e \alpha}{\hbar} \frac{M_s V H_k}{P} = \frac{4e \alpha}{\hbar} \frac{U}{P} \]

\[ I_c \simeq 50 \mu A \]

Potentially compatible CMOS technology!
Summary

- **Spin transfer is a new mechanism to manipulate nanoscale magnets:**
  - Reversal
  - Precession
  - Spin-waves

- **Many basic and open questions about the interactions and magnetic excitations**
  - Transport models
  - Micromagnetics (beyond LLGS)
  - Noise

- **Great variety of phenomena, materials and structures**

- **New types of devices are possible that operate at the nanoscale and can be realized with present day technology**
References

• Review Articles: