**Spins Dynamics in Nanomagnets**

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**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

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**Lecture 1:** Magnetic Interactions and Classical Magnetization Dynamics

**Lecture 2:** Spin Current Induced Magnetization Dynamics

**Lecture 3:** Quantum Spin Dynamics in Molecular Nanomagnets

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**Giant Magnetoresistance (GMR)**

![The Nobel Prize in Physics 2007](image)

"for the discovery of Giant Magnetoresistance"

- Albert Fert
  - 1/2 of the prize
  - France
  - Université Paris-Sud; Unité Mixte de Physique CNRS/UMR 8502, Orsay, France
  - b. 1938

- Peter Grünberg
  - 1/2 of the prize
  - Germany
  - Forschungszentrum Jülich, Germany
  - b. 1939

→ ‘Spintronics’= Spin+Transport+Electronics: control of current using the spin of electrons

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**GMR=5.4% at 4.2 K**

![Graph showing GMR](image)
**Spin Filtering by Ferromagnetic Layers**

**Parallel**
- low resistance state

**Antiparallel**
- high resistance state

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

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**The Two Channel Model of GMR**

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

- Resistance: $R_{\text{parallel}} \ll R_{\text{anti-parallel}}$
- $\Delta R/R \sim 1-10\%$

Key Idea!!

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

$\tau \approx I \sin\theta$

Slonczewski 1996 and Berger 1996
Seeds of the idea in Slonczewski, PRB 1989
**Spin Transfer – A new method to manipulate nanomagnets**

- Spin current induced switching, Coherent dynamic precession.

**Charge current**

- C. Oersted, 1819

**Spin current**

- 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

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**Dynamics: LLG+spin-torque (LLGS)**

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

\[
\vec{H}_{\text{eff}} = \vec{H} - M_{\text{eff}} (\hat{m} \cdot \hat{z}) \hat{z} + H_K (\hat{m} \cdot \hat{x}) \hat{x}
\]

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

Also possible: \( \vec{b}_J \hat{m} \times \hat{m}_P \) – ‘Current-Induced Effective field’

\[ \gamma / 2\pi = 28 \text{ GHz/T} \]

**Thin film elements**
**Magnetic Excitations**

Spin-current amplifies the motion for currents greater than a critical value:

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

J. Z. Sun, PRB 2000

**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:

\[ B_c = \frac{\mu_0 I_c}{2\pi r} \Rightarrow I_c \sim r \]

**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 \( R_{min} \): The critical current due to the spin-current will be less than that due to the charge current.*

\( R_{min} \approx 250 \text{ nm for Co} \)

**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 $M$

![Diagram](https://example.com/diagram1.png)

Microwave Oscillations of a Nanomagnet Driven by a Spin-Polarized Current

Microwave Oscillations in Point Contact Geometries

Kiselev et al., Nature 2003

Rippard et al. PRL 2004

Field applied perpendicular to the plane of the film

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


Spin-Transfer Induced Precession


Spin-Transfer Driven FMR

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

\[ I(t) = I_0 \sin(\omega t) \]
\[ R(t) = \frac{\Delta R_0}{2} (1 - \tilde{n}(t) \cdot \tilde{n}_0) \]

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

More recent experiments:
- Krivorotov et al., Science 2005

Thermal fluctuations and ST:
- Sun, 2003
- Li and Zhang, 2004
- Visscher and Apalkov 2005

More recent experiments:
- Kiselev et al., Nature (2003); Krivorotov et al., Science 2005
Nanopillar Characteristics: DC

Perpendicular applied field

- High field dV/dI shows current induced excitations of free layer at ~8 mA

Magnetic Field [kOe]
Current Bias [mA]
-15 -5 0 5 10 15
-15 -5 0 5 10

3.6 nm Co/Ni
10 nm Cu
12 nm Co

Spin-Transfer Driven FMR

Perpendicular Field, I_{dc} = 0, t=0.4 nm

- 20 nV/Hz^{1/2}
- ~2° precession
- rf from 4 to 16 GHz with 2 GHz steps
- Adjacent curves offset by 0.2 µV each

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

Mode Dispersion: Comparison of Films and Nanopillars

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

Linewidth & Damping

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

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

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

\[ I_c \sim 50 \mu A \]

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: