Spins Dynamics in Nanomagnets

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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

Outline

I. Magnetic Interactions
   - Exchange, Anisotropy and Dipolar Interactions
   - Zeeman Interaction

II. Micromagnetic Energy
   - Energy, Field and Length Scales
   - Examples of Magnetic Domain Structure

III. Magnetic Nanostructures
   - Single Domain Model
   - Experiments on Individual (classical) Nanomagnets
   - Thermal Activation and Quantum Tunneling of Magnetization

IV. Classical Magnetization Dynamics
   - Landau-Lifshitz-Gilbert Equation
   - Ferromagnetic Resonance

References
Magnetic Interactions

**Micromagnetic Energy**

- **Exchange**
  \[ H_{\text{exc}} = J \sum_{i>j} \vec{S}_i \cdot \vec{S}_j \]
  \[ E_{\text{exc}} = A (|\nabla m_x|^2 + |\nabla m_y|^2 + |\nabla m_z|^2) \]

  \[ J < 0 \] Ferromagnetic interactions

- **Anisotropy**
  \[ H_{\text{anis}} = -d \sum_i S_{ix}^2 \]
  \[ E_{\text{anis}} = -K m_z^2 \]

  \[ d > 0 \] Easy axis anisotropy

  \[ d < 0 \] Easy plane type anisotropy

- **Dipolar Interactions**
  \[ H_{ij} = \frac{\mu_0}{4\pi r^3} (3(\vec{m}_i \cdot \hat{r}_{ij})(\vec{m}_j \cdot \hat{r}_{ij}) - \vec{m}_i \cdot \vec{m}_j) \]
  \[ \vec{m} = -\gamma \vec{S} \]
  \[ \gamma = |g\mu_B/h| \]
  \[ H_{\text{dip}} = \frac{1}{2} \sum_{i>j} H_{ij} \]

**Magnetostatic Energy**

- **Zeeman Energy**
  \[ H_z = g\mu_B\mu_0 \sum_i \vec{S}_i \cdot \vec{H}_e \]
  \[ E = -\mu_0 \vec{H} \cdot \vec{H}_e \]

- **Magnetostatic Energy**
  May sometimes be approximated by a local contribution to the energy

**Examples:**

1. Uniformly magnetized ellipsoid of revolution
2. Single domain particles
3. Thin films with in-plane magnetization: see, for example, Kohn and Slastikov (2006)

Analytic solutions for the micromagnetic energy, saddle states, rate of thermally activated reversal, etc. are then possible.

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**Energy, Field and Length Scales**

- **Exchange** \(~1000\) K, \(100\) T
- **Curie Temperature**
- **Anisotropy** \(~10\) K, \(0.01\) to \(10\) T
- **Dipolar Interactions** \(~1\) K, \(mT\)

- **Exchange length** \[ l_{\text{ex}} = \sqrt{2A/(\mu_0 M_z^2)} \]
  \(~4\) nm

- **Domain wall width** \[ \lambda = \sqrt{2A/K} \]
  \(~5\) to \(100\) nm
Competing interactions lead to the formation of magnetic domains: exchange, anisotropy and magnetostatic

\[ Q = \frac{2K}{\mu_0 M_s^2} \]

- Flux closure domains
- Stripe domains

Examples

- Domain configurations as function of:
  - Linewidth
  - Magnetic history

- Neel-cross-tie walls
- (Asymmetric) Bloch walls
- Canted Bloch walls

Photoelectron emission microscopy--PEEM

Magnetization Reversal: Experiment and Simulation

*L. Thomas and S. S. P. Parkin
recently been demonstrated that samples exhibiting perpendicular to the plane magnetic anisotropy. The maximum of magnetocrystalline anisotropy is directly proportional to the anisotropy energy and for good adhesion of the whole stacking on sapphire. V was swept at a fixed microwave frequency, perpendicular to the magnetic anisotropy constant values and then observed in 2000 GHz using the saturation magnetization. The number of exploitable decades for macroscopic and nanoscopic in the SQUID and perpendicular to the easy axis for the micro-SQUID technique, with the easy axis magnetic resonance was conducted from 4 to 50 GHz using the saturation magnetization. For example for the micro-SQUID technique, with the easy axis

The overall magnetic anisotropy is quantitatively studied versus Co thickness. Figure 2.1 displays a typical measurement of switching fields in these samples. The applied field is plotted, which is clearly different in intensity and orientation because of the proper value for the switching field angles. The number of exploitable decades for macroscopic and nanoscopic multi-domain nucleation, propagation and annihilation of domain walls and single-domain uniform rotation curling magnetic moment quantum tunneling, quantization quantum interference

$\tau = \tau_0 \exp(U/k_B T)$

$U = U_0(1 - h)^β$

$\beta = 3/2$

Also known as the Macrospin or Stoner-Wohlfarth Model

$E = -Km^2 - \mu_0 M_0 m \cdot H$

When does the metastable state become unstable?

$H_a = 2K/(\mu_0 M_S)$

$E = \frac{1}{2}(\sin^{2/3} \theta + \cos^{2/3} \theta)^{3/2}$

$\frac{H_a}{H_a} = \frac{H_{SW}}{H_a}$

$H_{SW} = \frac{E_{SW}}{\mu_0 M_S}$

$E_{SW} = \frac{2}{3}K m^2$

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Thermal Activation and Quantum Tunneling

Thermal relaxation (over the barrier)

\[ T_c = \frac{U}{k_B B(0)} \]

see lecture 3

also, Enz and Schilling, van Hemmen and Suto (1986)

Classical Magnetization Dynamics

Effective Field

\[ \mu_0 H_{\text{eff}} = -\delta E/\delta M \]

Single Domain Model

\[ E = -K m_z^2 - \mu_0 M_s \vec{m} \cdot \vec{H} \]

\[ \vec{H}_{\text{eff}} = \vec{H} + \frac{2K}{M_s} m_z \]

\[ \frac{dL}{dt} = \text{Torque} = \mu_0 \vec{M} \times \vec{H}_{\text{eff}} \]

\[ \vec{M} = -\gamma \vec{L} \quad \gamma = |g\mu_B|/\hbar = |g|e/2m \]

\[ \frac{d\vec{M}}{dt} = -\gamma \mu_0 \vec{M} \times \vec{H}_{\text{eff}} \]

Magnetization Dynamics

Landau Lifshitz Gilbert Equation

\[ \frac{\partial \vec{M}}{\partial t} = -\gamma \mu_0 \vec{M} \times \vec{H}_{\text{eff}} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t} \]

Gyroscopic term

Damping term

Resonance

M is aligned with the effective field

\[ \omega_0 = \gamma H_{\text{eff}} \]

M precesses about \( H_{\text{eff}} \) at the Larmor frequency:

\[ \omega_0 = \gamma H_{\text{eff}} \]

Decrease of the angle of precession due to damping.

FERROMAGNETIC RESONANCE

FMR: Landau-Lifshitz-Gilbert Dynamics

\[ \frac{\partial \vec{M}}{\partial t} = -\gamma \mu_0 \vec{M} \times \vec{H}_{\text{eff}} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t} \]

FMR: fixed frequency rf field \( \perp \vec{H} \)

Linewidth: Homogeneous or intrinsic linewidth

\[ \Delta H = 4\pi \alpha f/(\mu_0 \gamma) \]

with inhomogeneous broadening

\[ \Delta H = \Delta H_0 + \frac{4\pi \alpha f}{\mu_0 \gamma} \]
Ferromagnetic Resonance Spectroscopy

Measurements methods:
- Cavity: fixed frequency
- Coplanar waveguide: broadband
- Magnetic field at a given frequency or sweeping frequency at a given dc magnetic field

Analysis of FMR data:
- Probe magnetic properties from frequency dependence and angular dependence of $H_{\text{res}}$
- Smit-Suhr equation:
  \[ \omega_{\text{res}} = \sqrt{\frac{\partial^2 E}{\partial \phi^2} - \frac{\partial^2 E}{\partial \phi^0 \partial \phi}} \]
- Extract the damping from $\Delta H$ vs. $f$
  \[ \Delta H = \Delta H_0 + \frac{4\pi \alpha}{\gamma} f \]

FMR Signal

- Magnetic Energy
  \[ E = -\mu_0 \mathbf{M} \cdot \mathbf{H} + \frac{1}{2} \mu_0 M_s^2 \sin^2 \phi - (K_1 + 2K_2) \sin^2 \phi + K_2 \sin^4 \phi \]
- Resonance Condition
  \[ \mu_0 \mathbf{H}_{\text{eff}} = -\delta E / \delta \mathbf{M} \rightarrow f = \frac{\gamma}{2\pi} \left( \mu_0 H_{\text{res}}^{\text{eff}} - \mu_0 M_s + \frac{2K_1}{M_s} \right) \]
  \[ \mu_0 M_{\text{eff}} = \mu_0 M_s - 2K_1/M_s \]

Spin Waves

Uniform Precession

Finite $k$ spin waves

Example: $\theta_H = 45^\circ$ situation

Spin wave band (at FMR)

Spin wave wave frequency (GHz)

Band of modes in between

FMR

Spin wave wave number $k$ (rad/cm)

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References

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