MINT Seminar

How to measure
Magnetic Anisotropy Constants

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1. Magnetic Anisotropy
2. Stoner-Wohlfarth Model
3. Torque Measurements
   3.1 Rotational hysteresis loss
   3.2 Torque analysis
   3.3 45° Torque method
4. Our new torque magnetometer
5. Users’ Guideline
1. Magnetic Anisotropy

1. Example

Magnetic anisotropy $K = \frac{1}{2} M_s \times H_s = \frac{1}{2} (1,400 \text{ emu/cc} \times 6.5\text{kOe}) = 5 \times 10^6 \text{ erg/cc}$

1 kA/m = 1 emu/cm³
1 kA/m = 12.57 Oe
1. Magnetic Anisotropy

2. Magnitude

\[ K_1 \text{ (Ni)}: 4 \times 10^4 \text{ erg/cc} \quad (0.2 \ \mu\text{eV/atom}) \]
\[ K_1 \text{ (Fe)}: 5 \times 10^5 \text{ erg/cc} \quad (2 \ \mu\text{eV/atom}) \]
\[ K_{u1} \text{ (Co)}: 5 \times 10^6 \text{ erg/cc} \quad (20 \ \mu\text{eV/atom}) \]

<< Binding energy (1-10 eV/atom),
Exchange energy (10 – 10^3 meV/atom)
1. Magnetic Anisotropy

3. Materials

\[ H_k \left(= \frac{2K_u}{M_s}\right) : 4 \rightarrow 20 \text{ T} \]

- K\(_u\) (erg/cc)
- \(M_s\) (emu/cc)

Materials:
- CoPt
- FePd
- SmCo\(_5\)
- Co\(_3\)Pt
- NdFeB
- MnBi
- MnAl
- Fe\(_3\)Pt
- CoPtCr
- Co

March 8, 2013 (takaosuzki@mint.ua.edu)
1. Magnetic Anisotropy

4. Origin

4.1 Magneto-crystalline anisotropy (*Intrinsic*)

4.2 Induced magnetic anisotropy (*Extrinsic*)
   - Pair-ordering
   - Shape anisotropy
   - Stress induced anisotropy
   - Surface/interface anisotropy
1. Magnetic Anisotropy
Magneto-crystalline Anisotropy

3d elements
Fe, Ni, Co

RE elements
Tb, Dy, Nd

Crystalline field
\( \lambda \cdot S \) Coupling

Lattice
Orbital Angular Momentum
Spin Angular Momentum
1. Magnetic Anisotropy

4. Origin

Two-ions Model

\[ \frac{K_1(T)}{K_1(0)} \sim \alpha M^2 + (1 - \alpha) M^3 \sim M^{3-\alpha} \]

\[ \alpha : \text{contribution from two-ion model} \]

1. Magnetic Anisotropy

Temperature dependence of $M_s$, $K_1$ and $K_2$ of Fe$_3$Pt

Substrate: MgO(100), MgO(111)

4. Origin

4.2 Induced magnetic anisotropy (*Extrinsic*)

- Surface/interface anisotropy
1. Magnetic Anisotropy

5. Phenomenological expression

**Hexagonal:** \[ E_a = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + K'_3 \sin^6 \theta \sin 6\phi, \]

**Tetragonal:** \[ E_a = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K'_2 \sin^4 \theta \cos 4\phi + K_3 \sin^6 \theta + K'_3 \sin^6 \theta \sin 4\phi, \]

**Cubic:** \[ E_a = K_{1c} (\alpha_1^2 \alpha_2^2 + a_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_{2c} (\alpha_1^2 \alpha_2^2 \alpha_3^2), \]
Magnetic anisotropy constants of Fe$_3$Pt/MgO

- $K_1 = -4 \times 10^6$ erg/cc
- $K_2 = 2 \times 10^7$ erg/cc

$\langle 110 \rangle$ is the easy axis, since those $K_1$ and $K_2$ fulfill the condition $K_2 > -9/4K_1$.

Reference:
Fig. 3. (a) Temperature dependence of $K_{u1}$ and $K_{u2}$, together with the data of Honda et al.\textsuperscript{1)} and Sucksmith et al.\textsuperscript{2)}

(b) The direction of the easy axis $\theta$ from the $c$-axis. ---: obtained from eq. (1);
---: obtained from the torque curves.

2. Stoner – Wolfarth Model

\[ E_{\text{tot}} = K_u \sin^2 \theta - \mu_0 M H \cos(\alpha - \theta). \]

Note: In reality, \( \alpha \neq \varnothing \) unless \( H > H_k \)


Two angles $\theta$ (= $\beta, \beta'$) for stable $M$ direction when $h$ (= $H/H_k$) < 1.
3. Torque Magnetometer

\[ \overline{L} = \overline{M} \times \overline{H} \]

- Diagram of a torque magnetometer with a sample, mirror, photo detector, and lamp.
- Graph showing oscillatory behavior with a peak at 15 kOe.
- Revolution of the sample around the easy axis (E.A.).

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Torque Analysis -1 -Rotational hysteresis-

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;&gt; 0.8 0.5+</td>
<td>5.45 0.738 0.489</td>
</tr>
<tr>
<td>1.0 0.7 0.5-</td>
<td>1.20 0.553 0.415</td>
</tr>
<tr>
<td>0.9 0.6 0.3</td>
<td>0.922 0.0.521 0.369</td>
</tr>
</tbody>
</table>

Floyd.B. Humphrey: JPL Research summary No.36-13 (1962)
Torque Analysis -1
-Rotational hysteresis-

Bi-axial anisotropy of fcc Co film

FIG. 1. Torque curves as a function of external field direction observed in the (110) plane for Nd$_2$Fe$_{14}$B in 90 kOe at 4.2 K (solid line) and corrected ones as a function of magnetization direction (broken line). The part drawn by a dashed-and-dot line is used for the determination of anisotropy constants.
Torque Analysis -2

45° Torque Method

\[ E = KV \sin^2 \theta - MVH \cos (\alpha - \theta) \]
\[ L = MVH \sin (\alpha - \theta) \]

For \( \alpha = 45° \),

\[ \left( \frac{L}{H} \right)^2 = - \left( \frac{M^2V}{2K} \right)L + \frac{1}{2} (MV)^2 \]

\( H.A. \) \hspace{2cm} \( M \) \hspace{2cm} \( \theta \) \hspace{2cm} \( E.A. \)

K and Ms can be estimated directly!


FIG. 5. An example of \( (L/H)^2 - v/s - L \) plot for a Permalloy film. The same experimental data were used in both Figs. 2 and 5.
Experimental torque curves:

\[ L(\phi,H_0) = L_1 \sin \phi + L_2 \sin 2\phi + L_3 \sin 3\phi + L_4 \sin 4\phi + \ldots, \]

Where \( L_1, L_2, L_3, L_4 \ldots \) can be obtained from the Fourier Decomposition of the torque curves as a function of \( H_0 \).

Two-fold component \( \rightarrow \) \( K_1 \) or \( K_{u1} \)

Four-fold component \( \rightarrow \) \( K_2 \) or \( K_{u2} \)
4. Our new Torque magnetometer

**PPMS DynaCool**

Cryogen-free Physical Property Measurement System

- 90 kOe (9T)
- $10^{-7}$ emu
- 2 ~ 400 K
- Torque mag

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Torque Magnetometer Specifications

- Sensitivity:
  - RMS Torque Noise Level: $1 \times 10^{-9}$ Nm for 40 sec sampling
  - RMS Moment Sensitivity: $1 \times 10^{-7}$ emu @ 9T for 40 sec sampling
  - $7 \times 10^{-8}$ emu @ 14T for 40 sec sampling
- Dynamic Range: $\pm 10^{-5}$ Nm
- Torque Repeatability: $1 \times 10^{-8}$ Nm
- Chip Dimensions: $6 \times 6 \times 1$ mm$^3$
- Sample Mounting Area: $2 \times 2$ mm$^2$
- Max. Sample Size: $1.5 \times 1.5 \times 0.5$ mm$^3$
- Max. Sample Weight: Up to 10 mg
- Angular Excursion: 360 degrees
- Angular Velocity:
  - 0.05 - 10 deg/sec (std)
  - 0.005 - 1 deg/sec (high res)
- Angular Resolution:
  - 0.05 deg (std); 0.005 deg (high res)
Torque Magnetometer Chip

Calibration loop
Torque lever
Piezoresistors
Wheatstone bridge

6 mm
2 mm
patterned bridge on torque chip

- Piezoresistors R1 and R2 on arms of chip
- R3 and R4 of same material
- bridge advantage:
  - inherently a difference measure
  - small voltages
Sample# 40248 SiO$_2$/\{Bi(3.2nm)/Mn (2.0nm)\} x 10  (annealing temp. : 240°C)

Torque data by Quantum Design

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Amplitude of Torque curve (x10^6 erg/cc)

300 K

\[ y = -4.40E+09x + 1.24E+06 \]
\[ R^2 = 9.50E-01 \]

2 K

\[ y = -1.23E+10x + 1.95E+06 \]
\[ R^2 = 8.20E-01 \]
Users’ Guideline

- Users must have
  - Understanding of *basic principle* of operation
  - Training for *how to operate*
  - Report each time in *logbook*
  - Report any *problems* to Mr. John Hawkins and Mr. Jason Foster, as well as your adviser
• Please become a member for IEEE Magnetics Society Alabama Chapter!