Magnetism of Surfaces, Thin Films, and Nanostructures

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Magnetism of Surfaces, Thin Films, and Nanostructures (I)

Basic Concepts in Magnetism:

\[ \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (\text{SI unit}) \]

\( \mathbf{M} = \text{Magnetization} = \text{magnetic dipole moment/unit volume} \)

\( \mathbf{M} = n\mu \) where: \( n = \text{number of atoms/unit volume} \)

\( \mu = \text{dipole moment/atom} \)

Three simple forms of Magnetism:

Diamagnetism: \( \mathbf{M} = \chi \mathbf{H}, \chi < 0 \)

Paramagnetism: \( \mathbf{M} = \chi \mathbf{H}, \chi > 0 \)

Ferromagnetism: \( \mathbf{M} \) NOT PROPORTIONAL to \( \mathbf{H} \)
-Nonlinear
-Hysteretic
-Spontaneous \( \mathbf{M} \) w/o \( \mathbf{H} \) for \( T < T_c \)
Diamagnetism (full shell)

In applied H, bound electrons precess at Larmor frequency:

\[
\omega_L = \frac{eB}{2m_e}
\]

\[\Rightarrow \mu = IA = -\frac{e\omega_L}{2\pi} \sum_i \langle \pi \rho_i^2 \rangle = -\frac{e^2ZB}{4m_e} \langle \rho^2 \rangle\]

\[Z = \text{atomic number (number of electrons)} \]
\[\rho \text{ is in plane } \Rightarrow \langle \rho^2 \rangle = \frac{2}{3}\langle r^2 \rangle\]

\[\mu = -\frac{e^2ZB}{6m_e} \langle r^2 \rangle \Rightarrow \chi = \frac{n\mu}{H} = -\frac{\mu_0e^2Zn}{6m_e} \langle r^2 \rangle\]

Which is the same as the quantum result

[ASIDE: Superconductor: \( \chi = -1 \)
\[\Rightarrow B = \mu_0[1 + (-1)]H = 0 \text{ inside Superconductor!!! }\]

\[\mu \text{ Moment per atom} \]
\[n \text{ # density of atoms} \]
\[m_e \text{ mass of electron} \]

\[B: \text{magnetic flux density or magnetic induction}\]
Paramagnetism

- Collection of non-interacting local moments
- Moments respond only to applied field

a) Local moments (often insulators)

For simplicity, consider spin $\frac{1}{2}$:

$$U = -\mu \cdot \vec{B} = m_J g \mu_B B$$

Boltzmann population of levels:

$$N_\downarrow = \frac{N e^{\mu_B B/kT}}{(e^{\mu_B B/kT} + e^{-\mu_B B/kT})}, \quad N_\uparrow = \frac{N e^{-\mu_B B/kT}}{(e^{\mu_B B/kT} + e^{-\mu_B B/kT})}$$

$$M = (N_\downarrow - N_\uparrow)\mu = N\mu \frac{e^{\mu_B B/kT} - e^{-\mu_B B/kT}}{(e^{\mu_B B/kT} + e^{-\mu_B B/kT})} = \mu N \tanh(\mu_B B/kT)$$

For: \[ \frac{\mu_B B}{kT} \ll 1 \quad \text{Then:} \quad \frac{\mu_B B}{kT} \frac{N}{H} = \frac{M}{kT} = \frac{\mu_0 N \mu_B^2}{C/T} = \text{Curie(-Weiss)'s Law} \]
Paramagnetism

b) Free electrons: Pauli Paramagnetism

Applied to good metals (Fermi Liquid)
\[ \varepsilon^\downarrow = \varepsilon(k) + \mu B \; ; \; \varepsilon^\uparrow = \varepsilon(k) - \mu B \]

\[ N^\uparrow - N^\downarrow = \int_0^\infty \left[ f_o(\varepsilon - \mu B) - f_o(\varepsilon + \mu B) \right] D(\varepsilon) d\varepsilon \]

\[ \approx \mu_B B \int_0^\infty \left( -\frac{\partial f}{\partial \varepsilon} \right) D(\varepsilon) d\varepsilon \]

\[ = \mu_B B D(\varepsilon_F) \]

\[ \Rightarrow M = \mu_B (N^\uparrow - N^\downarrow) = \mu_B^2 B D(\varepsilon_F) \]

NOTE: \( M \) or \( \chi \) is independent of T
(Anti-)Ferromagnetism

- Moments interact
- Respond to applied field AND local field from other $\mu$
- Mean field approach

Exchange interaction among spins: $V_{ex} = -2J_{ex} \mathbf{s}_i \cdot \mathbf{s}_j$

Nearby moments establish effective field: $H_E = \lambda \mathbf{M}$

a) Local moments

Recall paramagnetism: $M_{para} T = CH_o$

Let $M_{FM} T = C(H_o + H_E) = C(H_o + \lambda \mathbf{M})$

\[
\Rightarrow M = \frac{C}{(T - C\lambda)} H_o = \frac{C}{(T - T_c)} H_o
\]

So \[\chi = \frac{M}{H_o} = \frac{C}{(T - T_c)}\] diverges as $T \to T_c$ from above $\Rightarrow$ spontaneous magnetism

\[T_c = C\lambda = CzJ_{ex}\]
Ferromagnetism II

b) Itinerant electrons: **The Stoner Model**

Delocalized $e^{-}$ w/Coulomb repulsion
to $e^{-}$ of opposite spin

\[ \varepsilon_{\downarrow} = \varepsilon(k) + \mu_{B}H_{o} + UN_{\uparrow}; \quad \varepsilon_{\uparrow} = \varepsilon(k) - \mu_{B}H_{o} + UN_{\downarrow} \]

\[ N_{\uparrow} - N_{\downarrow} = \int_{0}^{\infty} \left[ f_{o}(\varepsilon - \mu_{B}H_{o} + UN_{\uparrow}) - f_{o}(\varepsilon + \mu_{B}H_{o} + UN_{\downarrow}) \right] D(\varepsilon) d\varepsilon \]

\[ \approx \frac{1}{2} [\mu_{B}H - UN_{\downarrow} + \mu_{B}H + UN_{\uparrow}] \int_{0}^{\infty} \left(-\frac{\partial f}{\partial \varepsilon}\right) D(\varepsilon) d\varepsilon \]

\[ = \mu_{B}H D(\varepsilon_{F}) + \frac{1}{2} U (N_{\uparrow} - N_{\downarrow}) D(\varepsilon_{F}) \]

\[ \Rightarrow M = \mu_{B} (N_{\uparrow} - N_{\downarrow}) = \frac{\mu_{B}^{2} D(\varepsilon_{F})}{(1 - \frac{1}{2} UD(\varepsilon_{F}))} H_{o} \]

\[ U \text{ coulomb repulsion} \]

So: if $\frac{1}{2} UD(\varepsilon_{F}) > 1$ then FERROMAGNETISM (Stoner Criterion)
Surface (thin film) Magnetism
(of ferromagnetic metals)

- Basically arises from Stoner criterion
- $U_{\text{surf}} \sim U_{\text{bulk}}$
- $D(\varepsilon_F)_{\text{surf}} > D(\varepsilon_F)_{\text{bulk}}$, typically

*ENHANCED* DOS at $E_F$ for surface because surface bands shift to maintain charge neutrality.

$\rightarrow$ TYPICALLY ENHANCED MOMENTS AT SURFACES
Magnetism in Thin Films

What to we expect??

Enhanced moment in monolayer films owing to band narrowing.

Unfortunately, cannot be verified experimentally owing to surface free energies!!!
Example: Cr - Antiferromagnetic bulk, ferromagnetic surface

Exchange coupling as a function of interatomic distance.
Relaxation at surface → ferromagnetic

Topological Anti-FM on Cr (001) surface
Pinning of SDW on surface

Topological Anti-FM on Cr (001) surface

Topology-Induced Spin Frustrations

PRL, 85, 4606 (2000)
ML Fe on W (001) surface: Anti-FM Fe !!

Fe on W(110)

2ML Fe
Tip: GdFe

1.6ML Fe
Tip: Fe

1ML Fe on W(001)


Kubetzka et al, PRL 94, 087205 (2005)
1ML Mn on W (110) surface

Chiral magnetic order at surfaces driven by inversion asymmetry

- Reduction of $T_c$ for thin films

Recall $T_c = C\lambda = CzJ_{ex}$

Lower dimension $\rightarrow$ smaller $z$ $\rightarrow$ lower $T_c$
Magnetic Imaging Techniques
Why do we want to “see” a magnetic image?

• magnetic domains
  – domain wall structure

• inhomogeneous magnets

• nano-magnets
  – superparamagnetism

• SC vortices

• magnetic record media
Why a FM is ferromagnetic?

• Exchange energy (Heisenberg)

\[ \mathcal{E} = -J \sum_{i,j} \mathbf{s}_i \cdot \mathbf{s}_j \quad \text{H}_{MF} = -J \sum_{\text{nearest neighbors}} \mathbf{s}_i \approx -Jz \langle \mathbf{s} \rangle = \lambda \mathbf{M} \]

\[ E_{\text{total}} = -\mathbf{\mu} \cdot \mathbf{B} = -|\mathbf{\mu}| \mathbf{B} \cos \theta \quad \mathbf{\mu}_z = \langle \cos \theta \rangle = \coth(x) - \frac{1}{x} \rightarrow 0 \quad x = \frac{\mu B}{k_B T} \]

• Magnetocrystalline anisotropy

- Uniaxial
  \[ \mathcal{E}_u = -K_1 m_z^2 + K_2 m_z^4 \]

- Cubic
  \[ \mathcal{E}_c = -K_1 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + K_2 m_x^2 m_y^2 m_z^2 \]

When \( 0 < T < T_C \) \quad KV \gg k_B T \quad \text{stable}

When \( KV \ll k_B T < k_B T_C \) \quad \text{Superparamagnetism}
Superparamagnetism (FM nanoparticles)

\[ E = -K_1 V \cos^2 \theta \]

The transition rate from 1\( \rightarrow \)2

\[ \frac{1}{\tau} \propto \exp\left(\frac{K_1 V}{k_B T}\right) \]

\( \tau \gg t_{\text{exp}} \) stable

\( \tau \ll t_{\text{exp}} \) unstable \( \rightarrow \) large \( \chi \)

Superparamagnetisme:

- high saturation magnetisation \( M_S \)
- no remanence \( M_R = 0 \)

minimum size for a magnetic bit at RT
Magnetostatic energy (domain)

\[ \mathcal{E}_{MS} = \mu_0 \int H_d^2 dV \]

Domain wall energy

\[ \mathcal{E}_{walls} = \gamma \cdot S \]

Total energy

\[ \mathcal{E}_{total} = \mathcal{E}_{MS} + \mathcal{E}_{walls} + \text{other...} \]

Surface anisotropy in thin film

\[ \mathcal{E}_S = \frac{1}{2} K_s^{\text{eff}} \int (\vec{n} \cdot \vec{m})^2 dS \]

a square 50µmx50µm Permalloy element

Ni\textsubscript{81}Fe\textsubscript{19}

• **Anisotropy**
Thin films are inherently anisotropic as translational symmetry is broken perpendicular to film.
Even bulk exhibits anisotropy (spin-orbital coupling)
→ “Easy” and “hard” directions for \( M \).

For surfaces and thin films:

• Reduced symmetry & steps may reduce orbital quenching
• Strain.

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**FIGURE 17.** Asymmetry of the overlap of electron distributions on neighboring ions provides one mechanism of magnetocrystalline anisotropy.
• Perpendicular Magnetization is a surprise!

Expect sample to orient magnetic domains to minimize magnetostatic energy.

\[ U_d = \frac{1}{8\pi} \int (H_d^2) d^3 r \]

“demagnetization” field

Therefore, expect M to lie in plane to minimize \( U_d \).
how to observe magnetic domains?

• Bitter decoration
• Photon-detection
  – MOKE, XMCD, XMLD
• Electron-detection
  – SEM
  – SEMPA, SPLEEM, PEEM
  – TEM (Lorentz, holograph)
• Scanning probe
  – MFM, SP-STM, SHPM, S-SQUID, NSOM
Surface Magneto-Optic Kerr Effect (SMOKE)  
(Faraday Effect in reflection)  
(Faraday effect is easier to understand, so we will start there)

Lorentz force on electron in material: \[ \ddot{\mathbf{r}} + \omega_o^2 \mathbf{r} = -\frac{e}{m}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

Assume: \[ \mathbf{B} = B_z \mathbf{\hat{z}} ; \mathbf{k} = k_o \mathbf{\hat{z}} \]

\[ \ddot{x} + \frac{eB}{m} \dot{y} + \omega_o^2 x = -\frac{e}{m} E_x \]  \hspace{1cm} (1)

\[ \ddot{y} - \frac{eB}{m} \dot{x} + \omega_o^2 y = -\frac{e}{m} E_y \]  \hspace{1cm} (2)

\( \pm i \) \hspace{0.5cm} \( \Rightarrow R_{\pm} \mp \frac{ieB}{m} \) \hspace{1cm} \( \omega_o^2 R_{\pm} = -\frac{e}{m} E_{\pm} \) \hspace{1cm} where \( R_{\pm} = (x \pm iy) \) and \( E_{\pm} = (E_x \pm iE_y) \)

Suppose: \( \tilde{E}_{inc} = E_x \hat{x} = E_x \cos(\omega t) \hat{x} \mid_{z=0} \)

Let \( P_{\pm} = (P_x \pm iP_y) = (x \pm iy) = NeR_{\pm} = NeCE_{\pm} = NeC'e^{i(\omega t - k_z z)} \)

Put into (3) \( \Rightarrow R_{\pm} = \frac{\frac{e}{m} E_x}{(\omega_o^2 - \omega^2) \pm \frac{e}{m} B_z \omega} \Rightarrow P_{\pm} = \frac{\frac{Ne^2}{m} E_x}{(\omega_o^2 - \omega^2) \pm \frac{e}{m} B_z \omega} \)

So different index of ref. for \( \pm \): \( n_{\pm} = 1 + \frac{\frac{\omega_p^2}{(\omega_o^2 \pm \frac{eB}{2m}) - \omega^2}}{} \)
So, traveling through the material, the polarization vector is rotated by:

$$\theta = \left(\frac{\pi L}{\lambda_o}\right)(n_- - n_+)$$

**Kerr Effect:** “Faraday Effect in reflection”

If $d \ll \lambda$, then rotation of layers is additive.

Signal from FM layers overwhelms that from NM layers.

Easily measure $M_R$ and $H_c$, hysteresis loops.

Kerr microscopy (MOKE)

"Confocal" scanning Kerr microscope

Scan focus while scanning slit

Images of 500 μm wide NiFe square

0 Oe field, no scanned slit

with confocal scanned slit

0 Oe field

100 Oe field

Difference


McCord, et al., JMMM 148, 244 (1995)
Applications of SMOKE

2.5 ML Fe/Ag(100)

Measure M(T)

$T_c$ (thin) < $T_c$ (thick)

$M(T) \sim (1 - T/T_c)^\beta$

$\beta = 0.124$; Ising: $\beta = 1/8$

2 ML Fe/W(001)

Stepped surface

4.7 miscut

Step-induced anisotropy

Easy axis perp. to steps [Opposite of Fe/Ag(100) and Co/Cu(100)]
**X-ray Magnetic-Circular Dichroism (XMCD)**

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**Elemental Selectivity!!!**

**Matrix Elements:**

\[
\langle \varphi_f | \hat{p} | \varphi_i \rangle = e^{\langle \varphi_f | \hat{r} | \varphi_i \rangle} 
\]

circular polarization \( \Rightarrow \hat{p} = \frac{1}{\sqrt{2}} (\hat{x} \pm i\hat{y}) \)

\[
\Rightarrow \langle \varphi_f | x \pm iy | \varphi_i \rangle 
\]

\[
x \pm iy = r (\cos \phi \pm i \sin \phi) = re^{\pm i\phi} 
\]

So for transition from \( p \rightarrow d \) \( \Rightarrow \langle R_{p_2} | R_{p_1} \rangle \langle Y_2^m | e^{\pm i\phi} | Y_1^{m'} \rangle \) \( \Rightarrow \) selection rule: \( m' = m \pm 1 \)

**Asymmetric Transitions!**

---

\[
\begin{align*}
\begin{array}{c|c|c|c|c|}
Y_2^2 & Y_2^1 & Y_2^0 & Y_2^{-1} & Y_2^{-2} \\
\hline
+\frac{1}{2} & -\frac{1}{2} \end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c|c|c|c|c|}
\frac{1}{2}Y_1^0 | \uparrow \rangle & \left( \frac{1}{\sqrt{3}} Y_1^0 | \uparrow \rangle \right) + \left( \frac{1}{\sqrt{3}} Y_1^{-1} | \uparrow \rangle \right) \\
\hline
\frac{1}{2}Y_1^0 | \downarrow \rangle & \left( \frac{1}{\sqrt{3}} Y_1^0 | \downarrow \rangle \right) + \left( \frac{1}{\sqrt{3}} Y_1^{-1} | \downarrow \rangle \right)
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c|c|c|c|c|}
Y_2^2 & Y_2^1 & Y_2^0 & Y_2^{-1} & Y_2^{-2} \\
\hline
+\frac{1}{2} & -\frac{1}{2} \end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{c|c|c|c|c|}
\frac{1}{2}Y_1^0 | \uparrow \rangle & \left( \frac{1}{\sqrt{3}} Y_1^0 | \uparrow \rangle \right) \left( \frac{1}{\sqrt{3}} Y_1^{-1} | \uparrow \rangle \right) \\
\hline
\frac{1}{2}Y_1^0 | \downarrow \rangle & \left( \frac{1}{\sqrt{3}} Y_1^0 | \downarrow \rangle \right) \left( \frac{1}{\sqrt{3}} Y_1^{-1} | \downarrow \rangle \right)
\end{array}
\end{align*}
\]
Let: $\left| \langle Y_2^\pm | \sigma_\pm | Y_1^\pm \rangle \right|^2 = A$  
where  $\sigma_\pm = e^{\pm i \phi}$

$\left| \langle Y_2^\pm | \sigma_\pm | Y_0 \rangle \right|^2 = B$

$\left| \langle Y_2^0 | \sigma_\pm | Y_1^\pm \rangle \right|^2 = C$

$\sigma_+ = A + (2/3)B + (1/3)C$
$\sigma_- = C + (2/3)B + (1/3)A$
$\sigma_+ + \sigma_- = (4/3)(A + B + C)$
$\sigma_+ - \sigma_- = (2/3)(A - C)$

$\sigma_+ = (1/3)B + (2/3)C$
$\sigma_- = (1/3)B + (2/3)A$
$\sigma_+ + \sigma_- = (2/3)(A + B + C)$
$\sigma_+ - \sigma_- = (2/3)(-A + C)$

So, w/o polarization: $L_3:L_2 = 2:1$

w/ polarization, asymmetry: $A_3:A_2 = -1:1$ !!!

http://www-ssrl.slac.stanford.edu/stohr/xmcd.htm
SPIN POLARIZED PHOTOEMISSION (SP-PEEM)
Dichroism in core levels without $B$!

EXAMPLES

Adsorbates do not necessarily destroy ferromagnetism at surfaces.

In fact, FM can be induced in some adsorbates.

Spin polarization of MQW states in Cu/Co/Cu(100)

States responsible for oscillatory magnetic coupling discussed earlier.
SEM with Polarization Analysis (SEMPA)

A surface sensitive, high spatial resolution (~10nm) technique

Example (From previous slide)

High Resolution SEMPA

spatial resolution (~5nm)


Magnetic domain image of SmCo₅
SEMPA (an example)

$65 \text{ K} \quad \text{La}_{2-2x}\text{Sr}_{1+2x}\text{Mn}_2\text{O}_7 \quad x=0.32 \quad 85 \text{ K}$

Konoto et al, PRB 71, 184441 (2005)
TEM (Lorentz mode)

\[ \vec{F} = e \cdot \vec{v} \times \vec{B} \]

**Double layer Manganite:** \( \text{La}_{2-2x}\text{Sr}_{1+2x}\text{Mn}_2\text{O}_7 \)  
Asaka *et al.*, PRL 95, 227204 (2005)
TEM (holography)

Fig. 2.31 Principle of conventional electron holography (a), optical reconstruction using a Mach-Zehnder interferometer (b), and the resulting image (c) showing the lines of magnetic flux (as averaged along the electron trajectories) inside a triangular cobalt platelet. The narrow lines at the sample edge are caused by the regular topographical phase shift. (Courtesy A. Tonomura)
Scanning Probe Microscopy

Schematic Scanning Probe Microscope (SPM):

- Sensor
- Probe
- Sample
  - XYZ Piezo Scanner
- AMP
- Computer
- Feedback Electronics
Atomic force microscopy (AFM)
Invented by Binnig, Quate and Gerber in 1986

Generalized Force microscopy: Magnetic, Electrostatic, etc.
Magnetic force microscopy (MFM)

- Ferromagnetic material on sharp tip attached to cantilever
- Magnetic force gradient causes effective change of spring constant $k$
- Drive cantilever at resonance, measure frequency shift as sample is scanned

\[
F = -\nabla U
\]

\[
U = -\mathbf{m} \cdot \mathbf{B}
\]

\[
f = f_0 \left(1 - \frac{F'_z}{k}\right)^{\frac{1}{2}} \quad \frac{\Delta f}{f_0} = -\frac{m_z}{2k} \frac{\partial^2 B_z}{\partial z^2}
\]

- low resolution (~10nm-100nm)
- qualitative information
- invasive detection (stray field)
- low cost, less surface sensitive
MFM images

MFM topograph

$15 \mu m$

Permalloy

(\text{La,Pr,Ca})\text{MnO}_3$

Hard disk
Scanning Tunneling Microscopy (STM)

- Nobel Prize in 1986
- “see” individual atoms
- Manipulate individual atoms
- Spectroscopy (LDOS)

\[ \frac{dI}{dV} \propto \rho_s(E_F - eV) \]

Rohrer and Binnig

controlled vacuum tunneling
Spin-polarized STM

Spin dependent tunneling (tunneling MR)

Comparison of magnetic imaging techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Sensitivity</th>
<th>Evaluation of the Magnetization vector</th>
<th>Allowed magnetic field</th>
<th>Sample preparation quality requirement</th>
<th>capital investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitter</td>
<td>very good</td>
<td>indirect</td>
<td>100 Oe</td>
<td>moderate-low</td>
<td>low</td>
</tr>
<tr>
<td>MOKE(^{(a)})</td>
<td>fair</td>
<td>direct</td>
<td>any</td>
<td>high</td>
<td>moderate</td>
</tr>
<tr>
<td>XMCD(^{(b)})</td>
<td>fair</td>
<td>direct</td>
<td>any</td>
<td>moderate-low</td>
<td>&quot;extremely high&quot;</td>
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<td>Lorentz TEM</td>
<td>very good</td>
<td>indirect</td>
<td>3000 Oe</td>
<td>high</td>
<td>high</td>
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<tr>
<td>Holograph TEM</td>
<td>good</td>
<td>quantitative</td>
<td>100 Oe</td>
<td>high</td>
<td>very high</td>
</tr>
<tr>
<td>SEMPA</td>
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<td>100 Oe</td>
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</tr>
<tr>
<td>MFM</td>
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<td>any</td>
<td>low</td>
<td>moderate</td>
</tr>
<tr>
<td>SPSTM(^{(c)})</td>
<td>fair</td>
<td>direct</td>
<td>any</td>
<td>very high</td>
<td>very high</td>
</tr>
</tbody>
</table>

(a) Dynamic study (record time ~ 1ns w/ pulsed laser)
(b) Dynamic study with synchrotron pulsed radiation
(c) Atomic resolution.

Modified from *Magnetic Domains* by Hubert & Schäfer
Acronyms

• SMOKE: Surface Magneto-Optics Kerr Effect
• XMCD: X-ray magnetic Circular Dichroism
• XMLD: X-ray magnetic Linear Dichroism
• TEM: Transmission Electron Microscopy
• SEMPA: Secondary Electron Microscopy with Polarization Analyzer
• SPLEEM: Spin-Polarized Low Energy Electron Microscopy
• PEEM: Photo-emission electron microscopy
• MFM: Magnetic Force Microscopy
• SPSTM: Spin-Polarized Scanning Tunneling Microscopy
• SPHM: Scanning Hall Probe Microscopy
• S-SQUID: Scanning Superconducting Quantum Interference Device
• NSOM: Near-field Scanning Optical Microscopy