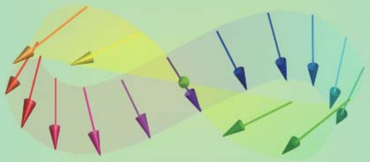
Introductory Nanotechnology

~ Basic Condensed Matter Physics ~



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Quick Review over the Last Lecture

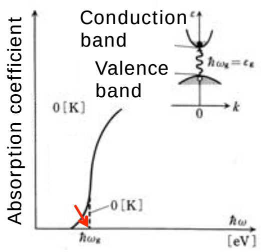
Quantum mechanics and classical dynamics

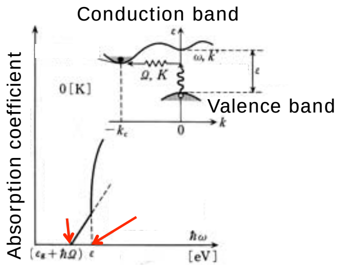
Quantum mechanics	Classical dynamics
equation	
ψ :	A :
$\|\psi\|^2$:	A^2 :

Quantum tunneling :

( ) + ( ) = 1

Optical absorption :





Contents of Introductory Nanotechnology

First half of the course :

Basic condensed matter physics

1. Why *solids* are *solid* ?
2. What is the *most common atom* on the earth ?
3. How does an electron travel in a material ?
4. How does lattices vibrate thermally ?
5. What is a *semi*-conductor ?
6. How does an electron tunnel through a barrier ?
7. Why does a magnet attract / retract ?
8. What happens at interfaces ?

Second half of the course :

Introduction to nanotechnology (nano-fabrication / application)

Why Does a Magnet Attract / Retract ?

- Magnetic moment
- Magnetisation curve
- Origin of magnetism
- Curie temperature
- Types of magnets
- Magnetic anisotropy
- Magnetic domains

How Did We Find a Magnet ?

• 6th century BC, from Magnesia (Μαγνησία) in Greece

found by shepherd Magnes ?

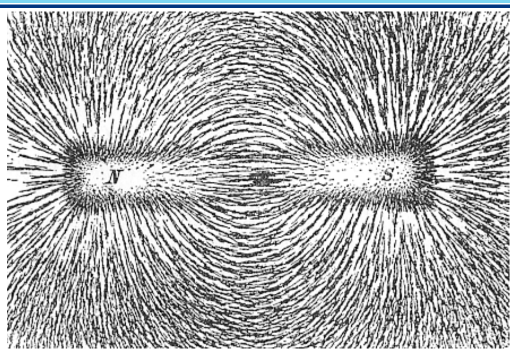
Magnetite (Fe_3O_4)

• 3th century BC, from Handan area (磁州) in China

220 ~ 265 AD, first compass

* http://www.wikipedia.org/

Magnet and Magnetism



Study on magnetism started by William Gilbert :

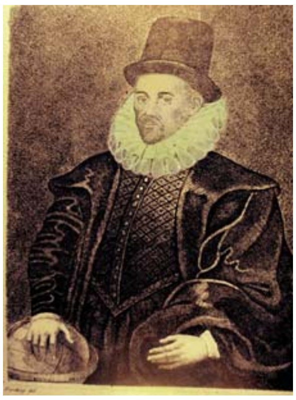
Magnete, Magneticisque Corporibus,

et de Magno Magnete Tellure (1600)

• The earth is a large magnet (compass).

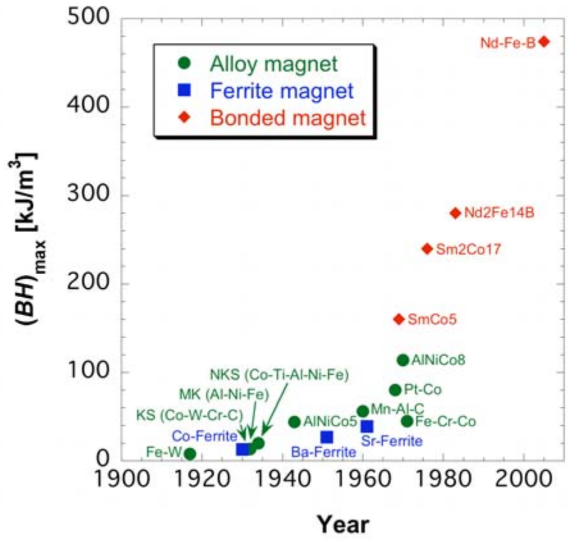
• Fe looses magnetism by heating.

• N / S poles always appear in pair.



* http://www.wikipedia.org/

Development of Permanent Magnets



Permanent magnets are used in various applications :

* Corresponding pages on the web.

Which Elements are magnetic ?

In the periodic table,

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pd	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Magnetic Moment

By dividing a magnet, N (+) and S (-) poles always appear :

- *No magnetic monopole* has been discovered !
- A pair of magnetic poles is the minimum unit : *magnetic (dipole) moment*.

$$|\boldsymbol{m}| = m$$

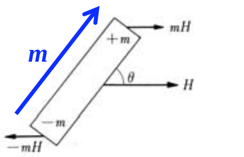


Fig. 1.1. A magnet under the action of a torque in a uniform magnetic field.

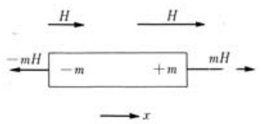


Fig. 1.2. A magnet under the action of a translational force in a gradient magnetic field.

Magnetisation :

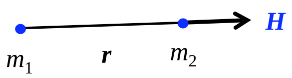
- Vector sum of $\boldsymbol{m}$ per unit volume

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Coulomb's Law

Force between two magnetic poles, m_1 [Wb] and m_2, separated with $\boldsymbol{r}$ [m] is defined as

$$\boldsymbol{F} = \frac{1}{4\pi\mu_0}\frac{m_1 m_2}{\boldsymbol{r}^2} \quad [\mathrm{N}]$$



Here, m_2 receives magnetic force (= magnetic field) :

$$\boldsymbol{F} = m_2\boldsymbol{H} \qquad \therefore \boldsymbol{H} = \frac{1}{4\pi\mu_0}\frac{m_1}{\boldsymbol{r}^2} \quad [\mathrm{N/Wb}] = [\mathrm{A/m}]$$

Magnetic flux density is proportional to the magnetic field :

Magnetic flux density at $\boldsymbol{r}$ from a magnetic pole m is $\boldsymbol{B} = \dfrac{m}{4\pi\boldsymbol{r}^2}$

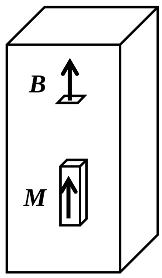
By comparing with $\boldsymbol{H}$, $\boldsymbol{B} = \mu_0\boldsymbol{H}$

$\rightarrow \mu_0$: magnetic permeability in a vacuum [H/m]

Under the presence of magnetisation, $\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M})$

If the system is not in a vacuum, $\boldsymbol{B} = \mu\boldsymbol{H}$

By assuming $\mu = \mu_0 + \chi$ (χ : susceptibility), $\boldsymbol{M} = (\chi/\mu_0)\boldsymbol{H}$



Magnetic Dipole Field and Magnetic Flux

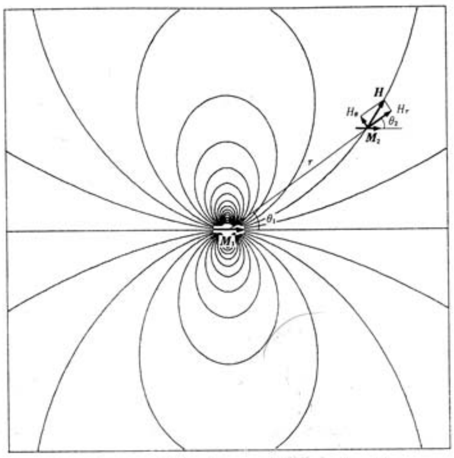


Fig. 1.4. Computer-drawn diagram of lines of magnetic force produced by a magnetic dipole.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Magnetisation Curve

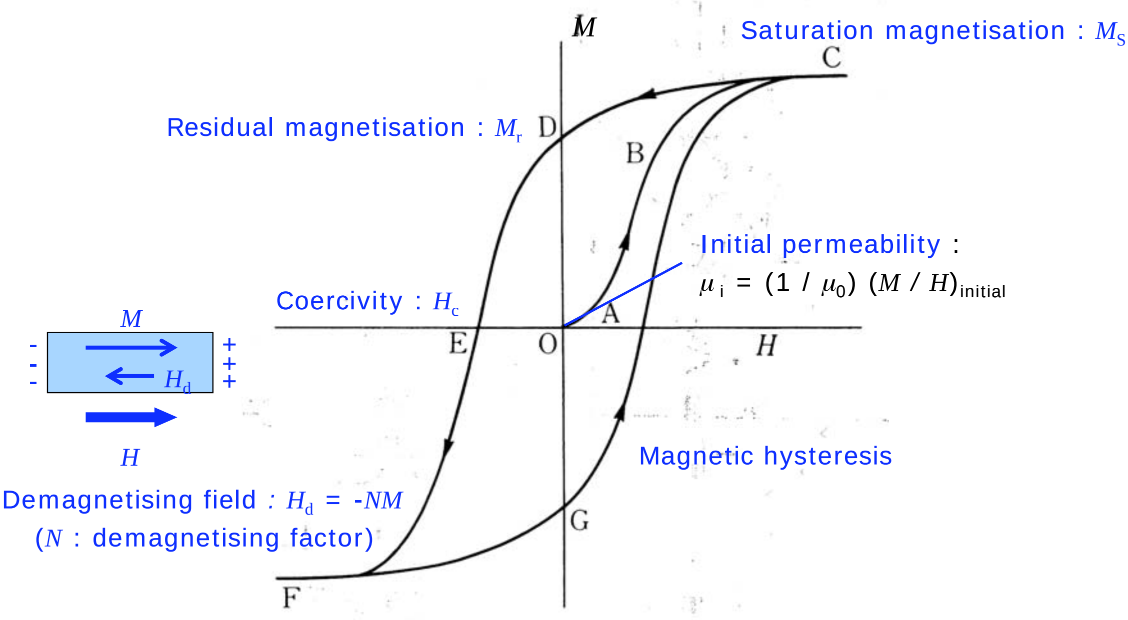


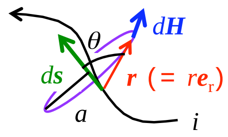
Fig. 1.12. Hysteresis loop.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Magnetic Field Induced by an Electrical Current

Biot-Savart Law :

According to the right-handed screw rule,



$$d\boldsymbol{H} = k\frac{1}{\boldsymbol{r}^2}\left(id\boldsymbol{s}\times\boldsymbol{e}_{\mathrm{r}}\right)$$

For an infinite straight wire, $H = \int_{-\infty}^{\infty}\frac{k}{r^2}i\sin\theta ds$

By substituting $\theta = a / r$ and $r = (a^2 + s^2)^{1/2}$,

$$H = kia\int_{-\infty}^{\infty}\frac{1}{r^3}ds = kia\int_{-\infty}^{\infty}\frac{1}{\left(a^2+s^2\right)^{3/2}}ds \qquad \left(\int\frac{dx}{\left(a^2+x^2\right)^{3/2}} = \frac{x}{a^2\left(a^2+x^2\right)^{1/2}}\right)$$

$$= kia\left[\frac{s}{a^2\left(a^2+s^2\right)^{1/2}}\right]_{-\infty}^{\infty} = \frac{ki}{a}\left[\frac{s}{a\left(a^2+s^2\right)^{1/2}}\right]_{-\infty}^{\infty} = \frac{2ki}{a}$$

By taking an integral along H,

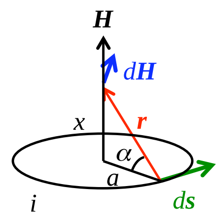
$$\oint Hdl = \int\frac{2ki}{a}dl = \int\frac{2ki}{a}ad\varphi = 2ki\int_0^{2\pi}d\varphi = 4\pi ki$$

→ Ampère's law $\oint Hdl = i \quad (4\pi k \equiv 1) \qquad \therefore \boxed{H = \frac{i}{2\pi a}}$

Magnetic Field Induced by an Electrical Current (Cont'd)

For a circular current, using the right-handed screw rule,

$$H = \int dH_x = \int dH\cos\alpha$$



By substituting the Biot-Savart law,

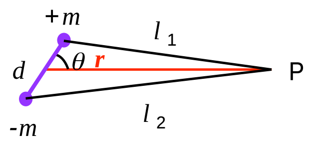
$$\boxed{H} = \oint\frac{1}{4\pi}\frac{ids}{r^2}\sin\left(\frac{\pi}{2}\right)\cos\alpha = \frac{i\cos\alpha}{4\pi r^2}\oint ds$$

$$= \frac{i\cos\alpha}{4\pi r^2}\cdot 2\pi a = \frac{ia\cos\alpha}{2r^2} = \boxed{\frac{ia^2}{2r^3}}$$

Magnetic Field Induced by a Magnetic Dipole

Potential φ at point P, which is separated $\boldsymbol{r}$ from the dipole :

$$\varphi = \frac{1}{4\pi\mu_0}\left(\frac{m}{l_1} + \frac{-m}{l_2}\right) = \frac{m}{4\pi\mu_0}\frac{l_2 - l_1}{l_1 l_2}$$



Here,

$$l_1 = \sqrt{r^2 + \left(\frac{d}{2}\right)^2 - rd\cos\theta}, \quad l_2 = \sqrt{r^2 + \left(\frac{d}{2}\right)^2 + rd\cos\theta}$$

For $r >> d$, d^2 and higher terms can be neglected.

$$\begin{cases} l_1 \approx r\sqrt{1 - \dfrac{d}{r}\cos\theta} \approx r\left(1 - \dfrac{d}{2r}\cos\theta\right) = r - \dfrac{d}{2}\cos\theta \\ l_2 \approx r + \dfrac{d}{2}\cos\theta \end{cases} \qquad \therefore \begin{cases} l_2 - l_1 \approx d\cos\theta \\ l_1 l_2 \approx r^2 \end{cases}$$

Therefore, potential is calculated to be $\varphi = \dfrac{m}{4\pi\mu_0}\dfrac{d\cos\theta}{r^2} = \dfrac{\boldsymbol{m}\cdot\boldsymbol{r}}{4\pi\mu_0 r^3}$

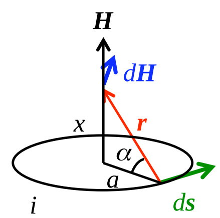
Magnetic field at P is

$$\boldsymbol{H} = -\nabla\varphi = \frac{-1}{4\pi\mu_0}\left[\nabla\left(\frac{\boldsymbol{m}}{r^3}\boldsymbol{r}\right)\right] = \frac{-1}{4\pi\mu_0}\left[\frac{\boldsymbol{m}}{r^3} - \frac{3}{r^4}(\boldsymbol{m}\cdot\boldsymbol{r})\frac{\boldsymbol{r}}{r}\right] = \frac{-1}{4\pi\mu_0 r^3}\left[\left(\boldsymbol{m} - \frac{3}{r^2}(\boldsymbol{m}\cdot\boldsymbol{r})\boldsymbol{r}\right)\right]$$

Magnetic Field Induced by a Magnetic Dipole (Cont'd)

In $\boldsymbol{H}$, a component along $\boldsymbol{m}$ is

$$\boldsymbol{H} = \frac{-1}{4\pi\mu_0 r^3}\left[\left(m - \frac{3}{r^2}mrr\right)\right] = \frac{m}{2\pi\mu_0 r^3}$$



Assuming $m = \mu_0 iA$ ($A = \pi a^2$),

$$\boldsymbol{H} = \frac{\mu_0 iA}{2\pi\mu_0 r^3} = \frac{ia^2}{2r^3}$$

→ Same as $\boldsymbol{H}$ induced by a circular electrical current

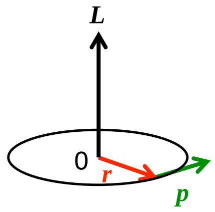
→ Circular current i holds a magnetic moment of $m = \mu_0 iA$.

→ *Circular current i is equivalent to a magnetic moment*.

Origin of Magnetism

Angular momentum $\boldsymbol{L}$ is defined with using momentum $\boldsymbol{p}$:

$$\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$$



z component is calculated to be $L_z = xp_y - yp_x$

In order to convert L_z into an operator, $p \to \frac{\hbar}{i}\frac{\partial}{\partial q}$

$$\mathbf{L}_z = \frac{\hbar}{i}\left(x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}\right)$$

By changing into a polar coordinate system, $\mathbf{L}_z = \frac{\hbar}{i}\frac{\partial}{\partial \varphi}$

Similarly,

$$\mathbf{L}_x = -\frac{\hbar}{i}\left(\sin\varphi\frac{\partial}{\partial\theta} + \cot\theta\cos\varphi\frac{\partial}{\partial\varphi}\right), \quad \mathbf{L}_y = -\frac{\hbar}{i}\left(-\cos\varphi\frac{\partial}{\partial\theta} + \cot\theta\sin\varphi\frac{\partial}{\partial\varphi}\right)$$

Therefore,

$$\mathbf{L}^2 = \mathbf{L}_x{}^2 + \mathbf{L}_y{}^2 + \mathbf{L}_z{}^2 = -\hbar^2\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial^2\varphi}\right]$$

In quantum mechanics, observation of state $\psi = R\Theta\Phi$ is written as

$$\mathbf{L}^2\psi = -\hbar^2\left[\frac{1}{\Theta\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Theta}{\partial\theta}\right) + \frac{m_l{}^2}{\sin^2\theta}\right]R\Theta\Phi \equiv \hbar^2 K(R\Theta\Phi) = l(l+1)\hbar^2\psi$$

Origin of Magnetism (Cont'd)

Thus, the eigenvalue for $\boldsymbol{L}^2$ is

$$\boldsymbol{L}^2 = l(l+1)\hbar^2 \qquad \therefore |\boldsymbol{L}| = \sqrt{l(l+1)}\hbar \qquad (l = 1,\ 2,\ 3,\ \ldots)$$

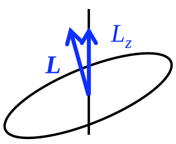
→ azimuthal quantum number (defines the magnitude of $\boldsymbol{L}$)

Similarly, for L_z,

$$L_z = m_l\hbar \qquad (m_l = 0,\ \pm 1,\ \pm 2,\ \ldots)$$

→ magnetic quantum number (defines the magnitude of L_z)

For a simple electron rotation,



→ Orientation of $\boldsymbol{L}$: quantized

In addition, principal quantum number :

defines electron shells

n = 1 (K), 2 (L), 3 (M), ...

For l = 1,

m_l = 1, 0, -1

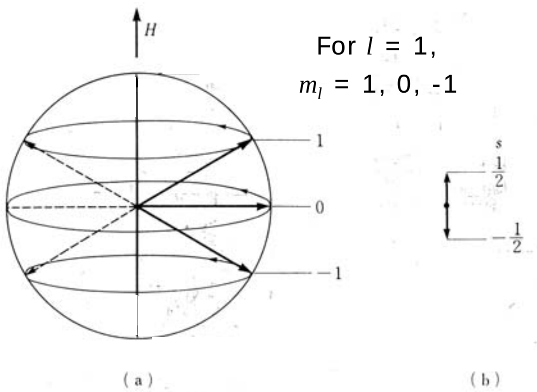


Fig. 3.3. Spatial quantization for orbital (a) and spin (b) angular momenta.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Orbital Moments

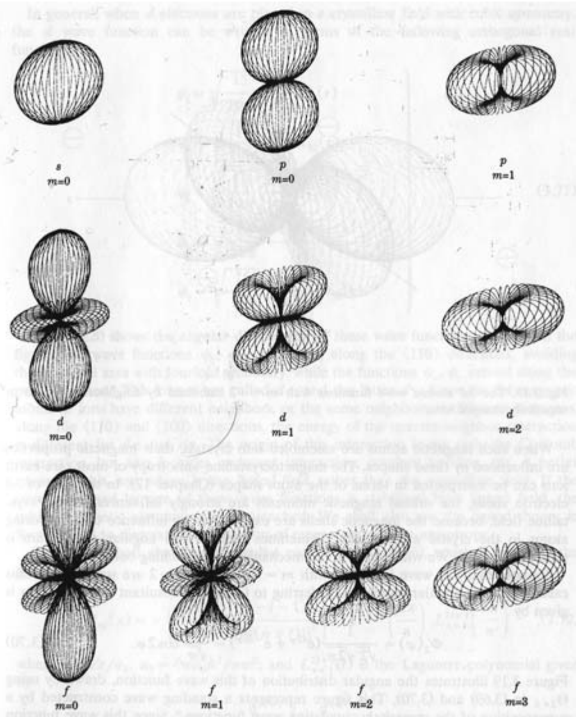


Fig. 3.18. Angular distribution of atomic wave functions with various orbital and magnetic quantum numbers.

Orbital motion of electron :

generates magnetic moment

$\boldsymbol{m} = -\mu_{\mathrm{B}} \boldsymbol{L}/\hbar$

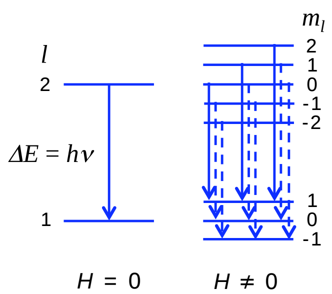
→ μ_{B} : Bohr magneton (1.165×10^{-29} Wb·m)

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Spin Moment and Magnetic Moment

Zeeman splitting :

For H atom, energy levels are split under H dependent upon m_l.



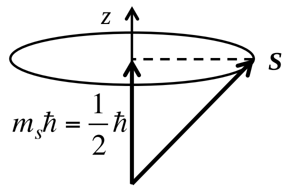
Spin momentum :

$$\begin{cases} \boldsymbol{L} \quad l \quad m_l = l, l-1, \ldots, 0, \ldots, -l \quad (2l+1) \\ \boldsymbol{S} \quad s \quad m_s = s, -s \quad \left(s = \frac{1}{2}\right) \quad 2 \end{cases}$$

$$\therefore |\boldsymbol{S}| = \sqrt{s(s+1)}\hbar = \sqrt{\frac{1}{2}\left(\frac{1}{2}+1\right)}\hbar$$

$$\therefore \boldsymbol{m} = -g\mu_{\mathrm{B}}\boldsymbol{J}/\hbar$$

→ g = 1 ($\boldsymbol{J}$: orbital), 2 ($\boldsymbol{J}$: spin)



Summation of angular momenta :

Russel-Saunders model $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$

Magnetic moment :

$$\boldsymbol{M} = \boldsymbol{M}_{\mathrm{orb}} + \boldsymbol{M}_{\mathrm{spin}} = -\mu_{\mathrm{B}}(\boldsymbol{L} + 2\boldsymbol{S})/\hbar = -g\mu_{\mathrm{B}}\boldsymbol{J}/\hbar$$

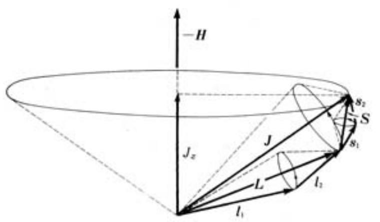


Fig. 3.7. Russell–Saunders coupling.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

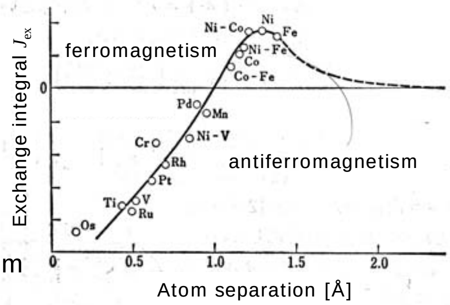
Exchange Energy and Magnetism

Exchange interaction between spins :

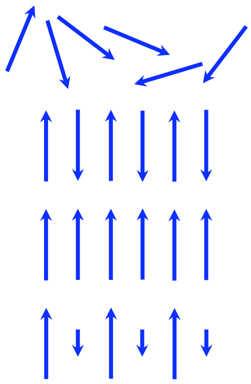
$$E_{ex} = -2J_{ex}\boldsymbol{S}_i\boldsymbol{S}_j$$

→ E_{ex} : minimum for parallel / antiparallel configurations

→ J_{ex} : exchange integral



Dipole moment arrangement :



Paramagnetism

Antiferromagnetism

Ferromagnetism

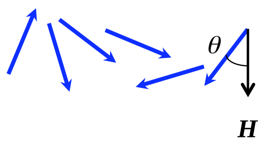
Ferrimagnetism

* K. Ota, *Fundamental Magnetic Engineering I* (Kyoritsu, Tokyo, 1973);

Paramagnetism

Applying a magnetic field $\boldsymbol{H}$, potential energy of a magnetic moment with θ is

$$U = -\boldsymbol{mH} = -mH\cos\theta$$ → $\boldsymbol{m}$ rotates to decrease U.



Assuming the numbers of moments with θ is n and energy increase with $\theta + d\theta$ is $+ dU$,

$$\frac{dn}{n} \propto \frac{1}{T}(-dU) \quad \therefore \ln n \propto \frac{-U}{T} + \text{const.} \quad \therefore \ln n = \frac{-U}{k_B T} + \ln n_0$$

$$\therefore n = n_0 \exp\left(\frac{-U}{k_B T}\right)$$ → Boltzmann distribution

Sum of the moments along z direction is between $-J$ and $+J$

$$M = \sum m_z n = \sum(-g\mu_B M_J) n_0 \exp\left(\frac{-U}{k_B T}\right) \quad (M_J : z \text{ component of } \boldsymbol{M})$$

Here, $N = \sum n = \sum n_0 \exp\left(\frac{-U}{k_B T}\right) \quad \therefore n_0 = N \Big/ \sum \exp\left(\frac{-U}{k_B T}\right)$

$$\therefore M = \frac{N\sum g\mu_B(-M_J)\exp\left(\frac{-U}{k_B T}\right)}{\sum \exp\left(\frac{-U}{k_B T}\right)} = Ng\mu_B \frac{\sum b\exp(by)}{\sum \exp(by)} \quad \left(b \equiv -M_J,\ y \equiv \frac{g\mu_B H}{k_B T}\right)$$

Paramagnetism (Cont'd)

Now, $\sum \exp(by) = e^{-Jy} + e^{-(J-1)y} + \cdots + e^{Jy} = e^{-Jy} + e^{-Jy}e^{y} + \cdots + e^{Jy} = \dfrac{e^{-Jy} - e^{Jy}e^{y}}{1-e^{y}}$

$$\therefore e^{-y/2}\sum \exp(by) = \frac{e^{-y/2}\left(e^{-Jy} - e^{Jy}e^{y}\right)}{e^{-y/2}\left(1-e^{y}\right)} = \frac{e^{-Jy}e^{-y/2} - e^{Jy}e^{y/2}}{e^{-y/2} - e^{y/2}}$$

Using $\sinh a = \frac{1}{2}\left(e^{a} - e^{-a}\right)$ $\qquad \therefore \sum e^{by} = \dfrac{e^{\left(J+\frac{1}{2}\right)y} - e^{-\left(J+\frac{1}{2}\right)y}}{e^{y/2} - e^{-y/2}} = \dfrac{\sinh\left(J+\frac{1}{2}\right)y}{\sinh\frac{y}{2}}$

Using $\dfrac{d}{dy}\left(\ln \sum e^{by}\right) = \dfrac{\sum b e^{by}}{\sum e^{by}}$

$$\frac{d}{dy}\left(\ln \sum e^{by}\right) = \frac{d}{dy}\left[\ln \frac{\sinh\left(J+\frac{1}{2}\right)y}{\sinh\frac{y}{2}}\right] = \frac{d}{dy}\left[\ln\sinh\left(J+\frac{1}{2}\right)y - \ln\sinh\frac{y}{2}\right]$$

$$= \frac{1}{\sinh\left(J+\frac{1}{2}\right)y}\cosh\left(J+\frac{1}{2}\right)y\cdot\left(J+\frac{1}{2}\right)y - \frac{1}{\sinh\frac{y}{2}}\cosh\frac{y}{2}\cdot\frac{1}{2}$$

$$= \left(J+\frac{1}{2}\right)\coth\left(J+\frac{1}{2}\right)y - \frac{1}{2}\coth\frac{y}{2}$$

$$= \left(\frac{2J+1}{2}\right)\coth\left(\frac{2J+1}{2}\right)a - \frac{1}{2}\coth\frac{a}{2J} \qquad (a \equiv Jy)$$

Paramagnetism (Cont'd)

Therefore,

$$M = Ng\mu_B J\left[\left(\frac{2J+1}{2J}\right)\coth\left(\frac{2J+1}{2J}\right)a - \frac{1}{2J}\coth\frac{a}{2J}\right] = Ng\mu_B J B_J(a) \qquad \left(a = \frac{g\mu_B JH}{k_B T}\right)$$

→ $B_J\ (a)$: Brillouin function

For $a \to \infty$ ($H \to \infty$ or $T \to 0$),

$$B_J(a) = 1 - \frac{1}{J}e^{-a/J} - \cdots \to 1 \qquad \boxed{M = M_0 = Ng\mu_B J}$$

Ferromagnetism

For $J \to 0$, $M \to 0$

For $J \to \infty$ (classical model),

$$\frac{2J+1}{2J} \to 1$$

$$\frac{1}{2J}\coth\frac{a}{2J} = \frac{1}{2J}\left(\cosh\frac{a}{2J}\Big/\sinh\frac{a}{2J}\right) \to \frac{1}{2J}\left(1\Big/\frac{a}{2J}\right) = \frac{1}{a}$$

$$\therefore B_\infty(a) = \coth a - \frac{1}{a} \equiv L(a)$$

→ $L\ (a)$: Langevin function

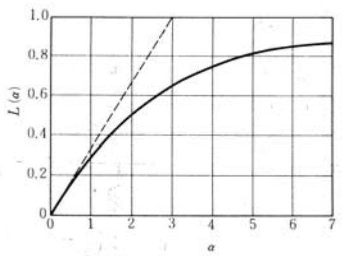


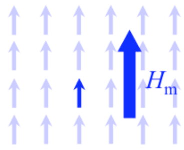
Fig. 5.9. Langevin function.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Ferromagnetism

Weiss molecular field : $H_m = wM$ (w : molecular field coefficient, M : magnetisation)

In paramagnetism theory, $M = Ng\mu_B J B_J(a),\ a = \dfrac{g\mu_B JH}{k_B T}$



Substituting H with $H + wM$, and replacing a with x,

$$M = Ng\mu_B J B_J(x),\ x = \frac{g\mu_B J}{k_B T}(H + wM)$$

Spontaneous magnetisation at $H = 0$ is obtained as $k_B T = g\mu_B JwM$

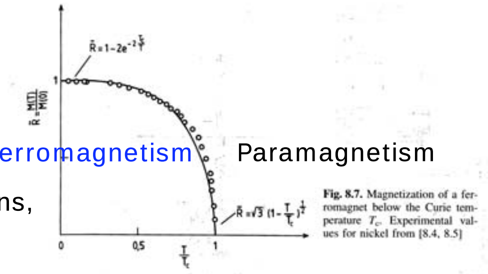
Using M_0 at $T = 0$,
$$\begin{cases} \dfrac{M}{M_0} = B_J(x) \\ \dfrac{M}{M_0} = \dfrac{k_B T x}{Ng^2\mu_B{}^2 J^2 w} \end{cases}$$

For $x << 1$, $B_J(x) \approx \dfrac{J+1}{3J}x$

Assuming $T = \Theta$ satisfies the above equations,

$$\frac{M}{M_0} = \frac{J+1}{3J}x = \frac{k_B\Theta}{Ng^2\mu_B{}^2 J^2 w}x$$

$$\therefore \Theta = \frac{Ng^2\mu_B{}^2 J(J+1)w}{3k_B} = \frac{Nm^2}{3k_B}w$$

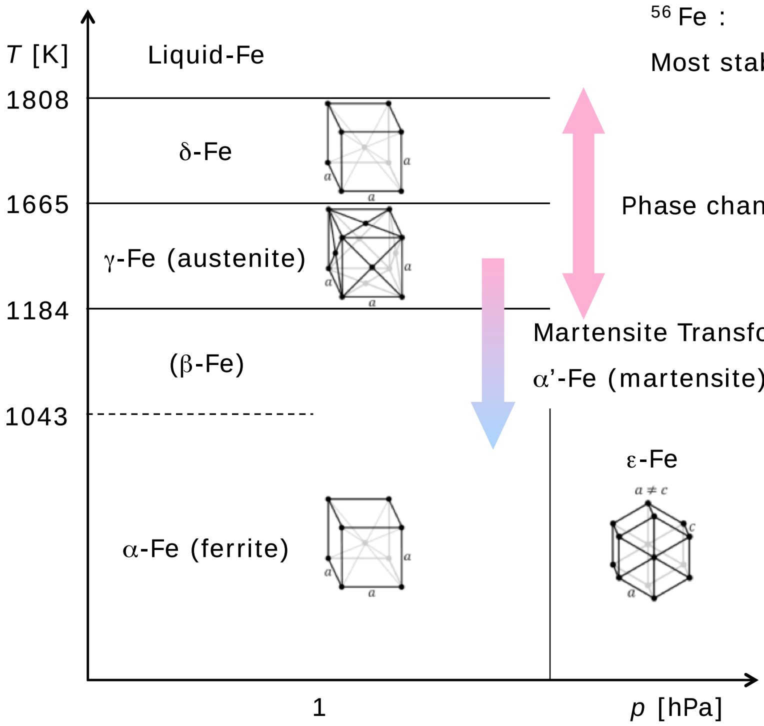


Θ (T_C) : Curie temperature

* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Major Phases of Fe

Fe changes the crystalline structures with temperature / pressure :



^{56}Fe :

Most stable atoms in the universe.

Phase change

Martensite Transformation :

α'-Fe (martensite)

Ferromagnetism (Cont'd)

For $x << 1$, $B_J(x) \approx \frac{J+1}{3J} x$

$$M = Ng\mu_B J B_J(x) = Ng\mu_B J(J+1)\frac{x}{3}$$

$$= Ng^2\mu_B{}^2 J(J+1)\frac{1}{3k_B T}(H + wM)$$

$$\therefore M = C\frac{1}{T}(H + wM) \quad \left(C \equiv Ng^2\mu_B{}^2 J(J+1)/3k_B = Nm^2/3k_B\right)$$

$$\therefore M = C\frac{H}{T - Cw}$$

Therefore, susceptibility χ is

$$\chi = \frac{M}{H} = \frac{C}{T - Cw} = \frac{C}{T - \Theta}$$

(C : Curie constant)

→ Curie-Weiss law

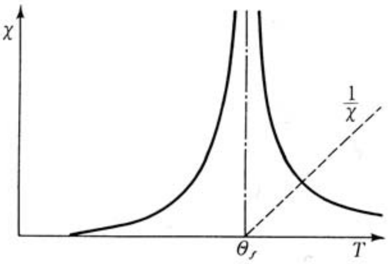


Fig. 6.4. Divergence of magnetic susceptibility in the vicinity of the Curie point.

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997);

Spin Density of States

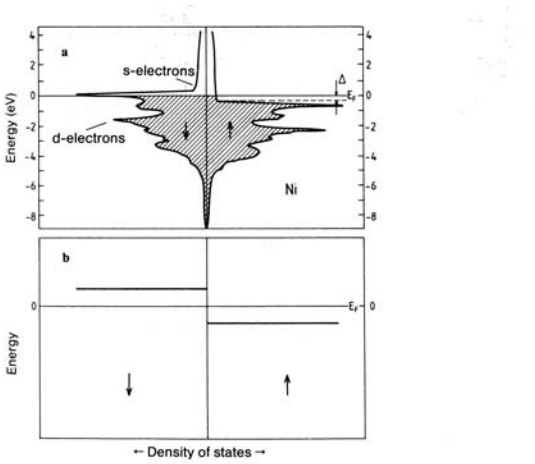


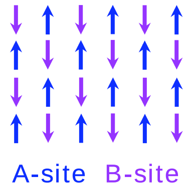
Fig. 8.6. (**a**) Calculated density of states of nickel (after [8.3]). The exchange splitting is calculated to be 0.6 eV. From photoelectron spectroscopy a value of about 0.3 eV is obtained. However the values cannot be directly compared, because a photoemitted electron leaves a hole behind, so that the solid remains in an excited state. The distance Δ between the upper edge of the *d*-band of majority spin electrons and the Fermi energy is known as the Stoner gap. In the bandstructure picture, this is the minimum energy for a spin flip process (the *s*-electrons are not considered in this treatment). (**b**) A model density of states to describe the thermal behavior of a ferromagnet

* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Antiferromagnetism

By applying the Weiss field onto independent A and B sites (for x <<1),

$$\begin{cases} M_A = \dfrac{1}{2} N g \mu_B J B_J(x_A) = \dfrac{Nm^2}{6k_B T} H_A = \dfrac{C}{2T} H_A \\ M_B = \dfrac{1}{2} N g \mu_B J B_J(x_A) = \dfrac{Nm^2}{6k_B T} H_B = \dfrac{C}{2T} H_B \end{cases}$$



Therefore, total magnetisation is

$$M = M_A + M_B = \frac{C}{2T}\left[\left(H - wM_A - w'M_B\right) + \left(H - w'M_A - wM_B\right)\right] = \frac{C}{2T}\left[2H + \left(w + w'\right)M\right]$$

$$\therefore \chi = \frac{M}{H} = \frac{C}{T + \frac{C}{2}\left(w + w'\right)} = \frac{C}{T + \Theta}$$

→ Néel temperature (T_N)

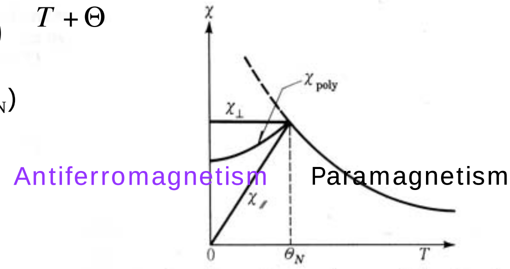


Fig. 7.7. Temperature dependence of magnetic susceptibility of antiferromagnetic materials. (Symbols are the same as Fig. 7.6.)

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997);

Magnetic Anisotropy

Magnetocrystalline anisotropy :

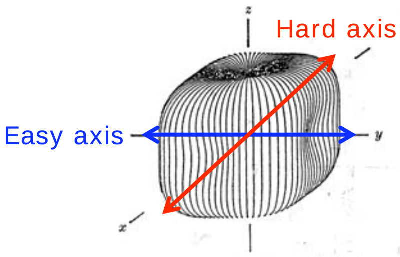


Fig. 12.2. Polar diagram of the cubic anisotropy energy for $K_1 > 0$ and $K_2 = 0$. (Radial vector is equal to $E_a + \frac{2}{3}K_1$.)

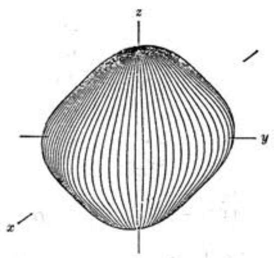


Fig. 12.3. Polar diagram of the cubic anisotropy energy for $K_1 < 0$ and $K_2 = 0$. (Radial vector is equal to $E_a + 2|K_1|$.)

Easy axis :

Magnetic anisotropy energy : minimum

Stable direction for spontaneous magnetisation

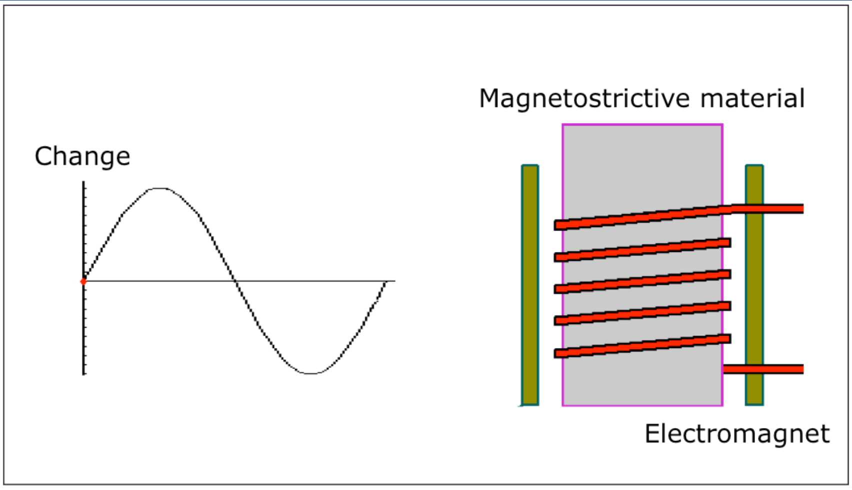
Hard axis :

Magnetic anisotropy energy : maximum

Unstable direction for spontaneous magnetisation

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Magnetostriction



Flat panel speaker

* http://www.gmmtech.co.jp/
** http://www.ednjapan.com/

Magnetic Domain Structures

Stable magnetic domain configuration is defined to minimize total energy :

$U = U_{mag} + U_{ex} + U_a$

U_{mag} : magnetostatic energy
maximum when magnetic poles appear at the edge.
minimum when no magnetic poles appear at the edge.

U_{ex} : exchange energy
maximum for antiparalell
minimum for parallel

U_a : magnetic anisotropy energy
maximum for hard axis
minimum for easy axis

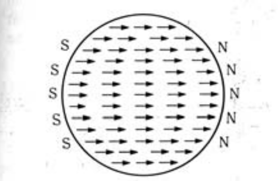


Fig. 16.1. Uniformly magnetized disk (single domain structure).

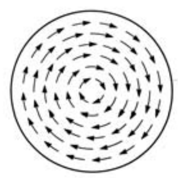


Fig. 16.2. Circularly magnetized disk (no free poles).

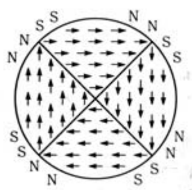


Fig. 16.4. Domain structures of a disk with cubic magnetocrystalline anisotropy.

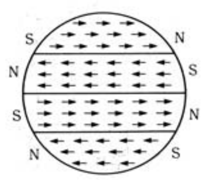
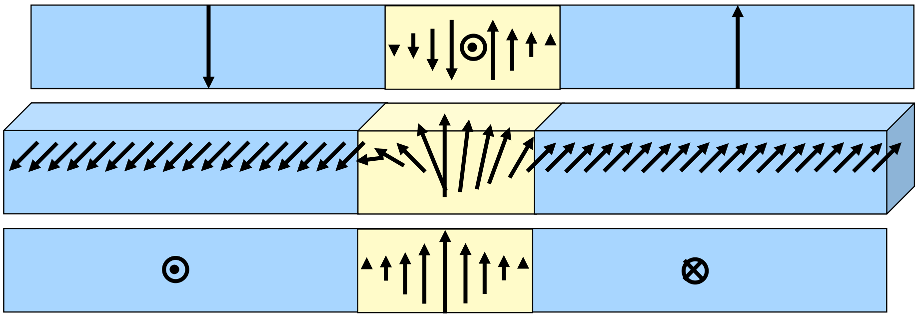


Fig. 16.5. Domain structures of a disk with uniaxial magnetocrystalline anisotropy.

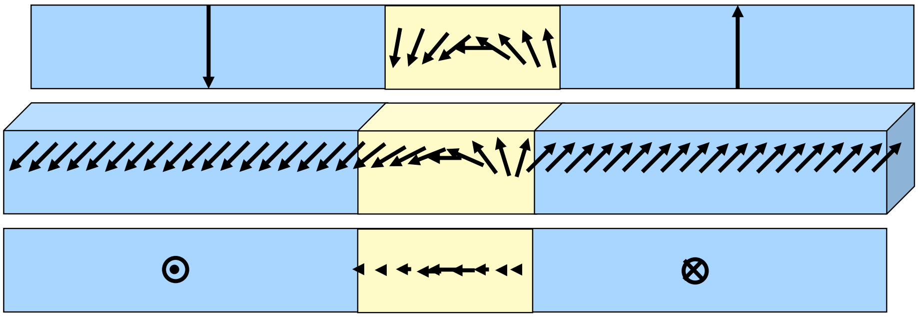
* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Magnetic Domain Walls

Bloch wall :



Néel wall :



Domain Wall Evolution with Film Thickness

Magnetic domain walls change the configuration with film thickness :

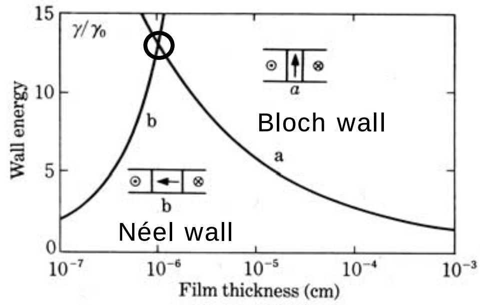


Fig. 16.28. Dependence of the wall energy on film thickness (a) Bloch wall; (b) Néel wall.[10]

Cross-tie wall

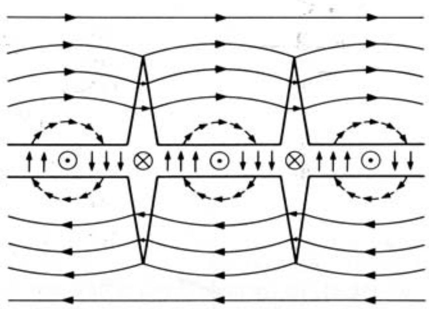


Fig. 16.29. Spin configurations inside and outside the cross-tie wall.[11]

* S. Chikazumi, *Physics of Ferromagnetism* (Oxford University Press, Oxford, 1997).

Domain Wall Displacement in a *M* - *H* Curve

In a magnetisation process, domains are annihilated / nucleated by a field :

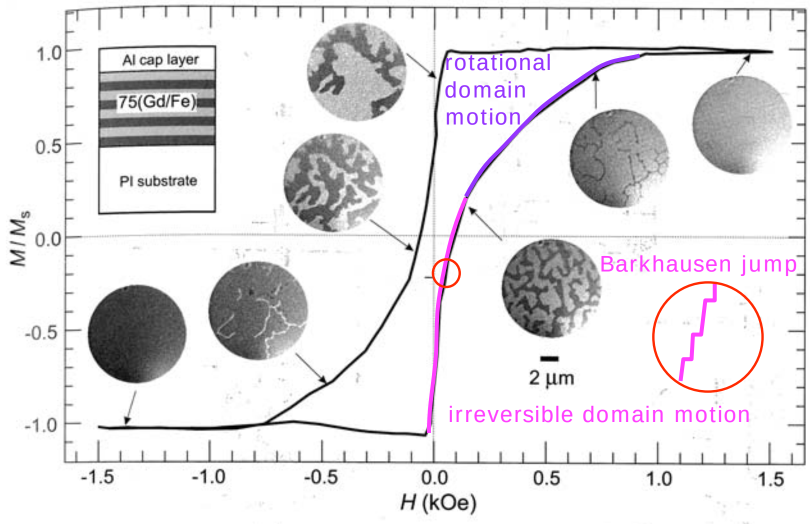


Fig. 10.22. TIXM images recorded at the FeL_3-edge as a function of applied field for a 75 × [Fe(4.1 Å)/Gd(4.5 Å)] multilayer deposited on polyimide and capped for protection with an Al layer [463, 482]

* J. Stoör and H. C. Siegmann, *Magnetism* (Springer, Berlin, 2006).