Part IV Magnetic Properties of Materials

Chap. 14 Foundations of Magnetism

Chap. 15 Magnetic Phenomena and Their Interpretation- Classical Approach

Chap. 16 Quantum Mechanical Considerations

Chap. 17 Applications

16.1 Paramagnetism and Diamagnetism

* Paramagnetism

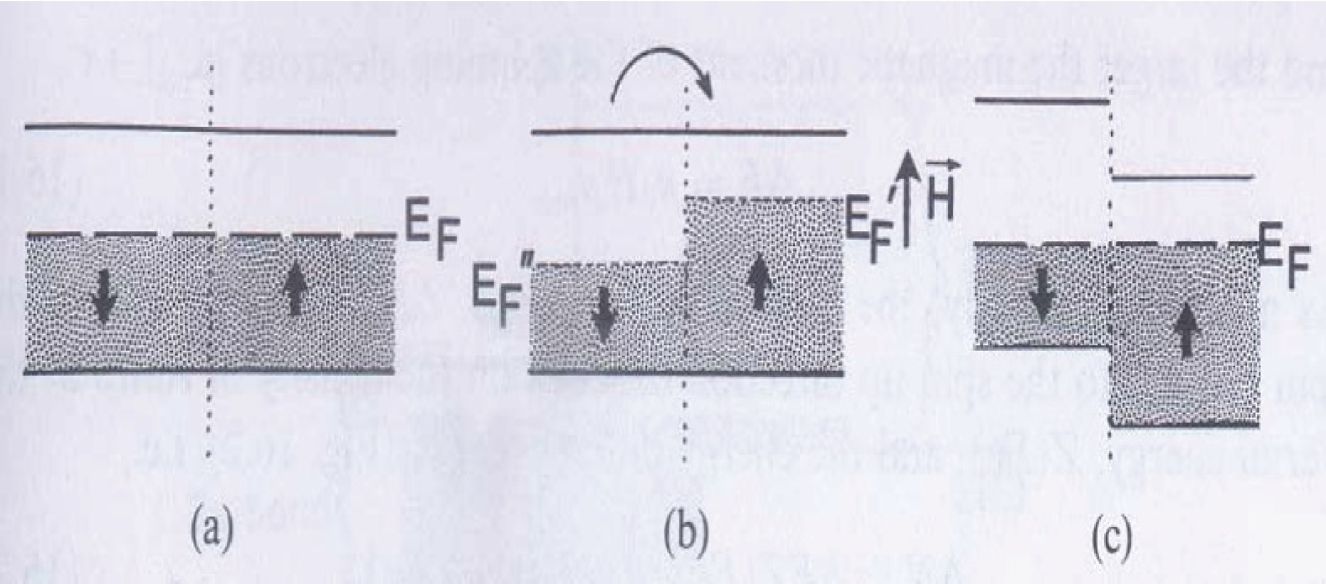

Fig16.1. Schematic representation of the effect of an external magnetic field on the electron distribvution in a partially filled electron band (a) Without magnetic field (b) and (c) with magnetic field.

- Magnetic moment of the spinning electrons: dominant contribution to paramagnetism
- Susceptibilities for paramagnetic metals based on the energy theory

16.1 Paramagnetism and Diamagnetism

Potential energy: $E_p = -\mu_0 \mathbf{m} \cdot \mathbf{H}$

$$\Delta E = \mu_0 H \mu_{ms}$$

$$\Delta N = \Delta E Z(E_F)$$

$$= \mu_0 H \mu_{ms} Z(E_F)$$

$$M = \frac{\mu_m}{V}$$

$$M = \frac{\mu_{ms}}{V} \Delta N = \frac{\mu^2_{ms} \mu_0 H Z(E_F)}{V}$$

$$\chi = \frac{M}{H} = \frac{\mu^2_{ms} \mu_0 Z(E_F)}{V}$$

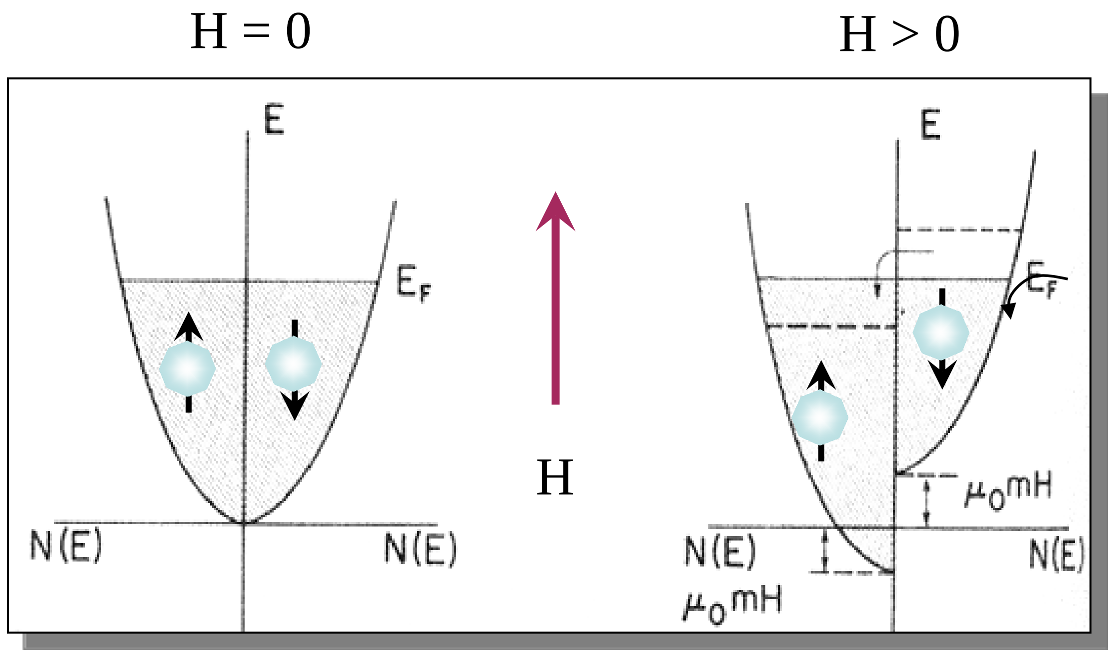

Figure 16.2. Schematic representation of the density of states $Z(E)$ in two half-bands. The shift of the two half-bands occurs as a result of an external magnetic field. Free electron case. (See also Fig. 16.1(c).) The area ΔN equals $\Delta E \cdot Z(E)$.

$$\chi_{spin,para} = \frac{\mu_B^2 \mu_0 Z(E_F)}{V}$$

16.1 Paramagnetism and Diamagnetism

*** Diamagnetism**

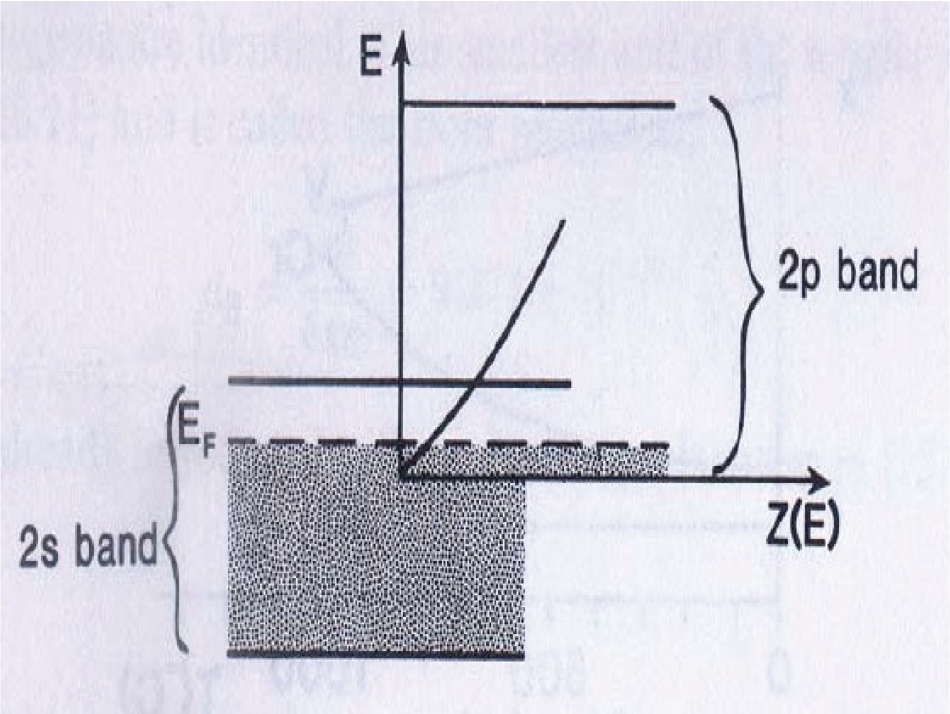

Fig16.3. Overlapping of 2*s*-and 2*p*-bands in Be and the density of states curve for the 2p-band.

$$\chi_{dia} = -\frac{e^2 Z r^2 \mu_0}{6mV}$$

16.1 Paramagnetism and Diamagnetism

$$\mu_m = I \times A = \frac{e}{t} A = \frac{e}{s/v} A = \frac{ev\pi r^2}{2\pi r} = \frac{evr}{2}$$ **(A= area of loop)**

$$2\pi r = n\lambda = n\frac{h}{p} \rightarrow \quad rp = \frac{h}{2\pi} n = \hbar n,$$ **(mvr = angular momentum)**

$$mvr = \hbar n = \frac{nh}{2\pi} \qquad (16.9)$$

$$\mu_m = \frac{enh}{4\pi m} \qquad (16.10)$$

For n =1, $$\mu_m = \frac{eh}{4\pi m} \qquad (16.11)$$

$$\mu_B = \frac{eh}{4\pi m} = 9.274 \times 10^{-24} \left(\frac{J}{T}\right) \qquad (16.12)$$

Bohr magneton

16.2 Ferromagnetism and Antiferromagnetism

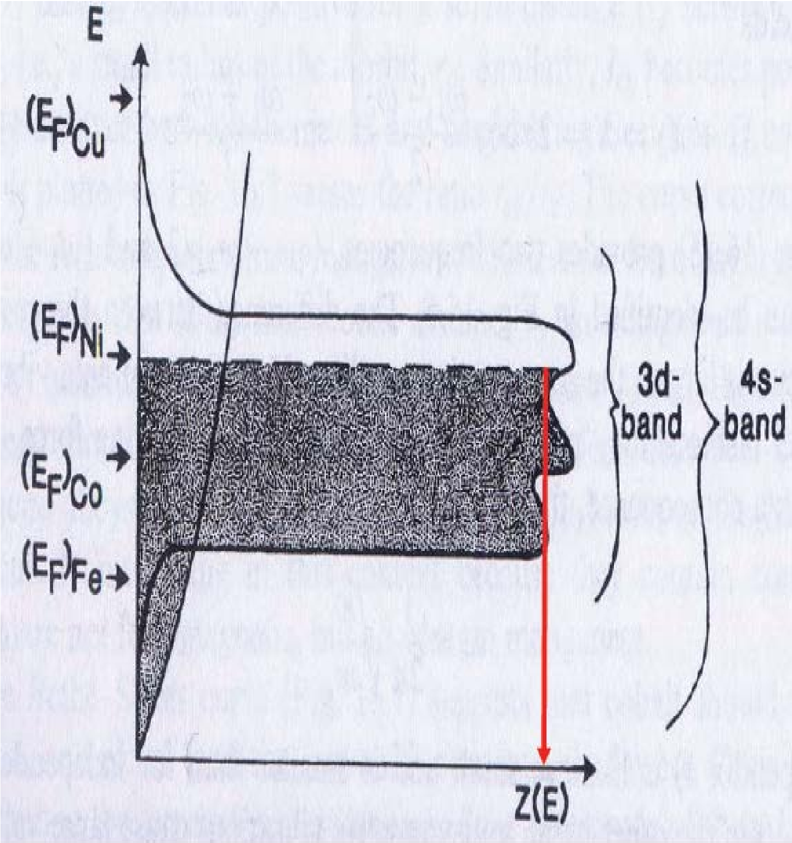

Fig 16.5. Schematic representation of the density of states for 4*s*-and 3*d*-bands the Fermi energies for iron, cobalt, nickel, and copper. The population of the bonds by the ten nickel (3*d*+4*s*)-electrons is indicated by the shaded area.

- d-bands overlap the next higher s-band. d-band can accommodate up to ten electrons, so that the density of states for a d-band is relatively large

- For instance, the density of states of Ni near Fermi energy are comparatively large, one needs only a relatively small amount of energy to transfer a considerable number of electrons from spin down into spin up configurations.

- only minimum energy is needed to change spin direction in the ferromagnetic metals.

16.2 Ferromagnetism and Antiferromagnetism

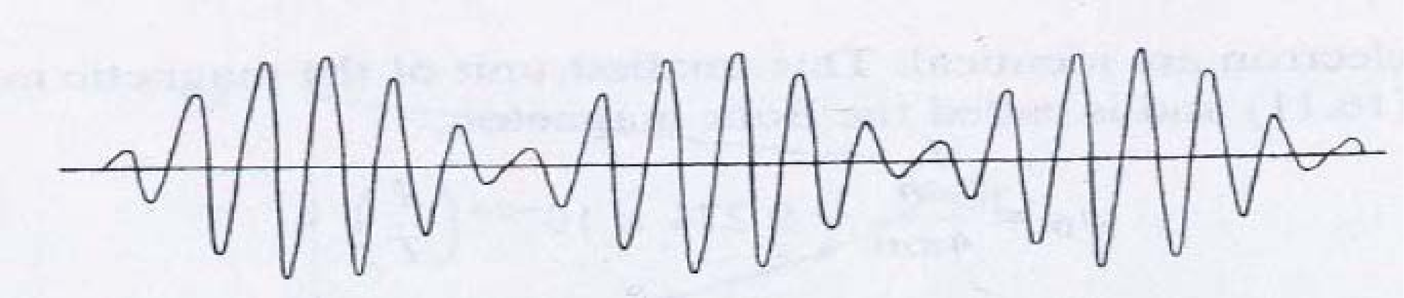

Fig16.6. Amplitude modulation resulting from the coupling of two pendula. The vibrational pattern shows beats, Similarly as known for two oscillators that have almost identical pitch.

$$X_1 = b \sin w_1 t \qquad (16.13)$$

$$X_2 = b \sin w_2 t \qquad (16.14)$$

$$X_1 + X_2 = X = 2b \cos \frac{w_1 - w_2}{2} t \sin \frac{w_1 + w_2}{2} t \qquad (16.15)$$

The difference of frequencies is larger, the stronger the coupling.

If the two pendula vibrate in a parallel fashing, the restoring force, *kx*, is small. As a result, the frequency is smaller than for independent vibration

$$\nu_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (16.16)$$

16.2 Ferromagnetism and Antiferromagnetism

$$I_{ex} = \int \psi_a(1)\psi_b(2)\psi_a(2)\psi_b(1)\left[\frac{1}{r_{ab}} - \frac{1}{r_{ab}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}}\right] d\tau$$

- I_{ex} is positive → parallel spins are energetically more favorable than antiparallel spins. (vice versa)

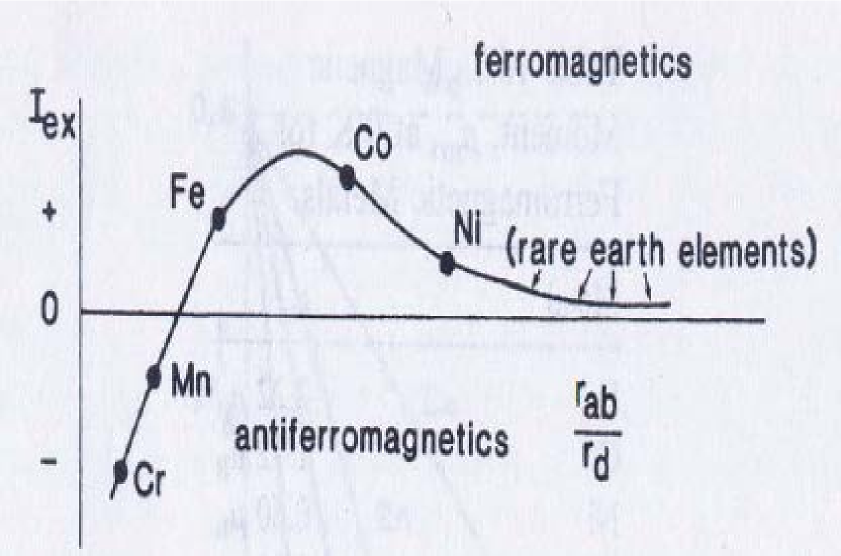

Fig 16.7. Exchange integral, I_{ex}, versus the ratio of inter atomic distance, r_{ab}, and the radius of an unfilled d-shell. The position of the rare earth elements (which have unfilled f-shells) are also shown for completeness. .

- I_{ex} becomes positive for a small distance r_{12} between the electrons, i.e., a small radius of the d-orbit, r_d. Similarly, I_{ex} becomes positive for a large distance between the nuclei and neighboring electrons r_{a2} and r_{b1}.

- I_{ex} *vs.* r_{ab}/r_d (Fig 16.7)

16.2 Ferromagnetism and Antiferromagnetism

❑ Magnetic behavior of Nickel-based alloys

(Fig 16.8)

Ni : $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $3d^8$ $4s^2$

Cu : $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $3d^{10}$ $4s^1$

- For Cu, no "unfilled d- or f-band", the condition for ferromagnetism.

- If copper is alloyed to nickel, the extra copper electrons progressively fill the *d*-band and compensate some of the unsaturated spins of nickel → the magnetic moment per atom of this alloy is reduced.

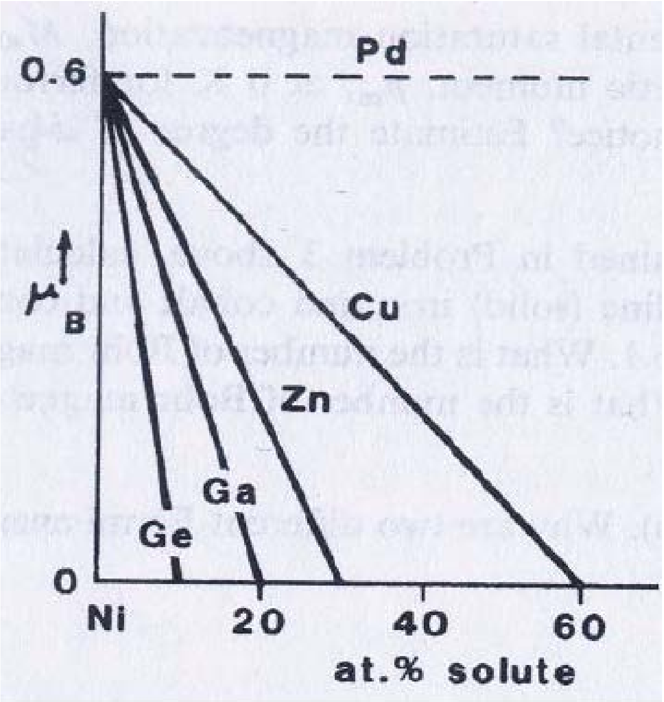

Fig16.8. Magnetic moment per nickel atom as a function of solute concentration

- The *3d* - band of Ni is filled by only 9.4 electrons (0.6 electron lacks per atom). Thus, about 60% copper atoms are needed until the magnetic moment of Ni has reached a zero value.

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Chap. 17 Applications

17.1 Introduction

- **The production of ferro- and ferrimagnetic materials is large-scale operation:**
  - The price of the material that goes into a chip is a minute fraction of the device fabrication cost.
  - The annual sales of electrical steel, used for electric motors and similar devices, reach the millions of tons

- **Other large-scale production items**
  - Permanent magnets for loudspeakers
  - Magnetic recording materials

17.2 Electrical Steels (Soft Magnetic Materials)

- The core loss is the energy that is dissipated in the form of heat within the core of electromagnetic devices
- Several types of losses : eddy current loss, hysteresis loss
- Typical core losses are between 0.3 and 3 W/kg (Table 17.1)

Table 17.1. Properties of Some Soft Magnetic Materials.

Name	Composition (mass %)	Permeability, μ_{max} (unitless)	Coercivity, H_c (Oe)	Coercivity, H_c (A/m)	Saturation induction[a], B_s (kG)	Saturation induction[a], B_s (T)	Resistivity, $\rho(\mu\Omega \cdot cm)$	Core loss at 1.5 T and 60 Hz (W/kg)
Low carbon steel	Fe–0.05% C	5×10^3	1.0	80	21.5	2.1	10	2.8
Nonoriented silicon iron	Fe–3% Si, 0.005% C, 0.15% Mn	7×10^3	0.5	40	19.7	2	60	0.9
Grain-oriented silicon iron	Fe–3% Si, 0.003% C, 0.07% Mn	4×10^4	0.1	8	20	2	47	0.3
78 Permalloy	Ni–22% Fe	10^5	0.05	4	10.8	1.1	16	≈2
Mumetal	77% Ni; 16% Fe, 5% Cu, 2% Cr	10^5	0.05	4	6.5	0.6	62	
Supermalloy	79% Ni; 16% Fe, 5% Mo	10^6	0.002	0.1	7.9	0.8	60	
Supermendur	49% Fe, 49% Co, 2% V	6×10^4	0.2	16	24	2.4	27	
Metglas #2605 annealed	$Fe_{80}B_{20}$	3×10^5	0.04	3.2	15	1.5	≈200	0.3

[a] Above B_s the magnetization is constant and $dB/d(\mu_0 H)$ is unity.

17.2 Electrical Steels (Soft Magnetic Materials)

17.2.1 Core Losses

: The energy that is dissipated in the form of heat within the core of electromagnetic devices when the core is subjected to an alternating magnetic field

Eddy current loss

An current in the primary coil causes an alternating magnetic flux in core → induces in the secondary coil an alternating V_e, see (14.7) and (15.9)

$$V_e \propto -\frac{d\phi}{dt} = -A\frac{dB}{dt}$$

This emf gives rise to the eddy current, I_e (Fig.17.1(a))
Larger eddy current → the larger μ ($B = \mu_0 \mu \cdot H$) → the larger conductivity σ of core material → the higher the applied frequency → the larger the cross-section A

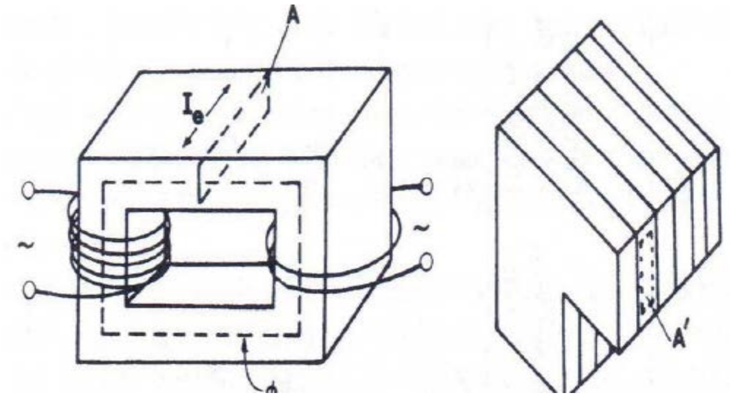

Figure 17.1. (a) Solid transformer core with eddy current, I_e, in a cross-sectional area A. Note the magnetic flux lines ϕ. (b) Cross section of a laminated transformer core. The area A' is smaller than area A in (a).

Skin effect

At high frequency, the eddy current shields the interior of the core from the magnetic field, so that only a thin exterior layer of the core contributes to the flux multiplication.

17.2 Electrical Steels (Soft Magnetic Materials)

17.2.2 Grain Orientation

Magnetic Anisotropy

__The magnetic properties of Crystalline ferromagnetic materials depend on the crystallographic direction in which an external field is applied__

__Magnetization curves of single crystals__

If the external field is applied in the <100> direction, saturation is achieved with the smallest possible field strength

Easy Direction

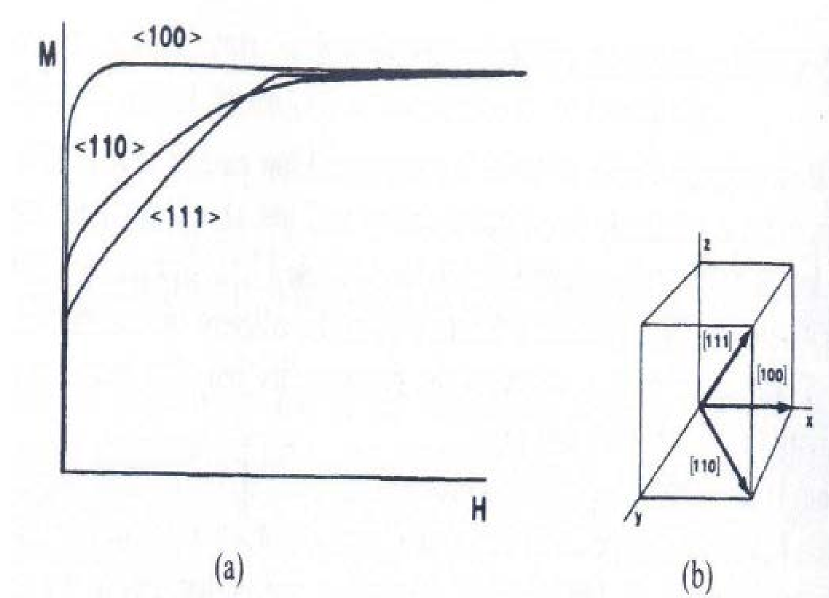

Figure 17.2. (a) Schematic magnetization curves for rod-shaped *iron single crystals* having different orientations (virgin curves). The magnetic field was applied in three different crystallographic directions. (Compare with Fig. 15.6, which refers to polycrystalline material). (b) Reminder of the indices which identify directions in space. (See also Footnote 14 in Section 5.6).

17.2.3 Composition of Core Materials

carbon steel

: The least expensive core material is commercial low relatively small permeability, higher core losses than grain-orientd silicon iron

Iron-silicon alloys

: higher permeability and a lower conductivity than low carbon steel, heat treatments of these alloys can be performed at much higher temperatures with out interference from phase changes during cooling

Permalloy, Supermalloy, Mumetal

: The highest permeability (multicomponent nickel based alloys)

17.3 Permanent Magnets (Hard Magnetic Materials)

: **Devices that retain their magnetic field indefinitely.**

Hard magnetic materials

- **A large remanence B_r (or M_r).**
- **A relatively large coercivity H_c.**
- **A large area within the hysteresis loop.**

Maximum energy product $(BH)_{max}$

- **The area within the hysteresis loop.**
- **The energy product peaks somewhere between these extreme values.**

Maximum energy product

Demagnetization curve

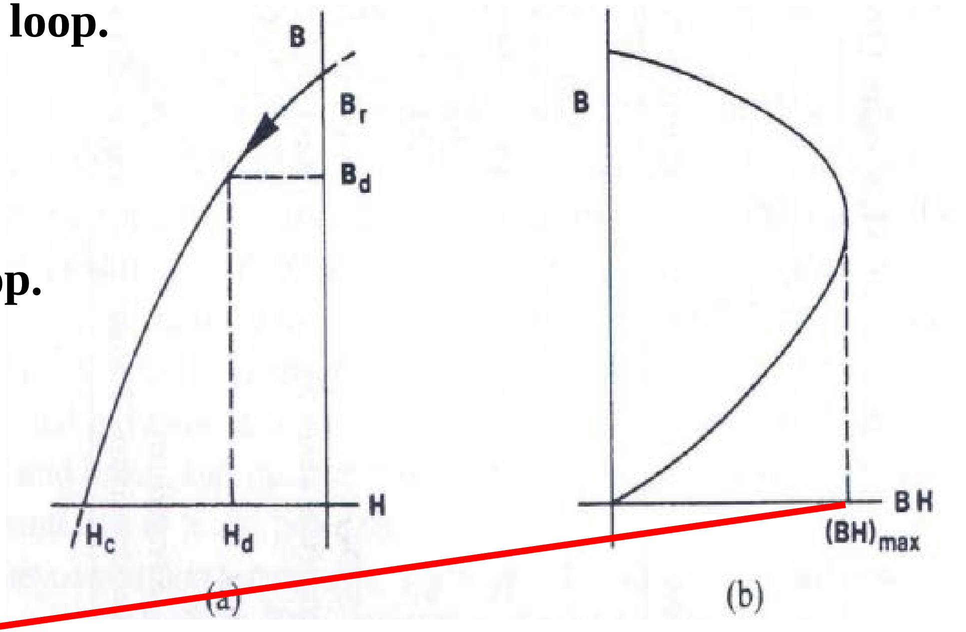

Figure 17.3. (a) Demagnetization curve for a ferromagnetic material. (Second quadrant in a B–H diagram.) (b) Energy product, BH, as a function of induction, B.

17.3 Permanent Magnets (Hard Magnetic Materials)

Table 17.2. Properties of Materials Used for Permanent Magnets.

Material	Composition (mass %)	Remanence B_r (kG)	Remanence B_r (T)	Coercivity H_c (Oe)	Coercivity H_c (A/m)	Maximum energy product $(BH)_{max}$ per Volume (MGOe)	Maximum energy product $(BH)_{max}$ per Volume (kJ/m^3)
Steel	Fe–1% C	9	0.9	51	4×10^3	0.2	1.6
36 Co steel	36 Co, 3.75 W, 5.75 Cr, 0.8 C	9.6	0.96	228	1.8×10^4	0.93	7.4
Alnico 2	12 Al, 26 Ni, 3 Cu, 63 Fe	7	0.7	650	5.2×10^4	1.7	13
Alnico 5	8 Al, 15 Ni, 24 Co, 3 Cu, 50 Fe	12	1.2	720	5.7×10^4	5.0	40
Alnico 5 DG	same as above	13.1	1.3	700	5.6×10^4	6.5	52
Ba-ferrite (Ceramic 5)	$BaO \cdot 6 Fe_2O_3$	3.95	0.4	2,400	1.9×10^5	3.5	28
PtCo	77 Pt, 24 Co	6.45	0.6	4,300	3.4×10^5	9.5	76
Remalloy	12 Co, 17 Mo, 71 Fe	10	1	230	1.8×10^4	1.1	8.7
Vicalloy 2	13 V, 52 Co, 35 Fe	10	1	450	3.6×10^4	3.0	24
Cobalt–Samarium	Co_5Sm	9	0.9	8,700	6.9×10^5	20	159
Iron–Neodymium–Boron	$Fe_{14}Nd_2B_1$	13	1.3	14,000	1.1×10^6	40	318

17.3 Permanent Magnets (Hard Magnetic Materials)

Demagnetizing Curve

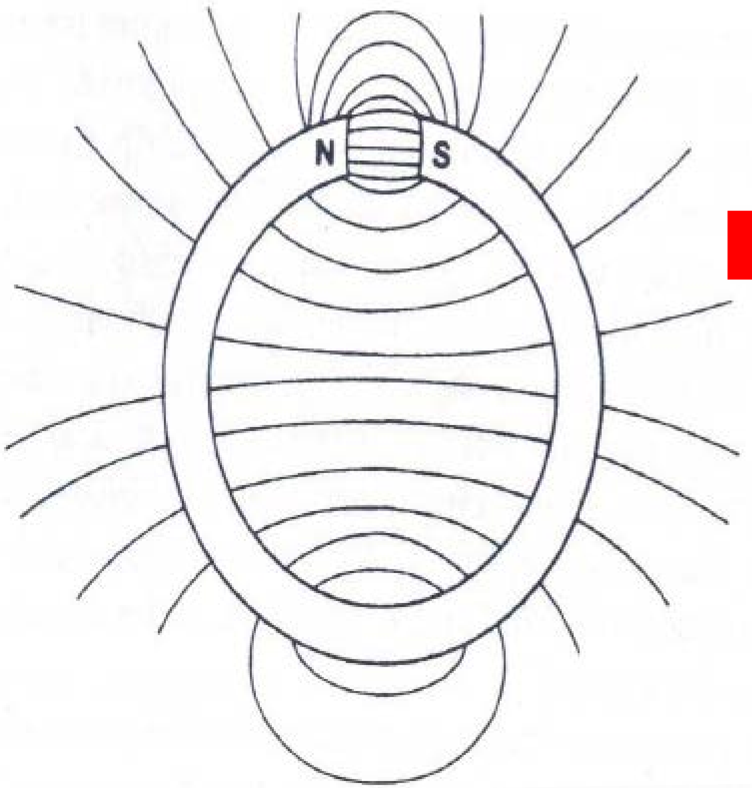

Figure 17.4. Fringing and leakage of a permanent magnet.

- All permanent magnets need to have exposed poles.
- The exposed poles create a demagnetizing field, $H_d \rightarrow$ reduces the B_r

The demagnetizing field depends on the shape, size, and gap length of magnet.

17.4 Magnetic Recording and Magnetic Memories

Magnetic recording tapes, disks, drums, or magnetic strips on credit cards consist of small, needlelike oxide particles about 0.1×0.5 μm.

Recording head

The recording head of a tape machine consist of a laminated electromagnet made of permalloy or soft ferrite (Table 17.1) which has air gap about 0.3 μm wide (Fig. 17.5)

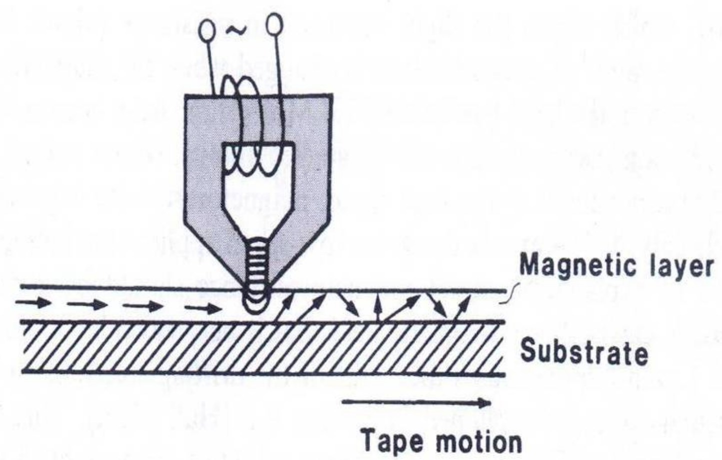

Figure 17.5. Schematic arrangement of a recording (playback) head and a magnetic tape. (Recording mode.) The gap width is exaggerated. The plastic substrate is about 25 μm thick.

17.4 Magnetic Recording and Magnetic Memories

❑ Magneto-resistance

- In magnetic field a conductor is perpendicular to an electric field, the Lorentz force causes the paths of the drifting electrons to bend in near circular form. (Hall effect)
- This bending leads to a decrease of the electron mobility, μ_e

$$\sigma_0 = N_e \cdot \mu_e \cdot e = \frac{1}{\rho_0} \quad (17.2)$$

- Conductivity, σ_0, decreases and the resistivity, ρ_0, increases. (N_e is the free electron concentration and e is the charge of an electron). The relative change in resistivity,

$$\frac{\Delta\rho}{\rho_0} = (\mu_e \Delta B)^2 \quad (17.3)$$

is proportional to the square of the variation in magnetic field strength, ΔB

- The magneto-resistive head senses this change in magnetic field strength and thus, yields a resistance change.

17.4 Magnetic Recording and Magnetic Memories

Ferrite-core memories

Two magnetization directions constitute the two possible values (0 and 1) in the binary system.

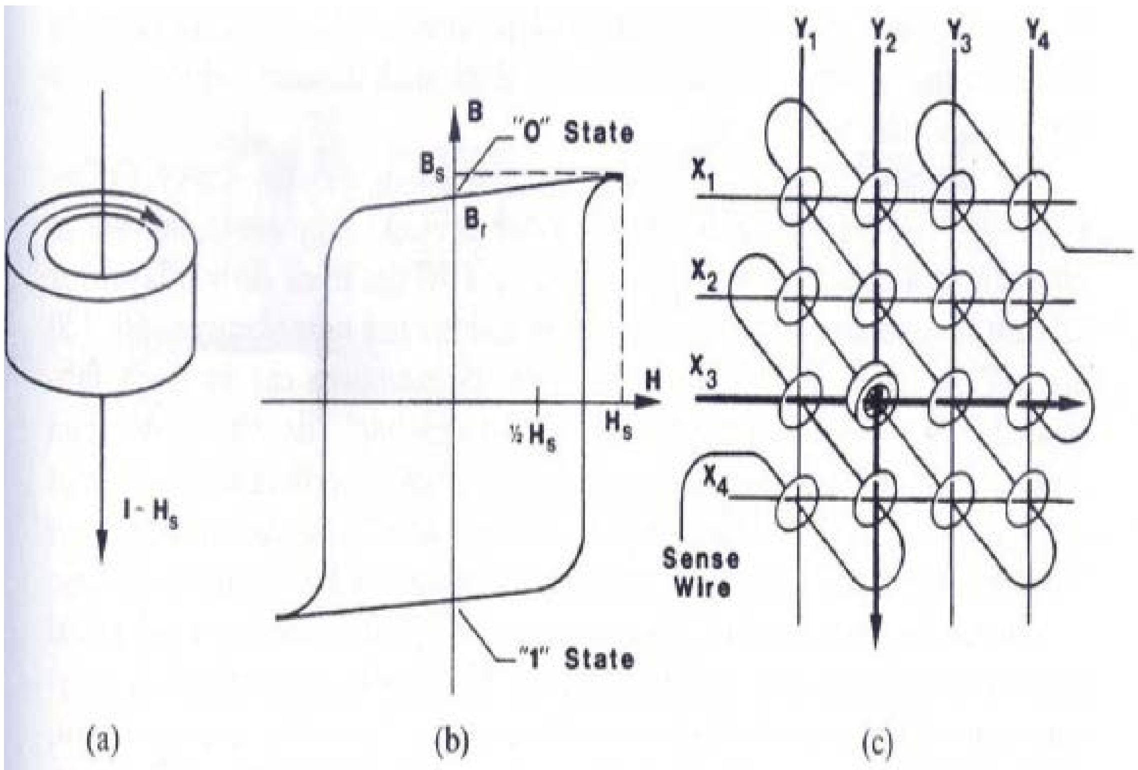

Figure 17.6. (a) Single ferrite core which is magnetized by a current-induced magnetic field; (b) square-shaped hysteresis loop of a soft ferrite memory core; and (c) one plane of a "coincident-current core memory device."

17.4 Magnetic Recording and Magnetic Memories

- **Bubble domain memory**
  - Form in thin crystals of "canted" anti-ferromagnetic oxides, amorphous alloyed films, or in ferri-magnetic materials.
  - The domains can be visibly observed and optically read by the way in which they rotate the plane of polarization of polarized light(Faraday effect, or Kerr effect).
  - Each such domain constitutes one bit of stored information.

- **Thin magnetic films**
  - Consisting of Co-Ni-Pt or Co-Cr-Ta or Co_{75}-Cr_{13}-Pt_{12} in hard-disk devices.
  - H_c : 60-120kA/m (750-1500Oe)
  - Easily fabricated –vapor deposition, sputtering, electroplating.
  - Switched rapidly, a small unit size.
  - A density of 1.8 Mbits/mm^2 with a track separation of 3μm and a bit length of 150nm.

17.4 Magnetic Recording and Magnetic Memories

- **Magneto-optical memories**
  - No mechanical contact between medium and beam.
  - A polycarbonate disk is covered by a certain magnetic material.
  - Their spins are initially vertically aligned ,see Fig. 17.7(a).
  - Laser beam heat→ cooling in magnetic field→ delivers the information to be stored

the spins in the magnetic domain re-orient according to the strength and direction of magnetic field.

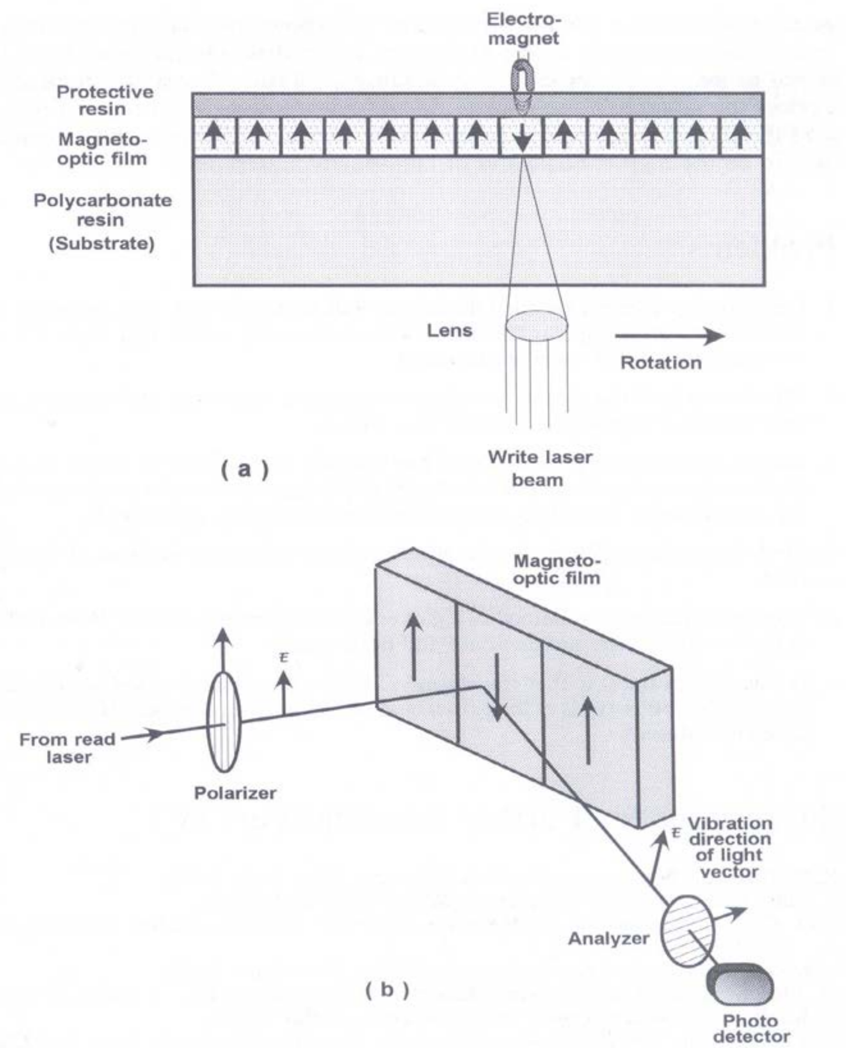

Figure 17.7. (a) Schematic representation of a magneto-optical disk in the writing mode (simplified). (b) Read-out mode of a magneto-optical device. (Polarizer and analyzer are identical devices.)