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

Paramagnetism and Diamagnetism

1. Paramagnetism

- Magnetic moment of the spinning electrons: dominant contribution to paramagnetism

- Susceptibilities for paramagnetic metals based on the energy theory

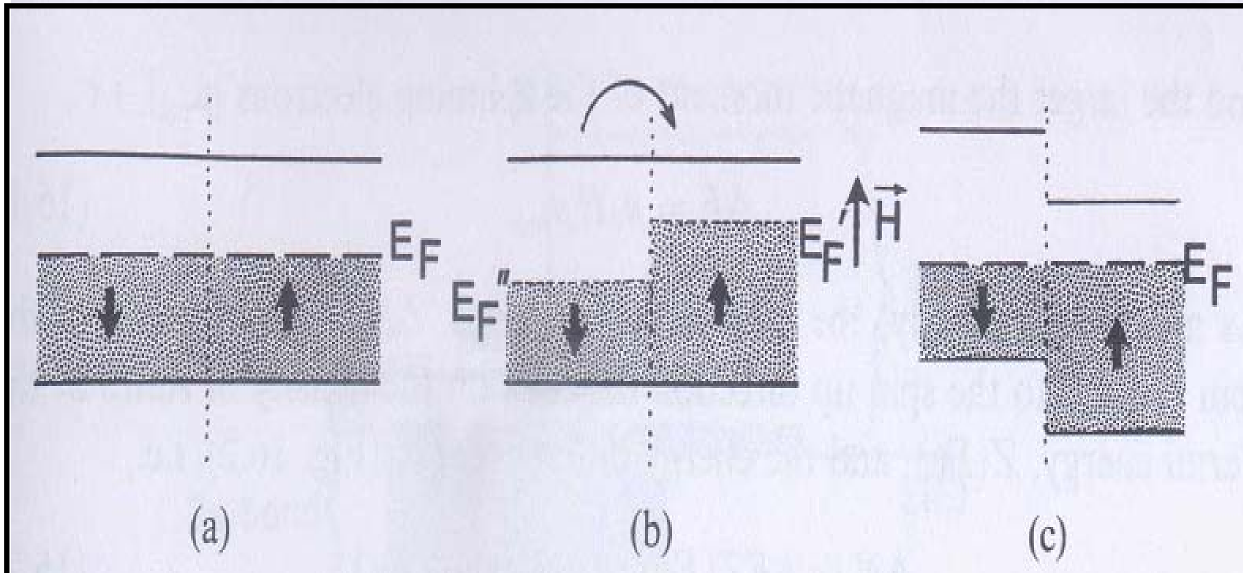

Fig16.1. Schematic representation of the effect of an external magnetic field on the electron distribution in a partially filled electron band (a) Without magnetic field (b) and (c) with magnetic field.

Paramagnetism and Diamagnetism

- **The density of states of the two half-bands (Fig. 16.2). We can observe a relatively large *Z(E)* near E_F. Thus, a small change in energy may cause a large number of electrons to switch to the opposite spin direction.**

- **The susceptibility ($\chi_{spin,\ para}$) of paramagnetism**

ΔE is larger - the larger the external magnetic field strength |H|,and the larger the magnetic moment of the spinning electrons $|\mu_{ms}|$

$$\Delta E = \mu_0 H \mu_{ms} \quad (16.1)$$

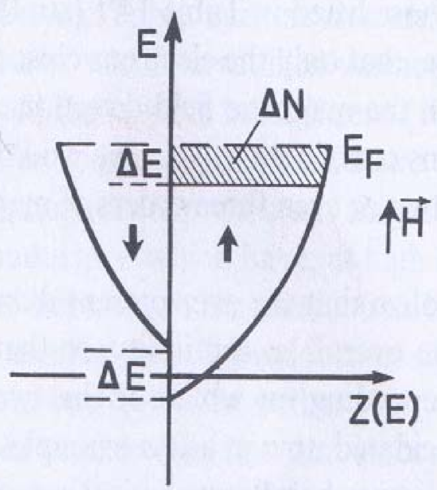

Figure 16.2. Schematic representation of the density of states $Z(E)$ in two half-bands. The shift of the two half-bands occurs as a result of an external magnetic field. Free electron case. (See also Fig. 16.1(c).) The area ΔN equals $\Delta E \cdot Z(E)$.

Paramagnetism and Diamagnetism

The number of electrons , *ΔN* (transferred from spin down to up) depends on the density of states at the Fermi energy, *Z(E$_F$)*

$$\Delta N = \Delta E Z(E_F) = \mu_0 H \mu_{ms} Z(E_F) \qquad (16.2)$$

The magnetization |**M**| is $$M = \frac{\mu_m}{V} \qquad (16.3)$$

The magnetization is larger, the more electrons are transferred from spin down into spin up states.

$$M = \frac{\mu_{ms}}{V}\Delta N = \frac{\mu^2{}_{ms}\,\mu_0 HZ(E_F)}{V} \qquad (16.4)$$

Thus, the susceptibility $$\chi = \frac{M}{H} = \frac{\mu^2{}_{ms}\mu_0 Z(E_F)}{V} \qquad (16.5)$$

The spin magnetic moment of one electron equals one Bohr magneton, μ_B

$$\boxed{\chi_{spin,para} = \frac{\mu_B{}^2\mu_0 Z(E_F)}{V}} \qquad (16.6)$$

2. Diamagnetism

- Susceptibility (χ) of metals might be positive or negative depending on which of the two components (paramagnetism, diamagnetism) predominates.

- Example of diamagnetism 1(beryllium)

 - Be is a bivalent metal having a filled *2s*-shell in its atomic state. However, in the crystalline state, band overlapping can be found, which causes some of the *2s*-electrons to spill over into the *2p*-band. *2s*-electrons populate the very bottom of *2p* band. (see Fig. 16.3)

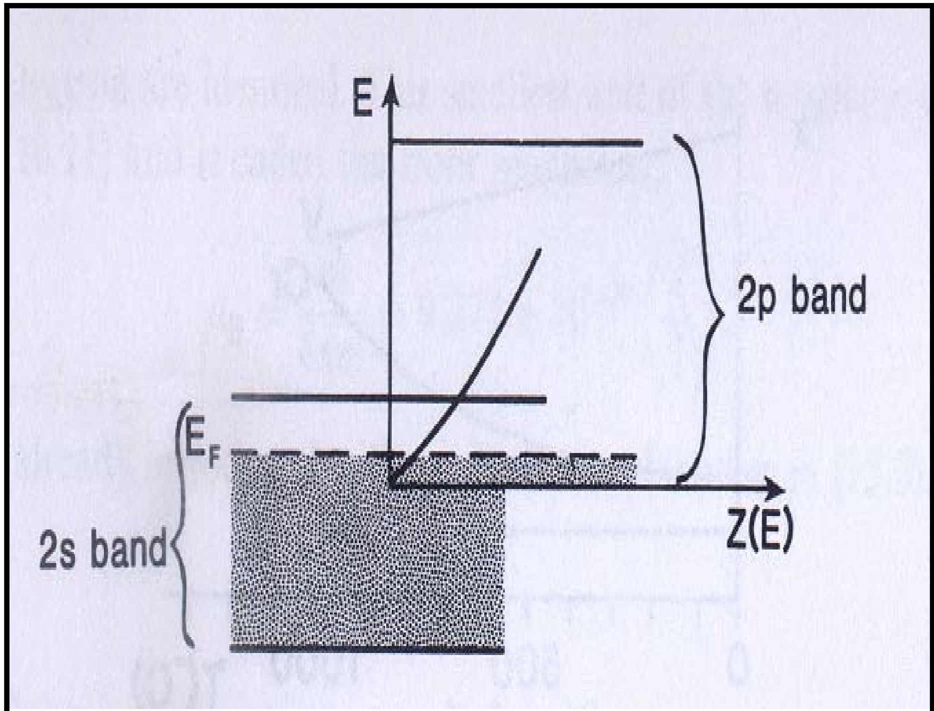

Fig16.3. Overlapping of 2s-and 2p-bands in Be and the density of states curve for the 2p-band.

Thus, the density of states at the Fermi level, and consequently, χ_{para}, is very small.→ Diamagnetic susceptibility predominates, which makes Be diamagnetic.

Paramagnetism and Diamagnetism

❑ Example of diamagnetism 2 (copper)

The Fermi energy of copper is close to the band edge. (see Fig. 5. 22). Thus, the density of states near E_F, and the paramagnetic susceptibility are relatively small compared with diamagnetic susceptibility.

❑ Diamagnetic susceptibility

$$\boxed{\chi_{dia} = -\frac{e^2 Z r^2 \mu_0}{6mV}} \qquad (16.7)$$

Copper has about ten 3*d*-electrons, which makes *Z*~10.

The radius of *d*-shells is fairly large.

→ Thus, for copper, χ_{dia} is large compared with χ_{para}

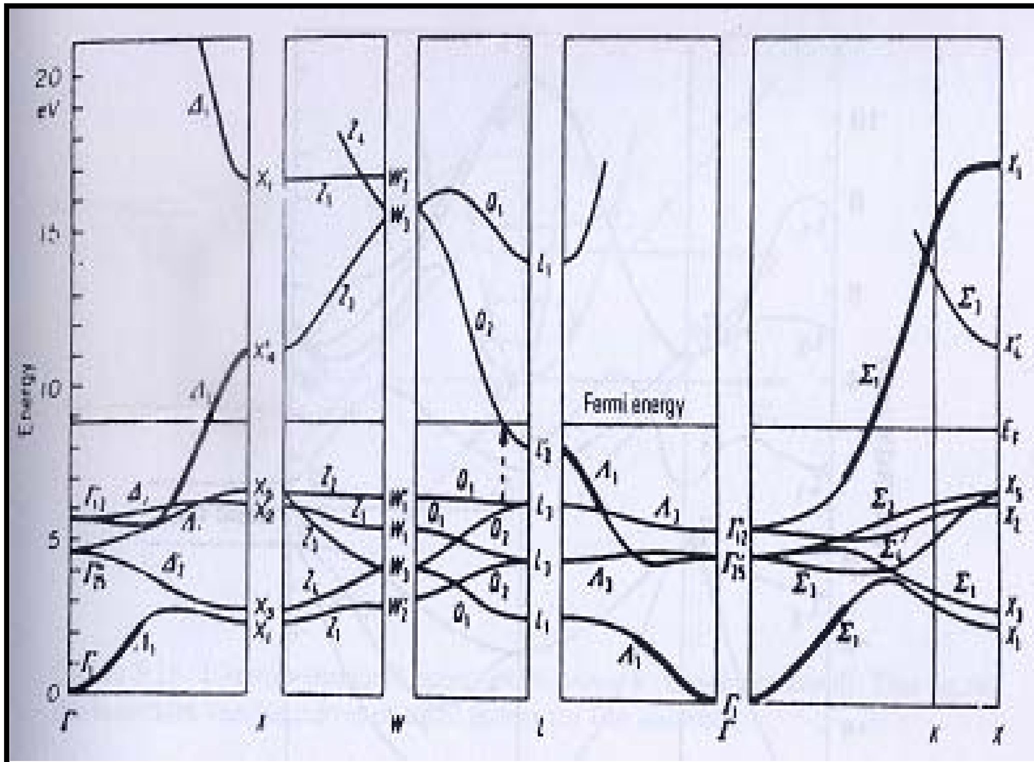

Fig 5. 22. Band structure of copper (fcc). Adapted from B.Segal, Phys. Rev. 125, 109 (1962). The calculation was made using the l-dependent potential.

3. Quantum-mechanical point of view of magnetic moment of an orbiting electron

- **The orbital motion of an electron induces a magnetic moment, μ_m.**

Recall μ_m from a current passing through a loop-shaped wire.

$$\boxed{\mu_m = I \times A = \frac{e}{t}A = \frac{e}{s/v}A = \frac{ev\pi r^2}{2\pi r} = \frac{evr}{2} \quad \textbf{(}A\textbf{= area of loop)}} \qquad (16.8)$$

Electrons which have mass, *m* can make de Brogli wave.

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

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

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

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

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

Ferromagnetism and Antiferromagnetism

❑ Characterization of ferromagnet (unfilled d-bands): *d* - band diagram of Fe,Co,Ni (Fig 16.5)

- 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.

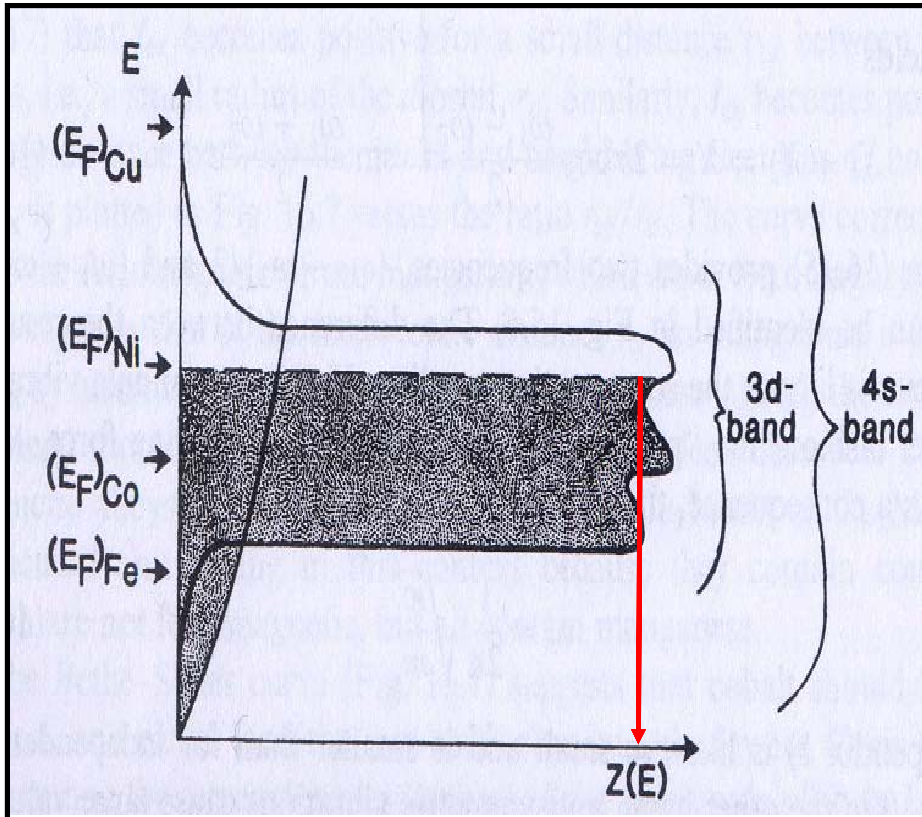

Fig 16.5. Schematic representation of the density of states for 4s-and 3d-bands the Fermi energies for iron, cobalt, nickel, and copper. The population of the bonds by the ten nickel (3d+4s)-electrons is indicated by the shaded area.

❑ Difference between para- and ferromagnet

- paramagnet: external magnetic field is needed for spin alignment, no magnetic domain

- ferromagnet: spontaneous spin alignment, magnetic domain formation

Ferromagnetism and Antiferromagnetism

❑ Exchange energy

“Set free” when equal atomic system are closely coupled, and in this way exchange their energy

❑ Explanation of exchange energy

- Two ferromagnetic atoms: two identical pendula interconnected by a spring.
- The spring represents the interactions of electrical and magnetic fields

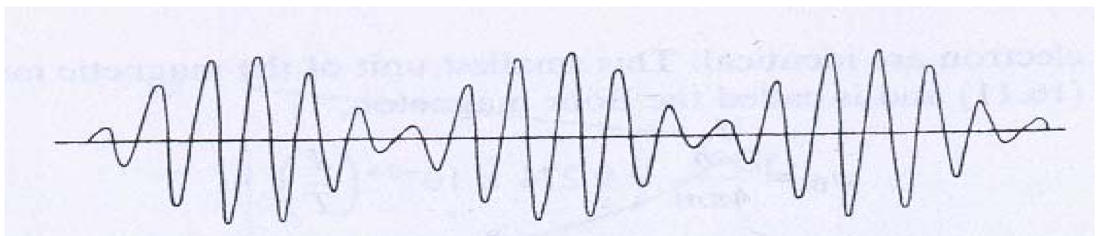

Fig16.6. Amplitude modulation resulting from the coupling of two pendula. The vibrational pattern shows beats, Similarly as known for two oscillators that have almost identical pitch.

- One pendulum deflect → its amplitude decrease, with energy transferring to 2nd pendulum, which in turn transfer its energy back to the 1st one.
- The amplitudes of two pendula decrease and increase periodically with time. (Fig16.6)

Ferromagnetism and Antiferromagnetism

The mathematical expression for two pendula pattern

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

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

which yields

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

Equation (16.15) provides two frequencies, $\frac{(w_1 - w_2)}{2}$, $\frac{(w_1 + w_2)}{2}$

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

Ferromagnetism and Antiferromagnetism

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

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

This equation shows that two coupled and systemically vibrating systems have a lower *E* two individual systems.

Ferromagnetism and Antiferromagnetism

- By solving the appropriate Schrodinger equation for two atoms only, ferromagnetism can be quantum mechanically explained.

$$I_{ex} = \int \psi_a(1)\psi_b(2)\psi_a(2)\psi_b(1)\left[\frac{1}{r_{ab}} - \frac{1}{r_{ab}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}}\right]d\tau \quad (16.17)$$

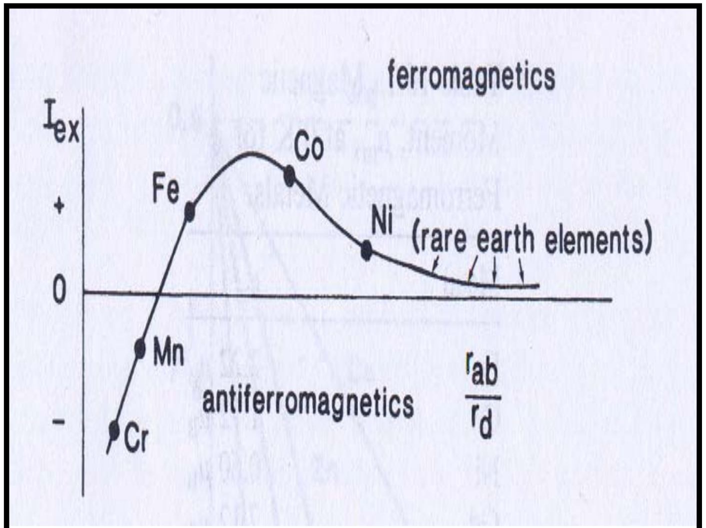

Fig 16.7. Exchange integral, I_{ex}, versus the ratio of inter atomic distance, r_{ab}, and the radius of an unfilled d-shell. The position of the rare earth elements (which have unfilled f-shells) are also shown for completeness.

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

- 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)

Ferromagnetism and Antiferromagnetism

- Bohr magneton of Ni

- Band overlapping is found between 3*d* and 4*s* band, so that combined ten (3*d*+4*s*)-electrons occupy the lower *s*-band and fill, almost completely, the *3d*-band.

→ Nickel 3*d*-band : filled by 9.4 electrons (experimentally) .

- Hund's rule : the electrons in a solid occupy the available electron states in a manner which maximizes the imbalance of spin moments.

- For Ni : 5 electrons are spin up and an average of 4.4 electrons are spin down. As a result, we can obtain a spin imbalance of 0.6 μ_B per atom.

Table 16.1. Magnetic Moment, μ_m, at 0 K for Ferromagnetic Metals.

Metal	μ_m
Fe	2.22 μ_B
Co	1.72 μ_B
Ni	0.60 μ_B
Gd	7.12 μ_B

Ferromagnetism and Antiferromagnetism

- Magnetic behavior of Nickel-based alloys (Fig 16.8)

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

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

- 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.

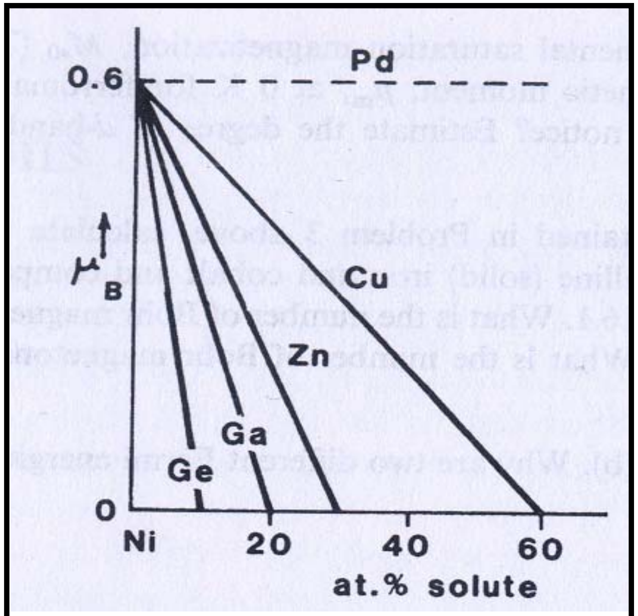

Fig16.8. Magnetic moment per nickel atom as a function of solute concentration

- 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.

Part IV Magnetic Properties of Materials

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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 electromotors and similar devices, reach the millions of tons

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

Electrical steels
(Soft Magnetic Materials)

1.Core Losses

- 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, $\rho(\mu\Omega \cdot \text{cm})$	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.

Electrical steels
(Soft Magnetic Materials)

- **Eddy current loss (Fig. 17.1)**
  - 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)

$$V_e \propto -\frac{d\phi}{dt} = -A\frac{dB}{dt} \qquad (17.1)$$

  - 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

  - 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.

Electrical steels
(Soft Magnetic Materials)

- **To minimize eddy current**
  - **Decreasing σ**
    - **Ferrite core**
    - **Insulating coated Fe core**

    -The decrease in σ is a large decrease in μ

  - **Decreasing lamination thickness . (Fig. 17.1(b))**
    - **The cross-section (*A*) is reduced, Decrease V_e**

      →additionally reduces losses (skin effect)

  - **These losses, however, less than 1% of the total energy transferred.**

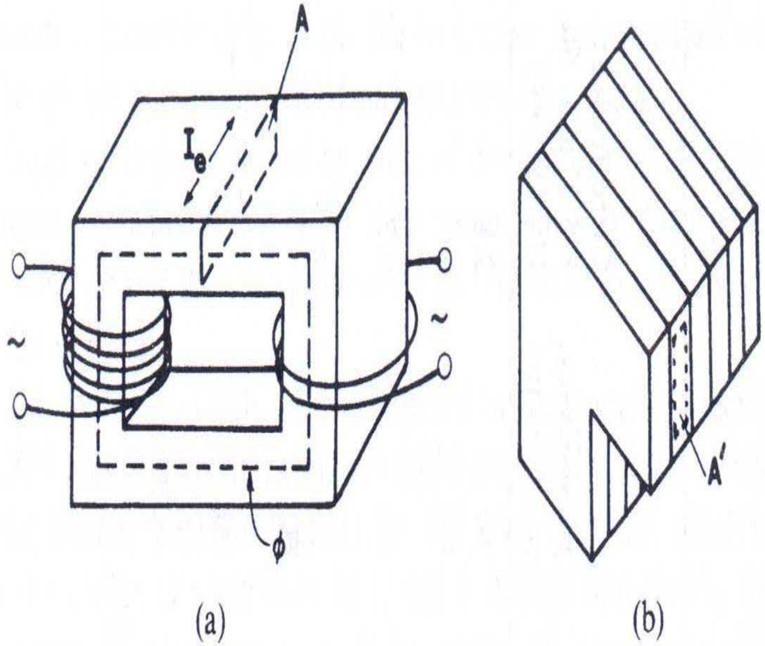

Figure 17.1. (a) Solid transformer core with eddy current, I_e, in a cross-sectional area A. Note the magnetic flux lines ϕ. (b) Cross section of a laminated transformer core. The area A' is smaller than area A in (a).

Electrical steels
(Soft Magnetic Materials)

- **Hysteresis loss**
  - Hysteresis losses are encountered when the magnetic core is subjected to a complete hysteresis cycle (Fig. 15.6)
  - The work thus dissipated into heat is proportional to the area enclosed by a B/H loop.
  - Proper materials selection and rolling of the materials with subsequent heat treatment greatly reduces the area of a hysteresis loop.

Electrical steels
(Soft Magnetic Materials)

2. Grain Orientation

- The permeability of electrical steel can be increased and hysteresis losses can be decreased by making use of favorable grain orientations in the material.

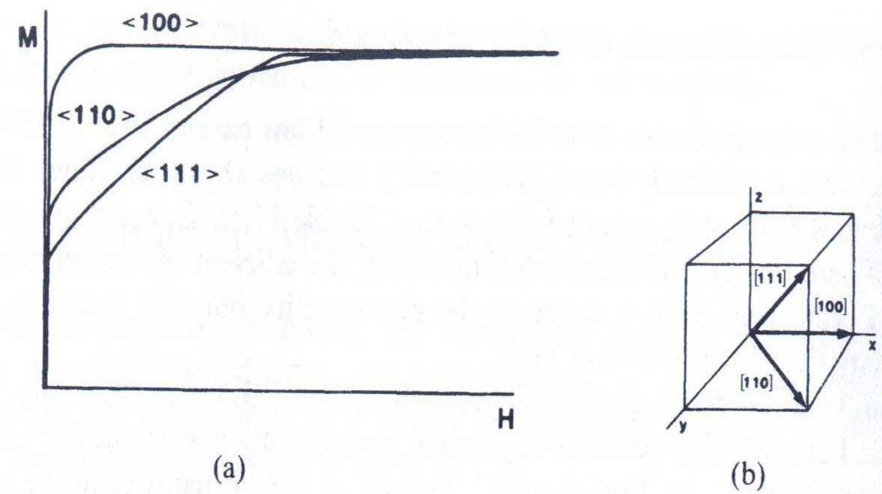

Figure 17.2. (a) Schematic magnetization curves for rod-shaped *iron single crystals* having different orientations (virgin curves). The magnetic field was applied in three different crystallographic directions. (Compare with Fig. 15.6, which refers to polycrystalline material). (b) Reminder of the indices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

- Magnetic anisotropy
  - Magnetic properties depend on the crystallographic direction in which an external field is applied.
  - Magnetization curves of iron (Fig.17.2(a))
    - Easy direction : Saturated direction is achieved with the smallest possible field strength. (Nickel→ easy direction<111>, hard direction <100>)
    - The spontaneous orientation of the spin magnetic moments in the demagnetized state.
    - They are aligned in the easy directions.

Electrical steels
(Soft Magnetic Materials)

- Grain-oriented electrical steel Process-Iron (Fig. 15.9)

①In pure iron the spins are aligned along the <100> directions.
②External field is applied parallel to an easy direction.
③The domains already having favorable alignment grow.
④The crystal contains one single domain.
➔**The energy consumed during this process is used to move the domain walls through the crystal.**
⑤Metal sheets possess a texture. → a preferred orientation of the grain.
⑥In α-iron and α-iron alloys the <100> direction is parallel to the rolling direction.
⑦ Utilizing electrical steel.
⑧During the rolling, the grains are elongated and their orientation is altered.
⑨The sheets are recrystallized, whereby some crystals grow in size at the expense of others.

Summary

- The magnetic properties of grain-oriented steels are best in the direction parallel to the direction of rolling.

Electrical steels
(Soft Magnetic Materials)

3. Composition of Core Materials

- **Low carbon steel (0.05%C)**
  - Low μ, high core losses (Table 17.1)
  - Low cost
  - Purification of iron → $\mu \uparrow$, σ (eddy current) $\uparrow$, cost $\uparrow$

Electrical steels
(Soft Magnetic Materials)

3. Composition of Core Materials

- **Iron-silicon alloys (1.4-3.5%Si)**
  - Higher μ, lower σ (than low carbon steel)
  - γ- loop (phase diagram)
  - The core losses decrease with increasing silicon content
  - For silicon concentrations above 4 or 5 wt%, material becomes too brittle to allow rolling.
  - Other contents in Iron-silicon alloy
    - Al, Mn (less than 1%) →influence on the grain structure → reduce hysteresis losses.
  - Grain-oriented silicon "steel"
    - Highly efficient-high flux multiplying core applications.
- **Multi-component Ni-based alloys**
  - Highest permeability
  - **Permalloy, Supermalloy, Mumetal** (Table 17.1)
  - Shield electronic equipment

Electrical steels
(Soft Magnetic Materials)

4. Amorphous Ferromagnets

- **Amorphous metals**
  - Consisting of Fe, Ni, or Co with B, Si, or phosphorus metals.
  - A higher μ and a lower H_c than grain-oriented silicon-iron (Table 17.1)
  - A large electrical resistivity.
  - Small eddy current losses.
  - Low saturation induction.
  - Core losses increase rapidly at higher flux densities (above 1.4T).

- **The application of metallic glasses**
  - Small flux densities (low currents)
    - Transformers.
    - Magnetic sensors.
    - Magnetostrictive transducers.

Permanent Magnets
(Hard Magnetic Materials)

- **Hard magnetic materials**
  - A large remanence B_r (or M_r).
  - A relatively large coercivity H_c.
  - A large area within the hysteresis loop.
- **Demagnetization curve**
  - A part of a hysteresis loop.
  - B times H is zero at the intercepts of the demagnetization curve.
- **Maximum energy product $(BH)_{max}$**
  - the area within the hysteresis loop.
  - the energy product peaks somewhere between these extreme values.

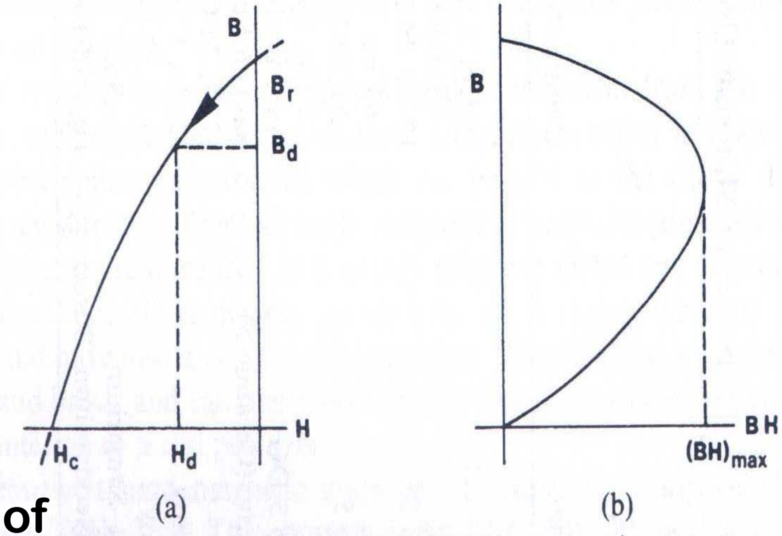

Figure 17.3. (a) Demagnetization curve for a ferromagnetic material. (Second quadrant in a B–H diagram.) (b) Energy product, BH, as a function of induction, B.

Depending on the shape and size of the hysteresis curve (Fig. 17.3)

Permanent Magnets
(Hard Magnetic Materials)

❑ Hard magnetic materials

the values of B_r, H_c, and $(BH)_{max}$ for some materials which are used as permanent magnets are listed in Table 17.2

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

Permanent Magnets
(Hard Magnetic Materials)

- **Hard magnetic materials**
  - The remanence B_r : the maximal residual induction.
- **Demagnetizing field**
  - All permanent magnets need to have exposed poles.
  - The exposed poles create a demagnetizing field, H_d→ reduces the B_r

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

  - A reduced value for the residual induction→ B_d (Fig. 17.3)
- **Fringing and leakage** (fig. 17.4)

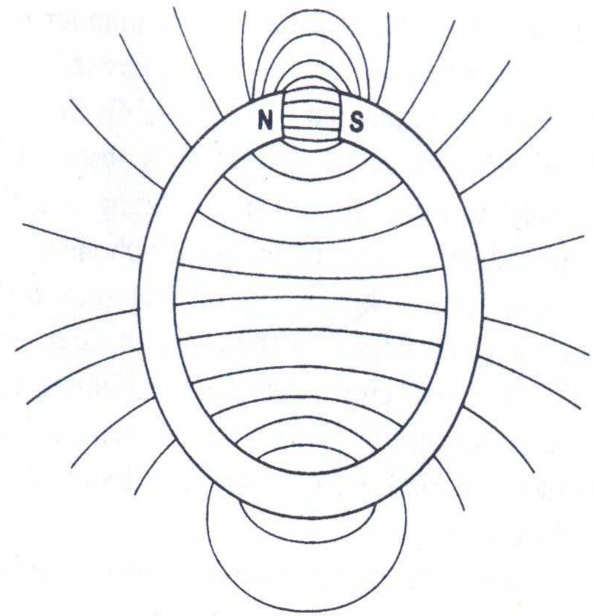

Figure 17.4. Fringing and leakage of a permanent magnet.

Permanent Magnets
(Hard Magnetic Materials)

- **Alnico alloys (Table 17.2)**
  - Based on Co-addition to Fe_2NiAl
    (minor constituents such as Cu and Ti).
  - Improvement
    - Alnico 2 : homogenization at 1250℃, fast cooling, and tempering at 600℃
    - Alnico 5 : cooling the alloys in a magnetic field.
    - Alnico 5-DG : A preferred orientation

    -long columnar grains with a preferred<100>axis (heat flow)

    -a magnetic field parallel to the <100> yields

    -shape anisotropy: parallel to the <100> directions
  - Neodymium-boron-iron
    - A superior coercivity, a larger $(BH)_{max}$
    - Disadvantage : low curie temperature of about 300 ℃

Permanent Magnets
(Hard Magnetic Materials)

- **Ceramic ferrite magnets**
  - BaO $\cdot 6Fe_2O_3$ or SrO $\cdot$ $6Fe_2O_3$(MO $\cdot$ $6Fe_2O_3$)
  - Brittle and relatively inexpensive.
  - Crystallized plates of hexagonal *c*-axis (easy axis) perpendicular to the plates
  - The flat plates arrange parallel during pressing and sintering
    →Some preferred orientation
  - Application : in the gaskets of refrigerator doors

- **High carbon steel magnets**
  - With or without Co, W, or Cr are only of historic interest.
  - The permanent magnetization of quenched steel stems from the martensite-induced internal stress, which impedes the domain walls from moving through the crystal.

Permanent Magnets
(Hard Magnetic Materials)

- **The goal of research on permanent magnetic materials**
  - To improve corrosion resistance, price, remanence, corecivity, magnetic ordering temperature, and processing procedures.
  - Carbon and nitrogen are increasingly used as the metalloid in iron/rare earth magnets such as in Fe-Nd-C or in $Fe_{17}Sm_2N_x$.
  - Nitrogen treatment of sintered $Fe_{14}Nd_2B$ raises the T_c by more than 100K.
  - Corrosion of the Fe-Nd-B sintered magnets is a serious problem.
  - The corrosion resistance can be improved by utilizing inter-metallic compounds such as Fe-Nd-Al or Fe-Nd-Ga, or by applying a moisture-impervious coating.

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 X 0.5 ㎛.

- The particles are too small to sustain a domain wall
  → a single magnetic domain which is magnetized to saturation along the major axis (shape anisotropy).

- The elongated particles are aligned by field during manufacturing.
  - Ferritmagnetic γ-Fe_2O_3 : H_c= 20-28 kA/m(250-350Oe), T_c =600℃
  - Ferromagnetic CrO_2 : H_c =40-80kA/m(500-1000Oe), T_c =128 ℃

- High H_c and high B_r prevent self-demagnetization and accidental erasure.
  → provide strong signals, and permit thinner coatings.
  - A high H_c – tape duplication by "contact printing"

- Video tape (Co-doped γ -Fe_2O_3) : higher T_c and a H_c of 48kA/m(600 Oe).
- Most recently, iron particles have been utilized (H_c =120kA/m).

Magnetic Recording and Magnetic Memories

- **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㎛ wide (Fig. 17.5)
  - The tape is passed along this electromagnet, whose fringing field redirects the spin moments of the particles in a certain pattern proportional to the current.
  - This leaves permanent record of the signal.
  - the moving tape induces an alternating emf in the coil
  - The emf - amplified, filterd, and fed to a loudspeaker.

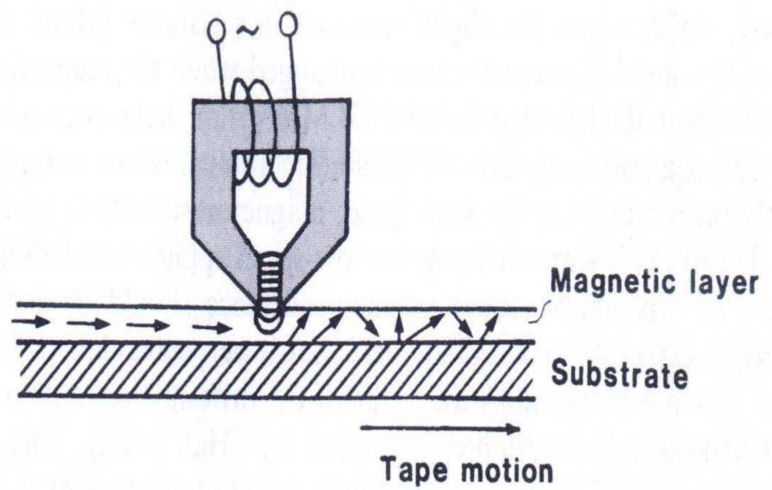

Figure 17.5. Schematic arrangement of a recording (playback) head and a magnetic tape. (Recording mode.) The gap width is exaggerated. The plastic substrate is about 25 μm thick.

Magnetic Recording and Magnetic Memories

- **Recording head**
  - Senust : gap surfaces are coated with a micrometer-thick metal layer composed of Al, Fe, and Si.
  - Metal-in-gap (M-I-G) technology

    →the superior high-frequency behavior and good wear properties of ferrites with the higher coercivity of ferromagnetic metals.
  - Thus, high fields are necessary to record efficiently on high density media.
  - For ultrahigh recording densities (extremely small bit sizes) the signal strength produced in the reading heads diminishes.
  - The lastest head technology→ a thin magneto-resistive element.

    →senses the slight variation in resistance (about 2%) that occurs as the angle of magnetization is changed when the magnetized data bits pass beneath the head.→1.8Mbits/mm^2
  - Inductive head : low-speed applications (credit cards)

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

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

  - 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,

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

    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.

Magnetic Recording and Magnetic Memories

- GMR (MnFe, MnNi, NiO)
  - Giant magneto-resistive materials
  - A resistance response of about 20%
- CMR (lanthanum manganate , etc.)
  - Colossal magneto-resistive materials
  - 50% resistance changes, allowing a further increase in areal densities.
- Ferrite-core memories
  - The dominant devices for random-access storage in computers.
  - A nearly square-shaped hysteresis loop and a low coercivity, is threaded with a wire (Fig. 17.6(a))
  - A sufficiently high current pulse→ the core becomes magnetically saturated.
  - An opposite-directed current pulse→ magnetizes the ferrite core counterclockwise.

Magnetic Recording and Magnetic Memories

- **Ferrite-core memories**
  - Two magnetization directions constitute the two possible values (0 and 1) in the binary system.
  - Memory system (Fig.17.6(c))
    →switch the X_3/Y_2 core from 0 to 1.
    →a current $\propto$ $H_s/2$
    →current is sent through each of the X1 and the Y2 wire (Fig.17.6(b)).
    →the X_3/Y_2 core with the necessary field for switching.
  - Requirement
    high weight / bit ratio

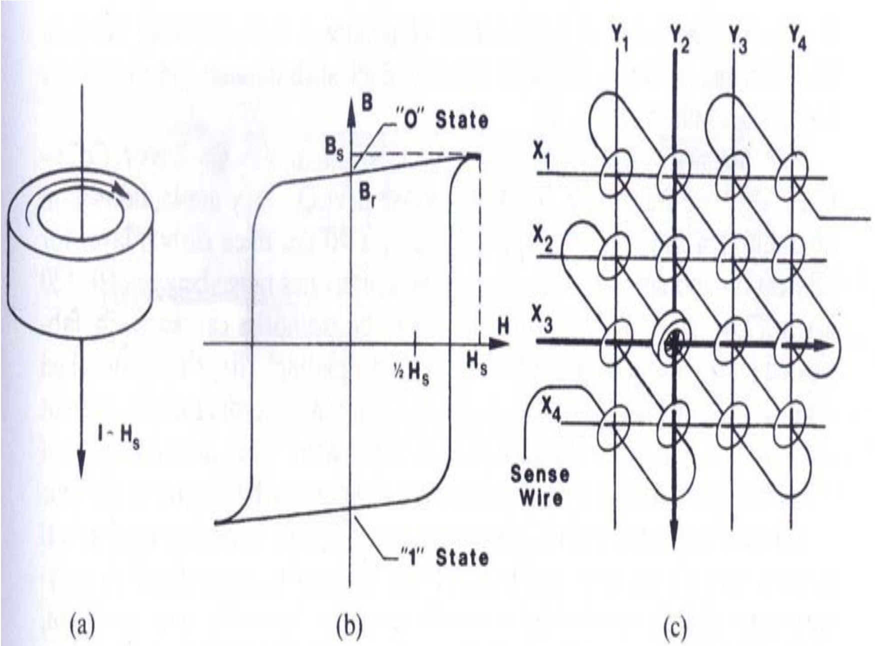

Figure 17.6. (a) Single ferrite core which is magnetized by a current-induced magnetic field; (b) square-shaped hysteresis loop of a soft ferrite memory core; and (c) one plane of a "coincident-current core memory device."

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 3 ㎛ and a bit length of 150nm.

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.

  - The newly oriented magnetic domain has been rotated (Fig. 17.7(b))
  - Spin up is a "one" and spin down is a "zero".

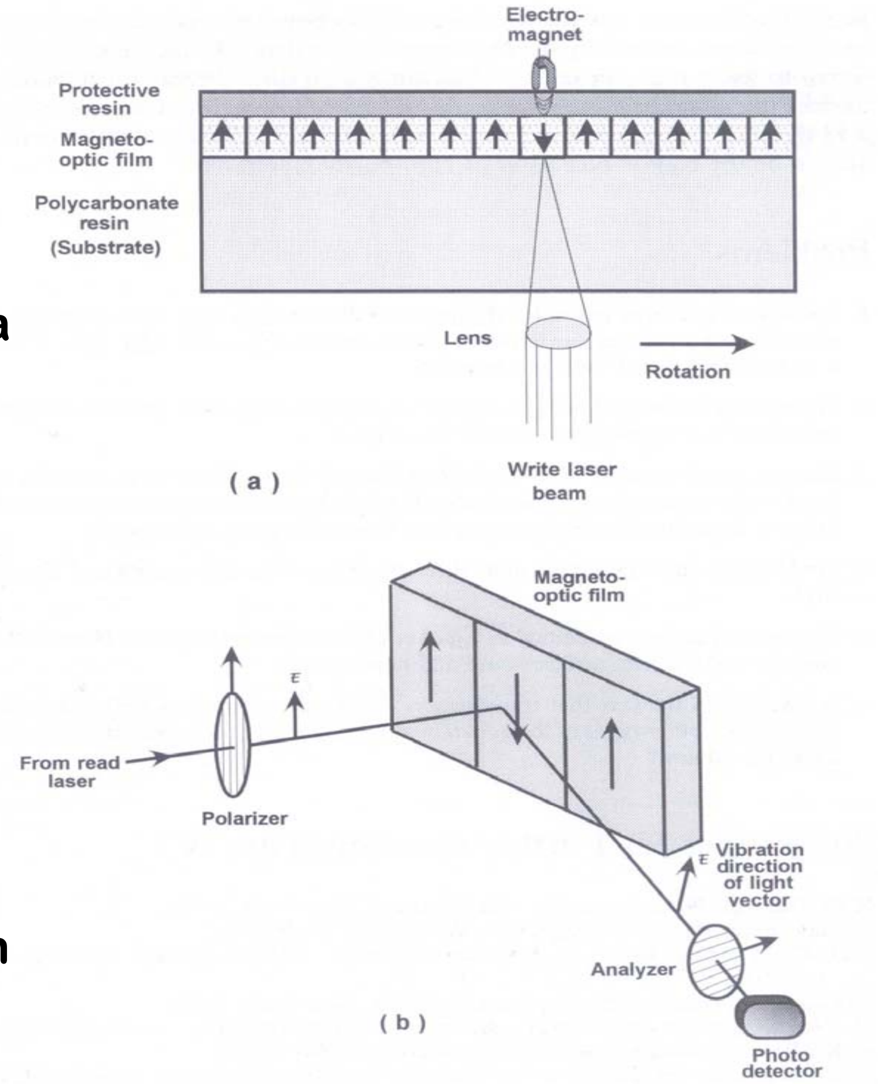

Figure 17.7. (a) Schematic representation of a magneto-optical disk in the writing mode (simplified). (b) Read-out mode of a magneto-optical device. (Polarizer and analyzer are identical devices.)

Magnetic Recording and Magnetic Memories

- **Magneto-optical memories**
  - Magneto-optical disks have a one thousand times larger storage density than common floppy disks and a ten times faster access time.

- Magnetic disks (for random access) or tapes (mainly for music recordings, etc.) are the choices for long-term, large-scale information storage, particularly since no electric energy is needed to retain the information.

- Tapes and floppy disks make direct contact with the recording (and playback) head.

- Hard drive system utilize a “flying head” that hovers a few micrometers or less above the recording medium on an air cushion, caused by the high speed of the disk.