LECTURE #7: MAGNETIC PROPERTIES OF MATERIALS

Basic question: Why are some solids magnetic while others are not?

The answers are linked to:

- Origin of magnetism
- Types of magnetic materials considered
- Effects of magnetization and demagnetization

Magnetic Solids

- Possess magnetic dipoles which are the sources of magnetism

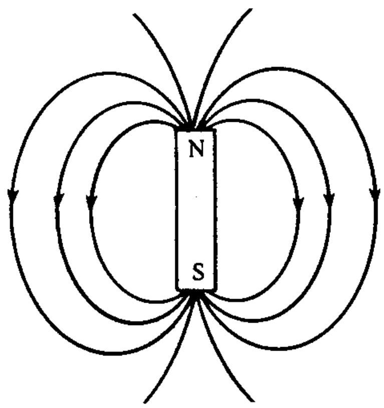

FIGURE 13.1-2 A "magnetic material" can generate a magnetic field without an electrical current. This simple bar magnet is an example.

- Found primarily in transition metals and metal oxides
- Characterized by a parameter known as permeability - it is defined as:

$$\mu = B/H \qquad (33)$$

where B is the magnetic flux density, and H is the magnetic field intensity.

Permeability can also be expressed as:

$$\mu = \mu_0 \mu_r \qquad (34)$$

where μ_0 (= 1.25 x 10^{-6} H/m) is the free-space permeability, and μ_r is the relative permeability.

Types of magnetization:

a) Diamagnetism

- Due to response of the orbiting electrons in the atoms - tendency to reject external magnetic field lines
- Reduces the permeability very slightly

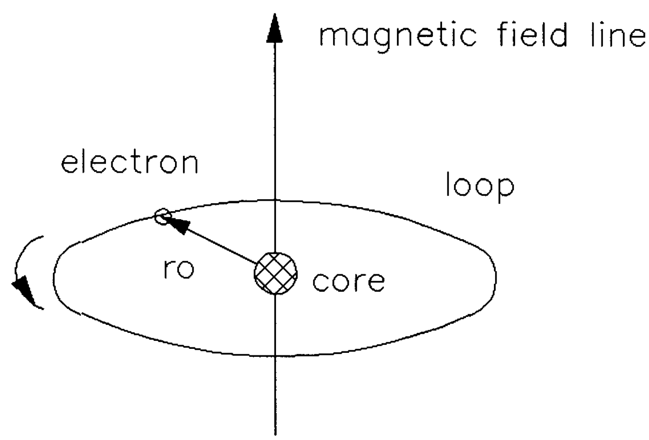

Fig.V−4: A current loop forming a magnetic dipole

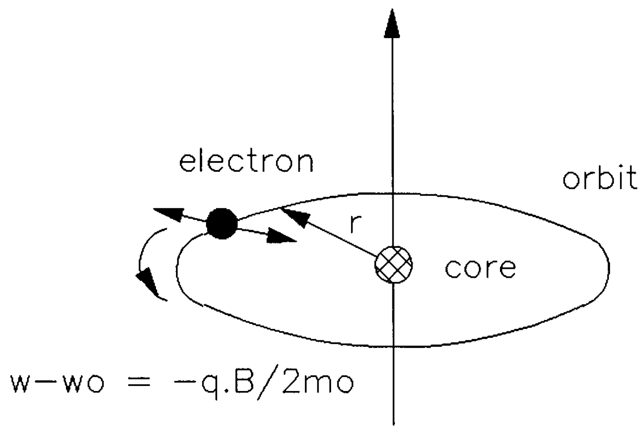

Fig.V−5: Forces acting on an electron

b) Paramagnetism

- Related to the alignment of the magnetic dipoles present in the solid - can be related to gyration of the electrons or their spins

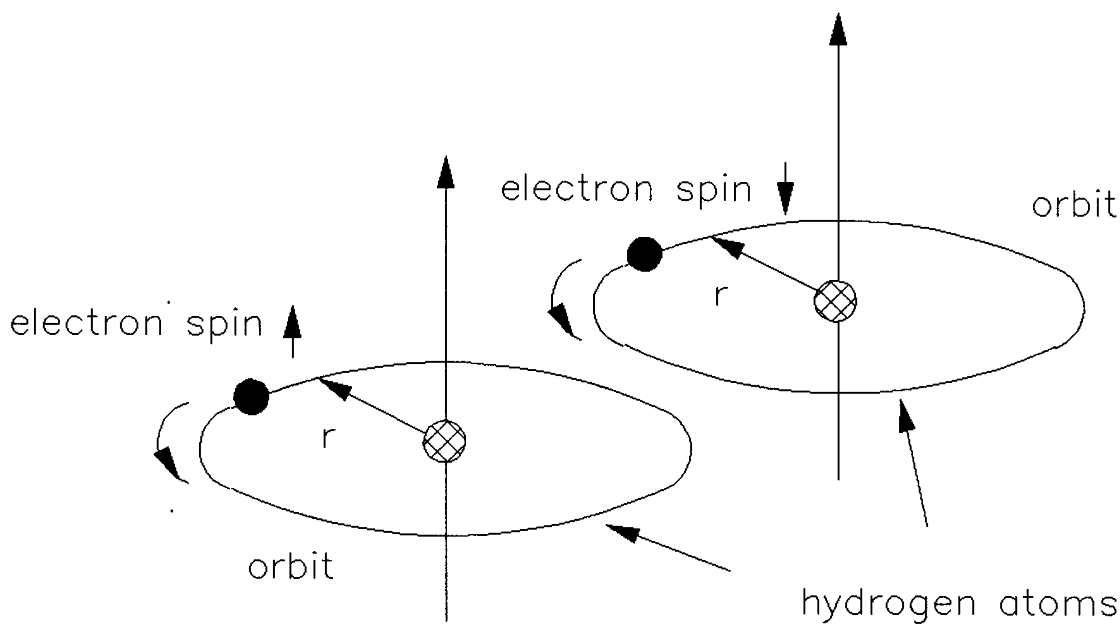

Fig.V−6: A hydrogen molecule with atoms of different spins

- Not significant except for spin paramagnetism

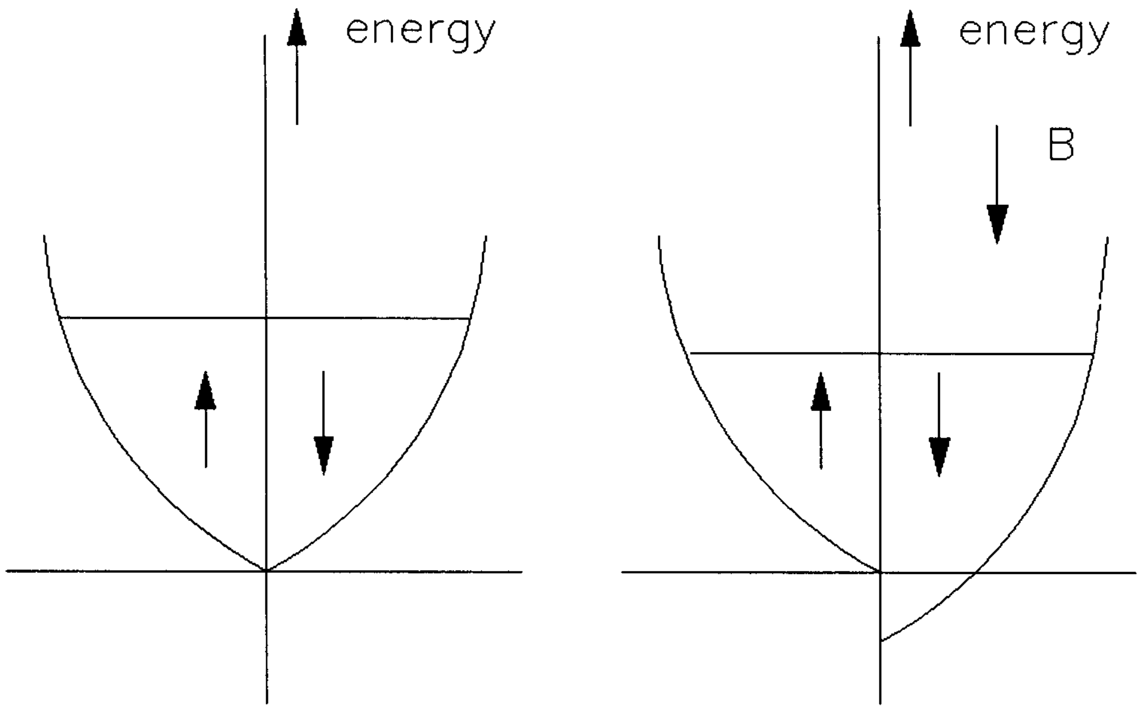

Fig.V-7: Energy shift in Pauli magnetism

c) Ferromagnetism

- Related to the alignment of <u>large domains</u> with significant <u>magnetic dipole moment</u>

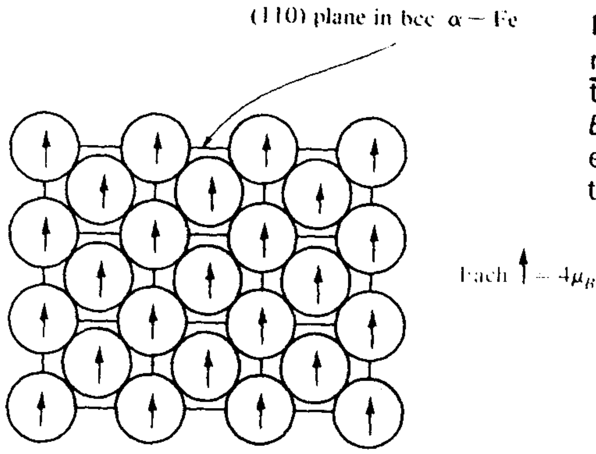

FIGURE 13.2-3 The alignment of magnetic moments for adjacent atoms leads to the large net magnetic moment (and B_s on a B–H plot) for the bulk solid. The example here is pure bcc iron at room temperature.

- Found frequently in transition metals with atoms possessing unbalanced electron spins

Atomic number	Element	Electronic structure of 3d					Moment (μ_B)
21	Sc	↑					1
22	Ti	↑	↑				2
23	V	↑	↑	↑			3
24	Cr	↑	↑	↑	↑	↑	5
25	Mn	↑	↑	↑	↑	↑	5
26	Fe	↑↓	↑	↑	↑	↑	4
27	Co	↑↓	↑↓	↑	↑	↑	3
28	Ni	↑↓	↑↓	↑↓	↑	↑	2
29	Cu	↑↓	↑↓	↑↓	↑↓	↑↓	0

↑ = electronic spin orientation

FIGURE 13.2-2 The electronic structure of the 3d orbital for transition metals. Unpaired electrons contribute to the "magnetic nature" of these metals.

- Give rise to strong magnetic effect

The unit of magnetic moment is the Bohr magneton (= 9.27 x 10^{-24} A.m^2).

Similar to the case of electric dipoles, magnetic permeability is given by:

$$\mu = \mu_0 (1 + N\, n\, \mu_B/H) \qquad (35)$$

where N is the atomic density, and n is the number of unpaired spins in the atoms.

Table 5.2 Relative permeabilities of the different magnetic materials

Material	Solid	μ_r
Paramagnetic	Al	1.00002
	Mn	1.00098
Diamagnetic	Cu	1.00001
	Au	1.00004
Magnetic	Fe	2×10^2
	Fe/Si	1×10^3
	Co/Fe/B/Si	4×10^6
	Ni/Fe alloy	1×10^5

d) Ferrimagnetism

- Occurs in compounds of iron and oxygen with special crystal structures such as the spinel structure

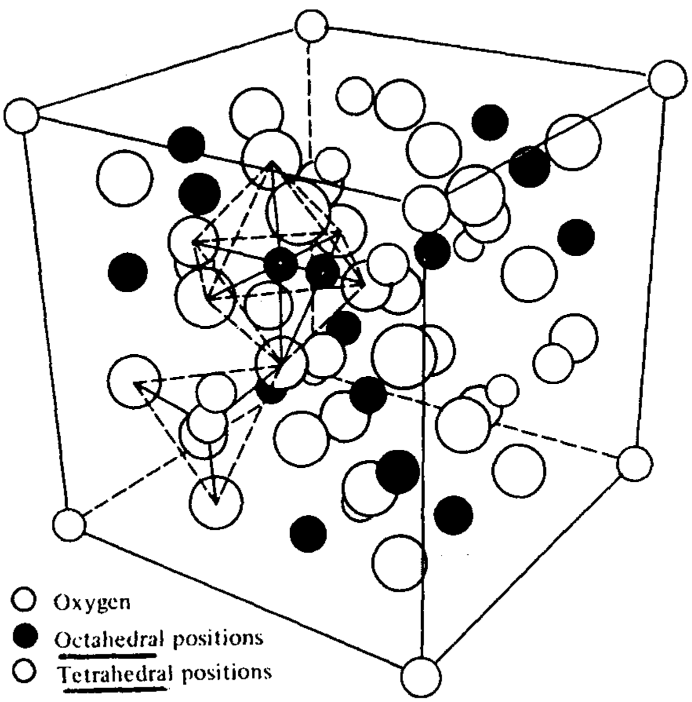

FIGURE 3.4-8 Ion positions in the spinel ($MgAl_2O_4$) unit cell. The circles in color represent Mg^{2+} ions (in tetrahedral or four-coordinated positions), and the black circles represent Al^{3+} ions (in octahedral or six-coordinated positions). [From F. G. Brockman, *Bull. Am. Ceram. Soc.* 47, 186 (1967).]

- Magnetic domains exist but the spins within a domain is not necessarily aligned - some in fact are anti -parallel
- Somewhat weaker magnetic properties
- Many ferrites are insulators and have low (conduction) loss

Origin of ferromagnetic effect

- In the natural state, magnetic solids have no net magnetic moment because the domains are randomly -oriented

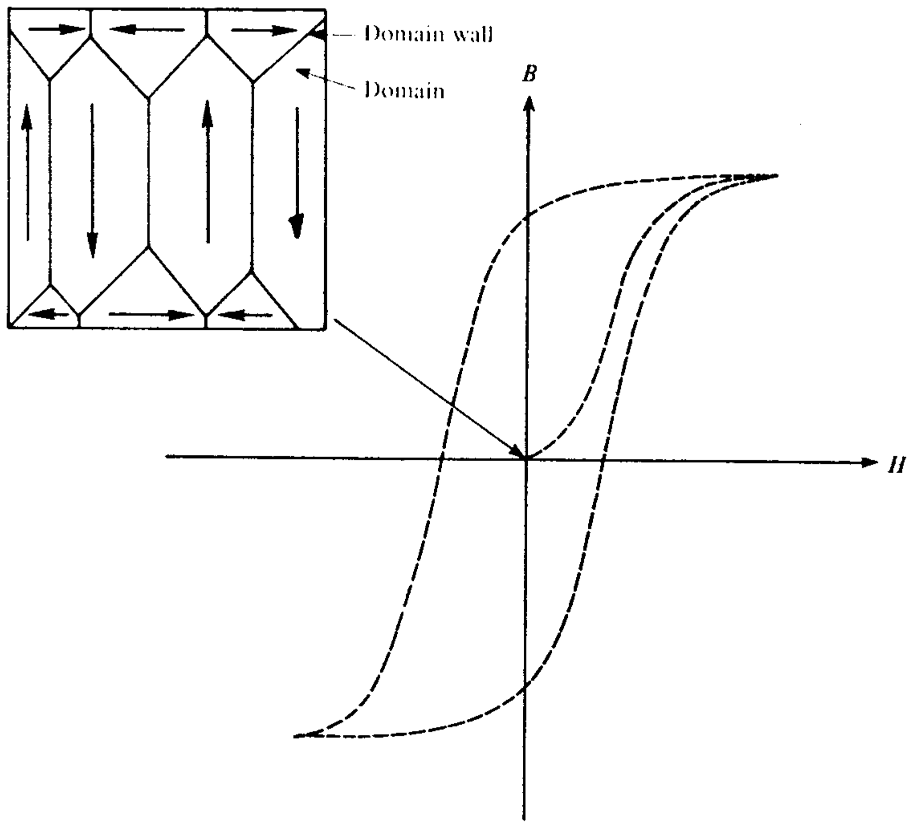

FIGURE 13.2-4 The domain structure of an unmagnetized iron crystal gives a net $B = 0$ even though individual domains have the large magnetic moment indicated by Figure 13.2-3.

- When a magnetic field is applied, the domains align and a strong magnetization results

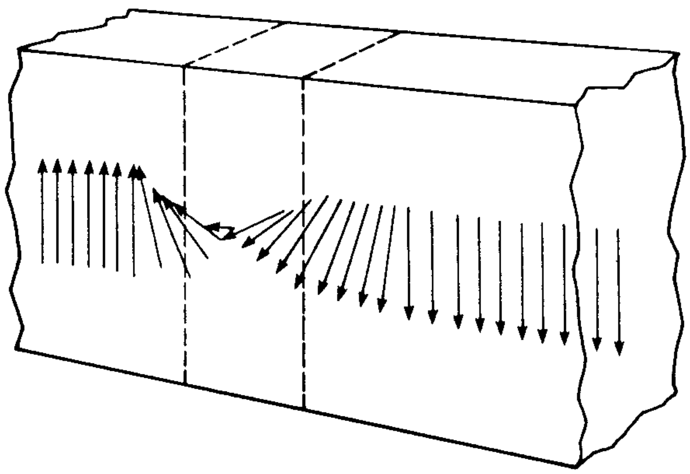

FIGURE 13.2-6 The domain (or Bloch) wall is a narrow region in which atomic moments change orientation by 180°. Domain wall motion (implied in Figures 13.2-4 and 13.2-5) simply involves a shift in this reorientation region. No atomic migration is required.

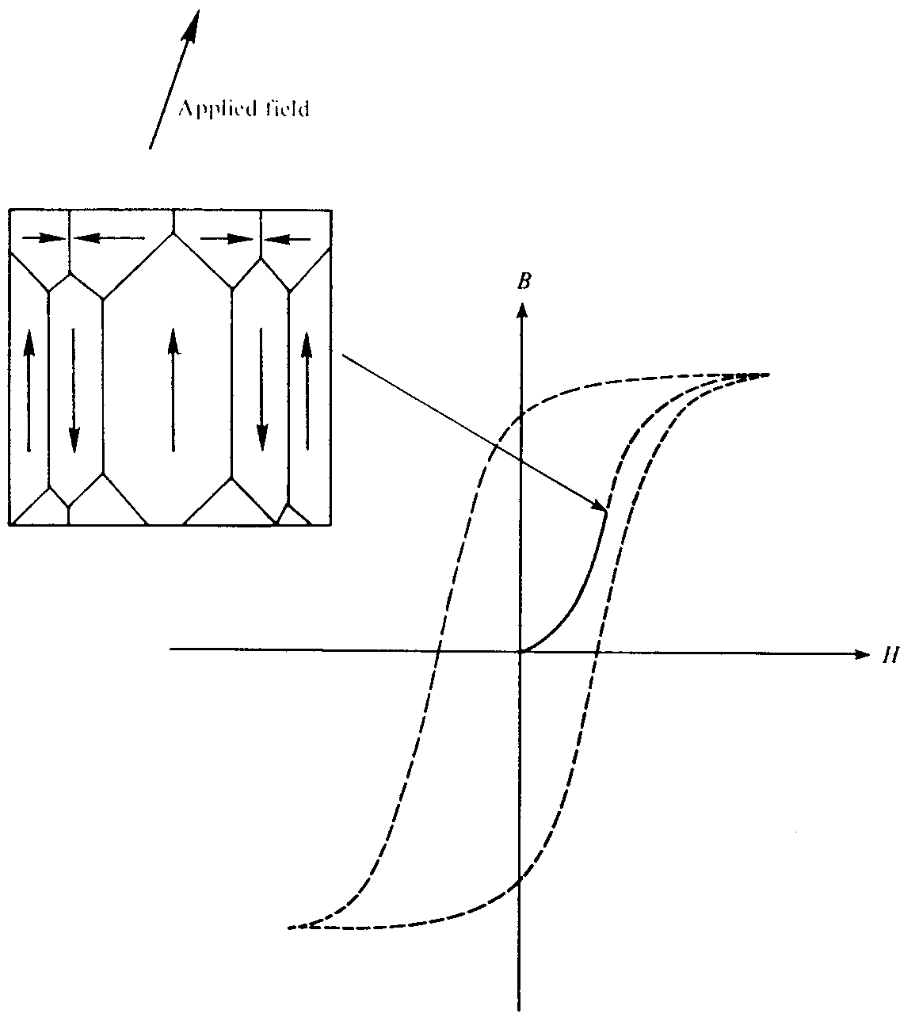

FIGURE 13.2-5 The sharp rise in *B* during initial magnetization is due to "domain growth."

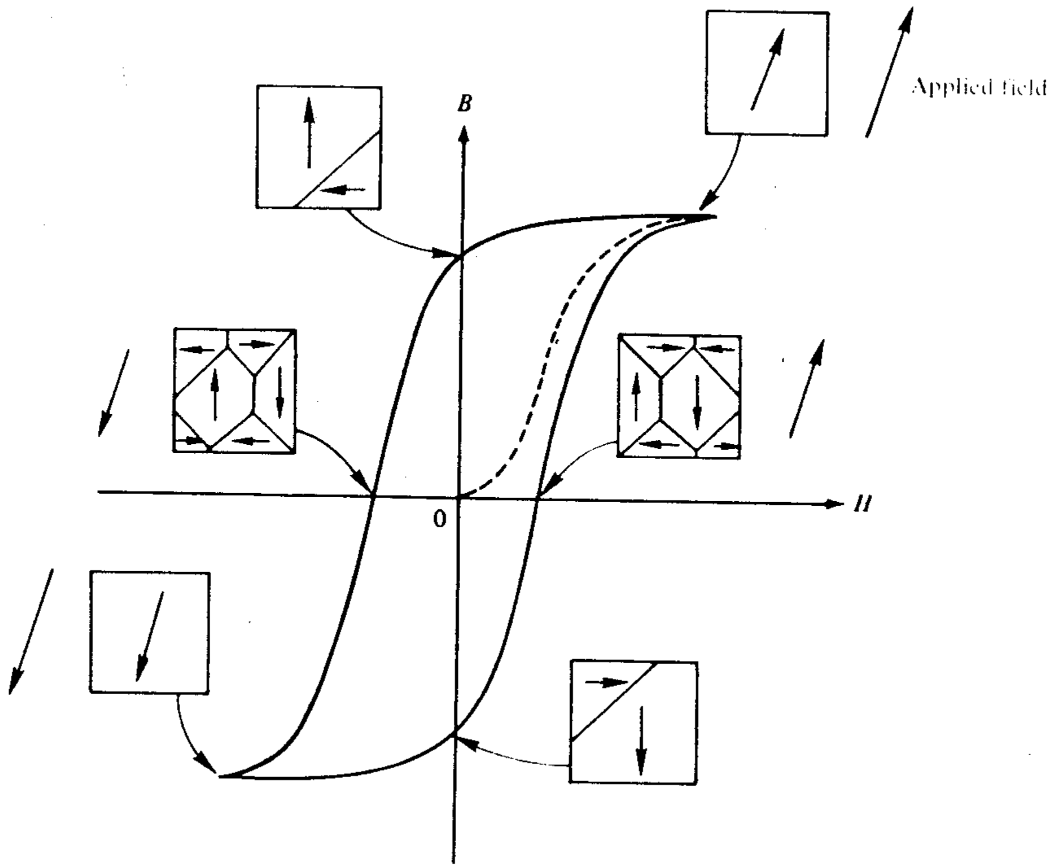

FIGURE 13.2-7 Summary of domain microstructures during the course of a ferromagnetic hysteresis loop.

- Removal of the magnetic field does not result in zero magnetization as some of the domains remain aligned to the field direction - this results in a remanent magnetic flux density B_0
- Remanent magnetization can be removed or even reversed by reversing the applied field, or heating the magnet to a high temperature
- Remanent magnetization results in <u>hysteresis</u> in the B-H plot

Classification

a) Hard Magnets

- Known as permanent magnets
- Primarily found in solids with domain walls that do not move easily
- Produces a large hysteresis loop and have high magnetic field strength - as reflected in the value of $(BH)_{max}$ - an example being the iron-nickel alloy

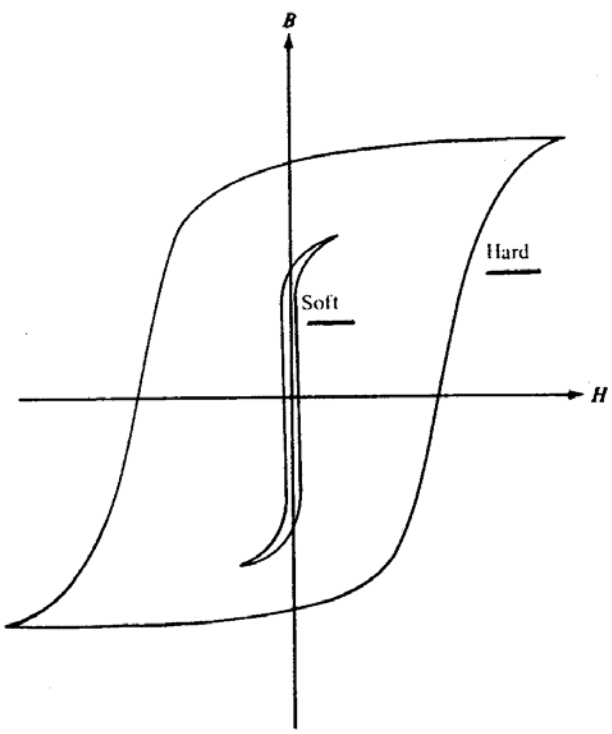

FIGURE 13.4-1 Comparison of typical hysteresis loops for "soft" and "hard" magnets.

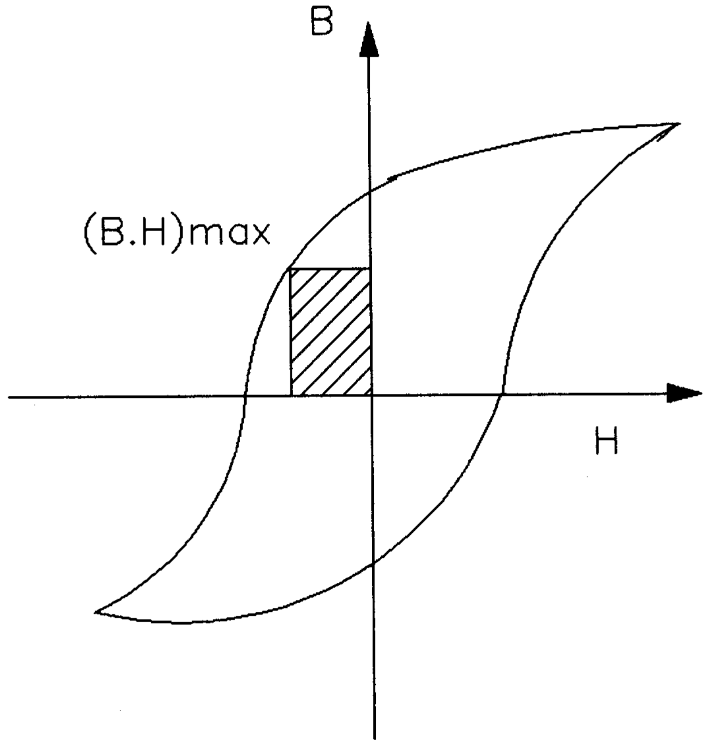

Fig.V–19: Hysteresis plot showing $(B.H)_{max}$

b) Soft Magnets

- Found in solids with domain walls that can move readily
- Area of the hysteresis loops is usually small
- Used in transformers
- Prepared to have high resistance (with the addition of impurities) to reduce ac loss
- Includes ceramic magnets such as ferrites and garnets (these are mixed metal oxides usually with the presence of iron)
- Applications include use in <u>magnetic tapes and disks</u>

TABLE 13.4-1 Typical Magnetic Properties of Various Soft Magnetic Metals

Material	Initial Relative Permeability (μ_r at $B \sim 0$)	Hysteresis Loss (J/m^3 per cycle)	Saturation Induction (Wb/m^2)
Commercial iron ingot	250	500	2.16
Fe–4% Si, random	500	50–150	1.95
Fe–3% Si, oriented	15,000	35–140	2.0
45 Permalloy (45% Ni–55% Fe)	2,700	120	1.6
Mumetal (75% Ni–5% Cu–2% Cr–18% Fe)	30,000	20	0.8
Supermalloy (79% Ni–15% Fe–5% Mo)	100,000	2	0.79
Amorphous ferrous alloys			
(80% Fe–20% B)	—	25	1.56
(82% Fe–10% B–8% Si)	—	15	1.63

Source: R. M. Rose, L. A. Shepard, and J. Wulff, *The Structure and Properties of Materials*, Vol 4: *Electronic Properties*, John Wiley & Sons, Inc., New York, 1966, and J. J. Gilman, "Ferrous Metallic Glasses," *Metal Progress*, July 1979.

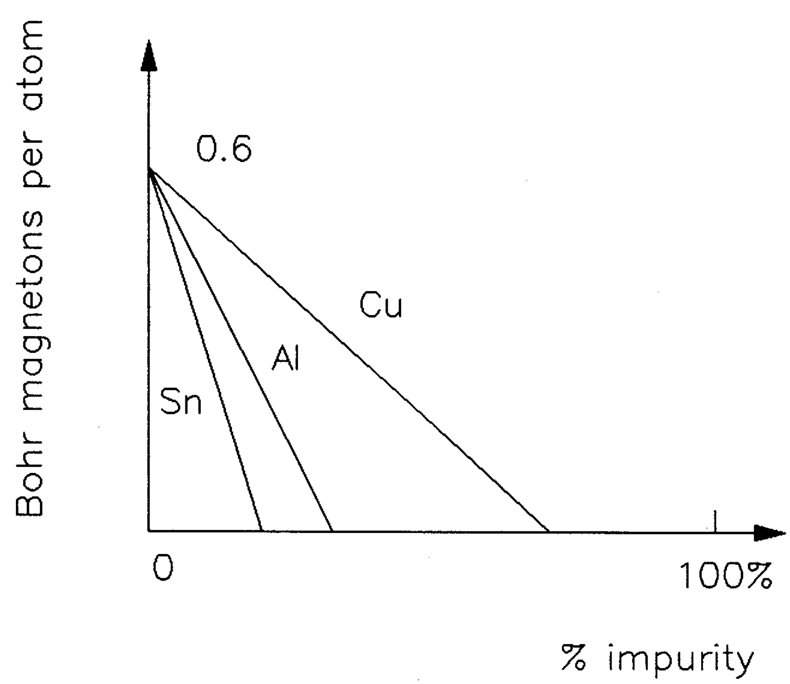

Fig.V–9: Effects of impurities on magnetization

Applications

Computer core memory

Computer core memory provides a means to store digital information. The magnetic cores are arranged in a matrix interlaced through fine metal wires both horizontally and vertically. A change in the magnetic state of the core is facilitated when the currents in the wires passing through the core reinforce each other. Otherwise, no change occurs. The cores can be accessed randomly.

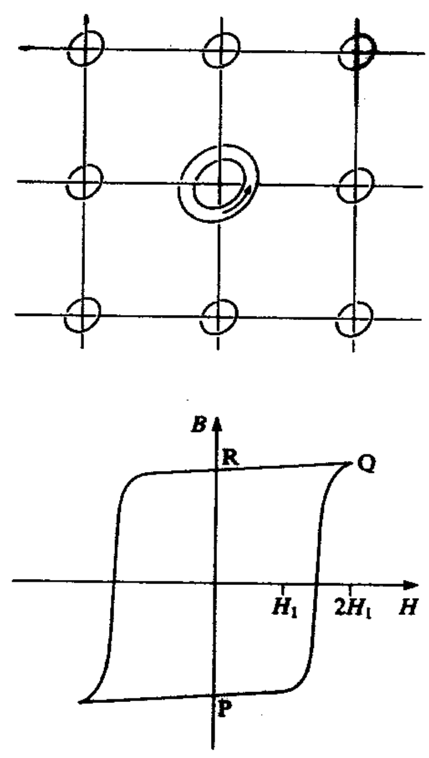

Figure 3.45 (a) Magnetic core.
(b) Corresponding B–H loop

Reading the information stored in a core requires a third (sense) wire threaded through the core. It picks up an induced current when test signals passing through the (access) wires change the state of the core.

Magnetic recording

Magnetic recording involves a magnetic tape/disk and a recording head. The principle relies on a current-carrying coil placed close to the magnetic medium such as a magnetic tape/disk.

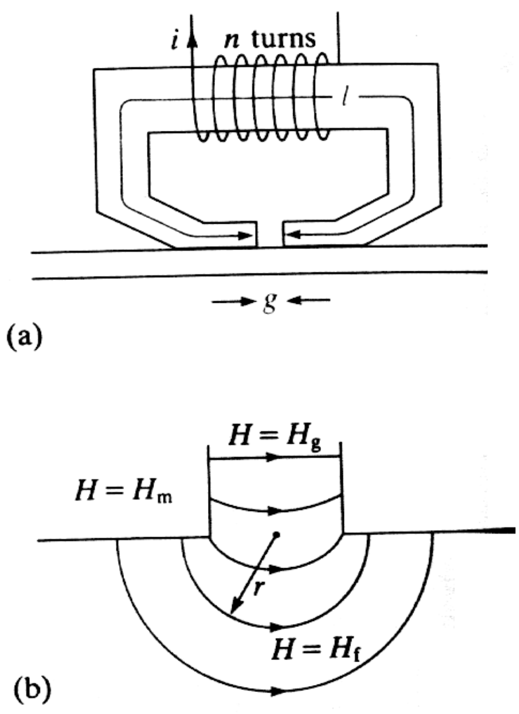

Figure 3.44 (a) Schematic gapped core
(b) Fringing field

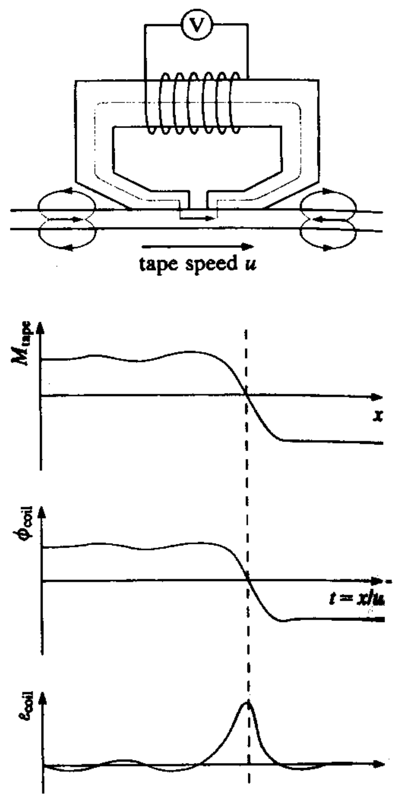

Figure 3.49 Reading process for tapes

The required current to magnetize the medium can sometimes be quite large and a coil of many windings is used. The latter forms a part of the recording head, which also consists of a magnetic armature. The current in the coil controls the strength of magnetization induced on the tape/disk.

Reading the tape/disk is simply the reverse of the recording process. The magnetic patterns in the tape/disk are sensed by the coil and picked up in the form of a voltage.

The induced voltage due to a changing flux, $d(\phi)/dx$ as the tape/disk moves through the recording head is given by:

$$V_{induced} = n \mu \, d(\phi)/dx \qquad (36)$$

where n is the number of windings in the coil, and μ is the speed of the tape/disk . *x* is the direction of motion.

<u>Example 7.1</u>: Compare the resistivity of magnetic solids in the crystalline state, as oxides, and in the amorphous state.

Solution:

Crystalline metals have a resistivity of about 10^{-7} Ω.m. Metallic amorphous Fe-related solids have a value of about 10^{-6} Ω.m, whereas a ferrite has a value of about 100 Ω.m.

<u>Example 7.2</u>: If the B-H plot of a ferromagnetic solid is given by: $B = H_o - H$, determine $(BH)_{max}$.

Solution:

To obtain the peak value, take $\partial(BH)/\partial H = 0$. Since $BH = H_oH - H^2$, $H_o = 2H$, or $H = H_o/2$. Therefore, $(BH)_{max} = H_o/2(H_o - H_o/2) = H_o/4$.

<u>Example 7.3</u>: Silicon is known to increase the resistivity of Fe. What will be the reduction in the eddy current loss if the silicon content of a Fe transformer core is increased from 3% to 10%? β for silicon in Fe is 117.

Solution:

The fractional increase in resistivity of the core is: $((1 + 0.1\beta) - (1 + 0.03\beta))/ (1 + 0.03\beta) = ((1 + 0.1 \times 117\beta) - (1 + 0.03 \times 117))/ (1 + 0.03 \times 117) = 1.81$. If nothing else changes, the eddy current loss will be reduced by 1.81 times.

<u>Example 7.4</u>: Which of the following materials are more suitable for a transformer core: i) Sheets of SiFe; ii) MnZn ferrite; or iii) dry air?

Solution:

Both ii) and iii) have low permeability and are not suitable. Their principal advantage, if any, would be low loss and possibly a high breakdown voltage.

<u>Example 7.5</u>: If a magnetic tape contains granular particles of diameter 0.1 μm, determine the speed of the rotor if a full cycle of the recording requires at least 10 grains and the audio (signal) range is 2 kHz.

Solution:

The shortest recording wavelength will be 0.1 μm x 10 = 1 μm. Speed = wavelength x frequency = 1 x 10^{-6} μm x 2 x 10^{3} /s = 2 x 10^{-3} m/s.