17.4.1 Fermi Energy

Consider that *N* free electrons are contained in a box at absolute temperature. At absolute zero all the energy levels below a certain level will be filled with electrons and the levels above this level will be empty. The energy level which divides the filled and empty levels is called '*Fermi level*' and the corresponding energy of that level is known as '*Fermi-energy*' E_F. In ground state of the system of *N* free electrons, the occupied

$$E_{\mathrm{F}} = \frac{\hbar^2}{2m_0}\left(\frac{3\pi^2 N}{V}\right)^{2/3}$$

17.4.2 Effect of Temperature on Fermi–Dirac Distribution

According to Fermi-Dirac distribution law, the most probable distribution is given by

$$n(E) = \frac{g(E)}{e^{(\alpha+\beta E)}+1} \tag{i}$$

where $\alpha = \frac{-E_F}{kT}$ and $\beta = \frac{1}{kT}$ together with *k* as Boltzmann constant. It is often convenient to introduce the Fermi-distribution function *f*(*E*), which is defined as

$$f(E) = \frac{n(E)}{g(E)} = \frac{1}{e^{(\alpha+\beta E)}+1}$$

With the values of α and β, this function can be written together with E_F as the Fermi energy

$$f(E) = \frac{1}{e^{(E-E_F)/kT}+1}$$

At absolute zero ($T = 0$)

$$\begin{aligned} \frac{E-E_F}{kT} &= -\infty, \qquad \text{if } E < E_F \\ &= +\infty \qquad \text{if } E > E_F \end{aligned}$$

and the Fermi distribution function

$$\begin{aligned} f(E) &= \frac{1}{e^{-\infty}+1} = 1 \qquad \text{for } E < E_F \\ &= \frac{1}{e^{+\infty}+1} = 0 \qquad \text{for } E > E_F \end{aligned}$$

At any temperature T, and for E = E_F,

$$f(E) = \frac{1}{e^{(E-E_F)kT}+1} = \frac{1}{e^0+1} = \frac{1}{1+1}$$

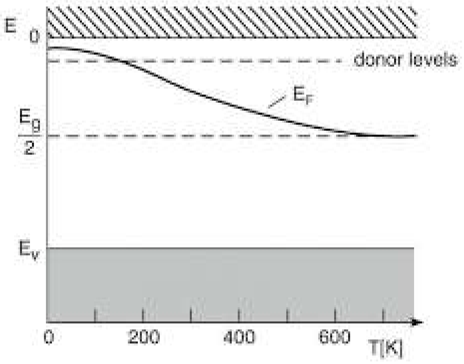
or $$f(E) = \frac{1}{2}$$

The energy level corresponding to $E = E_F$ is called Fermi level. Since at $E = E_F$, $f(E) = 1/2$, the Fermi level is defined as the energy level at which there is a 1/2 probability of finding an electron. It depends on the distribution of energy levels and the number of electrons available.

Effect of Temperature on the fermi level –

N n-TYPE SEMICONDUCTOR.

- At 0K the fermi level E_{Fn} (Energy of fermi level in n-type semiconductor) lies between the conduction band and the donor level.
- As temperature increases more and more electrons shift to the conduction band leaving behind equal number of holes in the valence band. These electron hole pairs are intrinsic carriers.
- With the increase in temperature the intrinsic carriers dominate the donors.
- To maintain the balance of the carrier density on both sides the fermi level gradually shifts downwards.
- Finally at high temperature when the donor density is almost negligible E_{Fn} is very close to E_{Fi} (Energy of fermi level in intrinsic semiconductor)



IN p-TYPE SEMICONDUCTOR.

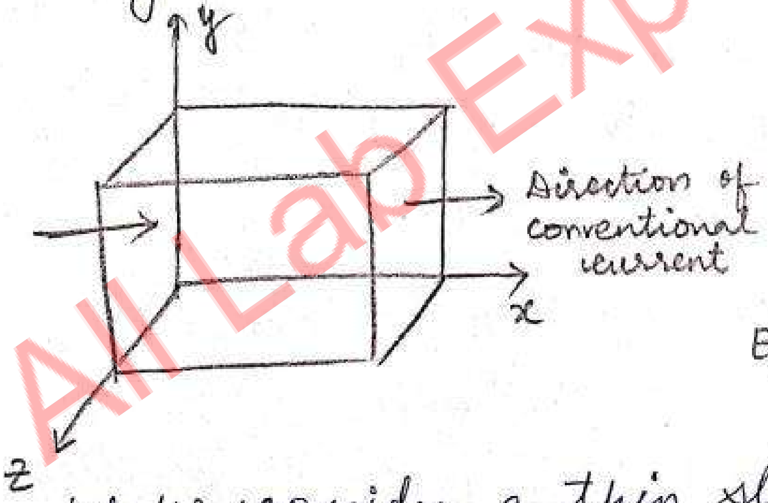
- At 0K the fermi level in a p-type semiconductor lies between the acceptor level and the valence band.
- With the increase in temperature more and more holes are created in the valence band as equal number of electrons move to the conduction band.
- As temperature increases the intrinsic holes dominate the acceptor holes.
- Hence the number of intrinsic carriers in the conduction band and in the valence band become nearly equal at high temperature.
- The fermi level gradually shifts upwards to maintain the balance of carrier density above and below it.
- At high temperature when the acceptor density become insignificant as compared to the intrinsic density

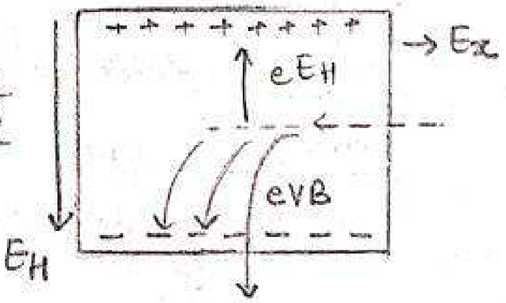
HALL EFFECT

①

It is used to distinguish the two type of carriers and also determines the density of charge carriers.

When a magnetic field is applied perpendicular to a current carrying conductor, a voltage is developed in the specimen in a direction perpendicular to both the current and the magnetic field. This phenomenon is called "Hall effect" and the generated voltage is called "Hall voltage"





Let us consider a thin slab of conductor subjected to electric field E. This produces a current I and causes a force of magnitude eE to act on the charge carriers.

2)

When this conductor is placed in magnetic field, a magnetic force is proportional to the strength of the magnetic field strength (B) and charge (e) and velocity (v) acts on the charge carriers.

This force is at right angle to the direction of B & v, Therefore each charge is deflected towards one side of the conductor. When charge reaches the surface of conductor, an electrical charge is built up there, which in turn gives rise to transverse field E_H called Hall field. It causes a compensating drift, such that force due to hall field exactly balance the lorentz force.

At equilibrium, $eE_H = e v_x B_z$

$$E_H = v_x B_z$$

If J_x = current density in x-direction

then $J_x = n e v_x$

$$v_x = \frac{J_x}{ne}$$

$$E_H = \frac{J_x B_z}{ne} = R_H J_x B_z$$

$$\boxed{E_H = R_H J_x B_z} \quad \text{——} ①$$

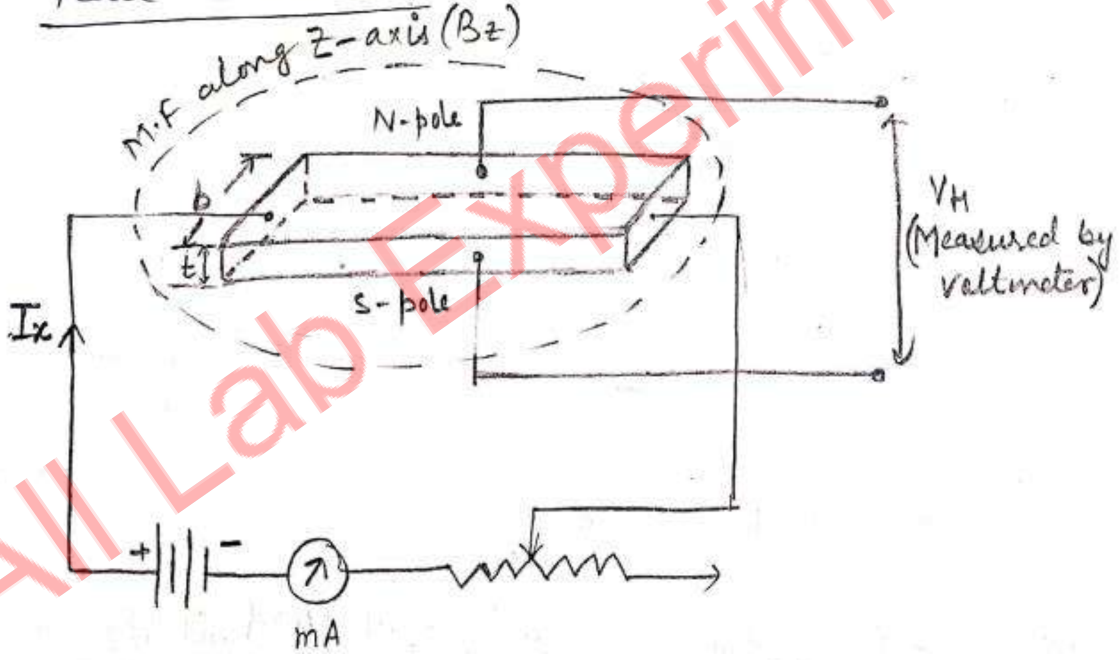
$\therefore$ $R_H = \frac{1}{ne}$ = Hall coefficient

also $R_H = \frac{E_H}{J_x B_z}$ = Hall coefficient

ie Hall coefficient is negative for n-type semiconductor and positive for P-type semiconductor.

$$\left\{ R_H = \frac{-1}{ne} = \frac{-E_H}{J_x B_z} \right. \text{ for } e^{\ominus}$$

Experimental set up and Determination of Hall constant :



APPLICATIONS OF Hall EFFECT :

1) Determination of type of Semiconductor

If $R_H = -ve$ — ntype semiconductor
$R_H = +ve$ — P-type semiconductor

2) Classification of Materials

If R_H = large — semiconductor
= small — Metal
$\Rightarrow \infty$ — Insulators

3) Determination of carrier concentrations

$n = \frac{-1}{eR_H}$ $\downarrow$ Electron conc.

$P = \frac{1}{eR_H}$ $\downarrow$ Hole Concentration

4) Determination of Carrier mobility

$V_H \propto B_z$

∴ Knowing magnetic density, one can measure mobility.

Dielectric Behavior

dielectric

electric dipole

A **dielectric** material is one that is electrically insulating (nonmetallic) and exhibits or may be made to exhibit an **electric dipole** structure; that is, there is a separation of positive and negative electrically charged entities on a molecular or atomic level. This concept of an electric dipole was introduced in Section 2.7. As a result of dipole interactions with electric fields, dielectric materials are used in capacitors.

12.18 CAPACITANCE

capacitance

When a voltage is applied across a capacitor, one plate becomes positively charged and the other negatively charged, with the corresponding electric field directed from the positive to the negative plate. The **capacitance** C is related to the quantity of charge stored on either plate Q by

Capacitance in terms of stored charge and applied voltage

$$C = \frac{Q}{V} \tag{12.24}$$

where V is the voltage applied across the capacitor. The units of capacitance are coulombs per volt, or farads (F).

Now, consider a parallel-plate capacitor with a vacuum in the region between the plates (Figure 12.28*a*). The capacitance may be computed from the relationship

Capacitance for a parallel-plate capacitor in a vacuum

$$C = \epsilon_0 \frac{A}{l} \tag{12.25}$$

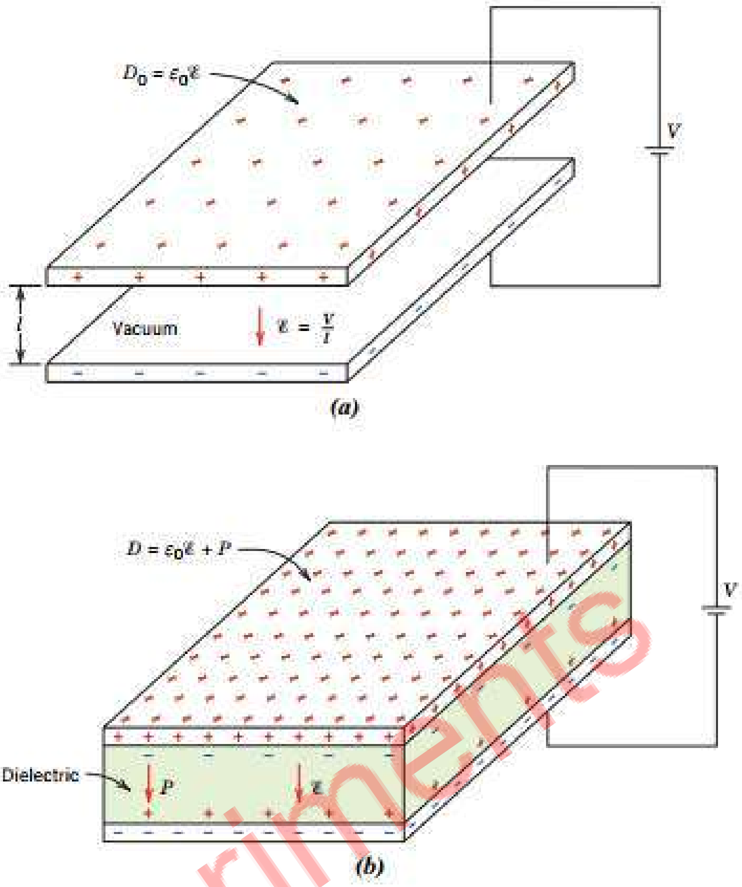


Figure 12.28 A parallel-plate capacitor (*a*) when a vacuum is present and (*b*) when a dielectric material is present.
(From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

permittivity

where A represents the area of the plates and l is the distance between them. The parameter ε_0, called the **permittivity** of a vacuum, is a universal constant having the value of 8.85×10^{-12} F/m.

If a dielectric material is inserted into the region within the plates (Figure 12.28*b*), then

Capacitance for a parallel-plate capacitor with dielectric material

$$C = \varepsilon \frac{A}{l} \tag{12.26}$$

dielectric constant

where ε is the permittivity of this dielectric medium, which is greater in magnitude than ε_0. The relative permittivity ε_r, often called the **dielectric constant**, is equal to the ratio

Definition of dielectric constant

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{12.27}$$

which is greater than unity and represents the increase in charge-storing capacity upon insertion of the dielectric medium between the plates. The dielectric constant is one material property of prime consideration for capacitor design. The ε_r values of a number of dielectric materials are given in Table 12.5.

12.19 FIELD VECTORS AND POLARIZATION

Perhaps the best approach to an explanation of the phenomenon of capacitance is with the aid of field vectors. To begin, for every electric dipole there is a separation between a positive and a negative electric charge, as demonstrated in Figure 12.29. An electric dipole moment p is associated with each dipole as follows:

Electric dipole moment

$$p = qd \tag{12.28}$$

where q is the magnitude of each dipole charge and d is the distance of separation between them. A dipole moment is a vector that is directed from the negative to the positive charge, as indicated in Figure 12.29. In the presence of an electric field $\mathscr{E}$, which is also a vector quantity, a force (or torque) comes to bear on an electric dipole to orient it with the applied field; this phenomenon is illustrated in Figure 12.30. The process of dipole alignment is termed **polarization.**

polarization

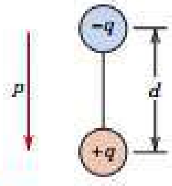


Figure 12.29 Schematic representation of an electric dipole generated by two electric charges (of magnitude q) separated by the distance d; the associated polarization vector p is also shown.

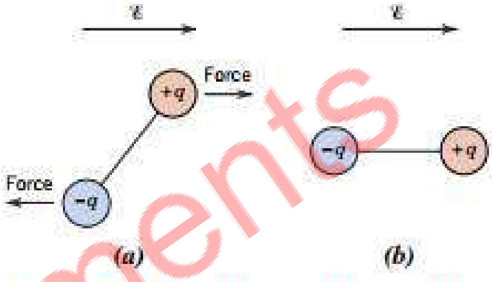


Figure 12.30 (*a*) Imposed forces (and torque) acting on a dipole by an electric field. (*b*) Final dipole alignment with the field.

Again, to return to the capacitor, the surface charge density D, or quantity of charge per unit area of capacitor plate (C/m^2), is proportional to the electric field. When a vacuum is present, then

Dielectric displacement (surface charge density) in a vacuum

$$D_0 = \varepsilon_0 \mathscr{E} \tag{12.29}$$

where the constant of proportionality is ε_0. Furthermore, an analogous expression exists for the dielectric case—that is,

Dielectric displacement when a dielectric medium is present

$$D = \varepsilon \mathscr{E} \tag{12.30}$$

Sometimes, D is also called the **dielectric displacement.**

dielectric displacement

The increase in capacitance, or dielectric constant, can be explained using a simplified model of polarization within a dielectric material. Consider the capacitor in Figure 12.31*a*—the vacuum situation—where a charge of $+Q_0$ is stored on the top plate and $-Q_0$ on the bottom plate. When a dielectric is introduced and an electric field is applied, the entire solid within the plates becomes polarized (Figure 12.31*c*). As a result of this polarization, there is a net accumulation of negative charge of magnitude $-Q'$ at the dielectric surface near the positively charged plate and, in a similar manner, a surplus of $+Q'$ charge at the surface adjacent to the negative plate. For the region of dielectric removed from these surfaces, polarization effects are not important. Thus, if each plate and its adjacent dielectric surface are considered to be a single entity, the induced charge from the dielectric ($+Q'$ or $-Q'$) may be thought of as nullifying some of the charge that originally existed on the plate for a vacuum ($-Q_0$ or $+Q_0$). The voltage imposed across the plates is maintained at the vacuum value by increasing the charge at the negative (or bottom) plate by an amount $-Q'$ and that at the top plate by $+Q'$. Electrons are caused to flow from the positive to the negative plate by the external voltage source such that the proper voltage is reestablished. Thus the charge on each plate is now $Q_0 + Q'$, having been increased by an amount Q'.

In the presence of a dielectric, the charge density between the plates, which is equal to the surface charge density on the plates of a capacitor, may also be represented by

Dielectric displacement—dependence on electric field intensity and polarization (of dielectric medium)

$$D = \varepsilon_0 \mathscr{E} + P \tag{12.31}$$

where P is the *polarization*, or the increase in charge density above that for a vacuum because of the presence of the dielectric; or, from Figure 12.31*c*, $P = Q'/A$, where A is the area of each plate. The units of P are the same as for D (C/m^2).

The polarization P may also be thought of as the total dipole moment per unit volume of the dielectric material, or as a polarization electric field within the dielectric that results from the mutual alignment of the many atomic or molecular dipoles with the externally applied field $\mathscr{E}$. For many dielectric materials, P is proportional to $\mathscr{E}$ through the relationship

Polarization of a dielectric medium—dependence on dielectric constant and electric field intensity

$$P = \varepsilon_0 (\varepsilon_r - 1)\mathscr{E} \tag{12.32}$$

in which case ε_r is independent of the magnitude of the electric field.

Table 12.6 lists dielectric parameters along with their units.

EXAMPLE PROBLEM 12.5

Computations of Capacitor Properties

Consider a parallel-plate capacitor having an area of 6.45×10^{-4} m^2 (1 in.^{2}) and a plate separation of 2×10^{-3} m (0.08 in.) across which a potential of 10 V is applied. If a material having a dielectric constant of 6.0 is positioned within the region between the plates, compute the following:

(a) The capacitance
(b) The magnitude of the charge stored on each plate
(c) The dielectric displacement D
(d) The polarization

Solution

(a) Capacitance is calculated using Equation 12.26; however, the permittivity ε of the dielectric medium must first be determined from Equation 12.27, as follows:

$$\begin{aligned}\varepsilon = \varepsilon_r\varepsilon_0 &= (6.0)(8.85 \times 10^{-12}\text{ F/m})\\ &= 5.31 \times 10^{-11}\text{ F/m}\end{aligned}$$

Thus, the capacitance is given by

$$\begin{aligned}C = \varepsilon\frac{A}{l} &= (5.31 \times 10^{-11}\text{ F/m})\left(\frac{6.45 \times 10^{-4}\text{ m}^2}{20 \times 10^{-3}\text{ m}}\right)\\ &= 1.71 \times 10^{-11}\text{ F}\end{aligned}$$

(b) Because the capacitance has been determined, the charge stored may be computed using Equation 12.24, according to

$$Q = CV = (1.71 \times 10^{-11}\text{ F})(10\text{ V}) = 1.71 \times 10^{-10}\text{ C}$$

(c) The dielectric displacement is calculated from Equation 12.30, which yields

$$\begin{aligned}D = \varepsilon\mathscr{E} = \varepsilon\frac{V}{l} &= \frac{(5.31 \times 10^{-11}\text{ F/m})(10\text{ V})}{2 \times 10^{-3}\text{ m}}\\ &= 2.66 \times 10^{-7}\text{ C/m}^2\end{aligned}$$

(d) Using Equation 12.31, the polarization may be determined as follows:

$$\begin{aligned}P = D - \varepsilon_0\mathscr{E} &= D - \varepsilon_0\frac{V}{l}\\ &= 2.66 \times 10^{-7}\text{ C/m}^2 - \frac{(8.85 \times 10^{-12}\text{ F/m})(10\text{ V})}{2 \times 10^{-3}\text{ m}}\\ &= 2.22 \times 10^{-7}\text{ C/m}^2\end{aligned}$$

TYPES OF POLARIZATION

Again, polarization is the alignment of permanent or induced atomic or molecular dipole moments with an externally applied electric field. There are three types or sources of polarization: electronic, ionic, and orientation. Dielectric materials typically exhibit at least one of these polarization types, depending on the material and the manner of external field application.

Electronic Polarization

electronic polarization

Electronic polarization may be induced to one degree or another in all atoms. It results from a displacement of the center of the negatively charged electron cloud relative to the positive nucleus of an atom by the electric field (Figure 12.32*a*). This polarization type is found in all dielectric materials and exists only while an electric field is present.

Ionic Polarization

ionic polarization

Ionic polarization occurs only in materials that are ionic. An applied field acts to displace cations in one direction and anions in the opposite direction, which gives rise to a net dipole moment. This phenomenon is illustrated in Figure 12.32*b*. The magnitude of the dipole moment for each ion pair p_i is equal to the product of the relative displacement d_i and the charge on each ion, or

Electric dipole moment for an ion pair

$$p_i = qd_i \tag{12.33}$$

Orientation Polarization

orientation polarization

The third type, **orientation polarization**, is found only in substances that possess permanent dipole moments. Polarization results from a rotation of the permanent moments into the direction of the applied field, as represented in Figure 12.32*c*. This alignment tendency is counteracted by the thermal vibrations of the atoms, such that polarization decreases with increasing temperature.

The total polarization P of a substance is equal to the sum of the electronic, ionic, and orientation polarizations (P_e, P_i, and P_o, respectively), or

Total polarization of a substance equals the sum of electronic, ionic, and orientation polarizations

$$P = P_e + P_i + P_o \tag{12.34}$$

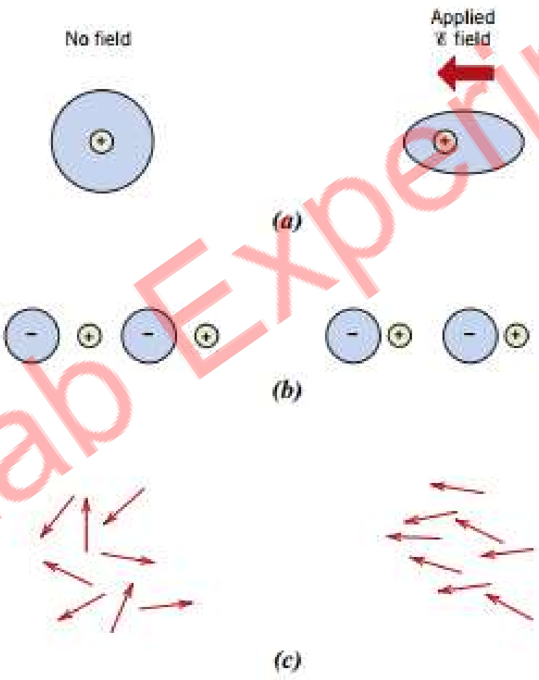


Figure 12.32 (*a*) Electronic polarization that results from the distortion of an atomic electron cloud by an electric field. (*b*) Ionic polarization that results from the relative displacements of electrically charged ions in response to an electric field. (*c*) Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization.

12.21 FREQUENCY DEPENDENCE OF THE DIELECTRIC CONSTANT

relaxation frequency

In many practical situations the current is alternating (ac)—that is, an applied voltage or electric field changes direction with time, as indicated in Figure 12.23*a*. Consider a dielectric material that is subject to polarization by an ac electric field. With each direction reversal, the dipoles attempt to reorient with the field, as illustrated in Figure 12.33, in a process requiring some finite time. For each polarization type, some minimum reorientation time exists that depends on the ease with which the particular dipoles are capable of realignment. The **relaxation frequency** is taken as the reciprocal of this minimum reorientation time.

A dipole cannot keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency and, therefore, it will not make a contribution to the dielectric constant. The dependence of ε_r on the field frequency is represented schematically in Figure 12.34 for a dielectric medium that exhibits all three types of polarization; note that the frequency axis is scaled logarithmically. As indicated in Figure 12.34, when a polarization mechanism ceases to function, there is an abrupt drop in the dielectric constant; otherwise, ε_r is virtually frequency independent. Table 12.5 gave values of the dielectric constant at 60 Hz and 1 MHz; these provide an indication of this frequency dependence at the low end of the frequency spectrum.

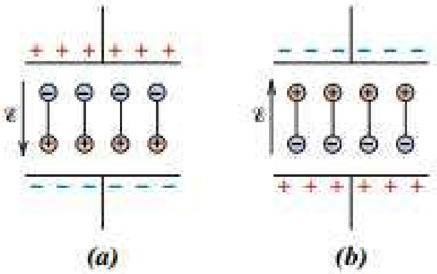


Figure 12.33 Dipole orientations for (*a*) one polarity of an alternating electric field and (*b*) the reversed polarity.
(From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications*, 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

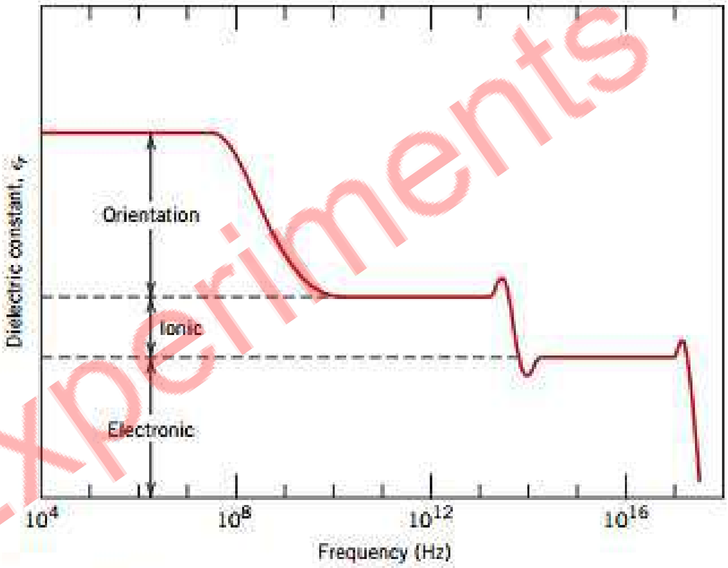


Figure 12.34 Variation of dielectric constant with frequency of an alternating electric field. Electronic, ionic, and orientation polarization contributions to the dielectric constant are indicated.

The absorption of electrical energy by a dielectric material that is subjected to an alternating electric field is termed *dielectric loss*. This loss may be important at electric field frequencies in the vicinity of the relaxation frequency for each of the operative dipole types for a specific material. A low dielectric loss is desired at the frequency of utilization.

Effect of temperature on polarization

Electronic and Ionic polarization are independent of temperature but orientational polarization is temperature dependent. If P = αE, here, P is polarization, E is the applied electric field and α is polarizability. In fact P = ($\alpha_e + \alpha_i + \alpha_o$)E, where the terms are electronic, ionic, and orientational polarizability. Orientational polarization is inversely proportional to the temperature.

$$\alpha_O = \frac{\mu^2}{3K_BT}$$

Total Polarization

The total polarizability of a dielectric is given by

$$\alpha = \alpha_e + \alpha_i + \alpha_o \tag{51}$$

or

$$\alpha = \alpha_e + \alpha_i + \frac{\mu^2}{3kT} \tag{52}$$

The total polarization P may be expressed as

$$P = P_e + P_i + P_o$$

$$= N\left[\alpha_e + \alpha_i + \frac{\mu^2}{3kT}\right]E \tag{53}$$

One can express the dielectric constant of a polar gaseous dielectric as

$$\varepsilon_0(\varepsilon_r - 1) = N\left(\alpha_e + \alpha_i + \frac{\mu^2}{3kT}\right) \tag{54}$$

A plot of ε_r or P with $1/T$ is a straight line (Fig. 24.18)

As stated earlier, it is possible for one or more of the contributions to the polarization to be either negligible in magnitude relative to the others or absent. For instance, the orientation polarization does not exist in non-polar dielectrics and ionic polarization in covalently bonded materials. In polar dielectrics, the electronic polarization is negligible as compared to dipolar polarization.

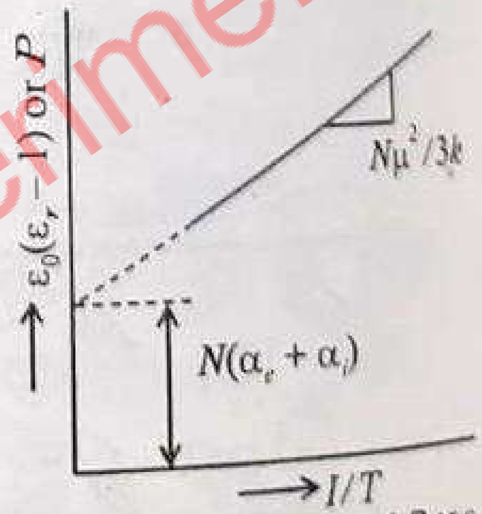


Fig. 24.18: Variation of P or ε_r with $1/T$. The permanent dipole moment can be determined from the slope of the curve

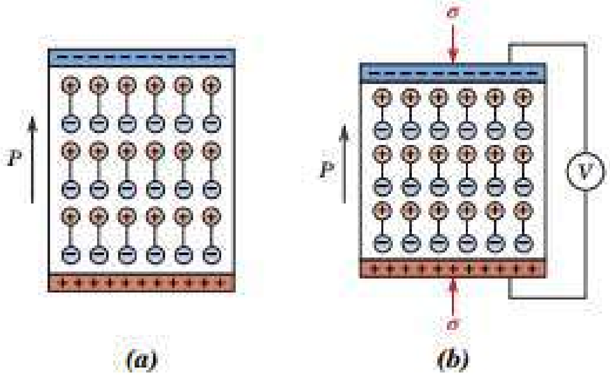
12.23 DIELECTRIC MATERIALS

A number of ceramics and polymers are used as insulators and/or in capacitors. Many of the ceramics, including glass, porcelain, steatite, and mica, have dielectric constants within the range of 6 to 10 (Table 12.5). These materials also exhibit a high degree of dimensional stability and mechanical strength. Typical applications include power line and electrical insulation, switch bases, and light receptacles. The titania (TiO_2) and titanate ceramics, such as barium titanate ($BaTiO_3$), can be made to have extremely high dielectric constants, which render them especially useful for some capacitor applications.

The magnitude of the dielectric constant for most polymers is less than for ceramics because the latter may exhibit greater dipole moments: ε_r values for polymers generally lie between 2 and 5. These materials are commonly used for insulation of wires, cables, motors, generators, and so on and, in addition, for some capacitors.

12.25 PIEZOELECTRICITY

An unusual phenomenon exhibited by a few ceramic materials (as well as some polymers) is *piezoelectricity*—literally, pressure electricity. Electric polarization (i.e., an electric field or voltage) is induced in the piezoelectric crystal as a result of a mechanical strain (dimensional change) produced from the application of an external force (Figure 12.36). Reversing the sign of the force (e.g., from tension to compression) reverses the direction of the field. The inverse piezoelectric effect is also displayed by this group of materials—that is, a mechanical strain results from the imposition of an electrical field.



(a) *(b)*

Figure 12.36 (*a*) Dipoles within a piezoelectric material. (*b*) A voltage is generated when the material is subjected to a compressive stress. (From L. H. Van Vlack, *A Textbook of Materials Technology*, Addison-Wesley Publishing Co., 1973. Reproduced with permission of the Estate of Lawrence H. Van Vlack.)

piezoelectric

Piezoelectric materials may be used as transducers between electrical and mechanical energies. One of the early uses of piezoelectric ceramics was in sonar systems, in which underwater objects (e.g., submarines) are detected and their positions determined using an ultrasonic emitting and receiving system. A piezoelectric crystal is caused to oscillate by an electrical signal, which produces high-frequency mechanical vibrations that are transmitted through the water. Upon encountering an object, the signals are reflected, and another piezoelectric material receives this reflected vibrational energy, which it then converts back into an electrical signal. Distance from the ultrasonic source and reflecting body is determined from the elapsed time between sending and receiving events.

More recently, the use of piezoelectric devices has grown dramatically as a consequence of increases in automation and consumer attraction to modern sophisticated gadgets. Piezoelectric devices are used in many of today's applications, including *automotive*—wheel balances, seat-belt buzzers, tread-wear indicators, keyless door entry, and airbag sensors; *computer/electronic*—microphones, speakers, microactuators for hard disks and notebook transformers; *commercial/consumer*—ink-jet printing heads, strain gauges, ultrasonic welders, and smoke detectors; and *medical*—insulin pumps, ultrasonic therapy, and ultrasonic cataract-removal devices.

Piezoelectric ceramic materials include titanates of barium and lead ($BaTiO_3$ and $PbTiO_3$), lead zirconate ($PbZrO_3$), lead zirconate–titanate (PZT) [$Pb(Zr,Ti)O_3$], and potassium niobate ($KNbO_3$). This property is characteristic of materials having complicated crystal structures with a low degree of symmetry. The piezoelectric behavior of a polycrystalline specimen may be improved by heating above its Curie temperature and then cooling to room temperature in a strong electric field.

MATERIAL OF IMPORTANCE

Piezoelectric Ceramic Ink-Jet Printer Heads

Piezoelectric materials are used in one kind of ink-jet printer head that has components and a mode of operation represented in the schematic diagrams in Figure 12.37*a* through 12.37*c*. One head component is a flexible, bilayer disk that consists of a piezoelectric ceramic (orange region) bonded to a nonpiezoelectric deformable material (green region); liquid ink and its reservoir are represented by blue areas in these diagrams. Short, horizontal arrows within the piezoelectric note the direction of the permanent dipole moment.

Printer head operation (i.e., ejection of ink droplets from the nozzle) is a result of the inverse piezoelectric effect—that is, the bilayer disk is caused to flex back and forth by the expansion and contraction of the piezoelectric layer in response to changes in bias of an applied voltage. For example, Figure 12.37*a* shows how the imposition of forward bias voltage causes the bilayer disk to flex in such a way as to pull (or draw) ink from the reservoir into the nozzle chamber. Reversing the voltage bias forces the bilayer disk to bend in the opposite direction—toward the nozzle—so as to eject a drop of ink (Figure 12.37*b*). Finally, removal of the voltage causes the disk to return to its unbent configuration (Figure 12.37*c*) in preparation for another ejection sequence.

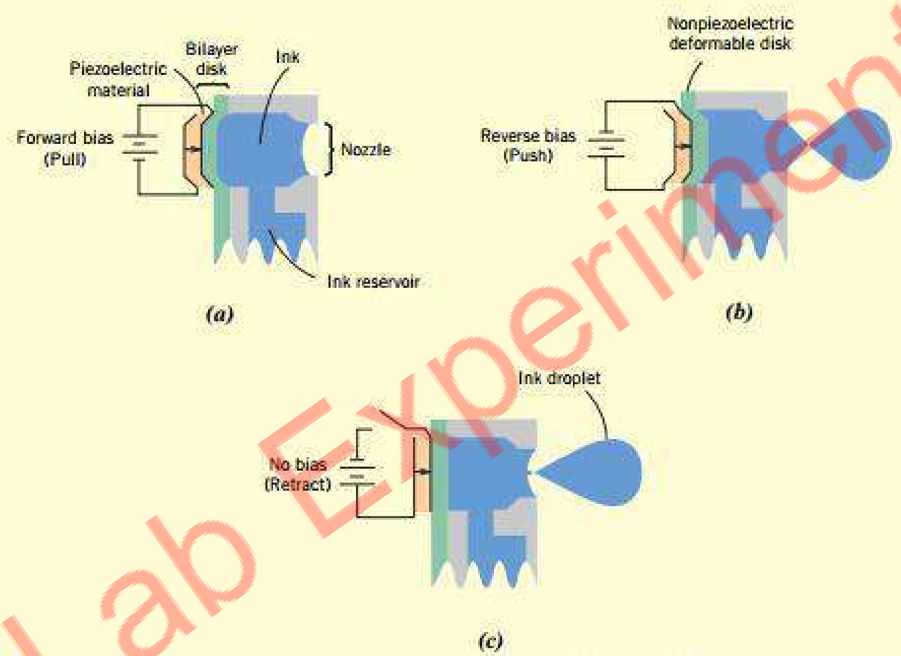


Figure 12.37 Operation sequence of a piezoelectric ceramic ink-jet printer head (schematic). (*a*) Imposing a forward-bias voltage draws ink into the nozzle chamber as the bilayer disk flexes in one direction. (*b*) Ejection of an ink drop by reversing the voltage bias and forcing the disk to flex in the opposite direction. (*c*) Removing the voltage retracts the bilayer disk to its unbent configuration in preparation for the next sequence.
(Images provided courtesy of Epson America, Inc.)

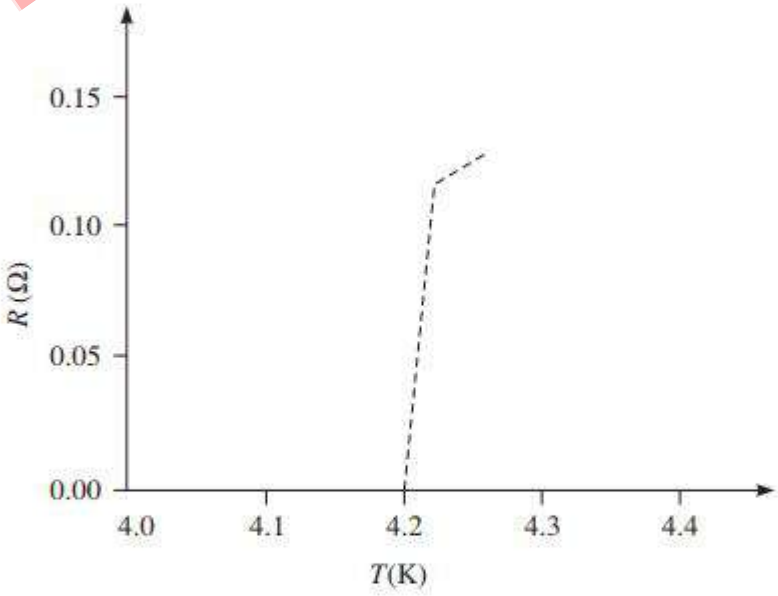
Superconductivity

The phenomenon of superconductivity was discovered by the Dutch physicist Kamerlingh Onnes while investigating the electrical properties of metals at very low temperatures. Though it was discovered in 1911, understanding of the subject proceeded very slowly. In this chapter, we will consider the basics of superconductivity and some of the phenomena associated with it.

7.1 INTRODUCTION

In 1911, Onnes discovered that for some materials there exists a certain temperature, called **critical temperature** or **transition temperature** T_C, below which the resistivity is zero and the conductivity $\sigma \to \infty$. This phenomenon is called **superconductivity**. Figure 7.1 shows a plot of the resistance of mercury versus temperature obtained by Onnes. The critical temperature for mercury is 4.2 K. The critical temperature varies from material to material, less than 0.1 K for hafnium to 9.2 K for niobium; below this temperature the electrical resistance of the material is zero. Table 7.1 lists the critical temperatures of some superconducting materials. Many metallic compounds are also superconductors. The superconducting alloy Nb_3Ge, discovered in 1973, has a critical temperature of 23.2 K. This was the highest critical temperature known until 1986.

There is no *d.c.* resistance for a superconductor below T_C. Hence, there can be a current in a ring shaped superconducting material even in the absence of a potential difference. Such currents are called **supercurrents.** In fact, steady currents have been observed to persist for years without loss, in superconducting rings without an electric field.



Plot of the resistance of mercury versus temperature, showing sudden decrease of the critical temperature T = 4.2 K.

Table 7.1 T_C and B_C values at 0 K for some superconductors

Type-I element*	T_C (K)	B_C (at 0 K) (T)	Type - II compound*	T_C (K)	B_C(at 0 K) (T)
Al	1.175	0.0105	Nb_3Sn	18.1	24.5
Cd	0.517	0.0028	Nb_3Ge	23.2	34.0
Hg	4.154	0.0411	NbN	16.0	15.3
In	3.408	0.0282	V_3Ga	16.5	35.0
Nb	9.25	0.2060	V_3Si	17.1	15.6
Os	0.66	0.0070	Pb MoS	14.4	6.0
Pb	7.196	0.0803	CNb	8.0	1.7
Sn	3.722	0.0305	Al_2CMo_3	9.8	15.6
Tl	2.38	0.0178	Rb_3C_{60}	29.0	?
Zn	0.85	0.0054	Cs_2RbC_{60}	33.0	?

7.2 MAGNETIC PROPERTIES

Consider a superconductor at a temperature T below its critical temperature T_C. When a magnetic field B is turned on, the critical temperature is lowered compared to the value when there is no field. As the magnetic field increases, the critical temperature decreases, as illustrated in Fig. 7.2. If the magnetic field is greater than B_C, called the **critical magnetic field,** superconductivity does not exist at any temperature. In a sense, the above diagram is a phase diagram where the lower left region represents the superconducting state and the upper right region its normal state. Table 7.1 also gives the values of B_C at 0 K.

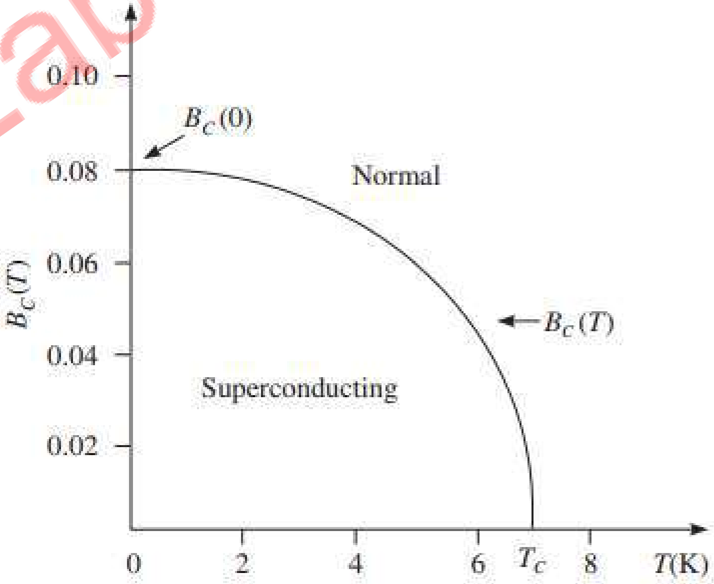


Fig. 7.2 Variation of the critical temperature with magnetic field for lead.

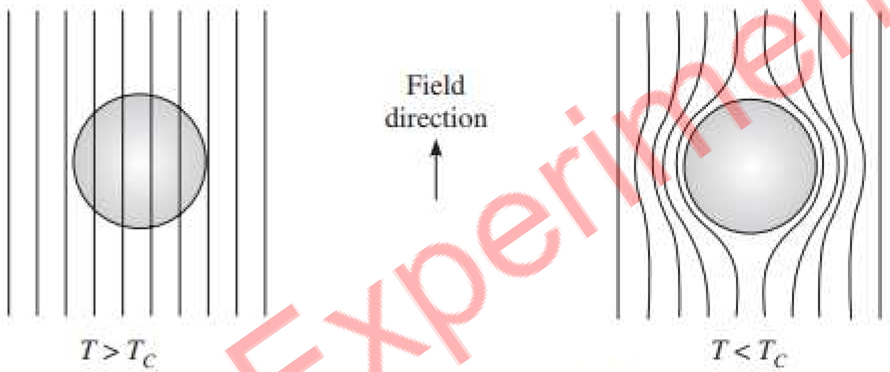
The magnetic field approaches zero as T approaches T_C. The variation of the critical magnetic field at temperature T can be represented by the relation:

$$B_C(T) = B_C(0)\left[1 - \frac{T^2}{T_C^2}\right] \tag{7.1}$$

where $B_C(0)$ is the critical magnetic field at 0 K and T_C is the critical temperature at $B = 0$.

7.3 MEISSNER EFFECT

Another interesting aspect of the magnetic properties of superconductors is the **Meissner effect.** Consider a superconducting material in the presence of a small external magnetic field $B < B_C$ at a temperature greater than the critical temperature. The magnetic field lines will be as illustrated in Fig. 7.3(a). If the material is cooled below the critical temperature T_C, it becomes a superconductor and the magnetic field lines will be as shown in Fig. 7.3(b). In other words, when a superconductor is cooled below the critical temperature in an external magnetic field, the magnetic field lines are expelled or cancelled from the superconductor and the magnetic field inside the superconductor becomes zero.



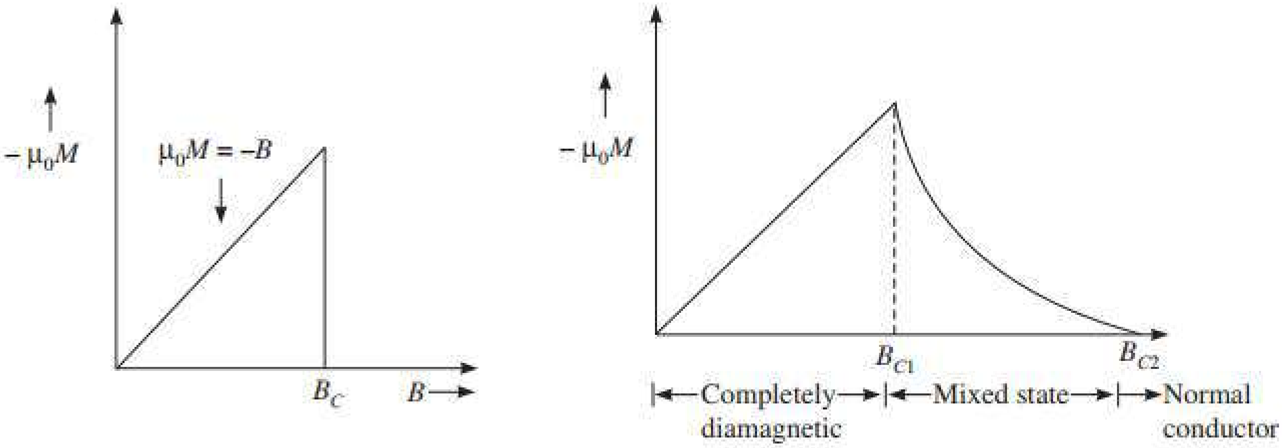
(a) The magnetic lines of force around a superconductor when $T > T_C$.

(b) Magnetic flux expulsion from the superconductor when $T < T_C$.

Fig. 7.3 The Meissner effect.

7.4 TYPE–I AND TYPE–II SUPERCONDUCTORS

Depending on the magnetization, superconducting materials can be classified into Type-I and Type-II superconductors. Only certain superconductors, called **type-I or soft superconductors,** exhibit complete Meissner effect. Some of the familiar examples are Al, Cd, Sn, and Zn, (Table 7.1). Figure 7.4(a) shows the plot of the magnetization (M) times μ_0 (permeability of free space) versus the applied magnetic field B for a type-I superconductor. For magnetic fields less than the critical field B_C, the magnetic field induced in the superconductor $\mu_0 M$ is equal and opposite to the external magnetic field. That is, the superconductor is a perfect diamagnet. For type-I superconductors, the values of B_C are very small (Table 7.1). Hence, such materials are not useful as coils of a superconducting magnet.



(a) For type-I super conductor (b) For type-II superconductor

Fig. 7.4 Magnetization versus magnetic field curve.

Type-II or hard superconductors have magnetization curve similar to that given in Fig. 7.4(b). Such materials are usually alloys or metals that have large resistivities in the normal state. Type-II superconductors exhibit two critical magnetic fields, B_{C1} and B_{C2} [Fig. 7.4(b)]. For applied fields less than B_{C1}, total magnetic flux cancellation will be there and the entire sample will be superconducting as in type-I superconductors. For applied fields greater than B_{C2}, complete penetration of the magnetic field throughout the sample will be there and the resistivity returns to the normal value. For applied fields between B_{C1} and B_{C2} there will be partial penetration of the magnetic fields, the field lines being confined to **flux tubes,** also called ***vortices.*** In the flux tubes, the material will have normal resistivity. The surrounding material remains field free and superconducting. Each flux tube contains one quantized unit of flux, called a **fluxoid** (Section 7.7).

For certain type-II superconductors, the critical field B_{C2} may be several hundred times larger than the typical values of critical fields for type-I superconductors. For example, Nb_3Ge has a B_{C2} of 34T. Such materials are used to construct high field superconducting magnets.

7.9 HIGH TEMPERATURE SUPERCONDUCTIVITY

Superconductors can be grouped into low T_C and high T_C based on their transition temperature. Substances having T_C around or below 24 K are considered as low T_C super-conductors and those above are **high T_C superconductors**. The low T_C superconductors range from ordinary metals and alloys such as Nb(T_C = 9.25 K) and Nb_3Ge(T_C = 23.2 K) to oxides like $BaPb_{1-x}Bi_xO_3$(T_C = 13 K). A class of compounds called **A-15**, Nb_3Ge, Nb_3Sn(T_C = 18.1 K) and Nb_3Ga(T_C = 20.3 K) and others, are the very familiar ones with T_C in and around 20 K. The BCS theory could explain the behaviour of low T_C superconductors.

A forward step was the observation of a T_C of 40 K in $La_{1-x}Sr_xCuO$ with $x = 0.15$ by Bednorz and Muller (1986), for which they were awarded the Nobel Prize in 1987. Changing lanthanum by yttrium and strontium by barium a T_C of 93 K in $YBa_2Cu_3O_7$ was reported in 1987. This compound is referred to as **1-2-3** following the ratio of the three metallic elements. This was a fantastic advancement, as the observed T_C surpassed 77 K, the boiling point of liquid nitrogen. Another interesting aspect about the type-II copper oxide superconductors is about their extremely high upper critical fields. For $Y Ba_2Cu_3O_7$ the upper critical field $B_{c2} \cong 100$ T at 77 K and about 300 T at 0 K.

A similar compound using bismuth and aluminum Bi $Al_{1-y}CaSrCoO_{7-d}$ with $d < 0.45$ and $0 < y < 0.3$ raised the value of T_C to 114 K. The thallium based compound $T1_2\ Ba_2Ca_{n-1}\ Cu_nO_{2n+4}$ is a very interesting since it gives different T_C values for different n; T_C of 80 K for $n = 1$, $T_C = 110$ K for $n = 2$ and $T_C = 125$ K for $n = 3$. There is a possibility of reaching very high T_C values if we can make compounds with $n > 3$. In 1993, a higher T_C (113 K) was achieved in the mercury based copper oxide $HaBa_2Ca_2Cu_3O_{1+x}$ with x being a small positive number. At extremely high pressures (about 300000 atmospheres) these mercury based superconductors reach transition temperature of 164 K. Most of these compounds fall in the category of ceramics.

Another class of superconductors is based on the organic molecule C_{60}. Pure C_{60} is not a superconducting element. When C_{60} is doped with the right amount of potassium, it forms the compound K_3C_{60} with a T_C of 18 K. Combination of C_{60} with thallium and rubidium increases the T_C to 42.5 K. The dream of the scientists is to achieve a T_C of about 300 K, so that they can eliminate the need for cryogenic fluids.

7.10 APPLICATIONS

The properties of zero resistance and the Meissner effect make superconductors ideal for many applications. The cost of cryogenic systems and fluids has also to be taken into account when we consider the applications. We discuss here some of the important applications.

7.10.1 SQUID

The Josephson junctions are used in devices known as **S**uperconducting **Qu**antum **I**nterference **D**evices (SQUID). The SQUID uses a pair of Josephen junctions in a current loop. The current is extremely sensitive to the magnetic flux applied to the loop. SQUIDS are used for measuring very small amounts of magnetic flux. They can be used to measure quantum fluxoid to within one part in 10^6. As ordinary magnetometers, SQUIDS are capable of measuring magnetic fluctuations of the order of 10^{-13} T. The biomedical applications of SQUIDS include the imaging of soft tissues such as the brain. They have also been used to detect the presence of bacteria, search for explosives, examine materials for defects, and search for oil.

7.10.2 Generation and Transmission of Electricity

Substantial amount of energy saving is possible if superconductors are used in electrical generators and motors. Most of the savings come from the replacement of the heavy iron cores by lighter superconducting magnets. The other part comes from the cutting of resistive losses. Superconducting transmission lines would save significant amounts of energy. Superconducting transmission requires no expensive transformers. For normal transmission one has to make the voltage as large as possible, which is not needed if $R = 0$. The large current densities possible in superconducting wires allow the reduction of the number and size of transmission lines. Superconducting energy storage rings would be of great use to store extra energy generated during low usage hours in power plants.

7.10.3 Superconducting Magnets

A conventional electromagnet is made by passing current through a metal wire wound in the shape of a solenoid. A maximum magnetic field of a few millitesla can be generated by this method. By placing an iron core within the solenoid, the magnetic field can be enhanced to about 2 to 3 T. The iron core is extremely heavy and cumbersome. Since we can achieve current densities of 10^7A/cm^2 in superconducting wires, it is possible to produce very large magnetic fields. An additional advantage is that no iron core is needed in this case. The superconducting material must have a critical field higher than the maximum field we want to generate. With type-II superconductors, it is possible to achieve upper critical fields of 50T (Section 7.4). Superconducting magnets are used for large particle accelerators. Large magnets are used to confine plasma in fusion research. One of the most important medical applications of large superconducting magnets is in Magnetic Resonance Imaging (MRI).

7.10.4 Other Applications

Josephson junctions could be used in integrated circuits. Superconducting computers are not cost-effective. They may have to be re-evaluated when room temperature superconductors

become available. The Josephson junction is used to measure and maintain voltage standards. In Japan, a magnetic leviation (maglev) train achieved a speed of 550 km/h. It is designed on the principle of Meissner effect to levitate the transport system. The idea is to make a more comfortable travel at higher speeds.

Example 7.1 A superconducting sample has a critical temperature of 3.722 K in zero magnetic field and a critical field of 0.0305 T at 0 K. Evaluate the critical field at 2 K.

Solution: We have $B_C(T) = B_C(0)\left[1 - \frac{T^2}{T_C^2}\right]$

$$B_C(2\text{K}) = (0.0305\ \text{T})\left[1 - \left(\frac{2\text{K}}{3.722\text{K}}\right)^2\right]$$

$$= 0.0217\ \text{T}$$

16.2 Magnetic Moments due to Electron Spin

Permanent magnetic moments can arise from three sources: the orbital magnetic moment of the electrons corresponding to the quantum number m_l, the spin magnetic moment of electrons corresponding to the spin quantum number m_s, and the spin magnetic moment of the nucleus. Of these, the spin magnetic moments of the electrons are the only ones that are important from our point of view. We will discuss only this source of magnetism.

This simple deduction of the net magnetic moment of an atom has to be modified in the solid state, where the electron energy levels of the outermost orbitals interact and form energy bands. In the transition metals, the energy bands due to the 4*s* orbital and the 3*d* orbital may *overlap* to some extent. The 4*s* electrons spend some time in the 3*d* band. If the 3*d* electrons are five or more in number, the spins of the overlapping 4*s* electrons must be opposite to that of the unpaired 3*d* electrons. Such an overlap, therefore, *reduces* the net magnetic moment. The iron atom with an outer electronic configuration of $3d^6 4s^2$ has a moment of 4 units as a free atom, but has a moment of only 2.2 as part of the crystal. Similarly, cobalt with a configuration of $3d^7 4s^2$ has a moment of 1.7 and nickel with a configuration of $3d^8 4s^2$ has a moment of only 0.6 unit in the crystal. In the case of gadolinium, the net magnetic moment of seven in the free atom remains unchanged in the solid state, as there is no overlap of the 4*f* orbitals with the other energy bands.

The magnetization of a solid is the sum of the magnetic moments in unit volume of the solid.

$$\text{Magnetization} = \text{magnetic moments/volume}$$

$$= \text{A m}^2/\text{m}^3$$

An electron can be crudely approximated to a charge-carrying particle spinning about its axis and creating its own magnetic field. The magnetic moment of an electron spin is taken as one unit, called the *Bohr magneton* μ_B. It has a value of 9.273×10^{-24} A m². The net magnetic moment of two electrons of opposite spins is zero. Atoms or molecules that have quantum states all of which have paired electrons have zero net magnetic moment. A number of atoms and molecules, however, have unpaired electrons. For instance, the alkali metal atoms have only one electron in the outermost *s* orbital. This electron is unpaired and can align itself in an applied field giving rise to paramagnetism.

The order of filling of electron orbitals in atoms is given by *Hund's rule*. An atom with three electrons in a *p* orbital will have all three spins aligned, giving rise to a net magnetic moment of three Bohr magnetons. On the other hand, an atom with four electrons in the *p* orbital will have a net moment of only two units, as the spin of the fourth electron is opposite to that of the first three. Similarly, an atom with five electrons in a *d* orbital has a net magnetic moment of five units. But an atom with nine electrons in the *d* orbital has a net moment of only one. Seven electrons in an *f* orbital will give a net magnetic moment of seven units.

18.3 DIAMAGNETISM AND PARAMAGNETISM

diamagnetism

Diamagnetism is a very weak form of magnetism that is nonpermanent and persists only while an external field is being applied. It is induced by a change in the orbital motion of electrons due to an applied magnetic field. The magnitude of the induced magnetic moment is extremely small and in a direction opposite to that of the applied field. Thus, the relative permeability μ_r is less than unity (however, only very slightly), and the magnetic susceptibility is negative—that is, the magnitude of the *B* field within a diamagnetic solid is less than that in a vacuum. The volume susceptibility χ_m for diamagnetic solid materials is on the order of -10^{-5}. When placed between the poles of a strong electromagnet, diamagnetic materials are attracted toward regions where the field is weak.

Figure 18.5*a* illustrates schematically the atomic magnetic dipole configurations for a diamagnetic material with and without an external field; here, the arrows represent atomic dipole moments, whereas for the preceding discussion, arrows denoted only electron moments. The dependence of *B* on the external field *H* for a material that exhibits diamagnetic behavior is presented in Figure 18.6. Table 18.2 gives the susceptibilities of several diamagnetic materials. Diamagnetism is found in all materials, but because it is so weak, it can be observed only when other types of magnetism are totally absent. This form of magnetism is of no practical importance.

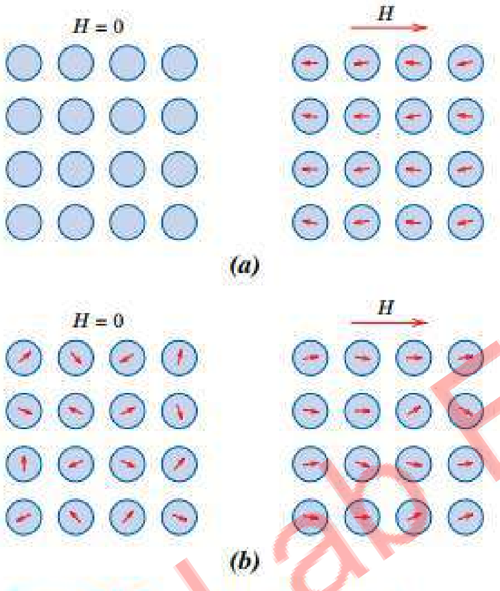


Figure 18.5 (*a*) The atomic dipole configuration for a diamagnetic material with and without a magnetic field. In the absence of an external field, no dipoles exist; in the presence of a field, dipoles are induced that are aligned opposite to the field direction. (*b*) Atomic dipole configuration with and without an external magnetic field for a paramagnetic material.

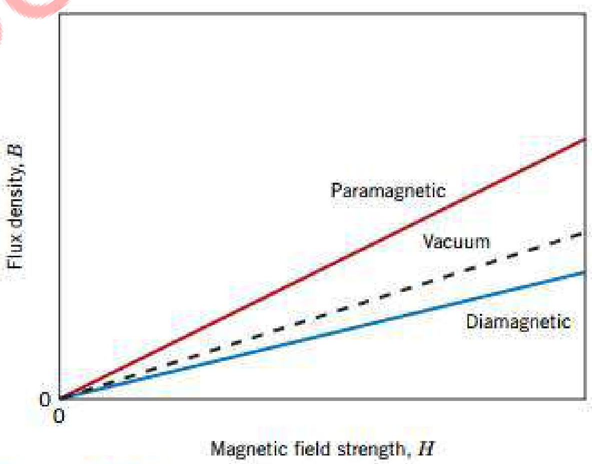


Figure 18.6 Schematic representation of the flux density *B* versus the magnetic field strength *H* for diamagnetic and paramagnetic materials.

18.4 FERROMAGNETISM

ferromagnetism

domain

saturation magnetization

Certain metallic materials possess a permanent magnetic moment in the absence of an external field and manifest very large and permanent magnetizations. These are the characteristics of **ferromagnetism,** and they are displayed by the transition metals iron (as BCC α-ferrite), cobalt, nickel, and some rare earth metals such as gadolinium (Gd). Magnetic susceptibilities as high as 10^6 are possible for ferromagnetic materials. Consequently, $H \ll M$, and from Equation 18.5 we write

For a ferromagnetic material, relationship between magnetic flux density and magnetization

$$B \cong \mu_0 M \tag{18.8}$$

Permanent magnetic moments in ferromagnetic materials result from atomic magnetic moments due to uncanceled electron spins as a consequence of the electron structure. There is also an orbital magnetic moment contribution that is small in comparison to the spin moment. Furthermore, in a ferromagnetic material, coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field. This is schematically illustrated in Figure 18.7. The origin of these coupling forces is not completely understood, but they are thought to arise from the electronic structure of the metal. This mutual spin alignment exists over relatively large-volume regions of the crystal called **domains** (see Section 18.7).

The maximum possible magnetization, or **saturation magnetization,** M_s, of a ferromagnetic material represents the magnetization that results when all the magnetic dipoles in a solid piece are mutually aligned with the external field; there is also a corresponding saturation flux density, B_s. The saturation magnetization is equal to the product of the net magnetic moment for each atom and the number of atoms present. For each of iron, cobalt, and nickel, the net magnetic moments per atom are 2.22, 1.72, and 0.60 Bohr magnetons, respectively.

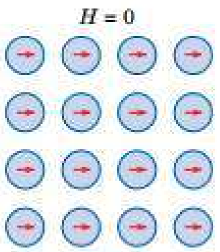


Figure 18.7 Schematic illustration of the mutual alignment of atomic dipoles for a ferromagnetic material, which will exist even in the absence of an external magnetic field.

18.5 ANTIFERROMAGNETISM AND FERRIMAGNETISM

Antiferromagnetism

antiferromagnetism

Magnetic moment coupling between adjacent atoms or ions also occurs in materials other than those that are ferromagnetic. In one such group, this coupling results in an antiparallel alignment; the alignment of the spin moments of neighboring atoms or ions in exactly opposite directions is termed **antiferromagnetism.** Manganese oxide (MnO) is one material that displays this behavior. Manganese oxide is a ceramic material that is ionic in character, having both Mn^{2+} and O^{2-} ions. No net magnetic moment is associated with the O^{2-} ions because there is a total cancellation of both spin and orbital moments. However, the Mn^{2+} ions possess a net magnetic moment that is predominantly of spin origin. These Mn^{2+} ions are arrayed in the crystal structure such that the moments of adjacent ions are antiparallel. This arrangement is represented schematically in Figure 18.8. The opposing magnetic moments cancel one another, and, as a consequence, the solid as a whole possesses no net magnetic moment.

Ferrimagnetism

ferrimagnetism

Some ceramics also exhibit a permanent magnetization, termed **ferrimagnetism.** The macroscopic magnetic characteristics of ferromagnets and ferrimagnets are similar; the distinction lies in the source of the net magnetic moments. The principles of ferrimagnetism are illustrated with the cubic ferrites.[2] These ionic materials may be represented by the chemical formula MFe_2O_4, in which M represents any one of several metallic elements. The prototype ferrite is Fe_3O_4—the mineral magnetite, sometimes called lodestone.

The formula for Fe_3O_4 may be written as $Fe^{2+}O^{2-}$–$(Fe^{3+})_2(O^{2-})_3$, in which the Fe ions exist in both +2 and +3 valence states in the ratio of 1:2. A net spin magnetic moment exists for each Fe^{2+} and Fe^{3+} ion, which corresponds to 4 and 5 Bohr magnetons, respectively, for the two ion types. Furthermore, the O^{2-} ions are magnetically neutral. There are antiparallel spin-coupling interactions between the Fe ions, similar in character to antiferromagnetism. However, the net ferrimagnetic moment arises from the incomplete cancellation of spin moments.

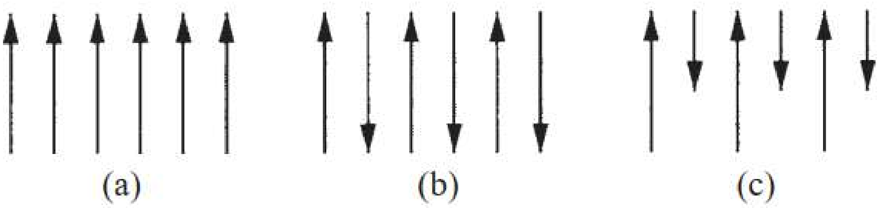


Fig. 16.2 (a) Ferromagnetic, (b) antiferromagnetic, and (c) ferrimagnetic coupling of electron spins in atoms denoted by arrows. The length of an arrow is a measure of the magnetic moment of the atom.

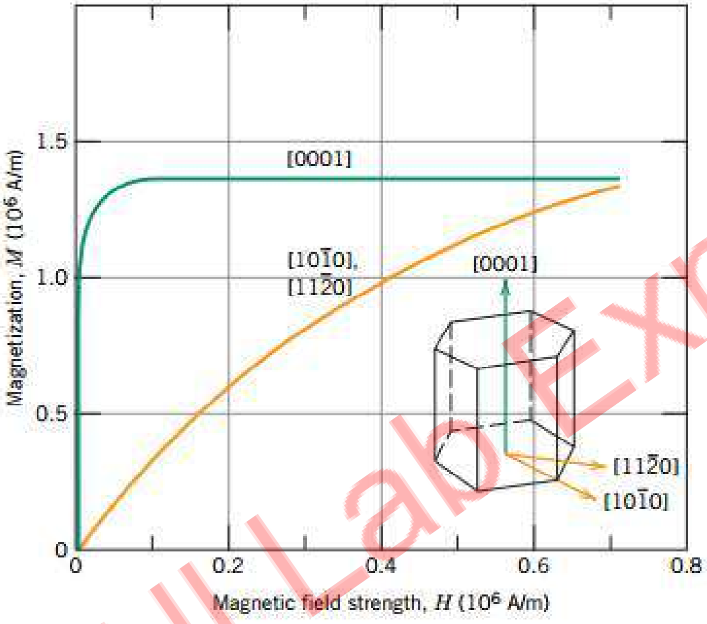


Figure 18.18 Magnetization curves for single crystals of cobalt. The curves were generated when the magnetic field was applied in [0001] and $[10\bar{1}0]/[11\bar{2}0]$ crystallographic directions.
[Adapted from S. Kaya, "On the Magnetisation of Single Crystals of Cobalt," *Sci. Rep. Tohoku Univ.*, **17**, 1157 (1928).]

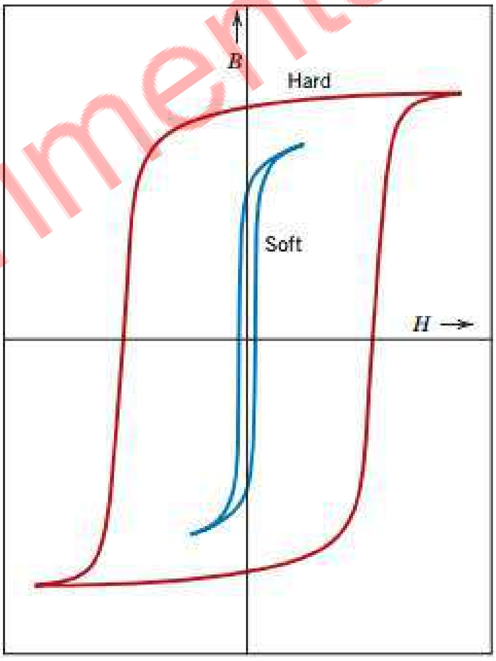


Figure 18.19 Schematic magnetization curves for soft and hard magnetic materials.
(From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

18.9 SOFT MAGNETIC MATERIALS

The size and shape of the hysteresis curve for ferro- and ferrimagnetic materials are of considerable practical importance. The area within a loop represents a magnetic energy loss per unit volume of material per magnetization–demagnetization cycle; this energy loss is manifested as heat that is generated within the magnetic specimen and is capable of raising its temperature.

soft magnetic material

Both ferro- and ferrimagnetic materials are classified as either *soft* or *hard* on the basis of their hysteresis characteristics. **Soft magnetic materials** are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low; one familiar example consists of transformer cores. For this reason the relative area within the hysteresis loop must be small; it is characteristically thin and narrow, as represented in Figure 18.19. Consequently, a soft magnetic material must have a high initial permeability and a low coercivity. A material possessing these properties may reach its saturation magnetization with a relatively low applied field (i.e., may be easily magnetized and demagnetized) and still have low hysteresis energy losses.

The saturation field or magnetization is determined only by the composition of the material. For example, in cubic ferrites, substitution of a divalent metal ion such as Ni^{2+} for Fe^{2+} in $FeO–Fe_2O_3$ changes the saturation magnetization. However, susceptibility and coercivity (H_c), which also influence the shape of the hysteresis curve, are sensitive to structural variables rather than to composition. For example, a low value of coercivity corresponds to the easy movement of domain walls as the magnetic field changes magnitude and/or direction. Structural defects such as particles of a nonmagnetic phase or voids in the magnetic material tend to restrict the motion of domain walls and thus increase the coercivity. Consequently, a soft magnetic material must be free of such structural defects.

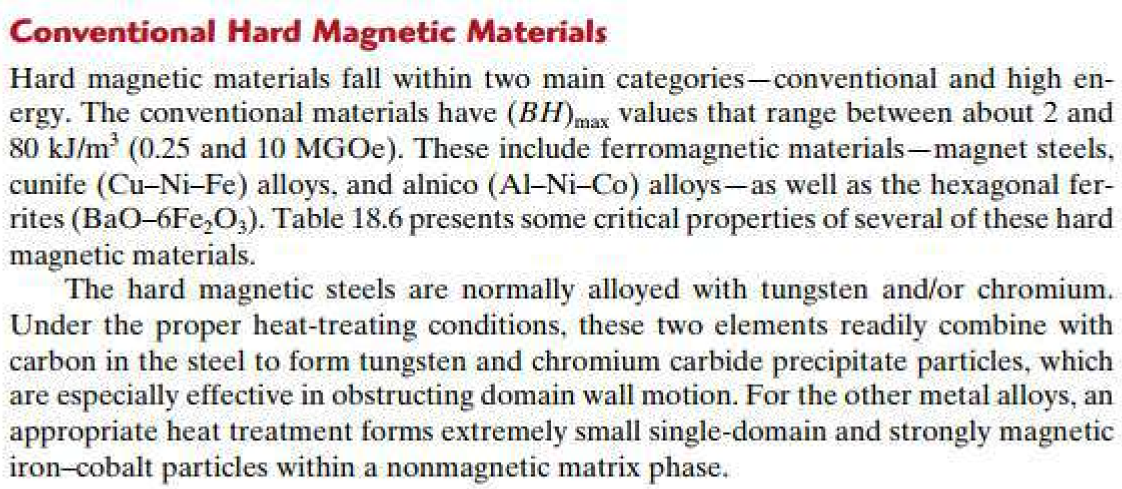
Another property consideration for soft magnetic materials is the electrical resistivity. In addition to the hysteresis energy losses described previously, energy losses may result from electrical currents that are induced in a magnetic material by a magnetic field that varies in magnitude and direction with time; these are called *eddy currents.* It is most desirable to minimize these energy losses in soft magnetic materials by increasing the electrical resistivity. This is accomplished in ferromagnetic materials by forming solid solution alloys; iron–silicon and iron–nickel alloys are examples. The ceramic ferrites are commonly used for applications requiring soft magnetic materials because they are intrinsically electrical insulators. Their applicability is somewhat limited, however, inasmuch as they have relatively small susceptibilities. The properties of some soft magnetic materials are shown in Table 18.5.

The hysteresis characteristics of soft magnetic materials may be enhanced for some applications by an appropriate heat treatment in the presence of a magnetic field. Using such a technique, a square hysteresis loop may be produced, which is desirable in some magnetic amplifier and pulse transformer applications. In addition, soft magnetic materials are used in generators, motors, dynamos, and switching circuits.

18.10 HARD MAGNETIC MATERIALS

hard magnetic material

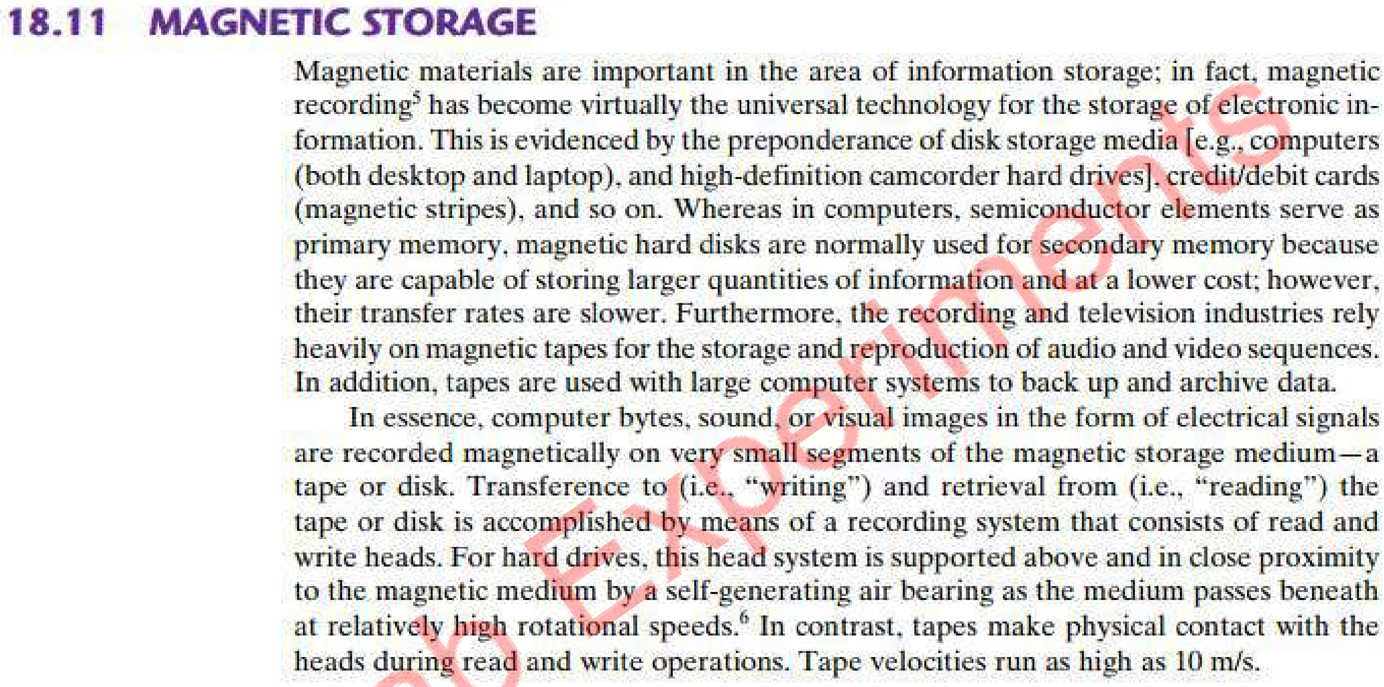
Hard magnetic materials are used in permanent magnets, which must have a high resistance to demagnetization. In terms of hysteresis behavior, a **hard magnetic material** has high remanence, coercivity, and saturation flux density, as well as low initial permeability and high hysteresis energy losses. The hysteresis characteristics for hard and soft magnetic materials are compared in Figure 18.19. The two most important characteristics relative to applications for these materials are the coercivity and what is termed the *energy product,* designated as $(BH)_{max}$. This $(BH)_{max}$ corresponds to the area of the largest B-H rectangle that can be constructed within the second quadrant of the hysteresis curve, Figure 18.22; its units are kJ/m^3 (MGOe).[4] The value of the energy product is



Conventional Hard Magnetic Materials

Hard magnetic materials fall within two main categories—conventional and high energy. The conventional materials have $(BH)_{max}$ values that range between about 2 and 80 kJ/m^3 (0.25 and 10 MGOe). These include ferromagnetic materials—magnet steels, cunife (Cu–Ni–Fe) alloys, and alnico (Al–Ni–Co) alloys—as well as the hexagonal ferrites (BaO–6Fe$_2$O$_3$). Table 18.6 presents some critical properties of several of these hard magnetic materials.

The hard magnetic steels are normally alloyed with tungsten and/or chromium. Under the proper heat-treating conditions, these two elements readily combine with carbon in the steel to form tungsten and chromium carbide precipitate particles, which are especially effective in obstructing domain wall motion. For the other metal alloys, an appropriate heat treatment forms extremely small single-domain and strongly magnetic iron–cobalt particles within a nonmagnetic matrix phase.



18.11 MAGNETIC STORAGE

Magnetic materials are important in the area of information storage; in fact, magnetic recording[5] has become virtually the universal technology for the storage of electronic information. This is evidenced by the preponderance of disk storage media [e.g., computers (both desktop and laptop), and high-definition camcorder hard drives], credit/debit cards (magnetic stripes), and so on. Whereas in computers, semiconductor elements serve as primary memory, magnetic hard disks are normally used for secondary memory because they are capable of storing larger quantities of information and at a lower cost; however, their transfer rates are slower. Furthermore, the recording and television industries rely heavily on magnetic tapes for the storage and reproduction of audio and video sequences. In addition, tapes are used with large computer systems to back up and archive data.

In essence, computer bytes, sound, or visual images in the form of electrical signals are recorded magnetically on very small segments of the magnetic storage medium—a tape or disk. Transference to (i.e., "writing") and retrieval from (i.e., "reading") the tape or disk is accomplished by means of a recording system that consists of read and write heads. For hard drives, this head system is supported above and in close proximity to the magnetic medium by a self-generating air bearing as the medium passes beneath at relatively high rotational speeds.[6] In contrast, tapes make physical contact with the heads during read and write operations. Tape velocities run as high as 10 m/s.

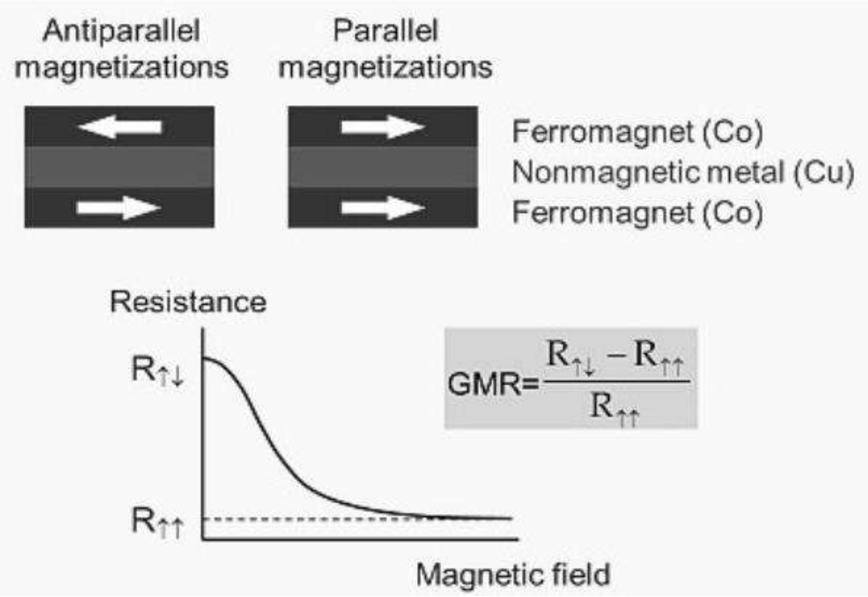
Spintronics –

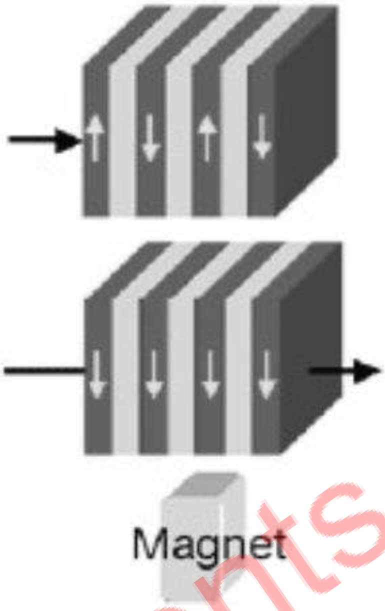
Spintronics, also known as **spin electronics**, is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices. Spintronics fundamentally differs from traditional electronics in that, in addition to charge state, electron spins are exploited as a further degree of freedom, with implications in the efficiency of data storage and transfer. Spintronic systems are most often realised in dilute magnetic semiconductors (DMS) and Heusler alloys and are of particular interest in the field of quantum computing and neuromorphic computing.

GMR (Giant Magnetoresistance) –

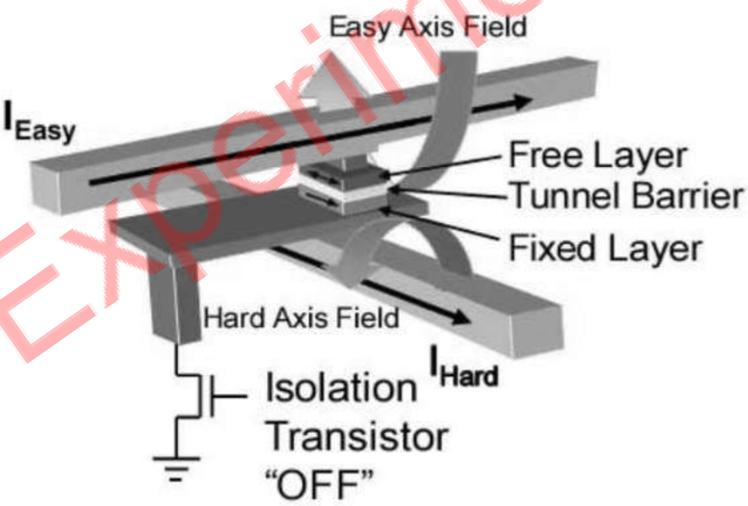
Like other magnetoresistive effects, giant magnetoresistance (GMR) is the change in electrical resistance of some materials in response to an applied magnetic field. It was discovered that the application of a magnetic field to magnetic metallic multilayers such as Fe/Cr and Co/Cu, in which ferromagnetic layers are separated by nonmagnetic spacer layers of a few nm thick, results in a significant reduction of the electrical resistance of the multilayer. This effect was found to be much larger than other magnetoresistive effects that had ever been observed in metals and was, therefore, called "giant magnetoresistance". In

Fe/Cr and Co/Cu multilayers the magnitude of GMR can be higher than 100% at low temperatures.

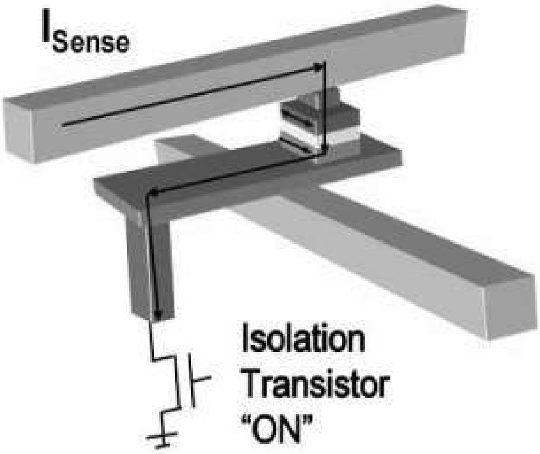




MRAM (Magnetoresistive Random Access Memory) uses electron spin to store data. Memory cells are integrated on an integrated circuit chip, and the function of the resulting device is like a semiconductor static RAM (SRAM) chip, with potentially higher density and the added feature that the data are nonvolatile, that is data are retained with power off. Typical “classic”or “conventional” MRAM uses spin-dependent tunnel junction memory cells and magnetic row and column write lines as illustrated.



The spin-dependent tunnel junction produces a large change in resistance depending on the predominant electron spin in a storage layer. The tunnel barrier is as thin as a few atomic layers--so thin that electrons can “tunnel” through the normally insulating material, causing a resistance change. Row and column magnetic write lines allow data to be written to a selected cell in a two-dimensional array:



Data are written by small electrical currents in the write lines that create a magnetic fields, which flip electron spins in the spin-dependent tunnel junction storage layer, thus changing the junction's resistance. Data is read by the tunneling current or resistance through the tunnel junction. Next-generation MRAM could reduce cell size and power consumption. Potential next-generation designs include Spin-Momentum Transfer, Magneto-Thermal MRAM, and Vertical Transport MRAM. Spin-Momentum Transfer (also "Spin-Transfer," "Spin Injection," or "Spin Torque Transfer") MRAM is based on changing the spin of storage electrons directly with an electrical current rather than an induced magnetic field. This method has the potential to significantly reduce MRAM write currents, especially with lithographic feature sizes less than 100 nanometers. M-T MRAM uses a combination of magnetic fields and ultra-fast heating from electrical current pulses to reduce the energy required to write data.

Applications –

MRAM can be made as discussed above, magnetic sensor can be made, hard disk reading speed can be increased using reading head based on GMR technology.