Chapter 20 Magnetic Properties

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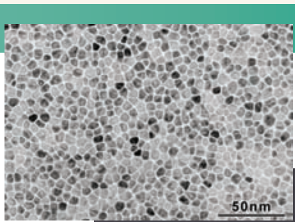

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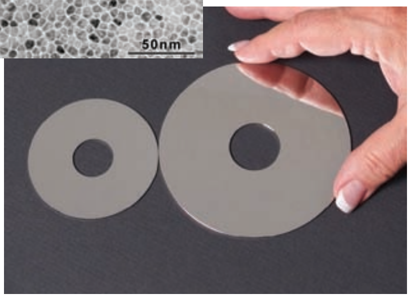

(a) Transmission electron micrograph showing the microstructure of the perpendicular magnetic recording medium used in hard-disk drives.

(b) Photograph of magnetic storage hard disks used in laptop (left) and desktop (right) computers.

(c) Photograph showing the inside of a hard disk drive. The circular disk will typically spin at a rotational velocity of 5400 or 7200 revolutions per minute.

(d) Photograph of a laptop computer; one of its internal components is a hard disk drive.

[Figure *(a)* courtesy of Seagate Recording Media; Figures *(c)* and *(d)* © iStockphoto.]

(c)



(d)

WHY STUDY *the Magnetic Properties of Materials?*

An understanding of the mechanism that explains the permanent magnetic behavior of some materials may allow us to alter and in some cases tailor the magnetic properties. For example, in Design Example 20.1 we note how the behavior of a ceramic magnetic material may be enhanced by changing its composition.

Learning Objectives

After studying this chapter you should be able to do the following:

1. **Determine the magnetization of some material given its magnetic susceptibility and the applied magnetic field strength.**
2. **From an electronic perspective, note and briefly explain the two sources of magnetic moments in materials.**
3. **Briefly explain the nature and source of (a) diamagnetism, (b) paramagnetism, and (c) ferromagnetism.**
4. **In terms of crystal structure, explain the source of ferrimagnetism for cubic ferrites.**
5. **(a) Describe magnetic hysteresis; (b) explain why ferromagnetic and ferrimagnetic materials experience magnetic hysteresis; and (c) explain why these materials may become permanent magnets.**
6. **Note the distinctive magnetic characteristics for both soft and hard magnetic materials.**
7. **Describe the phenomenon of *superconductivity*.**

20.1 INTRODUCTION

Magnetism, the phenomenon by which materials assert an attractive or repulsive force or influence on other materials, has been known for thousands of years. However, the underlying principles and mechanisms that explain the magnetic phenomenon are complex and subtle, and their understanding has eluded scientists until relatively recent times. Many of our modern technological devices rely on magnetism and magnetic materials; these include electrical power generators and transformers, electric motors, radio, television, telephones, computers, and components of sound and video reproduction systems.

Iron, some steels, and the naturally occurring mineral lodestone are well-known examples of materials that exhibit magnetic properties. Not so familiar, however, is the fact that all substances are influenced to one degree or another by the presence of a magnetic field. This chapter provides a brief description of the origin of magnetic fields and discusses the various magnetic field vectors and magnetic parameters; the phenomena of diamagnetism, paramagnetism, ferromagnetism, and ferrimagnetism; some of the different magnetic materials; and the phenomenon of superconductivity.

20.2 BASIC CONCEPTS

Magnetic Dipoles

Magnetic forces are generated by moving electrically charged particles; these magnetic forces are in addition to any electrostatic forces that may prevail. Many times it is convenient to think of magnetic forces in terms of fields. Imaginary lines of force may be drawn to indicate the direction of the force at positions in the vicinity of the field source. The magnetic field distributions as indicated by lines of force are shown for a current loop and also a bar magnet in Figure 20.1.

Magnetic dipoles are found to exist in magnetic materials, which, in some respects, are analogous to electric dipoles (Section 18.19). Magnetic dipoles may be thought of as small bar magnets composed of north and south poles instead of positive and negative electric charges. In the present discussion, magnetic dipole moments are represented by arrows, as shown in Figure 20.2. Magnetic dipoles are influenced by

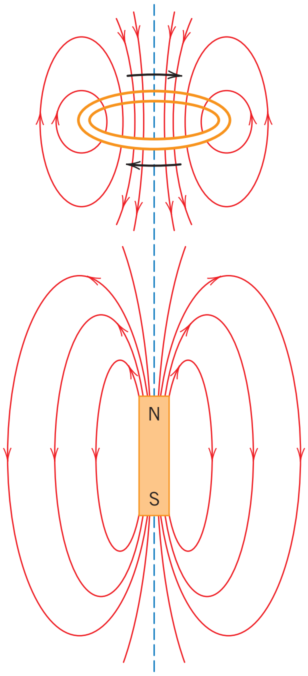

Figure 20.1 Magnetic field lines of force around a current loop and a bar magnet.

magnetic fields in a manner similar to the way in which electric dipoles are affected by electric fields (Figure 18.30). Within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the field. A familiar example is the way in which a magnetic compass needle lines up with the earth's magnetic field.

Magnetic Field Vectors

Before discussing the origin of magnetic moments in solid materials, we describe magnetic behavior in terms of several field vectors. The externally applied magnetic field, sometimes called the **magnetic field strength,** is designated by H. If the magnetic field is generated by means of a cylindrical coil (or solenoid) consisting of N closely spaced turns, having a length l, and carrying a current of magnitude I, then

magnetic field strength

Magnetic field strength within a coil—dependence on number of turns, applied current, and coil length

$$H = \frac{NI}{l} \tag{20.1}$$

A schematic diagram of such an arrangement is shown in Figure 20.3*a*. The magnetic field that is generated by the current loop and the bar magnet in Figure 20.1 is an H field. The units of H are ampere-turns per meter, or just amperes per meter.

magnetic induction

magnetic flux density

The **magnetic induction,** or **magnetic flux density,** denoted by B, represents the magnitude of the internal field strength within a substance that is subjected to an H field. The units for B are teslas [or webers per square meter (Wb/m^2)]. Both B and H are field vectors, being characterized not only by magnitude, but also by direction in space.

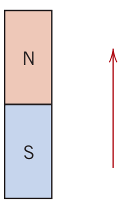

Figure 20.2 The magnetic moment as designated by an arrow.

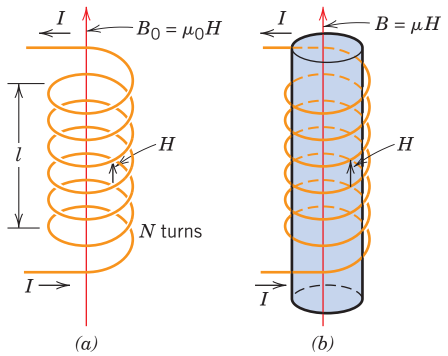

Figure 20.3 (*a*) The magnetic field H as generated by a cylindrical coil is dependent on the current I, the number of turns N, and the coil length l, according to Equation 20.1. The magnetic flux density B_0 in the presence of a vacuum is equal to $\mu_0 H$, where μ_0 is the permeability of a vacuum, $4\pi \times 10^{-7}$ H/m. (*b*) The magnetic flux density B within a solid material is equal to μH, where μ is the permeability of the solid material. (Adapted from A. G. Guy, *Essentials of Materials Science,* McGraw-Hill Book Company, New York, 1976.)

Magnetic flux density in a material—dependence on permeability and magnetic field strength

The magnetic field strength and flux density are related according to

$$B = \mu H \tag{20.2}$$

permeability

The parameter μ is called the **permeability,** which is a property of the specific medium through which the H field passes and in which B is measured, as illustrated in Figure 20.3*b*. The permeability has dimensions of webers per ampere-meter (Wb/A·m) or henries per meter (H/m).

In a vacuum,

Magnetic flux density in a vacuum

$$B_0 = \mu_0 H \tag{20.3}$$

where μ_0 is the *permeability of a vacuum,* a universal constant, which has a value of $4\pi \times 10^{-7}$ (1.257×10^{-6}) H/m. The parameter B_0 represents the flux density within a vacuum as demonstrated in Figure 20.3*a*.

Several parameters may be used to describe the magnetic properties of solids. One of these is the ratio of the permeability in a material to the permeability in a vacuum, or

Definition of relative permeability

$$\mu_r = \frac{\mu}{\mu_0} \tag{20.4}$$

where μ_r is called the *relative permeability,* which is unitless. The permeability or relative permeability of a material is a measure of the degree to which the material can be magnetized, or the ease with which a B field can be induced in the presence of an external H field.

magnetization

Another field quantity, M, called the **magnetization** of the solid, is defined by the expression

Magnetic flux density—as a function of magnetic field strength and magnetization of a material

$$B = \mu_0 H + \mu_0 M \tag{20.5}$$

In the presence of an H field, the magnetic moments within a material tend to become aligned with the field and to reinforce it by virtue of their magnetic fields; the term $\mu_0 M$ in Equation 20.5 is a measure of this contribution.

Table 20.1 Magnetic Units and Conversion Factors for the SI and cgs–emu Systems

Quantity	Symbol	SI Units: Derived	SI Units: Primary	cgs–emu Unit	Conversion
Magnetic induction (flux density)	B	tesla (Wb/m^2)[a]	kg/s·C	gauss	$1\ Wb/m^2 = 10^4$ gauss
Magnetic field strength	H	amp-turn/m	C/m·s	oersted	1 amp-turn/m = $4\pi \times 10^{-3}$ oersted
Magnetization	M (SI) I (cgs–emu)	amp-turn/m	C/m·s	$maxwell/cm^2$	1 amp-turn/m = $10^{-3}\ maxwell/cm^2$
Permeability of a vacuum	μ_0	henry/m[b]	$kg{\cdot}m/C^2$	Unitless (emu)	$4\pi \times 10^{-7}$ henry/m = 1 emu
Relative permeability	μ_r (SI) μ' (cgs–emu)	Unitless	Unitless	Unitless	$\mu_r = \mu'$
Susceptibility	χ_m (SI) χ'_m (cgs–emu)	Unitless	Unitless	Unitless	$\chi_m = 4\pi\chi'_m$

[a] Units of the weber (Wb) are volt-seconds.

[b] Units of the henry are webers per ampere.

Magnetization of a material—dependence on susceptibility and magnetic field strength

The magnitude of M is proportional to the applied field as follows:

$$M = \chi_m H \tag{20.6}$$

magnetic susceptibility

and χ_m is called the **magnetic susceptibility,** which is unitless.[1] The magnetic susceptibility and the relative permeability are related as follows:

Relationship between magnetic susceptibility and relative permeability

$$\chi_m = \mu_r - 1 \tag{20.7}$$

There is a dielectric analogue for each of the foregoing magnetic field parameters. The B and H fields are, respectively, analogous to the dielectric displacement D and the electric field $\mathscr{E}$, whereas the permeability μ parallels the permittivity ϵ (cf. Equations 20.2 and 18.30). Furthermore, the magnetization M and polarization P are correlates (Equations 20.5 and 18.31).

Magnetic units may be a source of confusion because there are really two systems in common use. The ones used thus far are SI [rationalized *MKS* (meter-kilogram-second)]; the others come from the *cgs–emu* (centimeter-gram-second–electromagnetic unit) system. The units for both systems as well as the appropriate conversion factors are contained in Table 20.1.

Origins of Magnetic Moments

The macroscopic magnetic properties of materials are a consequence of *magnetic moments* associated with individual electrons. Some of these concepts are relatively complex and involve some quantum-mechanical principles beyond the scope of this discussion; consequently, simplifications have been made and some of the details omitted. Each electron in an atom has magnetic moments that originate from two sources. One is related to its orbital motion around the nucleus; being a moving

[1] This χ_m is taken to be the volume susceptibility in SI units, which, when multiplied by H, yields the magnetization per unit volume (cubic meter) of material. Other susceptibilities are also possible; see Problem 20.3.

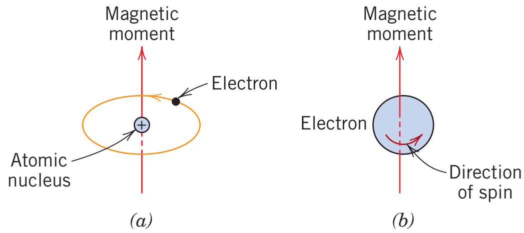

Figure 20.4 Demonstration of the magnetic moment associated with (*a*) an orbiting electron and (*b*) a spinning electron.

charge, an electron may be considered to be a small current loop, generating a very small magnetic field, and having a magnetic moment along its axis of rotation, as schematically illustrated in Figure 20.4*a*.

Each electron may also be thought of as spinning around an axis; the other magnetic moment originates from this electron spin, which is directed along the spin axis as shown in Figure 20.4*b*. Spin magnetic moments may be only in an "up" direction or in an antiparallel "down" direction. Thus each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments.

Bohr magneton

The most fundamental magnetic moment is the **Bohr magneton** μ_B, which is of magnitude 9.27×10^{-24} A·m^2. For each electron in an atom the spin magnetic moment is $\pm\mu_B$ (plus for spin up, minus for spin down). Furthermore, the orbital magnetic moment contribution is equal to $m_l\mu_B$, m_l being the magnetic quantum number of the electron, as mentioned in Section 2.3.

In each individual atom, orbital moments of some electron pairs cancel each other; this also holds for the spin moments. For example, the spin moment of an electron with spin up will cancel that of one with spin down. The net magnetic moment, then, for an atom is just the sum of the magnetic moments of each of the constituent electrons, including both orbital and spin contributions, and taking into account moment cancellation. For an atom having completely filled electron shells or subshells, when all electrons are considered, there is total cancellation of both orbital and spin moments. Thus materials composed of atoms having completely filled electron shells are not capable of being permanently magnetized. This category includes the inert gases (He, Ne, Ar, etc.) as well as some ionic materials. The types of magnetism include diamagnetism, paramagnetism, and ferromagnetism; in addition, antiferromagnetism and ferrimagnetism are considered to be subclasses of ferromagnetism. All materials exhibit at least one of these types, and the behavior depends on the response of electron and atomic magnetic dipoles to the application of an externally applied magnetic field.

20.3 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.