Chapter 20

- Introduction
- Basic concepts
- Diamagnetism and paramagnetism
- Ferromagnetism
- Antiferromagnetism and ferrimagnetism
- The influence of temperature on magnetic behavior
- Domains and hysteresis
- Magnetic anisotropy
- Soft magnetic materials
- Hard magnetic materials
- Magnetic storage
- Superconductivity
Magnetic Properties

(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.
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

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.
**Magnetic dipoles**

- Magnetic forces are generated by moving electrically charged particles.
- The magnetic field distributions as indicated by lines of force are shown for a current loop and also a bar magnetic in Fig. 20.1.
- Magnetic dipoles are found to exist in magnetic materials. **Magnetic dipoles** may be thought of as small bar magnets composed of north and south poles. Magnetic dipoles are influenced by magnetic fields.
- In present discussion, magnetic dipole moments are represented by arrows (Fig. 20.2).
- Within a magnetic field, the force of the field itself exerts a torque that tends to orient the dipoles with the field.

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

**Fig. 20.2** The magnetic moment as designated by an arrow.
**Magnetic field vectors**

- If the external applied magnetic field \( H \) (magnetic field strength, unit: A/m) 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 \( I \) (Fig. 20.3a), then

\[
H = \frac{NI}{l} \quad (20.1)
\]

- The magnetic induction \( B \) (magnetic flux density, unit: tesla or Wb/m² or kg/s·C) represents the magnitude of the internal field strength within a substance that is subjected to an \( H \) field.

\[
B = \mu H \quad (20.2)
\]

\( \mu \): permeability, Wb/A·m, H/m, kg·m/C²

Fig. 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 \( l \). The magnetic flux density \( B_0 \) in the presence of a vacuum is equal to \( \mu_0 H \), where \( \mu_0 \) 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 \( \mu H \), where \( \mu \) is the permeability of the solid material.
- **Permeability of a vacuum**: in a vacuum
  \[ B_0 = \mu_0 H \]  
  \( \mu_0 \): permeability of a vacuum, \( 4\pi \times 10^{-7} \) H/m, \( 4\pi \times 10^{-7} \) Wb/A\cdot m, \( 4\pi \times 10^{-7} \) kg\cdot m/C\(^2\).

- **Relative permeability**: the ratio of the permeability in a material to the permeability in a vacuum.
  \[ \mu_r = \mu / \mu_0 \]  
  \( \mu_r \): relative permeability, 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** (\( M \)) of the solid
  \[ B = \mu_0 H + \mu_0 M \]  
  (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 magnitude of \( M \) is proportional to the applied field \( H \).

\[ M = \chi_m H \]  
(20.6)

\( \chi_m \): magnetic susceptibility, unitless.
Basic Concepts

\[ B = \mu_0 H + \mu_0 M = \mu_0 H + \mu_0 \chi_m H = \mu_0 H \cdot (1 + \chi_m) \]

\[ B = \mu H = \mu_0 \mu_r H \]

\[ \Rightarrow \mu_0 \mu_r H = \mu_0 H \cdot (1 + \chi_m) \]

\[ \Rightarrow \chi_m = \mu_r - 1 \quad (20.7) \]
Basic Concepts

- Comparable symbol

magnetic dipole  electric dipole
\[ B \quad D \]
\[ H \quad \xi \]
\[ \mu \quad \varepsilon \]
\[ M \quad P \]

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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>SI Units</th>
<th>cgs–emu Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic induction</td>
<td>( B )</td>
<td>Derived ( \text{tesla (Wb/m}^2))</td>
<td>kg/s•C</td>
<td>gauss</td>
</tr>
<tr>
<td>(flux density)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>( H )</td>
<td>amp-turn/m</td>
<td>C/m•s</td>
<td>oersted</td>
</tr>
<tr>
<td>Magnetization</td>
<td>( M ) (SI)</td>
<td>amp-turn/m</td>
<td>C/m•s</td>
<td>maxwell/cm(^2)</td>
</tr>
<tr>
<td></td>
<td>( I ) (cgs–emu)</td>
<td>amp-turn/m</td>
<td>C/m•s</td>
<td></td>
</tr>
<tr>
<td>Permeability of a vacuum</td>
<td>( \mu_0 )</td>
<td>henry/m(^b)</td>
<td>kg•m/C(^2)</td>
<td>Unitless (emu)</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>( \mu_r ) (SI)</td>
<td>Unitless</td>
<td>Unitless</td>
<td>Unitless</td>
</tr>
<tr>
<td></td>
<td>( \mu' ) (cgs–emu)</td>
<td>Unitless</td>
<td>Unitless</td>
<td>Unitless</td>
</tr>
<tr>
<td>Susceptibility</td>
<td>( \chi_m ) (SI)</td>
<td>Unitless</td>
<td>Unitless</td>
<td>Unitless</td>
</tr>
<tr>
<td></td>
<td>( \chi'_m ) (cgs–emu)</td>
<td>Unitless</td>
<td>Unitless</td>
<td>Unitless</td>
</tr>
</tbody>
</table>

\(^a\) Units of the weber (Wb) are volt-seconds.

\(^b\) Units of the henry are webers per ampere.
• **Original of magnetic moments**
  - The macroscopic magnetic properties of materials are a consequence of magnetic moments associated with individual electrons.
  - Each electron in an atom has magnetic moments that originate from two sources. One is related to **electron orbital motion around the nucleus**; 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 (Fig. 20.4a). The other magnetic moment originates from **electron spin**, which is directed along the spin axis (Fig. 20.4b). Spin magnetic moments may be only in an “up” direction or in a “down” direction.

![Magnetic moment](image)

**Fig. 20.4** Demonstration of the magnetic moment associated with (a) an orbiting electron and (b) a spinning electron.
Each electron in an atom may be thought of as being a small magnet having permanent orbital and spin magnetic moments.

- The most fundamental magnetic moment is the Bohr magneton \( \mu_B \), \( 9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2 \).

For each electron in an atom the spin magnetic moment is \( \pm \mu_B \) (plus for spin up, minus for spin down).

The orbital magnetic moment contribution is equal to \( m_I \mu_B \), \( m_I \) being the magnetic quantum number of the electron.

- In each individual atom, orbital moments of some electron pairs cancel each other, this is also holds for the spin moments.

For an atom having completely filled electron shells or subshells, 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 gas (He, Ne, Ar, etc.) as well as some ionic materials.
Example Problem

Using the relationship $\mu_B = \frac{e \hbar}{4\pi m}$, show that the numerical value for a Bohr magneton is $9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$. ($e$: $1.6 \times 10^{-19} \text{ C}$, $\hbar$: $6.63 \times 10^{-34} \text{ J} \cdot \text{s}$, $m$: $9.11 \times 10^{-31} \text{ kg}$)

$$
\mu_B = \frac{e \hbar}{4\pi m} = \frac{1.60 \times 10^{-19} \text{ C} \times 6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{4\pi \times 9.11 \times 10^{-31} \text{ kg}} = 9.27 \times 10^{-24} \frac{\text{C} \cdot \text{J} \cdot \text{s}}{\text{kg}}
$$

$$
\therefore \frac{\text{C} \cdot \text{J} \cdot \text{s}}{\text{kg}} = \frac{(A \cdot \text{s}) \cdot (N \cdot \text{m}) \cdot \text{s}}{\text{kg}} = (A \cdot \text{s}) \cdot \frac{(\frac{\text{kg} \cdot \text{m}}{\text{s}^2} \cdot \text{m}) \cdot \text{s}}{\text{kg}} = A \cdot \text{m}^2
$$

$\Rightarrow \mu_B = 9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$
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 (Fig. 20.5a).
  - $\mu_r < 1, \chi_m (\approx -10^{-5}) < 0, B < B_0$.
  - The dependence of $B$ on the external field $H$ for a material that exhibits diamagnetic behavior is presented in Fig. 20.6. Table 20.2 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.
Fig. 20.5 (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 aligned opposite to the field direction. 
(b) Atomic dipole configuration with and without an external magnetic field for a paramagnetic material.
Diamagnetism and Paramagnetism

Fig. 20.6 Schematic representation of the flux density $B$ versus the magnetic field strength $H$ for Diamagnetic and paramagnetic materials.

Table 20.2  Room-Temperature Magnetic Susceptibilities for Diamagnetic and Paramagnetic Materials

<table>
<thead>
<tr>
<th>Diamagnetics</th>
<th>Susceptibility $\chi_m$ (volume) (SI units)</th>
<th>Paramagnetics</th>
<th>Susceptibility $\chi_m$ (volume) (SI units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>$-1.81 \times 10^{-5}$</td>
<td>Aluminum</td>
<td>$2.07 \times 10^{-5}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$-0.96 \times 10^{-5}$</td>
<td>Chromium</td>
<td>$3.13 \times 10^{-4}$</td>
</tr>
<tr>
<td>Gold</td>
<td>$-3.44 \times 10^{-5}$</td>
<td>Chromium chloride</td>
<td>$1.51 \times 10^{-3}$</td>
</tr>
<tr>
<td>Mercury</td>
<td>$-2.85 \times 10^{-5}$</td>
<td>Manganese sulfate</td>
<td>$3.70 \times 10^{-3}$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$-0.41 \times 10^{-5}$</td>
<td>Molybdenum</td>
<td>$1.19 \times 10^{-4}$</td>
</tr>
<tr>
<td>Silver</td>
<td>$-2.38 \times 10^{-5}$</td>
<td>Sodium</td>
<td>$8.48 \times 10^{-6}$</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>$-1.41 \times 10^{-5}$</td>
<td>Titanium</td>
<td>$1.81 \times 10^{-4}$</td>
</tr>
<tr>
<td>Zinc</td>
<td>$-1.56 \times 10^{-5}$</td>
<td>Zirconium</td>
<td>$1.09 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
**Diamagnetism and Paramagnetism**

- **Paramagnetism**
  - For some materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments. In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization. These atomic dipoles are free to rotate, and **paramagnetism** results when they preferentially align, by rotation, with an external field (Fig. 20.5b). These magnetic dipoles are acted on individually with no mutual interaction between adjacent dipoles.
  - $\mu_r > 1$, $\chi_m \times (10^{-5} - 10^{-2}) > 0$, $B > B_0$.
  - A schematic $B$-versus-$H$ curve for a paramagnetic material is shown in Fig. 20.6.
  - Both diamagnetic and paramagnetic materials are considered nonmagnetic because they exhibit magnetization only when in the presence of an external field.
**Ferromagnetism**

- Certain metallic materials posses a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations. These are characteristics of **ferromagnetism**. (Exists in Fe, Co, Ni, and some of rare earth metals.)
- It results from atomic magnetic moments due to **uncancelled electron spins** as a consequence of the electron structure.
- Magnetic susceptibilities as high as $10^6$ are possible for ferromagnetic materials. Consequently, $H \ll M$,
  \[ B = \mu_0 H + \mu_0 M \approx \mu_0 M \quad (20.8) \]
- 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.
- The mutual spin alignment exists over large volume regions of the crystal called **domains**.
- 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.

Fig. 20.7 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.
Calculate (a) the saturation magnetization and (b) the saturation flux density for nickel, which has a density of 8.90 g/cm\(^3\). (Molar weight 58.71 g/mol, Ni: 0.60 Bohr magneton, \(\mu_B = 9.27 \times 10^{-24}\) A\(\cdot\)m\(^2\), \(\mu_0 = 4\pi \times 10^{-7}\) H/m)

(a) \(8.90\, g / cm^3 = 8.90 \times 10^6\, g / m^3\)

\[
N_{Ni} = \frac{\rho_{Ni} N_A}{A_{Ni}} = \frac{(8.90 \times 10^6) \times (6.023 \times 10^{23})}{58.71} = 9.12 \times 10^{28}
\]

\[
M_S = 0.60 \cdot \mu_B \cdot N_{Ni} = 0.60 \times (9.27 \times 10^{-24}) \times (9.12 \times 10^{28}) = 5.1 \times 10^5 \quad (A/m)
\]

(b) \(B_S = \mu_0 M_S = (4\pi \times 10^{-7}) \times (5.1 \times 10^5) = 0.64 \quad (\text{Tesla})\)
Antiferromagnetism and Ferrimagnetism

- **Antiferromagnetism**
  - The alignment of the spin moments of neighboring atoms or ions in exactly opposite directions is termed *antiferromagnetism*.
  - Example: MnO

No net magnetic moment is associated with the O$^{2-}$ ions, because there is a total cancellation of both spin and orbital moments. 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 adjacent Mn$^{2+}$ ions are antiparallel (Fig. 20.8). ⇒ no net magnetic moment.

**Fig. 20.8** Schematic representation of antiparallel alignment of spin magnetic moments for antiferromagnetic manganese oxide.
Ferrimagnetism

- Some ceramics exhibit a permanent magnetization, termed ferrimagnetism. The principles of ferrimagnetism are illustrated with the cubic ferrites. These ionic materials may be represented by the chemical formula MFe$_2$O$_4$, in which M represents any one of several metallic elements.

- Example: the formula Fe$_3$O$_4$ may be written as Fe$^{2+}$O$^{2-}$(Fe$^{3+})_2$(O$^{2-})_3$. A net spin magnetic moment of Fe$^{2+}$ and Fe$^{3+}$ are 4 and 5 Bohr magnetons, respectively. The O$^{2-}$ ions are magnetically neutral.

The inverse spinel crystal structure might be thought of as having been generated by the stacking of close-packed planes of O$^{2-}$.

There are two types of positions that may be occupied by the iron cations (Fig. 12.7). For one, the coordination number is 4 (tetrahedral coordination). For the other, the coordination number is 6 (octahedral coordination).
Antiferromagnetism and Ferrimagnetism

Half the Fe$^{3+}$ ions are situated in octahedral positions, and the other half in tetrahedral positions. The spin moments of all Fe$^{3+}$ ions cancel one another (Fig. 20.9). All the Fe$^{2+}$ ions have their moments aligned in the same direction; this total moment is response for the net magnetization (Table 20.3). Thus, the saturation magnetization of a ferrimagnetic solid may be computed from the product of the net spin magnetic moment for Fe$^{2+}$ ion and the number of Fe$^{2+}$ ions.

- M$^{2+}$ may represent divalent ions such as Ni$^{2+}$, Mn$^{2+}$, Co$^{2+}$, and Cu$^{2+}$, each of which possesses a net spin magnetic moment different from 4 (Table 20.4). Thus, by adjustment of composition, ferrite compounds having a range of magnetic properties may be produced.

Fig. 20.9 Schematic diagram showing the spin magnetic moment configuration for Fe$^{2+}$ and Fe$^{3+}$ ions in Fe$_3$O$_4$. 
Antiferromagnetism and Ferrimagnetism

- The saturation magnetizations for ferrimagnetic materials are not as high as for ferromagnets.
- Ferrimagnetic materials are good electrical insulators.
- Application: high-frequency transformers.

<table>
<thead>
<tr>
<th>Cation</th>
<th>Octahedral Lattice Site</th>
<th>Tetrahedral Lattice Site</th>
<th>Net Magnetic Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe³⁺</td>
<td>↑↑↑↑↑↑↑↑</td>
<td>↓↓↓↓↓↓↓↓</td>
<td>Complete cancellation</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>↑↑↑↑↑↑↑↑</td>
<td>—</td>
<td>↑↑↑↑↑↑↑</td>
</tr>
</tbody>
</table>

Table 20.3 The Distribution of Spin Magnetic Moments for Fe²⁺ and Fe³⁺ Ions in a Unit Cell Fe₃O₄

Table 20.4 Net Magnetic Moments for Six Cations

<table>
<thead>
<tr>
<th>Cation</th>
<th>Net Spin Magnetic Moment (Bohr magnetons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe³⁺</td>
<td>5</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>4</td>
</tr>
<tr>
<td>Mn²⁺</td>
<td>5</td>
</tr>
<tr>
<td>Co²⁺</td>
<td>3</td>
</tr>
<tr>
<td>Ni²⁺</td>
<td>2</td>
</tr>
<tr>
<td>Cu²⁺</td>
<td>1</td>
</tr>
</tbody>
</table>

Each arrow represents the magnetic moment orientation for one of the cations.
Fig. (a) Unit cell of soft ferrite of the type MO·Fe$_2$O$_3$. This unit cell consists of 8 subcells. (b) The subcell for the FeO·Fe$_2$O$_3$ ferrite. The magnetic moments of the ions in the octahedral sites are aligned in one direction by the applied magnetic field, and those in the tetrahedral sites are aligned in the opposite direction. As a result, there is a net magnetic moment for the subcell and hence the material.
Antiferromagnetism and Ferrimagnetism

Normal spinel structure

- $c = 0$
- $c = 1/8$
- $c = 1/4$
- $c = 3/8$
- $c = 1/2$
- $c = 5/8$
- $c = 3/4$
- $c = 7/8$
- $c = 1$

- Oxygen
- Octahedral cation
- Tetrahedral cation
**Fig.** Electronic configurations and ionic magnetic moments for some 3d transition-element ions.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Number of electrons</th>
<th>Electron configuration 3d orbitals</th>
<th>Ionic magnetic moment (Bohr magnetons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$^{3+}$</td>
<td>23</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>5</td>
</tr>
<tr>
<td>Mn$^{2+}$</td>
<td>23</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>5</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>24</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>4</td>
</tr>
<tr>
<td>Co$^{2+}$</td>
<td>25</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>3</td>
</tr>
<tr>
<td>Ni$^{2+}$</td>
<td>26</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>2</td>
</tr>
<tr>
<td>Cu$^{2+}$</td>
<td>27</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>1</td>
</tr>
<tr>
<td>Zn$^{2+}$</td>
<td>28</td>
<td><img src="image" alt="Electron configuartions" /></td>
<td>0</td>
</tr>
</tbody>
</table>
Calculate a theoretical value for the saturation magnetization $M_s$ in amperes per meter and saturation induction $B_s$ in teslas for pure iron, assuming all magnetic moments due to the four unpaired 3d Fe electrons are aligned in a magnetic field. Use the equation $B_s \approx \mu_0 M_s$ and assume that $\mu_0 H$ can be neglected. Pure iron has a BCC unit cell with a lattice constant $a = 0.287$ nm. ($\mu_B = 9.27 \times 10^{-24}$ A·m², $\mu_0 = 4\pi \times 10^{-7}$ T·m/A)

In a BCC unit cell there are 2 Fe atoms in the cell. Each Fe atom has 4 Bohr magnetons.

$$M_s = \frac{\text{dipole - moment}}{\text{volume}} = \frac{2Fe}{V_{\text{cell}}} \times 4\mu_B / Fe = \frac{8\mu_B}{V_{\text{cell}}}$$

$$M_s = \frac{8 \times 9.27 \times 10^{-24} A \cdot m^2}{(0.287 \times 10^{-9} m)^3} = 3.14 \times 10^6 A/m$$

$$B_s \approx \mu_0 M_s = 4\pi \times 10^{-7} \frac{T \cdot m}{A} \times 3.14 \times 10^6 \frac{A}{m} = 3.94 T$$
Iron has a saturation magnetization of $1.71 \times 10^6$ A/m. What is the average number of Bohr magnetons per atom that contribute to this magnetization? Iron has the BCC crystal structure with $a = 0.287$ nm. ($\mu_B = 9.27 \times 10^{-24}$ A·m²)

In a BCC unit cell there are 2 Fe atoms in the cell. Supposed that each Fe atom has $x$ Bohr magnetons.

$$M_s = \frac{\text{dipole - moment}}{\text{volume}} = \frac{2Fe}{V_{\text{cell}}} \times x\mu_B / Fe = \frac{2x\mu_B}{V_{\text{cell}}}$$

$$M_s = \frac{2x \times 9.27 \times 10^{-24} A \cdot m^2}{\left(0.287 \times 10^{-9} m\right)^3} = 1.71 \times 10^6 A / m$$

$\Rightarrow x = 2.18$

Therefore, there are 2.18 Bohr magnetons for each Fe atom.
Example Problem 20.2

Calculate the saturation magnetization for Fe₃O₄ given that each cubic unit cell contains 8 Fe²⁺ and 16 Fe³⁺ ions, and that the unit cell edge length is 0.839 nm.

Edge length of unit cell = 0.839×10⁻⁹ m
Volume of unit cell = (0.839×10⁻⁹)³ m³
Magnetic moment per Fe²⁺ ion = 4 Bohr magnetons
Number of Fe²⁺ ions per unit cell = 8

\[ M_s = N_{Fe^{2+}} \times 4 \times \mu_B = \left( \frac{8}{(0.839 \times 10^{-9})^3} \right) \times 4 \times \left(9.27 \times 10^{-24}\right) = 5.0 \times 10^5 \text{ (A/m)} \]
Design a cubic mixed-ferrite magnetic material that has a saturation magnetization of $5.25 \times 10^5$ A/m. ($M_S$ for Fe$_3$O$_4$: $5.0 \times 10^5$ A/m, edge length of unit cell: 0.839 nm)

<table>
<thead>
<tr>
<th>Cation</th>
<th>Net Spin Magnetic Moment (Bohr magnetons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$^{3+}$</td>
<td>5</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>4</td>
</tr>
<tr>
<td>Mn$^{2+}$</td>
<td>5</td>
</tr>
<tr>
<td>Co$^{2+}$</td>
<td>3</td>
</tr>
<tr>
<td>Ni$^{2+}$</td>
<td>2</td>
</tr>
<tr>
<td>Cu$^{2+}$</td>
<td>1</td>
</tr>
</tbody>
</table>

For Fe$^{2+}$O$^2-$($Fe^{3+}$)$_2$(O$^{2-}$)$_3$

$$n_B = 4 \times 8 = 32$$

In order to increase the magnitude of $M_S$ it is necessary to replace some fraction of the Fe$^{2+}$ with a divalent metal ion that has a greater magnetic moment—for example Mn$^{2+}$.

$$M_S = \frac{n_B \mu_B}{a^3}$$

$$\Rightarrow 5.25 \times 10^5 = \frac{n_B \times (9.27 \times 10^{-24})}{(0.839 \times 10^{-9})^3}$$

$$\Rightarrow n_B = 33.45 \quad \text{(Bohr magnetons/unit cell)}$$

$$[(Mn^{2+})_x(Fe^{2+})_{1-x}O^{2-}(Fe^{3+})_2(O^{2-})_3]$$

$$\Rightarrow n_B = [5x + 4(1-x)] \times 8 = 33.45$$

$$\Rightarrow x = 0.181$$

If 18.1 at% of the Fe$^{2+}$ in Fe$_3$O$_4$ are replaced with Mn$^{2+}$, the saturation magnetization will be increased to $5.25 \times 10^5$ A/m.
• Influence of temperature

- With rising temperature, the increased thermal motion of the atoms tend to randomize the directions of any moments that may be aligned.
- The saturation magnetization is a maximum at 0 K, at which temperature thermal vibrations are a minimum. With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at what is called the Curie temperature $T_C$ (Fig. 20.10). (Fe: 768°C, Co: 1120°C, Ni: 335°C, Fe$_3$O$_4$: 585°C)

At $T_C$ the mutual spin-coupling forces are completely destroyed, such that for temperatures above $T_C$ both ferromagnetic and ferrimagnetic materials are paramagnetic.
- Antiferromagnetism is affected by temperature; this behavior vanishes at what is called the Néel temperature. At temperature above this point, antiferromagnetic materials become paramagnetic.
Fig. 20.10 Plot of saturation magnetization as a function of temperature for iron and Fe$_3$O$_4$. 
Domains and Hysteresis

- **Domain**

  - Any ferromagnetic or ferrimagnetic material that is at a temperature below $T_C$ is composed of small-volume regions in which there is a mutual alignment in the same direction of all magnetic dipole moments (Fig. 20.11). Such a region is called a **domain**, and each one is magnetized to its saturation magnetization.
  
  - Adjacent domains are separated by a **domain boundaries or walls**, across which the direction of magnetization gradually changes (Fig. 20.12).

**Fig. 20.11** Schematic depiction of domains in a ferromagnetic or ferrimagnetic material; arrows represent atomic magnetic dipoles. Within each domain, all dipoles are aligned, whereas the direction of alignment varies from one domain to another.

**Fig. 20.12** The gradual change in magnetic dipole orientation across a domain wall.
- For a polycrystalline specimen, each grain may consist of more than a single domain.

- The magnitude of the $M$ field for the entire solid is the vector sum of the magnetization of all the domains, each domain contribution being weighted by its volume fraction.

For an unmagnetized specimen, the appropriately weighted vector sum of the magnetizations of all the domains is zero.
• **Domains and hysteresis**
  - If the material is initially unmagnetized, then $B$ varies as a function of $H$ (Fig. 20.13).
  - The curve begins at the origin, and as $H$ is increased, the $B$ field begins to increase slowly, then more rapidly, finally leveling off and becoming independent of $H$.
  - The maximum value of $B$ is the **saturation flux density** $B_S$, and the corresponding magnetization is the **saturation magnetization** $M_S$.
  - Because the permeability $\mu$ changes with and is dependent on $H$, the slope of the $B$-versus-$H$ curve at $H = 0$ is specified as a material property, which is termed the **initial permeability** $\mu_i$.
  - As an $H$ field is applied, the domains change shape and size by the movement of domain boundaries.
  Initially, the moments of the constituent domains are randomly oriented such that there is no net $B$ (or $M$) field (inset U).
As the external field is applied, the domains that are oriented in directions favorable to (or nearly aligned with) the applied field grow at the expense of those that are unfavorably oriented (insets V through X). This process continues with increasing field strength until the macroscopic specimen becomes a single domain, which is nearly aligned with the field. Saturation is achieved when this domain becomes oriented with the $H$ field (inset Z).

**Fig. 20.13** The $B$-versus-$H$ behavior for a ferromagnetic or ferrimagnetic material that was initially unmagnetized. Domain configurations during several stages of magnetization are represented. Saturation flux density $B_S$, magnetization $M_S$, and initial permeability $\mu_i$ are also indicated.
- In Fig. 20.14, from saturation (point S), as the $H$ field is reduced by reversal of field direction, the curve does not retrace its original path. A hysteresis effect is produced in which the $B$ field lags behind the applied $H$ field, or decreases at a lower rate. At zero $H$ field (point R), there exists a residual $B$ field that is called remanence, or remanent flux density $B_r$; the material remains magnetized in the absence of an external $H$ field.

To reduce the $B$ field within the specimen to zero (point C), an $H$ field of magnitude $H_C$ must be applied in a direction opposite to that of the original field; $H_C$ is called the coercivity, or the coercive force.

**Fig. 20.14** Magnetic flux density versus the magnetic field strength for a ferromagnetic material that is subjected to forward and reverse saturations (points S and S’). The hysteresis loop is represented by the solid curve; the dashed curve indicates the initial magnetization. The remanence $B_r$ and the coercive force $H_C$ are also shown.
Domains and Hysteresis

- The $B$-versus-$H$ curve in Fig. 20.14 represents a hysteresis loop taken to saturation.
- It is not necessary to increase the $H$ field to saturation before reversing the field direction. In Fig. 20.15, loop NP is a hysteresis curve corresponding to less than saturation. It is possible to reverse the direction of the field at any point along the curve and generate other hysteresis loops.
- One method of demagnetizing a ferromagnet or ferrimagnet is to repeatedly cycle it in an $H$ field that alternates direction and decreases in magnitude.

\[
N = \frac{kg \cdot m}{s^2} = \frac{kg \cdot m^2}{s^2} \quad H = \frac{C}{m \cdot s}
\]

\[
J = N \cdot m = \frac{kg \cdot m^2}{s^2} \quad B \cdot H = \left( \frac{kg}{(s \cdot C)} \right) \cdot \left( \frac{C}{m \cdot s} \right) = \frac{kg}{m \cdot s^2}
\]

\[
B = \frac{kg}{s \cdot C} \quad \Rightarrow B \cdot H = \left( \frac{kg \cdot m^2}{s^2} \right) \cdot \left( \frac{1}{m^3} \right) = \frac{J}{m^3}
\]

**Fig. 20.15** A hysteresis curve at less than saturation (curve NP) within the saturation loop for a ferromagnetic material. The $B$-$H$ behavior for field reversal at other than saturation is indicated by curve LM.
- In Fig. 20.16, the linearity of paramagnetic and diamagnetic materials may be noted in the small inset plot, whereas the behavior of a typical ferromagnetic/ferrimagnetic is nonlinear.
- The ferromagnetic/ferrimagnetic materials flux density is on the order of 1.5 tesla, whereas for the paramagnetic and diamagnetic materials it is on the order of $5 \times 10^{-5}$ tesla.

**Fig. 20.16** Comparison of $B$-versus-$H$ behaviors for ferromagnetic/ferrimagnetic and diamagnetic/paramagnetic materials (inset plot). Here it may be noted that extremely small $B$ fields are generated in materials that experience only diamagnetic/paramagnetic behavior, which is why they are considered nonmagnetics.
Magnetic Anisotropy

- Magnetic anisotropy
  - The magnetic hysteresis curves will have different shapes depending on various factors: (1) whether the specimen is a single crystal or polycrystalline; (2) if polycrystalline, any preferred orientation of the grains; (3) the presence of pores or second-phase particles; and (4) other factors such as temperature and the stress state.
  - Fig. 20.17 shows the $B$ (or $M$) versus $H$ curve for single crystals of nickel (fcc) and iron (bcc).
  - Fig. 20.18 depicts the $B$ versus $H$ curve for single crystals of cobalt (hcp).

Fig. 20.17 Magnetization curves for single crystals of iron and nickel. For both metals, a different curve was generated when the magnetic field was applied in each of [100], [110], and [111] crystallographic directions.
- The dependence of magnetic behavior or crystallographic orientation is termed magnetic (magnetocrystalline) anisotropy.
- For each of these materials there is one crystallographic direction in which magnetization is easiest—that is, saturation (of $M$) is achieved at the lowest $H$ field; this is termed a direction of easy magnetization.

Easy magnetization directions for Ni, Fe, and Co are [111], [100], and [0001], respectively (Figs. 20.17 & 20.18).

- A hard crystallographic direction is that direction for which saturation magnetization is most difficult; hard directions for Ni, Fe, and Co are [100], [111], and [10$ar{1}$0]/[11$ar{2}$0].

**Fig. 20.18** Magnetization curves for single crystals of cobalt. The curves were generated when the magnetic field was applied in [0001] and [10$ar{1}$0]/[11$ar{2}$0] crystallographic directions.
Energies that Determine the Structure of Ferromagnetic Domains

- **Introduction**

The total magnetic energy of a ferromagnetic material is the sum of the contributions of the following energies: (1) exchange energy, (2) magnetostatic energy, (3) magnetocrystalline anisotropy energy, (4) domain wall energy, and (5) magnetostrictive energy.

- **Exchange energy**

  - The potential energy within a domain of a ferromagnetic solid is minimized when all its atomic dipoles are aligned in one direction (exchange energy). This alignment is associated with a positive exchange energy.
  
  - However, its external potential energy is increased by the formation of an external magnetic field.

*Fig.* Schematic illustration showing how reducing the domain size in a magnetic material decreases the magnetostatic energy by reducing the external magnetic field. (a) One domain, (b) two domains, and (c) four domains.
Magnetostatic energy

- Magnetostatic energy is the potential magnetic energy of a ferromagnetic material produced by its external field. This potential energy can be minimized in a ferromagnetic material by domain formation.

- Since the intensity of the external magnetic field of a ferromagnetic material is directly related to its magnetostatic energy, the formation of multiple domains reduces the magnetostatic energy of a unit volume of material.
• Magnetocrystalline anisotropy energy
  - Magnetization versus applied field curves for a single crystal of a ferromagnetic material can vary, depending on the crystal orientation relative to the applied field.
  - For single crystals of BCC iron, saturation magnetization occurs most easily for the <100> directions and with the highest applied field in the <111> directions. But for FCC nickel the easy directions of magnetization are the <111> directions and the <100> the hard directions.
  - The work done to rotate all the domains because of this anisotropy is called the magnetocrystalline anisotropy energy.

**Fig.** Magnetocrystalline anisotropy in BCC iron. Iron is magnetized easier in the <100> directions than in the <111> directions.
Energies that Determine the Structure of Ferromagnetic Domains

- Domain wall energy
  - A domain wall is the boundary between two domains whose overall magnetic moments are at different orientations. Grains change orientation abruptly and which is about three atoms wide. However, a domain changes orientation gradually with a domain boundary being ~300 atoms wide.
  - The large width of a domain wall is due to a balance between two forces: exchange energy and magnetocrystalline anisotropy. When there is only a small difference in orientation between the dipoles, the exchange forces between the dipoles are minimized and the exchange energy is reduced. Thus, the exchange forces will tend to widen the domain wall.

Fig. Schematic illustration of (a) magnetic dipole arrangements at domain wall and (b) relationship among magnetic exchange energy, magnetocrystalline anisotropy energy, and wall width. The equilibrium wall width is ~100 nm.
Energies that Determine the Structure of Ferromagnetic Domains

The wider the wall is, the greater will be the number of dipoles forced to line in directions different from those of easy magnetization, and the magnetocrystalline anisotropy energy will be increased. Thus, the equilibrium wall width will be reached at the width where the sum of the exchange and magnetocrystalline anisotropy energies is a minimum.

![Diagram showing the relationship between wall width and energy](image-url)
Energies that Determine the Structure of Ferromagnetic Domains

• Magnetostrictive energy
  - When a ferromagnetic material is magnetized, its dimensions change slightly, and the sample being magnetized either expands or contracts in the direction of magnetization. This magnetically induced reversible elastic strain ($\Delta l/l$) is called magnetostriction and is of the order of $10^{-6}$. The energy due to the mechanical stresses created by magnetostriction is called magnetostrictive energy.
  - The fields of the dipoles may attract or repel each other, leading to the contraction or expansion of the metal during magnetization.

**Fig.** Magnetostrictive behavior of Fe, Co, and Ni ferromagnetic elements. Magnetostriction is a fractional elongation (or contraction) and in this illustration is in units of micrometers per meter.
Energies that Determine the Structure of Ferromagnetic Domains

- Because of the cubic symmetry of the crystals, the formation of triangular-shaped domains, called **domains of closure**, at the ends of the crystal eliminates the magnetostatic energy associated with an external magnetic field and hence lowers the energy of the material.

- Very large domains possess the minimum wall energy. However, magnetostrictive stresses introduced during magnetization tend to be larger for larger domains. Thus, the equilibrium domain configuration is reached when the sum of the magnetostrictive and domain wall energies is a minimum.

- The equilibrium or most stable configuration occurs when the total magnetic energy is the lowest.

**Fig.** Magnetostriction in cubic magnetic materials. Schematic exaggeration of (a) negative and (b) positive magnetostriction pulling apart the domain boundaries of a magnetic material. (c) Lowering of magnetostrictive stresses by the creation of a smaller-domain-size structure.
- Soft magnetic materials
  - 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.
  - 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. A soft magnetic material must have a high initial permeability and a low coercivity (Fig. 20.19).
  A material possessing these properties may reach its saturation magnetization with a relatively low applied field and still has low hysteresis energy losses.
  - 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, a soft magnetic material must thus be free of such structural defects.
- MGOe
  1 MGOe = 10^6 gauss-oersted = 7.96 kJ/m³.
- 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 current**. 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.
- The ceramic ferrites are commonly used for applications requiring soft magnetic materials because they are intrinsically electrical insulators.
- Applications: transformer cores, magnetic amplifier, pulse transformer, generators, motors, dynamos, switching circuits.

**Fig. 20.19** Schematic magnetization curves for soft and hard magnetic materials.
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.

**Table 20.5 Typical Properties for Several Soft Magnetic Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (wt %)</th>
<th>Initial Relative Permeability $\mu_i$</th>
<th>Saturation Flux Density $B_s$ (tesla (gauss))</th>
<th>Hysteresis Loss/Cycle ($J/m^3$ (erg/cm$^3$))</th>
<th>Resistivity $\rho$ ($\Omega\cdot m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial iron ingot</td>
<td>99.95Fe</td>
<td>150</td>
<td>2.14</td>
<td>270</td>
<td>$1.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Silicon–iron (oriented)</td>
<td>97Fe, 3Si</td>
<td>1400</td>
<td>2.01</td>
<td>40</td>
<td>$4.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>45 Permalloy</td>
<td>55Fe, 45Ni</td>
<td>2500</td>
<td>1.60</td>
<td>120</td>
<td>$4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Supermalloy</td>
<td>79Ni, 15Fe, 5Mo, 0.5Mn</td>
<td>75,000</td>
<td>0.80</td>
<td>$-$</td>
<td>$6.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Ferroxcube A</td>
<td>48MnFe$_2$O$_4$, 52ZnFe$_2$O$_4$</td>
<td>1400</td>
<td>0.33</td>
<td>$\sim 40$</td>
<td>2000</td>
</tr>
<tr>
<td>Ferroxcube B</td>
<td>36NiFe$_2$O$_4$, 64ZnFe$_2$O$_4$</td>
<td>650</td>
<td>0.36</td>
<td>$\sim 35$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

Fe-Si alloy
- Transformer cores require the use of soft magnetic materials, what are easily magnetized and demagnetized.
- One alloy commonly used for transformer cores is the iron-silicon alloy (97 wt% Fe-3 wt% Si) (Table 20.5).
- Energy losses of transformers could be minimized if their cores were fabricated from single crystals such that a [100]-type direction (the direction of easy magnetization) is oriented parallel to the direction of an applied magnetic field (Fig. 20.20).
- Because single crystals are expensive to prepare, a better alternative is to fabricate cores from polycrystalline sheets of this alloys that are anisotropic.

Fig. 20.20 Schematic diagram of a transformer core, including the direction of the $B$ field that is generated.
- The grains in polycrystalline materials are randomly oriented, with the result that their properties are isotropic.

- One way of developing anisotropy in polycrystalline metals is via plastic deformation, for example by rolling. A flat sheet that has been rolled is said to have a rolling (or sheet) texture, or there is a preferred crystallographic orientation of the grains.

- A rolling texture is indicated by the plane-direction combination, \((hkl)[uvw]\). For body-centered cubic alloys (Fe-Si), the rolling texture is (110)[001] (Fig. 20.21).

- The magnetic characteristics of Fe-Si alloy may be further improved through a series of deformation and heat-treating procedures that produce a (100)[001] texture.

**Fig. 20.21** Schematic representation of the (110)[001] rolling texture for body-centered cubic iron.
**Hard magnetic materials**

- Hard magnetic materials are utilized in permanent magnets, which must have a high resistance to demagnetization. A hard material has a high remanence, coercivity, and saturation flux density, as well as a low initial permeability, and high hysteresis energy losses (Fig. 20.19).

- The value of the energy product \((BH)_{\text{max}}\) corresponds to the area of the largest \(B-H\) rectangle that can be constructed within the second quadrant of the hysteresis curves (Fig. 20.22). The value of the energy product is representative of the energy required to demagnetize a permanent magnet; that is, the larger \((BH)_{\text{max}}\) the harder is the material in terms of its magnetic characteristics.

- By impeding domain wall motion, the coersivity and susceptibility are enhanced, such that a large external field is required for demagnetization.

- Hard magnetic materials fall within two main categories: conventional and high energy hard magnetic materials.
Fig. 20.22 Schematic magnetization curve that displays hysteresis. Within the second quadrant are drawn two \( B-H \) energy product rectangles; the area of that rectangle labeled \((BH)_{\text{max}}\) is the largest possible, which is greater than the area defined by \(B_d - H_d\).
• **Conventional hard magnetic materials**
  - The conventional materials have \((BH)_{max}\) values that range between about 2 and 80 kJ/m³.
  - These include ferromagnetic materials (magnetic steel, cunife alloys: Cu-Ni-Fe, alnico alloys: Al-Ni-Co) and hexagonal ferrites (BaO-6Fe₂O₃).
  - The hard magnet steels are normally alloyed with tungsten and/or chromium. 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.
- **High-energy hard magnetic materials**
  - Permanent magnetic materials having energy products in excess ~80 kJ/m³ are considered to be of the high-energy type.
  - Permanent magnets are far superior to electromagnets in that their magnetic fields are continuously maintained and without the necessity of having to expend electrical power.
  - Samarium-cobalt magnets
    The energy products of the SmCo₅ materials (120-240 kJ/m³) are considerably higher than the conventional hard magnetic materials; in addition, they have relatively large coercivities. Powder metallurgical techniques are used to fabricate SmCo₅ magnets. The price of cobalt is variable and its sources are unreliable.
  - Neodymium-iron-boron magnets
    Energy product: 255 kJ/m³.
    Two different processing techniques are available for the fabrication of Nd₂Fe₁₄B magnets: powder metallurgy (sintering, same as SmCo₅) and rapid solidification (melt spinning).
# Hard Magnetic Materials

## Table 20.6  Typical Properties for Several Hard Magnetic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (wt%)</th>
<th>Remanence $B_r$ [tesla (gauss)]</th>
<th>Coercivity $H_c$ [amp-turn/m (Oe)]</th>
<th>$(BH)_{\text{max}}$ [kJ/m$^3$ (MG0e)]</th>
<th>Curie Temperature $T_c$ [°C (°F)]</th>
<th>Resistivity $\rho$ [Ω·m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten steel</td>
<td>92.8 Fe, 6 W, 0.5 Cr, 0.7 C</td>
<td>0.95 (9500)</td>
<td>5900 (74)</td>
<td>2.6 (0.33)</td>
<td>760 (1400)</td>
<td>$3.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Cunife</td>
<td>20 Fe, 20 Ni, 60 Cu</td>
<td>0.54 (5400)</td>
<td>44,000 (550)</td>
<td>12 (1.5)</td>
<td>410 (770)</td>
<td>$1.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sintered alnico 8</td>
<td>34 Fe, 7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti</td>
<td>0.76 (7600)</td>
<td>125,000 (1550)</td>
<td>36 (4.5)</td>
<td>860 (1580)</td>
<td>—</td>
</tr>
<tr>
<td>Sintered ferrite 3</td>
<td>BaO–6Fe$_2$O$_3$</td>
<td>0.32 (3200)</td>
<td>240,000 (3000)</td>
<td>20 (2.5)</td>
<td>450 (840)</td>
<td>$\sim 10^4$</td>
</tr>
<tr>
<td>Cobalt rare earth 1</td>
<td>SmCo$_5$</td>
<td>0.92 (9200)</td>
<td>720,000 (9,000)</td>
<td>170 (21)</td>
<td>725 (1340)</td>
<td>$5.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Sintered neodymium–iron–boron</td>
<td>Nd$<em>2$Fe$</em>{14}$B</td>
<td>1.16 (11,600)</td>
<td>848,000 (10,600)</td>
<td>255 (32)</td>
<td>310 (590)</td>
<td>$1.6 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Magnetic Storage

- Magnetic storage
  - Magnetic recording has become virtually the universal technology for the storage of electronic information. This is evidenced by the preponderance of disk storage media, credit/debit cards, and so on.
  - 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.
  - 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 (writing) and retrieval from (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.
• **Hard disk drives**
  - Hard disk magnetic storage hard drives consist of rigid circular disks. During read and write processes, disks rotate at relatively high velocities—5400 and 7200 rpm are common.
  - For the current HDD technology, “magnetic bits” point up or down perpendicular to the plane of the disk surface; this scheme is appropriately called **perpendicular magnetic recording (PMR)** (Fig. 20.23).

**Fig. 20.23** Schematic diagram of a hard disk drive that employs the perpendicular magnetic recording medium; also shown are inductive write and magnetoresistive-read heads.
Magnetic Storage

- Data (bits) are introduced (written) into the storage medium using an inductive write head. For one head design, a time-varying write magnetic flux is generated at the tip of the main pole—a ferromagnetic/ferrimagnetic core material around which a wire coil is wound—by an electric current (also time-variable) that passes through the coil. This flux penetrates through the magnetic storage layer into a magnetically soft underlayer and then reenters the head assembly through a return pole (Fig. 20.23). A very intense magnetic field is concentrated in the storage layer beneath the tip of the main pole. At this point, data are written as a very small region of the storage layer becomes magnetized. Upon removal of the field, the magnetization remains; that is, the signal (data) has been stored.

- Data retrieval from the storage medium is accomplished using a magnetoresistive-read head. During read-back, magnetic fields from the written magnetic patterns are sensed by this head; these fields produce changes in electrical resistance. The resulting signals are then processed so as to reproduce the original date.
- The storage layer is composed of granular media—a thin film (15-20 nm thick) consisting of very small (~10-nm diameter) and isolated grains of a HCP cobalt-chromium alloy that are magnetically anisotropic. Other alloying elements (Pt, Ta) are added to enhance the magnetic anisotropy as well as to form oxide grain-boundary segregants that isolate the grains (Fig. 20.24). Each grain is a single domain that is oriented with its $c$-axis ([0001] crystallographic direction) perpendicular to the disk surface. This [0001] direction is the direction of easy magnetization for Co.

**Fig. 20.24** Transmission electron micrograph showing the microstructure of the perpendicular magnetic recording medium used in hard-disk drives. This “granular medium” consists of small grains of a cobalt-chromium alloy (darker regions) that are isolated from one another by an oxide grain-boundary segregant (lighter regions).
Magnetic Storage

Reliable storage of data requires that each bit written on the disk encompasses ~100 grains.

There is a lower limit to the grain size; for grain sizes below this limit, there is the possibility that the direction of magnetization will spontaneously reverse because of the effects of thermal agitation, which causes a loss of stored data.

The current storage capacities of perpendicular HDDs are in excess of 16 Gbit/cm²; the ultimate goal for HDDs is a storage capacity of 160 Gbit/cm².
**Magnetic tapes**

- For the latest tape memory technology, storage media are particulates of magnetic materials that have dimensions on the order of tens of nanometers: ferromagnetic metal particles that are acicular (needle-shaped), and hexagonal and tabular (plate-shaped) ferrimagnetic barium-ferrite particles (Fig. 20.25). Tape products use one particle or the other (not both together).
- These magnetic particles are throughly and uniformly dispersed in a proprietary high-molecular-weight organic binder material to form a magnetic layer that is ~50 nm thick. Beneath this layer is nonmagnetic thin-film support substrate (of thickness between about 100 and 30 nm), which is attached to the tape.

**Fig. 20.25** Scanning electron micrographs showing particulate media used in tape-memory storage. (a) Needle-shaped ferromagnetic metal particles. (b) Plate-shaped ferrimagnetic particles.
Magnetic Storage

- Both particle types are magnetically anisotropic—that is, they have an “easy” or preferential direction along which they may be magnetized. During manufacture, these particles are aligned such that this direction parallels the direction of motion of the tape past the write head.
Inasmuch as each particle is a single domain that may be magnetized only in one direction or its opposite by the write head, two magnetic states are possible.
- A tape-storage density of 6.7 Gbit/in² has been achieved.
- **Superconductivity**
  
  - Superconducting materials are used primarily in magnets capable of generating high fields.
  - There are a few materials for which the resistivity, at a very low temperature, abruptly plunges from a finite value to one that is virtually zero and remains there upon further cooling. They are called *superconductors*, and the temperature at which they attain superconductivity is called the critical temperature $T_C$ (Fig. 20.26).
  - For metal and metal alloys, the critical temperature lies between less than 1 K and about 20 K, but for some complex oxide ceramics in excess of 100 K.

*Fig. 20.26* Temperature dependence of the electrical resistivity for normally conducting and superconducting materials in the vicinity of 0 K.
- At temperature below $T_C$, the superconducting state will cease upon application of a sufficient large magnetic field, termed the critical field $H_C$, decreases with increasing temperature.

- A critical applied current density $J_C$ exists below which a material is superconductive.

- For temperature, magnetic field, and current density values lying between the origin and this boundary, the material will be superconductive; outside the boundary, conduction is normal (Fig. 20.27).

- In essence, the superconductive state results from attractive interactions between pairs of conducting electrons; the motions of these paired electrons become coordinated such that scattering by thermal vibrations and impurity atoms is highly inefficient. Thus, the resistivity, being proportional to the incidence of electron scattering, is zero.

- Superconducting materials may be divided into two classes: type I and type II.

Fig. 20.22 Critical temperature, current density, and magnetic field boundary separating superconducting and normal conducting states.
Type I superconductors

- Type I materials, while in the superconducting state, are completely diamagnetic; that is, all of an applied magnetic field will be excluded from the body of material, a phenomenon known as the Meissner effect (Fig. 20.28).

- As $H$ is increased, the material remains diamagnetic until the critical magnetic field $H_C$ is reached. At this point, conduction becomes normal, and complete magnetic flux penetration takes place.

- Ex: Al, Pb, Sn, Hg.

Fig. 20.28 Representation of the Meissner effect. (a) While in the superconducting state, a body of material (circle) excludes a magnetic field (arrows) from its interior. (b) The magnetic field penetrates the same body of material once it becomes normally conductive.
• **Type II superconductors**
  - Type II superconductors are completely diamagnetic at low applied fields, and field exclusion is total. However, the transition from the superconducting state to the normal state is gradual and occurs between lower critical and upper critical fields, designated $H_{C1}$ and $H_{C2}$, respectively. (Fig. 20.28b)
  - The magnetic flux lines begin to penetrate into the body of material at $H_{C1}$, and with increasing applied magnetic field, this penetration continues; at $H_{C2}$, field penetration is complete.
  - For fields between $H_{C1}$ and $H_{C2}$, the material exists in the mixed state-both normal and superconducting regions are present.
- Type II superconductors are preferred over type I for most practical applications by virtue of their higher critical temperatures and critical magnetic fields.
- The three most commonly used superconductors are niobium-zirconium (Nb-Zr) and niobium-titanium (Nb-Ti) and the niobium-tin intermetallic compound Nb\(_3\)Sn.
- Recently, new superconducting ceramic materials reported to have even higher critical temperatures have been and are currently being developed. The technological potential of these materials is extremely promising inasmuch as their critical temperatures are above 77 K, which permits the use of liquid nitrogen. The chief drawback of these materials is brittle.
• **Current flow and magnetic fields in superconductors**
  - Type I superconductors are poor carriers of electrical current since current can only flow in the outer surface layer (0.1 μm) of a conducting specimen (Fig. 15.27a).
  - If the magnetic field in type II superconductors is between $H_{c1}$ and $H_{c2}$ (mixed state), the current can be carried inside the superconductor by filaments (Fig. 15.27b), and the field can penetrate the bulk of the superconductor in the form of individual quantized flux bundles called **fluxoids** (Fig. 15.28). With increasing magnetic-field strength, more and more fluxoids enter the superconductor and form a periodic array.
  - At $H_{c2}$ the super current vortex structure collapses and the material returns to the normal conducting state.
• High-current, high-field superconductors
  - Type II superconductors have a small current-carrying capacity below $T_c$ since the fluxoids are weakly tied to the crystal lattice and are relatively mobile.
  - The mobility of the fluxoids can greatly impeded by dislocations, grain boundaries, and fine precipitates, and thus $J_c$ can be raised by cold working and heat treatments.
  - The alloy Nb-45 wt% Ti and the compound Nb$_3$Sn have become the basic materials for modern high-current, high-field superconductor technology. The Nb-45 wt% Ti alloy is more ductile and easier to fabricate than the Nb$_3$Sn compound and so is preferred for many applications.
  - Commercial wires are made of many NbTi filaments, typically ~25 μm in diameter, embedded in a copper matrix (Fig. 15.29). The purpose of the copper matrix is to stabilize the superconductor wire during operation so that hot spots will not develop that could cause the superconducting material to return to the normal state.
- **High critical temperature superconducting oxides**
  - The most intensely studied high $T_c$ material has been the YBa$_2$Cu$_3$O$_y$ compound. From a crystal structure standpoint, this compound can be considered to have a defective perovskite structure with three perovskite cubic unit cells stacked on top of each other (Fig. 15.30).
  - For an ideal stack of three perovskite cubic unit cells, the YBa$_2$Cu$_3$O$_y$ compound should have the composition YBa$_2$Cu$_3$O$_9$. However, $y$ ranges from 6.65 to 6.90 for this material to be a superconductor. At $y = 6.90$, its $T_c$ is highest ($\sim$90 K), and at $y = 6.65$, superconductivity disappears. Thus, oxygen vacancies play a role in the superconductivity behavior of YBa$_2$Cu$_3$O$_y$.
- The YBa$_2$Cu$_3$O$_y$ compound, when slowly cooled from above 750°C in the presence of oxygen, undergoes a tetragonal to orthorhombic crystal structure change (Fig. 15.31a). If the oxygen content is close to $y = 7$, its unit cell has the constant $a = 3.82$ Å, $b = 3.88$ Å, and $c = 11.6$ Å (Fig. 15.30).
- Superconductivity is believed to be confined to the CuO$_2$ planes (Fig. 15.30), with the oxygen vacancies providing an electron coupling between the CuO$_2$ planes.
- Unfortunately, the high-temperature superconductors are essentially ceramics, which are brittle and in their bulk form have low current-density capability.
• Applications of Supercondors
  - Generating high fields with low power consumption. (existing)
  - Magnetic resonance imaging (MRI) in the medical field as a diagnostic tool. (existing)
  - Electrical power transmission through superconducting materials.
  - Magnets for high-energy particle accelerators.
  - Higher-speed switching and signal transmission for computers.
  - High-speed magnetically levitated trains.
  - The chief deterrent to the widespread application of these superconducting materials is the difficult in attaining and maintaining extremely low temperatures.
## Table 20.7 Critical Temperatures and Magnetic Fluxes for Selected Superconducting Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Critical Temperature $T_C$ (K)</th>
<th>Critical Magnetic Flux Density $B_C$ (tesla) $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.02</td>
<td>0.0001</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.40</td>
<td>0.0056</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.18</td>
<td>0.0105</td>
</tr>
<tr>
<td>Tin</td>
<td>3.72</td>
<td>0.0305</td>
</tr>
<tr>
<td>Mercury ($\alpha$)</td>
<td>4.15</td>
<td>0.0411</td>
</tr>
<tr>
<td>Lead</td>
<td>7.19</td>
<td>0.0803</td>
</tr>
<tr>
<td><strong>Compounds and Alloys</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb–Ti alloy</td>
<td>10.2</td>
<td>12</td>
</tr>
<tr>
<td>Nb–Zr alloy</td>
<td>10.8</td>
<td>11</td>
</tr>
<tr>
<td>PbMo$_6$S$_8$</td>
<td>14.0</td>
<td>45</td>
</tr>
<tr>
<td>V$_3$Ga</td>
<td>16.5</td>
<td>22</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.3</td>
<td>22</td>
</tr>
<tr>
<td>Nb$_3$Al</td>
<td>18.9</td>
<td>32</td>
</tr>
<tr>
<td>Nb$_3$Ge</td>
<td>23.0</td>
<td>30</td>
</tr>
<tr>
<td><strong>Ceramic Compounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_7$</td>
<td>92</td>
<td>—</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>110</td>
<td>—</td>
</tr>
<tr>
<td>Tl$_2$Ba$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>125</td>
<td>—</td>
</tr>
<tr>
<td>HgBa$_2$Ca$_2$Cu$_2$O$_8$</td>
<td>153</td>
<td>—</td>
</tr>
</tbody>
</table>

$^a$ The critical magnetic flux density ($\mu_0 H_C$) for the elements was measured at 0 K. For alloys and compounds, the flux is taken as $\mu_0 H_{C2}$ (in teslas), measured at 0 K.

$^b$ **Source:** Adapted with permission from *Materials at Low Temperatures*, R. P. Reed and A. F. Clark (Editors), American Society for Metals, Metals Park, OH, 1983.