Types of Magnetism, Summary

- Diamagnetism (weak, only in H field)
- Paramagnetism (only in H field)
- Ferromagnetism (Permanent magnets)
- Antiferromagnetism
- Ferrimagnetism (in Ceramics - permanent)
Influence of Temperature

For ferro, antiferro, and ferrimagnetic
Atomic thermal motions: (a) Counteract coupling forces; (b) Cause dipole misalignment and (c) Causes decrease in saturation magnetization
Saturation magnetization is maximum at 0K
At high enough temperature: Saturation magnetization goes abruptly to 0 (*Curie temperature* = \( T_C \)).

Figure 20.10  Plot of saturation magnetization as a function of temperature for iron and Fe₃O₄.
[Adapted from J. Smit and H. P. J. Wijn, *Ferrites*. Copyright © 1959 by N. V. Philips Gloeilampenfabrieken, Eindhoven (Holland). Reprinted by permission.]
Magnetic Domains

For ferro or ferrimagnetic materials

Below Curie Temperature: Small volume regions where dipoles are mutually aligned in the same direction. They are called a “domain”

Adjacent domains are separated by boundaries. Domain may be smaller than or as big as a grain

Magnitude of M. Vector sum of domains (weighted by vol. fraction). Usually 0 for unmagnitized specimen

“Magnetization” occurs. Placed in a magnetic field. Domain walls move

“Soft” magnetic materials: “thin” hysteresis loop

“Hard” magnetic materials: “fat” hysteresis loop
Fig. 3.1. Magnetization curve for 3% Si–Fe at 27°C. Inset shows the Barkhausen effect in the second part of the curve (Chen [1958]).
Fig. 3.6. Domain structure of a single crystal slab of iron (a) in the unmagnetized state; (b) after reversible movements of domain walls; (c) after irreversible movements of domain walls; (d) after all magnetization vectors have rotated into [010] and (e) during the rotation of magnetization vector from [010] to the field direction.
Hysteresis Loop

Effect of an alternating field.

Ferromagnetic hysteresis loop

1. No magnetic field
2. Magnetic field is applied. As an H field is applied, the domains change shape and size by the movement of domain boundaries.
3. Saturation magnetization. The macroscopic specimen becomes a single domain, which is nearly aligned with the field.
4. Remanence magnetism. Residual flux density, the material remains magnetized in the absence of an external H field.
5. Coercitivity. Field applied in the reverse direction to H necessary to reduce the flux density to zero.
6. Saturation in opposite direction.
**Figure 20.25** Complete magnetic hysteresis loop for a steel alloy.

**Figure 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.
Application of B-H Curve

Size and shape of the hysteresis loop for ferromagnetic and ferrimagnetic materials.
Area within a loop, energy loss per unit volume of material per magnetization-demagnetization cycle (heat generated).
Ferro and ferrimagnetic materials can be classified as **soft** and **hard**.

**Soft magnetic materials**: Used in devices that are subjected to alternating magnetic fields (energy losses must be small). E.g. transformer cores
Soft Magnetic Materials

High initial permeability. Low coercivity. Easily magnetized and demagnetized (easy movement of domain walls). Structural defects, such as particles, restrict the motion of domain walls. Energy losses from electrical currents induced by the magnetic field must be small (Eddy Current).

Table 20.5  Typical Properties for Several Soft Magnetic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition (wt %)</th>
<th>Initial Relative Permeability $\mu_r$</th>
<th>Saturation Flux Density $B_s$ [tesla (gauss)]</th>
<th>Hysteresis Loss/Cycle $H$ [J/m$^3$ (erg/cm$^3$)]</th>
<th>Resistivity $\rho$ [Ω·m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial iron ingot</td>
<td>99.95Fe</td>
<td>150</td>
<td>21.4 (1400)</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 (20,100)</td>
<td>40</td>
<td>$4.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>45 Peralloy</td>
<td>55Fe, 45Ni</td>
<td>2500</td>
<td>1.60 (16,000)</td>
<td>120</td>
<td>$4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Superalloy</td>
<td>79Ni, 15Fe, 5Mo, 0.5Mn</td>
<td>75,000</td>
<td>0.80 (8000)</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 (3000)</td>
<td>$\sim$40</td>
<td>2000</td>
</tr>
<tr>
<td>Ferroxcube B</td>
<td>36NiFe$_2$O$_4$, 64ZnFe$_2$O$_4$</td>
<td>650</td>
<td>0.36 (3600)</td>
<td>$\sim$35</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

The fact that different directions magnetize more easily than others in ferromagnetic materials is known as *magnetocrystalline anisotropy*. This can be measured by applying fields along different directions, e.g. here along [100], [110] and [111].

![Diagram of a transformer with labels and circuit symbols.](image)

Magnetostriction arises from the strain dependence of the anisotropy constants. Upon magnetization, a previously demagnetized crystal experiences a strain that can be measured as a function of applied field along the principal crystallographic axes. A magnetic material will therefore change its dimension when magnetized.

**Magnetostriiction**

Magnetostriiction arises from the strain dependence of the anisotropy constants. Upon magnetization, a previously demagnetized crystal experiences a strain that can be measured as a function of applied field along the principal crystallographic axes. A magnetic material will therefore change its dimension when magnetized.
**Hard Magnetic Materials**

Permanent Magnets. High resistance to demagnetization. High remanence, high coercitivity and high saturation flux density.

Low initial permeability and high hysteresis energy losses.

Energy product: Area of the largest B-H rectangle that can be constructed within the second quadrant of the hysteresis curve. The larger ($BH_{\text{max}}$) the harder is the material in terms of its magnetic characteristics.

Motors can be smaller than electromagnetic motors cordless drills, screw drivers

Automobile applications - starters, wipers, fan motors
An **electric motor**, is a machine which converts electrical energy into mechanical (rotational or kinetic) energy. A current is passed through a loop which is immersed in a magnetic field. A force exists on the top leg and on bottom leg of the loop which pushes the loop counterclockwise out of the paper.
### Table 20.6  Typical Properties for Several Hard Magnetic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Remanence $B_r$ [tesla]</th>
<th>Coercivity $H_c$ [amp-turn/m]</th>
<th>$(BH)_{max}$ [$kJ/m^3$ (MGOe)]</th>
<th>Curie Temperature $T_c$ [$^\circ C$ ($^\circ F$)]</th>
<th>Resistivity $\rho$ [$\Omega\cdot m$]</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 Ni, 30 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>

Conventional Hard Magnetic Materials

$(BH_{max})$ values that range between 2 and 80kJ.m$^{-3}$. Examples:
cunife (Cu-Ni-Fe), alnico (Al-Ni-Co), hexagonal ferrites (BaO-6Fe$_2$O$_3$). Normally alloyed with W and/or Cr, that will combine with carbon during heat treatment and form precipitates (inhibiting domain wall motion).
High Energy Hard Magnetic Materials
Permanent magnetic materials having energy products in excess of $\sim 80\text{kJ.m}^{-3}$.
New developments. Intermetallic compounds ($\text{SmCo}_5$ and $\text{Nd}_2\text{Fe}_{14}\text{B}$).
Magnetic Storage
Universal technology for storage of electronic information (E.g.: Audio, VCRs, hard drives, credit cards).
Secondary memory “costs less than computer memory”

How does it work?
**Single Domain Particles**

- Tiny particles contain only one domain
- Single domains magnetize by magnetic flipping
- Long, thin particles are hard to “flip”
- They make excellent tiny permanent magnets
- They are the basis for magnetic tape
- Magnetic tape is covered with such particles

*Figure 20.19* A scanning electron micrograph showing the microstructure of a magnetic storage disk. Needle-shaped particles of $\gamma$-$\text{Fe}_2\text{O}_3$ are oriented and embedded within an epoxy phenolic resin. 8000×. (Photograph courtesy of P. Rayner and N. L. Head, IBM Corporation.)
Recording Tape

- “Sound” current sent through ring-shaped electromagnet
- Split in ring develops north and south poles
- Very small nearby tape region becomes magnetized

Playing Back Tape

- Tape moves past gap in ring-shaped electromagnet
- Fluctuating magnetism in ring induces current in playback coil