The Electromagnetic Properties of Materials

• Electrical conduction
  – Metals
  – Semiconductors
  – Insulators (dielectrics)
  – Superconductors

• Magnetic materials
  – Ferromagnetic materials
  – Others

• Photonic Materials (optical)
  – Transmission of light
  – Photoactive materials
    • Photodetectors and photoconductors
    • Light emitters: LED, lasers
The Optical Properties of Materials: Photonic Materials

• “Optical” means the whole electromagnetic spectrum
  – From radio waves to γ-rays
  – Can be regarded as
    • Waves in space
    • Particles with quantized energies

• Light as waves
  – Refraction and reflection at an interface (windows, light pipes, solarium)
  – Absorption and scattering (optical fibers)
  – Diffraction (x-ray and electron crystallography)

• Light as particles
  – Transmission and absorption
  – Photodetectors and photoconductors: switches, photocopiers
  – Photoemitters: LEDs and lasers
Light as a Particle: Photons

- Transparency and color

- Photodetectors
  - Photoconductors
  - Photoelectronics
  - Photocopiers

- Photoemitters
  - Phosphors
  - Light-emitting diodes (LED)
  - Lasers
Light as a Particle: Photons

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Transparency and Color

- Materials are opaque to all radiation for which $\hbar \omega > E_G$
  - All materials with $E_G < \text{about 2.5 eV}$ are opaque to visible light

- Radiation with $h\nu = E_i$ is also absorbed
  - For all internal excitations (donors, acceptors, ionic excitations)
  - Leads to “colored” or “dimmed” light
Light as a Particle: Photons

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Photoconductivity

- Light of suitable wavelength excites carriers
  - $\sigma = n\varepsilon\mu$ ($n$ = steady state density from optical excitations)
  - Semiconductor or insulator becomes metal

- Note two kinds of semiconductor
  - “direct gap” produces carriers at $E_G$
  - “indirect gap” excitation requires phonons at $E<E_d$ - messy behavior
Photoconductors

- Light creates current
  - “Electric eye” circuits
  - Photodetectors (need multiple conductors to detect frequency)

- Photoelectronic transistors
  - Switch “on” when light “on”
  - Illumination plays the part of positive voltage at the base
Photocopiers

- Charge photoconductor plate
- Reflect light from page
  - Reflection from white spaces
  - Removes charge
  ⇒ Creates map of original print
- Pass through “toner”
  - Ink sticks to charge on plate
- Print
  - Press against paper to transfer ink
  ⇒ Faithful copy of original
- Color copying
  - Passes for the 3 primary colors
Light as a Particle: Photons

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Photoemitters: Phosphors

- A phosphor is an ionic emitter
  - Incident radiation ($\hbar\omega_i = E_i$) excites ion
  - Excited ion relaxes in lattice, changing energy
  - Excited state returns to ground state, emitting photon with $E_e = \hbar\omega'$
  - Since $\omega' \neq \omega_i$, photon is emitted from the material

- Phosphors used in monitors, etc.
  - Multiple phosphors used for color images
Photoemitters: Light Emitting Diodes (LED)

- To generate light from a p-n junction:
  - Use a “direct-gap” semiconductor in forward bias
  - Charge recombinations generate photons

- “Color” set by band gap
  - Long search for “blue” LED solved by GaN
Lasers:
Light Amplification by Stimulated Emission of Radiation

- **Three-level laser** (ruby):
  - Excite with incident radiation
  - Transition to level with difficult transition to ground state (inverted population)
  - Transitions stimulate further transitions, create beam of photons “in phase”

- **Light emission from laser**
  - Mirrors used for multiple reflections to amplify “in phase” beam
  - Mechanism such as “half-silvered” mirror to emit amplified light
Lasers:
Four-Level Lasers

- Three-level laser: Problem
  - $\hbar \omega_{13}$ can stimulate transition 1 $\rightarrow$ 3
  - One photon lost for each transition - loss of efficiency

- Four-level laser: Solution
  - Lasing transition to transient state 4
  - Immediate transition 4 $\rightarrow$ 1 empties level 4
  $\Rightarrow$ High efficiency since $\hbar \omega_{14}$ has nothing to excite
Semiconductor Lasers

- Use direct-gap semiconductor (GaAs)
  - Note GaAs gap such that “light” is infrared
- Create “well” where electrons are trapped
- Pump high density of carriers \( \Rightarrow \) exceed recombination rate
- Recombination enhanced by stimulated emission \( \Rightarrow \) laser

**Heterojunction GaAs Laser**
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Magnetic Materials

• Sources of magnetism
  – Unpaired electrons
    • Inner core: transition metals and rare earth elements
    • Electron bands (secondary)
  – Electron orbit (secondary)

• Types of magnetism
  – Diamagnetism:
    • Electron orbit changed in magnetic field
  – Paramagnetism:
    • Disordered, unpaired spins align in magnetic field
  – Magnetic order:
    • Unpaired atomic moments spontaneously order at low T
    • Adjacent moments parallel: ferromagnets
    • Adjacent moments antiparallel: antiferromagnets (ferrimagnets)
Sources of Magnetic Fields

- Circulating current creates magnetic moment
  - For a closed current loop of area A:
    - Magnetic moment: $m = IAn$
  - For solenoid of N turns per meter:
    - Magnetic field: $H = NIn$

- Spinning electron creates magnetic moment
  - $m = m_B$ (Bohr magneton)
Basic Relations for the Magnetic Field

- Magnetic field: \( H \)
- Magnetic flux: \( B \)
  \[
  B = \mu \mu_0 H \\
  \mu \geq 0 \text{ (=1 in free space)}
  \]
- Magnetization in material: \( M \)
  \[
  B = \mu_0 \left( H + M \right)
  \]
- Magnetic susceptibility: \( \chi \)
  \[
  M = \chi H \\
  \mu = 1 + \chi
  \]

Boundary conditions:
- Normal: \( B = \mu_0(H+M) \) is continuous
- Transverse: \( H = (B/\mu_0) - M \) is continuous
Magnetism in Valence Metals

- Diamagnetism (Cu, Au, Zn, Hg)
  - Magnetic (“Lorenz”) force ⇒ eddy currents
  - \( \mathbf{m} \) of current loop opposes \( \mathbf{B} \) (decreases \( \mathbf{H} \))
  - \( \chi < 0 \) but small (except in superconductors)

- Band paramagnetism (Al)
  - Electron moment (\( \mathbf{m}_B \)) preferentially aligns with \( \mathbf{B} \)
  - Increases electrons with parallel spins
  - \( \chi > 0 \) but small
### Core Magnetism: Transition Metals

<table>
<thead>
<tr>
<th>Element</th>
<th>Configuration</th>
<th>Spin Magnetic Moment ( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc</td>
<td>3d(^1)4s(^2)</td>
<td>( m = 1m_B )</td>
</tr>
<tr>
<td>Ti</td>
<td>3d(^2)4s(^2)</td>
<td>( m = 2m_B )</td>
</tr>
<tr>
<td>V</td>
<td>3d(^3)4s(^2)</td>
<td>( m = 3m_B )</td>
</tr>
<tr>
<td>Cr</td>
<td>3d(^5)4s(^1)</td>
<td>( m = 5m_B )</td>
</tr>
<tr>
<td>Mn</td>
<td>3d(^5)4s(^2)</td>
<td>( m = 5m_B )</td>
</tr>
<tr>
<td>Fe</td>
<td>3d(^6)4s(^2)</td>
<td>( m = 4m_B )</td>
</tr>
<tr>
<td>Co</td>
<td>3d(^7)4s(^2)</td>
<td>( m = 3m_B )</td>
</tr>
<tr>
<td>Ni</td>
<td>3d(^8)4s(^2)</td>
<td>( m = 2m_B )</td>
</tr>
<tr>
<td>Cu</td>
<td>3d(^{10})4s(^1)</td>
<td>( m = 0 )</td>
</tr>
</tbody>
</table>
Core Magnetism

- **High temperature:**
  - Spins disordered $\Rightarrow$ paramagnetism

- **Low Temperature ($T < T_c$)**
  - Spins align = ferromagnetism
    - Elements: Fe, Ni, Co, Gd, Dy
    - Alloys and compounds: AlNiCo, FeCrCo, SmCo$_5$, Fe$_{14}$Nd$_2$B
  - Like spins alternate = antiferromagnetism
  - Unlike spins alternate = ferrimagnetism
    - Compounds: Fe$_3$O$_4$ (lodestone, magnetite), CrO$_3$, SrFe$_2$O$_3$

- Ferromagnetic (and ferrimagnetic) materials have engineering applications
Ferromagnetism is Uncommon

Ferromagnetic elements are uncommon but several other elements form ferromagnetic or ferrimagnetic compounds.
Ferromagnetism

- Ferromagnetism occurs by mutation at $T_c$ (Curie T)
- Energy is minimized by ordering spins into “domains”
  - Net moment, $\mathbf{M}$, would cause external field, increase energy
  - Magnetic domains cancel so that $\mathbf{M} = 0$
  - Natural ferromagnetism does not produce net magnetic field
Ferromagnetism

- To magnetize a ferromagnet, impose $H$
  - Domains move to align $M$ and $H$
  - Defects impede domain motion
  - Moment ($M_r$) retained when $H$ removed

- Magnetic properties
  - $M_s =$ saturation magnetization
    - All spins aligned with field
  - $M_r =$ remanent magnetization
    - Useful moment of permanent magnet
  - $H_c =$ coercive force
    - Field required to “erase” moment
  - Area inside curve = magnetic hysteresis
    - Governs energy lost in magnetic cycle
Hard Magnets: High Field

- Strong natural magnet: maximize $M_s$
  - AlNiCo - $M_s \approx 1.0$ T
  - Sm(Co,Fe,Cu,Zr)$_8$ - $M_s \approx 1.2$ T
  - Fe$_{14}$Nd$_2$B - $M_s \approx 1.3$ T

- Microstructural obstacles: maximize $M_r/M_s$
  - Fine domain size
    - Grain size
    - Particle size (free particle or embedded precipitate)
  - Defects and non-magnetic inclusions
Hard Magnets: Magnetic Memory

• Magnetic elements on disc, tape or surface
  – Isolated, individual particles; field orientation records information
  – Magnetic elements:
    • Hard for good “memory”
    • Not too hard, for erasure and re-write

• Media characteristics
  – Generally magnetic oxides for shape and chemical stability
  – Size less than minimum domain size for “hardness”
  – Perpendicular recording difficult, but provides high density
“Soft” Magnets

- “Soft” magnetic materials
  - Small hysteresis loop
  - Low energy losses per cycle
  - Optimized for cyclic machinery
    - Generators, transformers
    - Motors
    - Read-write heads
    - Electromagnetic shielding

- Materials requirements
  - Magnetic isotropy
    - Low energy required to rotate moment
  - Homogenous, “defect-free” microstructure
  - Large grain size
    - Large-grained Fe-Si “transformer” steel
    - Amorphous “metallic glasses”
  - Electrical insulation minimizes electrical losses
    - Ferrites (Fe₂O₃, LiFe₂O₃)
Piezomagnetism (Magnetostriction)

- Magnetic field ⇔ elastic strain
  - Magnetic ⇔ mechanical
  - Can reach very high frequency
  - Small energy requirements

- Piezomagnetic transducers
  - High frequency oscillators
  - Sound recording
  - High quality speakers

- Materials
  - Ni
  - Ni-Fe (invar)
  - TbDyFe (terfenol)
Superconductivity

- Superconductivity = loss of electrical resistance

- Superconductors are not just good conductors
  - Electrons are “fermions”, obey Pauli Exclusion
  - Because of exclusion, all metals have resistance
    - Electron is excited to conduct
    - Loses energy on collision, returns to paired state
  - For superconductivity, must turn electrons into “bosons”
    - Electrons are paired into carriers with integral spin
    - Integral spin $\Rightarrow$ boson
    - All carriers may be in the same ground state

- Applications
  - Conductors: high field magnets, storage devices, transmission
  - Junctions: Josephson junctions used in detectors (SQUIDS)