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
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Insulators (Dielectrics)

- **Characteristics:**
  - Large band gap (> 2 eV)
  - Very low conductivity

- **Engineering uses**
  - Separate conductors
    - No leakage current
    - No interference
  - Support electric fields
    - Store energy (capacitors)
    - Induce charge (MOSFET)
Insulators: Material Properties

- Ability to insulate $\Rightarrow$ critical field ($E_c$)
  - Insulator separates conductors until $E$ reaches $E_c$

- Support internal field $\Rightarrow$ dielectric constant ($\varepsilon$)
  - High $\varepsilon$ $\Rightarrow$ high induced charge for given voltage
    - Capacitors: high $\varepsilon$ $\Rightarrow$ efficient energy storage
    - Oxide in MOSFET: high $\varepsilon$ $\Rightarrow$ low switching voltage
  - Low $\varepsilon$ $\Rightarrow$ small induced charges
    - “low-k” insulators essential for microelectronic packaging

- Energy dissipation from current $\Rightarrow$ loss tangent ($\delta$)
  - Low $\delta$ $\Rightarrow$ low rate of energy loss from propagating e-m fields
Insulators: Breakdown Voltage

- Insulator protects until
  - $E$ reaches $E_c$ “breakdown”
  - Catastrophic increase in $j$ at $E_c$
  - Example: lightning

- Common “cascade mechanism”
  - Electron accelerated in field
  - Excites new carriers by collision
  - These accelerate in chain reaction

- Material and microstructure variables
  - Band gap: $E_c$ increases with $E_G$
  - Purity: $E_c$ usually increases with purity
  - Temperature: minimum at intermediate $T$
    - Few carriers at low $T$
    - Low mobility at high $T$
Dielectrics

- Dielectrics (insulators) support internal fields
  - The “dielectric constant” relates field to charge
  - Sometimes use “susceptibility” $\chi = \varepsilon - 1$ ($\chi = 0$ in free space)

\[ Q = CV \]  
\[ \sigma A = C(Ed) \]  
\[ \sigma = D = \varepsilon \varepsilon_0 E \]

$C = \text{capacitance}$  
$D = \text{electric displacement}$  
$\varepsilon \geq 1$ (= 1 in free space)
Source of the Dielectric Constant

- **Internal polarization**
  - Dipoles align in applied field
  - Create reverse field ($E_I$)

\[ \varepsilon_0 E = \varepsilon_0 E_0 - \varepsilon_0 E_I = \sigma - P \]

\[ P = \sum_i p_i = \chi E \]

\[ D = \sigma = \varepsilon_0 E + P = \varepsilon\varepsilon_0 E \]

\[ \varepsilon = 1 + \frac{P}{\varepsilon_0 E} \]
Polarization Mechanisms

• Space charges
  – Porous materials (large pores)
  – Slow response in insulators

• Molecular dipoles
  – Large polar organics have big $\varepsilon$
  – Relatively slow response (like diffusion)

• Ionic displacements
  – Ionic crystals have moderate $\varepsilon$
  – Fast response (like optical phonon)

• Atomic dipole
  – Small $\varepsilon$
  – Very fast response (plasmon frequency)
Influence of the Dielectric Constant

- For given $\sigma$ (Q) increasing $\varepsilon$ decreases field (E)
- For given voltage drop (E), increasing $\varepsilon$ increases Q ($\sigma$)
  - Energy stored in a capacitor increases with $\varepsilon$
  - Induced charge between adjacent conductors increases with $\varepsilon$
    - MOSFET oxides need maximum $\varepsilon$
    - Insulators in microelectronic packaging need minimum $\varepsilon$
    - Both are major objectives in modern microelectronics
      - (many jobs, much money)

$$U = \frac{1}{2} DE = \frac{1}{2} \varepsilon \varepsilon_0 E^2$$
Ultra-low Dielectric Constant

- For a given voltage drop (E), increasing $\varepsilon$ increases $Q (\sigma)$
  $\Rightarrow$ Induced charge increases with $\varepsilon$

- “Low-k” materials
  - Critical for applications in electronic packaging

- Materials design
  - Organics based on non-polar molecules
  - Dense array of nanopores ($\varepsilon = 1$)

- Materials issues
  - Mechanical integrity - must support device
High Dielectric Constant - Ferroelectricity

- **Ferroelectric materials**
  - $\text{BaTiO}_3$ (for example)
  - Effective CsCl

- **At high $T$ ($T > T_c$)**
  - Central ion centered
  - No dipole moment

- **At low $T$ ($T < T_c$)**
  - Central ion displaces to create dipole
  - All neighboring cells displace parallel
  $\Rightarrow$ Large net dipole moment
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The Optical Properties of Materials: Photonic Materials

- **Beauty**: one-half of the earliest materials science
  - Pottery glazes (the origin of metals), paints and cosmetics
  - Jewelry - the development of metals and metalworking

- **Information**
  - Window glass
  - Optical fibers (rapidly replacing copper wire)

- **Light**
  - The electric light
  - LEDs and Lasers
  - Photodetectors and photoconductors

- **Power**
  - Photovoltaics (solar cells)
  - Laser power transmission (welding, surface treatments)
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
Electromagnetic Waves in Free Space

- Wave carries electric and magnetic fields
  - Oriented perpendicular to the direction of propagation
  - Wave:
    \[ E = E_0 \exp[-i(kx - \omega t)] \]
  - Particle:
    \[ \epsilon = h \nu = \hbar \omega \]

\[ k = \frac{2\pi}{\lambda} \] (\( \lambda = \) wavelength)
\[ \omega = 2\pi \nu \] (\( \nu = \) frequency)
\[ \frac{\omega}{k} = \nu \lambda = c \]  
\( c = \) speed
The Electromagnetic Spectrum

- **Visible light:**
  - $\lambda \sim 0.4$-1 $\mu$m
  - $E \sim 1.2$-3 eV
Light as a Wave

- Propagation through free space at velocity, $c$

- When light enters a material, it is
  - Refracted
  - Reflected
  - Attenuated

![Diagram of light wave with incident, reflected, and transmitted waves]
Refraction and Reflection at an Interface: Normal Incidence

• Refraction:
  – Wave "drags" charges
  – Friction slows propagation

• Index of refraction (n)
  – Property governing refraction
  – Related to dielectric constant:

\[
E = E^0 \exp[-i(kx - \omega t)]
\]

\[
k = nk_0 \implies \lambda = \frac{\lambda_0}{n}
\]

\[
v = \frac{\omega}{k} = \frac{c}{n}
\]

\[
n = \sqrt{\varepsilon}
\]

– Depends on frequency (dispersion)

\[
n = n(\omega) = \sqrt{\varepsilon(\omega)}
\]
Refraction at an Interface

• **Snells’ Law**
  \[ n_1 \sin \phi_1 = n_2 \sin \phi_2 \]
  – Light bends toward low-n region
  
• **The critical angle**
  – Light cannot exist region 1 if
  \[ \phi_2 > \phi_c = \sin^{-1}\left(\frac{n_1}{n_2}\right) \]
  – Principle of “light pipe”

Optical fiber confines light by reflection
Reflection at an Interface

- Normal incidence from $n_1$ to $n_2$
  - $\Delta n \Rightarrow$ reflection
  - Intensity thrown back

- Reflected intensity
  \[ R = \frac{I_r}{I_i} = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2} \]

- Transmitted intensity
  \[ T = \frac{I_t}{I_i} = 1 - R = \frac{4n_2}{(n_1 + n_2)^2} \]

- Note: depends on $\Delta n$
  - Not transparency
Propagation of Light: Attenuation

- $I_T$ is gradually attenuated
- Mechanisms of attenuation
  - Absorption
  - Rayleigh scattering
- Mechanisms of absorption
  - Conduction electrons
  - Phonons
  - Electronic transitions
    - Valence
    - Core

\[ I_T = I_0 \exp[-\eta x] \]
Absorption: Insulator or Semiconductor

- Absorption by
  - Optical phonons (solar panels)
  - Ionic transitions (color)
  - Band transitions (photoconductivity)
  - Core transitions (x-ray spectroscopy)
Attenuation: Rayleigh Scattering

- Light scatters from heterogeneities
  - Density fluctuations
  - Chemical heterogeneities
  - Defects and second-phase particles

- Only recently is it possible to produce clear, uniform glass
  - “As through a glass - darkly”
Diffraction

- Waves reflected from successive planes
  - Destructive interference unless
    - Bragg’s Law \( \Rightarrow \) strong intensity peak
  - \[ n\lambda = 2d \sin \theta \] (Bragg’s Law)

- Pattern of diffraction peaks identifies crystal structure
  - Use x-rays or electrons with \( \lambda \) of a few Å
Electron Diffraction of “Intercritically Tempered Steel”

- Electron microscopy
  - Photograph
  - Diffraction pattern

- Diffraction pattern
  - Peaks from crystal planes
  - Pattern identifies phases
  - Ex.: bcc and fcc Fe present

- Combined analysis
  - “Bright field” microstructure
  - Diffraction pattern shows phases
  - “Dark field” locates phases
    - Image diffraction spot
Exploiting the Light as a Wave: Examples

- **Optical fibers**
  - Transparent pipes that transmit light
  - Note that “light” need not be visible
    - GaAs systems operate in the infrared

- **Greenhouses and solar heaters**
  - Glass containers that let light in,
  - Then trap its energy for heat
Optical Fibers

- **Require**
  - Small diameter to minimize surface loss
  - Perfect cylinder to minimize surface scattering
  - Exceptional purity to suppress absorption
  - Exceptional uniformity to suppress Rayleigh scattering

- **Gradient fibers**
  - Rays that reflect from surface travel farther than rays on-axis
    - Loss of coherence and information
  - Want gradient in $n$ such that $n$ lower on outside
    - Rays that reflect from surface move faster
  - Can adjust $n$ with solute additions
Absorption:
The “Greenhouse” Effect

- Absorption by
  - Optical phonons (solar panels)
  - Ionic transitions (color)
  - Band transitions (photoconductivity)
  - Core transitions (x-ray spectroscopy)
The Solarium and Solar Heater

- Mechanism is glass
  - transparent in the visible
  - Opaque in the infrared

- Sunlight enters
  - Rays are absorbed and re-emitted in the infrared
  - Re-emitted rays cannot penetrate glass
  - Solar energy is trapped inside
Light as a Particle: Photons

• Transparency and color

• Photodetectors
  – Photoconductors
  – Photoelectronics
  – Photocopiers

• Photoemitters
  – Phosphors
  – Light-emitting diodes (LED)
  – Lasers