Chapter 16,18: Composite and Electrical Properties

ISSUES TO ADDRESS...

• What are the classes and types of composites?
• How do we estimate composite stiffness & strength?
• How are electrical conductance and resistance characterized?
• What are the physical phenomena that distinguish conductors, semiconductors, and insulators?
• For metals, how is conductivity affected by imperfections, $T$, and deformation?
• For semiconductors, how is conductivity affected by impurities (doping) and $T$?
Composites

• Combine materials with the objective of getting a more desirable combination of properties
  – Ex: get flexibility & weight of a polymer plus the strength of a ceramic

• Principle of combined action
  – Mixture gives “averaged” properties
Terminology/Classification

- **Composites**: Multiphase material with significant proportions of each phase.
- **Matrix**: The continuous phase, purpose is to:
  - transfer stress to other phases
  - protect phases from environment
  - Classification: MMC, CMC, PMC
- **Dispersed phase**: Purpose: enhance matrix properties.
  - MMC: increase $\sigma_y$, TS, creep resist.
  - CMC: increase $K_c$
  - PMC: increase $E$, $\sigma_y$, TS, creep resist.
  - Classification: Particle, fiber, structural
Composite Survey

Influencing factors of the dispersed phase:
- a) concentration
- b) size
- c) shape
- d) distribution
- e) orientation
Composite Survey: Particle-I

Particle-reinforced

- **Spheroidite steel**
  - matrix: ferrite ($\alpha$) (ductile)
  - particles: cementite ($\text{Fe}_3\text{C}$) (brittle)

- **WC/Co cemented carbide**
  - matrix: cobalt (ductile)
  - $V_m$: 10-15 vol%!
  - particles: WC (brittle, hard)

- **Automobile tires**
  - matrix: rubber (compliant)
  - particles: C (stiffer)

Adapted from Fig. 10.19, *Callister 7e.*
(Fig. 10.19 is copyright United States Steel Corporation, 1971.)

Adapted from Fig. 16.4, *Callister 7e.*
(Fig. 16.4 is courtesy Carboly Systems, Department, General Electric Company.)

Adapted from Fig. 16.5, *Callister 7e.*
(Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)
Composite Survey: Particle-II

• Elastic modulus, $E_c$, of composites:  
  -- two approaches.

  upper limit: “rule of mixtures”  
  $E_c = V_mE_m + V_pE_p$

  lower limit:  
  $\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$

Data:  
Cu matrix w/tungsten particles

Adapted from Fig. 16.3, *Callister 7e*. (Fig. 16.3 is from R.H. Krock, ASTM Proc, Vol. 63, 1963.)
Composite Survey: Fiber-I

- Fibers very strong
  - Provide significant strength improvement to material
  - Ex: fiber-glass
    - Continuous glass filaments in a polymer matrix
    - Strength due to fibers
    - Polymer simply holds them in place
Composite Survey: Fiber-II

Fiber-reinforced

Particle-reinforced

Structural

• Fiber Materials
  – Whiskers - Thin single crystals - large length to diameter ratio
    • graphite, SiN, SiC
    • high crystal perfection – extremely strong, strongest known
    • very expensive
  – Fibers
    • polycrystalline or amorphous
    • generally polymers or ceramics
    • Ex: Al₂O₃, Aramid, E-glass, Boron, UHMWPE
  – Wires
    • Metal – steel, Mo, W
Fiber Alignment

aligned continuous

aligned discontinuous

random

longitudinal (extensional) modulus

\[ E_{cl} = E_m V_m + E_f V_f \]

\( f = \text{fiber} \)

\( m = \text{matrix} \)

transverse modulus

\[ \frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \]

\[ E_c = E_m V_m + KE_f V_f \]

efficiency factor:

\[ 0.1 < K < 0.6 \]

-- random 2D: \( K = 3/8 \) (2D isotropy)

-- random 3D: \( K = 1/5 \) (3D isotropy)
Composite Survey: Structural

Particle-reinforced  Fiber-reinforced  Structural

- **Stacked and bonded fiber-reinforced sheets**
  -- stacking sequence: e.g., 0°/90°
  -- benefit: balanced, in-plane stiffness

- **Sandwich panels**
  -- low density, honeycomb core
  -- benefit: small weight, large bending stiffness

Adapted from Fig. 16.16, Callister 7e.

Adapted from Fig. 16.18, Callister 7e. (Fig. 16.18 is from Engineered Materials Handbook, Vol. 1, Composites, ASM International, Materials Park, OH, 1987.)
Electrical Conduction

• Ohm's Law:
  \[ \Delta V = I R \]
  - Voltage drop (volts = J/C)
  - Current (amps = C/s)
  - Resistance (Ohms)
  - \( C = \text{Coulomb} \)

• Resistivity, \( \rho \) and Conductivity, \( \sigma \):
  -- Geometry-independent forms of Ohm's Law
  -- Resistivity is a material property & is independent of sample geometry

\[ \rho = \frac{\Delta VA}{IL} \]

\[ \sigma = \frac{1}{\rho} \]

• Resistance:
  \[ R = \frac{\rho L}{A} = \frac{L}{A\sigma} \]
Electrical Properties

• Which will conduct more electricity?

\[ I = \frac{\Delta V}{R} \]

\[ R = \frac{\rho L}{A} = \frac{L}{A\sigma} \]

• Analogous to flow of water in a pipe
• So resistance depends on sample geometry, etc.
Definitions

Further definitions

\[ J = \sigma \varepsilon \] <= another way to state Ohm’s law

\[ J \equiv \text{current density} = \frac{\text{current}}{\text{surface area}} = \frac{I}{A} \] like a flux

\[ \varepsilon \equiv \text{electric field potential} = \frac{V}{\ell} \text{ or } \left( \frac{\Delta V}{\Delta \ell} \right) \]

\[ J = \sigma \left( \frac{\Delta V}{\Delta \ell} \right) \]

Electron flux  conductivity  voltage gradient

Current carriers

- electrons in most solids
- ions can also carry (particularly in liquid solutions)
## Conductivity: Comparison

- Room $T$ values $(\text{Ohm-m})^{-1} = (\Omega \cdot \text{m})^{-1}$

<table>
<thead>
<tr>
<th>METALS</th>
<th>CERAMICS</th>
<th>POLYMERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>$6.8 \times 10^7$</td>
<td>Soda-lime glass</td>
</tr>
<tr>
<td>Copper</td>
<td>$6.0 \times 10^7$</td>
<td>Concrete</td>
</tr>
<tr>
<td>Iron</td>
<td>$1.0 \times 10^7$</td>
<td>Aluminum oxide</td>
</tr>
<tr>
<td>Silicon</td>
<td>$4 \times 10^{-4}$</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>Germanium</td>
<td>$2 \times 10^0$</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>GaAs</td>
<td>$10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

Selected values from Tables 18.1, 18.3, and 18.4, *Callister 7e.*
Electronic Band Structures

Adapted from Fig. 18.2, Callister 7e.
Band Structure

- **Valence band** – filled – highest occupied energy levels
- **Conduction band** – empty – lowest unoccupied energy levels

Adapted from Fig. 18.3, *Callister 7e.*
Metal (conductor)

Fermi energy: the energy corresponding to the highest filled state at 0K.
Free electrons: electrons with energies above Fermi energy.
Conduction & Electron Transport

- **Metals (Conductors):**
  - Thermal energy puts many electrons into a higher energy state.

- **Energy States:**
  - For metals nearby energy states are accessible by thermal fluctuations.
Energy States: Insulators & Semiconductors

- **Insulators:**
  - Higher energy states not accessible due to gap (> 2 eV).

- **Semiconductors:**
  - Higher energy states separated by smaller gap (< 2 eV).
Metals: Resistivity vs T, Impurities

- Imperfections increase resistivity
  -- grain boundaries
  -- dislocations
  -- impurity atoms
  -- vacancies

These act to scatter electrons so that they take a less direct path.

- Resistivity increases with:
  -- temperature
  -- wt% impurity
  -- %CW

\[ \rho = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}} \]

\[ \rho_{\text{thermal}} = \rho_0 + aT \]

\[ \rho_{\text{impurity}} = A c_i (1-c_i) \]

Adapted from Fig. 18.8, *Callister 7e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* 5, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)
Charge Carriers

Metal Conductivity \( \sigma = n |e| \mu_e \)

- \( n \): number of conducting electron per unit volume,
- \( |e| \): absolute value of electrical charge on an electron,
- \( \mu_e \): electron mobility.

Semiconductor two charge carrying mechanisms

Electron – negative charge  
Hole – equal & opposite (positive) charge

Move at different speeds - drift velocity

Electrical Conductivity given by:

\[
\sigma = n |e| \mu_e + p |e| \mu_h
\]

- \( n \): number of conducting electrons per unit volume,
- \( p \): number of conducting holes per unit volume,
- \( |e| \): absolute value of electrical charge on an electron,
- \( \mu_e \): electron mobility,
- \( \mu_h \): hole mobility.
Pure Semiconductors: Conductivity vs T

- Data for Pure Silicon:
  -- $\sigma$ increases with $T$
  -- opposite to metals

Electrical conductivity, $\sigma$

$\sigma_{\text{undoped}} \propto e^{-E_{\text{gap}} / kT}$

Energy

Electrons can cross gap at higher $T$

<table>
<thead>
<tr>
<th>Material</th>
<th>Band gap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.11</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
</tr>
<tr>
<td>GaP</td>
<td>2.25</td>
</tr>
<tr>
<td>CdS</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Adapted from Fig. 19.15, Callister 5e. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, Phys. Rev. 75, p. 865, 1949.)
Intrinsic vs Extrinsic Conduction

- **Intrinsic:**
  
  \[ \sigma = n \left| e \right| \mu_e + p \left| e \right| \mu_h \]

  \[ = n \left| e \right| (\mu_e + \mu_h) \]

  \[ = p \left| e \right| (\mu_e + \mu_h) \]

  \# electrons = \# holes \((n = p)\)

  --case for pure Si

- **Extrinsic:**

  \[ \sigma \approx n\left| e \right| \mu_e \]

  \[ \sigma \approx p\left| e \right| \mu_h \]

  \(n \neq p\)

  --occurs when impurities are added with a different
  \# valence electrons than the host (e.g., Si atoms)

- **\(n\)-type Extrinsic:** \((n \gg p)\)

  - Phosphorus atom (donor)

  - Boron atom (acceptor)

  \[ \sigma \approx n\left| e \right| \mu_e \]

  \[ \sigma \approx p\left| e \right| \mu_h \]

Adapted from Figs. 18.12(a) & 18.14(a), Callister 7e.
Doped Semiconductor: electron concentration vs. T

- Comparison: intrinsic vs extrinsic conduction...

For extrinsic doping level: $10^{21}/m^3$ of a $n$-type donor impurity (such as P).

- when $T < 100$ K: "freeze-out", thermal energy insufficient to excite electrons.
- when $150$ K $< T < 450$ K: "extrinsic"
- when $T >> 450$ K: "intrinsic"
Measuring electron mobility

Hall Effect

\[ V_H = \frac{R_H I_x B_z}{d} \]

Hall coefficient:

\[ R_H = \frac{I}{n |e|} \]

\[ \mu_e = \frac{\sigma}{n |e|} = \left| R_H \right| \sigma \]

Measure conductivity \( \sigma \) and Hall coefficient \( R_H \) to get \( \mu_e \).

A force (\( F_y \)) is generated when charged particles (\( I_x \)) move perpendicular to a magnetic field (\( B_z \)).
**p-n Rectifying Junction**

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.

  --No applied potential: no net current flow.

  --Forward bias: carrier flow through p-type and n-type regions; holes and electrons recombine at p-n junction; current flows.

  --Reverse bias: carrier flow away from p-n junction; carrier conc. greatly reduced at junction; little current flow.
Properties of Rectifying Junction

Fig. 18.22, Callister 7e.

Fig. 18.23, Callister 7e.
Junction Transistor

Diagram showing the circuit and voltage levels for a Junction Transistor.
Transistor MOSFET

- MOSFET (metal oxide semiconductor field effect transistor)

Integrated Circuit Devices

- Integrated circuits - state of the art ca. 50 nm line width
  - > 100,000,000 components on chip
    - chip formed layer by layer
      - Al is the “wire”
Summary

• Electrical conductivity and resistivity are:
  -- material parameters.
  -- geometry independent.
• Electrical resistance is:
  -- a geometry and material dependent parameter.
• Conductors, semiconductors, and insulators...
  -- differ in accessibility of energy states for conductance electrons.
• For metals, conductivity is increased by
  -- reducing deformation
  -- reducing imperfections
  -- decreasing temperature.
• For pure semiconductors, conductivity is increased by
  -- increasing temperature
  -- doping (e.g., adding B to Si (p-type) or P to Si (n-type)).
Homework

18.5
18.28