Chapter 18: Electrical Properties

• Why study electrical properties?
• 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 $T$?
View of an Integrated Circuit

• Scanning electron microscope images of an IC:
  
  ![Image of IC with Al and Si](a)

  • A dot map showing location of Si (a semiconductor):
    -- Si shows up as light regions.

  ![Image of Si dot map](b)

  • A dot map showing location of Al (a conductor):
    -- Al shows up as light regions.

  ![Image of Al dot map](c)

Fig. (d) from Fig. 18.27 (a), *Callister 7e*. (Fig. 18.27 is courtesy Nick Gonzales, National Semiconductor Corp., West Jordan, UT.)

Fig. (a), (b), (c) from Fig. 18.0, *Callister 7e.*
Electrical Properties

• Which will conduct more electricity?

$$D$$

$$2D$$

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

$$\rho = \frac{RA}{l} = \frac{VA}{Il}$$
Electrical Conduction

- **Ohm's Law:**
  
  \[ \Delta V = I R \]

  - Voltage drop (volts = J/C)
  - Current (amps = C/s)
  - Resistance (Ohms)
  - Electric field intensity 
  - Cross sect. area

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

  \[ E = \frac{\Delta V}{L} = \frac{I}{A} \rho \]

  - \( E \): Electric field intensity
  - \( \rho \): Resistivity (Ohm-m)
  - \( J \): Current density

- **Resistance:**

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

  - Conductivity
Conductivity: Comparison

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

**METALS**
- Silver: $6.8 \times 10^7$
- Copper: $6.0 \times 10^7$
- Iron: $1.0 \times 10^7$

**CERAMICS**
- Soda-lime glass: $10^{-10} - 10^{-11}$
- Concrete: $10^{-9}$
- Aluminum oxide: $<10^{-13}$

**SEMICONDUCTORS**
- Silicon: $4 \times 10^{-4}$
- Germanium: $2 \times 10^0$
- GaAs: $10^{-6}$

**POLYMERS**
- Polystyrene: $<10^{-14}$
- Polyethylene: $10^{-15} - 10^{-17}$

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.*
Various possible electron band structures

- Fermi energy $E_f$: the energy corresponding to the highest filled state at 0 K

(a) Metal (Cu)

(b) Metal (Mg)

(c) Insulator

(d) Semiconductor
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
  - empty band
  - partly filled valence band
  - filled band

- GAP

+ Energy
  - empty band
  - filled valence band
  - filled band
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

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

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.)
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).
Charge Carriers

Two charge carrying mechanisms

Electron – negative charge
Hole – equal & opposite positive charge

Move at different speeds - drift velocity

Higher temp. promotes more electrons into the conduction band

\[ \therefore \sigma \uparrow \text{ as } T \uparrow \]

Electrons scattered by impurities, grain boundaries, etc.

Adapted from Fig. 18.6 (b), *Callister 7e.*
Pure Semiconductors: Conductivity vs T

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

Electrical conductivity, $\sigma$

\[
(\text{Ohm-m})^{-1}
\]

\[
\begin{array}{|c|c|}
\hline
\text{material} & \text{band gap (eV)} \\
\hline
\text{Si} & 1.11 \\
\text{Ge} & 0.67 \\
\text{GaP} & 2.25 \\
\text{CdS} & 2.40 \\
\hline
\end{array}
\]

Selected values from Table 18.3, *Callister 7e.*

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:**
  
  # electrons = # holes ($n = p$)
  
  --case for pure Si

- **Extrinsic:**
  
  --$n \neq p$
  
  --occurs when impurities are added with a different # valence electrons than the host (e.g., Si atoms)

- **$n$-type Extrinsic:** ($n >> p$)
  
  no applied electric field

- **$p$-type Extrinsic:** ($p >> n$)
  
  no applied electric field

\[
\sigma \approx n |e| \mu_e \\
\sigma \approx p |e| \mu_h
\]

Adapted from Figs. 18.12(a) & 18.14(a), Callister 7e.
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.