ISSUES TO ADDRESS...

• 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 $T$?
View of an Integrated Circuit

• Scanning electron microscope images of an IC:
  - A dot map showing location of Si (a semiconductor):
    -- Si shows up as light regions.
  - A dot map showing location of Al (a conductor):
    -- Al shows up as light regions.

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

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

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

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

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

- **Resistance:**
  \[ R = \frac{\rho L}{A} = \frac{L}{A \sigma} \]

- **Electric field intensity:**
  \[ E = \frac{\Delta V}{L} = \frac{I}{A \rho} \]

- **Current density:**
  \[ J = \frac{\Delta V}{L} = \frac{I}{A \sigma} \]
Electrical Properties

• Which will conduct more electricity?

\[ \rho = \frac{RA}{\ell} = \frac{VA}{I\ell} \]

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

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

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

\[ \epsilon \equiv \text{electric field potential} \quad = \frac{V}{\ell} \quad \text{or} \quad (\frac{\Delta V}{\Delta \ell}) \]

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

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>conductors</th>
<th>CERAMICS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>$6.8 \times 10^7$</td>
<td>Soda-lime glass</td>
<td>$10^{-10}$-$10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>$6.0 \times 10^7$</td>
<td>Concrete</td>
<td>$10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>$1.0 \times 10^7$</td>
<td>Aluminum oxide</td>
<td>$&lt;10^{-13}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>SEMICONDUCTORS</th>
<th></th>
<th>POLYMERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>$4 \times 10^{-4}$</td>
<td>Polystyrene</td>
<td>$&lt;10^{-14}$</td>
</tr>
<tr>
<td>Germanium</td>
<td>$2 \times 10^0$</td>
<td>Polyethylene</td>
<td>$10^{-15}$-$10^{-17}$</td>
</tr>
<tr>
<td>GaAs</td>
<td>$10^{-6}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Selected values from Tables 18.1, 18.3, and 18.4, *Callister 7e*. 
Example: Conductivity Problem

What is the minimum diameter \((D)\) of the wire so that \(\Delta V < 1.5\) V?

\[ 100m \quad e^- \quad I = 2.5A \quad + \]

\[ \Delta V \]

\[ R = \frac{L}{A\sigma} = \frac{\Delta V}{I} \]

\[ \frac{\pi D^2}{4} \]

\[ 6.07 \times 10^7 \text{ (Ohm-m)}^{-1} \]

Solve to get \(D > 1.87 \text{ mm}\)
Electronic Band Structures

2s Electron energy band (12 states)

Energy

Individual allowed energy states

2s Electron state

1s Electron energy band (12 states)

1s Electron state

Interatomic separation

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.*
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.

![Diagram of energy bands and states in metals]
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

∴ $\sigma \uparrow$ as $T \uparrow$

Electrons scattered by impurities, grain boundaries, etc.

Adapted from Fig. 18.6 (b), *Callister 7e.*
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.)
Estimating Conductivity

• Question:
  -- Estimate the electrical conductivity $\sigma$ of a Cu-Ni alloy that has a yield strength of 125 MPa.

\[
\rho = 30 \times 10^{-8} \text{ Ohm - m}
\]

From step 1:

$C_{\text{Ni}} = 21 \text{ wt}\% \text{Ni}$

\[
\sigma = \frac{1}{\rho} = 3.3 \times 10^6 \text{ (Ohm - m)}^{-1}
\]
Pure Semiconductors: Conductivity vs T

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

**Electrical conductivity, $\sigma$**

\[
\sigma_{\text{undoped}} \propto e^{-\frac{E_{\text{gap}}}{kT}}
\]

- $T$(K)
  - 50
  - 100
  - 1000

- $\sigma$ (Ohm-m)$^{-1}$
  - $10^4$
  - $10^3$
  - $10^2$
  - $10^1$
  - $10^0$
  - $10^{-1}$
  - $10^{-2}$

- material | band gap (eV)
  - Si | 1.11
  - Ge | 0.67
  - GaP | 2.25
  - CdS | 2.40

Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* 75, p. 865, 1949.)
Conduction in Terms of Electron and Hole Migration

• Concept of electrons and holes:
  - valence electron
  - electron
  - hole
  - pair creation
  - Si atom
  - no applied electric field
  - applied electric field
  - applied electric field

• Electrical Conductivity given by:

\[ \sigma = n_e e \mu_e + p_h e \mu_h \]

\# electrons/m^3
\# holes/m^3
hole mobility
electron mobility

Adapted from Fig. 18.11, Callister 7e.
Intrinsic vs Extrinsic Conduction

- **Intrinsic:**
  
  \[ \# \text{electrons} = \# \text{holes} \ (n = p) \]
  
  --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:** \( (n \gg p) \)
  
  \( \sigma \approx ne\mu_e \)

- **p-type Extrinsic:** \( (p \gg n) \)
  
  \( \sigma \approx pe\mu_h \)

Adapted from Figs. 18.12(a) & 18.14(a), Callister 7e.
**p-n Rectifying Junction**

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.
- Processing: diffuse P into one side of a B-doped crystal.
- Results:
  - 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.

Adapted from Fig. 18.21, Callister 7e.
Intrinsic Semiconductors

- Pure material semiconductors: e.g., silicon & germanium
  - Group IVA materials
- Compound semiconductors
  - III-V compounds
    - Ex: GaAs & InSb
  - II-VI compounds
    - Ex: CdS & ZnTe
  - The wider the electronegativity difference between the elements the wider the energy gap.
Doped Semiconductor: Conductivity vs. T

• Data for Doped Silicon:
  -- \( \sigma \) increases doping
  -- reason: imperfection sites lower the activation energy to produce mobile electrons.

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

• Comparison: intrinsic vs extrinsic conduction...
  -- extrinsic doping level: \( 10^{21}/m^3 \) of a \( n \)-type donor impurity (such as P).
  -- for \( T < 100 \text{ K} \): "freeze-out", thermal energy insufficient to excite electrons.
  -- for \( 150 \text{ K} < T < 450 \text{ K} \): "extrinsic"
  -- for \( T >> 450 \text{ K} \): "intrinsic"

Adapted from Fig. 18.17, Callister 7e. (Fig. 18.17 from S.M. Sze, Semiconductor Devices, Physics, and Technology, Bell Telephone Laboratories, Inc., 1985.)
Number of Charge Carriers

Intrinsic Conductivity

$$\sigma = n|e|\mu_e + p|e|\mu_e$$

- for intrinsic semiconductor $n = p$
  $$\therefore \sigma = n|e|(\mu_e + \mu_n)$$

- Ex: GaAs
  $$n = \frac{\sigma}{|e|(\mu_e + \mu_n)} = \frac{10^{-6} (\Omega \cdot m)^{-1}}{(1.6 \times 10^{-19} C)(0.85 + 0.45 \text{ m}^2/\text{V} \cdot \text{s})}$$
  For GaAs $n = 4.8 \times 10^{24} \text{ m}^{-3}$
  For Si $n = 1.3 \times 10^{16} \text{ m}^{-3}$
Properties of Rectifying Junction

Fig. 18.22, *Callister 7e.*

Fig. 18.23, *Callister 7e.*
Transistor MOSFET

- MOSFET (metal oxide semiconductor field effect transistor)

Fig. 18.24, Callister 7e.
Integrated Circuit Devices

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

Fig. 18.26, Callister 6e.
Ferroelectric Ceramics are dipolar below Curie $T_C = 120^\circ$C

- cooled below $T_c$ in strong electric field - make material with strong dipole moment

Fig. 18.35, Callister 7e.
Piezoelectric Materials

Piezoelectricity – application of pressure produces current

Adapted from Fig. 18.36, *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.
• For pure semiconductors, conductivity is increased by
  -- increasing temperature
  -- doping (e.g., adding B to Si (\(p\)-type) or P to Si (\(n\)-type).