Chapter 18: Electrical Properties

ISSUES TO ADDRESS...
• How are electrical conductance and resistance characterized?
• What are the physical phenomena that distinguish
• For metals, how is __________ affected by __________ and deformation?
• For semiconductors, how is conductivity affected by impurities (doping) and temperature?

View of an Integrated Circuit
• Scanning __________ micrographs of an IC:

Electrical Conduction
• ______ Law:
  \[ V = I \times R \]
  \( V \) = voltage drop (volts = J/C)
  \( I \) = current (amps = C/s)
  \( R \) = resistance (Ohms)

• ____________, \( \rho \):
  -- a material property that is independent of sample size and geometry
  \( \rho = \frac{RA}{\ell^2} \)
  \( R \) = surface area of current flow
  \( \ell \) = current flow path length
Chapter 18 - Electrical Properties

• Which will have the greater ____________?

\[ R = \frac{2\mu L}{nD} \]  
\[ R = \frac{\rho L}{\pi D^2/4} \]

• Analogous to flow of water in a pipe
• ____________ depends on sample geometry and size.

Chapter 18 - Definitions

Further definitions

\[ J = \text{current density} = \frac{I}{A} \]
\[ J = \text{electron flux} \]  
\[ z = \text{conductivity} \]

Electron flux  
conductivity

Chapter 18 - Conductivity: Comparison

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

METALS
- Silver 6.8 x 10\(^{-7}\)
- Copper 6.0 x 10\(^{-7}\)
- Iron 1.0 x 10\(^{-7}\)

POLYMERS
- Soda-lime glass 10\(^{10}\) - 10\(^{11}\)
- Concrete 10\(^{-9}\)
- Aluminum oxide <10\(^{-13}\)
- Polystyrene <10\(^{-14}\)
- Polyethylene 10\(^{-15}\) - 10\(^{-17}\)

Silicon 4 x 10\(^{-4}\)
Germanium 2 x 10\(^{-5}\)
GaAs 10\(^{-6}\)

Selected values from Tables 18.1, 18.3, and 18.4, Callister & Rethwisch 8e.
Example: Conductivity Problem

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

\[
\frac{nD^2}{4} \times 100 \text{ m} < 1.5 \text{ V}
\]

Solve to get \(D > \) ________

Electron Energy Band Structures

2s Electron energy band (12 states)

2s Electron state

1s Electron energy band (12 states)

1s Electron state

Individual allowed energy states

Interatomic separation

Band Structure Representation

Energy band

Energy band gap

Energy band

Equilibrium interatomic separation

Adapted from Fig. 18.2, Callister & Rethwisch 8e.

Adapted from Fig. 18.3, Callister & Rethwisch 8e.
Conduction & Electron Transport

- Metals (_____________):
  - for metals ________________ are adjacent to filled states.
  - thermal energy excites ________________ into empty higher energy states.
  - two types of band structures for metals
    - empty band that overlaps filled band

Energy Band Structures: Insulators & Semiconductors

- wide band gap (____ eV)
  - few electrons excited across band gap

- narrow band gap (____ eV)
  - more electrons excited across band gap

Metals: Influence of Temperature and Impurities on Resistivity

- grain boundaries
- impurity atoms
  - These act to scatter electrons so that they take a less direct path.

Resistivity, $\rho$ increases with:

- temperature
- wt% impurity
- %CW

Adapted from Fig. 18.8, Callister & Rethwisch 8e. (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.

$\rho = 30 \times 10^{-8}$ Ohm $\cdot$ m

From step 1:
$C_N = \underline{\text{Ni}}$

Charge Carriers in Insulators and Semiconductors

Two carriers:
- ___________ charge
- in conduction band
- ___________ charge
- vacant electron state in the valence band

Move at different speeds - drift velocities

Intrinsic Semiconductors

- Pure material _______________ : e.g., silicon & germanium
  - Group IVA materials
- Compound semiconductors
  - _______ compounds
    - Ex: GaAs & InSb
  - _______ compounds
    - Ex: CdS & ZnTe
  - The wider the electronegativity difference between the elements the wider the energy gap.
Intrinsic Semiconduction in Terms of Migration

- Concept of _______
  - valence electron
  - electron = hole
  - pair creation
  - applied electric field
  - electron = hole
  - pair migration
  - applied electric field

- Electrical _______ given by:
  - # holes/m³
  - # electrons/m³
  - electron mobility
  - hole mobility

- Concept of ______________:
  - +
  - -
  - electron
  - hole
  - pair creation
  - +
  - -
  - no applied
  - electron
  - hole
  - pair migration

Number of Charge Carriers

Conductivity

- for ______ semiconductor $n = p = n_i$
  - $\sigma = \frac{n_i e (\mu_e + \mu_h)}{A}$
  - Ex: GaAs
    - $n_i = \frac{10^{-6}(\Omega \cdot m)^{-1}}{(1.6 \times 10^{-19} C)(0.85 + 0.45 m^2/V \cdot s)}$
    - For GaAs $n_i = __________$
    - For Si $n_i = 1.3 \times 10^{16} m^{-3}$

Intrinsic Semiconductors: Conductivity vs T

- Data for _______
  - $\sigma$ increases with $T$
  - opposite to metals

- $n_i \propto e^{-E_{gap}/kT}$

<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>

Selected values from Table 18.3, Callister & Rethwisch 8e.
**Intrinsic vs Extrinsic Conduction**

- case for pure Si
  - # electrons = # ________ (n = p)

- electrical behavior is determined by presence of impurities that introduce excess electrons or holes

- n-type ________: (n >> p) • p-type Extrinsic: (p >> n)

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**Extrinsic Semiconductors: Conductivity vs. Temperature**

- Data for ________:
  - reason: imperfection sites lower the activation energy to produce mobile electrons.

- Comparison: ________ vs extrinsic conduction...
  - 10^18 of a n-type donor impurity (such as P).
  - for T << 150 K: "freeze-out", thermal energy insufficient to excite electrons.
  - for 150 K < T < 450 K: "extrinsic"
  - for T >> 450 K: "intrinsic"

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**p-n Rectifying Junction**

- Allows flow of ________ in one direction only (e.g., useful to convert ________ current to ________ current).

- Processing: diffuse P into one side of a B-doped crystal.
  - No applied ________:
  - ________ bias: carriers flow through p-type and n-type regions; holes and electrons recombine at p-n junction; current flows.
  - ________ bias: carriers flow away from p-n junction; junction region depleted of carriers; little current flow.
Chapter 18 - Properties of Rectifying Junction

![Properties of Rectifying Junction](image)

Chapter 18 - Junction Transistor

![Junction Transistor](image)

Chapter 18 - MOSFET Transistor

Integrated Circuit Device

![MOSFET Transistor](image)

- MOSFET
- Integrated circuits - state of the art ca. ___ nm line width
  - ~ 1,000,000,000 components on chip
  - chips formed one layer at a time
Chapter 18 - Ferroelectric Ceramics

- Experience __polarization

Fig. 18.35, Callister & Rethwisch 8e.

BaTiO$_3$ — ferroelectric below its ______ temperature (120ºC)

Chapter 18 - Piezoelectric Materials

- application of stress induces __________
- application of voltage induces dimensional change

Adapted from Fig. 18.36, Callister & Rethwisch 8e. (Fig. 18.36 from Van Vlack, Lawrence H., Elements of Materials Science and Engineering, 1989, p.482. Adapted by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)

Chapter 18 - Summary

- Electrical conductivity and resistivity are:
  - material parameters
  - geometry independent
- Conductors, semiconductors, and insulators...
  - differ in range of conductivity values
  - differ in availability of electron excitation states
- For metals, resistivity is increased by
  - increasing temperature
  - addition of imperfections
  - plastic deformation
- For pure semiconductors, conductivity is increased by
  - increasing temperature
  - doping [e.g., adding B to Si (p-type) or P to Si (n-type)]
- Other electrical characteristics
  - ferroelectricity
  - piezoelectricity

Chapter 18 - Summary