Chapter 18  Electrical properties

- Introduction
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- Electrical conductivity
- Electronic and ionic conduction
- Energy band structures in solids
- Conduction in terms of band and atomic bonding atoms
- Electron mobility
- Electrical resistivity of metals
- Electrical characteristics of commercial alloys
- Intrinsic semiconductors
- Extrinsic semiconductors

### Electrical conduction

- **Ohm’s Law:**
  \[
  \Delta V = I R
  \]
  voltage drop (volts = J/C)
  \( C = \text{Coulomb} \)
  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

  \[
  E: \text{electric field intensity} \quad \Delta V = \frac{I}{A} \rho
  \]
  \( A \) (cross sect. area)
  \( J: \text{current density} \)

- **Resistance:**
  \[
  R = \frac{\rho L}{A} = \frac{L}{A\sigma}
  \]
  conductivity \( \sigma = \frac{1}{\rho} \)
Electrical properties

- Which will conduct more electricity?

  ![Diagram of a pipe with dimensions D and 2D](image)

  \[ \rho = \frac{RA}{L} = \frac{VA}{IL} \]

- 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
  - \[ J = \text{current density} = \frac{\text{current}}{\text{surface area}} = \frac{I}{A} \] like a flux
  - \[ \varepsilon = \text{electric field potential} = \frac{V}{\ell} \text{ or } (\Delta V/\Delta \ell) \]

  \[ J = \sigma (\Delta V/\Delta \ell) \]

- Electron flux, conductivity, voltage gradient

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

<table>
<thead>
<tr>
<th>Room $T$ values (Ohm-m)$^{-1}$ = $(\Omega \cdot m)^{-1}$</th>
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</thead>
<tbody>
<tr>
<td><strong>METALS</strong></td>
</tr>
<tr>
<td>Silver</td>
</tr>
<tr>
<td>Copper</td>
</tr>
<tr>
<td>Iron</td>
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<tr>
<td><strong>CERAMICS</strong></td>
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<tr>
<td>Soda-lime glass</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>Aluminum oxide</td>
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<tr>
<td><strong>SEMICONDUCTORS</strong></td>
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<td>Silicon</td>
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<tr>
<td>Germanium</td>
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<tr>
<td>GaAs</td>
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<td><strong>POLYMERS</strong></td>
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<td>Polystyrene</td>
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</table>

### Example: Conductivity problem

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

\[
\Delta V = \frac{\pi D^2}{4} \sigma = \frac{L}{I}
\]

Solve to get $D > 1.87$ mm
Electronic band structures

2s Electron energy band (12 states)

1s Electron energy band (12 states)

Valence band – filled – highest occupied energy levels

Conduction band – empty – lowest unoccupied energy levels

Individual allowed energy states

1s Electron state

2s Electron state

Interatomic separation

Band structure

- Valence band – filled – highest occupied energy levels
- Conduction band – empty – lowest unoccupied energy levels
Various possible electron band structures

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

\[\text{Metal (Cu)} \quad \text{Metal (Mg)} \quad \text{Insulator} \quad \text{Semiconductor}\]

Conduction in terms of band and atomic bonding models

For a metal, occupancy of electron states (a) before and (b) after an electron excitation
Conduction in terms of band and atomic bonding models

For an insulator or semiconductor, occupancy of electron states (a) before and (b) after an electron excitation

Electron mobility

- Drifting velocity: average electron velocity in the direction of the force imposed by the applied field
  \[ v_d = \mu_e \vec{E} \]
  - Electron mobility \( \mu_e \): an indication of the frequency of scattering events (m^2/V-s)

- The conductivity
  \[ \sigma = n |e| \mu_e \]
Electrical resistivity of metals

- Mathiessen’s rule
  \[ \rho_{\text{total}} = \rho_i + \rho_T + \rho_d \]
  - Influence of T
    \[ \rho_i = \rho_0 + aT \]
  - Influence of impurity
    \[ \rho_i = A c_i (1 - c_i) \]
  - Influence of plastic deformation: increased numbers of electron-scattering dislocations

Intrinsic semiconductor

- Intrinsic semiconductor: its electrical behavior is based on the pure material
- Intrinsic semiconductor band structure
- A current arises from the flow of electrons and holes
Intrinsic semiconductor

- **Elemental semiconductor**
  - Group IVA, Si (Egap 1.1 eV), Ge (Egap 0.7 eV)

- **Compound semiconductor**
  - Group IIIA-VA, GaAs, InSb
  - Group IIB-VIA, CdS and ZnTe

- **Electric conductivity**

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

Extrinsic semiconductor

- The electrical behavior is determined by impurities.
- **N-type semiconductor**
  - Majority carrier: electrons
  - Minority charge carriers: holes

![Diagram](image)
Extrinsic semiconductors (cont.)

- **P-type semiconductor:** trivalent substitutional impurities aluminum, boron, and gallium
  - Majority carrier: holes
  - Minority charge carriers: electrons

![Diagram of P-type semiconductor with labels](image.png)

- Semiconductor atoms
- Impurity atom with three valence electrons
- Hole, or electron deficiency in a bond