**OUTLINE**

- INTRODUCTION
- ELECTRICAL CONDUCTION
- ENERGY BAND STRUCTURE IN SOLIDS
- INSULATORS AND SEMICONDUCTORS
- METALS: ELECTRON MOBILITY
- INFLUENCE OF TEMPERATURE
- INFLUENCE OF IMPURITY
- SEMICONDUCTORS
- P-N RECTIFYING JUNCTION
- SUMMARY

**INTRODUCTION**

- Scanning electron microscope images of an IC:

  ![Scanning electron microscope images](image)

  From Fig. 18.0 and 18.25, Callister 6e.

  - In SEM the electron beam causes the surface atoms to emit X-rays.
  - It is possible to filter all the rays but the ones from the atom of interest.
  - When these rays are projected on a cathode tube screen, they will generate white dots – *dot map*

**ELECTRICAL CONDUCTION**

- Ohm's Law:
  \[ V = IR \]

  - \( V \): voltage drop (volts)
  - \( I \): current (amps)
  - \( R \): resistance (Ohms)

- Resistivity, \( \rho \) and Conductivity, \( \sigma \):
  \( \sigma \) is geometry-independent forms of Ohm's Law

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

  \( \rho \): resistivity (Ohm-m)
  \( \sigma \): Conductivity
  \( J \): current density

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

**CONDUCTIVITY: COMPARISON**

- Solid materials exhibit a very wide range of electrical conductivity
  - ………… range compared to other phys. properties.
  - Materials can be classified according to their electrical conductivity.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (Ohm-m)^{-1} at room temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>METALS</strong></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>6.8 x 10^7</td>
</tr>
<tr>
<td>Copper</td>
<td>6.0 x 10^7</td>
</tr>
<tr>
<td>Iron</td>
<td>1.0 x 10^7</td>
</tr>
<tr>
<td><strong>CERAMICS</strong></td>
<td></td>
</tr>
<tr>
<td>Soda-lime glass</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>Concrete</td>
<td>10^{-9}</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>&lt;10^{-13}</td>
</tr>
<tr>
<td><strong>SEMICONDUCTORS</strong></td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>4 x 10^{-4}</td>
</tr>
<tr>
<td>Germanium</td>
<td>2 x 10^{-6}</td>
</tr>
<tr>
<td>GaAs</td>
<td>10^{-6}</td>
</tr>
<tr>
<td><strong>POLYMERS</strong></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>&lt;10^{-14}</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>10^{-15} - 10^{-17}</td>
</tr>
<tr>
<td><strong>INSULATORS</strong></td>
<td></td>
</tr>
</tbody>
</table>

Selected values from Tables 18.1, 18.2, and 18.3, Callister 6e.
EXAMPLE

A copper wire 100 m long must experience a voltage drop of less than 1.5 V when a current of 2.5 A passes through it. If $\sigma = 6.07 \times 10^7$ (Ohm-m)$^{-1}$, compute the minimum diameter of the wire.

\[ \Delta V \]

\[ \text{Cu wire} \]

\[ I = 2.5 A \]

\[ e^- \]

\[ 100 m \]

Energy Band Structure in Solids

The electrical properties of a solid material are a consequence of its arrangement of the outermost electron bands and the way in which they are filled with electrons.

The various possible electron band structures in solids at 0 K:

- Metals such as copper, in which electron states are available above and adjacent to filled states, in the same band.
- Insulators: the filled valence band is separated from the empty conduction band by a relatively large band gap (2 eV).
- Semiconductors: same as for insulators except that the band gap is relatively small (2 eV).

CONDUCTION & ELECTRON TRANSPORT

- Only electrons with energies greater than the Fermi energy $E_F$ (i.e., free electrons) may be acted on and accelerated when the electric field is applied.
- Holes have energies less than $E_F$ and also participate in electronic conduction.
- The electrical conductivity depends on the numbers of free electrons and holes.

- Metals:
  - Thermal energy ($kT$) puts many electrons into a higher energy state.
  - Energy States:
    - For metals the nearby energy states are accessible by thermal fluctuations.

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Free electrons are different from the electron sea! They do not become truly free until they have the required excitation ($E > E_F$).

INSULATORS AND SEMICONDUCTORS

- Insulators:
  - Higher energy states not accessible due to gap.

- Semiconductors:
  - Higher energy states separated by a smaller gap.

The …… the band gap, the …… is the electrical conductivity at a given temp.
• Imperfections resistivity
  - grain boundaries
  - dislocations
  - impurity atoms
  - vacancies

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

• Resistivity increases with temp., impurity concentration and %CW

\[ \rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{def}} \]

Where \( \rho_o \) and \( a \) are constants for each metal.

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

\( \rho_{\text{thermal}} \) rule

T \( \rightarrow \) vibration and lattice defects \( \rightarrow \) electron scattering

\%CW \( \rightarrow \) dislocation concentration \( \rightarrow \) resistivity

Ni atoms scatter the electrons \( \rightarrow \rho \uparrow \)

For a two phase alloy a rule of mixtures applies and the impurity resistivity can be estimated as:

\[ \rho_{\text{impurity}} = \rho_a V_a + \rho_{\beta} V_{\beta} \]

V’s and \( \rho \)'s are the volume fraction and individual resistivities for each phase.

Estimate the electrical conductivity of a Cu-Ni alloy that has a yield strength of 125 MPa.

For every electron excited into the conduction band there is left behind a missing electron -………

\[ \sigma_{\text{undoped}} \propto e^{-\frac{E_{\text{gap}}}{kT}} \]
Electrical Conductivity given by:

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

- \( n_e \) and \( p_h \) are the number of electrons and holes, respectively.
- \( \mu_e \) and \( \mu_h \) are the electron and hole mobilities, respectively.

\# electrons/m\(^3\) \hspace{1cm} \# holes/m\(^3\) \hspace{1cm} electron mobility \hspace{1cm} hole mobility

In intrinsic semiconductors \( n_e = p_h \)

Electron and Hole Migration

- No applied electric field
- Electron and hole pair creation
- Applied electric field
- Electron and hole pair migration

Adapted from Fig. 18.10, Callister 6e.

**Electron Conductivity**
- Occurs when impurities are added with more # valence electrons than the host (e.g., doping Si with P or B)

**Hole Conductivity**
- Occurs when impurities are added with fewer # valence electrons than the host (e.g., doping Si with B or Al)

Intrinsic vs Extrinsic Conduction

**Intrinsic:**
- \( n \neq p \)
- Occurs when impurities are added with a different # valence electrons than the host (e.g., doping Si with P or B)

**Extrinsic:**
- \( n \approx p \)
- No applied electric field
- Electron and hole pair migration

**N-type Extrinsic:** \( n >> p \)
- Phosphorus atom
- Donor impurities
- Group V: P, As, Sb
- Donor impurities have one extra electron
- Donor impurities donate an electron to Si

**P-type Extrinsic:** \( p >> n \)
- Boron atom
- Acceptor impurities
- Group III: B, Al, In, Ga
- Acceptor impurities have one fewer electrons
- Acceptor impurities accept electrons from Si

Semiconductors: Summary

- **Intrinsic Conductivity** (pure materials): electron-hole pairs
- Conductivity: \( Si \ 4 \times 10^{-4} \ (\Omega \ m)^{-1} \) vs. \( Fe \ 1 \times 10^{7} \ (\Omega \ m)^{-1} \)
- Electron has to overcome the energy gap \( E_g \)

Intrinsic conductivity strongly depends on temperature and as-present impurities

- **Extrinsic Conductivity**
  - Doping: substituting a Si atom in the lattice by an impurity atom (............) that has one extra or one fewer valence electrons
  - **Donor** impurities have one extra electron (group V: P, As, Sb), donate an electron to Si.
  - **Acceptor** impurities have one fewer electrons (group III: B, Al, In, Ga), accept electrons from Si which creates holes.
Doped Silicon:
- Dopant concentration $\uparrow$ - $\sigma$ $\uparrow$
- Reason: imperfection sites lower the activation energy to produce mobile electrons.

<table>
<thead>
<tr>
<th>Doping Level</th>
<th>Electrical Conductivity ($\sigma$)</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0013 at% B</td>
<td>$10^{-2}$ Ohm-m</td>
<td>$10^{21}$ m$^{-3}$ of a n-type donor impurity (such as P).</td>
</tr>
<tr>
<td>0.0052 at% B</td>
<td>$10^{-1}$ Ohm-m</td>
<td>for $T &lt; 100K$: thermal energy insufficient to excite electrons.</td>
</tr>
<tr>
<td>Pure (undoped)</td>
<td>$10^0$ Ohm-m</td>
<td>for $150K &lt; T &lt; 450K$: carrier flow away from p-n junction; carrier conc. Greatly reduced at junction; little current flow.</td>
</tr>
</tbody>
</table>

Adapted from Fig. 19.15, Callister 5e.

• Intrinsic vs Extrinsic conduction:
- extrinsic doping level: $10^{21}$/m$^3$ of a n-type donor impurity (such as P).
- for $T < 100K$: thermal energy insufficient to excite electrons.
- for $150K < T < 450K$: carrier flow away from p-n junction; carrier conc. Greatly reduced at junction; little current flow.
- for $T >> 450K$: carrier flow through p-type and n-type regions; holes and electrons recombine at p-n junction; current flows.

Adapted from Fig. 18.16, Callister 6e.

SUMMARY

• Electrical resistance is:
  - a geometry and material dependent parameter.

• Electrical conductivity and resistivity are:
  - material parameters and geometry independent.

• Conductors, semiconductors, and insulators...
  - different in whether there are accessible energy states for 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)).