Electrical conductivity

- **Ohm's Law:**
  
  \[ \Delta V = I R \]
  
  voltage drop (volts = J/C)
  
  \( E \): electric field intensity

  \( C \): Coulomb

  \( A \): (cross sect. area)

  \( L \): distance

- **Resistivity, \( \rho \) and Conductivity, \( \sigma \):**

  -- geometry-independent forms of Ohm's Law

  -- Resistivity is a material property & is independent of sample

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

  \( J \): current density

- **Resistance:**

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

  \( \sigma = \frac{1}{\rho} \)
Conductivity: comparison

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

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

<table>
<thead>
<tr>
<th>SEMICONDUCTORS</th>
<th>POLYMERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>4 x 10$^{-4}$</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>Germanium</td>
<td>2 x 10$^0$</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>GaAs</td>
<td>$10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

Selected values from Tables 18.1, 18.3, and 18.4, Callister 7e.
Electronic band structure

Adapted from Fig. 18.2, Callister 7e.
Electronic band structure

- **Valence band** – filled – highest occupied energy levels
- **Conduction band** – empty – lowest unoccupied energy levels

Adapted from Fig. 18.3, *Callister 7e.*
Conduction and 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 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.
Charge carriers

- 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.)
Pure semiconductors: Conductivity vs $T$

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

![Graph showing electrical conductivity ($\sigma$) vs temperature ($T$) for pure silicon.](image)

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

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

- **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
  - no applied electric field
  - applied electric field

• Electrical Conductivity given by:
  \[ \sigma = n e \mu_e + p e \mu_h \]
  - # holes/m\(^3\)
  - # electrons/m\(^3\)
  - electron mobility
  - hole mobility

Adapted from Fig. 18.11, Callister 7e.
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

Adapted from Figs. 18.12(a) & 18.14(a), *Callister 7e.*
Doped semiconductor: conductivity vs. T

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

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

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

Adapted from Fig. 18.17, *Callister 7e*. (Fig. 18.17 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)
Doped semiconductor: conductivity vs. T

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 $\quad n = 4.8 \times 10^{24} \text{ m}^{-3}$
For Si $\quad n = 1.3 \times 10^{16} \text{ m}^{-3}$
Corrosion of zinc in acid

- Two reactions are necessary:
  -- oxidation reaction: \( \text{Zn} \rightarrow \text{Zn}^{2+} + 2e^- \)
  -- reduction reaction: \( 2\text{H}^+ + 2e^- \rightarrow \text{H}_2(\text{gas}) \)

- Other reduction reactions:
  -- in an acid solution
    \( \text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \)
  -- in a neutral or base solution
    \( \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4(\text{OH})^- \)

Adapted from Fig. 17.1, *Callister 7e*. (Fig. 17.1 is from M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)
Standard hydrogen (EMF) test

- Two outcomes:
  -- Metal sample mass
    - Metal is the anode (-)
    - $V_{\text{metal}}^0 < 0$ (relative to Pt)

    ![Diagram of standard hydrogen test with platinum as reference electrode]

  -- Metal is the cathode (+)
    - $V_{\text{metal}}^0 > 0$ (relative to Pt)

Adapted from Fig. 17.2, Callister 7e.
Standard EMF series

- EMF series
  -金属  $V_{\text{metal}}^o$
  - Au  $+1.420 \text{ V}$
  - Cu  $+0.340$
  - Pb  $-0.126$
  - Sn  $-0.136$
  - Ni  $-0.250$
  - Co  $-0.277$
  - Cd  $-0.403$
  - Fe  $-0.440$
  - Cr  $-0.744$
  - Zn  $-0.763$
  - Al  $-1.662$
  - Mg  $-2.363$
  - Na  $-2.714$
  - K  $-2.924$

- Metal with smaller $V_{\text{metal}}^o$ corrodes.
- Ex: Cd-Ni cell

  - $\Delta V^o = 0.153 \text{ V}$

Data based on Table 17.1, *Callister 7e.*

Adapted from Fig. 17.2, *Callister 7e.*
Effect of solution concentration

- Ex: Cd-Ni cell with standard 1 M solutions
  
  \[ V_{\text{Ni}}^0 - V_{\text{Cd}}^0 = 0.153 \]

- Ex: Cd-Ni cell with non-standard solutions
  
  \[ V_{\text{Ni}} - V_{\text{Cd}} = V_{\text{Ni}}^0 - V_{\text{Cd}}^0 - \frac{RT}{nF} \ln \frac{X}{Y} \]

  \( n = \#e^- \) per unit oxid/red reaction (= 2 here)
  
  \( F = \) Faraday's constant = 96,500 C/mol.

- Reduce \( V_{\text{Ni}} - V_{\text{Cd}} \) by
  - increasing \( X \)
  - decreasing \( Y \)
Galvanic series

- Ranks the reactivity of metals/alloys in seawater

Platinum
Gold
Graphite
Titanium
Silver
316 Stainless Steel
Nickel (passive)
Copper
Nickel (active)
Tin
Lead
316 Stainless Steel
Iron/Steel
Aluminum Alloys
Cadmium
Zinc
Magnesium

Based on Table 17.2, Callister 7e. (Source of Table 17.2 is M.G. Fontana, Corrosion Engineering, 3rd ed., McGraw-Hill Book Company, 1986.)
Forms of corrosion

- **Uniform Attack**
  Oxidation & reduction occur uniformly over surface.

- **Selective Leaching**
  Preferred corrosion of one element/constituent (e.g., Zn from brass (Cu-Zn)).

- **Intergranular**
  Corrosion along grain boundaries, often where special phases exist.

- **Stress corrosion**
  Stress & corrosion work together at crack tips.

- **Galvanic**
  Dissimilar metals are physically joined. The more anodic one corrodes. (see Table 17.2) Zn & Mg very anodic.

- **Erosion-corrosion**
  Break down of passivating layer by erosion (pipe elbows).

- **Pitting**
  Downward propagation of small pits & holes.

- **Crevice**
  Between two pieces of the same metal.

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Fig. 17.15, *Callister 7e*. (Fig. 17.15 is courtesy LaQue Center for Corrosion Technology, Inc.)

Fig. 17.17, *Callister 7e*. (Fig. 17.17 from M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)

Fig. 17.18, *Callister 7e*.
Controlling corrosion

- Self-protecting metals!
  -- Metal ions combine with O to form a thin, adhering oxide layer that slows corrosion.

- Reduce $T$ (slows kinetics of oxidation and reduction)

- Add inhibitors
  -- Slow oxidation/reduction reactions by removing reactants (e.g., remove O$_2$ gas by reacting it w/an inhibitor).
  -- Slow oxidation reaction by attaching species to the surface (e.g., paint it!).

- Cathodic (or sacrificial) protection
  -- Attach a more anodic material to the one to be protected.

Adapted from Fig. 17.22(a), Callister 7e. (Fig. 17.22(a) is from M.G. Fontana, Corrosion Engineering, 3rd ed., McGraw-Hill Book Co., 1986.)