**Classification of Solids**

Classification by *conductivity*, which is related to the band structure:

(Filled bands are shown dark; \( D(E) \) = Density of states)

<table>
<thead>
<tr>
<th>Class</th>
<th>Electron Density Resistivity</th>
<th>Density of States ( D(E) ) versus Energy ( E )</th>
<th>Examples (Gap ( E_G ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Insulators</td>
<td>( 10^{10} \text{e}^-/\text{cm}^3 ) ( 10^{-6}\text{Ωcm} )</td>
<td><img src="image" alt="Conduction Band" /> ( E_G = \text{Band Gap} )</td>
<td>LiF (14eV) ( \text{SiO}_2 ) (9eV)</td>
</tr>
<tr>
<td>2) Semiconductors</td>
<td></td>
<td><img src="image" alt="Valence Band" /></td>
<td>GaAs (1.4eV) ( \text{Si} ) (1.1eV) ( \text{Ge} ) (0.7eV)</td>
</tr>
<tr>
<td>3) Semimetals</td>
<td>( 10^{20} \text{e}^-/\text{cm}^3 ) ( 10^{-4}\text{Ωcm} )</td>
<td><img src="image" alt="Energy Level" /> ( E_F = \text{Fermi Level} )</td>
<td>Bismuth ( \text{Graphite} )</td>
</tr>
<tr>
<td>4) Metals</td>
<td></td>
<td><img src="image" alt="Density of States" /> ( D(E) )</td>
<td>Al, Cu</td>
</tr>
</tbody>
</table>

**Energy scales:** Band width \( \approx 10^1\text{eV} \), Band gap \( \approx 10^0\text{eV} \), \( kT \approx 25\text{meV} \) (room temperature)

**Metals:** Resistance *increases* with increasing temperature.

Thermal lattice vibrations (phonons) scatter electrons.

**Semiconductors / Insulators:** Resistance *decreases* with increasing temperature.

Thermal excitation of electron/hole pairs (carriers).
Semiconductors

Conductivity

\[ J = \sigma \cdot E \]

defines conductivity \( \sigma \)

\[ v = \pm \mu \cdot E \]

defines mobility \( \mu \)

\[ J = n \cdot q \cdot v \]

\[ v = (q \tau / m^*) \cdot E \]

\[ \sigma = (n e^2 \tau) / m^* \]

\[ \mu = (e \tau) / m^* \]

Hall Effect

Hall voltage \( V_H = y \cdot E_y \) provides carrier density \( \rho \) and sign of \( q \).

\[ \frac{E_y}{J_x B_z} = \frac{1}{\rho q} = R_H \]

Quantum Hall Effect

Integer Quantum Hall Effect:
Electrons (dots) move in circular orbits and populate discrete Landau levels (magnetism notes p. 6). For a filling \( \nu = 1 \) of the lowest Landau level each electron orbits around one vortex (= magnetic flux quantum \( h/e \), arrows).

Fractional Quantum Hall Effect:
For a filling \( \nu = 1/3 \) each electron is associated with three vortices.

Fractional charge of \( e/3 \) for a hole (= single vortex without its share of \( 1/3 \) electron). Such extra vortices appear when \( B \) is higher than required for a filling \( \nu = 1/3 \).
Semiconductor Junctions

Start out with two neutral pieces. Put them into contact and let electrons flow to lower states until the two Fermi are equilibrated. Thereby, neutral dopants become ionized ("space charge") and an electrostatic potential builds up. $E_F$ is shown for $T=0$. 

**pn Junction**

Separate p- and n-type semiconductors:

- n-type
  - CB
  - $E_F$
  - VB

- p-type
  - CB
  - $E_F$
  - VB

After forming the pn-junction:

Electrons flow downhill from n to p until the Fermi levels $E_F$ line up.

**Rectifying Diode**

- Reverse bias
- Zero bias
- Forward bias

**Photodiode**

- Reverse bias
- Photon creates $e^-h^+$ pair

**Solar Cell**

- Forward bias

**LED (Light Emitting Diode)**

- Forward bias
- $e^-h^+$ pair recombines into a photon
Two separate semiconductors:

n-type intrinsic

After forming a junction:

Ionized Donors

Modulation Doping: Achieve high electron density without scattering of electrons by donors. Record mobilities of $>10^6 \text{ cm}^2/\text{Vs}$. Example: GaAlAs/GaAs

Used for creating a two-dimensional electron gas (quantum Hall effect).

Metal Oxide Semiconductor (MOS)

Shown for a p-type semiconductor = NMOS (conduction by n-type carriers in inversion)

Flatband

Accumulation

Inversion

Charging of a Capacitor
Field Effect Transistor (FET)

NMOS:

off:
\[ V_{\text{Gate}} = 0 \]

on:
\[ V_{\text{Gate}} > 0 \]

Channel conductivity controlled by the gate voltage.

CMOS (Complementary MOS)

Back-to-back NMOS and PMOS with common gate. Low power consumption, since it draws current during switching only. Most common device in today’s electronics.

Quantum Well Laser

A semiconductor with smaller band gap is inserted at the pn junction of a LED. It traps both electrons and holes and gives them more time to recombine into a photon.

CCD (Charge-Coupled-Device)

Array of MOS capacitors with highly positive gate voltage (inversion). They can store light-induced charge and pass it on along the array for readout.