Semiconductors and Devices based on $p$-$n$ Junctions

Chapter 7

Wednesday, October 28, 2015
Metals, Semiconductors, and Insulators

Metals
- Cu, Ag, Au
- Partially filled band

Semiconductors
- Si, Ge, GaAs, CdS
- 0.1 eV < $E_g$ < 4 eV
- Empty band
- Full band

Insulators
- Diamond, MgO
- $E_g$ > 4 eV
The Fermi level ($E_F$) is the chemical potential for electrons. It is the (possibly hypothetical) energy level at which the probability of electron occupancy is 50%.

The Fermi level cuts through band.

Fermi level near the middle of the gap.
Heat, light, and other stimuli can excite electrons across the band gap, resulting in mobile electrons (negative charges) and holes (electron vacancies, positive charges) and electrical conductivity.

$T = 0 \text{ K}$

$T = 298 \text{ K}$

Mobile electrons

Mobile holes

Valence band

Conduction band

Full band → no net current
<table>
<thead>
<tr>
<th>Semi-Conductor</th>
<th>Band Gap / eV</th>
<th>color</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$</td>
<td>3.0-3.2</td>
<td>colorless</td>
</tr>
<tr>
<td>CdS</td>
<td>2.4</td>
<td>yellow</td>
</tr>
<tr>
<td>HgS</td>
<td>2.1</td>
<td>red</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.5</td>
<td>black</td>
</tr>
<tr>
<td>Si</td>
<td>1.12</td>
<td>dark gray</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>light gray</td>
</tr>
</tbody>
</table>
Doping of Semiconductors

Doping means adding impurity atoms to a semiconductor to change its electrical properties. Consider silicon:

- **p-type SC**: Add boron impurities (B has 3 valence electrons)
- **pure crystalline Si**: Si has 4 valence electrons
- **n-type SC**: Add phosphorous impurities (P has 5 valence electrons)
Doping

Adding foreign atoms (dopants) of Group V or Group III to a Group IV semiconductor produces $n$-type or $p$-type semiconductors.

- **Dopant type:** donor or acceptor
- **Majority carrier:** electrons or holes
Advanced optoelectronic devices can be made by layering $p$-type and $n$-type semiconductors:

- transistors
- solar cells
- photodetectors
- LEDs and lasers
Consider what happens when a junction between $p$-type and $n$-type semiconductors is made:

Before contact, the Fermi level of the $n$-type SC is higher than that of the $p$-type SC.
Upon contact, electrons diffuse from the n side to the p side. Holes diffuse in the opposite direction (p to n).
Net diffusion occurs until balanced by an electric field at the junction. At this point, equilibrium is established (Fermi levels equal).
$p-n$ Junctions

at equilibrium:
The $p$-$n$ junction is an electrical **diode**, a device through which current flows in only one direction. At equilibrium (zero applied voltage), the net current is zero.
The $p$-$n$ junction is an electrical **diode**, a device through which current flows in only one direction.

**Under forward bias**, large positive current flows because the energy barrier for diffusion is reduced.

\[ \text{Net electron current} \]

\[ \text{Net hole current} \]

- **Forward bias**

\[ \text{Current} \]

\[ \text{Voltage} \]
The $p$-$n$ junction is an electrical diode, a device through which current flows in only one direction.

Under reverse bias, only tiny negative current flows because the energy barrier to diffusion is increased.

$p$-type SC

$n$-type SC

(V < 0)
\( p-n \) Junctions

\( p-n \) diodes are the basis for solar cells, photodiodes, light-emitting diodes (LEDs), and laser diodes.

1\(^{\text{st}}\) quadrant (dark): \textit{LED or LD}

3\(^{\text{rd}}\) quadrant: \textit{photodiode}

4\(^{\text{th}}\) quadrant: \textit{solar cell}
Solar cells are illuminated *p-n* junctions. They convert sunlight into electricity.

\[ \text{current} \times \text{voltage} = \text{power} \]
Photodiodes are \( p-n \) junctions held in reverse bias used to detect light.

Photodiode operated here to increase E-field & collect as much current as possible; also improves speed.
LEDs and Laser Diodes

Light-emitting diodes and laser diodes are \( p-n \) junctions held at large forward bias that convert electricity to light.
Chapter 7 Summary

Crystalline solids possess long-rang periodicity with a repeating unit called the unit cell.

All crystals belong to one of 14 Bravais lattices. Many crystals can be described in terms of close-packed arrays with some specific filling of tetrahedral sites (2 per ion) and octahedral sites (1 per ion).

The structures of ionic crystals depend on the ratio of ion radii, stoichiometry, and electronic factors. The lattice energy can be determined from Born-Haber cycles and calculated using the Born-Landé equation.

The frontier electronic structure of solids is characterized by valence and conduction bands, which are analogous to the HOMO and LUMO of molecules built from MO theory.

Junctions between \( p \)-type and \( n \)-type semiconductors are used to make solar cells, photodiodes, light-emitting diodes, and laser diodes.