Semiconductors

Last time we talked about solids. The most important points were that electrons are free to move about the crystal so they are in global energy levels.

- Many energy levels since many electrons
- Exclusion principle $\Rightarrow$ can’t all be in lowest.
- Fermi energy is top of “energy sea”
- $kT$ just smears it
- Conduction is due to electrons at top.

- Energy bands and gaps

\[ \begin{array}{ccc}
\text{Conductor} & \text{Insulator} & \text{Semiconductor} \\
\text{Free states} & \text{No easily accessible states} & \text{All states in the lower band full.} \\
\text{above } E_F & \text{due to gap} & \text{Conduction only by excitation across the gap. Thermal or photo} \\
\text{There are } v_{2V_F} & \text{states available} & \\
\end{array} \]
So a semiconductor only conducts due to excited charge carriers.

\[ J = n q v_d \quad \text{or} \quad \rho = \frac{M}{n e^2 \tau} \]

\( \tau \) time between collisions

\( n = \text{charge carrier density} \)

In copper, \( n = 1 \text{ electron/atom} \)

\( = 10^{29} \text{ m}^{-3} \)

\( \Rightarrow \rho \approx 10^{-8} \ \Omega \text{m} \)

For silicon (a semiconductor) \( n = 10^{16} \)

\( \rho \approx 10^3 \ \Omega \text{m} \)

Note that at \( T=0 \) \( n \to 0 \) for silicon. \( \rho \) increases w/ \( T \).

For a good insulator, like diamond (\( E_g \approx 5 \text{ eV} \)), \( \rho \approx 10^8 \ \Omega \text{m} \)

We can change the behavior of a semiconductor dramatically by adding charge carriers...
Doping:

Suppose we add a phosphorus atom (replace Si with phosphorus).

\[ \text{Si} = 1s^2 2s^2 2p^6 3s^2 3p^2 \]

\[ \text{P} = 1s^2 2s^2 2p^6 3s^2 3p^3 \]

The silicon atoms are normally happily sharing their 4 outer electrons \( \Rightarrow \) valence bond full.

A phosphorus atom has 5 valence electrons, leaving one odd man out.

The fifth guy is only loosely bound, \( \sim 0.05eV \) needed to bump it into conduction band. \( \Rightarrow KT \) easily makes it free.

\[ \text{conduction} \]

\[ \text{donor levels} \]

\[ \text{valence} \] A few normal holes
This doping drastically increases the number of free charge carriers and reduces the resistivity.

For example, we can increase the number of charge carriers from \( n/10^{16} \) to \( 10^{22} \) by adding \( 10^6 \) phosphorous atoms per meter. That is a tiny fraction of the \( \sim 10^{28} \) atoms/m\(^3\) there.

Very diffuse doping makes a huge difference, but still \( \ll \) coppers \( 10^{29} \) charge carriers/m\(^3\).

Doping this way makes the silicon "n-type" because it has negative charge carriers. (More correctly, an excess of negative charge carriers since there are always some e-hole pairs thermally generated.)
We can also dope it to be "p-type" meaning an excess of positive charge carriers, i.e. holes, by adding Aluminum (or Boron).

\[ +4 \quad +4 \quad +4 \quad \text{The missing electron site acts as an acceptor for neighboring electrons.} \]

As before, it doesn't take much to bump an electron into that site and leave a hole.

So, that produces "acceptor" energy levels.

\[ \text{A few electrons} \]

\[ \text{Acceptor levels} \]

\[ \text{A lot of holes} \]

Again, the difference between the valence & acceptor levels, \( \approx 0.05 \text{eV} \) is small enough to be \( kT \)-able.
P-N junction

Combining p and n-type semiconductors leads to a diode. It is a worthwhile example.

Excess holes   Excess electrons

Note: Neutral, but freedom & energy differ.

So, $e^-$ diffuse left and holes diffuse right. The free $e^-$ combine with the holes in p to give a net charge separation.

This produces a space charge that causes an electric field, a potential difference (about 0.6V for silicon).
This diffusion is "uphill" and stops when $E_f$ matches $E_F$.

An energy view is:

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\[ E_f \quad \rightarrow \quad \text{diffusion} \quad \rightarrow \quad \text{depletion} \]
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But if we thermally produce an $e^-$-hole pair (or photo produce it), then it flows down hill, due to the $E$ field, $\Rightarrow$ Depleted of free charge.

Equilibrium is when $I_{\text{diff}} = I_{\text{thermal}}$.

(The text calls these recombination and generation currents).
Now, if we apply an external voltage.

Reverse biased

Pumps more charge across $\Rightarrow$ larger depletion region less current.

Forward biased

$I = \exp \left( \frac{V}{0.6} \right)$