ECE 340
Lecture 7 : Intrinsic and Extrinsic Material II

Class Outline:

- Intrinsic Material
- Extrinsic Material
- Density of States
Key Questions

• How tightly bound are the outer carriers to the host impurities?
• What effect does temperature have on the dopants?
• How are impurities added to silicon?
• How do I add extra carriers to a compound semiconductor?
• What is the density of states?
Intrinsic Material

Remember intrinsic material in thermal equilibrium...

**Generation Rate:**

\[ G = G_{th} + G_{opt} + G_{mech} + ... \left( \frac{1}{cm^3 \cdot s} \right) \]

**Recombination Rate:**

\[ R \propto n \cdot p \left( \frac{1}{cm^3 \cdot s} \right) \]

- \( N \) - number of electrons
  - \( P \) - number of holes

- The generation rate must be balanced by the recombination rate.

\[
\begin{align*}
G_0 &= R_0 \Rightarrow n_0 p_0 = n_i^2 \\
n_0 &= p_0 \Rightarrow n_0 = p_0 = n_i
\end{align*}
\]
Extrinsic Materials

Adding dopants to semiconductors...

- We can change their properties many orders of magnitude by introducing the proper impurity atoms.
- Based on the location in the periodic table we can add:
  - Acceptors (holes)
  - Donors (electrons)
Extrinsic Materials

How tightly bound is the extra electron or hole?

- We can use the Bohr’s hydrogen model to get an idea.
- Electrons move in Si and not in a vacuum.
  - Different relative permittivity.
- The electron mass must be represented by the effective mass

\[ E_B = -\frac{m^*_n q^4}{32\pi^2(\varepsilon_0 \varepsilon_r)^2 \hbar^2} \]

<table>
<thead>
<tr>
<th>Donor in Si</th>
<th>P</th>
<th>As</th>
<th>Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binding energy (eV)</td>
<td>0.045</td>
<td>0.054</td>
<td>0.039</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acceptor in Si</th>
<th>B</th>
<th>Al</th>
<th>Ga</th>
<th>In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binding energy (eV)</td>
<td>0.045</td>
<td>0.067</td>
<td>0.072</td>
<td>0.16</td>
</tr>
</tbody>
</table>
In general, we can modify the materials properties with the introduction of immobile impurity atoms...

• We can
  – Selectively create regions of $n$ and $p$.
    • Needed for CMOS.
  – Modify the conductivity over several orders of magnitude.
  – Manipulate the number of conduction electrons over 5 orders of magnitude.
Extrinsic Materials

Visualizing donors on the band diagram...

Let's take a look at Silicon with Phosphorus impurity atoms:

$E_g = 1.12 \text{ eV}$

$0.045 \text{ eV}$
Extrinsic Material

Remember the intrinsic concentrations...

- For silicon
  - $5 \times 10^{23}$ atoms/cm$^3$
  - 4 bonds per atom
  - $2 \times 10^{23}$ bonds/cm$^3$
  - $n_i$ (300 K) $\sim 10^{10}$ cm$^{-3}$
  - 1 broken bond per $10^{13}$ bonds.

- Silicon
  - $n_i \sim 10^{10}$ cm$^{-3}$

- Germanium
  - $n_i \sim 2 \times 10^{13}$ cm$^{-3}$

- GaAs
  - $n_i \sim 2 \times 10^6$ cm$^{-3}$
Extrinsic Materials

Revisiting the effect of temperature...

\[ T = 0 \text{ K} \quad \rightarrow \quad T = 50 \text{ K} \quad \rightarrow \quad T = 300 \text{ K} \]
Extrinsic Materials

So, let’s review doping of elemental semiconductors...

- Dopants in Silicon
  - Reside on the lattice sites.
  - Group V elements contribute electrons to the conduction band and are called donors.
  - Group III elements contribute holes to the valence band and are called acceptors.
  - These impurities are totally ionized at room temperature.
  - Concentrations range from $10^{14}$ cm$^{-3}$ to $10^{20}$ cm$^{-3}$.
Extrinsic Materials

How do we add electrons or holes to a compound semiconductor?

• In silicon or germanium, we just added impurity atoms where we wanted them.

• Nevertheless, when the electrons or holes are released, they leave behind charged impurities
  – Leads to increased scattering.
  – Can spoil device performance

• Instead, use modulation doping.
Extrinsic Materials

Modulation doping of compound semiconductors...

• Connect a doped region to an undoped region.

• Dopants migrate from the higher concentration to the lower concentration.

• The ionized impurities create an electric field which attracts the liberated electrons or holes back to the ions.
  – Pins carriers against the potential barrier.
  – Creates a two dimensional electron gas (2DEG).

• Accomplishes two things:
  – Spatially separates carriers from ions to reduce scattering.
  – Creates a perfect 2DEG.
Commonly used terms:

- **Dopants** - specific impurity atoms that are added to semiconductors in controlled amounts for the express purpose of increasing either the electron or hole concentrations.

- **Intrinsic semiconductor** - undoped semiconductor; extremely pure semiconductor sample containing an insignificant amount of impurity atoms; a semiconductor whose properties are native to the material.

- **Extrinsic semiconductor** - doped semiconductor; a semiconductor whose properties are controlled by added impurity atoms.

- **Donor** - impurity atom that increases the electron concentration; n-type dopant.

- **Acceptor** - impurity atom that increases the hole concentration; p-type dopant.

- **N-type material** - a donor doped material; a semiconductor containing more electrons than holes.

- **P-type material** - an acceptor doped material; a semiconductor containing more holes than electrons.

- **Majority carrier** - the most abundant carrier in a given semiconductor sample; electrons in n-type and holes in p-type.

- **Minority carrier** - the least abundant carrier in a given semiconductor sample; electrons in p-type and holes in n-type.
Density of States

How many states are available in the bands?

- Solving the Schrödinger equation subject to periodic boundary conditions gives rise to discretization.
- Each one of the particular momentum states can be occupied by, at most, 2 electrons
  – Pauli Exclusion Principle

\[
\begin{align*}
  k_x &= \frac{2\pi n_x}{L_x}, \quad n_x = 0, \pm 1, \pm 2, \pm 3 \\
  k_y &= \frac{2\pi n_y}{L_y}, \quad n_y = 0, \pm 1, \pm 2, \pm 3 \\
  k_z &= \frac{2\pi n_z}{L_z}, \quad n_z = 0, \pm 1, \pm 2, \pm 3
\end{align*}
\]
Density of States

Let's start counting states...

The volume enclosed by each unit cell is:

\[ V = \left( \frac{2\pi}{L_x} \right) \left( \frac{2\pi}{L_y} \right) \left( \frac{2\pi}{L_z} \right) = \frac{8\pi^3}{\Omega} \]

The number of states enclosed by each unit cell is:

\[ \text{States}_{\text{total}} = \frac{2}{8\pi^3} \Delta k \]

Therefore the total number of states in a small region of volume \( \Delta k \) can be written as:

\[ N_{3D}(K) = \frac{2}{8\pi^3} \Delta k \]

In general:

\[ N_{n-D}(K) = \frac{2}{(2\pi)^n} \Delta k \]
**Density of States**

We want to know the number of states available as a function of energy:

Consider free electrons, the volume of the sphere between the two spheres:

\[ \Delta k = 4\pi k^2 \, dk \]

The separation \( dK \) corresponds to an energy difference (for free electrons):

\[
k = \sqrt{\frac{2m^* E}{\hbar^2}}
\]

\[
dk = \left( \frac{1}{\hbar} \sqrt{\frac{m^*}{2}} \right) \frac{1}{\sqrt{E}} \, dE
\]
Density of States

Final representation as a function of energy:

The number of states in the shell is given in terms of the density of states in energy by:

\[ N(E) dE \]

We now equate the two expressions:

\[ N_{3d}(E) dE = \frac{2}{8\pi^3} (4\pi k^2) dk \]

Integrate to get the final result:

\[ N_{3d}(E) = \frac{m^*}{\pi^2 \hbar^3} \sqrt{2m^*E} \]