ECE 541/ME 541
Microelectronic Fabrication Techniques

Review of Semiconductor Fundamentals

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Semiconductor

• A semiconductor is an ‘almost’ insulating material, in which by contamination (doping) positive or negative charge carriers can be introduced.
# Semiconductor materials

## Table 1.1: Semiconductor Materials

<table>
<thead>
<tr>
<th>General Classification</th>
<th>Symbol</th>
<th>Semiconductor Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Elemental</td>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>Germanium</td>
</tr>
<tr>
<td>(2) Compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) IV-IV</td>
<td>C</td>
<td>Silicon carbide</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>Aluminum phosphide</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>Aluminum arsenide</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>Aluminum antimonide</td>
</tr>
<tr>
<td></td>
<td>Si</td>
<td>Gallium nitride</td>
</tr>
<tr>
<td></td>
<td>Ge</td>
<td>Gallium phosphide</td>
</tr>
<tr>
<td></td>
<td>Ga</td>
<td>Gallium arsenide</td>
</tr>
<tr>
<td></td>
<td>As</td>
<td>Gallium antimonide</td>
</tr>
<tr>
<td></td>
<td>Se</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>Indium arsenide</td>
</tr>
<tr>
<td></td>
<td>Sb</td>
<td>Indium antimonide</td>
</tr>
<tr>
<td>(b) III-V</td>
<td>AlP</td>
<td>Aluminum phosphide</td>
</tr>
<tr>
<td></td>
<td>AlAs</td>
<td>Aluminum arsenide</td>
</tr>
<tr>
<td></td>
<td>AlSb</td>
<td>Aluminum antimonide</td>
</tr>
<tr>
<td></td>
<td>GaN</td>
<td>Gallium nitride</td>
</tr>
<tr>
<td></td>
<td>GaP</td>
<td>Gallium phosphide</td>
</tr>
<tr>
<td></td>
<td>GaAs</td>
<td>Gallium arsenide</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>Indium phosphide</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td>Indium arsenide</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>Indium antimonide</td>
</tr>
<tr>
<td>(c) II-VI</td>
<td>ZnO</td>
<td>Zinc oxide</td>
</tr>
<tr>
<td></td>
<td>ZnS</td>
<td>Zinc sulfide</td>
</tr>
<tr>
<td></td>
<td>ZnSe</td>
<td>Zinc selenide</td>
</tr>
<tr>
<td></td>
<td>ZnTe</td>
<td>Zinc telluride</td>
</tr>
<tr>
<td></td>
<td>CdS</td>
<td>Cadmium sulfide</td>
</tr>
<tr>
<td></td>
<td>CdSe</td>
<td>Cadmium selenide</td>
</tr>
<tr>
<td></td>
<td>CdTe</td>
<td>Cadmium telluride</td>
</tr>
<tr>
<td></td>
<td>HgS</td>
<td>Mercury sulfide</td>
</tr>
<tr>
<td></td>
<td>PbS</td>
<td>Lead sulfide</td>
</tr>
<tr>
<td></td>
<td>PbSe</td>
<td>Lead selenide</td>
</tr>
<tr>
<td></td>
<td>PbTe</td>
<td>Lead telluride</td>
</tr>
</tbody>
</table>

- High-power Electronics: $\text{SiC} \& \text{GaN}$
- LED, Light emitting diode: $\text{GaN, AlGaN}$
- High-speed device: $\text{InP, ZnGe}$
- $\text{GaAs/AlGaAs (HEMT)}$
Energy levels

- Electrons can only have discrete values of energy
- Electrons in the outermost shell, called Valence Electrons.
- With large number of atoms in solid, energy levels form bands
- Important bands are the valence band, conduction band and energy gap

\[ E_g \quad \downarrow \quad E_v \]

\[ C: \quad 1s^22s^22p^2 \]
**Electronic properties of materials – general case.**

Insulators.

> $5-6 \text{ eV}$

Conductors.

Semi-conductors. ($>5 \text{ eV}$)
Energy diagrams of three categories material

(a) Insulator
(b) Semiconductor
(c) Conductor
Semiconductor

The energy band gap between the conduction band and valance band determines the conductive properties of the materials.

**Metal**
Negligible band gap

**Insulator**
Large band gap, >6eV

**Semiconductor**
Medium band gap, 0~4 eV

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- **Conduction Band**
- **Valence Band**

- **Conduction Band**
- **Valence Band**

- **Conduction Band**
- **Valence Band**

- **SiO₂, Si₃N₄, Al₂O₃, HfO₂, etc.**
- **Si, Ge, GaAs, GaN, SiC, ZnO, etc.**

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- **Fe**
- **Pb**
- **Sn**
- **Sb**

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**Covalence Bonds**

- Atoms of solid materials form crystals, which are 3D structures held together by strong bonds between atoms—covalence bonds like Silicon.

- Silicon forms a covalent crystal. The shared electrons are not mobile. Therefore there is an energy gap between the valence band and the conduction band.
Holes

- An electron hole is the **conceptual** and mathematical opposite of an electron
- Holes do not travel like electrons
- Only electrons can move from atom to atom

When a valence electron moves left to right to fill a hole while leaving another hole behind, a hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.
Doping in Silicon

• Pure silicon wafers are called intrinsic silicon
• Intrinsic silicon doesn’t have enough free electrons for current conduction.
• So impurities are introduced to increase conductivity
• The introduction of these impurities is called doping
Donors and Acceptors

- Donors are dopant atoms that added to a semiconductor to provide electrons
- Acceptors are dopant atoms that provide holes

Si
\[ \rightarrow \text{donors: } P, As, Sb \]
\[ \rightarrow \text{acceptors: } B \]

\[ Ec \]
\[ Ev \]
Type of doping

\( n \)

• N (negative) type: doped with donors and has extra free electrons.

\( p \)

• P (positive) type: doped with acceptors and has extra holes.
Electronic properties of doped silicon – qualitative picture.

(a)

(b)

(c)
Methods for doping (↑) Diffusion

- Diffusion
  - Impurities move by a difference in concentration gradients
  - Conducted at very high temperatures
  - Gas sources are the most common but liquids and solids are also used
  - The sources react with silicon to form dopant oxide which then diffuses into the rest of the substrate by the increase of temperature
Methods for doping (2) – Ion Implantation

- Ion implantation: Alternative to high temperature diffusion
- A beam of highly energetic dopant ions is aimed at the semiconductor surface
- Collision with ion distorts the crystal structure
- Annealing has to be performed to correct the damage
**Electronic properties: Silicon in general.**

\[
E_G = 1.12 \text{ eV}
\]

Boltzmann constant: \( k = 8.62 \times 10^{-5} \text{ eV/K} \)

Fundamental materials property:

\[
n = N_v \times e^{-\frac{(E_c - E_F)}{kT}}
\]

Where \( n \) = concentration of negative (electron) carriers (typically in \( \text{cm}^{-3} \))

\( E_c \) is the energy level of the conduction band

\( E_F \) is the Fermi level.

\( N_v \) is the intrinsic density of states in the conduction band (\( \text{cm}^{-3} \)).

Similarly,

\[
p = N_v \times e^{-\frac{(E_F - E_v)}{kT}}
\]

Where \( p \) = concentration of positive (hole) carriers (typically in \( \text{cm}^{-3} \))

\( E_v \) is the energy level of the valence band

\( N_v \) is the intrinsic density of states in the valence band (\( \text{cm}^{-3} \)).

\[
\begin{aligned}
n &= N_v \cdot e^{\frac{E_F - E_c}{k_0T}} \\
p &= N_v \cdot e^{\frac{E_v - E_F}{k_0T}}
\end{aligned}
\]

\[
\begin{aligned}
n_i &= 10^{18} \text{ cm}^{-3} \\
p_i &= 10^{18} \text{ cm}^{-3}
\end{aligned}
\]

\[
\begin{aligned}
h &= 10^{18} \text{ cm}^{-3} \\
p &= 10^{18} \text{ cm}^{-3}
\end{aligned}
\]

\[
\begin{aligned}
E_F - E_v &= k_0T \ln \frac{n_i}{n} \\
E_v &= k_0T \ln \frac{n_i}{n}
\end{aligned}
\]

\[
\begin{aligned}
E_F - E_v &= 2.6 \text{ meV} \ln \frac{10^{18}}{10^{18}} \\
E_v &= 2.6 \times 8 \times 10^{10} \\
&= 2 \times 8 \times 2.3 \\
&= 47.8 \text{ (meV)}
\end{aligned}
\]
Electronic properties: intrinsic (undoped) silicon.

Density of states in conduction band, \( N_C \) (cm\(^{-3}\)) \( 3.22 \times 10^{19} \)
Density of states in valence band, \( N_V \) (cm\(^{-3}\)) \( 1.83 \times 10^{19} \)

Note: without doping, \( n = p \equiv n_i \) where \( n_i \) is the intrinsic carrier concentration.

For pure silicon, then

\[ n_i^2 = N_C N_V \exp(-E_G / kT) \]

Thus \( n_i = 1 \times 10^{10} \) cm\(^{-3}\)

Similarly the Fermi level for the intrinsic silicon is,

\[ E_i = E_V + (E_C - E_V) / 2 + (1/2)kT \ln(N_V / N_C) \]

Where we have used \( E_i \) to indicate intrinsic Fermi level for Si.
Consider doping with n-type (or electron donating) dopant (such as Arsenic).

Then \( n \approx N_D \) where \( N_D \) is the arsenic doping concentration.

The injection of negative (electron) carriers dramatically alters the Fermi level of the system since there are now a significant sea of negative carriers available.

We can determine the new Fermi level as well as the resulting change in positive carriers.

\[
n_i^2 = pn = N_c N_V \exp(-E_G/kT)
\]

Thus \( p = n_i^2/N_D \).

And \( E_F = E_i + kT \ln(N_D/n_i) \)
Correspondingly, for p-type (acceptor) dopants such at Boron:

Thus \( n = n_i^2 / N_A \).

And \( E_F = E_i - kT \ln (N_A / n_i) \)

Resistivity

\[
\rho = \frac{1}{q(n\mu_n + p\mu_p)}
\]

Where \( q \) is electron charge and \( \mu \) are mobilities.
Equations to remember

\[ n = n_i e^{(E_F - E_i)/kT} \]
\[ p = n_i e^{(E_F - E_F)/kT} \]
\[ np = n_i^2 \]
\[ p - n + N_D - N_A = 0 \]

Note: Our interest was in determining \( n \) and \( p \). Free carriers strongly influence the properties of semiconductors.
Example 1

(a) Consider Si doped with $10^{14}$ cm$^{-3}$ boron atoms. Calculate the carrier concentration ($n$ and $p$) at 300 K.

(b) Determine the position of the Fermi level and plot the band diagram.
Example 2

Consider a Si sample doped with $3 \times 10^{16}$ cm$^{-3}$ of phosphorous (P) atoms and $10^{16}$ cm$^{-3}$ of boron (B) atoms.

(a) Is the semiconductor n-type or p-type?

(b) Determine the free carrier concentration (hole and electron concentrations, or $p$ and $n$) at 300K.

(c) Determine the position of the Fermi level and draw the band diagram.