Exercise 1

Find the probability of occupation of a level of 0.05 eV above the conduction band edge of a Silicon device if the Fermi level is 0.7 eV above the valence band edge.

Assume the bandgap \( (E_g) \) of Silicon is 1.1 eV and the effective mass of electron in Silicon is

\[
0.40 \times (0.91 \times 10^{-30} \text{ kg}).
\]

The Boltzmann constant \( (k_B) \) is \( 1.4 \times 10^{-23} \text{ J/K} \), the Planck constant is \( 6.6 \times 10^{-34} \text{ J s} \) and the temperature is 300K.

Use the conversion ratio: 1 eV = \( 1.6 \times 10^{-19} \text{ J} \).
Carrier density can be defined by

\[ n = \frac{2\pi \cdot 0.40 \times 0.91 \times 10^{-30} [\text{kg}] \cdot 1.4 \times 10^{-23} [\text{J/K}] \cdot 300 [\text{K}]}{6.6 \times 10^{-34} [\text{J/s}]^2} \]

Here, the effective density of states at the conduction band is defined as

\[ N_c = \]

where \( m_e \) is the effective mass of electron.

\[ n = 2 \left( \frac{2\pi \cdot 0.40 \times 0.91 \times 10^{-30} [\text{kg}] \cdot 1.4 \times 10^{-23} [\text{J/K}] \cdot 300 [\text{K}]}{6.6 \times 10^{-34} [\text{J/s}]^2} \right)^{3/2} \]

\[ \times \exp \left( \frac{0.7 - (1.1 + 0.05)[\text{eV}] \cdot 1.6 \times 10^{-10} [\text{J}]}{1.4 \times 10^{-23} [\text{J/K}] \cdot 300 [\text{K}] \cdot 1.6 \times 10^{-10} [\text{J}]} \right) \]

\[ = 2 \left(2.21\cdots \times 10^{16} [\text{kg/J} \cdot \text{s}^2]\right)^{3/2} \cdot \exp(-17.1) \]

\[ = 2 \left(2.21\cdots \times 10^{16} [\text{m}^2]\right)^{3/2} \cdot \exp(-17.1) \quad [\text{J}]=[\text{kg} \cdot \text{m}^2/\text{s}^2] \]

\[ = 6.55\cdots \times 10^{24} \cdot 3.74\cdots \times 10^{-8} = 2.44\cdots \times 10^{17} [\text{m}^3] \]

\[ = \]

22 Extrinsic Semiconductor

- Doping
- Donor / acceptor
- Carrier density
Extrinsic Semiconductors

$p$-type band structures:

\[ E \]

- Group IV semiconductors:
  - ( )
  - ( )

- Group III-V semiconductors:
  - GaAs and GaN
  - ( ): Be, Zn, Cd and Ge

\[ E \]

$n$-type band structures:

- Group IV semiconductors:
  - ( )
  - ( )

- Group III-V semiconductors:
  - GaAs and GaN
  - ( ): Se, Te, Si and Ge

* http://www.wikipedia.org/

Atomic Structure of $p$-Type Semiconductors

$p$-type semiconductor structures:

- Group IV semiconductors: Si and Ge
  - Acceptors: B and Al

- Group III-V semiconductors: GaAs and GaN
  - Acceptors: Be, Zn, Cd and Ge

* http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html
Energy potential created by an acceptor ion:

Conduction band

Energy bandgap 1.12 eV

Energy bandgap ~0.05 eV

Valence band

Atomic Structure of p-Type Semiconductors

p-type band structures:
Carrier Number Density

Numbers of holes in the valence band $E_v$ should equal to the sum of those of electrons in the conduction band $E_C$ and in the acceptor level $E_A$:

$$p = n + n_A$$

Similar to the intrinsic case,

$$p = N_V f_p(0) = N_V \exp\left(-\frac{E_F}{k_B T}\right)$$

$$n = N_C f_c(E_g) = N_C \exp\left(-\frac{E_g - E_F}{k_B T}\right)$$

Assuming numbers of neutral acceptors are $N_{A'}$

$$n_A = \frac{N_A}{1 + 2\exp\left(\frac{E_A - E_F}{k_B T}\right)}$$

For $E_A - E_F > k_B T$, $n_A = N_A$

$$\therefore N_V \exp\left(-\frac{E_F}{k_B T}\right) \approx N_C \exp\left(-\frac{E_g - E_F}{k_B T}\right) + N_A$$

Carrier Number Density (Cont'd)

At low temperature, one can assume $p >> n$, 

$$p \approx n_A$$

As $n_A$ is very small, $E_A > E_F$

$$n_A = \frac{N_A}{2} \exp\left(-\frac{E_A - E_F}{k_B T}\right)$$

$$\therefore N_V \exp\left(-\frac{E_F}{k_B T}\right) \approx \frac{N_A}{2} \exp\left(-\frac{E_A - E_F}{k_B T}\right)$$

$$\therefore \exp\left(-\frac{E_F}{k_B T}\right) \approx \sqrt{\frac{N_A}{2N_V}} \exp\left(-\frac{E_A}{2k_B T}\right)$$

$$\therefore E_F \approx \frac{k_B T}{2} \ln \frac{2N_V}{N_A} + \frac{E_A}{2}$$

By substituting $N_V = N_{V_F} T^{3/2}$

$$\therefore E_F \approx \frac{k_B T}{2} \ln \left(\frac{2N_{V_F} T^{3/2}}{N_A}\right) + \frac{E_A}{2}$$

For $T \sim$ ,

At high temperature, one can assume $n >> n_A$, 

$$p \approx n$$

Similar to the intrinsic case, for $m_e^* = m_p^*$,
Typical Band Structures

Acceptor level near the valence bands:

![Typical Band Structures Diagram](http://www.phys.chuo-u.ac.jp/labs/wakabaya/lecture/applphys/2C_4.3.pdf)

Atomic Structure of \(n\)-Type Semiconductors

\(n\)-type semiconductor structures:

- **Group IV semiconductors:**
  - Si and Ge
  - Donors: P and As

- **Group III-V semiconductors:**
  - GaAs and GaN
  - Donors: Se, Te, Si and Ge

![Atomic Structure Diagram](http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html)
Energy potential created by a donor ion:

\[ E(-\epsilon) \]

Conduction electron

Conduction band

\[ E_c \]

\[ \sim 0.05\text{eV} \]

Energy bandgap

\[ 1.12\text{eV} \]

Valence band

\[ E_v \]

Atomic Structure of \( n \)-Type Semiconductors

\( n \)-type band structures:

\[ E_c \]

\[ E_F \]

\[ E_g \]

\[ E_v \]

\[ N_c(E) \]

\[ 1-f(E) \]

\[ f(E) \]

\[ n(E) \text{ and } p(E) \]

\[ n>n_i \]

\[ p<n_i \]
Temperature Dependence of an Extrinsic Semiconductor

Carrier Densities of Extrinsic Semiconductors

\[ n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A} \]

\[ E_F = E_i + k_B T \ln \frac{N_D}{n_i} \]

\[ p = \frac{n_i^2}{N_D} \]

\[ n = \frac{n_i^2}{n} \]

\[ E_F = E_i - k_B T \ln \frac{N_A}{n_i} \]


* http://www.optique-ingeneur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html
A junction made by attaching \( p- \) and \( n- \) doped semiconductors:

Widely used to insulate transistors.

Common circuit to convert ac to dc in a battery charger.

Exercise 2

For the Silicon material with doping, estimate the dopant concentration \( (N_D) \) needed to manufacture a 1 M\( \Omega \) resistor measuring 100 \( \mu \)m in length and 5 \( \mu \)m\(^2\) in cross section.

Assume that the transport of current will be carried out by majority carriers and that for Silicon, intrinsic carrier density: \( n_i = 10^{16} \) m\(^{-3}\), mobility of electrons: \( \mu_e = 0.135 \) m\(^2\)/V\cdot s and mobility of holes: \( \mu_h = 0.05 \) m\(^2\)/V\cdot s.