Fermi Level location of Intrinsic Semiconductor

The location of the Fermi level is a function of the carrier concentration. We will use Eqs. (4) and (5) to identify the Fermi level.

For intrinsic semiconductor, $n_o = p_o$

$$N_c.exp\left(\frac{-(E_c - E_F)}{kT}\right) = N_v.exp\left(\frac{-(E_F - E_v)}{kT}\right)$$

$$E_F = \frac{1}{2}(E_c + E_v) + \frac{1}{2}kT\ ln\left(\frac{N_v}{N_c}\right) \ldots\ldots..(9)$$

Because $N_c = 2\left(\frac{2\,\pi\, m_n^* k\, T}{h^2}\right)^{3/2}$ and $N_v = 2\left(\frac{2\,\pi\, m_p^*\, k\, T}{h^2}\right)^{3/2}$

Equation (9) becomes:

$$E_F = \frac{1}{2}(E_c + E_v) + \frac{3}{4}kT\ ln\left(\frac{m_p^*}{m_n^*}\right) \ldots\ldots..(10)$$

The term $\frac{1}{2}(E_c + E_v)$ is midgap energy. Eq.(10) rewrite:

$$E_F = E_{\mathrm{midgap}} + \frac{3}{4}kT\ ln\left(\frac{m_p^*}{m_n^*}\right) \ldots\ldots..(11)$$

Example: Where is E_F located in the energy band of silicon, at 300K with n_o=10^{17} cm^{-3}? And for p_o = 10^{14} cm^{-3}?

The values of $N_c = 2.8 \times 10^{19}\mathrm{cm}^{-3}$ and $N_v = 1.04 \times 10^{19}\mathrm{cm}^{-3}$.

Solution:

$$n_o = N_c.exp\left(\frac{-(E_c - E_F)}{kT}\right)$$

$$E_c - E_F = kT.\,ln\left(\frac{N_c}{n_o}\right) = 0.026\ln\left(\frac{2.8\times10^{19}}{10^{17}}\right) = 0.146\ \text{eV}$$

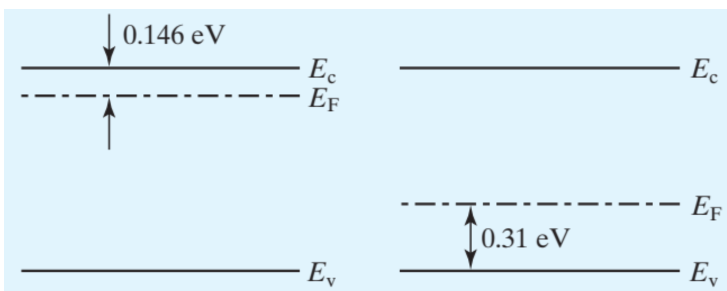
Therefore, E_F is located at 146 meV below E_c, as shown in Figure.

For p_o = 10^{14} cm^{-3},

$$p_o = N_v.\,exp\left(\frac{-(E_F - E_v)}{kT}\right)$$

$$E_F - E_v = kT.\,ln\left(\frac{N_v}{p_o}\right) = 0.026\ln\left(\frac{1.04\times10^{19}}{10^{14}}\right) = 0.31\ \text{eV}$$

Therefore E_F is located at 0.31 eV above E_v.



Thermal Motion of Electrons and Holes

Even without an applied electric field, carriers are not at rest but possess finite kinetic energies. The **average kinetic energy of electrons** is

$$\text{The average kinetic energy of electron} = \frac{\text{total kinetic energy}}{\text{number of electrons}}$$

$$= \frac{\int_{E_c}^{top} g_c(E)\, f(E)\, (E - E_c) dE}{\int_{E_c}^{top} g_c(E)\, f(E)\, dE} \quad \ldots\ldots\ldots.(1)$$

After solving Eq. (1), the result is

$$\text{Average kinetic energy} = \frac{3}{2}\mathrm{k}T \text{ ………….. (2)}$$

Eq. (2) is true for both electrons and holes. The kinetic energy of electrons or holes can be used in Eq. (2),

$$\frac{1}{2}m^{*}v_{th}^{2} = \frac{3}{2}\mathrm{k}T \text{ ………….. (3)}$$

So, the thermal velocity (v_{th}) can be written:

$$v_{th} = \sqrt{\frac{3kT}{m^{*}}} \text{ … … … … … (4)}$$

where m^{*} is the effective mass of electron / hole.

<u>Example:</u> What are the approximate thermal velocities of electrons and holes in silicon at room temperature? $m_e^{*} = 0.26\, m_o$ and $m_h^{*} = 0.39\, m_o$

<u>Solution:</u>

For the electrons, $v_{th} = \sqrt{\frac{3kT}{m^{*}}} = \sqrt{\frac{3\times\left(1.38\times10^{-23}\frac{\mathrm{J}}{\mathrm{K}}\right)\times(300\ \mathrm{K})}{0.26\times9.1\times10^{-31}\ \mathrm{kg}}} = 2.3\times10^{5}\ \mathrm{m/s}$

For the holes, $v_{th} = \sqrt{\frac{3kT}{m^{*}}} = \sqrt{\frac{3\times\left(1.38\times10^{-23}\frac{\mathrm{J}}{\mathrm{K}}\right)\times(300\ \mathrm{K})}{0.39\times9.1\times10^{-31}\ \mathrm{kg}}} = 2.2\times10^{5}\ \mathrm{m/s}$

Note 1: 1 J = 1 kg.m^2/s^2

Note 2: The typical thermal velocity of electrons and holes is about 1000 times slower than the speed of light and 100 times faster than the sonic speed.