Atomic Structure and Semiconductor

Lecture - 38

(16/17/19/04/2021)

B.Sc (Electronics)
TDC PART - I
Paper – 1 (Group – B)
Chapter – 4
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➢ Carrier Concentration in Intrinsic Semiconductor (PART – 2)

⇨ The band model of an intrinsic semiconductor at **0 ^{O}K** is shown below in **Figure (1). Filled Valence Band and Empty Conduction Band** are **separated** by an **energy gap** E_g. At **T = 0 ^{O}K**, **no conduction is possible** but as the **temperature is raised** the **electrons are thermally excited** from **Valence Band** to the **Conduction Band**. In **Conduction Band** these electrons become free so that conduction is possible. Both, **electrons in Conduction Band**, n_c, and the **Holes in Valence band** n_h will contribute to the electrical conductivity.

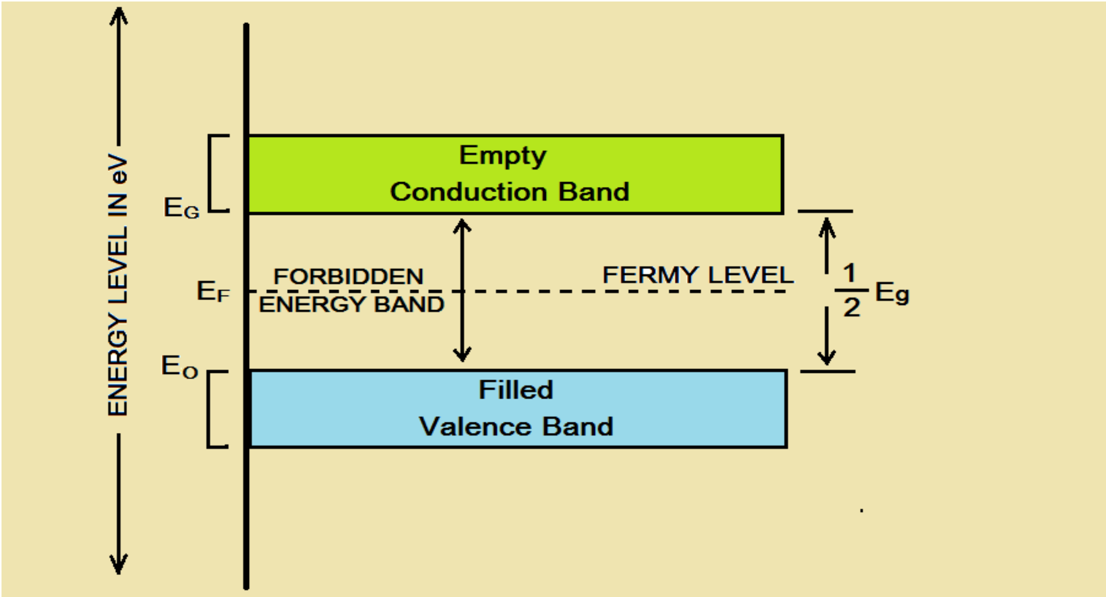

Fig. (1) Shown Band Model in an Intrinsic Semiconductor.

➢ Calculation of Electron and Hole Concentration

⇨ We shell now **calculate the number of electrons** excited into the **Conduction Band** at **Temperature** T and also the **Hole Concentration** in the **Valence Band**. It will be assumed that **Electrons** in the **Conduction Band** behave as if they are free particles with an **Effective mass** m_e^*, also the **Holes** near the top of the **Valence Band** behave as if they are free particles with **Effective mass** m_h^* .

⇨ In calculating the **Carrier Concentrations in Intrinsic Semiconductor** we shell proceed in two ways:-

(1) In the first way we assume that **widths of Conduction and Valence Bands** are small as compared with **Forbidden Gap** so that we can take that **all the conduction electrons have energy equal to** E_C, whereas **all Valence electrons have energy equal to** E_V**.** That is the **energy of Valence Band** can be presented by a **single energy** E_V and that of **Conduction Band** by E_C**.** This assumption is not accurate.

(2) As stated in above **Point (1),** it is not justified to take up a single value of energy for a complete band and we take up the widths of allowed energy band as comparable to **Forbidden Gap**. We take that the **electrons in Conduction Band** may have **energy lying between** E_C **to** ∞ while the **electrons in Valence Band** of **energy lying from** **-∞ to** E_V.

- The derivation done in first way will not be accurate since in an **Intrinsic Semiconductor** neither all the **electrons in Valence Band** have **energy equal to** E_V, nor all the **Electrons in Conduction Band** possess **energy equal to** E_C. **Electrons** in **Conduction Band** may have, **energies laying from** E_C **to** ∞ while the **Electrons** in **Valence Band** may have **energies lying from -∞ to** E_V**.**

(B) Density of Holes in Valence Band:-

- To **calculate the Density of Holes** n_h **in Valence Band,** we shall use $[-F(E)]$ instead $F(E)$ as this represents the **Probability for a State of Energy** E to be unoccupied. $F(E)$**is the Probability for a State of Energy** E **to be occupied. Therefore Probability for a State of Energy** E **to be unoccupied will be** $[1-F(E)]$**.** Therefore,

- $$n_c = \int_{-\infty}^{E_V} Z(E)\,[1-F(E)]\,dE \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

- where, the lower limit has been taken $-\infty$ for convenience and for it will include certainly all the **Holes in Valence Band**. With $(E_F - E) \gg$ **a few** $K_B\,T$, then we get,

⇨ $\therefore\ [1 - F(E)] = 1 - \left[exp\left\{\left(\frac{E - E_F}{K_B\,T}\right)\right\} + 1\right]^{-1}$ .... **(12)**

⇨ or, $[1 - F(E)] = 1 - \left[1 - exp\left\{\frac{(E - E_F)}{K_B\,T}\right\}\right]$ .... **(13)**

⇨ or, $[1 - F(E)] = exp\left\{\frac{(E - E_F)}{K_B\,T}\right\}$ .... **(14)**

⇨ From this we infer that since in **Valence Band** $E < E_{F,}$ **function** $[1 - F(E)]$ **decreases exponentially**. In other words, in **going down below the top of Valence Band, probability of finding holes decreases. This implies that holes reside near the top of Valence Band**. The value of ***Z(E)*** **near the top of Valence Band** is,

⇨ $Z(E) = \frac{4\,\pi}{h^3}\,(2\,m_h^*)^{\frac{3}{2}}\,(E_V - E\,)^{\frac{1}{2}}$ .... **(15)**

⇨ where m_h^* is the **effective mass of hole near the top of Valence Band**. Therefore from **equation (11)** we get,

⇨ $\therefore\ n_h = \frac{4\,\pi}{h^3}\,(2\,m_h^*)^{\frac{3}{2}}\int_{-\infty}^{E_V}(E_V - E\,)^{\frac{1}{2}}\ \mathrm{exp}\left(\frac{E - E_F}{K_B\,T}\right)dE$ .... **(16)**

⇨ $n_h = \frac{4\,\pi}{h^3}\,(2\,m_h^*)^{\frac{3}{2}} \times \mathrm{exp}\left(\frac{E_V - E_F}{K_B\,T}\right)\int_{-\infty}^{E_V}(E_V - E\,)^{\frac{1}{2}}\ \mathrm{exp}\left(\frac{E - E_F}{K_B\,T}\right)dE$

.... **(17)**

⇨ Now Putting $\frac{E_V - E}{K_B\,T} = x$ and $dE = -\,K_B T\,dx$ in the above **equation (17),** then we get,

⇨ $n_h = \frac{4\,\pi}{h^3}\,(2\,m_h^*)^{\frac{3}{2}} \times \mathrm{exp}\left(\frac{E_V - E_F}{K_B\,T}\right)\int_{\infty}^{0}(x\,K_B\,T)^{\frac{1}{2}}\ e^{-x}\,(-\,K_B\,T)\,dx$

.... **(18)**

⇨ $n_h = \frac{4\,\pi}{h^3} \left(2\, m_h^*\right)^{\frac{3}{2}} \times \exp\left(\frac{E_V - E_F}{K_B\, T}\right) (K_B\, T)^{\frac{3}{2}} \int_0^{\infty} x^{\frac{1}{2}}\; e^{-x}\, dx$

.... **(19)**

⇨ $n_h = \frac{4\,\pi}{h^3} \left(2\, m_h^*\right)^{\frac{3}{2}} \times (K_B\, T)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B\, T}\right) . \frac{\pi^{\frac{1}{2}}}{2}$

.... **(20)**

⇨ where, for **Integrand**, $\frac{\pi^{\frac{1}{2}}}{2}$ has been substituted, then we get,

⇨ Thus,

⇨ $n_h = 2 \left(\frac{2\,\pi\, m_h^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B\, T}\right)$ .... **(21)**

(C) Fermi Level in an Intrinsic Semiconductor :-

⇨ In an **Intrinsic (pure) Semiconductor**, we know that $n_C = n_h$. Now Equating the values of n_C and n_h from **equation (10)** and **equation (21),** then we get,

⇨ $\because\; n_C = n_h$

⇨ **or,** $2 \left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{K_B\, T}\right) = 2 \left(\frac{2\,\pi\, m_h^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B\, T}\right)$

.... **(22)**

⇨ **or,** $\left(m_e^* \right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{K_B\, T}\right) = \left(m_h^* \right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B\, T}\right)$

.... **(23)**

⇨ or, $\exp\left(\frac{2\,E_F - E_C - E_V}{K_B\,T}\right) = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}}$ .... (24)

⇨ Taking **logarithm** **above equation (24)**, then we get,

⇨ or, $\left(\frac{2\,E_F - E_C - E_V}{K_B\,T}\right) = \frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right)$ .... (25)

⇨ or, $E_F = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{2}K_B\,T\,\log\left(\frac{m_h^*}{m_e^*}\right)$ .... (26)

⇨ Now when $m_h^* = m_e^*$, we find,

⇨ or, $E_F = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{2}K_B\,T\,\log\left(\frac{m_e^*}{m_e^*}\right)$ .... (27)

⇨ or, $E_F = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{2}K_B\,T\,\log(1)$ .... (28)

⇨ Since we know that **$\log(1)$ is zero,** then we get,

⇨ or, $E_F = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{2}K_B\,T \times 0$

⇨ or, $E_F = \left(\frac{E_C + E_V}{2}\right) + 0$

⇨ $\therefore\ E_F = \left(\frac{E_C + E_V}{2}\right)$ .... (29)

⇨ **Again we know that** $E_g = E_C + E_V$ then we get,

⇨ $\therefore \; E_F = \frac{1}{2} E_g$ ………………………………………………………… **(30)**

⇨ From above **equation (29) and equation (30),** this means that **Fermi Level lies exactly half way between the top of valence band and bottom of Conduction Band.**

⇨ But in actual case m_h^* is greater than m_e^* and **Fermi Level** is raised slightly as **T increases.**

⇨ Detailed of the **Density of Electrons in Conduction Band n_c , and Density of Holes in Valence Band n_h in Terms of Band Gap E_g(PART – 3)** are discussed in next **Lecture – 39.**

to be continued ……………………………

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