Atomic Structure and Semiconductor

Lecture - 39

(22/04/2021)

B.Sc (Electronics)
TDC PART - I
Paper – 1 (Group – B)
Chapter – 4
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➢ 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) :-

⇨ From **equation (26)** of **Lecture - 38**, we already have,

$$\because\ E_F = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{2} K_B T \log\left(\frac{m_h^*}{m_e^*}\right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(26)}$$

$$\text{or, } (E_F - E_C) = \left(\frac{E_V - E_C}{2}\right) + \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right) \quad \dots\dots\dots\dots\dots\dots \textbf{(31)}$$

$$\therefore (E_F - E_C) = -\frac{E_g}{2} + \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(32)}$$

⇨ **Similarly,**

⇨ From **equation (26)** of **Lecture - 38**, we already have,

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

$$\text{or, } (E_V - E_F) = \left(\frac{E_V - E_C}{2}\right) - \frac{3}{4}\, K_B\, T\, \log\left(\frac{m_h^*}{m_e^*}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

$$\therefore\ (E_V - E_F) = -\frac{E_g}{2} - \frac{3}{4}\, K_B\, T\, \log\left(\frac{m_h^*}{m_e^*}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

⇨ Now substituting the above values of $(E_F - E_C)$ of **equation (32)** in **equation (10)** of **Lecture – 37** then we get the **Density of Electrons in Conduction Band** n_c ,

$$\because\ n_c = 2\left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{K_B\, T}\right) \ \ldots\ \text{From lecture – 37} \ \ldots\ldots\ (10)$$

$$\text{or, } n_c = 2\left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left[-\frac{E_g}{2} + \frac{3}{4}\, K_B\, T\, \log\left(\frac{m_h^*}{m_e^*}\right)\right] \ \ldots\ (35)$$

$$\text{or, } n_c = 2\left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left[-\frac{E_g}{2\, K_B\, T} + \frac{3}{4}\, \log\left(\frac{m_h^*}{m_e^*}\right)\right] \ \ldots\ldots\ (36)$$

$$\text{or, } n_c = 2\left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{-E_g}{2\, K_B\, T}\right) \exp\left[\log\left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{4}}\right] \ \ldots\ (37)$$

$$\text{or, } n_c = 2\left(\frac{2\,\pi\, m_e^*\, K_B\, T}{h^2}\right)^{\frac{3}{2}} \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\, K_B\, T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (38)$$

$$\therefore\ n_c = 2\left(\frac{2\,\pi K_B\, T}{h^2}\right)^{\frac{3}{2}} \left(m_h^*\ m_e^*\right)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\, K_B\, T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (39)$$

⇨ Similarly, substituting the the above values of $(E_V - E_F)$ of **equation (34)** in **equation (21)** of **Lecture – 38** then we get the **Density of Holes in Valence Band** n_h ,

$$\because n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B T}\right) \text{ From lecture – 38} \quad \ldots\ldots\ldots\ldots \quad (21)$$

$$\text{or, } n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \exp\left[-\frac{E_g}{2} - \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right)\right] \quad \ldots \quad (40)$$

$$\text{or, } n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \exp\left[-\frac{E_g}{2 K_B T} - \frac{3}{4}\log\left(\frac{m_h^*}{m_e^*}\right)\right] \quad \ldots\ldots\ldots \quad (41)$$

$$\text{or, } n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{-E_g}{2 K_B T}\right) \exp\left[\log\left(\frac{m_h^*}{m_e^*}\right)^{-\frac{3}{4}}\right] \quad .. \quad (42)$$

$$\text{or, } n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \left(\frac{m_h^*}{m_e^*}\right)^{-\frac{3}{4}} \exp\left(\frac{-E_g}{2 K_B T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (43)$$

$$\text{or, } n_h = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{\frac{3}{2}} \left(\frac{m_e^*}{m_h^*}\right)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2 K_B T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (44)$$

$$\therefore n_h = 2\left(\frac{2\pi K_B T}{h^2}\right)^{\frac{3}{2}} (m_h^* \; m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2 K_B T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (45)$$

⇨ From the above **equation (39)** and **equation (45),** we infer that $n_c = n_h = n_i$ and conclude that,

(1) ***In an intrinsic semiconductor, density of electrons in conduction band equals the density of holes in valence band, and***

(2) n_c **or** n_h ***increases exponentially as the temperature increases.***

⇨ However, the **results have been deduced** on **assuming that Fermi Level is more than a few** $K_B T$ away from the bottom of the **Conduction Band** and from the top of the **Valence Band.**

➢ Electrical Conductivity

⇨ The **Conductivity of Intrinsic Semiconductor** is given by,

$$\because \sigma = n_i \, e \left(\mu_n + \mu_p\right) \quad \ldots\ldots (46)$$

Now substituting the above values of $n_c = n_h = n_i$ of **equation (39) and equation (45)** in **equation (46)** then we get,

$$\therefore \sigma = 2 \left(\frac{2\pi K_B T}{h^2}\right)^{\frac{3}{2}} \left(m_h^* \; m_e^*\right)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2 K_B T}\right) e \left(\mu_n + \mu_p\right) \quad \ldots \; (47)$$

⇨ The **Mobilities** μ_n and μ_p have a **temperature dependence and will largely cancel** the $T^{\frac{3}{2}}$ Temperature variation of the term,

$$\left(\frac{2\pi K_B T}{h^2}\right)^{\frac{3}{2}} \left(m_h^* \; m_e^*\right)^{\frac{3}{4}} \quad \ldots\ldots (48)$$

⇨ So that the **Conductivity,** σ**,** is **dominated by exponential term,** $e^{\frac{-E_g}{2 K_B T}}$.

Therefore we can write equation as ,

⇨ **Conductivity** $\sigma = \text{constt.}\, e^{\frac{-E_g}{2 K_B T}} \quad \ldots\ldots (49)$

or,

⇨ **Resistivity** $\rho = \text{constt.}\, e^{\frac{E_g}{2 K_B T}} \quad \ldots\ldots (50)$

or,

⇨ $\log_e \rho = \log_e \text{constt.} + \frac{E_g}{2 K_B T} \quad \ldots\ldots (51)$

⇨ which is the **equation of Straight line.**

⇨ This is confirmed by **plotting** of **Resistivity** $log_e \rho$ against **Temperature** $\frac{1}{T}$ for some **Intrinsic Semiconductors** shown below in **Figure (1).**

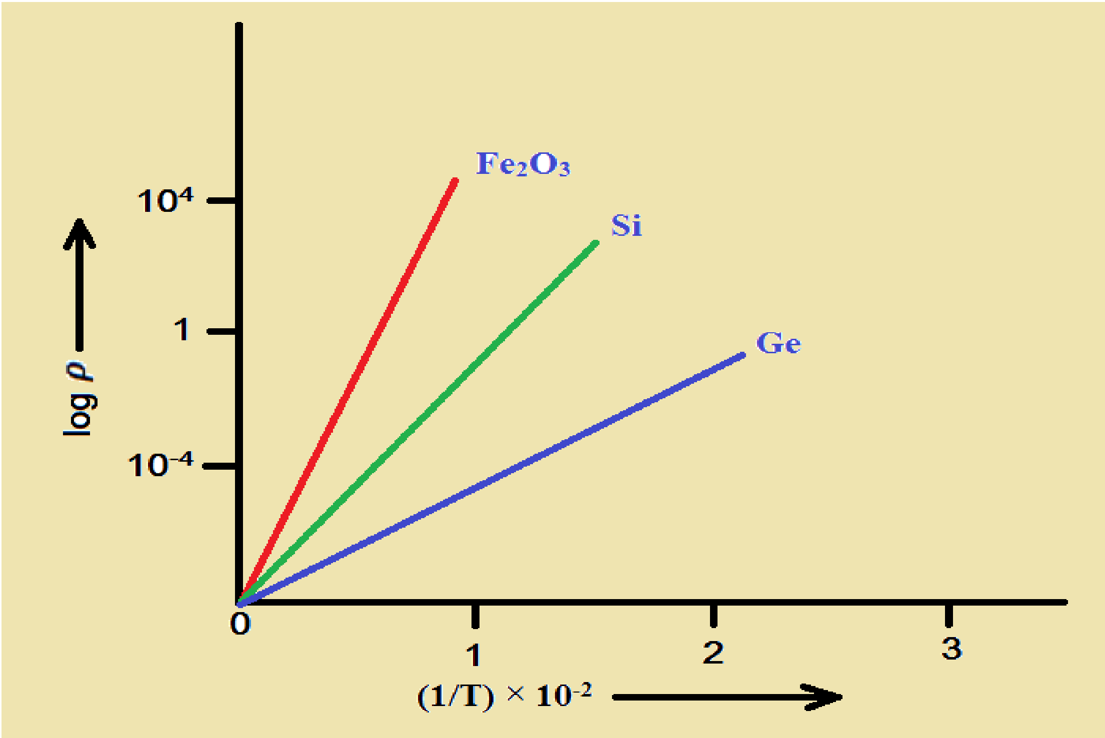

Fig. (1) Shown Plot of **Resistivity** $log_e \rho$ against **Temperature** $\frac{1}{T}$.

⇨ The **slop of the lines**, $\frac{E_g}{2K_B T}$, will provide the value of **Energy Gap** E_g. In **Germanium** it is **0.78 eV** and in **Silicon** it is **1.21 eV.**

⇨ In the **Table shown below**, **Resistivity** ρ, at **room temperature** and the **Energy Gap,** E_g, for the **elements in the Fourth Group (IVA)** of periodic table are shown.

IV A	C	Si	Ge	Sn	Pb
ρ ohm. meter	10^{14}	3.10^{3}	0.47	2.10^{-6}	2.10^{-7}
$E_g eV$	5.2	1.21	0.75	0.08	No gap

⇨ As we look from **Carbon to lead,** we note a **gradual transition** from an **insulator to a metal.** In lead, there is **no energy gap** and the **density of electrons** in the **Conduction Band** is essentially independent of temperature.

➢ Law of Mass Action

⇨ From **equation (39)** and **equation (45),** we find that,

$$\because\ n_c = 2\left(\frac{2\,\pi K_B\,T}{h^2}\right)^{\frac{3}{2}} (m_h^*\ \ m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\,K_B\,T}\right) \quad \text{..................} \quad (39)$$

$$\because\ n_h = 2\left(\frac{2\,\pi K_B\,T}{h^2}\right)^{\frac{3}{2}} (m_h^*\ \ m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\,K_B\,T}\right) \quad \text{..................} \quad (45)$$

$$\therefore\ n_c\,n_h = 2\left(\frac{2\,\pi K_B\,T}{h^2}\right)^{\frac{3}{2}} (m_h^*\ \ m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\,K_B\,T}\right) \times$$

$$2\left(\frac{2\,\pi K_B\,T}{h^2}\right)^{\frac{3}{2}} (m_h^*\ \ m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\,K_B\,T}\right) \quad \text{..................................} \quad (52)$$

or, $$n_c\,n_h = 4\left(\frac{2\,\pi K_B\,T}{h^2}\right)^{\frac{3}{2}} (m_h^*\ \ m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\,K_B\,T}\right) \quad \text{..............} \quad (53)$$

⇨ We infer that a **given Temperature** the **Product of Hole and Electron Densities ($n_c\,n_h$) is Constant and is Independent of the Fermi Level.**

⇨ If n and p be the **total Concentrations of Electrons and Holes in Conduction and Valence Band respectively,** then by using he fact that:-

⇨ $n_c = n =$ **Number of Electrons in Conduction Band**, **and**

⇨ $n_h = p =$ **Number of Holes in Valence Band, we write,**

$$n_c\, n_h = n\, p = 4 \left(\frac{2\,\pi K_B\, T}{h^2}\right)^{\frac{3}{2}} (m_h^* \;\; m_e^*)^{\frac{3}{4}} \exp\left(\frac{-E_g}{2\, K_B\, T}\right) \quad \text{........} \quad (54)$$

= a constant at a constant temperature,

⇨ Thus the **Product of Electron and Hole Concentrations** $(n_c\, n_h)$, for a **given material**, is **Constant at a given Temperature**.

⇨ If **Impurity is added to Increase** n, **there will be corresponding Decrease in** p, so that **Product** $n\, p$ **remains Constant**. **This is known as Law of Mass Action.**

⇨ Therefore in an **Intrinsic Semiconductor** $n\, p = n_i\, n_i = n_i^2$ **,**

⇨ Since $n = p = n_i$ for **such a Semiconductor**.

⇨ The **Product** $n\, p$ **remains Constant for a Semiconductor irrespective of its being Extrinsic or Intrinsic:** n_i is **called the Intrinsic Density of either Carrier.**

⇨ Detailed of the **Fermi Level in an Extrinsic Semiconductor (PART – 1)** are discussed in next **Lecture – 40.**

to be continued ....

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