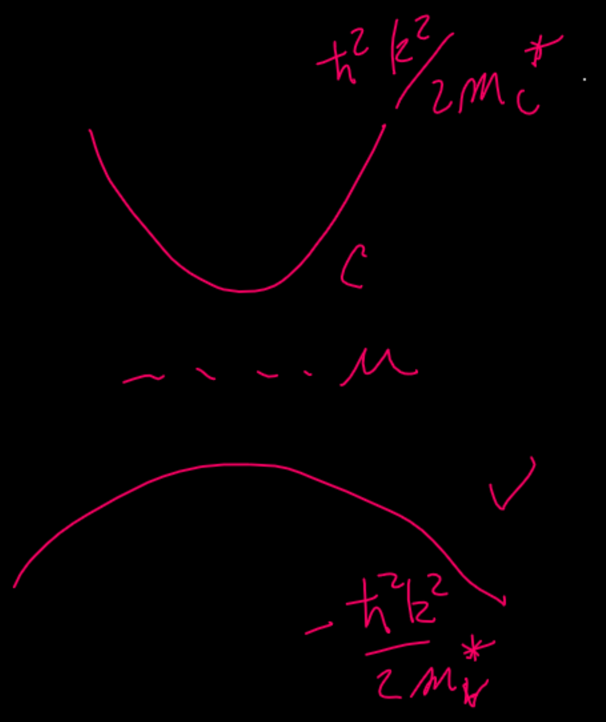
Lecture 19

Friday, Feb. 26, 2021

INTRINSIC CARRIER CONCENTRATION
(UNDOPED)



$$n_c(T) = \int_{\varepsilon_c}^{\infty} d\varepsilon \; \underbrace{g_c(\varepsilon)}_{\text{DENSITY OF STATES/VOLUME}} \; \frac{1}{e^{(\varepsilon-\mu)/k_BT}+1}$$

$$p_v(T) = \int_{-\infty}^{\varepsilon_v} d\varepsilon \; g_v(\varepsilon) \left(1 - \frac{1}{e^{(\varepsilon-\mu)/k_BT}+1} \right)$$

$$1 - f_e^v \equiv f_h$$ ← HOLE FERMI FUNCTION

$$\frac{1}{e^{(\mu-\varepsilon)/k_BT}+1} = f_h$$

$g_{c,v}(\varepsilon) \longrightarrow$ DIMENSION, $\varepsilon(k)$ $\Big\}$ 3D $\varepsilon(k) = \dfrac{\hbar^2 k^2}{2 m^*_{c,v}}$

$$g_{c,v} = \frac{(m^*_{c,v})^{3/2}\sqrt{2}}{\hbar^3 \pi^2}\sqrt{|\varepsilon - \varepsilon_{c,v}|}$$

$$\varepsilon_{c,v}(k) = \varepsilon_{c,v} \pm \frac{\hbar^2 k^2}{2 m^*_{c,v}}$$

$$\mu - \varepsilon_v \gg k_B T \Longrightarrow \frac{1}{e^{(\mu-\varepsilon)/k_B T}+1} \approx e^{-(\mu-\varepsilon)/k_B T}$$

$$\varepsilon_c - \mu \gg k_B T$$

$$\varepsilon_c - \mu >> k_B T \qquad e^{\cdots} + 1$$

FERMI DIRAC

MAXWELL BOLTZMANN

$$n_c(T) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} \mathrm{EXP}(\mu/k_B T) \int_{\varepsilon_c}^{\infty} \underbrace{(\varepsilon - \varepsilon_c)^{\frac{1}{2}}}_{\text{D.O.S.}} \underbrace{e^{-\varepsilon/k_B T}}_{\text{M.B. DISTN.}} d\varepsilon$$

$$n_c(T) = 2\left(\frac{m_e^* k_B T}{2\pi\hbar^2}\right)^{3/2} \mathrm{EXP}\left((\mu - \varepsilon_c)/k_B T\right)$$

$$p_v(T) = 2\left(\frac{m_h^* k_B T}{2\pi\hbar^2}\right)^{3/2} \mathrm{EXP}\left((\varepsilon_v - \mu)/k_B T\right)$$

(NOTE $T^{3/2}$ IN FRONT OF EXP)

NEED TO KNOW μ! $\quad \mu \leftrightarrow n_c, p_v$

$$\boxed{n_c(T)\, p_v(T) = 4\left(\frac{k_B T}{2\pi\hbar^2}\right)^3 (m_e^* m_h^*)^{3/2}\, \mathrm{EXP}\left(-E_g/k_B T\right)}$$

① IND. OF μ!!

② HOLDS INTRINSIC CASE, BUT ALSO FOR DOPED

"LAW OF MASS ACTION"

INTRINSIC LIMIT

$n_c = p_v = n = p$

$$\boxed{\begin{aligned} n = p &= 2\left(\frac{k_B T}{2\pi\hbar^2}\right)^{3/2}\left(m_e^* m_h^*\right)^{3/4} \mathrm{EXP}\left(-E_g/2k_BT\right) \\ \mu &= \frac{E_g}{2} + \frac{3}{4}k_BT\,\mathrm{LN}\left(\frac{m_h^*}{m_e^*}\right) \end{aligned}}$$

NOTE *

1. $T = 0 \Rightarrow \mu = E_g/2$
2. $m_h^* = m_e^* \Rightarrow \mu = E_g/2 \;\; \forall T$

DOPED CASE? (IMPURITIES)

DOPED CASE: (IMPURITIES)
(EXTRINSIC SEMICONDUCTORS)

(DOPED $\mu \neq \mu_i$)

$n_c \neq p_v$ $\qquad$ $n_c - p_v = \Delta n \neq 0$

$n_c p_v = n_i^2$ (LAW OF MASS ACTION)

$$n_c^2 - \Delta n\, n_c - n_i^2 = 0$$

$$\Rightarrow \quad n_c = \frac{\Delta n}{2} \pm \frac{1}{2}\sqrt{\Delta n^2 + 4 n_i^2}$$

$-$ ROOT IS NOT ALLOWED

$$p_v = -\frac{\Delta n}{2} + \sqrt{\Delta n^2 + 4 n_i^2}$$

$$n_c = e^{\beta(\mu-\mu_i)} n_i$$

$$p_v = e^{-\beta(\mu-\mu_i)} p_i$$

$$n_i^2 \left(e^{\beta(\mu-\mu_i)} \right)^2 - \Delta n \, n_i e^{\beta(\mu-\mu_i)} - n_i^2 = 0$$

$$\Rightarrow \quad \frac{\Delta n}{n_i} = \frac{\left(e^{\beta(\mu-\mu_i)}\right)^2 - 1}{e^{\beta(\mu-\mu_i)}} = \underbrace{e^{\beta(\mu-\mu_i)} - e^{-\beta(\mu-\mu_i)}}_{2 \sinh \beta(\mu-\mu_i)}$$

$$\boxed{\frac{\Delta n}{n_i} = 2 \sinh\left(\beta(\mu - \mu_i)\right)}$$

$\Delta n \Longleftrightarrow \mu$

Δn IS EASIER TO FIGURE OUT!!

DEPENDS ON NATURE OF IMPURITIES

$$(\Delta n \approx N_d - N_A)$$