

Lecture No. 10

Semiconductor Crystals 2

Prof. Nasser S. Alzayed

Semiconductor Crystals Holes

- The properties of vacant orbitals in an otherwise filled band are important in semiconductor physics and in solid state electronics. Vacant orbitals in a band are commonly called holes, and without holes there would be no transistors.
- A hole acts in applied electric and magnetic fields as if it has a positive charge +e. The reason is given in five steps:
- 1- k_h = -k_e (8.17)
 □ The total wavevector of the electrons in a filled band is zero: Σk = 0, where the sum is over all states in a Brillouin zone.
- If the band is filled all pairs of orbitals k and -k are filled, and the total wavevector is zero
- □ If an electron is missing from an orbital of wavevector k_e , the total wavevector of the system is -k, and is attributed to the hole
- □ The hole is an alternate of a band with one missing electron.

Semiconductor Crystals

Electron – Hole Conservation of Total Momentum



Figure 7 Absorption of a photon of energy $\hbar\omega$ and negligible wavevector takes an electron from E in the filled valence band to Q in the conduction band. If \mathbf{k}_e was the wavevector of the electron at E, it becomes the wavevector of the electron at Q. The total wavevector of the valence band after the absorption is $-\mathbf{k}_e$, and this is the wavevector we must ascribe to the hole if we describe the valence band as occupied by one hole. Thus $\mathbf{k}_h = -\mathbf{k}_e$; the wavevector of the hole is the same as the wavevector of the electron which remains at G. For the entire system the total wavevector after the absorption of the photon is $\mathbf{k}_e + \mathbf{k}_h = 0$, so that the total wavevector is unchanged by the absorption of the photon and the creation of a free electron and free hole.

Semiconductor Crystals Holes

$$2- \varepsilon_h(k_h) = -\varepsilon_e(k_e)$$
(8.18)

- Here the zero of energy of the valence band is at the top of the band.
- The lower in the band the missing electron lies; the higher the energy of the system.
- The energy of the hole is opposite in sign to the energy of the missing electron, because it takes more work to remove an electron from a low orbital than from a high orbital
- □ Thus if the band is symmetric: $\varepsilon_e(k_e) = \varepsilon_e(-k_e) = -\varepsilon_h(-k_e) = -\varepsilon_h(k_h)$.

3- $V_h = V_e$ (8.19) The velocity of the hole is equal to the velocity of the missing electron

Semiconductor Crystals Electron – Hole Conservation of Total Momentum



Figure 8 The upper half of the figure shows the hole band that simulates the dynamics of a hole, constructed by inversion of the valence band in the origin. The wavevector and energy of the hole are equal, but opposite in sign, to the wavevector and energy of the empty electron orbital in the valence band. We do not show the disposition of the electron removed from the valence band at \mathbf{k}_{e} .

Semiconductor Crystals Holes

$$4- m_h = -m_e \tag{8.20}$$

□ We show below that the effective mass is inversely proportional to the curvature $d^2 \varepsilon/dk^2$ and for the hole band this has the opposite sign to that for an electron in the valence band. Near the top of the valence band m_e is negative, so that m_h is positive

(8.21)

$$5 - \hbar \frac{d\mathbf{k}_h}{dt} = e\left(\mathbf{E} + \frac{1}{c}\boldsymbol{v}_h \times \mathbf{B}\right)$$

The equation of motion for a hole is that of a particle of positive charge *e*.

Current:

j = (-e)v(G) = (-e)[-v(E)] = ev(E) (8.23)

The hole and electron drift velocities are in opposite directions



Semiconductor Crystals Holes and Electrons (Comparison)

□ In the next table: We quickly compare between Holes & Electrons. Momentum, Energy, Velocity , mass and Eq. of motion

Hole	Electron	Quantity	
$\mathbf{K}_{\mathrm{h}} = -\mathbf{k}_{\mathrm{e}}$	k _e	Momentum	
$\boldsymbol{\varepsilon}_{h}(\mathbf{k}_{h}) = -\boldsymbol{\varepsilon}_{e}(\mathbf{k}_{e})$	$\boldsymbol{\epsilon}_{e}(\boldsymbol{k}_{e})$	Energy	
V _h =V _e	V _e	Velocity	
$m_h = -m_e$	m _e	Mass	
$\hbar \frac{d\mathbf{k}_h}{dt} = e(\mathbf{E} + \frac{1}{c} \mathbf{v}_h \times \mathbf{B})$	$\hbar \frac{d\mathbf{k}_e}{dt} = -e(\mathbf{E} + \frac{1}{c}\mathbf{v_e} \times \mathbf{B})$	Equation of Motion	

Semiconductor Crystals *Effective Mass m**

- □ When we look at the energy-wavevector relation $\varepsilon = (\hbar^2/2m)k^2$ for free electrons, we see that the coefficient of k^2 determines the curvature of ε versus k. Turned about, we can say that 1/m, the reciprocal mass, determines the curvature.
- □ For electrons in a band there can be regions of unusually high curvature near the band gap at the zone boundary.
- □ In semiconductors the band width is of the order of 20 eV, while the band gap is of the order of 0.2 to 2 eV.
- Thus, the reciprocal mass is enhanced by a factor 10 to 100, and the effective mass is reduced to 0.1-0.01 of the free electron mass.
- These values apply near the band gap; as we go away from the gap the curvatures and the masses are likely to approach those of free electrons.

Semiconductor Crystals *Effective Mass m**



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Semiconductor Crystals Effective Mass Equation

First differentiate group velocity with time:

Wave function of a free electron is expressed as: $e^{ik.x}$:

$$v_g = \frac{d\omega}{dk} = \frac{1}{\hbar} \frac{d\varepsilon}{dk}$$
(8.26)

Change of energy of electron by the work don by E is:

$$d\varepsilon = \frac{d\varepsilon}{dk}dk = -eEdx = -eEvdt = \frac{-eE}{\hbar}\frac{d\varepsilon}{dk}dt$$
(8.27)
$$\because \frac{dp}{dt} = \frac{d\hbar k}{dt} = \hbar \frac{dk}{dt} = m\frac{dv}{dt}$$

$$\therefore \frac{\hbar}{m}\frac{dk}{dt} = \frac{1}{\hbar}\frac{d}{dt}\frac{d\varepsilon}{dk} = \frac{1}{\hbar}\frac{d^{2}\varepsilon}{dk^{2}}\frac{dk}{dt}$$

$$\Rightarrow \frac{1}{m^{*}} = \frac{1}{\hbar^{2}}\frac{d^{2}\varepsilon}{dk^{2}}$$
(8.28)

Semiconductor Crystals Effective Masses in Semiconductors

- In many semiconductors it has been possible to determine by cyclotron resonance the effective masses of carriers in the conduction and valence bands near the band edges.
- □ The determination of the energy surface is equivalent to a determination of the effective mass.
- Cyclotron resonance in a semiconductor is carried out so that the current carriers are accelerated in helical orbits about the axis of a static magnetic field.
- \Box The angular rotation frequency ω_c is:

$$\omega_c = \frac{eB}{m^*} \tag{8.30}$$

where m* is the appropriate cyclotron effective mass

Semiconductor Crystals Effective Masses in Semiconductors

- Resonant absorption of energy from an rf electric field perpendicular to the static magnetic field occurs when the rf frequency is equal to the cyclotron frequency.
- Holes and electrons rotate in opposite directions.



Table 2 Effective masses of electrons and holes in direct-gap semiconductors

Crystal	Electron m/m	Heavy hole m_{hh}/m	$\frac{\text{Light hole}}{m_{h}/m}$	Split-off hole m_{sob}/m	Spin-orbit Δ, eV
InSb	0.015	0.39	0.021	(0.11)	0.82
InAs	0.026	0.41	0.025	0.08	0.43
InP	0.073	0.4	(0.078)	(0.15)	0.11
GaSb	0.047	0.3	0.06	(0.14)	0.80
GaAs	0.066	0.5	0.082	0.17	0.34
Cu_2O	0.99		0.58	0.69	0.13

Semiconductor Crystals Electron – Hole Conservation of Total Momentum

Figure 14 Calculated band structure of germanium. The general features are in good agreement with experiment. The four valence bands are shown in gray. The fine structure of the valence band edge is caused by spin-orbit splitting. The energy gap is indirect; the conduction band edge is at the point $(2\pi/a)(\frac{1}{2}\frac{1}{2})$.



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The
$$\frac{2\pi}{a}(\frac{1}{2}\frac{1}{2}\frac{1}{2})$$
 is a point in Recipspace
*This point is called & L-point in First B.2 & FCC
* Remember fac in normal space
 \Rightarrow Bace reciprov
* L-point is at the center of Hax. And & B.2
 \Rightarrow L-point is at $\frac{1}{2}\frac{1}{2}$
 $\forall \cdot \cdot \cdot K = h\overline{b}_{1} + k\overline{b}_{2} + l \overline{b}_{3}$
 $\Rightarrow (hkl) = (\frac{1}{2}\frac{1}{2}\frac{1}{2})$
 $\frac{1}{b_{1}} = \frac{2\pi}{a}(1,0,0)$ $\overline{b}_{2} = \frac{2\pi}{a}(0,1,0)$
 $\overline{b}_{3} = \frac{2\pi}{a}(0,0,1)$

Semiconductor Crystals Electron – Hole Conservation of Total Momentum

$$* \rightarrow \vec{k} := \frac{2\pi}{3} \left(\frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2} \right)$$

$$* :: 1 - point is ato = \frac{2\pi}{3} \left(\frac{1}{2} \cdot \frac{1}{2} \cdot \frac{1}{2} \right) \times$$

Semiconductor Crystals Electron – Hole Conservation of Total Momentum





Figure 17a Constant energy ellipsoids for electrons in silicon, drawn for $m_t/m_t = 5$.

- We want the concentration of intrinsic carriers as a function of temperature, in terms of the band gap.
- we assume that $\epsilon_{\mu} >> k_{B}T$, so that the Fermi-Dirac distribution function reduces to:

$$T_e \approx e^{\left[\frac{\mu-\varepsilon}{k_BT}\right]}$$
 (8.35)

- □ This is the probability that a conduction electron orbital is occupied, in an approximation valid when $f_e << 1$.
- □ The energy of an electron in the conduction band is:

$$\varepsilon_k = E_c + \frac{\hbar^2 k^2}{2m_e^*} \tag{8.36}$$

 \Box where E_c is the energy at the conduction band edge.

Semiconductor Crystals Electron – Hole Conservation of Total Momentum



Figure 18 Energy scale for statistical calculations. The Fermi distribution function is shown on the same scale, for a temperature $k_BT \ll E_g$. The Fermi level μ is taken to lie well within the band gap, as for an intrinsic semiconductor. If $\epsilon = \mu$, then $f = \frac{1}{2}$.

Thus from (6.20) the density of states at ϵ is:

$$D_e(\varepsilon) = \frac{1}{2\pi^2} \left(\frac{2m_e}{\hbar^2}\right) (\varepsilon - E_c)^{1/2}$$
(8.37)

The concentration of electrons in the conduction band is :

$$n = \int_{E_c}^{\infty} D_e(\varepsilon) f_e(\varepsilon) d\varepsilon$$

= $\frac{1}{2\pi^2} \left(\frac{2m_e}{\hbar^2}\right) e^{\mu/k_B T} \int_{E_c}^{\infty} (\varepsilon - E_c)^{1/2} e^{-\varepsilon/k_B T} d\varepsilon$ (8.38)

which integrates to give:

$$n = 2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} e^{(\mu - E_c)/k_B T}$$
(8.39)

Chat GPT show us how to derive n in (8.39) by taking a snapshot of (8.38), pasting it and asking for full derivative:

The integral in question is:

$$\int_{E_c}^\infty (\epsilon-E_c)^{1/2} e^{-\epsilon/k_BT} d\epsilon$$

Change of Variables

To simplify this integral, perform a change of variables:

$$u=\epsilon-E_c\Rightarrow du=d\epsilon$$
 $\epsilon=u+E_c$

When
$$\epsilon = E_c$$
, $u = 0$. When $\epsilon = \infty$, $u = \infty$.

The integral becomes:

$$\int_0^\infty u^{1/2} e^{-(u+E_c)/k_BT} du$$

Factor Out Constants

Extract the term e^{-E_c/k_BT} which does not depend on u:

$$e^{-E_c/k_BT}\int_0^\infty u^{1/2}e^{-u/k_BT}du$$

Use the Gamma Function

The remaining integral is a standard form that involves the gamma function, $\Gamma(n)$, for n=3/2:

$$\int_0^\infty u^{n-1} e^{-u/a} du = \Gamma(n) a^n$$

where $a=k_BT$ and n=3/2.

Thus, the integral evaluates to:

 $\Gamma(3/2)(k_BT)^{3/2}$

The gamma function $\Gamma(3/2)=rac{\sqrt{\pi}}{2}$, hence the integral becomes:

$$e^{-E_c/k_BT}rac{\sqrt{\pi}}{2}(k_BT)^{3/2}$$

This gives the complete solution:

$$rac{\sqrt{\pi}}{2}(k_BT)^{3/2}e^{-E_c/k_BT}$$

1. Density of States, $D(\epsilon)$:

$$D(\epsilon) = rac{1}{2\pi^2} \left(rac{2m}{\hbar^2}
ight)^{3/2} \sqrt{\epsilon-E_c} \, ,$$

This term gives the density of states for a 3D parabolic band. It counts the number of available states at each energy level that electrons can occupy.

2. Fermi-Dirac Distribution, $f(\epsilon)$:

$$f(\epsilon) = rac{1}{e^{(\epsilon-\mu)/k_BT}+1}$$

For simplicity, assuming $T \to 0$ (absolute zero), this function can be approximated as a step function that is 1 for $\epsilon \leq \mu$ (chemical potential) and 0 for $\epsilon > \mu$. At non-zero temperatures, it smoothly transitions around μ .

3. Multiplying and Integrating:

The product $D(\epsilon)f(\epsilon)$ is integrated from the conduction band edge E_c to infinity to find the total number of electrons per unit volume in the conduction band. The integral simplifies at low temperatures to:

$$n=\int_{E_c}^\infty D(\epsilon)f(\epsilon)d\epsilon=rac{1}{2\pi^2}\left(rac{2m}{\hbar^2}
ight)^{3/2}\int_{E_c}^\infty (\epsilon-E_c)^{1/2}e^{-\epsilon/k_BT}d\epsilon$$

4. Solution of the Integral:

As calculated previously, this integral is:

$$rac{\sqrt{\pi}}{2} (k_B T)^{3/2} e^{-E_c/k_B T}$$

Plugging this back into the equation for n yields:

$$n = rac{1}{2\pi^2} \left(rac{2m}{\hbar^2}
ight)^{3/2} rac{\sqrt{\pi}}{2} (k_B T)^{3/2} e^{-E_c/k_B T}$$

Simplifying this expression gives:

$$n=rac{(2m)^{3/2}(k_BT)^{3/2}e^{-E_c/k_BT}}{4\pi^2\hbar^3}$$

This simplifies further to the form shown in your image:

$$n=rac{m^{3/2}k_BT}{2\pi^2\hbar^3}^{3/2}e^{-(E_c-\mu)/k_BT}$$

Please note: I am using Chat GPT to show you how powerful it is in solving hard equations and simplyfiy them. The final solution requires just few adjustment to fit for our form.

□ Home Work: (not to be submitted)

Please construct an equation similar to (8.39) but for p this time, then use Chat GPT to solve it for p (eq. 8.42)

$$f_{h} = 1 - \frac{1}{\exp(\varepsilon - \mu / k_{B}T) + 1} = \frac{1}{\exp(\mu - \varepsilon / k_{B}T) + 1}$$
(8.40)
$$\approx \exp[\varepsilon - \mu / k_{B}T]$$

we have:

 \square For the holes $c_{\rm L} = 1 \times K T$

$$D_{h}(\varepsilon) = \frac{1}{2\pi^{2}} \left(\frac{2m_{h}}{\hbar^{2}}\right)^{3/2} \left(E_{v} - \varepsilon\right)^{1/2}$$

$$\therefore p = 2 \left(\frac{m_{h}^{*}k_{B}T}{2\pi\hbar^{2}}\right)^{3/2} e^{(E_{c} - \mu)/k_{B}T}$$
(8.41)
(8.42)

From (8.39) and (8.42) we obtain the equilibrium relation:

$$np = 4 \left(\frac{k_B T}{2\pi\hbar^2}\right)^3 \left(m_e^* m_h^*\right)^{3/2} e^{-E_g/k_B T}$$
(8.43)

- \Box This useful result does not involve the Fermi level μ .
- At 300 K the value of np is 2.10 X 10¹⁹ /cm⁶, 2.89 X 10²⁶ /cm⁶, and 6.55 X 10¹²/cm⁶, for the actual band structures of Si, Ge, and GaAs, respectively.
- We have nowhere assumed in the derivation that the material is intrinsic: the result holds for impurity ionization as well.
- □ The only assumption made is that the distance of the Fermi level from the edge of both bands is large in comparison with k_BT

- We should notice that (np) as a whole is constant at any given temperature:
- **To prove this:**
- Suppose that the equilibrium population of electrons and holes is maintained by black-body photon radiation at temperature *T*.
- □ Let A(T) be the electron-hole pairs generation.
- Let B(T)np is the rate of the recombination reaction e + h = photon.

(8.44)

Then:

$$\frac{dn}{dt} = A(T) - B(T)np = \frac{dp}{dt}$$

In equilibrium : $\frac{dn}{dt} = \frac{dp}{dt} = 0$ and $np = \frac{A(T)}{B(T)}$

Because the product of the electron and hole concentrations is a constant independent of impurity concentration at a given temperature, the introduction of a small proportion of a suitable impurity to increase *n*, say, must decrease *p*.

This result is important in practice-we can reduce the total carrier concentration *n* + *p* in an impure crystal, sometimes enormously, by the controlled introduction of suitable impurities. Such a reduction is called compensation.

□ In an intrinsic semiconductor the number of electrons is equal to the number of holes, because the thermal excitation of an electron leaves behind a hole in the valence band. (8.43) →

$$n_{i} = n = p_{i} = 2 \left(\frac{k_{B}T}{2\pi\hbar^{2}}\right)^{3/2} \left(m_{e}^{*}m_{h}^{*}\right)^{3/4} e^{-E_{g}/2k_{B}T}$$
(8.45)

2. For intrinsic semiconductor:

- $n = p = n_i$
- Fermi level μ lies near midgap, symmetrically.
- Charge neutrality.

Thus, multiply n imes p:

$$n_i^2 = n imes p$$

Substitute both expressions:

$$n_i^2 = \left[2\left(rac{m_ek_BT}{2\pi\hbar^2}
ight)^{3/2}e^{(\mu-E_c)/k_BT}
ight] imes \left[2\left(rac{m_hk_BT}{2\pi\hbar^2}
ight)^{3/2}e^{(E_v-\mu)/k_BT}
ight]$$

3. Simplify:

Group terms:

$$n_i^2 = 4 \left(rac{k_B T}{2\pi \hbar^2}
ight)^3 (m_e m_h)^{3/2} e^{(E_v-E_c)/k_B T}$$

 \Box Intrinsic carrier concentration depends exponentially on $E_g/2k_BT_{,...}$ We set (8.39) = (8.42) to obtain, for the Fermi level as measured from the top of the valence band: (*please derive at home*):

$$e^{\frac{2\mu}{K_B T}} = \left(\frac{m_h}{m_e}\right)^{3/2} e^{\frac{E_g}{K_B T}}$$
(8.45)
$$\mu = \frac{1}{2} E_g + \frac{3}{4} K_B T \ln \frac{m_h}{m_e}$$
(8.47)

If $m_h = m_e$ then $\mu = \frac{1}{2}E_g$ and the Fermi level is in the middle of the forbidden gap.

 m_{o}

2

□ Intrinsic carrier concentration depends exponentially on $E_g/2k_BT$, We let (8.39) = (8.42) to obtain, for the Fermi level as measured from the top of the valence band: (*please derive at home*):

$$n = 2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} e^{(\mu - E_c)/k_B T}$$
(8.39)

$$\therefore p = 2\left(\frac{m_h k_B T}{2\pi\hbar^2}\right) \quad e^{(E_c - \mu)/k_B T}$$
(8.42)

□ Make them = and derive the eq. (8.47)

1. Set n = p using their full expressions:

Thus:

$$2\left(rac{m_ek_BT}{2\pi\hbar^2}
ight)^{3/2}e^{(\mu-E_c)/k_BT}=2\left(rac{m_hk_BT}{2\pi\hbar^2}
ight)^{3/2}e^{(E_v-\mu)/k_BT}$$

Divide both sides by 2 and group:

$$\left(rac{m_e}{m_h}
ight)^{3/2} e^{(\mu-E_c+\mu-E_v)/k_BT} = 1$$

Simplify the exponent:

$$(\mu-E_c)+(\mu-E_v)=2\mu-(E_c+E_v)$$

Thus:

$$\left(rac{m_e}{m_h}
ight)^{3/2} e^{(2\mu - (E_c + E_v))/k_BT} = 1$$

2. Rearrange:

Take reciprocal:

$$\left(rac{m_h}{m_e}
ight)^{3/2} = e^{(2\mu - (E_c + E_v))/k_BT}$$

Write it as:

$$e^{2\mu/k_BT}=\left(rac{m_h}{m_e}
ight)^{3/2}e^{(E_c+E_v)/k_BT}$$

Notice:

$$E_c-E_v=E_g \quad \Rightarrow \quad E_c+E_v=2E_v+E_g$$

but usually if the midgap is considered symmetric:

$$(E_c + E_v) pprox E_g$$

(So we approximate $E_c+E_vpprox E_g$ in this treatment.)

Thus:

$$e^{2\mu/k_BT}=\left(rac{m_h}{m_e}
ight)^{3/2}e^{E_g/k_BT}$$

This matches equation (46)!

3. Now take natural logarithm (In) of both sides:

$$rac{2\mu}{k_BT} = rac{3}{2}\ln\left(rac{m_h}{m_e}
ight) + rac{E_g}{k_BT}$$

Multiply through by k_BT :

$$2\mu = E_g + rac{3}{2}k_BT\ln\left(rac{m_h}{m_e}
ight)$$

Thus:

$$\mu = rac{1}{2}E_g + rac{3}{4}k_BT\ln\left(rac{m_h}{m_e}
ight)$$

Exactly equation (47)!

□ The mobility is the magnitude of the drift velocity of a charge carrier per unit electric field:

$$\mu = |v| / E \tag{8.48}$$

The mobility is defined to be positive for both electrons and holes, although their drift velocities are opposite in a given field.
 For distinction : use μ_e for electrons and μ_h for holes.
 Electrical conductivity is the sum of both:

$$\sigma = (ne\mu_e + pe\mu_h)$$

$$\therefore v = \frac{q\tau E}{m} \quad \text{(from Chapter 6)}$$

$$\therefore \mu_e = \frac{e\tau_e}{m_e} \quad and \quad \mu_h = \frac{e\tau_h}{m_h}$$
(8.50)

where τ is the collision time

- □ In Ge; let $E_g = 0.670 \ eV$, m^{*} = 0.55 m_o, chemical potential μ , is given by μ = -7.69x10⁻³ eV. Find:
- a) $\epsilon_{\rm F}$ relative to the TOP of valence band.
- b) Probability of occupancy at the bottom of conduction band $f(E_c)$ for T = 300 K
- c) Density of electrons at same temperature

(a)

From Fig. 18:

$$\varepsilon_F = \frac{1}{2} (E_v - E_c)$$

Let E_v be at $0 eV$
 $\Rightarrow \varepsilon_F = \frac{1}{2} (0 + 0.67) = 0.335 eV$

(b) for the case when $(\varepsilon - \mu) >> k_B T$ (at 300 K) $f(\varepsilon) \approx e^{(\mu - \varepsilon)/k_B}$

 $\therefore f(E_C) = e^{(\mu - E_C)/k_B} = e^{\frac{-7.69 \times 10^{-3} - 0.67 + 0.335}{8.62 \times 10^{-5} \times 300}}$ $= 1.7 \times 10^{-6} \ eV$

$$\therefore n(e) = 2 \left[\frac{m^* k_B T}{2\pi\hbar^2} \right]^{3/2} e^{\frac{\mu - E_C}{k_B T}}$$
$$= 2 \left[\frac{0.55 \times 9.11 \times 10^{-31} \times 1.38 \times 10^{-23} \times 300}{2\pi \times (1.05 \times 10^{-24})^2} \right]^{3/2} \times 1.74 \times 10^{-6}$$
$$= 6.55 \times 10^{18} \ e \ / \ m^3$$

□ In Si; if we have: $m_e^* = 0.259 \text{ m}_o$, $\mu_e = 0.135 \text{ m}^2/\text{v.s}$, $\mu_h = 0.048$, and $m_h^* = 0.537 \text{ m}_e$. Calculate relaxation time for (e) and (holes).

Solution:

From Eq. (5):

$$\begin{split} \tau_{e} &= \frac{m_{e}^{*} \mu_{e}}{e} = \frac{0.259 \times 9.11 \times 10^{-31} \times 0.135}{1.6 \times 10^{-19}} = 1.99 \times 10^{-13} \, Sec \\ \tau_{h} &= \frac{m_{h}^{*} \mu_{h}}{e} = \frac{0.537 \times 9.11 \times 10^{-31} \times 0.048}{1.6 \times 10^{-19}} = 1.47 \times 10^{-13} \, Sec \end{split}$$

