HW3 EE 344 Fall 2008 ①

I Carrier Densities 80/80

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T=300K

S_1	S_2
$N_A = 0$	$N_A = 0$
$N_D = 10^{15}/cm^3$	$N_D = 10^5/cm^3$

Also $$\boxed{n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}} \quad *$$

+1 if justification below are using this formula

For silicon $n_i = 10^{10}/cm^3$.

* For S_1
- 1 • $N_D \gg n_i \Rightarrow$ it is an extrinsic regime.
- 1 • $n \simeq N_D$ from (*)

* For S_2
- 1 • $N_D \ll n_i \Rightarrow$ it is an intrinsic regime.
- 1 • $n \simeq n_i$ from (*)

* if $T \nearrow$ in Silicon, $n_i \nearrow$ as well such that for very high T $n_i > N_d$ and Si enters in the intrinsic regime 2.

(2) 10/10

$$n_i = \sqrt{N_c N_v}\; e^{-E_G/2k_BT}$$

n_i depends explicitly of the temperature T with the term $e^{-E_g/2k_BT}$
we will not consider the implicit temperature dependence of N_c, N_v, E_g, m^*.

$$\Rightarrow \ln\left(\frac{n_i}{\sqrt{N_c N_v}}\right) = \frac{-E_G}{2k_BT} \Rightarrow \boxed{T = \frac{-E_G}{2k_B \ln\left(\frac{n_i}{\sqrt{N_c N_v}}\right)}}$$ /4

$n_i = 2\cdot 10^{13}/cm^3$ (Ge at 300K)

Let us suppose that even if $T \neq 300K$

$$N_{c,v} = (2.51\times 10^{19})\left(\frac{m^*_{n,p}}{m^*_0}\right)^{3/2}$$

<u>For Silicon</u>

$m^*_n = 1.18\, m_0 \quad m^d_p = 0.81\, m_0$

$E_G = 1.12\,eV$ (or 1.12q Joule)

$$\boxed{T \simeq 463K}$$ /3

<u>For GaAs</u>

$m^*_n = 0.066 \quad m^*_p = 0.52$

$E_G = 1.42\,eV$

$$\boxed{T \simeq 715K}$$ /3

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$E_G^A = 1eV \qquad E_G^B = 2eV.$

$$n_i^{A,B} = \sqrt{N_C^{A,B} N_V^{A,B}}\, e^{-E_G^{A,B}/2k_BT} \quad /2$$

We suppose $N_C^A = N_C^B$, $N_V^A = N_V^B$.

$$\boxed{\left(\frac{n_i^A}{n_i^B}\right) = e^{-(E_G^A - E_G^B)/2k_BT} \simeq 2.5 \times 10^8} \; !! \quad /4$$

at $T = 300K$

Comments: the carrier concentration (intrinsic carrier density) increases exponentially if E_G decreases. /4

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(a) 3/3 $T = 300K$ N-type $N_D = 10^{15}/cm^3$.

$n \simeq N_D = 10^{15}/cm^3$

$$p = \frac{n_i^2}{N_D} = \frac{(10^{10})^2}{10^{15}} = 10^5/cm^3. \quad /3.$$

(b) $T = 300K$ P-type $N_A = 10^{16}/cm^3$

3/3

$$p \simeq N_A = 10^{16}/cm^3$$

$$n = \frac{n_i^2}{p} = \frac{(10^{10})^2}{10^{16}} = 10^4/cm^3$$

/3

(c) $T = 300K$ $N_A = 9 \cdot 10^{15}/cm^3$ $N_D = 10^{16}/cm^3$.

3/3

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2\right]^{1/2} = 10^{15}/cm^3$$

$$p = \frac{n_i^2}{n} = \frac{(10^{10})^2}{10^{15}} = 10^5/cm^3$$

/3

(d) 5/5

$T = 450K$ $N_A = 0$ $N_D = 10^{14}/cm^3$

we cannot say $n \simeq N_D$ since p may be important here as well.

we use $$n = \frac{N_D}{2} + \left[\left(\frac{N_D}{2}\right)^2 + n_i^2\right]^{1/2}$$

However, what is n_i at $T = 450K$?

$$n_i = \sqrt{N_C N_V}\, e^{-E_G/2k_BT}$$

$E_G = 1.08\, eV$

$m_n^* = 1.18\, m_0$

$m_p^* = 0.81\, m_0$

$$N_C N_V = 4(m_n^* m_p^*)^{3/2}\left(\frac{k_BT}{2\pi\hbar^2}\right)^3$$

$n_i = 4 \cdot 10^{19}/m^3 \Rightarrow \boxed{n_i = 4 \cdot 10^{13}/cm^3}$ /2

one could also use the formula in textbook (directly in /cm^3).

$$n_i = (2.510 \times 10^{19}) \left(\frac{m_n^* m_p^*}{m_0^2}\right)^{3/4} \exp\left(-\frac{E_G}{2k_0T}\right)\left(\frac{T}{300}\right)^{3/2}$$

Finally $\boxed{n = 1.14 \cdot 10^{14}/cm^3}$ /3

and $\boxed{p = \frac{n_i^2}{n} = 1.4 \cdot 10^{13}/cm^3}$

(c) 5/5 $T = 650K \quad N_A = 0 \quad N_D = 10^{15}$

the same $E_G = 1.015$ eV.

$\boxed{n_i \simeq 9.1 \cdot 10^{15}/cm^3}$ also look at Fig 2.20 /2

$$\Rightarrow \left[\begin{array}{l} n \simeq 9.15 \cdot 10^{15}/cm^3 \simeq n_i \\ p = \frac{n_i^2}{n} \simeq n_i \end{array}\right\}$$

intrinsic regime

Look at Fig 2.22 /3

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6/6 N-Type

$E_C - E_F = 0.2\,eV$

$n \simeq N_D = N_C \exp\left(\frac{E_C - E_F}{k_0 T}\right)$ /3

$\Rightarrow \boxed{N_D = 1.2 \cdot 10^{16}/cm^3}$ /3

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8/8 $N_D = 2.3 \cdot 10^{17}/cm^3 \Rightarrow$ N-Type . GaAs

~~[illegible]~~ if non degenerate

$$\begin{cases} n \simeq N_D = 2.3 \cdot 10^{17}/cm^3 \\ p = \frac{n_i^2}{n} = 1.4 \cdot 10^{-5}/cm^3 \end{cases}$$ /2

$n_i = 1.8 \cdot 10^{6}/cm^3$

* $E_C - E_F$? $= \underbrace{E_C - E_i}_{\frac{E_g}{2}} + \underbrace{E_i - E_F}_{\frac{k_0 T}{q} \ln\left(\frac{n}{n_i}\right)} \simeq 0.05\,eV$ /2

$(E_G = 1.42\,eV)$

The condition $E_C - E_F > 3k_0T$ is not satisfied !!

E_F is very close to $E_C \Rightarrow$ SC is degenerate. /4

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2 Consequences (i) ~~...~~ the formula $n_i^2 = np$ is not valid

the results previously obtained for n and p are questionable.

(ii) $E_i - E_F$ cannot be approximated by $\frac{k_BT}{q} \ln\left|\frac{n}{n_i}\right|$, $\Rightarrow E_c - E_F$ is not correct.

however $E_V - E_F$ can be approximated by $\frac{k_BT}{q} \ln\left(\frac{q}{N_V}\right)$

$(E_F - E_V \gg 3k_BT)$.

$$\Rightarrow E_c - E_F = \underbrace{E_V - E_F}_{\substack{4 \\ -1.41eV}} + \underbrace{E_c - E_V}_{E_g} = \boxed{0.01eV}$$

E_F is even ~~...~~ closer to E_c.

7 12/12 $n_i = 10^{13}/cm^3$ $n = 2p$ $N_A = 0$.

- $n = \frac{n_i^2}{p} = 2\frac{n_i^2}{n} \Rightarrow \boxed{n = \sqrt{2}\, n_i} = 1.41 \times 10^{13}/cm^3$ 3
- $\boxed{p = \frac{n_i}{\sqrt{2}}} = 7.07 \times 10^{12}/cm^3$ /3

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- $n = p + N_d \rightarrow \boxed{N_d = n - p = 7.07 \cdot 10^{12}/cm^3}$ /3

- $|E_F - E_i| = k_BT \ln\left(\frac{n}{n_i^2}\right) = \frac{k_BT}{2} \ln(2) = 1.593 \cdot 10^{-21}$ J

$\cancel{\approx} \; 0.009 eV$ /3

8 8/8.

$n_i^{(1)} = n_{i\,InAs}$ $\quad n_i^{(2)} = n_{i\,GaAs}$ $\quad$ indexes $\left[\begin{array}{l} (1) \text{ for InAs} \\ (2) \text{ for GaAs} \end{array}\right.$

$n_i^{(1)} = \sqrt{N_c^{(1)} N_v^{(1)}}\, e^{-E_g^{(1)}/2k_BT}$ /2

$n_i^{(2)} = \sqrt{N_c^{(2)} N_v^{(2)}}\, e^{-E_g^{(2)}/2k_BT}$

$$\boxed{\frac{n_i^{(1)}}{n_i^{(2)}} = \left(\frac{m_n^{*(1)} m_p^{*(1)}}{m_n^{*(2)} m_p^{*(2)}}\right)^{3/4} e^{-\left[E_g^{(1)} - E_g^{(2)}\right]/2k_BT}}$$ /4

~~$n_{i\,InAs} = n_{i\,GaAs} \left(\frac{m_n^{*(1)}}{m}\right.$~~

$\Rightarrow \boxed{n_{i\,InAs} = 2.93 \cdot 10^8 \, n_{i\,GaAs}} = \boxed{5.86 \cdot 10^{14}/cm^3}$ /2

see comment on problem (3)

II Carrier transport 20/20

① 8/8

$$\rho = \frac{1}{(q\mu_n n + q\mu_p p)}$$

if intrinsic $n = p = n_i$

$$\boxed{\rho = \frac{1}{q n_i(\mu_n + \mu_p)}}$$ /2

GaAs $\Rightarrow \begin{cases} n_i = 1.8 \cdot 10^6/cm^3 \\ \mu_n = 8000\ cm^2/V.s \\ \mu_p = 400\ cm^2/V.s \end{cases} \Rightarrow \boxed{\rho = 413 \cdot 10^6\ \Omega.cm}$ /2

Si $\Rightarrow \begin{cases} n_i = 10^{10}/cm^3 \\ \mu_n \simeq 1360\ cm^2/V.s \\ \mu_p \simeq 460\ cm^2/V.s \end{cases}$ $\boxed{\rho = 343 \times 10^3\ \Omega.cm}$ /2

Ge $\Rightarrow \begin{cases} n_i = 2.0 * 10^{13}/cm^3 \\ \mu_n = 3900\ cm^2/V.s \\ \mu_p = 1900\ cm^2/V.s \end{cases}$ $\boxed{\rho \simeq 54\ \Omega.cm}$ /2

(2) $N_A = 10^{17}/cm^3$

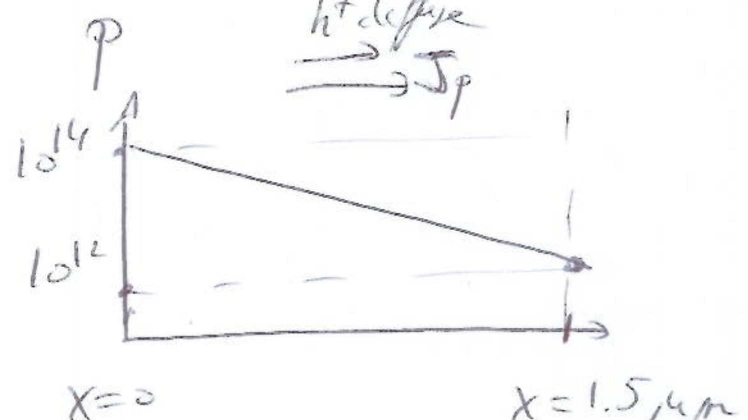
2/2 $\mu_p = 317\ cm^2/V.s$

$p \simeq N_A$ (p-type)

$$\boxed{\rho = \frac{1}{q N_A \mu_p} = 0.197\ \Omega.cm}$$ /2

(3) $N_D = 10^{17}/cm^3$

6/6



$J_p = q D_p \left(\frac{dp}{dx}\right)$ ✓/2 $\quad \boxed{D_p = \frac{k_B T}{q} \mu_p} = 8.2\ cm^2/s$ /2

$$\boxed{J_p = q D_p \left[\frac{9.9 \cdot 10^{13}}{1.5 \cdot 10^{-4}}\right] \simeq 0.866\ A/cm^2}$$ /2

$\underbrace{D_p \to cm^2/s, \quad 9.9\cdot10^{13} \to 1/cm^3, \quad 1.5\cdot10^{-4} \to cm}$

Rq. the best is to transform anything in S.I

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$\mu_n = 8800\ cm^2/V.s$

$\boxed{\tau_c = \frac{\mu_n m_e^*}{q} = 0.34\ ps}$ /2

mean free path $v_e = 10^7\ cm/s$

$\boxed{l = v.\tau_c = 34\ nm}$ /2