# HW#2 SOLUTION

1) prob. 2.16

a) as $T \to 0$, $n \to 0$ and $p \to 0$

b) Since $N \gg n_i$, one would have

$n = N_D$ and $p = n_i^2/N_D$ ... if a donor.

$p = N_A$ and $n = n_i^2/N_A$ ... if an acceptor.

we are told $n = N$ and $p = n_i^2/N$

$\therefore$ impurity is a donor.

c) Here we are given the minority carrier concentration, $n = 10^5/cm^3$. As long as the Si is nondegenerate, we can write

$$np = n_i^2$$

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

d) Given $E_F - E_i = 0.259\,eV$ and $T = 300K$,

$$n = n_i e^{(E_F - E_i)/kT} = (10^{10}) e^{0.259/0.0259} = 2.20 \times 10^{14}\ cm^{-3}$$

$$p = n_i e^{(E_i - E_F)/kT} = (10^{10}) e^{-0.259/0.0259} = 4.54 \times 10^{5}\ cm^{-3}$$

e) Employing the np product relationship,

$$np = n^2/2 = n_i^2$$

$$n = \sqrt{2}\, n_i = 1.414 \times 10^{13}\ cm^{-3}$$

Next, employing the charge neutrality relationship,

$$p - n + N_D - N_A = n/2 - n + N_D = 0$$

$$N_D = n/2 = n_i/\sqrt{2} = 0.707 \times 10^{13}\ cm^{-3}$$

2)

a) $N_d - N_a = 3\times10^{15}\ cm^{-3} \gg n_i.$

$\therefore n = 3\times10^{15}\ cm^{-3}$

from $n_i^2 = n\cdot p.$

$$p = \frac{n_i^2}{n} = \frac{(1.1\times10^{10})^2}{3\times10^{15}} = 4.03\times10^{4}\ cm^{-3}$$

b) $n_i = 1.1\times10^{10} = \sqrt{N_cN_v}\, e^{-E_g/2kT}$,

from $E_g \Rightarrow 2E_g.$

$$n_{i\,new} = \sqrt{N_cN_v}\, e^{-2E_g/2kT} = \sqrt{N_cN_v}\, e^{-E_g/2kT}\cdot e^{-E_g/2kT} = 1.1\times10^{10}\times e^{-\frac{1.1}{2\times0.026}}$$

$$= 0.336\ cm^{-3}$$

$\therefore$ new $n_i = 0.336\ cm^{-3}$

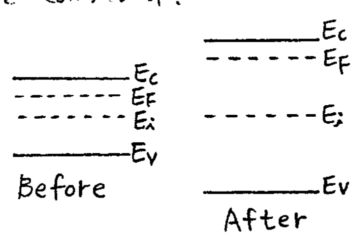
$$\therefore p = \frac{n_i^2}{n} = \frac{(0.336)^2}{3\times10^{15}} = 3.76\times10^{-17}\ cm^{-3}$$ : almost nothing.

from eq. $n = N_c e^{(E_F - E_c)/kT}$, all variables are constant.

$\therefore E_F$ don't move with respect to $E_c$

from eq. $n = n_i e^{(E_F - E_i)/kT}$, $n_i$ is changed.

$\therefore E_F$ move with respect to $E_i$.

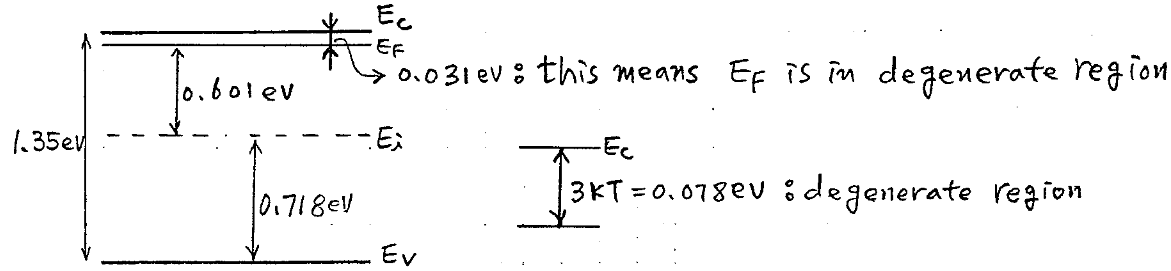



3) $\begin{cases} N_d - N_a = 1\times10^{17} \gg n_i \\ E_g = 1.35\ eV. \end{cases}$

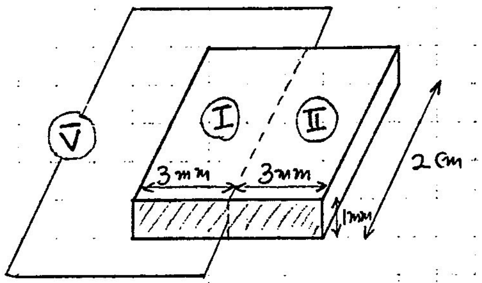
$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right) = \frac{1.35}{2} + \frac{3}{4}\times0.026\times\ln\left(\frac{0.54}{0.06}\right)$$

$$= 0.718\ eV$$

$$E_F - E_i = kT\ln\left(\frac{N_D - N_A}{n_i}\right) = 0.026\times\ln\left(\frac{1\times10^{17}}{9\times10^{6}}\right) = 0.601\ eV$$



4)




Ⓘ $N_a = 7 \times 10^{16}\ cm^{-3}$ : Boron
$N_d = 6 \times 10^{16}\ cm^{-3}$ : Arsenic

Ⓘⓘ $N_d = 1 \times 10^{17}\ cm^{-3}$ : Arsenic
$N_a = 3 \times 10^{16}\ cm^{-3}$ : Boron

for Ⓘ $\quad N_a - N_d = 1 \times 10^{16} \gg n_i$ : p-type Si

for Ⓘⓘ $\quad N_d - N_a = 7 \times 10^{16} \gg n_i$ : n-type Si

$$R_s = \frac{1}{\frac{1}{R_{I}} + \frac{1}{R_{II}}}$$

$$R_{I} = \frac{\rho l}{A} = \frac{l}{\sigma A} = \frac{l}{q\mu_p p A} = \frac{2}{1.6\times10^{-19} \times 300 \times 1\times10^{16} \times 0.1 \times 0.3}$$

$$= 138.89\ (\Omega)$$

NOTE: mobilities taken using $N_A + N_D = 1.3 \times 10^{17}$
(happens to be the same in both I and II) and estimated from table

$$R_{II} = \frac{l}{q\mu_n n A} = \frac{2}{1.6\times10^{-19} \times 700 \times 7\times10^{16} \times 0.1 \times 0.3}$$

$$= 8.50\ (\Omega)$$

$$\therefore R_s = \frac{138.89 \times 8.50}{138.89 + 8.50} = 8.01\ (\Omega)$$

5)

a) Yes for all cases. The semiconductor is concluded to be in equilibrium because the Fermi level has the same energy value (it is constant) as a function of position.

b) V vs. x has the same functional form as the "upside down" of $E_c$ (or $E_i$ or $E_v$). the sketches that follow were constructed taking the arbitrary reference voltage to be $V=0$ at $x=0$.

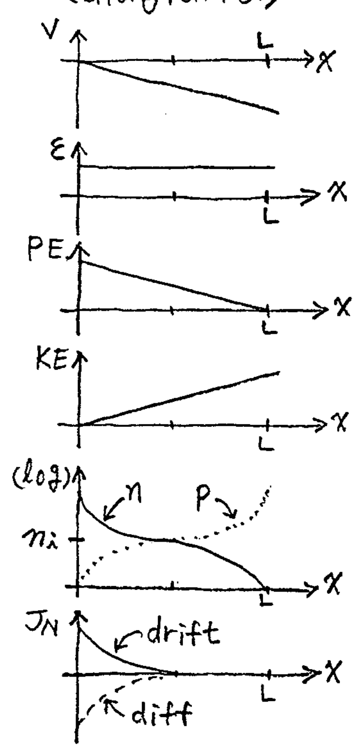
c) $\mathcal{E}$ vs. $x$ is determined by noting the slope of the energy bands as a function of position.

d) For electrons: $PE = E_c - E_F$ and $KE = E - E_c$
For holes : $PE = E_F - E_v$ and $KE = E_v - E$.

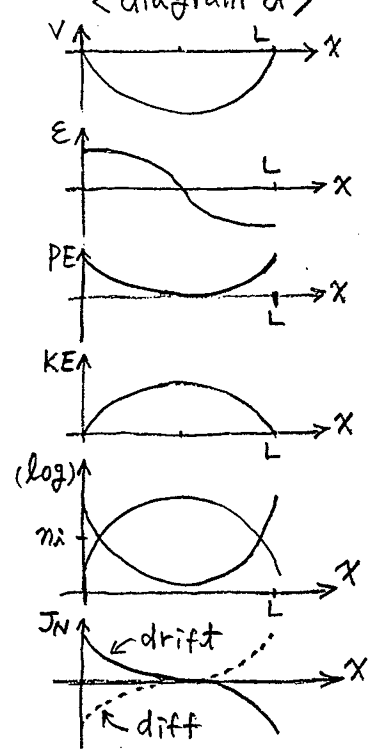
e) The general carrier concentration variation can be deduced by noting $E_F - E_i$ vs. $x$. Under equilibrium conditions, $n = n_i \exp[(E_F - E_i)/kT]$ and $p = n_i \exp[(E_i - E_F)/kT]$ if it is nondegenerate.

f) Since $J_{N,drift} = q\mu_n n \mathcal{E}$, the general variation of $J_{N,drift}$ can be deduced by conceptually forming the product of the $\mathcal{E}$ vs. $x$ dependence sketched in part c) and the $n$ vs. $x$ dependence sketched in part e). Under equilibrium conditions, $J_N = J_{N,drift} + J_{N,diff} = 0$ thus $J_{N,diff} = -J_{N,drift}$.

<diagram a>



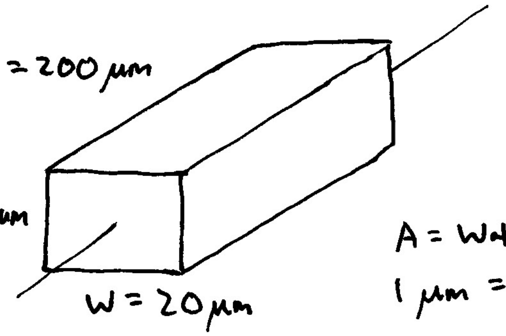

<diagram d>



(final exam spring 2007 problem 2)

6.

intrinsic silicon $T = 300K$




$A = W \cdot H$

$1\ \mu m = 10^{-4}\ cm$

a) resistance $R = \dfrac{\rho L}{A}$

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

$n = p = n_i = 1.1 \times 10^{10}\ cm^{-3}$ $\quad \mu_n \approx 1358\ cm^2/V\cdot sec \quad \mu_p \approx 461\ cm^2/V\cdot sec$

$$\rho = \frac{1}{1.6\times10^{-19}\,(1358 \cdot 1.1\times10^{10} + 461 \cdot 1.1\times10^{10})} = 3.124 \times 10^5\ \Omega cm$$

$$R = \frac{(3.124\times10^5) \cdot 0.02\ cm}{0.002 \cdot 0.002\ cm^2} = 1.56 \times 10^9\ \Omega = 1.56\ G\Omega$$

b) The fastest-changing, and therefore determining, parameter under changing temperatures is the intrinsic carrier concentration $n_i$, which increases with temperature (more thermal energy enables increased carrier generation).

Resistivity is inversely proportional to $n_i$ ($\doteq n = p$ in intrinsic Si), so it will <u>decrease</u> with increasing temperature. Resistance will do the same.

Heating a metal resistor usually increases its resistance;

metals are already flush with carriers, which experience resistance by scattering off ions, so higher temperatures only impede their progress more.

c) $\rho = \frac{1}{q(\mu_n + \mu_p) n_i}$

$n_i \approx \sqrt{N_c N_v}\, e^{-E_g/2kT}$

Now $\mu_n, \mu_p, N_c, N_v$ all depend on temperature, but they have a much weaker dependence than $e^{-E_g/kT}$

$\therefore$ Ignore these lesser factors

$\rho \propto e^{E_g/2kT}$

$\frac{d\rho}{dT} \propto e^{E_g/2kT} \frac{E_g}{2k}(-T^{-2})$

$\frac{d\rho}{dT} = \rho \frac{-E_g}{2kT^2}$

$\frac{\frac{d\rho}{dT}}{\rho} = \frac{-E_g}{2kT^2} = \frac{-1.1eV}{2(.026eV)(300K)}$

$$\boxed{\frac{\left(\frac{d\rho}{dT}\right)}{\rho} = .07/K = 7\%/K}$$