Home Work # 4 Solutions EE482-W 2011

1) The material is p-type silicon

$\rho = 1\ \Omega\text{-cm}$ $N_t = 10^{12}\ cm^{-3}$ $E_i - E_t = 0.2eV$

$\sigma_n = \sigma_p = 10^{-15}\ cm^2$ $V_{thn} = 10^7\ cms^{-1}$ $V_{thp} = 6 \times 10^6\ cms^{-1}$

$T = 300K$

a) Need to find the carrier conc. during irradiation, i.e. we need to know both the generated conc. and the "baseline" conc.

To find the "baseline", we can use the resistivity to look up the doping level. P. 5 in notes $\rightarrow \underline{N_a = 1.5 \times 10^{16}\ cm^{-3}}$

$G_L = 10^{18}\ cm^{-3}s^{-1} \rightarrow$ can assume low level injection

$$\tau_n = \frac{1}{V_{thp}\sigma_p N_t} = \frac{1}{(10^7\ cms^{-1})(10^{-15}cm^2)(10^{12}cm^{-3})} = \underline{\underline{100\mu s}}$$

$$G_L = \frac{\Delta n}{\tau_n} \Rightarrow \Delta n = G_L \tau_n = 10^{18}\ cm^{-3}s^{-1} \times 100\mu s = \underline{\underline{10^{14}\ cm^{-3}}}$$

$\Delta P = \Delta n = 10^{14}\ cm^{-3} \ll N_A$, so the LLI assumption was $\underline{\text{fine}}$.

$$\Longrightarrow \begin{cases} n = n_o + \Delta n \simeq \underline{\underline{10^{14}}}\ cm^{-3} \\ P = P_o + \Delta n = (1.5 \times 10^{16} + 10^{14})cm^{-3} \simeq 1.5 \times 10^{16}\ cm^{-3} \end{cases}$$

1 (b) $G_L = 10^{24}\ cm^{-3} s^{-1} \longrightarrow$ Can not assume L.L.I

Assuming very High level injection $\Longrightarrow \Delta n = \Delta p >> n_0, p_0$

$$G_L = \frac{(p_0+\Delta p)(n_0+\Delta n) - n_0 p_0}{\tau_n (p_0+\Delta p+p_1) + \tau_p (n_0+\Delta n+n_1)}$$

$$n_1 = n_i \exp\left(\frac{E_t - E_i}{kT}\right) \qquad p_1 = n_i \exp\left(\frac{E_i - E_t}{kT}\right)$$

$$\Longrightarrow G_L \simeq \frac{\Delta p^2}{\Delta p(\tau_n+\tau_p)} = \frac{\Delta P}{\tau_n+\tau_p}$$

$$\tau_p = \frac{1}{v_{thp}\, \sigma_p\, N_t} = 167\,\mu s$$

$$\Longrightarrow \Delta P = \Delta n = G_L(\tau_n+\tau_p) = (10^{24}\ cm^{-3} s^{-1})(100+167)\mu s$$

$$= \underline{2.67 \times 10^{20}\ cm^{-3}}$$

$$\Longrightarrow n \simeq p \simeq \Delta n \simeq \Delta P = \underline{2.67 \times 10^{20}}\ cm^{-3}$$

(*) And high level injection assumption was correct.

1 (c) Equation (28) from note becomes

$$R = \frac{pn - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$$n_1 = n_i \exp\left(\frac{E_i - E_t}{kT}\right) = (10^{10}\,cm^{-3})\left(\exp\left(\frac{-0.1}{25\times10^{-3}}\right)\right)$$

$$= 1.8 \times 10^{8}\ cm^{-3}$$

$$p_1 = (10^{10}\,cm^{-3})\left(\exp\left(\frac{+0.1}{25\times10^{-3}}\right)\right) = 5.5\times10^{11}\ cm^{-3}$$

$n \ll n_0$

$$\Rightarrow R = \frac{-n_i^2}{\tau_p n_1 + \tau_n(p_0+p_1)}$$

$$= \frac{-10^{+20}\ cm^{-6}}{(167\mu s)(1.8\times10^{8}\ cm^{-3}) + (100\mu s)(1.5\times10^{16}\,cm^{-3} + 5.5\times10^{11}\,cm^{-3})}$$

$$= \underline{6.66\times10^{7}\ cm^{-3}s^{-1}}$$

2) P-type Silicon $N_a = 10^{17} cm^{-3}$

$600\mu m = 600 \times 10^{-4} cm = 0.06 cm$ thick

$G_L = 10^{18} cm^{-3} s^{-1}$ (uniform)

S = Recombination velocity @ top and bottom surfaces $S = 10^3 cm$

$\tau_n = 10\mu s$ $\tau_p = 16\mu s$

a) Given diffusion approximation is true $\Rightarrow$ ignore minority drift current.

- This is also a hint to use minority carriers to solve for this.

- $\Delta n = \Delta p \rightarrow$ So solving Δn would give Δp.

assuming this is low level injection, at steady state, using equation (36)

$$\underset{\text{Diffusion}}{\underbrace{D_n \frac{\partial^2 \Delta n}{\partial x^2}}} - \underset{\text{Recomb.}}{\underbrace{\frac{\Delta n}{\tau_n}}} + \underset{\text{Generation (No drift term)}}{\underbrace{G_L}} = 0$$

$$\Rightarrow \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{D_n \tau_n} + \frac{G_L}{D_n} = 0$$

Let $\Delta n = Ae^{x/L_n} + Be^{-x/L_n}$ (General Solution)

where $L_n = \sqrt{D_n \tau_n} \Longrightarrow \dfrac{d\Delta n}{dx} = \dfrac{A}{L_n} e^{x/L_n} - \dfrac{B}{L_n} e^{-\frac{x}{L_n}}$

we need some boundary Conditions for A and B.

using flux at $x=0$: (or also the flux at $x = L/2$ which is zero.

$$D_n \left.\frac{d\Delta n}{dx}\right|_{x=0} = \frac{D_n}{L_n}(A-B) = SG_L\tau_n + S\Delta n\Big|_{x=0}$$

(Diffusion current) (General Solution)

$$= S(G_L\tau_n + A + B)$$

①

using flux at $x=L$:

$$-D_n \left.\frac{d\Delta n}{dx}\right|_{x=L} = \frac{-D_n}{L_n}\left(Ae^{L/L_n} - Be^{-\frac{L}{L_n}}\right) = S\left(G_L\tau_n + Ae^{L/L_n} + Be^{-\frac{L}{L_n}}\right)$$

②

we have two equations and two unknowns.

$$\Longrightarrow \begin{cases} A = -5.7 \times 10^{10}\ cm^{-3} \\ B = -4.1 \times 10^{12}\ cm^{-3} \end{cases}$$

$\boxed{N_a = 10^{17} cm^{-3} \Longrightarrow \mu_n = 800\ cm^2/Vs \Longrightarrow D_n = 20\ cm^2/s \Longrightarrow L_n = 0.014\ cm}$

Particular Solution : $\Delta n = C$ and Substituting gives:

$$C = G_L\tau_n = \underline{\underline{10^{13}\ cm^{-3}}}$$

So, overall:

$$\Longrightarrow \Delta n(x) = \left[10^{13} - 5.71 \times 10^{10} \times e^{\left(\frac{x}{L_n}\right)} - 4.1 \times 10^{12} e^{\left(-\frac{x}{L_n}\right)}\right] cm^{-3}$$

$\Delta n = \Delta p$

2-b) $\Delta n(0) = \underline{\underline{5.9 \times 10^{12}}}\ cm^{-3}$

for electrons: $n = n_0 + \Delta n = \frac{n_i^2}{N_a} + \Delta n = (10^3 + 5.9 \times 10^{12})\ cm^{-3}$

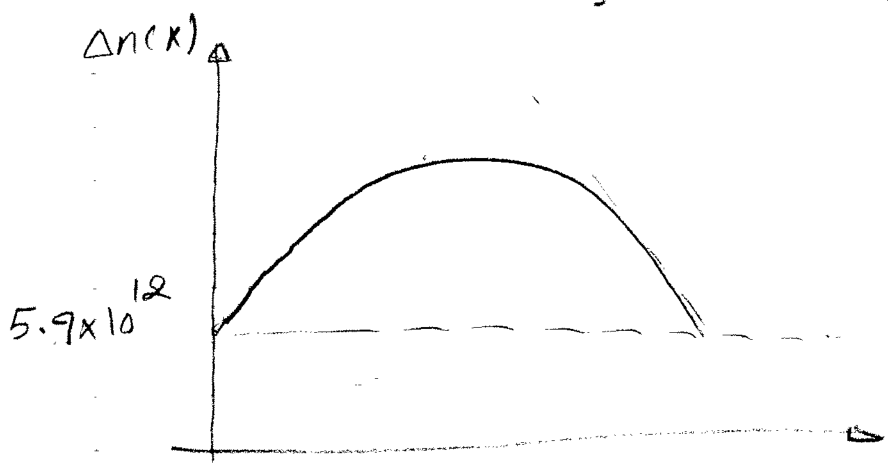
$\Longrightarrow n \simeq \underline{\underline{5.9 \times 10^{12}}}\ cm^{-3}$

for holes $\simeq \underline{\underline{P_o = 10^{17} cm^{-3}}}$

$$\frac{\text{top surface recomb. carriers}}{\text{all light generated carriers}} \times 100\% = \frac{\overbrace{10^3\ cm/s}^{S} \times \overbrace{5.9 \times 10^{12}}^{\Delta n(0)}\ cm^{-3}}{(10^{18}\ cm^{-3}/s)(600 \mu m)}$$

$$= \frac{5.9 \times 10^{15}\ cm^{-2}/s}{600 \times 10^{-4} \times 10^{18}\ cm^{2}/s} \times 100 = \underline{\underline{9.8\ \%}}$$

(And because of <u>symmetry</u> this ratio is <u>the same</u> at the bottom)



$$\underbrace{}_{}^{①} \qquad \underbrace{}_{}^{②}$$

2c) $J_n = J_p \Longrightarrow \underbrace{J_{n(drift)} + J_{n(diff)}}_{①} = \underbrace{J_{p(drift)} + J_{p(diff)}}_{②}$

$$J_n(Diff) = qD_n \frac{\partial \Delta n}{\partial x} = q\frac{D_n}{L_n}\left(Ae^{x/L_n} - Be^{-x/L_n}\right)$$

$$\xRightarrow{@\, x=0} J_n(diff) = q\frac{D_n}{L_n}(A-B) = q\frac{D_n}{L_n} \times 4.44 \times 10^{12}$$

$$J_p(diff) = -q\frac{D_p}{L_n}(A-B) = -q\frac{D_p}{L_n} \times 4.1 \times 10^{12}$$

$$J_p(drift) = q\mu_p p\mathcal{E} = q \times 10^{17}\,cm^{-3} \times 250\,\frac{cm^2}{VS} \times \mathcal{E}$$

$$① \simeq \cancel{q}\frac{D_n}{L_n} \times 4.1 \times 10^{12} = ② = -\cancel{q}\frac{D_p}{L_n} \times 4.1 \times 10^{12} + q \times 25 \times 10^{18} \times \mathcal{E}$$

$$\Longrightarrow \left(\frac{D_n + D_p}{L_n}\right) \times 4.1 \times 10^{12} = 25 \times 10^{18}\,\mathcal{E}$$

$$\frac{26.25}{0.014} \times 4.1 \times 10^{12} = 25 \times 10^{18}\,\mathcal{E}$$

$$\Longrightarrow \mathcal{E} = 3.1 \times 10^{-4}\ V/cm$$

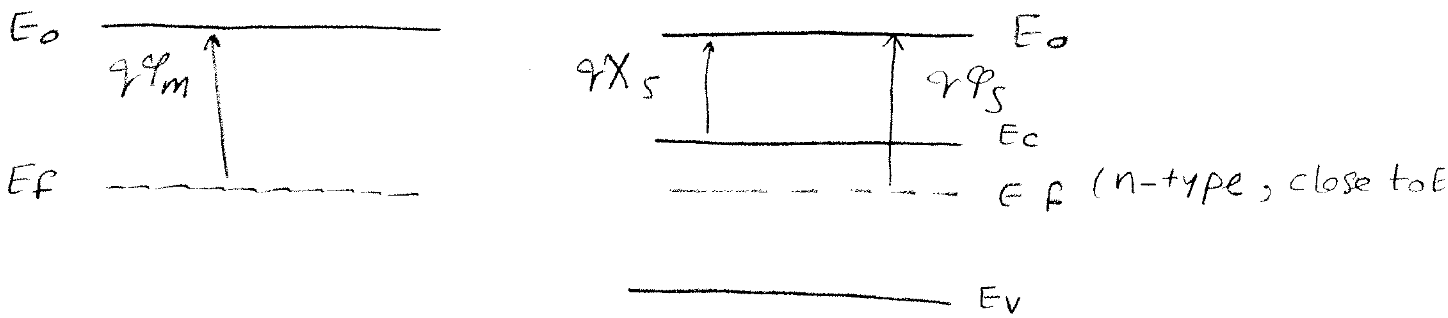
$$\Longrightarrow J_n(drift) = q\mu_n n\mathcal{E} = q \times 800\,\frac{cm^2}{VS} \times 3.1 \times 10^{-4}\,\frac{V}{cm} \times 10^{12}\,cm^{-3}$$

$$= q \times 2.46 \times 10^{11}\,\frac{cm^{-2}}{S} \ll J_n(diffusion) \Longrightarrow$$ Diffusion Approx. is Valid

3. $N_d = 10^{17} cm^{-3}$, $k_{Si}/\epsilon_{Si} = 11.7$, metal: Al: $q\varphi_m = 4.1eV$

Si, $q\chi_s = 4.05eV$

a) Ignoring Surface States, need to find φ_s:



We only need to consider majority carriers in metal-

-Semiconductor contacts.

$\varphi_s \Longrightarrow$ need to find E_f location:

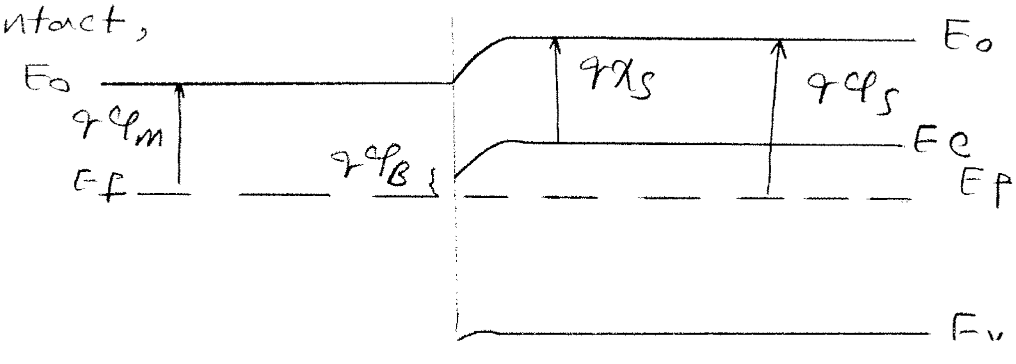
$$E_f = E_C - kT\ln\left(\frac{N_C}{N_d}\right) = E_C - 25meV\ln\left(\frac{2.8\times10^{19}}{10^{17}}\right)$$

$$= \underline{\underline{E_C - 0.141eV}}$$

From the diagram, we can see that

$$q\varphi_s = q\chi_s + E_c - E_f = 4.05ev + 0.141ev = \underline{\underline{4.19eV}}$$

Once in contact,



$q\varphi_B = q\varphi_m - q\chi_S = \underline{\underline{0.05\,eV}}$ → defined as the barrier for majority carriers from metal to semiconducto

$q\varphi_i = q\varphi_B - (E_C - E_f) =$

$= 0.05\,eV - 0.141\,eV = -\underline{\underline{0.091\,eV}}$ → barrier for majority carriers from semi-

-conductor to metal

The contact is <u>OHMIC</u>. The barrier is small @ 0.05eV

Given that $n \propto n_0 \exp\left(-\frac{q\varphi_i}{KT}\right) \Rightarrow$

we have charge accumulation $\Rightarrow$

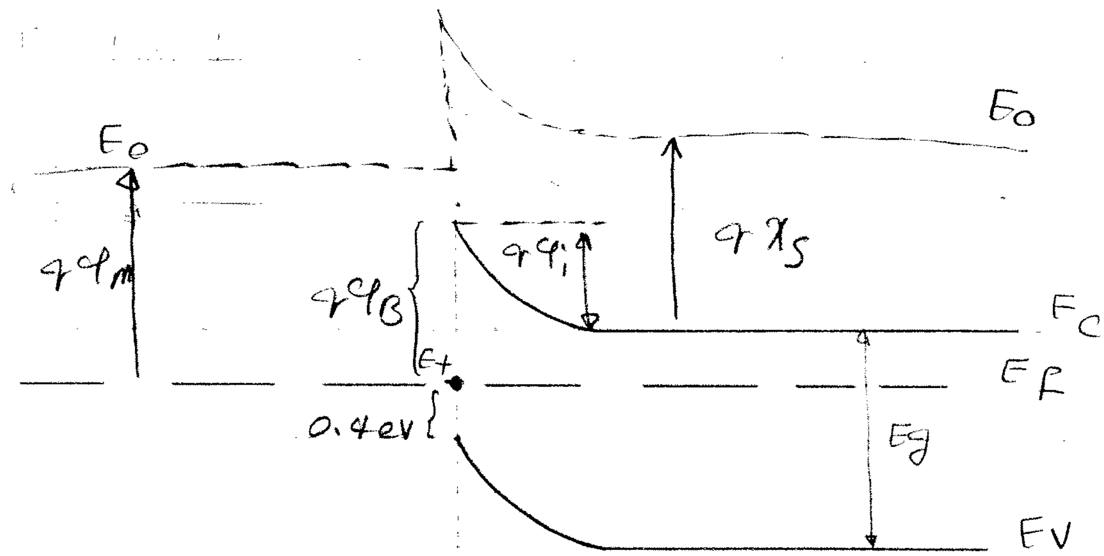
Metal has a large amount of carriers and the surface is accumulated $\Rightarrow$ lots of them would easily go through.

3 b) This time, very large number of surface States @ 0.4eV above E_V.

Surface states are effectively "trap level".

In large number, they "Pin" the Fermi level to the trap level.

The band diagram is modified:



$$q\varphi_B = E_g - 0.4\,eV = (1.12 - 0.4)\,eV = \underline{0.12\,eV}$$

$$q\varphi_i = q\varphi_B - (E_C - E_F) = (0.12 - 0.141)\,eV = \underline{0.579e}$$

It is rectifying because there is a barrier for electrons in metal to get in the semiconductor.

We can also check if tunneling can happen:

Metal - Semiconductor Junction

$$\varphi_i = \frac{1}{2} X_d \, |E_{max}| = \frac{1}{2} \frac{q N_d}{K \epsilon_o} X_d^2$$

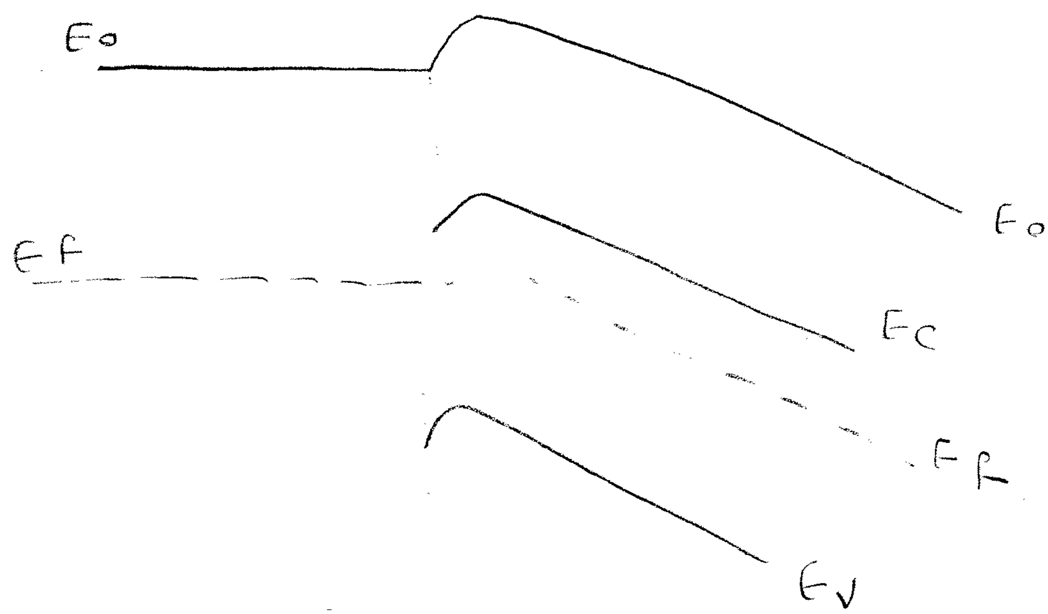
$$\Longrightarrow X_d = \sqrt{\frac{2K\epsilon_o \varphi_i}{q N_d}} = \underline{86.6\,nm}$$

$X_d >> 50\,A^\circ \Longrightarrow$ tunneling would not happen.

$\Longrightarrow$ The contact is <u>rectifying</u>

3-c) 0.2V bias applied to both cases.
(on the semiconductor relative to metal)

(i) case ① → no depletion region → voltage dropped across semiconductor → bias on semiconductor is higher $\bar{e}$ potential.



(ii) case ②, barrier height increases voltage drop across X_d.