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1(a) $N_a = 10^{16}\,cm^{-3}$ $N_d = 0$, $n_i = 1.5\times10^{10}\,cm^{-3}$

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a-N_d}{2}\right)^2 + n_i^2} = \frac{N_a}{2} + \sqrt{\frac{N_a^2}{4}+n_i^2} = 10^{16}\,cm^{-3}$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^{4}\,cm^{-3}$$

$$D_n\frac{\partial^2(\delta n)}{\partial x^2} + \mu_n E\frac{\partial(\delta n)}{\partial x} + g' - \frac{\delta n}{\tau_{n0}} = \frac{\partial(\delta n)}{\partial t} \Rightarrow$$

Uniformly doped: $\frac{\partial(\delta n)}{\partial x} = 0$, excess carrier uniformly generated: $D_n\frac{\partial^2(\delta n)}{\partial x^2} = 0$

$g' - \frac{\delta n}{\tau_{n0}} = \frac{\partial(\delta n)}{\partial t}$ Homogeneous: $\delta n = Ae^{-\frac{t}{\tau_{n0}}}$ particular: $\delta n = g'\tau_{n0}$

$\delta n = g'\tau_{n0} + Ae^{-\frac{t}{\tau_{n0}}}$ $t=0$, $\delta n = 0 \Rightarrow A + g'\tau_{n0} = 0 \Rightarrow A = -g'\tau_{n0} \Rightarrow \delta n = g'\tau_{n0}(1-e^{-\frac{t}{\tau_{n0}}})$

$g' = 8\times10^{20}\,cm^{-3}\cdot s^{-1}$ $\tau_{n0} = 5\times10^{-7}s$

$\delta n = 4\times10^{14}(1-e^{-2\times10^6 t})$

$\sigma = e(\mu_n n + \mu_p p) = e\mu_n n_0 + e\mu_p p_0 + e(\mu_n+\mu_p)\delta n \approx e\mu_p p_0 + e(\mu_n+\mu_p)\delta n$

$\mu_n = 900\,cm^2/V\cdot s$, $\mu_p = 380\,cm^2/V\cdot s$

$\sigma = 0.691 - 0.0820e^{-2\times10^6 t}$ $(\Omega\cdot cm)^{-1}$

$= 0.609 + 0.0820(1-e^{-2\times10^6 t})$ $(\Omega\cdot cm)^{-1}$ $(t>0)$

(b) (i) $t=0$ $\sigma = 0.609\,(\Omega\cdot cm)^{-1}$

(ii) $t=\infty$ $\sigma = 0.691\,(\Omega\cdot cm)^{-1}$

2. (a) $0 \le t \le 2\times10^{-6}s$

$$D_n\frac{\partial^2(\delta n)}{\partial x^2} + \mu_n E\frac{\partial(\delta n)}{\partial x} + g' - \frac{\delta n}{\tau_{n0}} = \frac{\partial(\delta n)}{\partial t}$$

$D_n\frac{\partial^2(\delta n)}{\partial x^2} = 0$ $\mu_n E\frac{\partial(\delta n)}{\partial x} = 0$ $g' = 0$ $\frac{\partial(\delta n)}{\partial t} + \frac{\delta n}{\tau_{n0}} = 0 \Rightarrow \delta n = Ae^{-\frac{t}{\tau_{n0}}}$

$g' = 10^{21}\,cm^{-3}\cdot s^{-1}$ $t=0$ $\delta n = g'\tau_{n0} = A$ $\Rightarrow \delta n = g'\tau_{n0}e^{-\frac{t}{\tau_{n0}}}$

$\tau_{n0} = 5\times10^{-7}s$

$\delta n = 5\times10^{14}e^{-2\times10^6 t}$ cm^{-3}

$\rightarrow 2\times10^{-6}s$ $\delta n = Ae^{-\frac{t-2\times10^{-6}}{\tau_{n0}}} + B$ $t=\infty$ $\delta n = g'\tau_{n0} = B = 5\times10^{14}\,cm^{-3}$

$t = 2\times10^{-6}s$, $\delta n = A + 5\times10^{14} = 9.158\times10^{12}\,cm^{-3} \Rightarrow A = -4.908\times10^{14}$

$\delta n = -4.908\times10^{14}e^{-2\times10^6(t-2\times10^{-6})} + 5\times10^{14}$

$= -4.908\times10^{14}e^{-2\times10^6 t + 4} + 5\times10^{14}$

$$\delta n = \begin{cases} 5\times10^{14}e^{-2\times10^6 t}, & 0 \le t \le 2\times10^{-6}s \\ -4.908\times10^{14}e^{-2\times10^6 t+4} + 5\times10^{14}, & t > 2\times10^{-6}s \end{cases} \quad (cm^{-3})$$

(b) From (a), we have

(i) $t=0$ $\delta n = 5\times 10^{14}\ cm^{-3}$

(ii) $t = 2\times 10^{-6}$ $\delta n = 9.158\times 10^{12}\ cm^{-3}$

(iii) $t=\infty$ $\delta n = 5\times 10^{10}\ cm^{-3}$

(c) See attached pages

3. Steady-state $\frac{\partial \delta p}{\partial t} = 0$ $E=0$ minority carrier lifetime is infinite: $\frac{\delta p}{\tau_{p0}} = 0$

Thus, $D_p \frac{\partial^2(\delta p)}{\partial x^2} + g' = 0$ $g' = G_0'$. $-L<x<+L$

$D_p\frac{\partial^2(\delta p)}{\partial x^2} + G_0' = 0 \Rightarrow \frac{\partial^2(\delta p)}{\partial x^2} = -\frac{G_0'}{D_p}$,

Solving the ODE, general solution, $\delta p = -\frac{G_0'}{2D_p}x^2 + C_1 x + C_2$

when $-3L \le x \le -L$, $L \le x \le 3L$, $g' = 0$ $D_p\frac{\partial^2(\delta p)}{\partial x^2} = 0$ $\Rightarrow \delta p = C_3 x + C_4$ $(-3L \le x \le -L)$

$\delta p = C_5 x + C_6$ $(L \le x \le 3L)$

$\delta p(-3L) = \delta p(3L) = 0$

$\Rightarrow -3LC_3 + C_4 = 3LC_5 + C_6 = 0$

BC: $\delta p(L) = -\frac{G_0'}{2D_p}L^2 + C_1 L + C_2 = C_5 L + C_6$

$\delta p(-L) = -\frac{G_0'}{2D_p}L^2 - C_1 L + C_2 = -C_3 L + C_4$

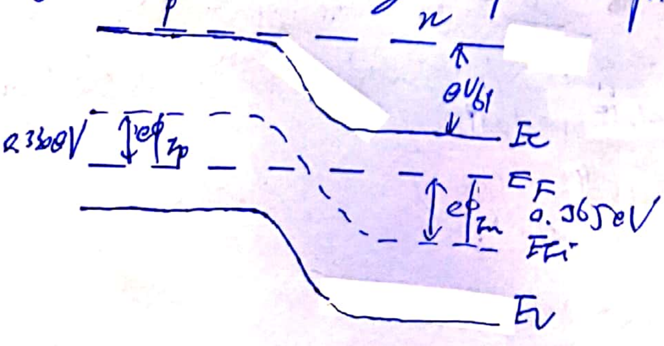
continuous: $\frac{\partial(\delta p(L))}{\partial x} = -\frac{G_0'}{D_p}L + C_1 = C_5$, $\frac{\partial(\delta p(-L))}{\partial x} = \frac{G_0'}{D_p}L + C_1 = C_3$

Solving the equations, $C_1 = 0$, $C_4 = C_6 = \frac{3G_0'}{D_p}L^2$, $C_3 = \frac{G_0'}{D_p}L$, $C_5 = -\frac{G_0'}{D_p}L$

$C_2 = \frac{5G_0'}{2D_p}L^2$

Therefore, $\delta p(x) = \begin{cases} \frac{G_0'}{D_p}x + \frac{3G_0'}{D_p}L^2, & -3L \le x < -L \\ -\frac{G_0'}{2D_p}x^2 + \frac{5G_0'}{2D_p}L^2, & -L \le x \le L \\ -\frac{G_0'}{D_p}x + 3\frac{G_0'}{D_p}L^2, & L < x \le 3L \end{cases}$

4. (a) The energy-band diagram for the pn junction:



(b) p-region:

$$N_a = n_i \exp\left(\frac{E_{Fi}-E_F}{kT}\right)$$
$$= 1.5\times10^{10} \exp\left(\frac{0.330\,e}{300k}\right)$$
$$= 5.25\times10^{15}\ cm^{-3}$$

n-region:

$$N_d = n_i \exp\left(\frac{E_F-E_{Fi}}{kT}\right)$$
$$= 1.5\times10^{10} \exp\left(\frac{0.365\,e}{300k}\right)$$
$$= 2.03\times10^{16}\ cm^{-3}$$

(c) $V_{bi} = |\varphi_{Fn}| + |\varphi_{Fp}|$
$$= 0.330 + 0.365$$
$$= 0.695\,V$$

5.(a) (i) $x_n = \sqrt{\frac{2\varepsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]}$ $\quad x_p = \sqrt{\frac{2\varepsilon_s V_{bi}}{e}\left(\frac{N_d}{N_a}\right)\left(\frac{1}{N_a+N_d}\right)}$

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_s V_{bi}}{e}\,\frac{N_a+N_d}{N_a N_d}} \qquad x_n = 25\%\,W \Rightarrow N_d = 3N_a$$

$$V_{bi} = V_t \ln\frac{N_a N_d}{n_i^2} = \frac{kT}{e}\ln\frac{N_a N_d}{n_i^2} \Rightarrow N_a N_d = n_i^2 \exp\left(\frac{eV_{bi}}{kT}\right) \quad , n_i = 1.5\times10^{10}\ cm^{-3},\ V_{bi} = 0.710\,V$$

$$N_a = \frac{n_i}{\sqrt{3}}\sqrt{\exp\left(\frac{eV_{bi}}{kT}\right)} = \frac{n_i}{\sqrt{3}}\exp\left(\frac{eV_{bi}}{2kT}\right) = 7.97\times10^{15}\ cm^{-3}$$

(ii) $N_d = \sqrt{3}\,n_i \exp\left(\frac{eV_{bi}}{2kT}\right) = 2.39\times10^{16}\ cm^{-3}$

$\boxed{\varepsilon_s = 11.7\,\varepsilon_0}$

(iii) $x_n = \sqrt{\frac{2\varepsilon_s V_{bi}}{3e}\,\frac{\sqrt{3}}{n_i}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = \sqrt{\frac{\sqrt{3}\,\varepsilon_s V_{bi}}{6en_i}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = 9.800\times10^{-6}\ cm$

(iv) $x_p = \sqrt{\frac{6\varepsilon_s V_{bi}}{e}\,\frac{\sqrt{3}}{4n_i}\exp\left(-\frac{eV_{bi}}{2kT}\right)} = \sqrt{\frac{3\sqrt{3}\,\varepsilon_s V_{bi}}{2en_i}\exp\left(-\frac{eV_{bi}}{2kT}\right)} = 2.940\times10^{-5}\ cm$

(v) $|E_{max}| = \frac{eN_d x_n}{\varepsilon_s} = \sqrt{3}\,en_i\exp\left(\frac{eV_{bi}}{2kT}\right)\sqrt{\frac{\sqrt{3}V_{bi}}{6n_i e\varepsilon_s}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = \sqrt{\frac{\sqrt{3}\,V_{bi}en_i}{2\varepsilon_s}\exp\left(\frac{eV_{bi}}{2kT}\right)}$

$$= 3.62\times10^{4}\ V/cm$$

(b) (i) $n_i = 1.8\times10^{6}\ cm^{-3}$, $V_{bi} = 1.180\,V$

$$N_a = \frac{n_i}{\sqrt{3}}\exp\left(\frac{eV_{bi}}{2kT}\right) = 8.478\times10^{15}\ cm^{-3}$$

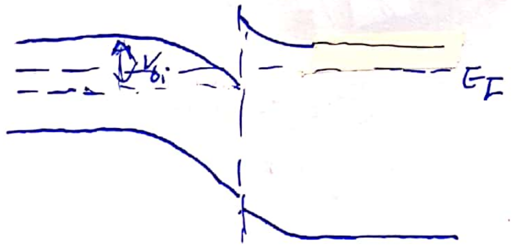
(ii) $N_d = \sqrt{3}\,n_i\exp\left(\frac{eV_{bi}}{2kT}\right) = 2.543\times10^{16}\ cm^{-3}$ $\quad \boxed{\varepsilon_s = 13.1\,\varepsilon_0}$

(iii) $x_n = \sqrt{\frac{\sqrt{3}\,\varepsilon_s V_{bi}}{6en_i}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = 1.296\times10^{-5}\ cm$

(iv) $x_p = \sqrt{\frac{3\sqrt{3}\,\varepsilon_s V_{bi}}{6en_i}\exp\left(-\frac{eV_{bi}}{2kT}\right)} = 3.888\times10^{-5}\ cm$

(v) $|E_{max}| = \sqrt{\frac{\sqrt{3}\,V_{bi}en_i}{2\varepsilon_s}\exp\left(\frac{eV_{bi}}{2kT}\right)} = 4.552\times10^{4}\ V/cm$

6. (a)



(b) $n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$ $n_{01} = N_{d1} = 10^{16}\ cm^{-3}$
$n_{02} = N_{d2} = 10^{15}\ cm^{-3}$

$E_{F1} - E_{Fi1} = kT \ln\left(\frac{n_{01}}{n_i}\right) = 5.55\times10^{-20} J = 0.347 eV$

$E_{F2} - E_{Fi2} = kT \ln\left(\frac{n_{02}}{n_i}\right) = 4.60\times10^{-20} J = 0.287 eV$

$V_{bi} = \frac{\Delta(E_F - E_{Fi})}{e} = 0.0595 V$

(c) The charge on the left of the junction is equal to the charge on the right of the junction
with concentration $10^{-16} cm^{-3}$ with concentration $10^{-15} cm^{-3}$
There are carriers in the depletion region decreasing from left to right
from $10^{-16} cm^{-3}$ to $10^{-15} cm^{-3}$

7. (a) $V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) \Rightarrow N_a N_d = n_i^2 \exp\left(\frac{eV_{bi}}{kT}\right)$
$= 0.740 V$ $= 80 N_a^2$

$N_a = \frac{n_i}{4\sqrt{5}} \exp\left(\frac{eV_{bi}}{2kT}\right) = 2.76\times10^{15}\ cm^{-3}$

$N_d = 4\sqrt{5} n_i \exp\left(\frac{eV_{bi}}{2kT}\right) = 2.20\times10^{17}\ cm^{-3}$

(b) $x_p = \sqrt{\frac{2\epsilon_s(V_{bi}+V_R)4\sqrt{5}}{80\, e n_i\, 81}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = \sqrt{\frac{\sqrt{5}\epsilon_s(V_{bi}+V_R)}{810\, e n_i}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = 2.79\times10^{-6} m$

$x_n = \sqrt{\frac{640\sqrt{5}\epsilon_s(V_{bi}+V_R)}{81 e n_i}\exp\left(\frac{-eV_{bi}}{2kT}\right)} = 2.23\times10^{-4} m$

(c) $|E_{max}| = \frac{2(V_{bi}+V_R)}{W} = 2\times10.74 \times \sqrt{\frac{e}{2\epsilon_s V_{bi}}\frac{N_a N_d}{N_a+N_d}} = 21.48\sqrt{\frac{2\sqrt{5} e n_i}{81\epsilon_s V_{bi}}}\exp\left(\frac{eV_{bi}}{4kT}\right)$

$= 9.51\times10^{4} V/cm$

(d) $C' = \sqrt{\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}} = 4.59\times10^{-9} F/cm^2$

8. (a) $V_{bi} = \frac{kT}{e}\left(\frac{n_{n0}\cdot p_{p0}}{n_i^2}\right) = 0.58V$, $n_{n0} = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d-N_a}{2}\right)^2 + n_i^2} = 10^{14} cm^{-3}$

$p_{p0} = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a-N_d}{2}\right)^2 + n_i^2} = 5\times10^{15} cm^{-3}$

(b) $x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{e}\frac{N_a}{N_d}\frac{1}{N_a+N_d}} = 2.66\times10^{-4} cm$

$x_p = \sqrt{\frac{2\epsilon_s V_{bi}}{e}\frac{N_d}{N_a}\frac{1}{N_a+N_d}} = 5.32\times10^{-6} cm$

(c) $x_n = \sqrt{\frac{2\epsilon_s(V_{bi}+V_R)}{e}\frac{N_a}{N_d}\frac{1}{N_a+N_d}} = 3\times10^{-3} cm$

$V_R = \frac{x_n^2 e}{2\epsilon_s}\frac{N_d}{N_a}(N_a+N_d) - V_{bi} = 70.4 V$

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