HW#4 SOLUTION

Problem 6.10

(a) Reverse Biased - There is a deficit of minority carriers in the quasineutral immediately adjacent to the depletion region

(b) Low-level injection DOES prevail. As required for low-level injection

$$|\Delta n_p|_{max} \cong n_{po} << p_p \quad \text{for } x \le -x_p$$

$$|\Delta p_n|_{max} \cong p_{no} << n_n \quad \text{for } x \ge x_n$$

(C) Since we have low-level injection,

$$N_A \cong p_{po} \cong p_p = 10^{14}/cm^3$$

$$N_D \cong n_{no} \cong n_n = 10^{15}/cm^3$$

(d) Invoking the law of the junction,

$$n(-x_p)p(-x_p) = n_i^2 e^{qV_A/kT}$$

or

$$V_A = \frac{kT}{q} \ln\left[\frac{n(-x_p)p(-x_p)}{n_i^2}\right]$$

as deduced from Fig. P6.10,

$$n(-x_p) = 10^3/cm^3$$

$$p(-x_p) = 10^{14}/cm^3$$

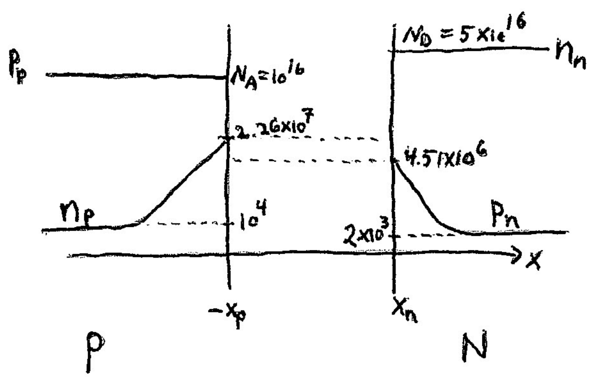
and

$$n_i = \sqrt{n(\infty)p(\infty)} = \sqrt{n(-\infty)p(-\infty)} = \sqrt{10^{20}} = 10^{10}/cm^3$$

The foregoing manipulation was necessary because the semiconductor fabricating the diode was not specified in the problem. Lastly, Substituting gives:

$$V_A = (0.0259)\ln\left[\frac{(10^3)(10^{14})}{10^{20}}\right] = \boxed{-0.18\,V = V_A}$$

2) (a) Forward Bias:



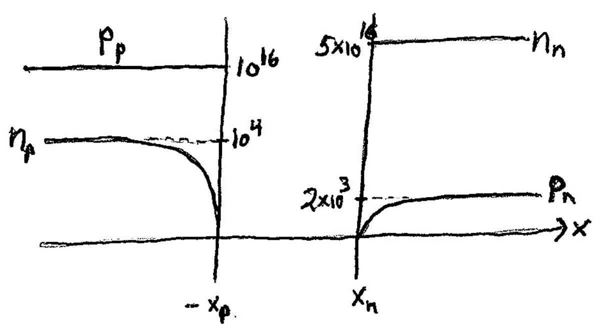
$$\frac{n_i^2}{N_A} = \frac{10^{20}}{10^{16}} = 10^4$$

$$\frac{n_i^2}{N_D} = \frac{10^{20}}{5\times10^{16}} = 2\times10^3$$

$$n_p(-x_p) = n_{po}\, e^{qV_A/kT} = (10^4)e^{(0.2/0.0259)}$$
$$= 2.26\times10^7$$

$$p_n(x_n) = p_{no}\, e^{qV_A/kT} = (2\times10^3)e^{0.2/0.0259}$$
$$= 4.51\times10^6$$

Reverse Bias:



(b) $D_p = \frac{kT\mu_p}{q}$ From the graph, $\mu_p = 378$ @ $N_D = 5\times10^{16}$

$= (0.0259)(378) = 9.79$

$L_p = \sqrt{D_p\tau_p} = \sqrt{9.79\cdot10^{-6}} = 0.00313\text{cm}$

$D_n = \frac{kT\mu_n}{q} = (0.0259)(1248)$ From the graph, $\mu_n = 1248$ @ $N_A = 10^{16}$

$= 32.32$

$L_n = \sqrt{D_n\tau_n} = \sqrt{32.32\cdot10^{-6}} = 0.00569\text{cm}$

$Q_p = qA\Delta p_n L_p = (1.6\times10^{-19})(1\text{cm}^2)(4.5\times10^6)(0.00313) = \boxed{2.26\times10^{-15}\text{C}}$

$\Delta p_n = \frac{n_i^2}{N_D}\left(e^{qV_A/kT} - 1\right) = 2\times10^3\left(e^{0.2/0.0259} - 1\right) = 4.5\times10^6$

$\Delta n_p = \frac{n_i^2}{N_A}\left(e^{qV_A/kT} - 1\right) = 10^4\left(e^{0.2/0.0259} - 1\right) = 2.256\times10^6$

$Q_n = qA\Delta n_p L_n = (-1.6\times10^{-19}\text{C})(1\text{cm}^2)(2.256\times10^6)(0.00569) = -2.054\times10^{-14}\text{C}$

$|Q_n| \neq |Q_p|$ because $N_D > N_A$, so $|Q_n| > |Q_p|$

(c) $J_o = qn_i^2\left[\frac{D_p}{N_D L_p} + \frac{D_n}{N_A L_n}\right] = (1.6\times10^{-19})(10^{20})\left[\frac{9.79}{5\times10^{16}\cdot0.00313} + \frac{32.32}{10^{16}\cdot0.00569}\right] = \boxed{1.639\times10^{-11}\,\text{A/cm}^2}$

3) (a) $V_A = -5V$ $I_{r-g} = \frac{-qAn_i}{2\tau_o} W$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = (0.0259)\ln\left(\frac{(5\times10^{16})(2\times10^{16})}{10^{20}}\right) = 0.775\,V$$

$$W = \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}-V_A)\right]^{1/2}$$

$$= \left[\frac{2(11.8)(8.85\times10^{-14})}{1.6\times10^{-19}}\left(\frac{5\times10^{16}+2\times10^{16}}{(5\times10^{16})(2\times10^{16})}\right)(0.775-(-5))\right]^{1/2}$$

$$W = 7.26\times10^{-5}\,cm$$

$$\tau_o = \frac{1}{2}\left(\tau_p e^{(E_T-E_i)/kT} + \tau_n e^{(E_i-E_T)/kT}\right) = \frac{1}{2}(\tau_n+\tau_p) = \frac{1}{2}(1\mu s + 1\mu s) = 1\mu s$$

$$I \approx I_{r-g} = \frac{-qAn_i}{2\tau_o} W$$ since reverse bias > few $\frac{kT}{q}$

$$= \frac{-(1.6\times10^{-19})(1\,cm^2)(10^{10})}{2(1\times10^{-6})}(7.26\times10^{-5})$$

$$\boxed{I = 5.81\times10^{-8}\,A}$$

This is due to generation in the depletion region.

(b) $$I_{leak} = \underbrace{qAn_i^2\left[\frac{D_p}{N_d L_p} + \frac{D_n}{N_a L_n}\right]\left[e^{qV_A/kT}-1\right]}_{I_{diff}} + \underbrace{\frac{-qAn_i}{2\tau_o}W}_{I_{r-g}}$$

I_{diff} would dominate if $\tau_o \gg W$ (making I_{r-g} small), or if the device has a narrow bandgap and a large n_i, so that n_i^2 dominates n_i, such as Germanium.

(c) For Si, $\mathcal{E}_{CR} = 4\times10^5$

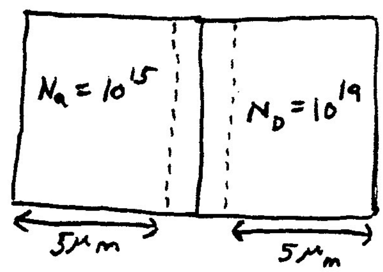
$$V_{BR} = \frac{K_s\varepsilon_o\mathcal{E}_{CR}^2}{2q}\,\frac{N_A+N_D}{N_A N_D} = \frac{(11.8)(8.85\times10^{-14})(4\times10^5)^2}{2(1.6\times10^{-19})}\cdot\frac{5\times10^{16}+2\times10^{16}}{5\times10^{16}\cdot 2\times10^{16}}$$

$$\boxed{V_{BR} = 36.55\,V}$$

(d) $$W_{BR} = \sqrt{\frac{2\varepsilon}{q}(V_{bi}-V_{BR})\frac{N_A+N_D}{N_A N_D}} = \sqrt{\frac{2(11.8)(8.85\times10^{-14})}{1.6\times10^{-19}}(0.775-(-36.55))\frac{(5\times10^{16}+2\times10^{16})}{5\times10^{16}\times2\times10^{16}}}$$

$$\boxed{W_{BR} = 1.847\times10^{-4}\,cm}$$

4)



$\mu_n = 1345$ @ $N_a = 10^{15}$

$\mu_p \approx 60$ @ $N_d = 10^{19}$

$D_n = \frac{kT}{q}\mu_n = (0.0259)(1345) = 34.84$

$L_n = \sqrt{D_n \tau_n} = \sqrt{(34.84)(1\mu s)} = 5.902$

$D_p = \frac{kT}{q}\mu_p = (0.0259)(60) = 1.554$

$L_p = \sqrt{D_p \tau_p} = \sqrt{(1.554)(10^{-6})} = 1.247 \times 10^{-3}$

Since $N_D >> N_A$, assume most of the voltage drop occurs on the p side of the diode.

$$\rho = \frac{1}{q\mu_p N_A} = \frac{1}{(1.6\times10^{-19})(60)(10^{15})} = 104.17\ \Omega\cdot cm$$

$$R = \frac{\rho l}{A} = \frac{(104.17)(5\mu m)}{A} = 5.21 \quad \Omega/A$$

$V = IR \Rightarrow 0.1V = I(5.21/A)$

$$I = qAn_i^2\left[\frac{D_p}{N_d L_p} + \frac{D_n}{N_a L_n}\right]\left[e^{qV_A/kT} - 1\right]$$

$$= (1.6\times10^{-19})A(10^{10})^2\left[\frac{1.554}{10^{19}(1.247\times10^{-3})} + \frac{34.84}{10^{15}(5.902)}\right]\left[e^{qV_A/kT} - 1\right]$$

$$I = (94.44)(A)\left[e^{qV_A/kT} - 1\right] \times 10^{-12}$$

$$0.1V = V = IR = (94.44\cancel{A})(\tfrac{5.21}{\cancel{A}})\left[e^{V_A/0.0259} - 1\right]\times10^{-12}$$

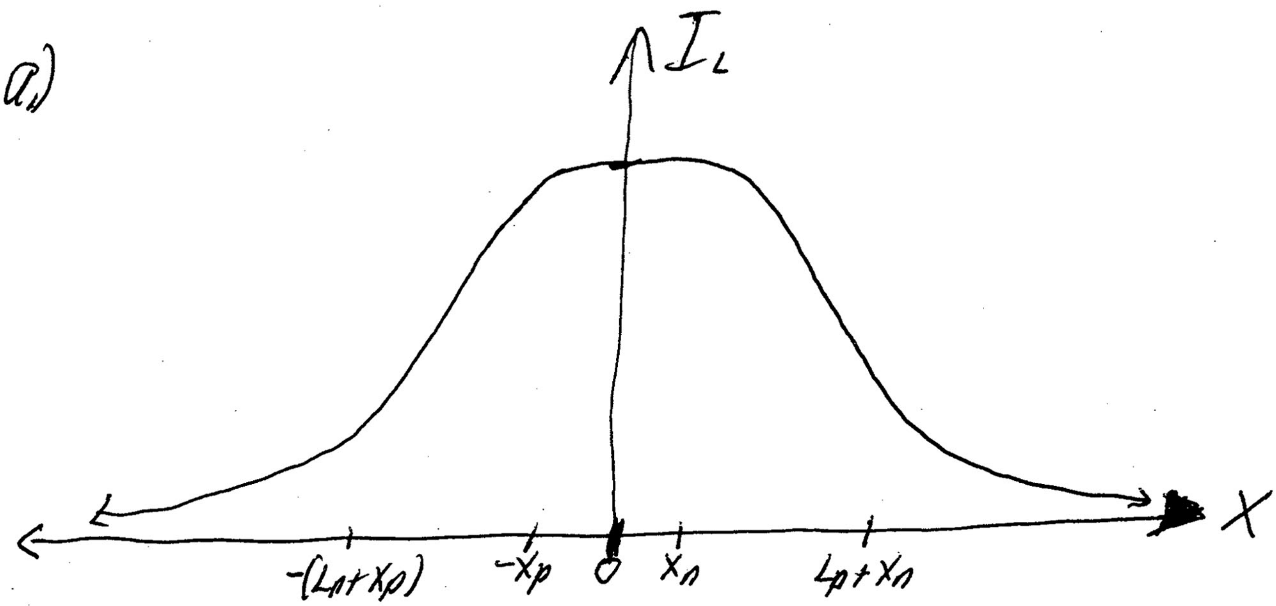
$$\Rightarrow e^{V_A/0.0259} - 1 = 2.033\times10^{8}$$

$$\Rightarrow V_A = \ln(2.033\times10^{8} + 1)(0.0259) = 0.495\ V$$

using this value, $J_{gen} \approx 9.76\times10^{-15} \sim 0$, so that term can be reasonably ignored in this case.

Problem 2, midterm exam # 2, spring 2007

5 a)



All Light absorbed in depletion region is useful photocurrent, Light outside depletion region produces minority carriers that may not be able to diffuse to the depletion region (and swept to their majority region) before recombination. The lengths for the diffusion process are $\sim L_n, L_p$

b) $I = \frac{q n_i}{2\tau_0} A W$ reverse bias no light

$I_L = q \underbrace{A G_L}_{\text{generated over a volume of } 1\mu m \times 1\mu m \times 10\mu m} \cancel{(W + L_n + L_p)}$ for uniform light across junction

For this device, the light dictates the volume, $\therefore A(W+L_n+L_p)$ is irrelevant

$$I_L = q\,G_L(1\mu m \times 1\mu m \times 10\mu m)$$

$$\boxed{I_L = .16\,pA}$$

light on

$$I = \frac{q n_i}{2\tau_0} A W \qquad W = \sqrt{\frac{2\epsilon_{si}}{q}\frac{N_A+N_D}{N_A N_D} V_{bi}}$$

$$V_{bi} = \frac{kT}{q}\ln\frac{N_a N_d}{n_i^2} = .71V$$

$$W = .43\,\mu m$$

$$\boxed{I_{OFF} = .38\,pA}$$

We assume here that V_A is not large enough to cause an enormous change from W's equilibrium value; without a value for V_A given, V_{bi} suffices to get an estimate.

The light is too narrow & dim to dominate! (But it can still be detected, of course.)