ECE 321, Electronics I — Quiz 2 (Fall 2015), pn Junction

Name Solution — Section ________

1. (25 points) The ideal Shockley diode equation is given by

$$I_D = qAn_i^2\left(\frac{D_P}{L_P N_D} + \frac{D_N}{L_N N_A}\right)\left(e^{V_A/V_T} - 1\right)$$

Calculate the built-in voltage V_{bi} and the diode current I_D for a 10^{-4} cm^2 silicon junction at room temperature under forward bias (V_A=0.5 V) where

$N_D=5\cdot10^{15}\ cm^{-3}$, $D_N=30\ cm^2\cdot s^{-1}$, $L_N=10\cdot10^{-4}$ cm, $N_A=1\cdot10^{17}\ cm^{-3}$, $D_P=12\ cm^2\cdot s^{-1}$, $L_P=15\cdot10^{-4}$ cm, $n_i=1\cdot10^{10}\ cm^{-3}$

$$V_{bi} = kT\ \ln\left(\frac{N_A N_D}{n_i^2}\right) = \boxed{0.731\ V}\quad (\text{using } V_T = 25\ mV)$$

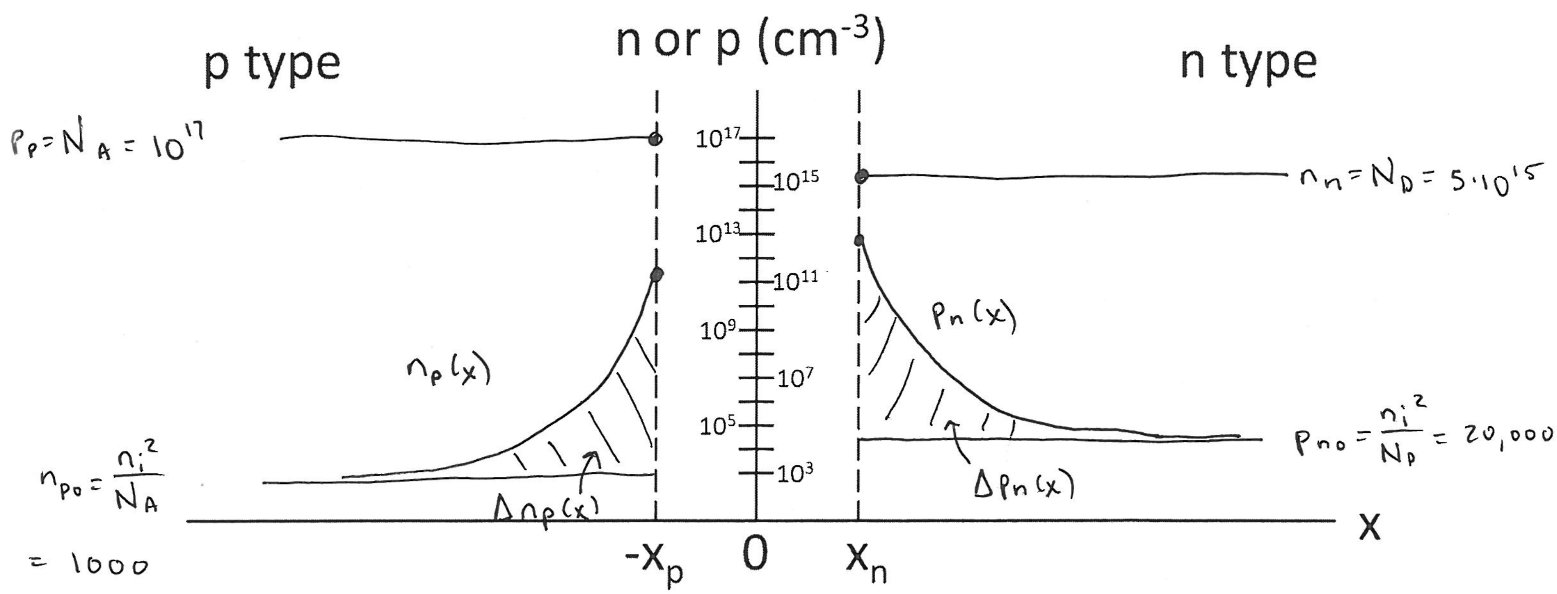
$$I_D = (1.6\cdot10^{-19} c)(10^{-4} cm^2)(10^{10} cm^{-3})^3\left(\frac{12\ cm^2/s}{15\cdot10^{-4} cm\cdot 5\cdot10^{15} cm^{-3}} + \frac{30\ cm^2/s}{10\cdot10^{-4} cm\cdot 10^{17} cm^{-3}}\right)\left(e^{0.5/0.025} - 1\right)$$

$$= \boxed{1.47\ \mu m}$$

2. (25 points) On the graph below and using the numbers from above under forward bias (V_A=~~0.7~~ 0.5 V) at 300 K, sketch $p_n(x)$, p_{no}, p_p, $n_p(x)$, n_{po}, and n_n at the appropriate values. Use V_T=25 mV. Remember the excess minority carriers at the edges of the depletion region are

$$\Delta p_n = p_{no}\left(e^{V_A/V_T} - 1\right) \text{ and } = 9.7\cdot10^{12}\ cm^{-3} \approx p_n(x_p)$$

$$\Delta n_p = n_{po}\left(e^{V_A/V_T} - 1\right) = 4.9\cdot10^{11}\ cm^{-3} \approx n_p(-x_n)$$



3. (35 points) Derive the ideal Shockley diode equation for I_D. Remember under steady state, the minority carrier diffusion equation for holes with boundary conditions is given by,

$$D_P \frac{d^2 \Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_p} = 0 \text{ where } \Delta p_n(\infty) = 0 \text{ and } \Delta p_n(x_n) = p_{no}\left(e^{V_A/V_T} - 1\right)$$

The diffusion current for holes J_P is given below. The diffusion current for electrons J_N follows the same process. The total current J is then the sum of these currents.

$$J_P = -qD_P \frac{d\Delta p_n}{dx} \text{ and } J = J_P + J_N = \frac{I_D}{A}$$

Also remember the minority carrier diffusion length for holes L_P is related to the diffusion constant D_P and minority carrier diffusion time τ_P through

$$L_P = \sqrt{D_P \tau_P}$$

Minority Carrier Diffusion Eq for holes $D_p \frac{d^2 \Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_p} = 0$

Boundary Conditions: $\Delta p_n(x \to \infty) = 0$; $\Delta p_n(x_n) = p_{no}\left(e^{V_A/nV_T} - 1\right)$

1. Solve the 2nd order diff eq
$\Delta p_n(x')\big|_{x'=0} = A_1 e^{-x/L_P} + A_2 e^{x/L_P}$
2. Solve for $A_{1,2}$ using boundary conditions
$\Delta p_n(\infty) = A_1 e^{-\infty} + A_2 e^{\infty}$ so $A_2 = 0$
$\Delta p_n(x'=0) = A_1 = p_{no}\left(e^{V_A/nV_T} - 1\right)$
3. Write the equation $\Delta p_n(x) = p_{no}\left(e^{V_A/nV_T} - 1\right) e^{-x/L_P}$
4. take derivative to find J_P
$J_P\big|_{x'=0} = -qD_P\, p_{no}\left(e^{V_A/nV_T} - 1\right) e^{-x/L_P} \times {-1}/L_P$
$= q\frac{D_P}{L_P} p_{no}\left(e^{V_A/nV_T} - 1\right)$ where $p_{no} = \frac{n_i^2}{N_D}$
5. $J_P = q\frac{D_P}{L_P N_D} n_i^2 \left(e^{V_A/nV_T} - 1\right)$
6. J_N is same process
$J_N = q\frac{D_N}{L_N N_D} n_i^2 \left(e^{V_A/nV_T} - 1\right)$
7. $J = J_P + J_N = \frac{I}{A}$
8. $I_D = qAn_i^2\left(\frac{D_P}{L_P N_D} + \frac{D_N}{L_N N_A}\right)\left(e^{V_A/nV_T} - 1\right)$

Q.E.D.

4. (15 points) Real diodes exhibit nonidealities particularly in the breakdown region. Describe in your own words the concept of "Avalanche". Use an energy band diagram to help convey your thoughts.

Electric field accelerates electrons in the depletion region to such a high energy it can create additional electron-hole pairs by breaking bonds creating a large reverse current