ECE 340 # Homework Solution #7 **Fall 2015**

1. An n-p Junction

(a). The intrinsic carrier concentration of Si at T = 300 K is: $n_i = 1.5\times10^{10}$ cm^{-3} (though $n_i = 1\times10^{10}$ is acceptable and those answers are marked in red-orange color)

n-side

Charge Neutrality: $n_0 + N_a^- = p_0 + N_d^+$

Assuming all donors are ionized, we can say $N_d^+ = 3\times10^{17}$ cm^{-3}. Since this is an n-type material, $N_a^- = 0$. Also, since the ionized donor level is far greater than n_i, we can safely assume that p_0 can be neglected, resulting in: $n_0 = 3\times10^{17}$ cm^{-3}.

Starting with the familiar equation relating the Fermi level to the carrier concentration:

$$n_0 = n_i \cdot e^{\frac{E_{fn}-E_i}{kT}} \tag{1.1}$$

And solving for E_{f_n} - E_i:

$$E_{f_n} - E_i = kT \cdot \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \cdot \ln\left(\frac{3\times10^{17}}{1.5\times10^{10}}\right) = \text{0.435 eV} \tag{1.2}$$

Or if using $n_i = 1\times10^{10}$:

$$E_{f_n} - E_i = kT \cdot \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \cdot \ln\left(\frac{3\times10^{17}}{1\times10^{10}}\right) = \text{0.446 eV} \tag{1.3}$$

p-side

Charge Neutrality: $n_0 + N_a^- = p_0 + N_d^+$

Assuming all donors are ionized, we can say $N_a^- = 4\times10^{16}$ cm^{-3}. Since this is a p-type material, $N_d^+ = 0$. Also, since the ionized acceptor level is far greater than n_i, we can safely assume that n_0 can be neglected, resulting in: $p_0 = 4\times10^{16}$ cm^{-3}.

Starting with the familiar equation relating the Fermi level to the carrier concentration:

$$p_0 = n_i \cdot e^{\frac{E_i-E_{fp}}{kT}} \tag{1.4}$$

And solving for E_i - E_{f_p}:

$$E_i - E_{f_p} = kT \cdot \ln\left(\frac{p_0}{n_i}\right) = 0.0259 \cdot \ln\left(\frac{4\times10^{16}}{1.5\times10^{10}}\right) = \text{0.383 eV} \tag{1.5}$$

Or if using $n_i = 1\times10^{10}$:

$$E_i - E_{f_p} = kT \cdot \ln\left(\frac{p_0}{n_i}\right) = 0.0259 \cdot \ln\left(\frac{4 \times 10^{16}}{1.5 \times 10^{10}}\right) = 0.394 \text{ eV} \tag{1.6}$$

Calculate contact potential V_0

There are multiple ways to calculate the contact potential:

$$qV_0 = (E_{f_n} - E_i) + (E_i - E_{f_p}) = 0.818 \text{ eV} \tag{1.7}$$

Or if using $n_i = 1 \times 10^{10}$:

$$qV_0 = (E_{f_n} - E_i) + (E_i - E_{f_p}) = 0.84 \text{ eV} \tag{1.8}$$

So:

$$\begin{aligned} qV_0 &= 0.818 \text{ eV} \\ V_0 &= 0.818 \text{ V} \end{aligned} \tag{1.9}$$

Or:

$$\begin{aligned} qV_0 &= 0.84 \text{ eV} \\ V_0 &= 0.84 \text{ V} \end{aligned} \tag{1.10}$$

Can also use*:

$$qV_0 = kT \ln\left(\frac{N_d N_a}{n_i^2}\right) = 0.0259 \cdot \ln\left(\frac{3 \times 10^{17} \cdot 4 \times 10^{16}}{2.25 \times 10^{20}}\right) = 0.818 \text{ eV} \tag{1.11}$$

*Note: This formula can only be used for non-degenerate semiconductors (where the Fermi level is at least 3 kT from the conduction or valence band edge) since it relies on an approximation of the Fermi integral.

(B). First, please note that you were asked to draw the band diagram assuming an n-p junction. Though this is physically no different than a p-n junction, your band diagrams will look the reverse of those drawn in the book, since those all assume p-n. The point of this was to get you to think about what you are representing instead of simply copying the figures.

The band diagrams for the individual n and p sides are shown below:
When the junction is formed the Fermi level is constant over the entire structure since the system is in thermal equilibrium, while the conduction, valence, and intrinsic energy levels all bend as a result of the different constant potentials in the n and p regions:

(C). From Eqn. 5-21 of the book, the total depletion width can be calculated as:

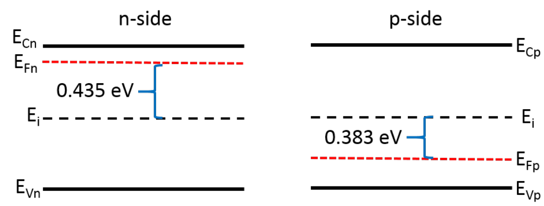

Figure 1.1: Band diagrams of n and p-sides before contact.

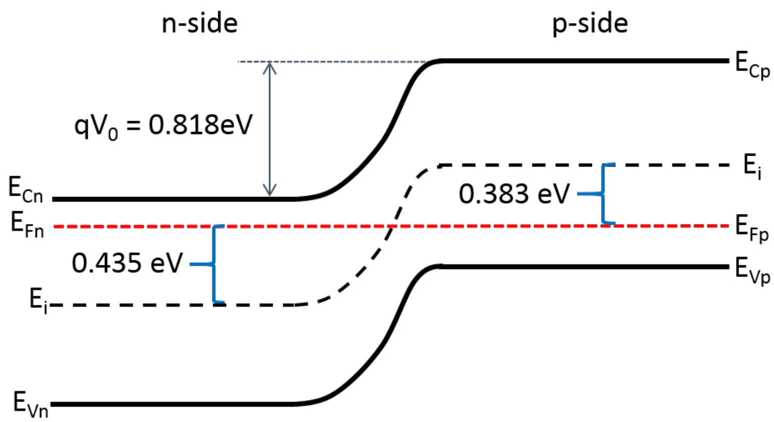

Figure 1.2: Band diagram of an n-p junction at equilibrium.

$$\mathrm{W} = \left[\frac{2\varepsilon V_0}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2} \tag{1.12}$$

For Si: $\varepsilon = \varepsilon_r \varepsilon_0 = (11.8)(8.85\times10^{-14}\text{ F/cm})$

$$\mathrm{W} = \left[\frac{2\cdot 11.8\cdot 8.85\times10^{-14}\cdot 0.818}{1.60\times10^{-19}}\left(\frac{1}{4\times10^{16}}+\frac{1}{3\times10^{17}}\right)\right]^{1/2} = 1.74\times10^{-5}\text{ cm} = 0.174\ \mu\text{m} \tag{1.13}$$

Or:

$$\mathrm{W} = 1.76\times10^{-5}\ \text{ cm} = 0.176\ \ \mu\text{m} \tag{1.14}$$

From Eqn. 5-23:

$$\begin{aligned} x_{n0} &= \frac{\mathrm{W}N_a}{N_a+N_d} = \frac{1.74\times10^{-5}\cdot 4\times10^{16}}{4\times10^{16}+3\times10^{17}} \\ x_{n0} &= 2.05\times10^{-6}\text{ cm} = 0.0205\ \mu\text{m} \end{aligned} \tag{1.15}$$

Or:

$$x_{n0} = \boxed{2.07\times10^{-6}\ \text{cm} = 0.0207\ \mu\text{m}} \tag{1.16}$$

And:

$$\begin{aligned} x_{p0} &= \frac{\mathrm{W}N_d}{N_a+N_d} = \frac{1.74\times10^{-5}\cdot 3\times10^{17}}{4\times10^{16}+3\times10^{17}} \\ x_{p0} &= \boxed{1.54\times10^{-5}\ \text{cm} = 0.154\ \mu\text{m}} \end{aligned} \tag{1.17}$$

Or:

$$x_{p0} = \boxed{1.55\times10^{-5}\ \text{cm} = 0.155\ \mu\text{m}} \tag{1.18}$$

Physically, this makes sense for x$_{p0}$ to be larger than x$_{n0}$ since the p-side has a lighter doping concentration, so the depletion region must extend further into it than on the n-side to encompass an equal number of ionized dopants (charges). Also, as a check to make sure our values are correct:

$$\mathrm{W}\ = x_{p0}+x_{n0} = 0.154\ \mu\text{m} + 0.0205\ \mu\text{m} = 0.1745\ \mu\text{m} \tag{1.19}$$

From Eqn. 5-13:

$$\begin{aligned} Q_- &= -qAx_{p0}N_a = 1.6\times10^{-19}\cdot\pi\left(\frac{50\times10^{-4}}{2}\right)^2\cdot 1.54\times10^{-5}\cdot 4\times10^{16} \\ Q_- &= \boxed{-1.94\times10^{-12}\ \text{C}} \end{aligned} \tag{1.20}$$

Or:

$$Q_- = \boxed{-1.95\times10^{-12}\ \text{C}} \tag{1.21}$$

This number should be negative since the problem is asking for the number of fixed charges created in the depletion region due to the themalization of acceptors, which capture an electron, resulting in a net negative charge of the atom.

The maximum of the built-in electric field can be calculated using Eqn. 5-17. However, note that this equation must be multiplied by -1 since this problem is for an n-p diode, while the book formulas are derived for a p-n diode. The difference here is that the built-in field points from the n to p side, which in the book is defined as the negative direction, making it point in the positive direction for an n-p diode.

$$\begin{aligned} \mathscr{E}_0 &= \frac{q}{\varepsilon}x_{p0}N_a = \frac{1.60\times10^{-19}}{11.8\cdot 8.85\times10^{-14}}1.54\times10^{-5}\cdot 4\times10^{16} \\ \mathscr{E}_0 &= \boxed{9.44\times10^{4}\ \text{V/cm}} \end{aligned} \tag{1.22}$$

Or:

$$\mathscr{E}_0 = \boxed{9.50\times10^4 \text{ V/cm}} \tag{1.23}$$

This can also be calculated by replacing $x_{p0}N_a$ with $x_{n0}N_d$.

(D). Since the doping is constant as a function of position, the charge density on either side of the junction is also constant.

$$\rho(x) = \begin{cases} qN_d^+ & -x_{n0} \le x \le 0 \\ -qN_A^- & 0 \le x \le x_{p0} \end{cases} \tag{1.24}$$

So:

$$\rho(x) = \begin{cases} 0.048\frac{C}{cm^3} & -0.0205 \le x \le 0 \\ -0.0064\frac{C}{cm^3} & 0 \le x \le 0.154 \end{cases} \tag{1.25}$$

The plot of the charge density as a function of position should look like the following:

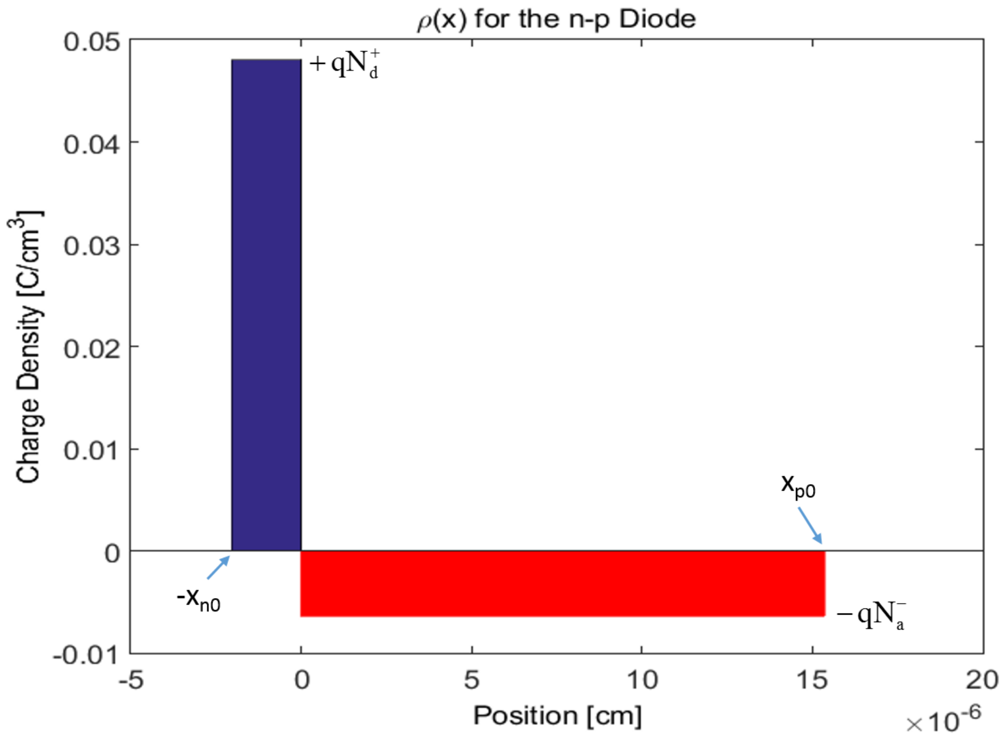

Figure 1.3: Charge density for the n-p diode.

Using Poisson's equation we can calculate the electric field in the depletion region as a function of position:

$$\mathscr{E}(\mathrm{x}) = \int \frac{\rho(\mathrm{x})}{\varepsilon}\,\mathrm{dx} \tag{1.26}$$

Since we are assuming the depletion approximation, we can say the electric field at the edges of the depletion region is exactly zero, or $\mathscr{E}(-\mathrm{x}_{n0}) = \mathscr{E}(\mathrm{x}_{p0}) = 0$.

For $-\mathrm{x}_{n0} \leq \mathrm{x} \leq 0$:

$$\mathscr{E}_n(\mathrm{x}) = \int_{-x_{n0}}^{x} \frac{q}{\varepsilon} N_d^+\,\mathrm{dx}' = \frac{q}{\varepsilon} N_d^+\,(\mathrm{x} + \mathrm{x}_{n0}) \tag{1.27}$$

For $0 \leq \mathrm{x} \leq \mathrm{x}_{p0}$:

$$\mathscr{E}_n(\mathrm{x}) = -\int_{x}^{x_{p0}} -\frac{q}{\varepsilon} N_a^-\,\mathrm{dx}' = -\frac{q}{\varepsilon} N_a^-\,(\mathrm{x} - \mathrm{x}_{p0}) \tag{1.28}$$

The plot of the electric field in the depletion region of the n-p junction should look like the following picture:

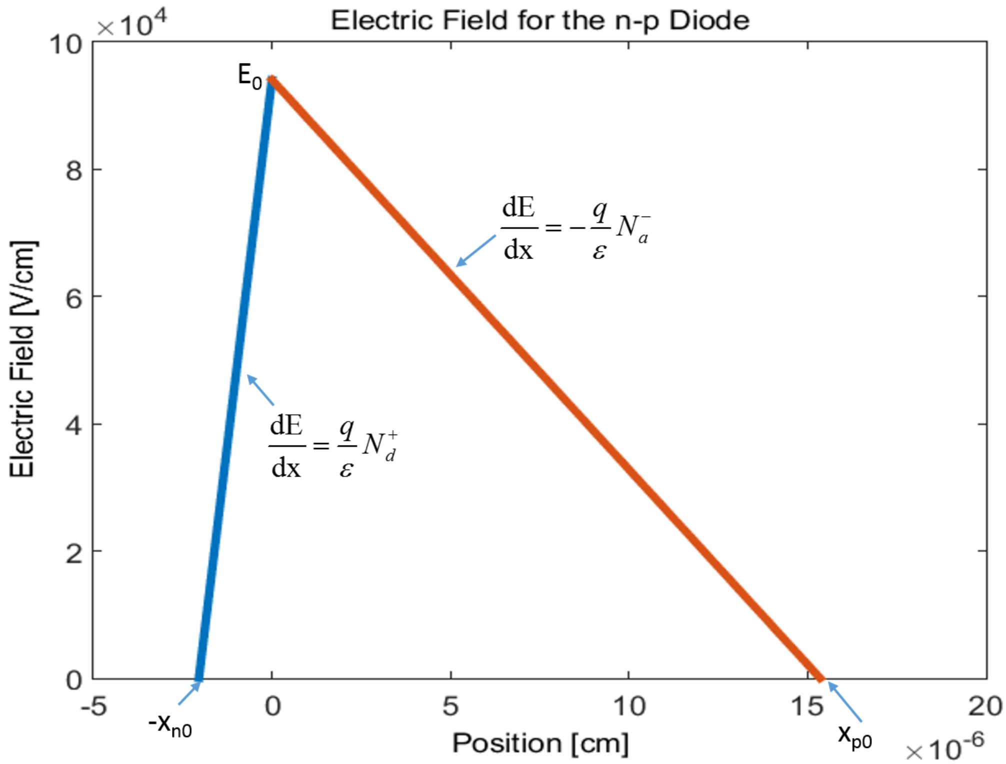

Figure 1.4: Electric field in the depletion region of the n-p diode.

(E). Again using Poisson's Equation:

$$V(\mathrm{x}) = -\int \mathscr{E}(\mathrm{x})\,\mathrm{dx} \tag{1.29}$$

This integral must be done piecewise, also taking into account V(0) = 0, which was given in the problem. For brevity, only the initial integral and solution are shown, though a more complete derivation can be shown upon request:

For -$\mathrm{x}_{n0} \leq \mathrm{x} \leq 0$:

$$V_n(\mathrm{x}) = -\int_{-x_{n0}}^{x} \mathscr{E}_n(\mathrm{x}')\,\mathrm{dx}' = -\int_{-x_{n0}}^{x} \frac{q}{\varepsilon} N_d^+ \left(\mathrm{x}' + \mathrm{x}_{n0}\right)\,\mathrm{dx}' = \boxed{-\frac{q}{2\varepsilon} N_d^+ \left(\mathrm{x} + \mathrm{x}_{n0}\right)^2 + \frac{q}{2\varepsilon} N_d^+\, \mathrm{x}_{n0}^2} \tag{1.30}$$

For $0 \leq \mathrm{x} \leq \mathrm{x}_{p0}$:

$$V_p(\mathrm{x}) = \int_{x}^{-x_{p0}} \mathscr{E}_p(\mathrm{x}')\,\mathrm{dx}' = \int_{x}^{-x_{p0}} -\frac{q}{\varepsilon} N_a^- \left(\mathrm{x}' - \mathrm{x}_{p0}\right)\,\mathrm{dx}' = \boxed{\frac{q}{2\varepsilon} N_a^- \left(\mathrm{x} - \mathrm{x}_{p0}\right)^2 - \frac{q}{2\varepsilon} N_a^-\, \mathrm{x}_{p0}^2} \tag{1.31}$$

The final plot should look like the following:

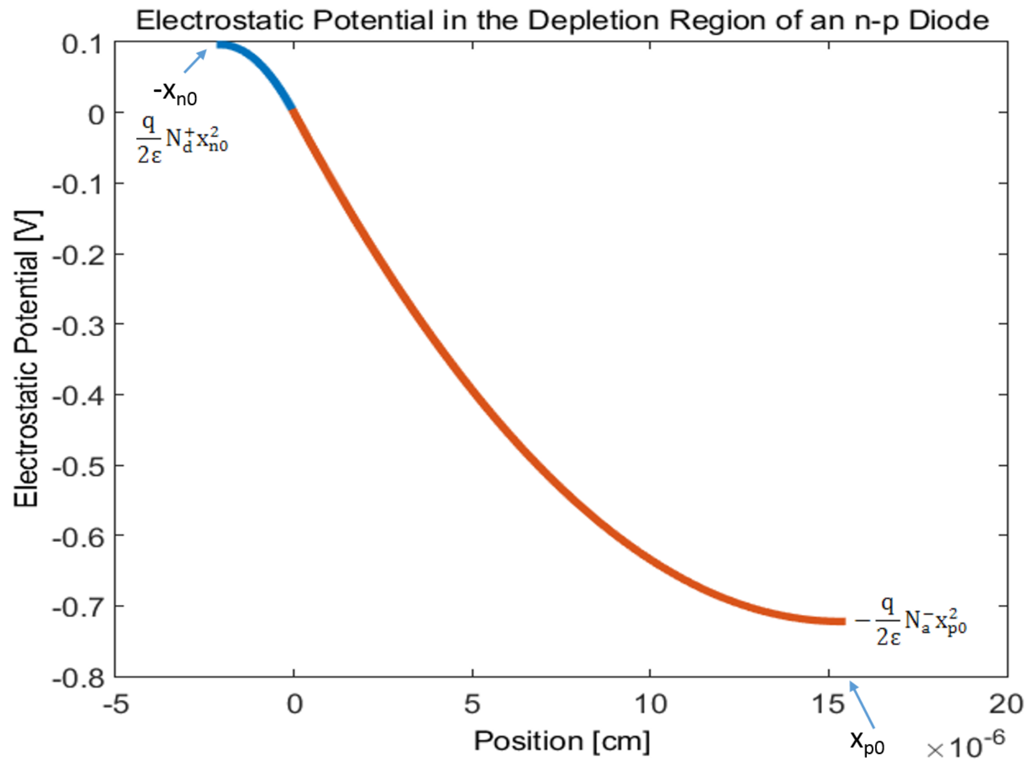

Figure 1.5: Electrostatic potential in the depletion region of the n-p diode.

2. A Biased n-p Junction

(A). When the junction is forward biased, we know that the contact potential decreases to V = V_0 - V_f. Since the depletion width, W, depends on the square root of the contact potential, if the contact potential decreases then the depletion width (and, consequently, x_{n0} and x_{p0}) will shrink. Since Q_- depends linearly on x_{n0}, it also decreases. Physically, this occurs due to the decrease in the depletion width. Mathematically we can see E_0 decreases as well, but physically we can assume this simply because the forward bias electric field from the circuit is set up to oppose the built-in electric field (since the positive terminal is connected to the p-side and ground is connected to the n-side). Thus, E_0 must shrink since the total electric field strength has decreased across the now smaller depletion region. To recalculate the values, simply use V = V_0 - V_f for your calculation of W, and substitute that into all further calculations:

$$W = 1.23 \times 10^{-5}\ \text{cm} = 0.123\ \mu\text{m} \quad 1.25{\times}10^{-5}\ \text{cm} = 0.125\ \mu\text{m} \tag{2.1}$$

$$x_{n0} = 1.45 \times 10^{-6}\ \text{cm} = 0.0145\ \mu\text{m} \quad 1.47{\times}10^{-6}\ \text{cm} = 0.0147\ \mu\text{m} \tag{2.2}$$

$$x_{p0} = 1.09 \times 10^{-5}\ \text{cm} = 0.109\ \mu\text{m} \quad 1.10{\times}10^{-5}\ \text{cm} = 0.110\ \mu\text{m} \tag{2.3}$$

$$Q_- = -1.36 \times 10^{-12}\ \text{C} \quad -1.38{\times}10^{-12}\ \text{C} \tag{2.4}$$

$$\mathscr{E}_0 = 6.65 \times 10^{4}\ \text{V/cm} \quad 6.74{\times}10^{4}\ \text{V/cm} \tag{2.5}$$

(B). When the junction is forward biased, the contact potential is decreased from its equilibrium value of V_0 to V_0 - V_f, where V_f is the bias amount. More majority carriers are able to diffuse over the reduced potential barrier (electrons from the n-side diffuse to the p-side where they are minority carriers and holes from the p-side diffuse to the n-side where they are minority carriers). Since the majority of the voltage drop occurs over the depletion region, the quasi-Fermi level of the holes on the n-side splits down towards the valence band and the quasi-Fermi level of the electrons on the p-side splits up towards the conduction band. In the depletion region itself, the quasi-Fermi levels are separated by a value qV_f. Since there is an excess of minority carriers near the edge of the depletion region from the increase in diffusion, it makes sense intuitively that the quasi-Fermi level for that minority carrier should be closer to the conduction (for electrons) or valence (for holes) band:

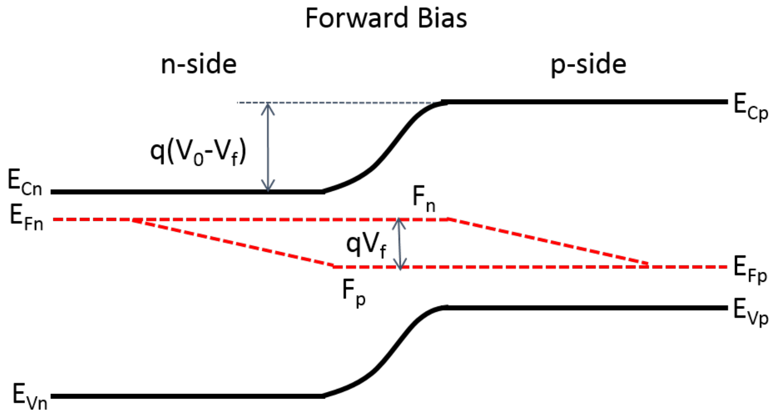

Figure 2.1: Forward bias band diagram of the n-p junction.

(C). At equilibrium we expect the minority carrier concentrations on either side of the depletion region to be exactly that of a bulk semiconductor with the same doping. This is because that even though minority carriers may be swept away after diffusion into the depletion region, they are replenished by majority carrier diffusing over the potential barrier from the other side of the junction. However, when the device is forward biased, the barrier is lowered and the diffusion of majority carriers exponentially increases with applied bias (derivation not shown). Using Equation 5-29 for holes and 5-30 for electrons we can calculate the excess minority carrier concentration at the very edge of the depletion region (which is the maximum value), keeping in mind that we can use $n_0p_0 = n_i^2$ to calculate the equilibrium minority carrier concentration on either side of the junction:

$$\Delta p_n = p_n\left(e^{qV_f/kT} - 1\right) = 5.48\times10^{9}\ \text{cm}^{-3}\quad 3.65\times10^{9}\ \text{cm}^{-3} \tag{2.6}$$

$$\Delta n_p = n_p\left(e^{qV_f/kT} - 1\right) = 4.11\times10^{10}\ \text{cm}^{-3}\quad 2.74\times10^{10}\ \text{cm}^{-3} \tag{2.7}$$

(D). The equation for reverse bias saturation current (take the magnitude of 5-37b) consists of an electron and hole component. One important thing to note is that all quantities such as the diffusion coefficient, diffusion length, and carrier concentration are all for the minority carrier values. So, D_n should be calculated using the electron value of mobility in the **p-region**.

Hole Component (n-side)

$$D_p = \frac{kT}{q}\mu_p = 6.475\ \text{cm}^2\text{s}^{-1} \tag{2.8}$$

$$L_p = \sqrt{\tau_p D_p} = 0.0074\ \text{cm} \tag{2.9}$$

$$I_{p,sat} = qA\left(\frac{D_p}{L_p}p_n\right) = 2.06\times10^{-18}\ \text{A}\quad 9.14\times10^{-19}\ \text{A} \tag{2.10}$$

Electron Component (p-side)

$$D_n = \frac{kT}{q}\mu_n = 28.49 \text{ cm}^2\text{s}^{-1} \tag{2.11}$$

$$L_n = \sqrt{\tau_n D_n} = 0.0029 \text{ cm} \tag{2.12}$$

$$I_{n,sat} = qA\left(\frac{D_n}{L_n}n_p\right) = 1.72 \times 10^{-16} \text{ A} \quad 7.65\times10^{-17} \text{ A} \tag{2.13}$$

The total reverse bias saturation current is simply the sum of the p and n components:

$$I_0 = 1.74 \times 10^{-16} \text{ A} \quad 7.75\times10^{-17} \text{ A} \tag{2.14}$$

The total current for both forward and reverse bias can be calculated from Equation 5-36. When the diode is forward biased by $V_f = V_0/2$, the total current is:

$$I = 1.27 \times 10^{-9} \text{ A} \quad 8.48\times10^{-10} \text{ A} \tag{2.15}$$

(E). The following plots are the qualitative current component plots for the forward biased n-p junction with $V_f = V_0/2$. The first plot represents the actual magnitude of the current (which should be negative since it points in the negative x-direction. The second plot represents the absolute value of the current components. Either one is acceptable as long as your total current calculated in part (d) is negative, indicating you know the proper direction of carrier flow.

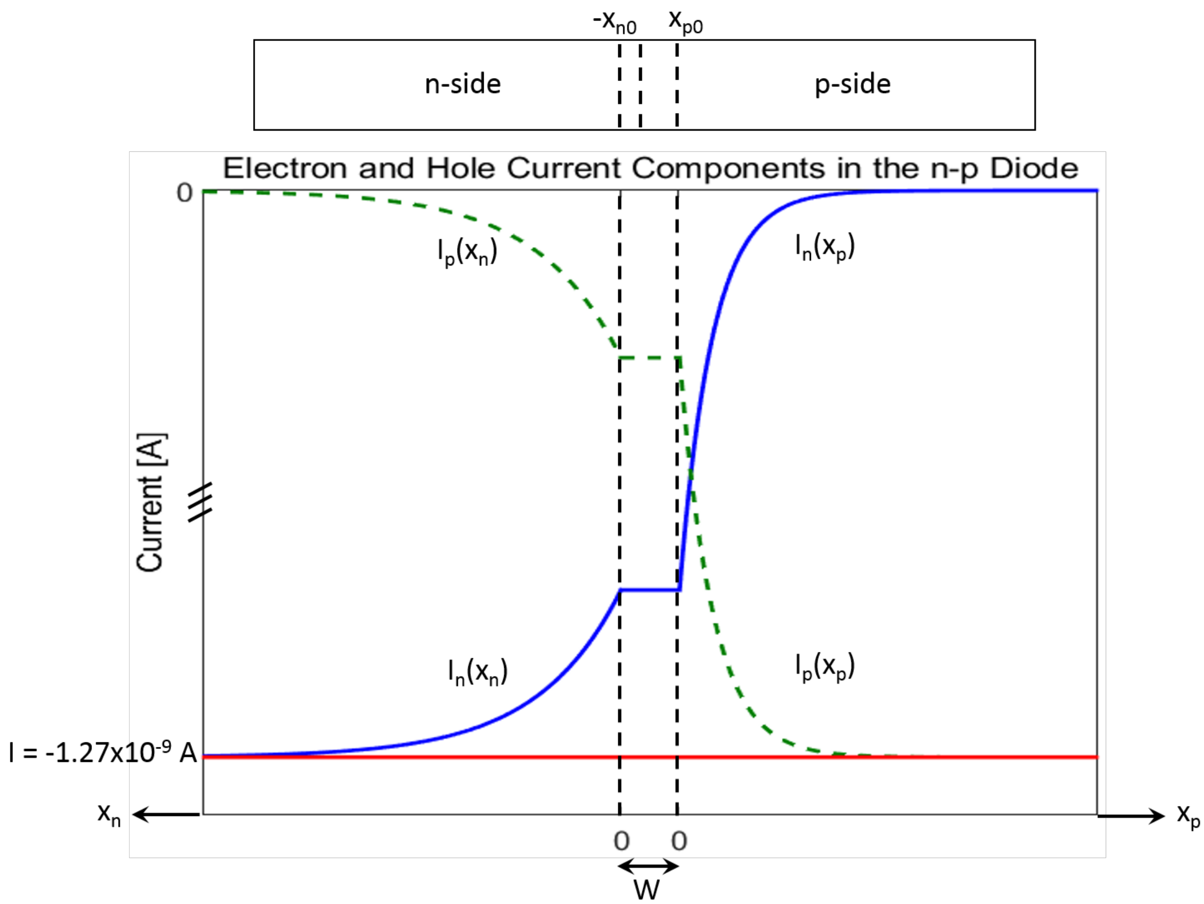

Figure 2.2: Current components in a forward biased n-p junction.

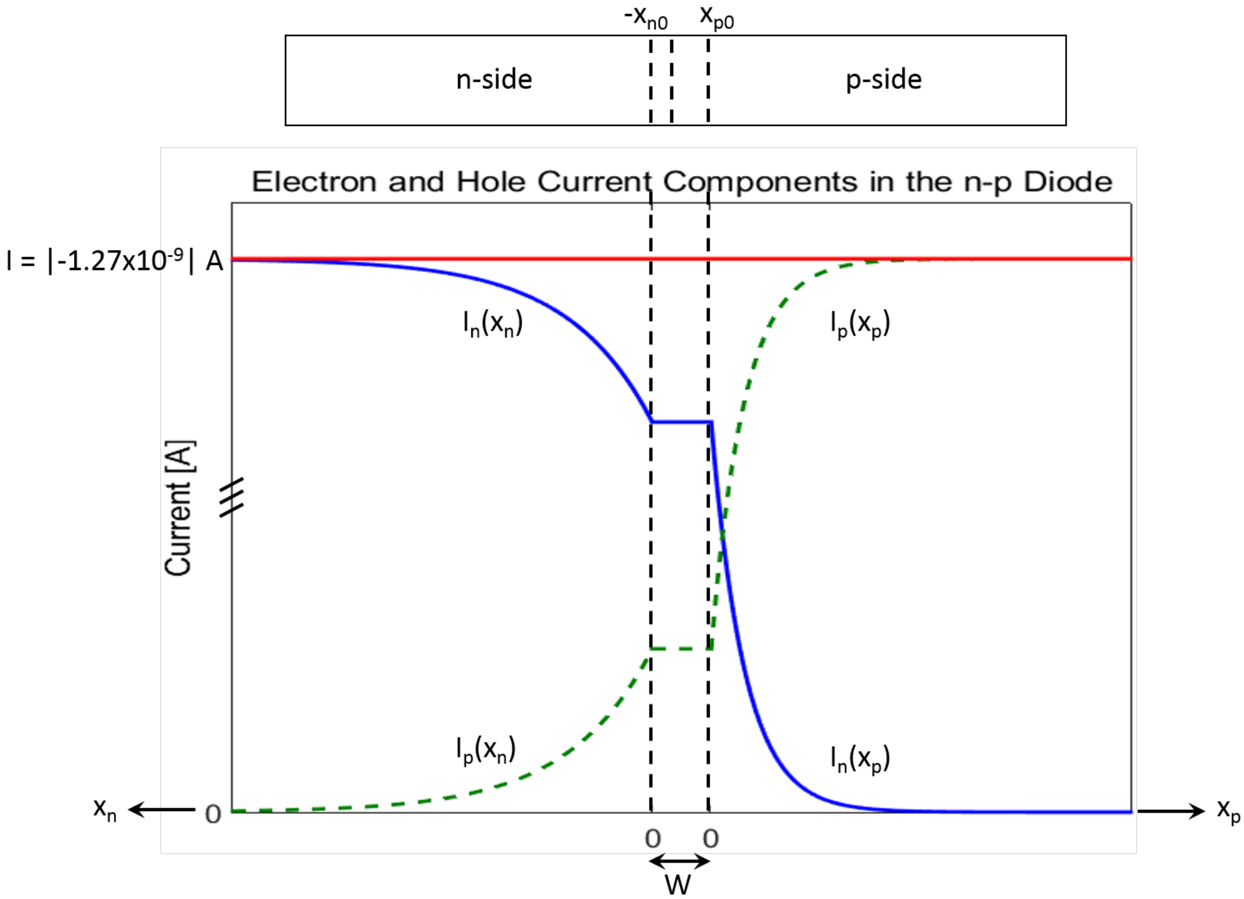

Figure 2.3: Absolute value of the current components in a forward biased n-p junction.

(F). When the junction is reverse biased (assuming this means that V_r is negative), the contact potential increases to $V = V_0 - V_r$. Thus, the exact opposite case from the forward biased case occurs and W, x_{n0}, x_{p0}, Q_-, and E_0 all increase. In reverse bias, the electric field created across the depletion region due to the terminals is in the same direction as the build-in field (pointing from n to p) which increases the total field strength across the depletion region. To recalculate the values, simply use $V = V_0 - V_r$ for your calculation of W, and substitute that into all further equations:

$$\mathrm{W} = 2.46 \times 10^{-5}\ \mathrm{cm} = 0.246\ \mu\mathrm{m} \quad 2.49 \times 10^{-5}\ \mathrm{cm} = 0.249\ \mu\mathrm{m} \tag{2.16}$$

$$x_{n0} = 2.90 \times 10^{-6}\ \mathrm{cm} = 0.0290\ \mu\mathrm{m} \quad 2.93 \times 10^{-6}\ \mathrm{cm} = 0.0293\ \mu\mathrm{m} \tag{2.17}$$

$$x_{p0} = 2.17 \times 10^{-5}\ \mathrm{cm} = 0.217\ \mu\mathrm{m} \quad 2.20 \times 10^{-5}\ \mathrm{cm} = 0.220\ \mu\mathrm{m} \tag{2.18}$$

$$Q_- = -2.73 \times 10^{-12}\ \mathrm{C} \quad -2.76 \times 10^{-12}\ \mathrm{C} \tag{2.19}$$

$$\mathscr{E}_0 = 1.33 \times 10^5 \text{ V/cm} \quad 1.35\times10^5 \text{ V/cm} \tag{2.20}$$

(G). When the junction is reverse biased, the contact potential is increased from its equilibrium value of V_0 to $V_0 + V_r$, where V_r is the absolute value of the reverse bias. When V_r is greater than a few kT, the potential barrier becomes so large that essentially zero carriers have enough energy to diffuse over it, meaning the current in the device is due to thermally generated minority carriers that can random walk to the depletion region and drift along the electric field. The lack of carriers diffusing over the barrier and the immediate removal of any minority carriers at the edge of the depletion region due to the built-in electric field means the minority carrier concentration near the depletion region is essentially zero. This is represented by the quasi-Fermi level of the minority carrier being either above the conduction band (for holes on the n-side) or below the valence band (for electrons on the p-side), which indicates a very low occupation probability for holes in the valence band or electrons in the conduction band, respectively. It is important to note that the reverse bias current will not change in an ideal diode after a reverse bias of a few kT is reached, even though the electric field strength in the depletion region is increasing. This is because is is not how fast carriers are being swept along by the electric field but how many carriers are being swept (this value is the thermal generation rate, which only changes with temperature!):

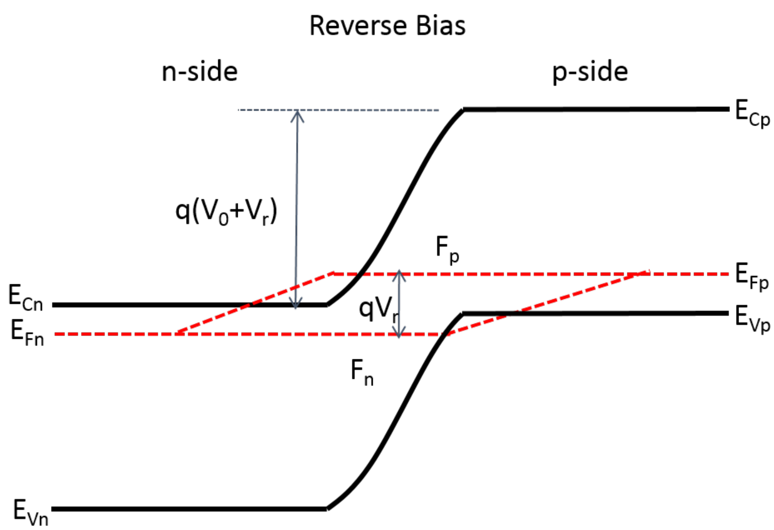

Figure 2.4: Reverse bias band diagram of the n-p junction.

3. Carrier Concentrations in a p-n Junction

(A). The diode is reverse biased. Since little to no carriers can diffuse over the barrier as the reverse bias voltage increases past a few kT, any thermally generated carriers generated within a few diffusion lengths of the depletion width that random walk into the depletion region are swept away by the built-in electric field and are not replenished by carriers diffusions over the barrier from the other side of the junction.

As a result, the minority carriers within a few diffusion lengths are depleted and the excess minority carrier concentration is negative, rapidly approaching the limit of Δn_p = -n_p and Δp_n = -p_n as the reverse bias voltage increases past a few kT. Since this picture has a depletion of minority carriers outside the junction, it is reverse biased.

(B). Since this diode is reverse biased then low-level injection conditions definitely apply since the change in minority carrier concentration at the edge of the depletion is much less than the majority carrier concentration at the edge of the depletion region.

(C). Since low-level injection applies and this is at room temperature (T = 300 K), we can assume all the donors and acceptors are ionized and that the majority carrier concentration far from the depletion region equals the ionized doping concentration (and thus the doping concentration). In other words:

$$\mathrm{N}_a = \mathrm{N}_a^- = \mathrm{p}_p = 1 \times 10^{16}\ \mathrm{cm}^{-3} \tag{3.1}$$

$$\mathrm{N}_d = \mathrm{N}_d^+ = \mathrm{n}_n = 1 \times 10^{15}\ \mathrm{cm}^{-3} \tag{3.2}$$

(D). Using Equation 5-28 we can compare the non-equilibrium steady-state minority carrier concentration at the edge of the depletion region to the equilibrium minority carrier concentration in the semiconductor. We can use either the n or p side since the applied bias is across the entire device. Solving for V we find that the applied voltage is negative (indicating reverse bias) and equal to:

$$\mathrm{V} = \frac{\mathrm{kT}}{q} \ln\left(\frac{10^2}{10^5}\right) = -0.179\ \mathrm{V} \tag{3.3}$$

(E). Since the picture is a reverse biased diode, if it is now biased opposite it is simply a forward biased diode. In forward bias, minority electrons are injected into the p-side from the n-side via diffusion over the reduced barrier, and minority holes are injected into the n-side from the p-side via the same process. Thus, there will be an excess of minority carriers at the edge of the depletion region compared to the equilibrium value. These carriers will then diffuse into the semiconductor and eventually recombine with majority carriers in the region, their concentration exponentially decaying to the equilibrium value. The following plot illustrates this concept:

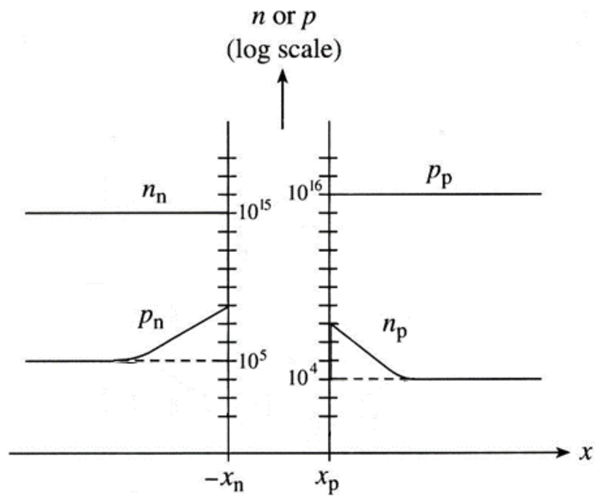

Figure 3.1: Minority carrier concentration as a function of position on either side of a forward biased p-n junction.

4. A P$^+$-N JUNCTION

(A). The intrinsic carrier concentration of Si at T = 300 K is: $n_i = 1.5\times10^{10}$ cm^{-3} (though $n_i = 1\times10^{10}$ is acceptable and those answers are marked in red-orange color)

n-side

Charge Neutrality: $n_0 + N_a^- = p_0 + N_d^+$

Assuming all donors are ionized, we can say $N_d^+ = 1\times10^{14}$ cm^{-3}. Since this is an n-type material, $N_a^- = 0$. Also, since the ionized donor level is far greater than n_i, we can safely assume that p_0 can be neglected, resulting in: $n_0 = 1\times10^{14}$ cm^{-3}.

Starting with the familiar equation relating the Fermi level to the carrier concentration:

$$n_0 = n_i \cdot e^{\frac{E_{f_n}-E_i}{kT}} \tag{4.1}$$

And solving for E_{f_n} - E_i:

$$E_{f_n} - E_i = \boxed{0.228\ \text{eV}}\ \boxed{0.239\ \text{eV}} \tag{4.2}$$

p$^+$-side

Charge Neutrality: $n_0 + N_a^- = p_0 + N_d^+$

Assuming all donors are ionized, we can say $N_a^- = 1\times10^{19}$ cm^{-3}. Since this is a p-type material, $N_d^+ = 0$. Also, since the ionized acceptor level is far greater than n_i, we can safely assume that n_0 can be neglected, resulting in:

$p_0 = 1\times10^{19}$ cm^{-3}.

Starting with the familiar equation relating the Fermi level to the carrier concentration:

$$p_0 = n_i \cdot e^{\frac{E_i - E_{f_p}}{kT}} \tag{4.3}$$

And solving for E_i - E_{f_p}:

$$E_i - E_{f_p} = \text{0.526 eV} \;\; \text{0.537 eV} \tag{4.4}$$

Calculate contact potential V_0

There are multiple ways to calculate the contact potential:

$$qV_0 = (E_{f_n} - E_i) + (E_i - E_{f_p}) = 0.754 \text{ eV} \tag{4.5}$$

Or if using $n_i = 1\times10^{10}$:

$$qV_0 = (E_{f_n} - E_i) + (E_i - E_{f_p}) = 0.775 \text{ eV} \tag{4.6}$$

So:

$$\begin{gathered} qV_0 = 0.754 \text{ eV} \;\; qV_0 = 0.776 \text{ eV} \\ V_0 = 0.754 \text{ V} \;\; V_0 = 0.776 \text{ V} \end{gathered} \tag{4.7}$$

(B). The calculation of these values is done the same as in Problem 1:

$$\text{W} = 3.1379\times10^{-4} \text{ cm} = 3.1379\ \mu\text{m} \;\; 3.1813\times10^{-4} \text{ cm} = 3.1813\ \mu\text{m} \tag{4.8}$$

$$x_{n0} = 3.1378\times10^{-4} \text{ cm} = 3.1378\ \mu\text{m} \;\; 3.1812\times10^{-4} \text{ cm} = 3.1812\ \mu\text{m} \tag{4.9}$$

$$x_{p0} = 3.1378\times10^{-9} \text{ cm} = 0.031378 \text{ nm} \;\; 3.1812\times10^{-9} \text{ cm} = 0.031812 \text{ nm} \tag{4.10}$$

As you can see, the portion of the depletion region that extends into the n-type material is 5 orders of magnitude larger than the portion of the depletion region inside the heavily doped p^+-region (which has a sub-Angstrom width). For a junction like this where one side is doped much more heavily than the other, it is generally a safe assumption to make that the portion of the depletion width inside the lightly doped region is equal to the total depletion width. In this case, $x_{n0} \approx$ W.

(C).

$$\Delta p_n = p_n\left(e^{qV_f/kT} - 1\right) = 4.74\times10^{12} \text{ cm}^{-3} \;\; 3.16\times10^{12} \text{ cm}^{-3} \tag{4.11}$$

$$\Delta n_p = n_p \left(\mathrm{e}^{\mathrm{q}\mathrm{V}_f/\mathrm{kT}} - 1\right) = 4.74 \times 10^7 \ \mathrm{cm}^{-3} \quad 3.16 \times 10^7 \ \mathrm{cm}^{-3} \tag{4.12}$$

The first thing we notice is that the excess minority hole concentration at the edge of the depletion region in the n-side is 5 orders of magnitude larger than the excess minority carrier electron concentration at the edge of the depletion region in the p-side. This means that the hole current injected into the n-side is going to be much larger than the electron current injected into the p-side (indeed we can see this is true by looking at Equations 5-33 and 5-34 in the book).

This asymmetrical junction can be viewed as a very useful electronic device - a single carrier injection device. That is, a small amount of electrons injected across the junction into the heavily doped p$^+$-region will result in the injection of a large amount of holes into the lightly doped n-region. This type of junction forms the basis of a very important semiconductor electronic device, the bipolar junction transistor (BJT), a three-terminal device that utilizes this aspect of an asymmetric junction to, among other things, act as a current amplifier in a circuit.