1. Breakdown of p-n Junction

(A). First we calculate the depletion region width on either side of the junction:

$$x_{n0} = \sqrt{\frac{2(V_0+V_{br})}{q}\left(\frac{N_A}{N_D(N_A+N_D)}\right)} = \sqrt{\frac{\epsilon(V_0+V_{br})}{qN_D}} \text{ for} N_A = N_D \tag{1.1}$$

Using eq. 5-17 from the textbook:

$$E_{max} = -\frac{q}{\epsilon}N_D x_{n0} = -\frac{q}{\epsilon}N_D\sqrt{\frac{\epsilon(V_0+V_{br})}{qN_D}} = -\sqrt{\frac{qN_D(V_0+V_{br})}{\epsilon}} \tag{1.2}$$

We know $E_{max} = 6\times10^5$ V/cm, therefore:

$$(V_0+V_{br}) = \frac{\epsilon E_{max}^2}{qN_D} = \frac{11.8\times8.85\times10^{-14}\times(6\times10^5)^2}{1.6\times10^{-19}\times1\times10^{17}} = 23.50\text{ V} \tag{1.3}$$

Calculate V_0:

$$V_0 = 2\frac{kT}{q}\ln(\frac{N_D}{n_i}) = 0.93\text{ V} \tag{1.4}$$

Finally:

$$V_{br} = 4.70 - 0.93 = \boxed{22.57\text{ V}} \tag{1.5}$$

(B). To find the depletion region thickness just prior to avalanche breakdown, we simply apply (1.1) and multiply by two ($N_A = N_D$)

$$W_{br} = 2\sqrt{\frac{\epsilon(V_0+V_{br})}{qN_D}} = \boxed{0.78\mu\text{m}} \tag{1.6}$$

2. Junction Capacitance of a Si p^+-n Junction

(A). For a p^+-n junction, $N_A \gg N_D$ and $x_{no} \simeq W$, the capacitance is as follows

$$C_j = A\left(\frac{q\epsilon}{2(V_o-V)}N_D\right)^{1/2} \tag{2.1}$$

First we find the built in voltage:

$$V_0 = 0.56V + 0.259V\times\ln(\frac{N_D}{n_i}) = 0.56V + 0.33V = 0.89V \tag{2.2}$$

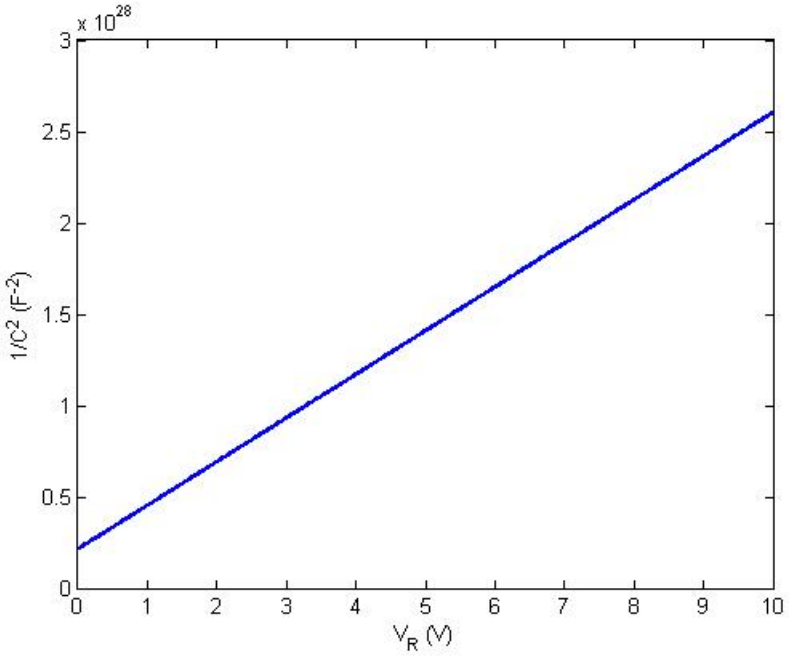
Calculating the capacitance:

$$C_{j,1V} = A\left(\frac{q\epsilon}{2(V_o-V)}N_D\right)^{1/2} = 100\times10^{-8}\left(\frac{(1.6\times10^{-19})(11.8\times8.85\times10^{-14})(5\times10^{15})}{2\times(0.89+1)}\right)^{1/2} = \boxed{1.49\times10^{-14}\text{ F}} \tag{2.3}$$

Using the same method, we find $\boxed{C_{j,5V} = 8.42\times10^{-15}F}$ and $\boxed{C_{j,10V} = 6.19\times10^{-15}F}$.

(B). Using (2.1):

$$\frac{1}{C^2} = \frac{1}{A^2} \cdot \frac{V_0 - V}{qN_D(\frac{\epsilon}{2})} = 2.39 \times 10^{27}(0.89 - V) \tag{2.4}$$



(C). From (2.4), we know the relationship between the square of the capacitance and the doping. Therefore, by measuring capacitance over enough data points (sweep V_R), we can determine the doping level of a material in a one-sided junction.

3. Effect of Doping in a P-N$^+$ Junction

(A). *Increases*:

$$C = |\, dQ/dV \,| \; and \; |\, Q \,| \propto N_A \tag{3.1}$$

The amount of static charge in the junction increases with increased doping. Therefore if the acceptor doping N_A increases, the capacitance will also increase.

(B). *Increases*:

$$V_o = \frac{kT}{q} \ln(\frac{N_A N_D}{{n_i}^2}) \tag{3.2}$$

If the acceptor doping N_A is quadrupled, it means the difference between E_{ip} and E_f will increase, while the difference between E_f and $E_i n$ remains the same. This means the built-in potential or the contact potential will increase due to the change.

(C). *Decreases*:
As the acceptor doping N_A is quadrupled, W decreases. This means electron can tunnel more easily through the junction under a given reverse bias. Also, the increase in built-in potential means the built-in field is larger, so it takes less reverse bias to cause the junction to break down.

(D). *Decreases*:
For a one-sided junction, the depletion region width is dominated by the doping on the weakly doped side. Since the depletion width is inversely related to the doping, the depletion width decreases when the p-doping is quadrupled.

(E). *Decreases*:
Ohmic losses are related to the resistance of quasineutral regions. Larger doping means more carriers in the p-region, increasing conductivity. Hence, the ohmic losses decrease.

4. Solar Cells

(A). The short circuit current is the current in the device when V = 0. Note that since the solar cell is under constant illumination, the short circuit current is not simply zero. The total current consists of the familiar diode equation as well as an optical generation component. From equation [8-2]:

$$I = qA(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p)(e^{qV/kT} - 1) - qAg_{op}(L_p + L_n + W) \tag{4.1}$$

When V = 0 we get:

$$I_{sc} = -qAg_{op}(L_p + L_n + W) \tag{4.2}$$

L_p, L_n and W can be calculated as follows:

$$L_p = \sqrt{D_p\tau_p} = 10\mu\text{m} \tag{4.3}$$

$$L_n = \sqrt{D_n\tau_n} = 20\mu\text{m} \tag{4.4}$$

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.70\,\text{V} \tag{4.5}$$

$$W = \left(\frac{2\epsilon V_0}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right)^{1/2} = 0.69\mu\text{m} \tag{4.6}$$

$$I_{sc} = -19.64\mu\text{A} \tag{4.7}$$

(B). The drift photocurrent refers to current from EHPs that are generated in the depletion region and are immediately swept by the electric field. The diffusion photocurrent refers to current from electrons and holes generated within a diffusion length from the edges of the depletion region. These carriers need to diffuse to the depletion region edge before they can be swept by the electric field to the opposite side. Note that although both these components provide a current at steady state, the drift photocurrent has a much faster response time because the electrons and holes do not have to diffuse into the depletion region before getting swept by the electric field.

The dominant component in the photocurrent is the diffusion component.

$$\text{Fraction of total current} = \frac{(L_p + L_n)}{(L_p + L_n + W)} = 0.98 \tag{4.8}$$

(C).

On the n side:

$$p_{n,max} = \frac{n_i^2}{n_n} + g_{op}\tau_p = \frac{(1.5\times10^{10})^2}{(2\times10^{15})} + (4\times10^{16})(0.1\times10^{-6}) = 4\times10^9 cm^{-3} \tag{4.9}$$

On the p side:

$$n_{p,max} = \frac{n_i^2}{p_p} + g_{op}\tau_n = \frac{(1.5\times10^{10})^2}{(6\times10^{16})} + (4\times10^{16})(0.2\times10^{-6}) = 8\times10^9 cm^{-3} \tag{4.10}$$

5. PHOTODIODES AND LIGHT EMITTING DIODES

(A). In a reverse biased photodiode, any EHP generated within the depletion region will be immediately swept away due to the electric field in the depletion region. A large depletion width allows the photodiode to capture more photons under a given illumination intensity, thus sensitivity increases with increasing depletion width. The response time of a photodiode is limited by its RC time constant. A large depletion width means smaller capacitance, therefore response time decreases with increasing depletion width. However, when the depletion width is too large, the time it takes for the EHP to reach quasineutral regions (transit time) may dominate over the RC charging time, resulting in degraded response time.

(B). A highly doped photodiode has low resistance which is desirable for fast response time. However, high doping makes for thin depletion width which results in low sensitivity. A common practice is to lightly dope one side of the junction and heavily dope the other side (e.g. p-n^+) to get low resistance on one side and maintain a large depletion width. Another method, as described in the textbook, is to use a p-i-n structure where a region with very low doping is wedged between the p and n regions. When a reverse bias is applied to this structure, a constant electric field occurs over the intrinsic region and it behaves similar to a p-n junction depletion region. With this method, it is possible to use the width of the intrinsic region to set the active area while reasonably high doping values can be used in the p and n regions.

(C). Group-IV and III-V semiconductors have a specific energy gap and can emit a certain wavelength. However, their natural emission wavelengths are not always practically useful. In most applications an LED/laser is part of a system where the emission wavelength is dictated by the other system constituents. For example, since attenuation in a typical silica glass fiber is minimum at 1.55μm, it is desirable to use transmitters with 1.55μm emission wavelength. The emission wavelength of ternary alloys can be altered based on the composition, making them suitable for such applications. Furthermore, quarternary alloys possess a further degree of freedom to the lattice constant, enabling crystal growth on a variety of substrates and fabrication of complex heterostructures.

(D). For 650nm emission, a semiconductor with bandgap of 1.91eV is required. Referring to Fig. 3-6, the required x composition for $Al_xGa_{1-x}As$ is 0.38. For $GaAs_{1-x}P_x$, according to Fig. 8-11, the required x composition is around 0.38. Note that for these compositions, the semiconductors have direct band gaps since they have Γ-valley minima.