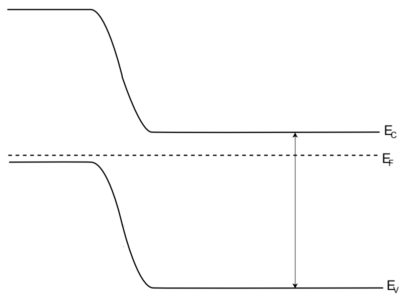
University of Delaware

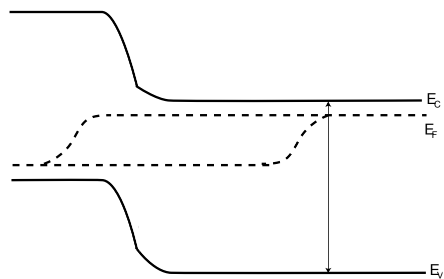
Department of Electrical and Computer Engineering

ELEG620: Solar Electric Systems: Homework #3: Solar Cells

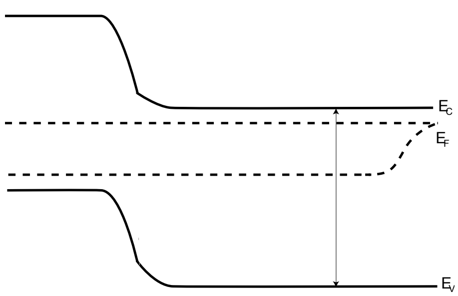
1. The following band diagrams are all for the same solar cell, under varying conditions. Determine: (a) Which side is more heavily doped; (b) The bias condition in each case; (c) If possible, information about the minority carrier lifetime and/or surface recombination.



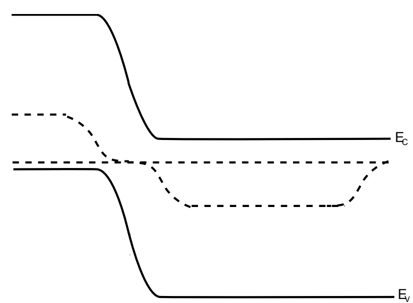
Case (1)



Case (2)



Case (3)



Case (4)

(a) The p-type side is more heavily doped. This can be seen most clearly from Case (1) where the Fermi level is closer to the valence band edge on the p-type side than to the conduction band edge on the n-type side.

(b) Case 1: Equilibrium (flat quasi-Fermi level); Case (2): Forward bias: there is a forward bias voltage across the device (split in quasi-Fermi levels at junction). There is no significant light generation near the surface, so no light bias. Case (3) Open circuit voltage; the quasi-Fermi levels are flat over substantial portions of the device, which means that the device has the maximum voltage across is for that given light intensity, which in turn corresponds to open circuit voltage; Case (4): Short circuit current; there is light generation at the surface and throughout the device, but the bias at the junction is zero.

(c) The minority carrier lifetime is longer on the n-type (right) side than the p-type. This can be seen both from (2) (forward bias) where the excess minority carriers concentration is higher for a longer distance away from the junction. The surface recombination velocity at the front is very small, since the minority carrier concentrations near the surface when there is carrier generation at the surface (ie light generation, cases (3) and (4)) is large. The rear surface recombination velocity is large, since even when there is carrier generation at the rear (cases (3) and (4)), the carrier concentration is zero at the rear. The diode equation for the solar cell is likely to be a wide base diode equation, since the minority carriers under forward bias decay to zero before they reach the surface.

2. The following plot is the normalized saturation current density J_0'/J_0 versus normalized thickness. The normalized saturation current density is J_0'/J_0 where J_0 is the ideal wide base diode case and J_0' is the saturation current including the effects of surfaces. Normalized thickness is the ratio of the physical thickness to the diffusion length.

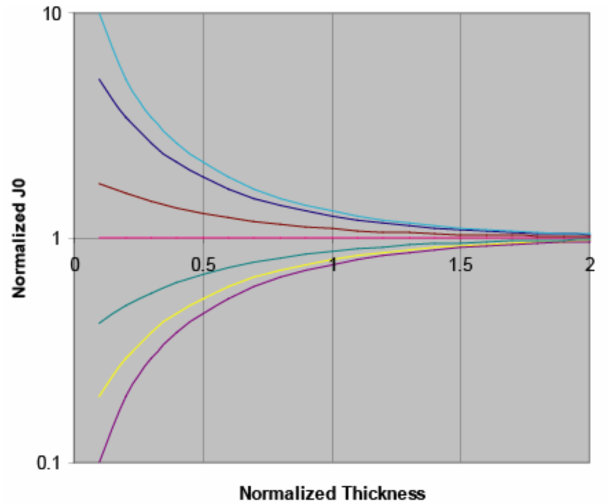


Figure 1: Normalized saturation current density vs. normalized thickness. The different curves correspond to changing SL/D, with SL/D = 0.001 (light blue), 0.1, 0.5, 1, 3, 10, 1000.

(a) Explain physically why the saturation current changes with thickness as shown in the plot.

The saturation current changes with thickness because of the interplay between surface and bulk recombination. A low saturation current for a given region results when the recombination in the volume of material on that particular side of the junction is low. When the surface recombination is low, making the device thinner (decreasing the volume for recombination) reduces the overall recombination. When the surface recombination is above some value (SL/D > 1), then moving a high recombination surface close to the junction increases the recombination.

(b) Explain physically and mathematically why SL/D = 1 has a normalized J_0 of unity.

The general equation for one side of the junction shown below. When SL/D = 1, then the term with the hyperbolic terms drops out, giving the wide base diode equation.

$$J_0 = \left(\frac{qD_n n_i^2}{L_n N_A} \cdot \frac{\cosh\left(\frac{W_P}{L_n}\right) + \frac{D_n}{S_n L_n}\sinh\left(\frac{W_P}{L_n}\right)}{\frac{D_n}{S_n L_n}\cosh\left(\frac{W_P}{L_n}\right) + \sinh\left(\frac{W_P}{L_n}\right)} \cdot \right)$$

Physically, the ratio of D/L is indicative of how fast carriers move away from the junction, and S is the rate at which they recombine at a particular surface. When these tow are equal (SL/D =1), then in terms of recombination, it doesn't matter.

(c) What implications does the above plot have for solar cell design?

The plot has several implications for solar cell design. First, the plot highlights the importance of surface recombination velocity, particularly the front surface recombination velocity. Since the generation at the front surface is so large, a high collection efficiency indicates putting the junction close to the surface, certainly well within a diffusion length of the front surface. This means that the front surface passivation must be low, or the J_0 increases and Voc decreases.

The plot also has implications for the base design. It shows the potential for high open circuit voltage if the base is made thin, provided that the rear surface recombination is low and, depending on how thin the device gets, that large light trapping can be included.

3. The following is a plot of carrier concentration in the base of a solar cell.

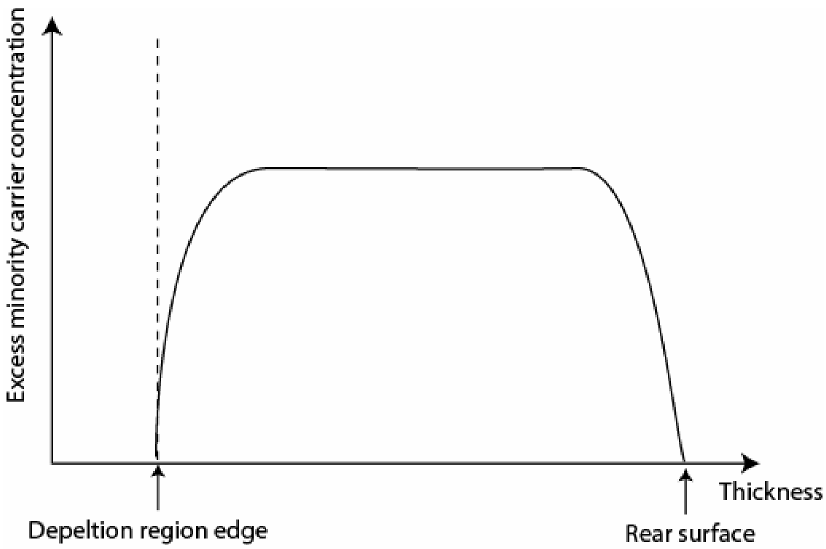


Figure 2: Excess minority carrier concentration vs. thickness in the base of a solar cell.

(a) What are the bias conditions (short circuit, open circuit, forward bias in the dark, etc) for the plot of the carrier concentration?

The device is under short circuit. There is light generation (indicated by excess carrier generation throughout the base) and the voltage at the junction is zero (indicated by zero carrier concentration).

(b) What is the surface recombination velocity at the rear of the solar cell – is it high, low, etc. Justify your answer.

The rear surface recombination is large. This can be seen because there is generation at the rear (since there is large generation in the rest of the base), but the carrier concentration at the rear is zero.

(c) What is the generation rate in the base of the solar cell? Justify you answer.

The generation rate is nearly constant throughout the base of the solar cell. This can be seen because, except for the impact of the junction and rear, the generation rate is nearly flat. This in turn implies that the light shining on the solar cell is relatively near its band gap. An expression between the excess minority carrier concentration and the generation rate is $\Delta n = G\tau$

(d) Estimate how many of the light generated carriers are collected by the base of the solar cell. Justify your answer.

Light generated carriers in the base will diffuse towards a region with lower carrier concentration. In the case shown above, the excess carriers are zero both at the junction and at the rear surface. Therefore, there will be a diffusion current towards both of these regions. Carriers diffusing towards the rear junction recombine there and are lost. Assuming uniform generation, the carriers generated closer to the junction, diffuse to the junction, while the carriers generated closer to the rear diffuse towards the rear. Therefore, about 50% of the carriers generated in the base are collected as current.