Appendix C

Current through pn Junction

It is a bit challenging to think through this clearly, because … it *is* a complicated matter.

However, below is a list of things to keep in mind. The list provides as best a way to think clearly as possible.

We will work in the ideal diode approximation.

So here is the list of things to keep in mind, to think clearly about the current in an ideal diode. Much of it has been already discussed in LN 15-16, where you can find fuller discussions. Item 4 below comes from the perturbation theory, and is perhaps the most crucial to keep in mind.

1. Account for the minority currents in the quasi-neutral p region and the quasi-neutral n region (just outside the depletion region).
2. To get the total current, add the two from the previous step, since J_n and J_p are constant in the depletion region.
3. Do not attempt to directly calculate the majority current from the first principles, since E is unknown. The majority current comes out from 1 and 2!
4. When thinking perturbatively, the starting point is to assume that the charge carrier density just outside the depletion region corresponds to zero current.
5. Do not try to think what is happening in the depletion region, because it is complicated (cf. Appendix B). Rather, think what is happening outside it. This brings us back to item 1.

Question 1 Why is the net drift current independent of V_A?

Answer 1 Following the principle 4 above, consider the equilibrium carrier densities just outside the depletion region. We consider the p side. Then, we must consider $n_{p,0}$, the equilibrium carrier density. However, note that in equilibrium, carriers get generated and die away all the time. Per unit time, we have $n_{p,0}/\tau_n$ electrons generated per volume. We like to count those electrons that pass through $x = -x_p$, the left end of the depletion region, into the depletion region. Then, only those that are generated within L_n (diffusion length) will count! So, the net drift current density is given by $-en_{p,0}L_n/\tau_n$ (negative means n to p through the depletion region). What we calculated is independent of V_A, since we took $n_p = n_{p,0}$ (cf. Appendix B), and, notice that it exactly corresponds to the 2nd term of Eq. 16.12, since $n_{p,0} = n_i^2/N_A$ and $L_n/\tau_n = D_n/L_n$. Similarly, the hole drift current density from the n side to the p side is given as $-ep_{n,0}L_p/\tau_p$.

Question 2 What is the net diffusion current?

Answer 2 Having considered the previous question, this is easy. Without V_A, this diffusion current would be the same as what we just considered for the net drift current. However, the potential barrier lowering or raising has an exponential effect on the diffusion current, and so $J_{diff} = -J_{drift}\exp(e\beta V_A)$. Thus, we get

$$J_n = \frac{en_{p,0}L_n}{\tau_n}(1 - \exp(e\beta V_A))$$

and

$$J_p = \frac{ep_{n,0}L_p}{\tau_p}(1 - \exp(e\beta V_A))$$

which are identical with Eqs. 16.12 and 16.14, respectively. These two equations, when combined and multiplied by A (crossection of device), give the Shockley equation, Eq. 16.9.

Question 3 When a pn junction is illuminated with light, what is the photo-induced current I_L in a steady state? (Slides 13,14 of LN 17) Assume G_L is the photo-induced e-h pair generation rate.

Answer 3 Within the ideal diode approximation, the following is the answer. Again, consider the p side first. Following the principle 4 above, we must first assume that $\Delta n_p = G_L\tau_n$, which is the steady state value. This is the photo-induced carrier density. Again, by counting only those electrons that pass through the $x = -x_p$ point, we get $I_{L,n} = -G_L\tau_n L_n A/\tau_n = -G_L L_n A$, since these carriers live only for τ_n and travelling L_n during that time. What about the holes that these electrons leave behind?! Since they are majority carriers, use principles 3 above! Then, we get $I_{L,p} = -G_L L_p A$, and therefore

$$I_L = -G_L A(L_n + L_p)$$

which is a partial proof of the equation in slide 14 of LN 17. So, here is a conclusion (which may be somewhat confusing!) – as N. said and I agreed, the hole left behind by the electron that disappeared into the depletion region does contribute to the current, but it is already included in this formula! There is no factor of 2 to consider! Now, a full proof that will include the explanation of the W part will require going beyond the ideal diode approximation, and I am not certain whether there is a proof… Perhaps there should be a factor of 2 in front of W after all…