Introduction to Semiconductor Devices
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Lecture – 5.4
Current in Reverse Biased PN Junction

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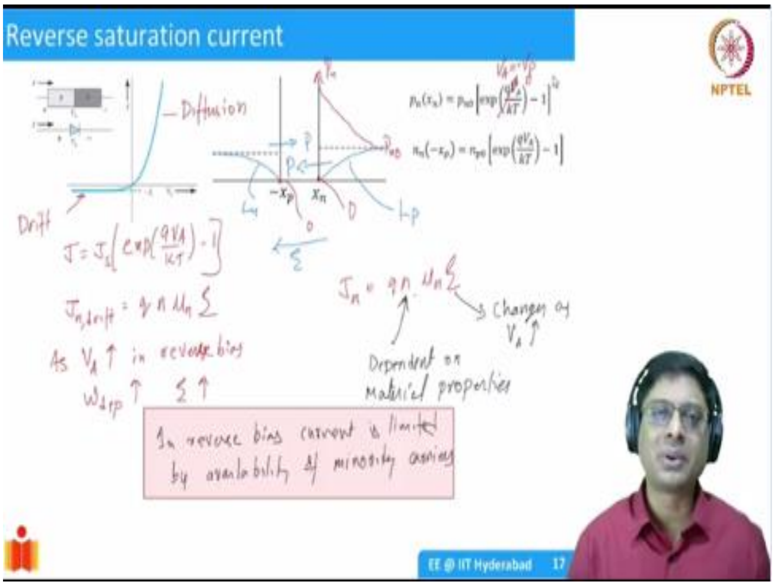

Reverse saturation current

$V_A = -V_R$

$p_n(x_n) = p_{n0}\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$

$n_p(-x_p) = n_{p0}\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$

$J = J_s\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$

$J_{n,drift} = q n \mu_n \mathcal{E}$

As $V_A \uparrow$ in reverse bias

$W_{dep} \uparrow$ $\mathcal{E} \uparrow$

$J_n = q n \mu_n \mathcal{E}$

Dependent on material properties

Changes as $V_A \uparrow$

In reverse bias current is limited by availability of minority carriers

Welcome back. So, in this video, we would like to study the behaviour of reverse saturation current. We already mentioned, we know that reverse saturation current is essentially this which is coming out of the expression. For example, if you write the total current, current is going to be:

$$J = J_s(e^{\frac{qV_A}{kT}} - 1)$$

So, when VA is negative, it is going to be –J s. And that is what we are showing here.

In the forward bias, we said the diffusion current is dominant. And that is seems to be okay. You have, as you increase the applied voltage, there is a greater amount of diffusion and you see greater amount of current flowing. But if you look at the reverse bias, here, we said that drift is dominant, drift current, there is no diffusion, because this is a barrier.

When the drift current is present, the drift current expression is let us, if you just take electrons:

$$J_{n,drift} = qn\mu_n E$$

And as you apply electric, as V A is increased in reverse bias. What do we expect? The depletion width is going to increase; W depletion is going to increase. And essentially, what is electric field?

Electric field is simply:

$$E = \frac{V_{applied}}{Width}$$

It is not exactly this, because we know the functional form; it is an integral; you have to take the charge density and you have to compute the integral. So, as the width is increasing, the electric field should increase. The peak electric field will definitely increase. So, as you go further and further into reverse bias, the electric field is increasing, but the drift current seems to be constant.

You get the drift essentially. So essentially, what we are saying is: as you increase the reverse bias voltage, the depletion width is increasing, that means peak electric field is increasing. Even the electric field is increasing; it seems that the drift current is constant, which is a very strange thing. We never see that, whenever we studied the drift current, you saw that the drift current is proportional to electric.

If electric field increases, the drift increases. That is what we are seeing in the simple semiconductor cases. Now, it is something different. And it is kind of a puzzle; I want you to think about it, what is happening here. If you thought about it to answer this puzzle, you have to understand how the minority carrier profiles look like. So, we have seen this multiple times.

So essentially, in forward bias, the minority carrier profile is going to be like this. What happens in reverse bias? How does a minority carrier profile look like? If you simply plug into the equation here, so if VA is negative, VA = –VR, let us say something, you apply a negative voltage, this term is what about 0. So, the minority carrier density at xn is going to be –p0.

So, this is going to be essentially 0 because this is your pn if you take it, so this is your pn0, and you subtract pn0 from it, you are going to get 0 at x = xn. And similarly, here, you are going to get 0. So, what does it mean? It means that instead of having excess minority carriers, we have a deficit of minority carriers. Minority carriers are being removed. And why are they be removed? Well, look at the electric filed.

Electric filed directly is this from n to p. So, happily, you know, your minority carrier holes will travel. So, p will you know, holes will go in this direction. Electrons will go in this direction. So, the minority carriers whatever are present in the n and the p regions, they are going to be swept away across the depletion region. So, we are creating deficit of minority carriers. What happens when you have deficit of minority carriers?

Well, always remember semiconductor is going to try to come back to equilibrium. If you have excess minority carriers, they will recombine and come back to equilibrium. If you have a deficit of minority carriers, it is going to generate and come back to equilibrium. Equilibrium is something that nature loves. So, we always try to come back to equilibrium. So, how does the profile look like in the reverse class?

The minority carrier profile is going to be exponentially increasing the same diffusion length Lp is going to be there. So, over a few diffusion lengths, the minority carriers are going to come back to equilibrium. Similarly, on the electron side, they are going to come back to equilibrium. Sorry, on the p side, electrons are going to come back to the equilibrium after a few diffusion lengths. So, can this explain dilemma? Well, it does.

In the reverse bias, the important thing is not really the electric field, but the number of carriers that are important. So, I have kind of you know, deliberately not emphasize so,

$$J_n = qn\mu_n E$$

E changes as V applied increases in reverse bias. But, what happens to n? This is dependent on the material properties.

What is the diffusion length? What is the doping and all that? And everything is interrelated. Essentially, this depends on material properties. J in reverse bias, current is limited by availability of minority carriers where minority carrier is the edge of the depletion region.

As many electrons as many minority carriers are present, those many of them will be swept across the depletion region. Electric field is sufficient to sweep them off. But we are going to be limited with a number of carriers. That is why in the reverse bias, the current is constant. So, this is a very subtle point. But this is important to consider.

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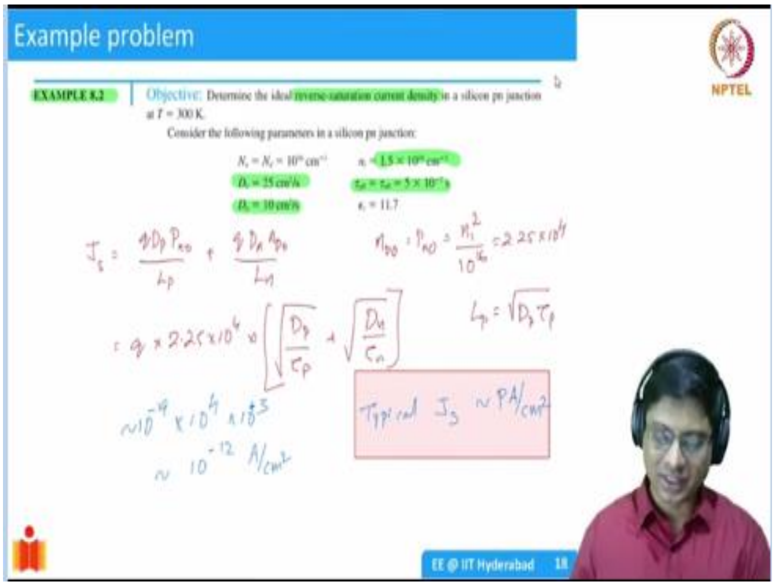

Example problem

EXAMPLE 8.2 Objective: Determine the ideal reverse-saturation current density in a silicon pn junction at $T = 300$ K.

Consider the following parameters in a silicon pn junction:

$N_a = N_d = 10^{16}$ cm^{-3} $n_i = 1.5 \times 10^{10}$ cm^{-3}

$D_n = 25$ cm^2/s $\tau_{p0} = \tau_{n0} = 5 \times 10^{-7}$ s

$D_p = 10$ cm^2/s $\epsilon_r = 11.7$

$$J_s = \frac{qD_p P_{no}}{L_p} + \frac{qD_n n_{po}}{L_n}$$

$$n_{po} = P_{no} = \frac{n_i^2}{10^{16}} = 2.25 \times 10^4$$

$$= q \times 2.25 \times 10^4 \times \left[\sqrt{\frac{D_p}{\tau_p}} + \sqrt{\frac{D_n}{\tau_n}}\right]$$

$$L_p = \sqrt{D_p \tau_p}$$

$$\sim 10^{-19} \times 10^4 \times 10^{+3}$$

$$\sim 10^{-12} \; A/cm^2$$

$$\boxed{\text{Typical } J_s \sim pA/cm^2}$$

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Let us try to solve a small problem, but I am not going to fully solve it. This is from the example from the textbook 8.2. The solution is given. So, I would like you to go back and you know, do it by yourself. But let us just walk through the procedure right now. So, we are given a semiconductor with Na Nd is equal to 10^16; ni is given. So, diffusion coefficients are given to you and then $\tau's$ are given to you; lifetimes are given to you.

So, you are asked to calculate the reverse saturation current density. How much is it? Well, that is going to be dependent on; now, we have to calculate the numbers.

$$J_s = \frac{qD_pP_{no}}{L_p} + \frac{qD_nn_{po}}{L_n}$$

$$n_{po} = p_{no} = \frac{n_i^2}{10^{16}}$$

$$= 2.2.5 * 10^4$$

$$= 2.25 * 10^4 * \left[\frac{D_p}{\tau_p} + \frac{D_n}{\tau_n}\right]; \quad Lp = \sqrt{D_pL_p}$$

$$= \sim 10^{-19} * 10^4[10^{+3}]$$

$$= \sim 10^{-12}$$

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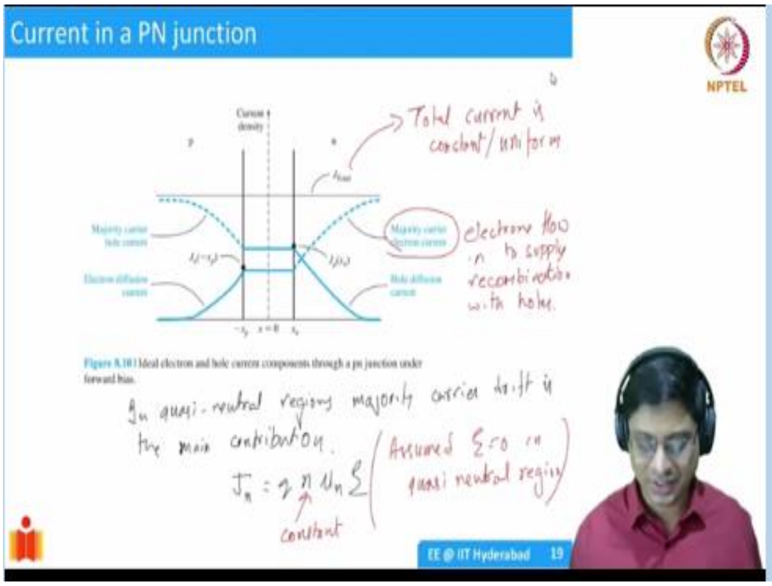

Current in a PN junction

Figure 8.10 | Ideal electron and hole current components through a pn junction under forward bias.

Total current is constant/uniform

electrons flow in to supply recombination with holes.

In quasi-neutral regions majority carrier drift is the main contribution.

$J_n = q\,n\,\mu_n\,\xi$

constant

(Assumed $\xi \neq 0$ in quasi neutral region)

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And then with that, we can essentially sum up what are the different currents in a PN junction. So, if you look at the various contributions, we saw that at the edge of the depletion region, you have the diffusion current which is going to be dominant. And as you go deeper into the semiconductor, the diffusion current is going to reduce. As you go into the N type semiconductor, the diffusion, sorry P type semiconductor is going to reduce and as holes are reducing, number of electrons is increasing.

So, essentially, this was a minority carrier current which is reducing and that is being substituted by the majority carrier current which is basically the electrons; electrons flowing to supply recombination with holes. So, the diffusion is providing only holes. Electrons have to come in. Electrons will come in for the N type semiconductor, so the majority carriers. So, as you go deeper into the semiconductor, you will see that the majority carrier current is picking up.

And similarly, on the P side, at the junction, you have the diffusion current, which is there, but as you go deeper into the P type, the majority carrier holes will be supplied by the P type semiconductor, so, that is dominant. So, overall, one important tool that can never be broken is that the total current is constant or rather, uniform, because you are not having any other source of sync of current.

So, essentially whatever is coming from the left has to go into the right; only the distribution changes in the Quasi neutral regions, you have the drift current which is dominating. It is a majority carry drift that is dominating, but at the junction, it is a diffusion of minority carriers that is dominating. So, please take a moment; look at this diagram and try to draw it by yourself.

When you do that, you will see that there are a lot of assumptions that are here which are kind of not mentioned, but you will see that you know, how they are coming into picture. So, this is about a total current. Let us try to answer one more puzzle, I am not sure if you have thought about it. So, what I am saying is here. In the Quasi neutral regions, majority carrier drift is the main contribution actually.

So, we come back to the same problem. What is drift? Drift is going to be J n:

$$J_n = qn\mu_n E$$

In the Quasi neutral region n is constant. This is constant. Is not it? And μ and q are material constants. And remember we assumed E = 0; in quasi neutral regions when we are drawing the band diagrams, we said E is going to be 0.

Is it really true? Because there is some current. And of course, it is a uniformly doped semiconductor. So, there is no n changing; there is no q changing; there is no μ changing. So, there is going to be some electric field. So, we would like to compute the electric field also.

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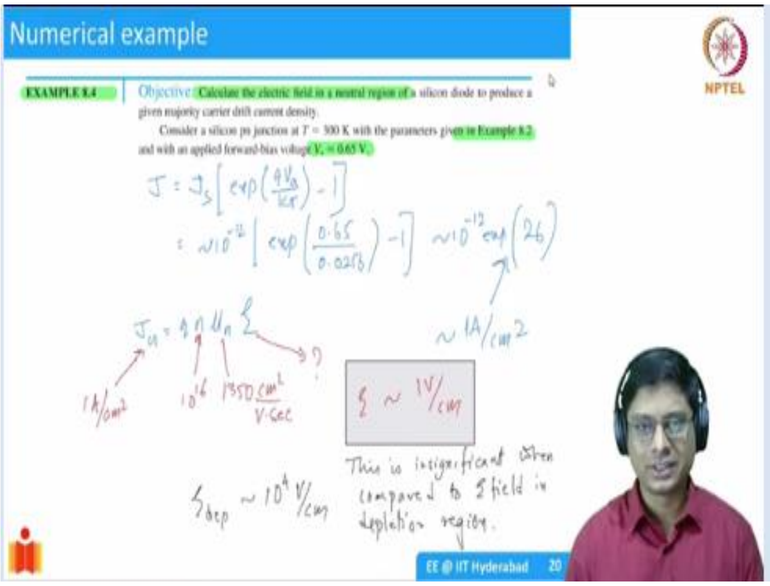

Numerical example

EXAMPLE 8.4 Objective: Calculate the electric field in a neutral region of a silicon diode to produce a given majority carrier drift current density.

Consider a silicon pn junction at $T = 300$ K with the parameters given in Example 8.2 and with an applied forward-bias voltage $V_a = 0.65$ V.

$$J = J_s\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$$

$$= \sim 10^{-12}\left[\exp\left(\frac{0.65}{0.0258}\right) - 1\right] \sim 10^{-12}\exp(26)$$

$$\sim 1\,A/cm^2$$

$$J_n = q\,n\,\mu_n\,\xi$$

$$\boxed{\xi \sim 1\,V/cm}$$

$$\xi_{dep} \sim 10^4\,V/cm$$

This is insignificant when compared to ξ field in depletion region.

And that is what is done in this problem. I will leave it to you as homework. The solution is there. Please go and understand the problem. So, essentially, here, they are asking you to calculate the electric field in the Quasi neutral region. How will you calculate that? First we will calculate Js saturation current and then calculate J:

$$
\begin{aligned}
J &= J_s\left(e^{\frac{qV_A}{kT}} - 1\right)\\
&= \sim 10^{-12}\left[e^{\frac{0.65}{0.0256}} - 1\right]\\
&= \sim 10^{-12}e^{26}\\
&= \sim 1A/cm^2
\end{aligned}
$$

So, if you have 1 amp per centimetre square, what is the electric field?

$$J_n = qn\mu_n E$$

$J_n = 1\frac{A}{cm^2}$, $q = 10^{16}$, $\mu_n = 1350\frac{cm^2}{Vsec}$. What is the electric field? We compute. We have everything given to you. So, you will see that this is going to be approximately some 1 volt/centimetre. That is going to be a range. So, there is a very small electric field. So, this is insignificant when compared to E field in depletion region. How much was it in the depletion region? Remember, $E_{depletion} = 10^4\ V/cm$.

It is reasonably high I mean, 4 orders of magnitude higher when compared to the electric field in the Quasi neutral region. And that is why we can make that assumption. That assumption is still correct. It is not wrong whatever band diagrams we are drawn are not wrong. It just ignores the minor point that there is a small electric field across a Quasi neutral region, not a large electric.

Well, it is also possible because, you know, it is kind of plausible because it is a semiconductor. Semiconductors are going to have some, you know, have finite resistivity. They are not like metals. In metal, we say that electric field is purely 0 because they have huge carrier density. Then, electric field, I mean even then it is going to be small thing but it would be negligible.

So, with that, I would like to stop this discussion on the reverse saturation current. In the next lecture, we will talk about capacitors, you know, how the depletion capacitance changes. So, we will see that there is certain depletion capacitance associated with the PN junction. And then we will also talk about a few non-idealities in a PN junction device. So, that is it for now. Thank you very much for your attention. I look forward to seeing you in the next lecture. Bye.