Introduction to Semiconductor Devices
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Lecture - 5.3
Current in Forward Biased PN Junction

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Hello everyone, welcome back to Introduction to Semiconductor Devices. In the last lecture, we looked at the basic biasing schemes for the PN junctions. So, essentially we have forward bias and reverse bias. And we look at what. How the band diagrams will change for these conditions? And then we looked at the injection of excess minority carriers.

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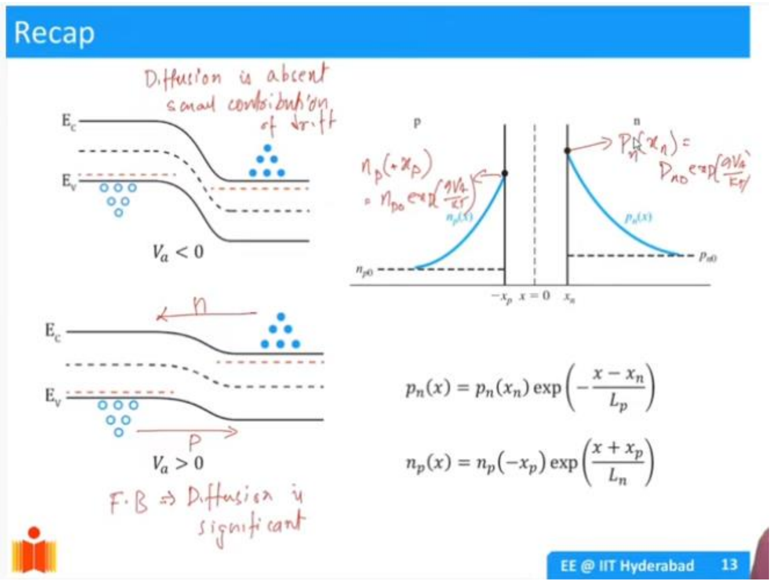

So, quickly to recap, we have seen that if you have reverse bias, diffusion is insignificant diffusion is you can say even absent because there is a large potential barrier, diffusion is absent. So, and there is also small contribution of drift because there is an electric field there is going to be a drift of minority carriers. And since the total number of minority carriers is small, the drift current is going to be small. This is for reverse bias.

When you come to forward bias, we saw that the potential barrier is reduced and because of which you have the drift of holes sorry drift of electrons from N type to P type and holes from P type to N type. So, forward bias implies diffusion is dominant is significant whatever. There is going to be a small contribution of drift, but that is going to be negligible when compared to the diffusion contribution.

And then we also looked at how the excess minority carriers are injected. We saw this diagram. At the edge of the depletion region, we can write an expression for the holes in this case. Holes are getting injected from the P type semiconductor

$$p_n(x_n) = p_{no}exp\left(\frac{qVa}{KT}\right)$$

So, I need you to really you know go through it multiple times.That is the reason why I am also writing it so that you will sort of understand the full thought flow. And, what about the electron concentrations in the P type at x = - X_p?

$$n_p(x_p) = n_{po}exp\left(\frac{qVa}{KT}\right)$$

So, this is at the edge of the depletion. And once you have that, we can solve the minority carrier diffusion equation. And we can get this exponentially decaying profile.

Why do the holes decay? As you go deeper into the N type semiconductor, the reason they decay is that they will recombine with the electrons and then the holes are removed. So, essentially we go back to equilibrium. This we have discussed in the lecture about excess minority carriers. And similarly, you have for electron there is a decaying profile on the in the P type semiconductor. So, today, we would like to determine the current in the forward direction.

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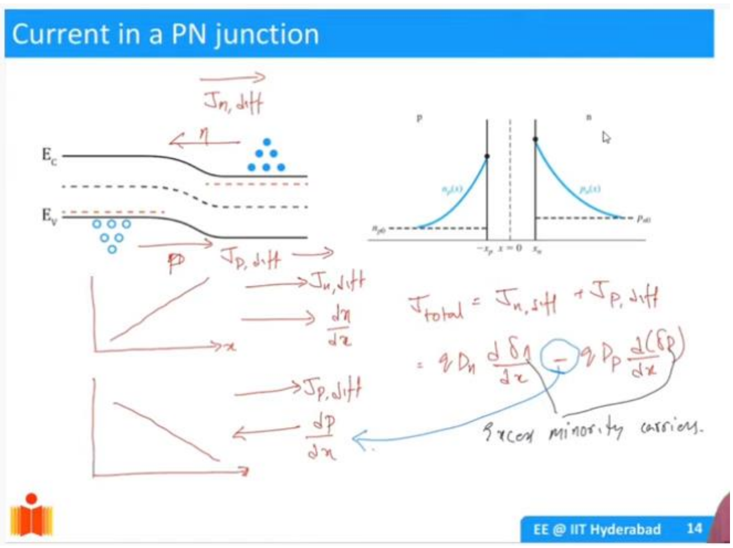

In this video, we will talk about current in the forward bias regime. So, well, you have electron diffusion and hole diffusion. What is the direction of current? If you analyze if you look at just the electrons I just want to draw the gradient. So, essentially as a function of x if I want to draw how the electron concentration is changing, I see that electrons are increasing as you go from left to right.

And the current direction is essentially because electrons are going from right to left Jn diffusion is going to be from left to right. So, what is happening is you have this is a Jn diffusion and your gradient $\frac{dn}{dx}$ also is in the same direction. Whereas, if you look at holes the concentration of holes is reducing as you go from left to right. And the current hole current is essentially sorry, this is I do not know what. This is P.
So, this is Jp diffusion. The hole current is in the left to right direction. So, Jp diffusion is left to right. Whereas, dP/dx is in the opposing direction. That is why we can write basically the

$$J_{total} = J_{n,diff} + J_{p,diff}$$

. The total contribution is from electrons and holes. The drift is not going to contribute significantly. So, we can write this as

$$qD_n \frac{d\delta n}{dx} - qD_p \frac{d\delta p}{dx}$$

So, this $d\delta n$ and $d\delta p$ are the excess minority carriers. And note this is coming because this sign is coming due to this the diffusion current is actually opposing the gradient. That is why there is a minus sign. So, now, we can easily derive the currents. Let us do it for holes.

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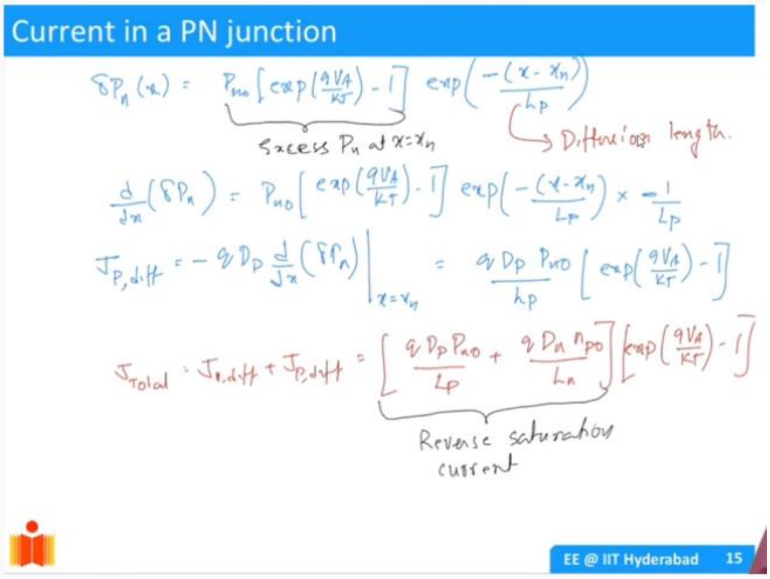

So, first let us write out, what is the excess hole density? We can write I mean this is a function of x. So, this is going to be the total hole density which is going to

$$\delta p_n(x) = P_{no}\left(exp\left(\frac{qV_A}{KT}\right) - 1\right)$$

So, essentially I am taking this is my excess Pn at x = x n. And we know that as you go deeper into the semiconductor, there is an exponential decay.

So, this guy should be multiplied by

$$\delta p_n(x) = P_{no}\left(exp\left(\frac{qV_A}{KT}\right) - 1\right)\exp\left(-\frac{(x-x_n)}{L_p}\right)$$

So, this is essentially capturing the diffusion length. So, what this is telling you is that as you go deeper into semiconductor, there is an exponential decay. So, let us take the derivative of this. Since the diffusion term has a derivative, let us do that

So, that is going to be minus 1 by L P. So, now, J P diffusion is going to be minus q D P d by dx of delta P n. We do not need to compute this at all x. We just need to know it at x equal to x n. Because at other points, it is going to reduce but let us focus on that because that is where the maximum diffusion current is going to be there. So, then this is going to be equal to the minus and minus will cancel out.

$$\frac{d}{dx}(\delta p_n) = \ Pno\left[exp\left(\frac{qVA}{KT}\right) - 1\right]exp[-\left(\frac{(x - x_n)}{L_p}\right)] \times \frac{-1}{L_p}$$

$$Jp,diff \ = \ -qD_p\frac{d}{dx}(\delta P_n)\Big|_{x-x_n} \ = \ qDpPno\left[exp(\frac{qVA}{KT}) - 1\right]$$

$$J_{Total} = \ J_{n,diff} + J_{p,diff} \ = \ \left[\frac{qDpp_{no}}{L_p} + \frac{qDnn_{po}}{L_n}\right]\left[exp\left(\frac{qVA}{KT}\right) - 1\right]$$

This is the total current. And this particular term here in the brackets, we call it reverse saturation current. We will see in a moment why that is. But anyway this is the overall form. So, now, so, how does the current look like?

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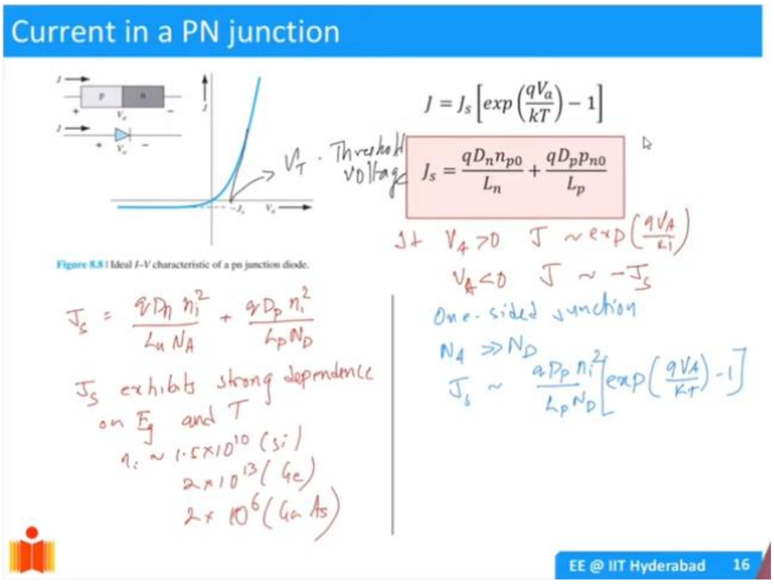

Well, you could summarize it this way, the same expressions now is written in you know legible form here.

$$J = Js\left[exp\left(\frac{qVa}{KT}\right) - 1\right]$$

$$Js = \frac{qDnn_{p0}}{L_n} + \frac{qDpPno}{L_p}$$

That is a reverse saturation current. And your current is going to be. So, immediately, you will see that as the applied voltage is increased, as Va is increased, exponential term will grow significantly. And then that will dominate. So, in the forward direction, your PN junction tends to contribute.

The current tends to increase exponentially as you increase voltage. Whereas if you go to reverse bias, what happens is as you know as Va I can write

If Va >0

$$J \sim exp\left(\frac{qVa}{KT}\right)$$

If Va < 0,

$$J \sim -J_s$$

So, that is why the current can be drawn for a diode in this fashion. So, for negative voltages, you have a constant current. And as you go into forward bias, it starts increasing exponentially. So, this is the action of a diode which we must have studied you know in our plus 2 and so on. So, that is how you get these expressions. We can analyze these expressions a little bit. We can make couple of points.

The first one is, you see here that there is a n_{p0} and Pno. These are minority carrier densities. And we have seen that the minority carrier densities are essentially dependent on doping and ni. So, I can write my minority carrier density in this form. So, I will say

$$Js = \frac{qD_n n_i^2}{L_n NA} + \frac{qD_P n_i^2}{L_P N_D}$$

So, one of the important things we will see here is the saturation J_S saturation current density, it exhibits strong dependence on the temperature and band gap because we know that ni is having a strong dependence on the band gap and temperature. So, J S also exhibits strong dependence on Eg and temperature.

For example, you know, we have seen ni for silicon it is 1.5×10^{10} for silicon. For germanium, it was I think it was $2 \times 10^{13}$for germanium whereas for gallium arsenide it was 2×10^{6} .So, you see that if you make a diode out of different materials immediately you are going to have a dramatically different saturation current density.

So, saturation density current densities cannot be compared across materials. See, because it is n_i^2 the saturation current density has n_i^2 dependence. So, the dark currents will be much higher in germanium whereas in gallium arsenide they are going to be small. So, this is one of the points we can make from the expression just purely mathematically. The other thing is, we have introduced what is called as a one sided junction.

So, what happens in a one sided junction? We said that if one of the doping densities is higher for example let us say $N_A >> N_D$. So, what current will flow essentially? So, essentially this is going to mean that the since N_A is higher the contribution you know this in the expression here J_S will approximately will become

$$Js \sim \frac{qDnn_i^2}{L_p ND}\left(exp\left(\frac{qVA}{KT}\right) - 1\right)$$

The reason this happens is ni is in the denominator for the electron term. So, electron term is not going to be significant. So, I mean it could also be understood physically. N_A is high means that P region has high large number of holes. And this large density of holes is getting injected into the other side. So, the current is going to be predominantly in the form of hole diffusion.

The electron diffusion contribution is going to be neglible. That is what this means. So, depending on what type of doping is high that is going to dominate . If you have a N type doping higher that N_D is higher, then electron diffusion is going to dominate. So, we can look at relative doping densities and decide, you know, what is the dominant contribution?

So, overall we see that the current in a diode exhibits an exponential dependence. And I forgot to mention that, you know, if you look at this exponential, you can draw basically intercept where it intercepts the x axis, draw the current and take it to intercept. And this point is called as V_T and which we call as threshold voltage. So, it is kind of a voltage at which essentially the diode turns on.

You have a large current flowing below that it does not allow any current to flow. So, that is the diode action. And we will analyze a few more things especially the reverse bias, reverse saturation current we will analyze in a little bit more depth in the next video. So, but I would like to stop here. And then we will continue in the next video. Thank you.