Introduction to Semiconductor Devices
Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture - 5.2
Minority Carrier Injection in PN Junctions

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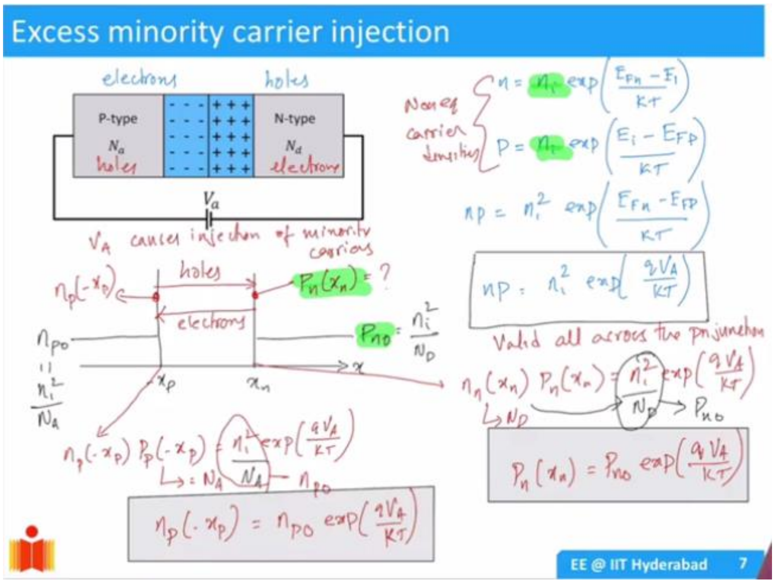

Welcome back. So, now, we would like to understand the current flow in a PN junction more quantitatively. To do that, we need to understand how the minority carrier injection takes place. So, what is minority carrier injection? So, we have seen that we have a P type semiconductor and a N type semiconductor. So, the majority carriers are here in this case it is holes here electrons.

It turns out that the current flow in a PN junction is not dictated by the majority carriers but it is actually dictated by the minority carriers. So, what are the minority carriers now? Minority carriers in case of P type semiconductor are electrons and on the N type it is holes. How these carriers flow is what is going to influence. So, to understand that, we will actually draw a diagram multiple time today.

So, I will just take a moment to just quickly run through that. So, what we would like to plot is a minority carrier concentration as a function of position. So, what I will do is I will take let me say x axis. And on the y axis, I would like to plot the minority carrier concentration. So, I will just first denote my minus xp which is the edge of the depletion region on the P side. And xn which is a depletion width edge of the depletion region on the N side.

So, once I have this, what is the concentration of minority carriers in the N type semiconductor? So, the concentration of minority carriers I will represent by I will say P. Holes of the minority carriers so P. But in the N type semiconductor, an equilibrium minority carrier density is what I want to first find out. What is it going to be?

$$P_{no} = n_i^2/N_D$$

And same thing I want to do on the P side. So, how would you do that? So, I can say, there will be, in this case, electrons are the minority carriers.

$$N_{po} = n_i^2/N_A$$

So, this is how the equilibrium minority carrier concentrations are without any applied voltage.

Now, what happens when we apply a voltage? That is where a lot of interesting things happen. So, when we apply a voltage, we said that we are actually injecting holes into the N side. Similarly, we are injecting electrons to the P side. So, essentially, VA causes injection of minority carriers. In an N type semiconductor, we are injecting holes into it.

Similarly, in the P type semiconductor, we are injecting electrons. So, the question we want to ask is what is the concentration of holes at the edge of the depletion region? So, I will say, concentration of holes in the N type semiconductor at xn is equal to how much? That is very important for us, because, once we know that we can find out what happens, you know, further into the N type semiconductor.

Similarly, I want to find out what is the concentration of electrons in the P type semiconductor at -xP. If I know this, then I can determine the rest of the concentrations because I have the minority carrier diffusion equation with me. So, how do we determine this?

Remember, this quantity $P_n(x_n)$ is a non-equilibrium situation, it is going to be higher than the P_{no}. P_{no} were an equilibrium density and we saw that P_{no} was relatively low because that doping was 10^{14} whatever and correspondingly the P_{no} will be lower. But now, we are taking the majority carriers on the P side, which has a lot of them, it can be 10^{16}.

And then we are injecting into the other side of the barrier and we saw the barrier width was about one micron. So, we are easily injecting holes into the N side. So, lot we are like putting too many minority carriers. What happens? How do we determine this? Well, to understand the minority carrier dynamics, or whenever you have non-equilibrium situations, we introduce the concept of quasi-Fermi levels.

So, we will make use of that. So, I would like you to review or you know, try to recollect the carrier densities in terms of the quasi-Fermi levels. So, what are they? So, for non-equilibrium electron concentration. And that is given by the quasi-Fermi level.

$$n = n_i e(\frac{E_{fn} - E_i}{kT})$$

This is a definition of the quasi-Fermi level for a N type semiconductor for an electron. And, what about the P for the holes?

$$p = n_i e(\frac{E_i - E_{fp}}{kT})$$

Remember, I am using this as a reference level ni. My majority carriers are going to be higher than that I just think about that, and then I put an appropriate sign. Otherwise, there is a chance of getting confused with the sign in the exponential. So, please form your, whatever works for you, you just figure it out. So, you have this non-equilibrium carrier densities. So, what?

Well, you can take an np product I said non-equilibrium means it is not equal to ni^2. But now, what exactly is it? So, it turns out that if you take np product:

$$np = n_i^2 e\left(\frac{E_{fn} - E_{fp}}{kT}\right)$$

$$np = n_i^2 e\left(\frac{qV_A}{kT}\right); Valid\ all\ across\ the\ pn\ junction$$

We said that the difference in the Fermi levels in the N and the P is basically the applied voltage. So, now, how does this help us? This is actually very important relation. We call it actually the *law of the junction*. So, what this is telling us is this is valid all across the PN junction. So, now we will try to apply it. So, let us try to apply first at this point -xp. So, what is n at -xp?

$$n_p(-x_p)p_p(-x_p) = n_i^2 e\left(\frac{qV_A}{kT}\right)$$

$$n_p(-x_p)N_A = n_i^2 e\left(\frac{qV_A}{kT}\right)$$

$$n_p(-x_p) = \frac{n_i^2}{N_A} e\left(\frac{qV_A}{kT}\right)$$

$$n_p(-x_p) = n_{po} e\left(\frac{qV_A}{kT}\right)$$

Similarly, I can do the same analysis at xn. We are writing simply np product. So, here, it is an N type semiconductor. So, I will write electrons in the N type semiconductor at my point xn. xn is the edge of the depletion region at that point I want to know.

$$n_n(-x_n)p_n(-x_n) = n_i^2 e\left(\frac{qV_A}{kT}\right)$$

$$n_n(-x_n)N_D = n_i^2 e\left(\frac{qV_A}{kT}\right)$$

$$n_n(-x_n) = \frac{n_i^2}{N_D} e\left(\frac{qV_A}{kT}\right)$$

$$n_n(-x_n) = n_{po} e\left(\frac{qV_A}{kT}\right); Law\ of\ Juntion$$

So, this is my minority carrier densities at the edges of the depletion region.

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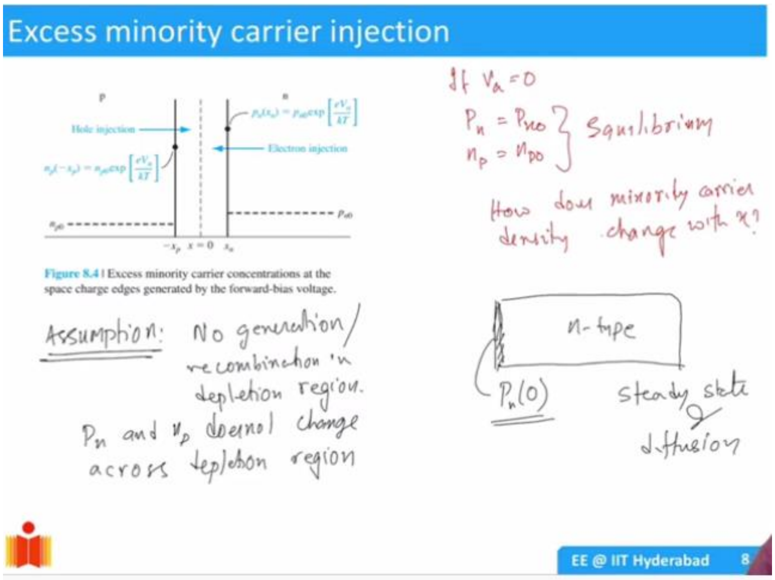

So, the edge is your equilibrium density of holes was lower and now this you have the excess minority carriers, which is you know on the scale here. Similarly, the electrons were low. But because this electron injection has happened across the depletion region, there is an excess minority carrier density in the N type region.

Well, we made a very implicit assumption without actually specifying it. So, the assumption we made was there is no generation or recombination in depletion region. This is actually a not a very strong assumption. I mean, it is not a well-qualified assumption, I would say. The reason is, whenever you take semiconductor out of equilibrium, it will try to come back to equilibrium.

So, we saw that if you introduce excess electron hole pairs, they will recombine and come back to equilibrium. Similarly, if you remove electron hole pairs, that is what we did in the depletion region, electron hole pairs will be generated and then it will try to come back to equilibrium. So, there is going to be some generation of electron hole pairs. That is going to influence your current slightly. But for now we are neglecting it.

The reason is it is, it makes our mathematics simpler for now. And in the end, we will show you the effect of violating this assumption. It is not going to be that significant. So, we say okay it is fine even if we had neglected. So, we say, you know, it is a kind of a roundabout way of proving something. If you want to prove x equal to y, we can sort out by actually saying that x is not equal to y. But if you do that, you are still consistent.

So, x is not equal to y is not consistent. So, x has to be equal to y. That sort of a proof we are doing something similar here. So, essentially, when we are saying that there is no generation and recombination, we are saying that pn and np does not change across depletion region. So, this is what your excess minority carrier looks like. Now, let us do a quick sanity check.

I mean, I mentioned this, but you know just for completeness, let us say if VA equal to 0, what happens? Your minority carrier density pn is going to be equal to p_{no}. Similarly, np is equal to n_{po}. So, this is equilibrium. Only when applied voltage is not equal to 0, then you have non-equilibrium situations. Now, the next question is how does the minority carrier density change with position?

So, all we have done so far is we know the minority carrier density at the edges of the depletion region? How does it change with position change with x? Think about it. Or you know you might recall in the third week I think we have done. We have discussed the minority carrier diffusion equation, MCDE. So, we have taken a situation wherein you have, let us say a semiconductor. And somehow, we are introducing some minority carriers here.

So, let us say, if it is an N type semiconductor, you have introduced let us say pn at 0 point. And then assume that you have reached steady state we applied a voltage or current applied a voltage and waited. So, we are introducing a steady number of p_{no} pn at 0. What happens to the density as you move into the semiconductor? So, we have taken the case of you know, we have to steady state and diffusion.

I do not remember which case it was, but one of the cases was this. So, we saw that when you have a situation like this, there is going to be an exponential decay. That is exactly what you know, we will not solve it now.

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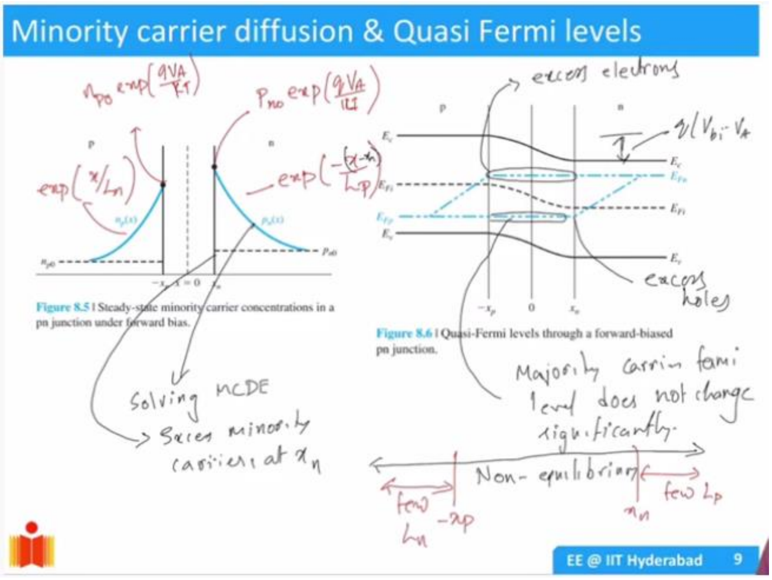

If you are not convinced, go back and look at that particular lecture and it will become clearer. So, what our analysis told us is, this is simply going to be $p_{no}e(\frac{qV_A}{kT})$ at the edge. And then, if you are going into the semiconductor, here, this is going to be simply $-e(-x/L_p)$.

Similarly, on this side, this is going to be $e(x/L_n)$. Here, minority carriers are electrons. I removed the minus because x is minus on this side, so I just you know left it for that you know. So, x is going to be minus so it is going to decay. And we know of course, this is basically $n_{po}e(\frac{qV_A}{kT})$.

So, you have this excess minority carriers and they are going to decay into the semiconductor. And, how was this obtained? This is actually obtained by solving MCDE. So, I mentioned that this point is a source you know excess minority carriers at xn. I should correct myself here. This is not simply x. This is x - xn because at x equal to xn, this is going to be the maximum $p_{no}e(\frac{qV_A}{kT})$. So, now, what happens to the band diagram? The band diagram becomes slightly more complicated. But we know what happens whenever you have a decay exponential decay in the minority carriers that will show up as a straight line on the band diagram.

So, we have taken the original you know forward bias PN junction. So, this is basically lower. So, this is going to be my $q(V_{bi} - V_{applied})$. So, the barrier has reduced. And you have the majority carriers which are electrons here. And the majority carriers are more or less same, but we have injected a number of minority carriers here.
So, here you have electrons and you are injecting them into the P side. The moment you come into the P side; it essentially becomes minority carrier. So, this is my point of excess electrons. And here, this is excess holes which are minority carriers. And as you go deeper into the N type semiconductor, these holes will recombine with electrons and eventually the quasi-Fermi level will go back and merge with the Fermi level.

So, similarly, on the P side, we have injected electrons here which are the minority carriers. As they go deeper into the P type semiconductor, the holes will recombine with electrons. Sorry, in this case, electrons will recombine with holes. And then they go back to equilibrium Fermi level. So, remember always, this is the majority carrier Fermi level. So, majority carrier Fermi level does not change much change significantly.

There is going to be some slope but it is very small. Of course, it also depends on how much excess minority carriers you have introduced. If you have introduced a lot of minority carriers then it will change. Anyway, that was electron hole reproduction in the case we have discussed for the MCDE in the Week 6. I think it was Lecture 6 I believe, Lecture 5. So, there we are producing both electron and holes.

But now, we are simply injecting only electrons or holes. So, EF for the majority carriers it is going to be flat. So, if you look at this band diagram, can you tell me where is the semiconductor in equilibrium where it is not in equilibrium? Well, it is in non-equilibrium for -x. Well, actually this is -xp let us say. This is x n. So, it is going to be non-equilibrium for a few diffusion lengths.

This is basically few diffusion lengths; few Ln. Similarly, this is you know few Lp. So, for the entire region here, spanning the depletion region and a few diffusion lengths outside that as well you know this is going to be non-equilibrium. Everything else outside is in equilibrium. So, that is why we should see that the Fermi level is constant. There is only one Fermi level.

Whenever, you have splitting of Fermi level into 2 quasi-Fermi levels that is a sign that we are in non-equilibrium situation. So, we have excess, in this case, excess holes. Here, we have excess electrons. How do we know that it is the minority carrier? Because minority carriers will change majority carriers are not changing. You do not need to know much. You just I can give you this just these lines which are the band diagrams.

And then that will tell you everything you need to know Let me take a few minutes to just solve one numerical problem so that we get an order of magnitude.

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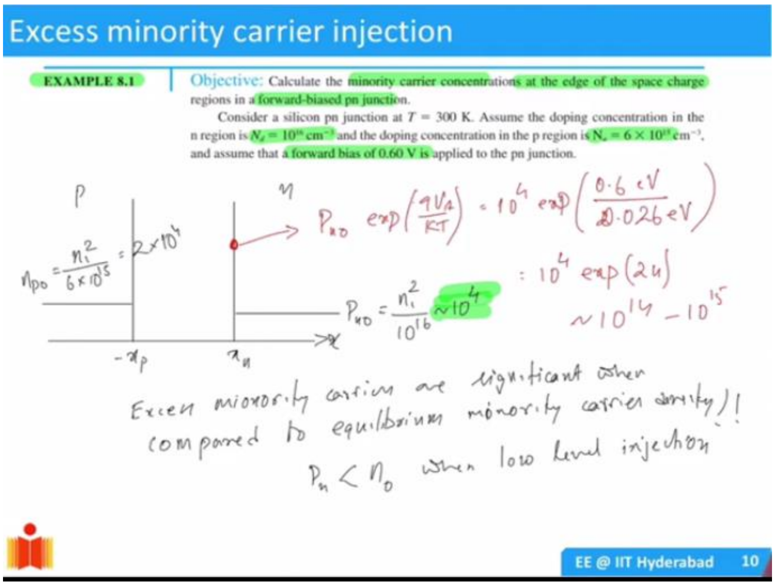

You know, we understand how much it is. So, to do that, here is a simple problem from the textbook, Example 8.1. So, please go back and refer if you have any concerns or doubts. And then we are essentially talking about forward bias PN junction with the ND given NA given. And there is an applied forward bias voltage. And we are asked to calculate the minority carrier concentrations at the edge of the space charge region minority carrier concentrations.

So, essentially, let us draw the diagram, I want you to practice it. Let me say there is x and then there is a depletion edge. And there is another depletion edge. So, this is my xn, this is my xp. So, I wanted to show the carrier concentrations here.

So, what will it be for the N type semiconductor? This is N type and this is P type and this is between depletion width. So, in the N type semiconductor, we are going to talk off P_{no} equilibrium density of holes.

$$P_{no} = n_i^2/10^{16}$$

What about the P type semiconductor? P type has a slightly lower doping density. So, the minority carrier concentration is going to be slightly higher. So, here I want

$$n_{po} = \frac{n_i^2}{6 * 10^{15}}$$

So, please make sure that you verify these answers. So, you have the initial equilibrium densities. Now, how do you find the total minority carrier concentration for a forward bias? So, it is going to be somewhere here. The holes are going to be higher than the equilibrium density. And this is going to be equal to:

$$P_{no} = e\left(\frac{qV_A}{kT}\right)$$

$$= 10^4 e\left(\frac{0.6eV}{0.026eV}\right)$$

$$= \sim 10\text{^}14$$

So, we are injecting a very high number of high amounts of minority carriers. It is not a small number of carriers. Relative to, of course, that starting doping you know minority carrier density was very small 10^4. And we have essentially introduced almost like 10^{10} orders of magnitude higher holes into the N type semiconductor.

Similarly, I could do the same thing in a P type semiconductor so that the problem requires you to calculate both of these. The point you need to remember is that excess minority carriers are significant when compared to equilibrium minority carrier density. You cannot ignore this. Of course, you know, we are assuming still that, let us say, if you are talking about holes injected into the N type that is less than n_o.

You know the majority carrier density it is still less than the majority carriers you know when low level injection is present. If you have even more than that, then we break down some of these assumptions and you know our analysis will not be accurate. Our analysis is accurate, as far as you know, your introduced minority carriers are still less than the majority carriers and significantly greater than the minority carriers.

So, please, you know, it is not enough for many of you, this is probably the first time you are going to see this. And we are actually focusing on you know significantly on the qualitative understanding. We are really developing very strong fundamentals. If you are able to follow along with this course, I mean, it gives you a solid foundation to study semiconductor devices at a graduate level or in a PhD level.

So, please make sure that you spend the time. You know, I mean, even if you do not want to do research, even in the GATE exams, I see that sometimes, you know, you have all these problems, you know, what is excess minority density and so on? So, these days, you know, for the last 4, 5 years, there have been increasingly larger number of problems from semiconductor devices.

And so that will, you know, this will help you answer all that even if you are not interested in the research aspect. But I would you know urge you to look at it carefully. Thank you very much. So, I will stop here. It is already close to 1 hour. We will take up in the next lecture, where you know, we will derive the expressions for current in a semiconductor. Thank you so much, we will meet you later. Bye.