Introduction to Semiconductor Devices
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Lecture – 3.4
Equilibrium Vs Non-equilibrium Carrier Response

Hello everyone, welcome back to Introduction to Semiconductor Devices. This is lecture 8 of week 3. So, in the last lecture, we were talking about the diffusion process. And we also looked at the current expressions for diffusion and the drift currents. And after that we looked at what happens to semiconductor band diagrams when you have an applied electric field and also the case of non-uniform doping.

We saw that there was a built-in field that is created within the semiconductor when you have a non-uniform doping. And we also looked at how to analyse band diagrams.

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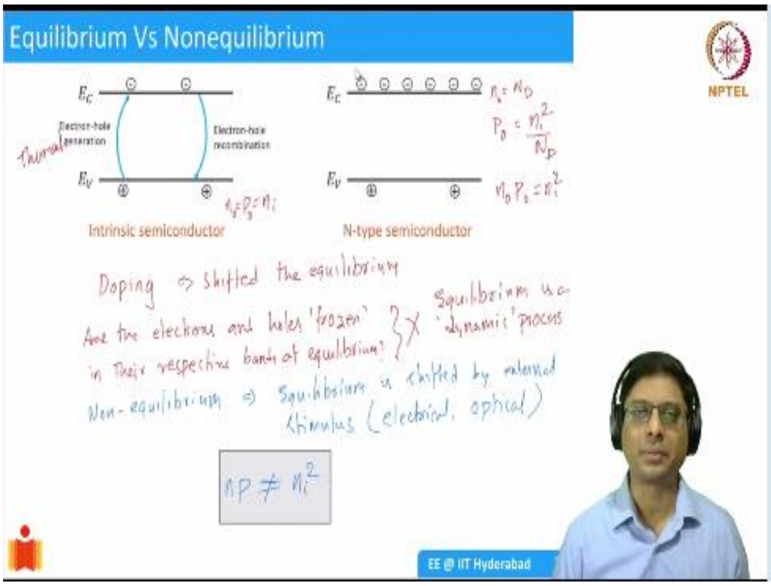

So, today we will move further, and we will talk about one very important concept which is known as non-equilibrium response. We have seen the equilibrium response many, many times so far. So, if you have a intrinsic semiconductor, there is electron hole pair generation process that happens because of thermal energy and you have the recombination process that happens because when you have a electron hole pairs.

Electrons in the conduction band and the holes in the valence band, it is possible that at some points, you have electrons and holes at the same location physically and then they can recombine. Essentially, the electron gets absorbed into the bond. So, the electron hole pair is not annihilated and because of that, we have the intrinsic carrier density. So, we have seen multiple times.

We kept on emphasising that $n = p = n_i$ is essentially the intrinsic carrier density and you know, electron and hole concentrations are same, and we sometimes denoted that by using an a subscript 0 to indicate equilibrium. So, when you have equilibrium, then the Fermi energy was at the middle of the band gaps. Now, we also show the cases of extrinsic semiconductors wherein we try to use doping.

And what doping did was shift the equilibrium,? it shifted the equilibrium and therefore, you have more electrons and less holes. So, if you have an n type doping, let us say donors, donor atoms, then we shift the Fermi level closer to the conduction band. And that is why in a extensive semiconductor n was N_d and p, let us say equilibrium density of electrons was N_d the number of dopes and p_0 is basically,

$$p_0 = \frac{n_i^2}{N_d}$$

and we said that $n_0 p_0 = n_i^2$. This is valid even for an extrinsic semiconductor in equilibrium.

So, we want to ask as in a very important question. Let us say we are able to somehow identify each individual electron in the conduction band. And similarly, each individual hole in the valence band. So we ask, are the electrons and holes frozen? Are the electrons and holes, I will say frozen essentially indicating that if you are able to identify a particular electron, will it always stay in the conduction band?

A particular hole, will it always stay in the valence band? So, are they frozen in their respective bands at equilibrium? That is a question we asked. Since, we said that the electron and hole concentrations are whatever given by these expressions, does it mean that a particular electron is always going to be in a particular band? Well, the answer is no. It is not true. So, equilibrium implies that the net electrons and net holes are going to be the same.

So, equilibrium is a dynamic process by which I mean that electron and hole pair are continuously generated. And simultaneously, they are getting annihilated. So, particular electron and hole pair can annihilated at one point and at a particular location in you know, lattice and at some other position in the lattice, a different electron hole pair could be generated.

There is no way for us to know which electron is you know, in which band. I mean, is it bound to the lattice or is it free to move about we will not know that. Equilibrium only means that the net electron and hole densities are going to be whatever is given by these expressions in equilibrium. So, what does non-equilibrium mean? So, basically, whenever we disturb, non-equilibrium means, let us say, we are disturbing the equilibrium. How can we disturb the equilibrium?

We could apply an external stimulus. For example, if I apply electrical voltage to a particular you know, semiconductor device, let us say and somehow I am going to introduce additional holes or additional electrons, but we will see that this is possible. So, this becomes a non-equilibrium situation. So, essentially, this is equilibrium, is shifted by external stimulus. Well, the stimulus could be electrical or it could be optical.

We have seen many times this one already. So, if you shine photons, you are able to introduce electron hole pairs, which are going to be in excess of the existing equilibrium carrier density. So, it is an external stimulus and we are taking the semiconductor out of equilibrium. So, one of the properties or one of the ways to identify a non-equilibrium situation is when you have the product $np \neq n_i^2$.

So, what this means is, we will take an example and show you this. So, this is how you can characterise, whenever you have an equilibrium situation you have $np = n_i^2$. And if you have a non-equilibrium situation, the $np \neq n_i^2$. So, let us see how this happens.

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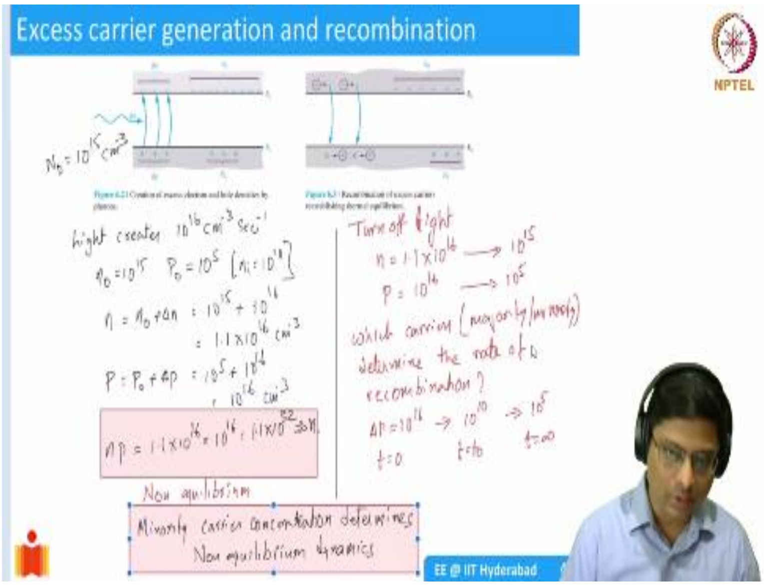

So, let us consider the n type semiconductor. Let us say the doping basically, will take an n type semiconductor let us say, with doping density $N_D=10^{15}$ cm^{-3}. This is the doping density. So, we have $n_0 = 10^{15}$. So, we take the semiconductor and we shine light, we turn on the light, suddenly. And this light, basically, light creates, let us assume 10^{16} electron hole pairs. Let us assume per second and you should also do it per second but anyway, per second. Let us assume this.

So, for one second, you turn on the light. So, what happens? The rate at which the electron hole pairs are created is actually this. So, let us say and we started out with what. We started out with $n_0=10^{15}$ and $p_0=10^5$. By this point, you should be comfortable, how to get this. I am assuming that $n_i=10^{10}$. This is enough for me to do the calculations for right now. So, now, when I shine my electron hole pair, I mean say, I am saying that I am introducing 10^{16} electron hole pairs.

So, after the second, how many electron hole pairs will be there? n. Now, I will introduce n to denote non equilibrium, the total carrier density; $n=10^{15}$, the equilibrium density plus Δn. So, I will write it as, $n = n_0 + \Delta n = 10^{15} + 10^{16}$, Δn is the excess electron hole pair and creating the lattice 10^{16} per second, so that way.

So, similarly, so, what will this be? This is going to be , $n = 10^{15} + 10^{16} = 1.1 \times 10^{16}$. Similarly, what will be the P, the total hole density? It will be the equilibrium density $p = p_0 + \Delta p = 10^5 + 10^{16} \sim 10^{16}\ cm^{-3}$.So, what do you notice by choosing my external stimulus, I am able to create much more, a lot of minority carriers.

Of course, this depends on the rate at which you are generating, but let us do the n-p product. What is it? Now, $np = 1.1 \times 10^{16} \times 10^{16} = 1.1 \times 10^{32} \gg n_i$. So, basically, this implies that say, non-equilibrium situation, non-equilibrium condition. So, what if you have non-equilibrium? What happens when you have non-equilibrium?

Well, to understand that, let us see, you turned off like you switched on, we created this. We have the steady state and we have created carrier density this way. n and p we have changed. Now, you turn on the light, what will happen? So, then you have these excess electrons and hole pairs. So, they will recombine, we talked about multiple times, So, essentially an electron and hole when they occur at the same position in the lattice.

When they come into the same position, then they can annihilate the electron hole pair, can be annihilated in it. So, if you turn off light, sorry light, essentially, what is going to happen? Your electron density which was, I will write here itself; $n = 1.1 \times 10^{16}$. It should eventually go back to equilibrium, because excess electron hole pairs will recombine. So, it will go back to equilibrium. So, this becomes, equilibrium was 10^{15}.

And similarly, p should become started out with 10^{16}. And that should become 10^{5}. So, it should go back to equilibrium. So, the driving force or the stimulus which was creating excess electron hole pairs is a light in this case, in this example. So, when we have that we have this excess carriers, but once the light is removed, they have to go back to equilibrium.

So, I will ask you a very important question that I need you to pay attention too. So, think about which carriers majority or minority determine the rate of recombination. What did I miss this? You saw that when you have a perturbation, let us say external stimulus, which is causing which is perturbing electron hole densities, you saw that the majority carriers are not significantly affected.

But minority carriers have a significant affected, of course, depending on the strength of the perturbation. But when will the electron hole pairs recombine? When you have sufficient number of electrons and holes, in this case, what happens is: your Δn is only going to change from 10^{16} to 10^{15}, not a whole 1 out of change. But delta p will change over, now, in this case, 10^{16} to 10^{5} 11 out of magnitude change.

So, what happens is, let us say, initially, you started out with $\Delta p = 10^{16}$ at t = 0. You started out that. And after a certain time t_0, it might have become, you know, 10^{10}, let us say $t = t_0$ and then after a very long time, we will define what this very long time is, it is going to become 10^5. Let us say, t = infinity just as a example. It is not going to be really infinity, we are going to get a; we will see an examples.

What this is meaning is, the rate at which the recombination happens is proportional to the minority carrier density. So, when you see have a very high minority carrier density, excess minority carrier density, then the rate of recombination is going to be large and it is going to decay very, very fast. But once the number of the minority carriers, excess minority carriers comes down, then the rate of recombination slows down.

And this is an important thing. So, we will make a very important conclusion here. We will say that minority carrier concentration determines non-equilibrium dynamics. Because you see that always there are sufficient number of minority carriers present. We do not have to worry about the availability of majority carriers. The rate of recombination is going to be purely determined by the minority carriers. So, that is why we conclude this.

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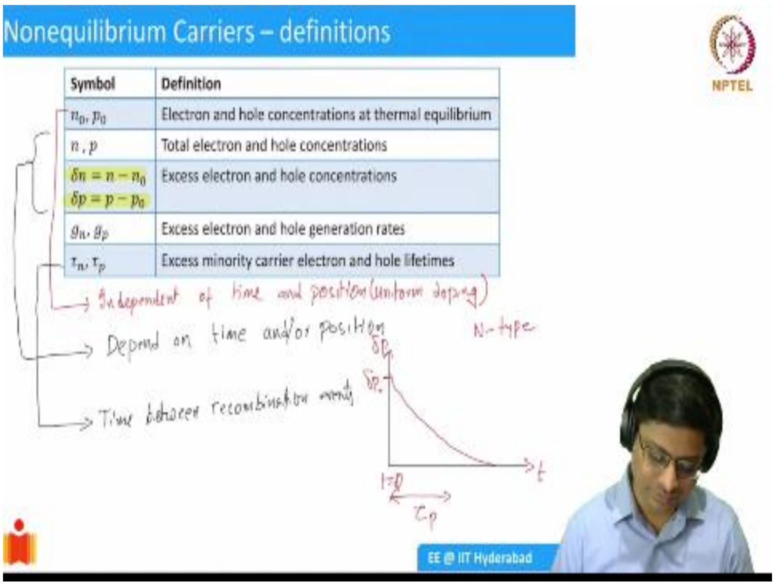

So, now let us take one more step forward. What I will do is; I will just quickly you know, summarise some definitions that we will be using, you are already familiar with n_0 and p_0 and n and p; n_0 p_0 on the electron and hole concentration at thermal equilibrium. n and p are the total electron and hole concentrations. So, you see that n_0 and p_0 are going to be essentially independent of time.

These are independent of time and most often position because if most of the time we will talk of uniform doping, whenever you have uniform doping, equilibrium concentration is going to be uniform, whenever you have uniform doping, position independent of position. So, now, what I will do is; I have this total electron concentrations and I will define excess minority carrier concentration as δn and δp so, the change from the concentrations.

So, these 2 quantities n and p and δn, δp, put it in black, these 2 quantities are going to be depend on time and or I mean, it could even depend on time and position or one of them. So, it depends on, you know, what particular excitation we have and where the excitation is located. So, that will give you, these are functions of time and position. And then there are g_n and g_p which we are essentially calling the excess electron and hole generation rates.

So, how many carriers have been created per second sort of? And the last important quantity that I want you to pay attention to is the excess minority carrier lifetimes. So, basically, this means, this is essentially time between recombination events. So, you have plenty of electron hole pairs present. But it is going to take a certain amount of time for them to recombine. So, how many events per, you know, how many recombinations per unit time?

And you just look at how many, what is the average time between recombination events. That is excess minority carrier lifetime. What this means is : we could try to plot it, you know, just as; now, we will see it again, but just for now, to give you an idea, let us say I have a semiconductor and I have excess minority, somehow I introduced minority carriers. So, I introduced let us say Δp, I am plotting only axis.

This is Δp and this is Δp_0; at time t = 0 have a Δp_0, which is introduced that. To maintain convention, let me take it as small delta. So, this will be your Δp and this will be Δp_0. So, we created that at time t = 0, this is time t = 0 and this is time t, this is time. So, how will the excess minority carrier density for? By the way, we are talking about delta p that means I am taking n type semiconductor.

Because Δp for a p type semiconductor, it does not really play a role because it is a majority carrier density, excess majority carrier density does not play much, much of a role. But if you have talking about minority carrier density, that is important. So, you introduce somehow and then you remove the stimulus, then it is going to come back. It is going to take some function.

Right now, you do not know what that function is, but towards the end, you will see that this is an exponential function. Towards end of this lecture, we will see this. So, essentially, the time required, you know, this is going to be some time. This is τ, which is basically τ_p which is the excess minority carrier recombination time. So, how much time does it require for the density to fall to one over e value.

We will actually solve it and show you this in the end of the lecture today. So, these are the definitions.