Introduction to Semiconductor Devices

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Lecture – 3.3
Non-uniform Doping

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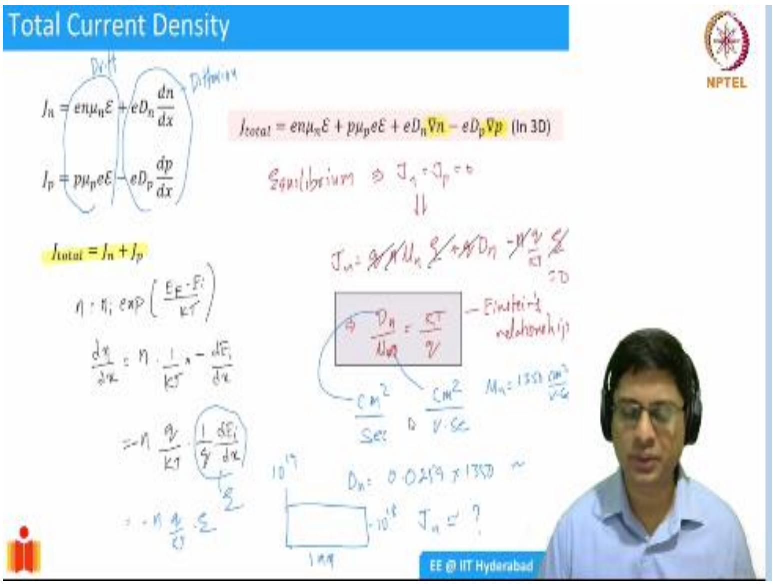

Drift current also is going to be significant. We have to take both into account. So, when you would have diffusion. So far, we have seen that doping was very uniform, the E_C was constant, so the density was constant all the time. Whenever you have density constant, $\frac{dy}{dx}$ is going to be 0 so, diffusion is not going to be there.

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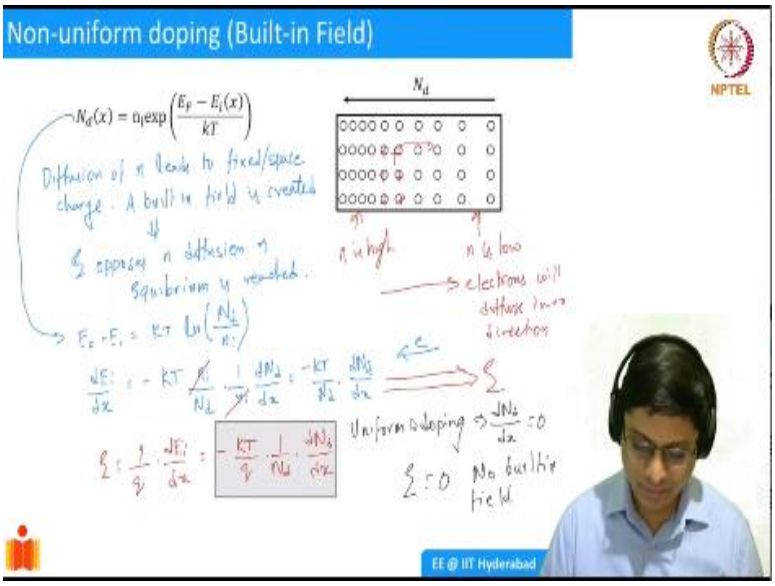

The only time when you have diffusion is going to be there is when you have non-uniform doping. Let us say you put different amounts of N_d in different locations of semiconductor or you put n type and p type together and things like that. So, that is when diffusion is going to happen. If you have a simple uniform doping, you are not going to have diffusion. So, here, we would like to consider what happens when non-uniform doping exists.

So, this is N_d.

$$N_d(x) = n_i e^{\left(\frac{E_F - E_i(x)}{KT}\right)}$$

I deliberately wrote E_i as a function of x because you will see in the end that there is going to be a gradient in the electric field sorry, the gradient in the bands which will be electric field that is why I deliberately wrote E_i as a function of x. So, essentially consider a situation here wherein you have some semiconductor dope with donors.

So, you have some electrons here. Let us say this is your; n is high in this region and here n is low. So, what would happen? It would essentially lead to diffusion of carriers what we have seen before. So, from high concentration electrons will diffuse in the positive x direction. How long will they diffuse? Is it continuously till everything all electrons gone? Well, what happens when you have an electron diffusing away from a location will be left with a positive charge.

So, essentially, let us imagine if this electron has moved, it leaves behind a positive charge in its original location. Similarly, positive charges will be left behind in these locations where electron has moved. So, whenever this happens, you have a sort of a gradient in the charge, space charge that results in electric field. So, in this case, you will see that there will be an electric field in the positive x direction.

Well, yes, Electric field in the positive x direction because greater amount of positive charge on the left side and the lower amount of positive charge on the right side. So, there is going to be a difference in the charge and that is why there is an electric field. So, whenever you have a built in field like this, the field will oppose the flow of current. So basically, here, if you have field like this, electron has to go in opposite direction.

So diffusion, essentially, diffusion of n leads to what we call as fixed charge or space charge by which we mean essentially, the carriers that dopants atoms are exposed, essentially, you remove an electron, you will be left with a positive charge. So, that is a fixed charge. That cannot move that we saw. We have seen in the previous cases where the dopant atoms cannot move, they are bonded to the lattice, so they are fixed.

So, basically, lead to a fixed charge and we can immediately compute what is the electric field associated with the fixed charge. We can apply Gauss law and calculate this, we will do it later. But right now, this actually, we will, a built in field is created. We are saying it is a built in field because it is actually coming from the doping distribution in the lattice. And at some point, this built in field, essentially built in field will oppose this.

So initially, there will be a huge concentration gradient creating some flow of current diffusion current, but at some point, the diffusion field sorry, the built in field opposes the diffusion process and an equilibrium is reached. E opposes n diffusion implies equilibrium is reached. This is what happens physically. How much electric field? You can actually compute that. You know, because from the expression here given here, you could write.

$$E_F - E_i = KT \ ln\left(\frac{N_d}{n_i}\right)$$

And we know that electric field is simply derivative of the E_i. So, we could actually take $\frac{dE_i}{dx}$, this is going to be

$$\frac{dE_i}{dx} = -KT\frac{n_i}{N_d}\frac{1}{n_i}\frac{dN_d}{dx}$$

So, essentially, this n_i will go out. What we will end up getting is

$$\frac{dE_i}{dx} = -\frac{KT}{N_d}\frac{dN_d}{dx}$$

And if this is there, electric field is simply going to be, I will write it here ; electric field is simply going to be.

$$E = \frac{1}{q}\frac{dE_i}{dx} = -\frac{KT}{q}\frac{1}{N_d}\frac{dN_d}{dx}$$

So, this is going to be a built in field. This is an expression for that. Well, you could do a sanity check what happens if you have uniform doping.

Uniform doping implies $\frac{dN_d}{dx} = 0$ that implies $E = 0$, no built in field. So, this is how we can analyse and let us take an example. What happens if you have how will the band diagram look like when you have a non-uniform doping?

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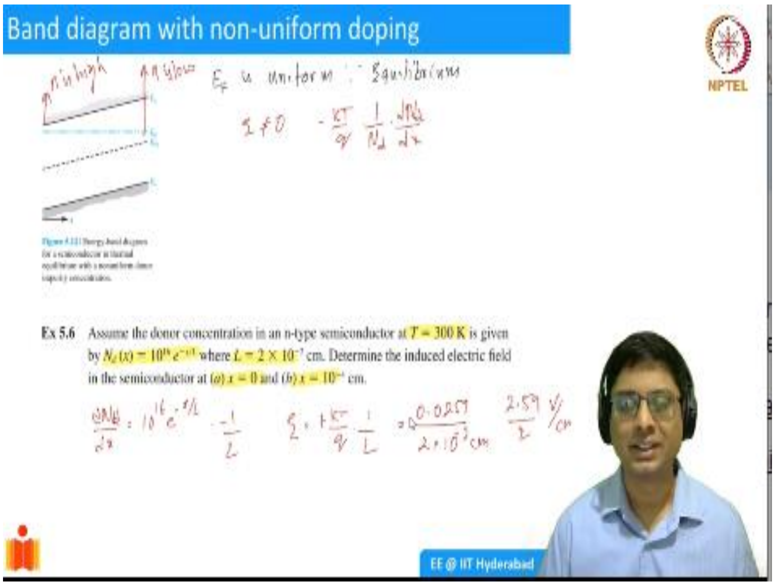

So, this is what it will be. So, essentially, you have, it is the process in equilibrium. So, E_F is going to be constant. E_F is uniform, maybe better uniform, because equilibrium. Sample is in equilibrium. So, it has to be constant. And then what it tells you is E is not going to be 0. And the band diagram essentially, E is positive; essentially bands will move upwards; here moving upwards here, essentially indicating that electric field is positive.

And then the distance from E_C and E_F is going to be carrier density. In this case, you have high carrier density here, n is high; here n is low. You should be able to see that because E_F is farther away from E_C that concentration is low. So, there is a built in field which is positive here. Well, I mean, we could try to check out this. So, in this case, you have $E_0 \neq 0$. So,

$$E = -\frac{KT}{q}\frac{1}{N_d}\frac{dN_d}{dx}$$

This is going to be a built in field.

Let us take an example. So, here, I could have, should have higher anyway. So, this is the n type semiconductor at temperature T = 300. Remember always these diffusion coefficients, mobility, everything will be dependent on temperature. N_d is given as some exponential function. The length of the semiconductor is given. You are asked to calculate the induced electric field at x = 0 and x = 10^{-4} centimetres.

Well, it is fairly straightforward. We have the expression. So, if you calculate $\frac{dN_d}{dx}$, it is going to be,

$$\frac{dN_d}{dx} = 10^{16}e^{\frac{-x}{L}}\left(\frac{-1}{L}\right)$$

So, E is going to be,

$$E = \frac{KT}{q}\frac{1}{L}$$

So, this is going to be our built-in electric field substitute, you know

$$E = \frac{KT}{q}\frac{1}{L} = \frac{0.029}{2\times10^{-2}cm}$$

In semiconductors length, we do not use metres, but we are using centimetres all the time that is how convention is. So, then you calculate this and then you estimate how much is going to be. $E = \frac{0.029}{2\times10^{-2}cm} = \frac{2.59}{2}\frac{V}{cm}$ Will this depend on the position b basically x =10^{-4}? Please check it out whether this is going to depend on a position. So, this is how we will deal with semiconductors which are in having non-uniform doping.

And this is a very common thing because whenever we make a p-n junction, we have non-uniform doping. Whenever we make a MOS cap, we have a non-uniform, you have, of course, an insulator in between but non-uniform doping is there. It is very, very common.

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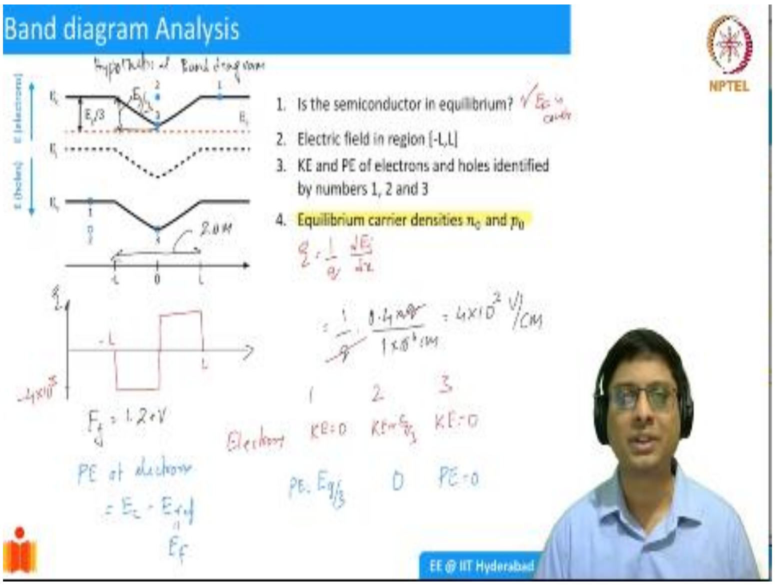

So, I have been telling you many, many times that band diagrams are very useful for analysing how semiconductor behaves. So, I am going to put this as part of a homework problem. But let me just quickly tell you, essentially, what we are showing you some hypothetical structure again. This is a hypothetical band diagram. It is never going to be like this. So, from minus L to L, there are E_C, E_V that is shown here.

E_i is shown here. And E_F is going to be a constant. So, basically, the first question you are asked is, is a semiconductor in equilibrium? Well, it is an equilibrium because E_F is constant. That is why it is in equilibrium. What is the electric field in the regions -L to L? Well, electric field is going to be what? Electric field,

$$E = \frac{1}{q}\frac{dE_i}{dx}$$

I mean sometimes I write it as $\frac{dE_C}{dx}$, $\frac{dE_V}{dx}$; it does not matter if all of them are parallel.

Remember, if they are not parallel, then E_g is going to change and that is not going to be a realistic situation for semiconductor normal devices. So, there is going to be a basically electric field which is a, let me see, first I will draw an axis. And then I am taking, so this is my electric field; it is going to be in this -L to 0, the gradient is downwards. So, electric field is negative; $\frac{dE}{dx}$ is negative.

What is the magnitude of the electric field? You can easily estimate actually. Let us say, I assume that, let us assume this is 2 microns. I put it on top. So, let us assume this is 2 µm. So, what will be the electric field? So, electric field is always going to be $\frac{dE_i}{dx}$. Let us assume you know, let me take E_g=1.2eV for simplifying calculations,. So, essentially what we are saying is, this change the bands right here, this part is going to be delta change in the E_C is going to be E_g/3.

So, electric field gradient is, this is going to be, I am assuming that, this is very, very close. So, this distance, I am assuming it to be E_g/3. Energy exchanges E_g/3. So, dE_i is going to be,

$$E = \frac{1}{q}\frac{0.4 \times q}{1 \times 10^{-4} cm}$$

So, if you do that, it is turning out to be q will cancel out. So, this is going to be

$$E = 4 \times 10^3\ V/cm$$

You see, there can be a significant amount of electric field in the semiconductor that is all I just wanted to do because your dx is going to be small, you can have large electric fields. So, electric field can be plotted as here, from here to here, you have – 4 $\times 10^3\ V/cm$.

And then from 0 to L, it is a positive electric field. So, I am going to plot it like this. This is going to L, this is going to -L. So, this is the profile of your electric field. In the real cases, of course, you are not going to get a sharp profile like this; there is something else. We will talk about it later. And then what is the kinetic energy of electrons and holes identified by the numbers 1, 2, 3? That is going to be interesting, because we said that whenever the electron is at the band edge, it is going to have a kinetic energy of 0.

So, you can actually do this analysis. I will post probably, you know solution for this and you okay? Let me see. So, position 1, 2 and 3, right? So, the electrons KE, KE=0 here, at position 1. At position 3, also KE=0. At position 2, if you assume that that difference is E_g/3, it is going to be, KE is going to be; if the bands are bend by E_g/3, then it will be approximately E_g/3 that is the higher can. So, electron has got kinetic energy as it travels.

What about potential energy? Well, potential energy, I mean, you have to basically consider reference. So, PE of electrons, we said is going to be.

$$PE = E_C - E_{ref}$$

This reference, you can take it as you know, this equal to E_F, you can take it, there is no harm. So, basically the distance from E_F, so, it is going to be high. And then once you go to position 3, you are going to have low.

PE, I just write it as PE = 0, let us assume that E_C was almost at E_F close, very close; if you get a difference, but let us take it as equal to. And then this was going to be $E_g/3$. And this is going to be again, you know, it is still, it does not change. So, this is again going to be 0. So, you can write out this is potential energy. PE is going to be 0, $E_g/3$. So, you can analyse this way for holes also.

But just remember that for holes, potential energy I mean, energy increases in the downward direction and electrons energy increases in upward direction. There is a lot of subtlety here. You may not follow all the details. It is okay. Because you see that at position 2, you will wonder about energy conservation, you might say you know, how is the energy conservation is being satisfied.

So, it is a little bit tricky. So, we will discuss this when we discuss in detail at a later date. But at this point, I want you to be able to look at a band diagram and identify you know, if the electron has kinetic energy is 0 or nonzero, what is the electric field in different locations of the band diagram? So, potential energy, we will again talk about it when we talk of potential barriers.

Right now, I would say potential energy, you can take it as a information you can just think about it, we will again come back and then revisit this topic. So, with that, I would like to stop. You are almost getting close to one hour. So, what we did today was essentially we started out with semiconductor in electric field, we talked about you know, how the band bend when you have an electric field, you have a gradient and then we talked about diffusion of carriers, which can happen whenever you have non-uniform doping in semiconductors.

And then you have talked about how the total current, we can write in terms of the diffusion current and the drift current. And then we established one important factor, the Fermi energy is going to be uniform or constant in semiconductor at equilibrium. And then, we talked about; we derived Einstein relation which is a very, very important relation that we will use multiple times in the course.

So, typically, you know, your GATE and all those exams, you will get a problem based on that. We did that. And also, you know, well, I did not mention I had left the last question here that equilibrium carrier densities n_0, p_0 you can determine once you know, how much is the distance from of E_F from E_C, you will be able to determine what it is. So, please try out these things.

I will meet you in the next lecture, where we will talk about minority carriers and non-equilibrium situations. So, next 2 lectures will be again related to some concepts. And with that, we will have a strong foundation necessary for us to understand p-n junctions and further. So, thank you so much for your attention. I will look forward to seeing you in the next lecture. Thank you very much.