Introduction to Semiconductor Devices
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Lecture – 3.2
Diffusion Current

So, this is how you know, this is about how semiconductors behave in an electric field.

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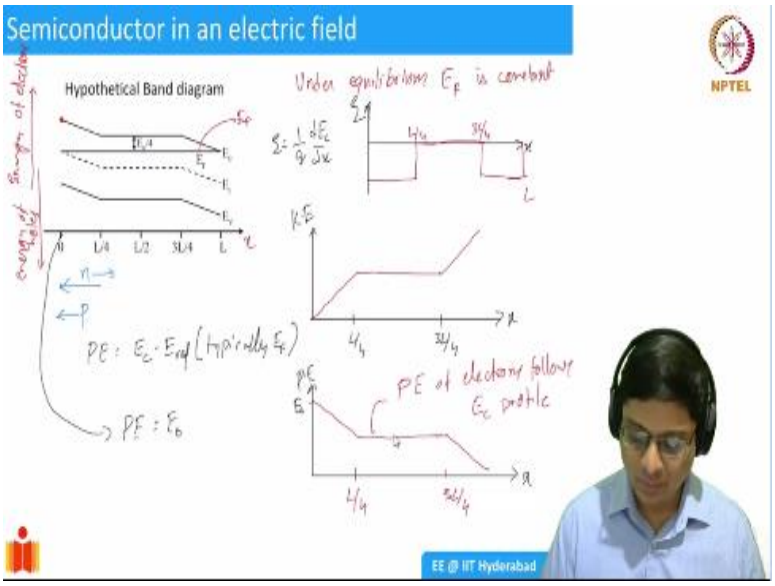

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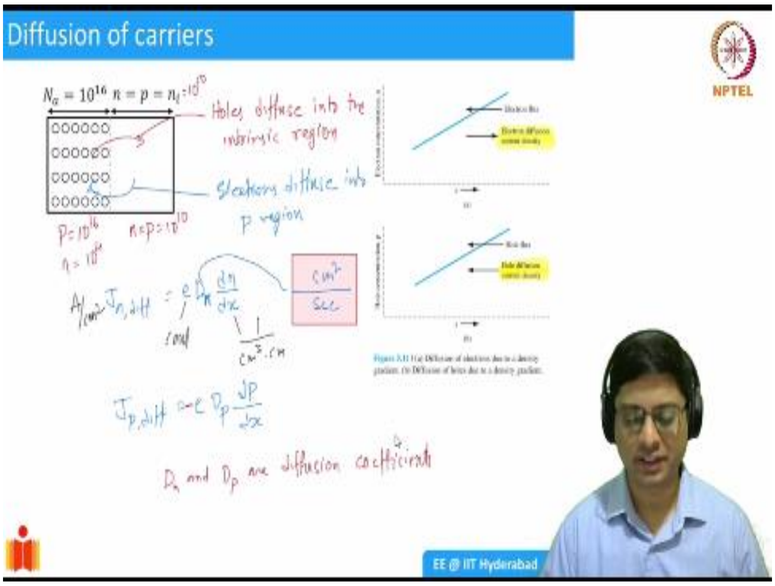

So, now I would like to introduce another type of carrier conduction, which you call as diffusion. We have seen drift which is essentially a result of electric fields, which are applied to the semiconductor. And diffusion is basically a result of concentration gradients. For example, think of a semiconductor, which is a hypothetical case here; we are having a semiconductor with some carriers.

And in some region of semiconductor is not having. It is an intrinsic region, let us assume. It is going to have some few electron hole pairs. But just intrinsic region, in adjacent to a region with a lot of holes. What will happen? Well, diffusion process, we are all familiar, you know, how gases diffuse from high concentration to low concentration region. The same thing happens even in the case of semiconductors.

So, that, this is schematically shown in the picture on the right. Before I do that, let me see. So, you have additional holes here. So, holes are going to diffuse here. So, this is basically holes diffuse into the intrinsic region or electrons going to diffuse? Think about it. So, we are talking about holes. Holes in the, you know, in the left side, you have holes, lot of holes here, they want to diffuse. These are going to be any electron diffusion.

Well, it is going to be there. The reason is, remember, what is the concentration of holes here? Concentration of holes is going to be simply $N_A = 10^{16}$. What is the concentration of electrons? Concentration of electrons is going to be n, $n = 10^4$. I will say that n_i^2, I will take $n_i = 10^{10}$ .So, $(10^{10})^2 = 10^{20}$, $N_A = 10^{16}$. So, $n = \frac{10^{20}}{10^{16}} = 10^4$ approximately.

I am not doing the exact 1.5×10^{10}, I am just taking $n_i = 10^{10}$. What will be in this region? Here, $n = p = 10^{10}$. So, you see that there is a higher concentration of holes in this region. So, they are going to travel. I mean, there is got to be a concentration gradient, because higher concentration of electrons are going to be there here.

And then it is going to come here, there is some certainty involved here. It is not that simple. We will have to go a little bit more detail, we will do that in the next lecture. So, what we are concluding is essentially, you are going to have hole diffusion. And you are going to also have electron diffusion. Electrons diffuse into lets say P region. So, I mean, essentially, both, you saw that, in the drift, we saw that both electrons and holes are contributing to drift current.

Similarly, even in the diffusion, we have both electrons and holes. Basically, majority and minority carriers both will contribute to current conduction anyway. And you could also understand it from you know, this picture here on the right, which is essentially showing you as a position of x, what is the electron concentration? Let us say the electron concentration is like this. So, there is a positive gradient to the electron concentration.

You have higher number of electron concentrations on the right and the lower concentrations on the left. So, because of the diffusion, because of the concentration gradient, the electrons are going to flow in this direction. And by convention, whenever you have electrons travelling, we take it to be the, the current will be in opposite direction. So, we say that electron diffusion density is going to be in the positive x direction. Because electrons, flux is going to be in the negative x direction.

So, by the convention, current is going to be in the positive x direction. So, this is for electrons. What happens to holes? Let us say, you assume a similar concentration holes as well. So, you see this positive you know, gradient. So, hole flux is going to be in the opposite minus x direction and the current density because now it is positive charge, it is going to be in the same direction.

Remember, this subtle difference, you saw that in the case of drift, the current density is always in the direction of electric field. Whether electron or hole, both current densities are in the same direction. But diffusion, the whole diffusion current is going to be in the negative direction related to the concentration gradient. So, this can be you know, written in the form of a current expression.

So, what we will say is, let us write, electrons, I will write it as diffusion current $J_{n,diff}$, I will say. So, essentially, this diffusion current is going to be proportional to of course, the charge. And then there is going to be a concentration gradient and then there will be a diffusion coefficient which is going to capture whenever you talk of diffusion equation. We might have solved or you will see it later.

So, essentially a second order differential equation space, you could solve it and the coefficient of that is going to be the diffusion coefficient which is going to be represented by D_n, the diffusion coefficient times (dn/dx).

$$J_{n,diff} = eD_n \frac{dn}{dx}$$

So, what are the units of diffusion coefficient? Always, whenever you see equation, please take a little bit of time to analyse the units that will help you clarify and also you know at any point of time if you get confused, you can always verify it.

So, the current density is always going to be $\frac{A}{cm^2}$ and e is going to be coulomb and this $\frac{dn}{dx}$ is going to be what. So, dn is basically per centimetre cube and then dx is going to be centimetre. So, this $\frac{dn}{dx}$ is going to be $\frac{1}{cm^2 cm}$. So, D has to be, in the denominator it has to have a second because coulomb per second is going to be an ampere and then on the left hand side, you have cm^2; on the right hand side, you have cm^4.

So, it has to be cm^2. So, the diffusion current has a units of, sorry, diffusion coefficient has a units of $\frac{cm^2}{sec}$ .So, these are the units. And similarly, I could talk of a diffusion current for holes. So, I will say $J_{p,diff}$ is going to be the charge times diffusion coefficient for holes times $\frac{dp}{dx}$. And the same units for dp. Well, is a equation correct?

$$J_{p,diff} = eD_p \frac{dp}{dx}$$

Look at the gradient in the holes, the $\frac{dp}{dx}$ is going to be the gradient in holes. This is $\frac{dp}{dx}$ and the current density has to be opposite the gradient; it is negative of that. So, you have to put a negative sign for this. Please do remember this. Only for diffusion current for holes, it is going to be opposite minus. D_n and D_p are diffusion coefficients.

We will tell you what there are numbers, you can calculate easily. So, this is a diffusion process, which is the second major processing in a semiconductor current carrying characteristics.

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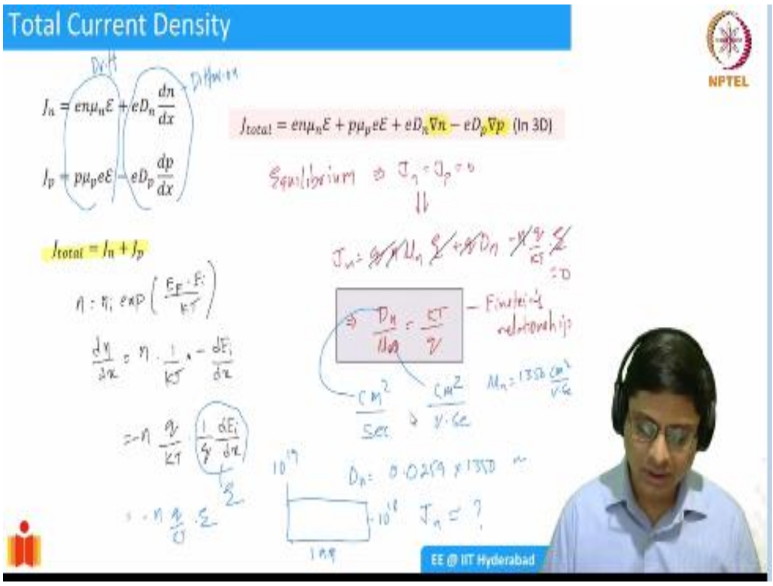

So, to sum it up, in a semiconductor, you have 2 forms of current, the drift and the diffusion. So, you have the drift component here. This is drift and this is going to be a diffusion. So, you have the electron contribution and the hole contribution. So, you can sum up all of it and write it as this expression here. And it just summed it up. So, what it has is, this is for one dimension, typically we will only deal with one dimension.

Two dimensions is very difficult to analytically solve and it is not going to give us any more insight. So, most of the time we will use one dimensional equations, but in general if you have a semiconductor, we have to use 3 dimensional equations in which case you have to basically these things become ex ey ez; e becomes a vector and then your concentration gradients become sorry concentration $\frac{dn}{dx}$ and $\frac{dp}{dx}$becomes gradient of n and gradient of P.

So, it has to be a full 3 dimensional solution, which can be done using computers. We do it routinely but for this course, we do not need it. We will most of the time focus on one dimension case. So, what happens to a semiconductor which is an equilibrium? Equilibrium remains the electron current is going to be 0 and the hole current is going to be 0. The reason for that is that you already said that equilibrium means there is a balancing of $J_n = J_p = 0$.

So, basically the diffusion and the drift currents cancel each other and you get 0 current. So, there is no net contribution of current from other electrons or holes. This has a very important implication for us. So, let us see. So, what is $J_n = 0$ mean? So, if you look at the J_n expression, you have the drift current. For a moment, let us try to compute what is the carrier density.

The carrier density, it will become clearer in a short-while while we are doing this.

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

This is your carrier density. So, what will be (dn/dx)? (dn/dx) is going to be the same thing. Exponential derivative if you take it, it will become the same thing.

$$\frac{dn}{dx} = n\frac{1}{KT}\left(\frac{-dE_i}{dx}\right)$$

What is (dEi/dx)? We could try to rewrite it in form of electric field.

$$\frac{dn}{dx} = -n\frac{q}{KT}\frac{1}{q}\frac{dE_i}{dx} = -n\frac{q}{KT}E$$

So, now, if I say J_n, you know this implies J_n, this implies J_n equal to, pardon my interchangeable use of q and E, but you should be comfortable with that. So,

$$J_n = \; qn\mu_n E + qD_n - n\frac{q}{KT}E$$

So, your E cancels out, n cancels out, q cancels out.

So, what you end up getting? And this is going to be equal to 0. So, this will imply that equal to 0, you can actually take D_n the other side. So, this will imply that

$$\frac{D_n}{\mu_n} = \frac{KT}{q}$$

You take D_n other side and take the μ_n in the bottom and then KT goes on the top, this is correct. So, essentially this is an important expression for us. So, essentially what this is doing is: it is giving a relation between mobility and the diffusion coefficient. This is called Einstein's relationship.

So, we can also verify from the dimensionality, we know that D is going to be $\frac{cm^2}{sec}$. μ_n is going to be $\frac{cm^2}{V-sec}$. So, if you do (D / μ_n), you end up getting volts, (KT/q) is going to be volts. So, that is why this is valid. So, you should remember this equation because many times you know you are given μ_n but not given D. So, you could immediately calculate.

(KT/q) is going to be a point; let us estimate. Let us take an example. μ_n is going to be let us say 18. Sorry not 18, what was that? μ_n was 1450; in the last lecture we have; in the first slide, we had some number right 1350 sorry. μ_n was 1350$\frac{cm^2}{V-sec}$. So, what is D_n? D_n = 0.0259×1350 so, whatever. It is going to be some number. It is going to be some 1345 some number like that. Please check it out.

And also remember, this can be a significant amount of current. It is not a small thing. The reason is, you could take a piece of, as an exercise, take a semiconductor, let us say, take a semiconductor of size, let us say one millimetre. Assume that there is a concentration here was 10^{19} . And here, concentration is 10^{18}. So, there is a gradient in concentration n. n = 10^{18}, let us say

And then you have D_n. You calculate what is D_n and compute what is the current. So, compute J_n for this scenario, how much approximately. You will see that it is going to be some $\frac{A}{cm^2}$, 10's of $\frac{A}{cm^2}$, probably. It is a reasonably large amount of current that can flow in a semiconductor. So, diffusion current is going to be significant and drift current also is going to be significant. We have to take both into account.