Introduction to Semiconductor Devices

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Lecture – 2.7
Charge Neutrality Relationship

This document is intended to accompany the lecture videos of the course "Introduction to Semiconductor Devices" offered by Dr. Naresh Emani on the NPTEL platform. It has been our effort to remove ambiguities and make the document readable. However, there may be some inadvertent errors. The reader is advised to refer to the original lecture video if he/she needs any clarification.

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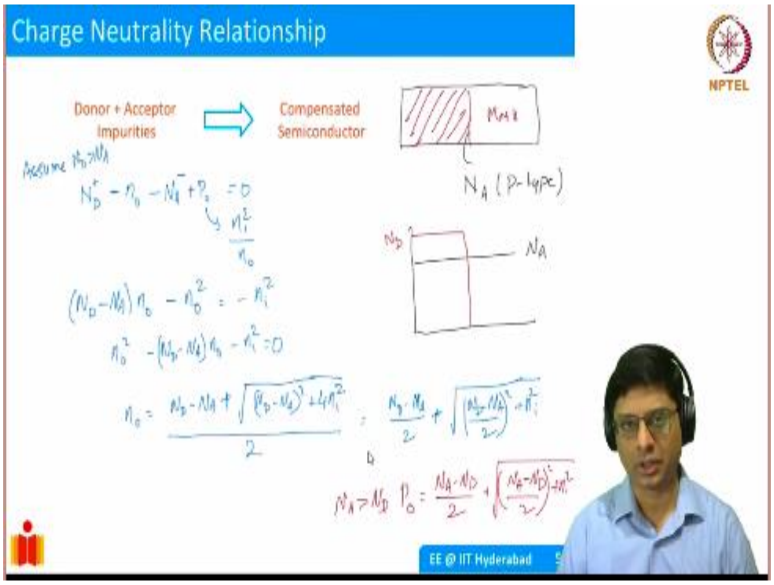

So far what we have done is we have talked about acceptors and donors. So, we can dope with acceptors and donors. But in reality, most often what we do is we have both donor and acceptor impurities in a semiconductor. And such as semiconductor, we call it as a compensated semiconductor. Why would we do that? For example, take a semiconductor. Let us say it has a, no generally we do not work with intrinsic semiconductors we have a starting doping, let us say, background doping of N_A.

We have a p-type semiconductor. We have a p-type semiconductor, initially, it's a block, I am just representing. Now, because I want to make, I need both n-type and p-type devices. We cannot work with only one of them. We could do something but it is not going to be very helpful. It is essentially a piece of resistor you could say right, only one type of carrier is there, nothing much.

I mean, it will have some resistivity, but nothing much interesting happens. But if you have, if you combine both n-type and p-type, a lot of interesting things can be done. So, I take this initial piece of p-type semiconductor, and I want to make it n-type. How would I do that? So, what does it mean if you have a piece of semiconductor which is so, if I plot the density, when essentially you started with N_A.

Then what I will do is, if I want to make it some part of it, I want to make it n-type. Let us say, I want to make this part of it n-type. What would I do? I simply you know, dope it with higher amount of N_D. So, half of it, I will mask. This I will mask. I will not expose it and then I will only dope only one particular region where I want the concentration to be n-type. This is what we regularly do. So, this is a very important thing.

What happens to carrier densities in a compensated semiconductor? This is an important thing that, you know, you might have to regularly use to calculate. So, to do that, we use what is known as charge neutrality relationship by which what we mean is, initially your dopant is charge neutral. Silicon lattice is charge neutral. When we put in these charges, again, the charge neutrality has to remain.

So whenever we add a donor, we said that donor use an electron. So, electron is negatively charged, the donor atom becomes positively charged. So, I will simply represent that. So, basically, you have N_D and just to say that it is positive, I am putting a superscript positive and you are introducing an electron into the lattice, which is negatively charged. So, I will put a minus n, which is representing.

Or I will take an equilibrium concentration so, minus n_0. Now, this is with the donor impurities? What happens with the acceptor impurities? Acceptor impurities are those that are accepting electrons from the lattice. So, they are becoming negatively charged. So, an acceptor impurity, I will put a minus sign N_A^- and then it is creating a hole in the lattice which is essentially a vacancy of an electron. A lack of an electron is called as a hole.

So I will say it is p_0. Now, because we are starting with uncharged dopants and you know, neutral dopants and silicon lattice, this total has to remain 0 ($N_D^+ - n_0 - N_A^- + p_0 = 0$). So, we also said since it is an equilibrium, we know that this guy is going to be $p_0 = \frac{n_i^2}{N_D}$. I am assuming that Assume this is only analysis for, assume $N_D > N_A$. So, majority carriers are electrons. I am assuming that. Inherently.

So, if I do this so, I can put, $p_0 = \frac{n_i^2}{n_0}$

Then I can just, you know, play around with these numbers. So, what I will do is, I will drop the positive and negative just. I will simply write it as $N_D - N_A$. And then I will take the n_i^2 to the other side. So, I can write this as and then I multiply. Sorry, this is this kind of looks weird, but this is n_0.

So this, I will write it as $(N_D - N_A)n_0 - n_0^2 = -n_i^2$ That is what it should be. If I do this, I will rearrange terms. So, I will say, n_0^2, I will take it the other side. So, it is going to be,

$$n_0^2 - (N_D - N_A)n_0 - n_i^2 = 0$$

So, essentially, what we are seeing is your carrier density is a quadratic equation. So, you could simply write out the solutions.

So n_0 is going to be you know, we will only take the positive root, we will see in a moment why we take only the positive root. So, if you take the negative root, then at some point the carrier concentration might be 0, which we cannot have.

$$n_0 = \frac{N_D - N_A + \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2}$$

So, I can rearrange the terms.

$$n_0 = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

So, this is your carrier concentration for a case when you have a compensated semiconductor with $N_D>N_A$. And if I have $N_A>N_D$, I will simply I will not, you know, prove it. But I will write. For $N_A>N_D$, p_0 is going to be

$$P_0 = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

You could verify it. It will work out. So, this is your majority carrier concentration, and the corresponding minority carrier concentration will be simply n_i square divided by whatever is a major carrier concentration. So, this is an important relation that, you know, we come across. Let us take an example and try to solve it.

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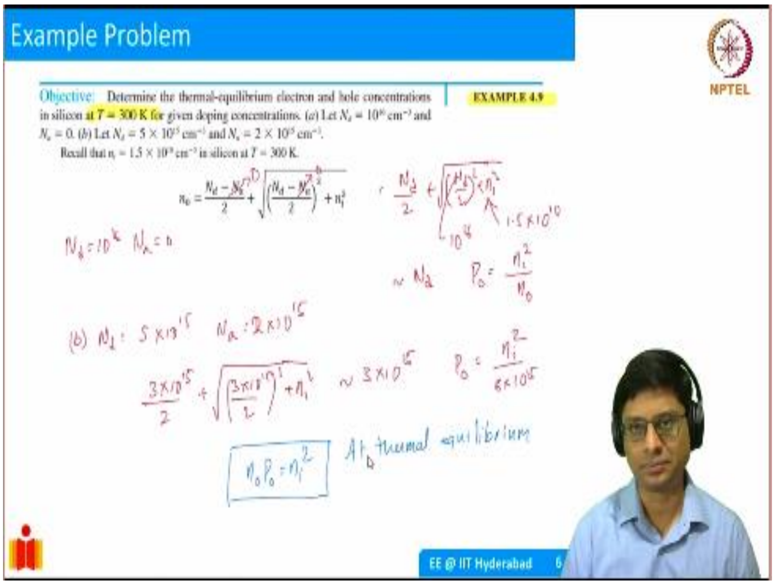

So, let us see. So, we have a problem here, this is from example problem, please go back and verify that, you know, if you want to make sure that you know you get it So, what I am asking is here, determine the thermal equilibrium electron and hole concentrations in silicon at T = 300. It is only at a certain temperature. And given that there are some doping, you know, N_D.

Let us take the case one, $N_D = 10^{16}$. I am not writing the units, $N_A = 0$. If $N_D = 10^{16}$,and $N_A = 0$, so, basically this goes to 0, this goes to 0. And so, you have essentially.

$$n_0 = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

And remember this n_i^2 is going to be quite small. It is 1.5×10^{10} , compared to N_D which is 10^{16}. This is going to be 10^{16}.

So, you can neglect the n_i^2 . So, this will be almost equal to $n_0 = N_D$ .So, basically we got back whatever we had the situation whenever you had only donor atoms, we said electron concentration is simply going to be N_D. And then what will be the hole concentration?

$$p_0 = \frac{n_i^2}{n_0}$$

This is a hole concentration for the part A.

But part B what we are saying is we are given that N_D, sorry should be written as $N_D = 10^{16}$. Oh well no. It is different $N_D = 5\times10^{15}$, $N_A = 2\times10^{15}$. So, you have acceptors and donors, so, now you can try to calculate it. So, it should be $N_D - N_A$. So, $(N_D - NA) = 3\times10^{15.}$

$$N_d = \frac{3 \times 10^{15}}{2} + \sqrt{(\frac{3 \times 10^{15}}{2})^2 + n_i^2} \sim 3 \times 10^{15}$$

So, this is n_0 , $p_0 = \frac{n_i^2}{3\times10^{15}}$. Of course I am sorry, I should actually in the previous case, you should be careful this I should not say as N_D I should call it n_0. So, that you know because , you get the drift.

So please, you know, make sure that you verify this thing, see what happens as you adopt different carrier densities. And always remember this relation which we $n_0 p_0 = n_i^2$ whenever you have thermal equilibrium. And the next week I will, I will talk a little bit more about what is equilibrium, steady state and so on. We will come to it in a little bit more detail. But for now, we saw that there are these 2 processes.Whenever they are equilibrium we call $n_0 p_0 = n_i^2$