Introduction to Semiconductor Devices
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Lecture – 2.3
Doping and Extrinsic Semiconductors

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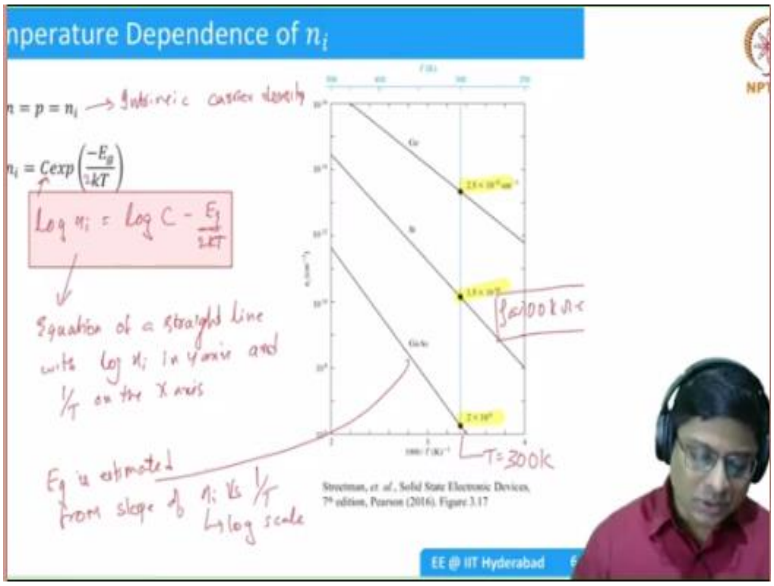

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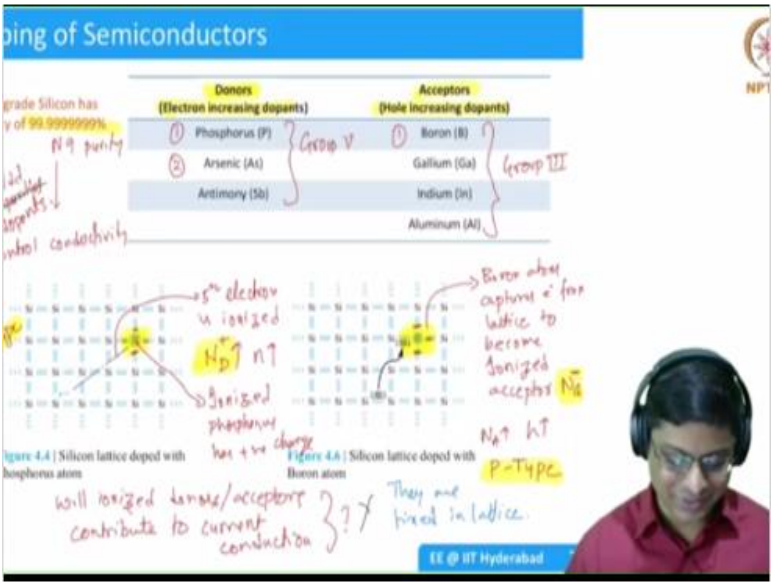

To do that we adopt a process which is known as doping. This is central to semiconductor devices. So, when we start, we start with you know that IC grade silicon has a very very high degree of purity. In fact, it has a purity that I mentioned this in passing last time, so, it has a purity of which we call this number as N9 basically and 9 indicating that it has 9 nines, 99.9999% purity.

It means that it has you know basically in 1 billion or 100 billion items, we will find one impurity or even more than that probably. You have to calculate that it will definitely be 1000, maybe up to a trillion also, I guess one part per trillion kind of a concentration, I think. You can check it out. So, essentially you have a very very highly pure perfect lattice that you start with.

But then that is not very useful. Because it is intrinsic we saw that the resistivity was 100 kilo ohms centimetre. It is not enough. So, what we do is we start introducing impurities. So, to this silicon, we add impurities. Actually, these I mean, we do not call them impurities, we call them dopants. The reason is, these are what we like. So, even though these are foreign items, we call them dopants.

Add dopants, when we do that, we achieve you know, we can control conductivity. So, there are various types of dopants. For example, you have donors like phosphorus, arsenic, and antimony. So, you have a perfect crystal of let us say silicon like this. We saw this before, so silicon bonded to 4 different atoms. So, now go and remove one silicon and replace it with a phosphorus atom.

When you place a phosphorus atom essentially we are doping with phosphorus. So, what happens when you dope with phosphorus? If you look at all these dopants these are called us donors or they increase electrons in the lattice. So, these are all what you would call as group 5 elements. Group 5 elements have 5 electrons in outermost shell. So, we removed one silicon and replaced with group 5 element, let us say phosphorus, which has which has 5 electrons in the outermost shell.

So, what do the 5 electrons do? So, 4 of them 4 of those electrons will be used up to form covalent bond with the neighbouring silicon atoms. But then there is one electron which is still there extra. And this can get ionized, you know, this electron, the fifth electron. Fifth electron is ionized and it is free to move around in a lattice. Basically ionize means it is going away from the dopant site.

It is not staying with the doping site. And then it can move around in the lattice. So, what happens to the so, when it moves around most electron moves around in the lattice it can actually contribute to conduction And if you increase the number of dopants, you know, these are donor impurities. So, if you increase N_D, we call them N_D, just to represent that number of donors.

If N_D increases, the electron concentration increases, this is how you achieve higher electron concentration in semiconductors. So, that is how we can control conductivity .What happens to the phosphorus atom? The phosphorus atom is now having charge. Because ionized phosphorus has a positive charge, because we have taken an electron away from the phosphorus.

Initially silicon lattice is electrically neutral and even the phosphorus atom was electrically neutral. Then, from the phosphorus atom, we have taken out one electron. So, that is why you are creating a donor atom. Whenever you dope a semiconductor with donors, we call it n-type semiconductor. n-type means basically it has a lot of electrons. This is an n-type semiconductor. It has more electrons than holes.

Now, we could also substitute a silicon atom with a group 3 element. For example, here you have a list of group 3 elements, which are essentially, they increase the number of holes So, what we do is we substitute with group 3. When you do that group 3, group 3 elements have 3 electrons in the outermost shell. So, now, if you put a, now we will take a piece of boron and put it here in the lattice. What would happen?

It has 3 electrons. So, it will use those 3 electrons to form a bond with the neighbouring atoms, but then it can only form 3 bonds. There is this deficiency of an electron. So, it cannot really be boron in principle and can accept one more electron to become stable or to fill its valence shell. But that electron, where will it get it from? Of course, it tries to get that electron right because it wants to be stable. So, where do you need to get it from?
It will get it from one of those neighbouring bonds. The neighbouring bonds can break like you know what is shown here and then that will release an electron and that electron will be

captured by the boron atom. So, the boron atom captures electrons from the lattice and this process is called ionization. Basically it becomes an ionized acceptor. We call this as N_A.

And actually this acceptor has a negative charge now, because initially the boron atom was electrically neutral, but now it has accepted an electron So, it becomes negative So, N_A- we denote it And similarly in the case of N_D+ we call it N_D+ because the donor require a positive charge. So, N_D+ it is basically and then here it is N_A-. So, acceptors require a negative charge.

And of course, we have a hole which is now in the lattice. So, if you increase the number of N_A, N_A increases, holes increase in the lattice. This is how you can create a p-type semiconductor. A semiconductor which has more holes is known as a p-type semiconductor, which has more electrons is called n-type semiconductor. So, these electrons and holes can contribute to current conduction.

Now, let me ask you a question. Will the ionized acceptors or donors contribute to conduction? Let us think about it. If you want to, you can pause the video and then think about it. So, will ionized donors or acceptors contribute to current conduction? Will they? They cannot. This answer is going to be no. The reason is they are fixed in lattice.

These ionized impurities or dopants are actually bonded to 3 different or 4 different silicon atoms lying next to each other, next to them. So, they cannot move and so, they cannot contribute. They are only contributing some charge and this charge is actually a fixed charge. Remember this ionized donors have plus charge, acceptors have negative charge. And these are actually fixed in the lattice. They cannot move.

What can move is the electrons in the holes they actually add into the lattice. So, this is an important process and this is very, very important that you know you get a hang of it. So, the most common dopants are listed here. For n-type we have phosphorus, arsenic and antimony. Out of which usually phosphorus is what we use most of the most of the time. Sometimes we use arsenic. Antimony I have not seen that many no examples.

Similarly for p-type I find that most of the time it is boron, even gallium is actually very rare. So, this is how you dope semiconductors. So, the same dopants will work even for germanium.

But what will work for gallium arsenide, gallium arsenide is a 3 5 semiconductor, what do you use? Shall we use groups 2 and groups 6? We can use them for gallium arsenide.

It turns out that you could also use group 4 elements. For example, you can use silicon as a dopant in gallium arsenide. Because silicon can either take away an electron or give an electron depending on whether it is you know, taking an electron I mean to which it is replacing. If you replace gallium you get one type of a doping configuration, if you replace arsenic you get another type of doping concentration. So, think about it.

So, sometimes doping can actually act as both donor and acceptor. Those are called amphoteric doping. Basically, it can be both electrons and holes, amphoteric elements, silicon in gallium arsenide is an example of that. So, anyway, we are not talking about gallium arsenide, so, silicon this is enough,

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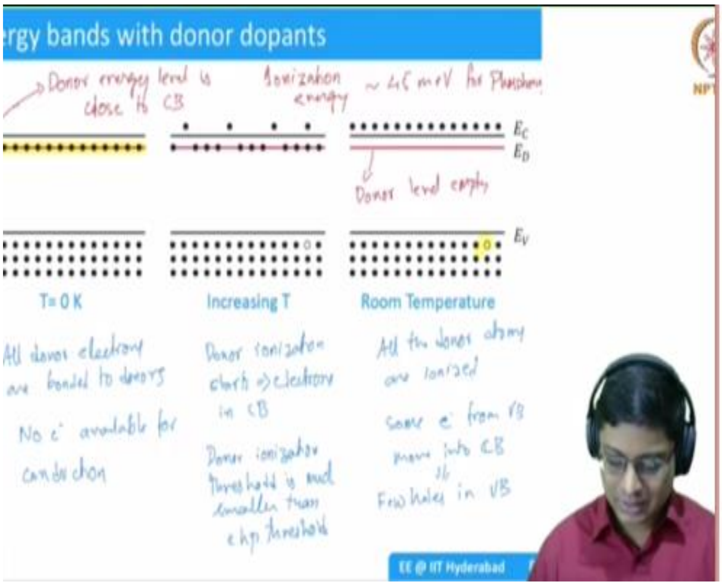

So what? This is basically physically we understand what is happening. We are replacing an atom and then it is causing these things. But what is happening with the energy bands? So, I said that the dopants, the donor, are getting ionized. So, the acceptor is getting ionized, but then that requires some energy. How does it get ionized? So, it also turns out that these energy levels because we study these energy levels that come.

Because of the atoms and lattice and all that we understand that from the particle in the box,

So, this dopants are actually quite close to the silicon atom. In the periodic table, it is just next to it in the periodic table. So, when that happens, it turns out that the donor energy levels, now let me. This is a donor energy level E_D, I call it you have the original E_C and E_V and you can also put a donor level which is E_D,

So, the donor energy level is close to the conduction band. Why this happens is not necessary, but you can think of it. Like you know, it is quite close in lattice constant. I mean, it is just next to it in the periodic table. So, you can expect that the energy levels are also similar. So, you have this donors and if you are at 0 Kelvin, 0 degrees, what happens?

Your valence band is completely filled up with all the silicon electrons and then there is this donor level and that has some electrons. But those are all in the donor itself. They are not free to move around. So, basically, this is where we show the electrons as at the donor level. That means they are tied to the donor atoms. So, they are not going to contribute to conduction. When will they start contributing to conduction?

They should get ionized. That means electrons should get out of the donor atom and to do that, we require some ionization energy. Ionization energy and this turns out to be about 45 milli electron volts for phosphorus. So, this is quite small energy, we said room temperature and energy KT right was 25 ,26 milli electron volts. So, quite close to that. So, as you start increasing the temperature we are adding energy to the lattice.

So, then, slowly you will find that these electrons are actually moving into the conduction band. Some of these electrons are moving into the conduction band and they are getting ionized. And of course, as further temperature increases, you will have you know, if you reach room temperature, room temperature is 300 degrees Kelvin. And at that temperature it is sufficient and you will see that all the donor atoms are ionized.

That is why here at room temperature the donor level is empty. That means all the donors have been ionized and you have N_D+. So, let me just repeat it one more time, this is an important process. So, at 0 degrees, what happens? All electrons are all donor electrons. Let us only talk about donor electrons. Donor electrons are bonded to donors So, basically, there are no electrons available for conduction.

Now, as you increase temperature, donor ionization starts. That means electrons start escaping from the donor atoms. And this implies that you have electrons in the conduction band. That means they can carry current. You might ask as temperature increases you could also have electron hole pair generation. You will have some electron hole pair generation.

But remember the energy required for electron hole pair generation is E_g whereas, the energy required for donor ionization is very small. It is about 45 milli electron volts. E_g=1.12 eV. So, basically the donor ionization threshold is much smaller than the ehp threshold by which I just mean that you need energy higher amount of energy to get electron hole pair. So, what you see is that most of the electrons are coming from the donor level instead of from the valence band.

But as you further increase of course, you know at room temperature we will actually have to calculate how many electrons are there and holes are there. We will calculate that, But at room temperature all the donor atoms are ionized. And actually even some electrons from VB moving to CB. Basically ehp generation happens So, this leaves some holes as well.

So, when the donor surrenders you have electrons and implies few holes in few holes in valence band So, there I have indicated a small you know one hole here essentially just to indicate qualitatively what happens. We will actually compute this, down the line you know how many electrons can be there how many holes can be there So, whenever you know by the way whenever you introduce a dopant let us say you are introducing donors.

You are essentially creating electrons, a lot of electrons so, electrons are called as a majority carriers. But in the process you will get a few of the holes. In this case holes are called the minority carriers.

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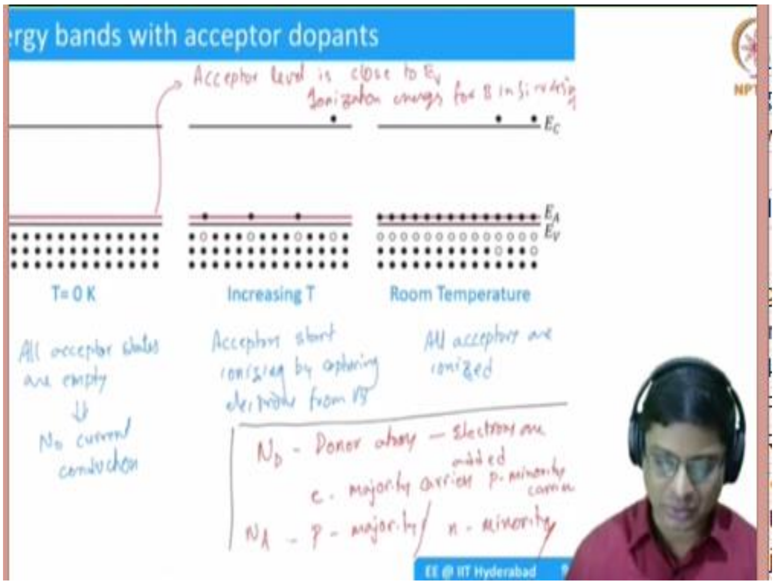

You will see that the situation is reversed when you have acceptor dopants. The same story. Basically in this case the acceptor level is close to E_V valence band. And it has a small ionization energy. Ionization energy for boron in silicon is also about 45 meV. I mean the numbers are you know we can check from the textbook but I think it should be about 40 to 45 meV or something.

So, when you have this what happens to the as the temperature changes. At T=0 all acceptor states are empty. Implies no current conduction. When there are no states available, how can they you know everything is bonded. Every electron is bonded so there is nothing there is no conduction. But as T increases, you start seeing that some of these electrons from the valence band jump into the acceptor states.

When they jump essentially the boron atom is capturing the electrons from the lattice. And so, basically, we are saying that acceptors start ionizing by capturing electrons from valence bands. Remember the valence band has lots of electrons. The same story again. Even the ionization threshold here is actually much smaller than the electron hole pair regeneration threshold.

And as you further increase temperature, you see that all acceptors are ionized. So, let me know one thing. Let me say N_D basically donor atoms. When you add donor atoms, you create electrons. Okay electrons are added. Electrons are added in significant number actually. So, basically electrons are majority carriers and holes are few in number. So, we call them minority carriers.

Whenever you dope with donors you get electrons are the majority carriers and holes are the minority carriers. And when you dope with acceptors N_A, so, basically you are adding more holes because you can control the number of acceptor ions in the lattice. So, if you add more holes you get holes as a majority carriers and electrons or I should say n right, n is a minority carrier.

So, this is first time I guess we are introducing this so, this is you should think about it. We just the definition we keep talking about it multiple times majority carriers minority carriers. Whenever donors are added electrons are majority carriers and holes become minority carriers. Whenever acceptors are added holes are the majority carriers and electrons are the minority carriers.

We will see why they are also because we will compute the numbers and you will see the difference in the ratio.

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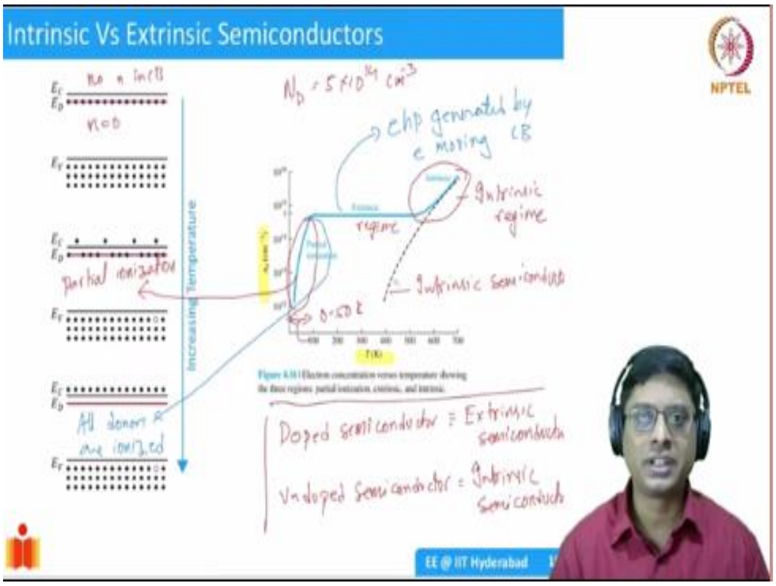

So, I mean this temperature dependence is a very very important part of understanding what is happening in the lattice. So, I just plotted a different graph. So, let us imagine okay. So, far we are not taking any numbers. Now, let us try to imagine, we have added N_D. $N_D = 5\times10^{14}$ cm^{-3}. This is the number of dopants I am adding into the lattice. How am I adding we can think about it later.

But I am adding donor atoms 5×10^{14}. So, what happens as you increase the temperature? This is very, very good way of understanding. If you understand this particular graph on the right, you would have understood a lot about semiconductors. How they are operating? So, when temperature is 0, I mean this is not a log plot. Again it is not 1 over T plot.

This is simply the carrier concentration and, and versus temperature. So, as that temperature is very, very small. I mean, let us assume 0 temperature what happens? You know, n = 0. The reason is, all the donors are not ionized and electrons are all in the valence band. There are no electrons in the no electrons, no n in CB. So, there is no carrier concentration at all, n is 0.

But as you increase the temperature, we will start seeing that you have donor ionization is happening. And this particular part whatever we called as partial ionization as the temperature increases slowly the electrons concentration increases. This is basically partial ionization, what we talked about in the last couple of slides. At some point all the donors are ionized. And you do not require a lot of temperature to achieve this.

So, when you have all the, you know, this is a point where all donors are ionized. And then there is nothing much. If you increase the temperature further, what should happen? As you increase the temperature there will be electrons in this part. Electrons, electron hole pairs can be created. Electron hole pair is generated because by electrons moving into CB they jump from valence band into the conduction band that can happen.

So, because of that you have ehp generated. But that number is very very small. Remember at low temperatures, the electron hole pair generation process is very you know the number carriers generated is very small. So, if you have a semiconductor which is doped, doped semiconductor I will call this as extrinsic semiconductor. Okay undoped semiconductor I will call this us intrinsic semiconductor this is the language we use.

So, if you have an extrinsic semiconductor once you have ionized all the donors the carrier concentration cannot increase. So, it sort of stays constant because there are no further donors to ionize. All of them are ionized. But then as you continue increasing the temperature at some point the Ni will start increasing. We saw that even if you have an interest in semiconductor as you increase the temperature more and more electron hole pairs are produced.

So, at some point the electron hole pairs produced from the intrinsic contribution or from the valence band electrons jumping into the conduction band increases. At some point that will take over because of which your carrier concentration now in the blue it starts increasing. So, in this case, when you reach this regime, we call it the intrinsic regime.

The reason it is intrinsic regime is that the increase in the carrier concentration is dominated by the excitation of electrons from the valence band into the conduction band. So, this is the intrinsic regime. And at intermediate temperatures, this is extrinsic regime. Because, essentially the carrier concentration is flat because all the donors are ionized. There is nothing more to ionize.

So, the carrier concentration does not change with temperature. And in the very small temperatures, up to about 50 Kelvin, this is usually up to about 50 Kelvin, 0 to 50 Kelvin, I would say or even 100 maybe a little bit close to that 50 to 75 Kelvin. At that temperature, you will see that only a few of the domains are ionized and because of it, you have an increase in the carrier concentration.

So, you should be able to plot the carrier concentration changes as a function of temperature. So, the blue one is extrinsic semiconductor and the dashed line is an intrinsic semiconductor. This is an intrinsic semiconductor wherein, you have as you increase temperature, we already saw that Ni keeps increasing n = p = Ni. That increases. So, I would like to stop here. It is already 55 minutes. So, I would like to stop here.

So, today what we did was, we started out with basically how the effective, we introduced a concept called as the effective mass in semiconductor. We said you know, how the carriers move about in a lattice can be captured by this quantity known as effective mass. And that can be calculated based on the E k dispersion. We gave you a formula to calculate the effective mass. It is simply the second derivative. It is proportional to the second derivative.

And we gave you know, we gave you we showed you one problem, we did not solve it, but I leave it as an assignment in the homework. If you just solve it, a few cases and that will help you. But the concept should be clear if you are not just revisit this slide. And then we talked about intrinsic carrier density, how that changes. How it varies across different materials germanium silicon and gallium arsenide and then how it changes to temperature.

So, this is what again we came back in the last also. So, finally we talked about doping. Doping is essential to semiconductors, so please make sure that you understand doping. We keep using this again and again. So, you should be quite comfortable with this. So we explain how donors will impact, how the ionization happens in donors, and how it happens in acceptors.

So whenever you dope with acceptors, we get holes. So, we call it p-type, we call it p-type semiconductor. Whenever you dope it with donors, we get electron, so we call it n-type semiconductor. So, please try to summarise it on your own. Take a piece of paper, write it on your own, make sure that is correct. That will help you clear up any concepts. So, conceptually, the physics has been described quite, I think quite well.

So you just have to make sure that you follow through the chain of thoughts. And once you are able to do it on your own, you should be good for the next lectures. So, in the next lecture, what I will try to do is, you know, we will introduce one more, a few more things. We will actually go deeper. We will talk about what is known as Fermi function, how that influences carrier density.

And we will also start know, calculating some numbers. I will meet you in the next lecture. Till then, take care. Bye.