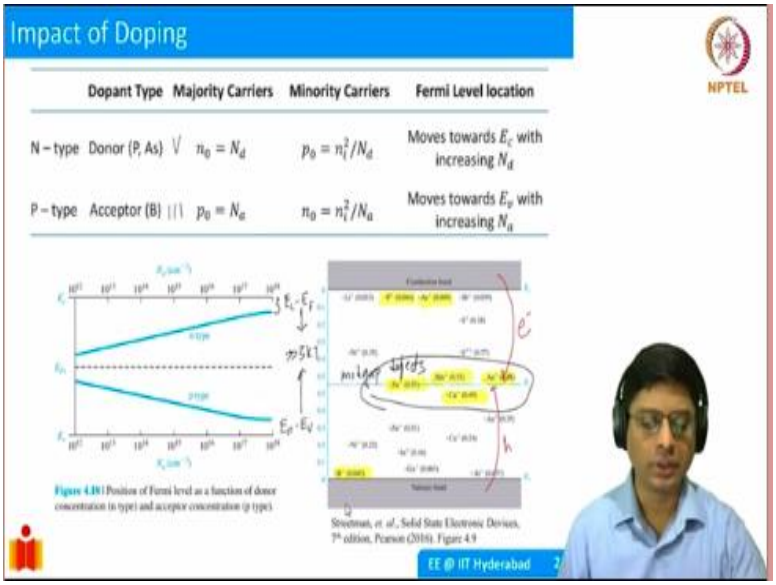
Introduction to Semiconductor Devices
Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture – 2.6
Temperature Dependence of Semiconductors

Hello everyone, welcome back to Introduction to semiconductor devices. In the last lecture, we introduced the concept of doping.

(Refer Slide Time: 00:11)



We explained qualitatively what happens when we introduce dopants into semiconductor. And then we talked about how the Fermi levels change in a semiconductor. So, quick recap. So, we said that there are 2 types of semiconductors you know n-type semiconductors and p-type semiconductors. We get n type semiconductors when we introduce donor atoms into the lattice.

For example, it could be arsenic, it could be phosphorus. So, then we introduce these elements. These are group 5 elements. So, these are group 5 elements and so, they have 5 electrons in the outer most shell. So, these that single additional electron is going to go into the lattice and then it will contribute to electrons So, we have majority carriers as electrons in an n type semiconductor.

And the concentration of electrons would be essentially given by the doping density. If you have more dopant atoms you have more electrons. And we also saw that there was a relation which is, $n_0 p_0 = n_i^2$. And from that you could calculate the number of minority carriers which are holes and that will turn out to be some number which is given by expression here.

So, analogously, we also looked at p-type semiconductors wherein if you let us say put boron into the lattice, which is group 3 element boron and so, it requires one more electron. And so that it can form 8 covalent bonds with the, it can share 8 electrons with the neighbouring silicon atoms. So, because of that, it will accept an electron from the silicon lattice and becomes negatively charged.

And it creates a hole in the process. We saw this. So, in p- type semiconductors the majority carriers are the holes and the minority carriers are the electrons. So, these are exactly the reverse of what it was in n-type semiconductors. So, we also saw how the Fermi level changes when you change the doping density. So, we said that if you have very less number of dopants, then essentially the number of electrons or holes being introduced is very very small compared to the intrinsic carrier density and the Fermi level will be close to the E_i.

But as you increase let us say the donor density, the number of electrons increases and slowly the Fermi level moves towards the conduction band. And similarly, for acceptor density if it increases the Fermi level moves towards the valence band. And we also noted that this difference here basically $E_C - E_F$ in the case of conduction band, and $E_F - E_V$ in the case of valence band is very, very important.

We said that these numbers should be greater than 3 kT. The reason we said that was because if you have the Fermi level closer than this 3 kT, then the doping tends to be you know, it is basically, we say that it is a degenerate doping level. We do not like it. The expressions we give are actually only valid for non degenerate doping. When you have non degenerate doping where we are okay?

Otherwise, we have to take additional expressions and it becomes a little bit more complicated. We will not deal with them. You might ask a question. Now we have all these you know

phosphorus, arsenic, boron, why only those elements? Why not other elements? To understand that, we have to look back at the origin of how these you know bands are forming.

We have the silicon lattice, and you have the bands, conduction and valence bands. We have seen it multiple times. Now, these dopant atoms are essentially like defects in the lattice. If you, if you have a lot of dopant atoms, then they will actually form defect bands. But generally the defects are you know, the dopants are going to be smaller in number. So we can represent them by an energy level.

And we saw this already in the last lecture. We said that the donor level is going to be slightly below the E_C, and the acceptor level is going to be slightly above E_V. But how did we come to that? You could actually calculate the energy levels; we can actually calculate how a defect in a silicon lattice behaves. And then we can determine what the energy level of the defect is and here are some of the examples are shown.

For example, phosphorus. Phosphorus has an ionisation energy of about 45 milli electron volts. Similarly, arsenic has about 50 milli electron volts, and boron has about 45 milli electron volts. So what this tells us is that the energy is quite close to the conduction band. These are ionisation energies in silicon lattice. So these 3 elements have energies which are very close to the conduction and valence bands.

And that is why they can be used as acceptors and donors. So, why not other elements? Let us take a few examples here. So there are many different examples which are elements which are shown here. But first, the important things are zinc, manganese, copper, gold. So these have defect levels or the energy levels which are very very in the centre of the band. And these become very, very critical for us.

And of course, there are many other you know, like tin and zinc, indium and so on, which also can contribute to energy levels in between the band. So, the reason we are particularly interested in these mid gap levels, you know, these 4 of these which I have highlighted here. These are known as the mid gap levels, mid gap defects, you can call it. The reason we are interested in it is we will you know, first of all, we try to make sure the semiconductor is extremely pure so that it does not have any of these defects.

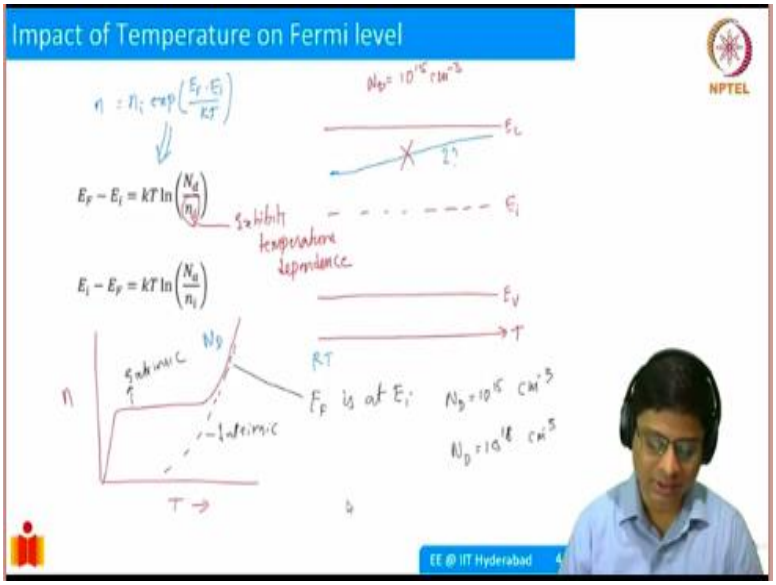
That is why we say that you know, it is 9 in purity we said right. The reason we ensure that is even if you have a small trace amount of zinc or manganese or even then it causes defect levels and that can cause to problems in current conduction. That is why we purified and then deliberately introduced arsenic or boron or phosphorus, one of them. We try to make sure that there are no other defects present.

But by chance, in the fabrication process some amount of gold or zinc got in, what would happen? We are saying that the defect level is close to the mid gap in the middle of the band gap. So, what would happen is the zinc or a gold dopant can act like a trap centre you know. We initially we said electrons are going to get excited from electron hole pairs are created when electrons jump from valence band to conduction band.

That is one of the processes driving the equilibrium and the opposite process was the recombination. So, it so happens that if you have a trap centre right in the middle, then it can actually trap an electron from the conduction band. So it will trap it. Similarly, it can also trap a hole from the valence band. And because energy differences now are only $E_g/2$, in the previous case, the electron hole to recombine the energy difference was E_g, and it was less probable.

But if you have the energy differences, $E_g/2$, this sort of a trapping behaviour is much more probable. And it will actually cause dissipate, it will recombine electrons and holes will recombine and dissipate as heat. And we do not like that in semiconductor devices. That is why we do not like these, you know, energy levels, which are in the middle of the band. So we will stick to phosphorus, arsenic and boron in the rest of the lecture period.

(Refer Slide Time: 07:22)



So now, let me ask you a question. We saw how the Fermi level changes with dopant density? How does it change with temperature? If you want to analyse that, we will have to look at the expression because we are interested in plotting. For example, I am interested in plotting, let me say I have E_C, E_V. And now the question I am asking is, as I change the temperature, what would happen to the Fermi level?

Let us say initially, you know, the Fermi level was somewhere. Let us take some doping density, I do not know. Maybe it would take 10^{15} donors. If you take that, for example, this is E_i. Let us start with $N_D=10^{15}$ cm^{-3}. If you do that, what happens is, let us say the Fermi level was originally somewhere in here, that is the initial point. Now let us say this is at room temperature.

This is at RT, room temperature. Now as I increase temperature, what happens to the fermi level? Think about it. Take a moment. If you look at this expression here, which is given on the left, it says,

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

So as the temperature increases, does the $E_F - E_i$ increase? is a question that you should ask.

So we will go like this with the E_F-Ei, as temperature increases, does this happen? It is a question. Please think about it carefully. And by the way, how did we get this expression.

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

Remember last time we have derived this expression, or we gave you this expression, we said that n is equal to n_i, exponential. We said n_i is the reference levels of intrinsic level. So that has minimum carrier density.

And now if you add dopants it is going to increase So your exponential is going to have $\frac{E_F - E_i}{KT}$.

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

So as you increase the dopant density E_F goes closer to E_C. And so E_F–E_i increases. And therefore, the electron concentration increases, and you can rewrite this in this form here. Similarly, you will have an expression for holes. So now, what will happen to the doping density as we change the temperature?

Or rather what happened to the Fermi level as we change the temperature? What I have shown here, this is wrong. It will not happen like this. The reason is, n_i also exhibits temperature, exhibits temperature dependence. You know, I really like this sort of you know graphs which will tell you know, qualitatively what happens with changes in temperature doping density and so on.

Because, if you are able to correctly do the draw these graphs, you understand quite a lot of physics. So, please try to make sure that you are independently able to explain the graphs. Whenever you see a graph showing some parameters mainly, just think about it. That will really help clear up a lot of concepts for you. So now how does the temperature influence the doping density?

We saw this in the last the 4th lecture video wherein we said that if you have an extrinsic semiconductor and this is your temperature and this is your doping, let us say electron density. So, initially you would have you had the partial ionization with you and then there is an extrinsic regime and then there is an intrinsic regime. So, this is for a like let us say N_D doping let us some number.

And correspondingly you also have another curve, which was an intrinsic part. So, as you change as you increase temperature, more and more electron hole pairs are generated. So, this is your intrinsic and this is your extrinsic semiconductor you could say. So, as I increase

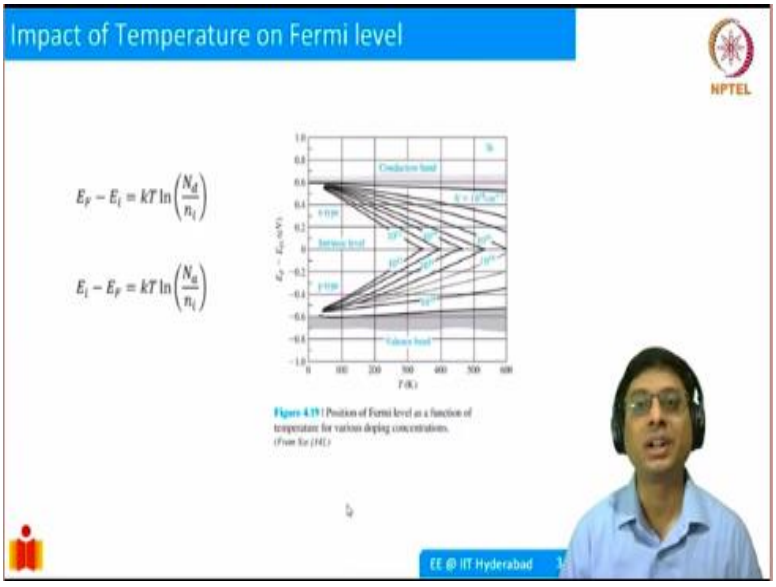
temperature, this is what is happening. So now, physically looking at what is happening? You know, you should not see much of temperature variation.

Whenever your semiconductor is in the extrinsic regime here, you should not see any changes in the Fermi level with temperature. But once that semiconductor reaches intrinsic regime, then you start seeing that the number of electrons is going to be equivalent to the intrinsic carrier density. So, the intrinsic carrier density is going to drive your electron hole pair electron concentration.

And we know that whenever it is in the intrinsic regime, E_F is at E_i. Because, intrinsic semiconductor, E_F has to be E_i. We proved it actually in one of the lectures in the last lecture maybe. So, what should happen now? So, it looks like as you increase temperature semiconductor becomes intrinsic that means you have you know, the electron hole pair generation which is dominant, and which will take the Fermi level close to the E_F.

So, please think about it for a moment. Try to draw , take $N_D = 10^{15}$, $N_D = 10^{18}$. And, let us say just draw for these 2 per centimetre cube, because everything is per centimetre cube whenever I talk of density.

(Refer Slide Time: 12:50)



So please draw the graph of this and verify whether what you are getting and then you can compare it with this expression, this graph here. So this is what happens. So, as we said, as temperature increases, the semiconductor becomes more and more intrinsic. And of course, if

you are doping density is high, it takes higher temperature to make it intrinsic. But if your doping density is low, it quickly becomes intrinsic.

So n-type, p-type, so please make sure that you understand this. Even though you know, in a paper based exam, I typically ask these questions because it can use a lot of insight into understanding the student.