Semiconductor Devices and Circuits

Prof. Sanjiv Sambandan
Department of Instrumentation and Applied Physics
Indian Institute of Science, Bangalore

Lecture – 13
Doping - Continued

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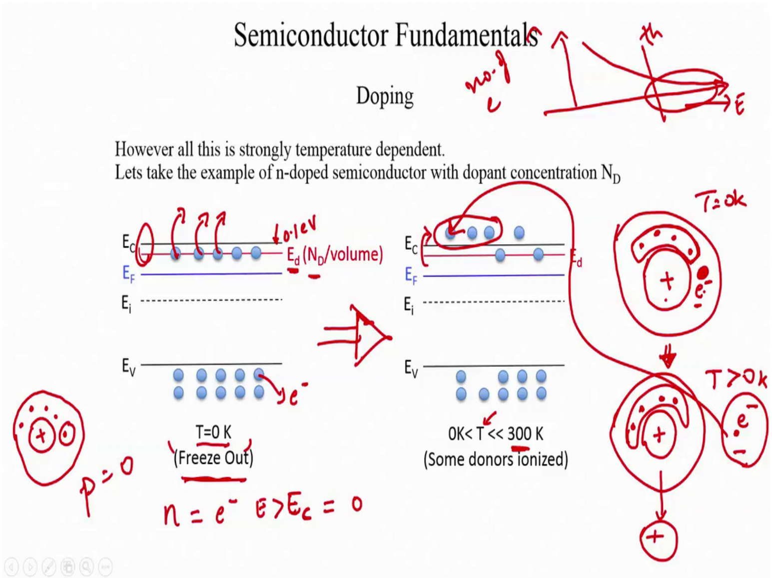

Now, what we will do is look at the temperature dependence of doping ok. So, first let us take a condition, where we have added these let us take an N type semiconductor again ok. We have added these donor dopants right. So, we have populated the semiconductor with N D per unit volume donor dopants. And it is all created this little bunch of states at an energy level E d, which we had found that was you know very close to the conduction band edge, it was about 0.1 electron volts or less close to the conduction band edge. And all these donor atoms have got five they are all initially neutral, they have they all have five valence electrons, (Refer time: 01:14) talking about silicon, and they are all occupying these states.

So, what we have shown here is that these blue circles that you see, these circles are all electrons. And what this implies by my placing electrons on this, it implies that the fifth electron is still attached to the donor dopants, so this is still one entire species ok. So, if you think of the donor as having say a nucleus and it has this many electrons and we will only show the valence electrons, so five valence electrons. So, these four are going to participate in the bonding with the silicon ok, they are participating in the bonding with the silicon and this entire thing gather is charged neutral ok.

But, the moment this electron moves away, it is going to leave a positively charged core behind. So which is this is charge neutral, this is an electron, so there is a negative charge here, there is a positive charge here, the entire species charge neutral. But then, the moment you pull that electron away, so let us say you have these four that are participating in bonding and this is my species. The moment this electron exits, it gets into the conduction band, you leave behind a positively charged.This entire entity is now got positively charged, and it is fixed, whereas the negatively charged electron is moved away.

So, at T equal to 0, what is being shown here is that this electron has still not moved away, and it is this electron that is being shown in this picture here ok. So it is that electron we are talking about. By placing an electron in these states, it is this electron that will eventually get to the conduction band that we are showing. So, all these states are now charged neutral ok, they have got their fixed ion, but it is still not ionized and the electron is still with the donor atom. And this happens at T equal to 0 Kelvin, and this condition is called as freeze out.

So, since there is no thermal energy, and we are at thermal equilibrium, there is no temperature, there is no thermal energy, the electrons do not have any energy. And therefore all the electrons are sitting in the valence band. They are not able to get promoted to the conduction band. And since, it is exactly 0 Kelvin, it is not only the electrons in the valence band that do not have energy to go to the conduction band, it is also the electrons present at E d that is with these donors that are not able to escape the clutch of the donor atoms. So, it is all bound together, and it is all sitting there.

So, the number of electrons in the conduction band is 0. So, if you look at the N count, which is the electrons at E greater than E c, which is what I am interested in for calculating the currents is 0 ok, so the electron concentration is here. What is the whole concentration in the valence band? That is also 0; the P is also 0, because there are no vacancies here, all the states are filled. So, this is the temperature; this is the condition at T equal to 0, and it is something called as freeze out. So, I think this is a technical term, it is called as freeze out condition. So, doping really does not help you, if your T is equal to 0.

Now, let us say we start increasing the temperature. We will go from this diagram, we will move over to this diagram here, we start increasing the temperature a little. So, let us say we pull up the temperature, we cross 10 Kelvin and then head to 50 Kelvin, but we are still well below 300 Kelvin, and (Refer Time: 05:13) still not reach to room temperature ok, so what happens. You will find that, since the temperature is now increased, the electrons do have some thermal energy.

Now, since this energy gap is much smaller than that energy gap, you will find that many of the electrons that were here have all now moved up. They have taken this little thermal energy, they have and that is sufficient for them to cross this energy gap. And therefore they have all populated the conduction band, which means this condition. These donor atoms, they moved from this state to this state at a temperature T greater than 0. And this is at T equal to 0 ok. These electrons have now gotten enough energy to jump into the conduction band. It is these electrons that we are talking about.

But then, is also statistics right, there are still many electrons that did not acquire that energy. T is greater than 0 Kelvin, a certain population. So let us say this is the energy distribution for the electrons, so let us say that is the energy, and that is the number of electrons ok. So, let me draw it let me draw it better. So, let us say it is we are looking at a tail like this, and this is the threshold. So, it is only these electrons that can jump up from here to there.

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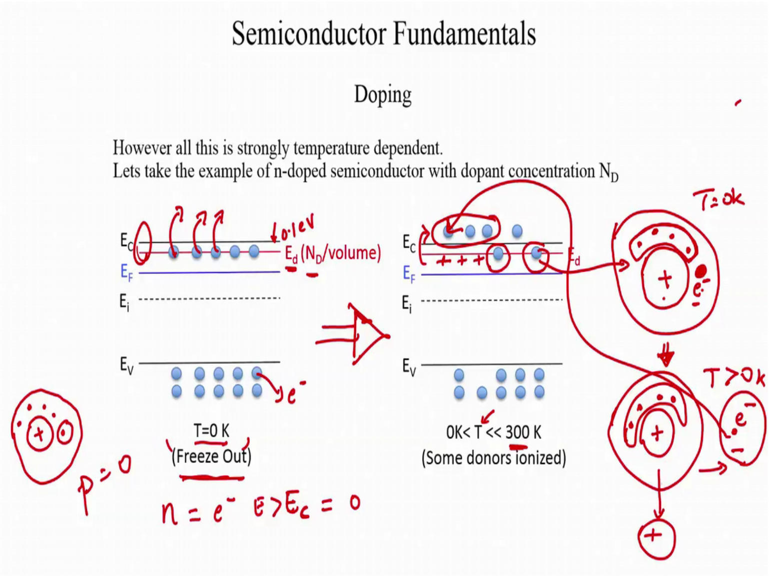

So, you still do have some donors that are not ionized, because those electrons did not statistically collect enough energy to cross this point one electron volt barrier. And therefore, you do have some of the donor atoms still in this condition with the electrons still bound to the donor. Whereas, many of the donor atoms are now ionized, they have left behind positive course. I should have shown the positive core here. They left behind this positive positive core and promoted the electron into the conduction band. So, these there are many several of them, where the electron has escaped the clutch of the donor atom ok, so that is the case at T equal to some temperature greater than 0 Kelvin, but less than 300.

And since, the temperature is still much less than 300, you do have quite a few of these donors that are ionized, but then most of the electrons in the valence band are still stuck to the valence band. You might find one or two that could statistically collect enough energy to get pass the energy gap, but this gap is you know almost ten times that gap, and therefore that count is going to be very few. So, we have shown you know say three of four of them escaping this and maybe just one escaping the valence band. So, but the numbers are going to be much more different ok, so that is what happens when you start to increase the temperature slowly. Some of the donors get ionized, and some of them contribute to the electrons.

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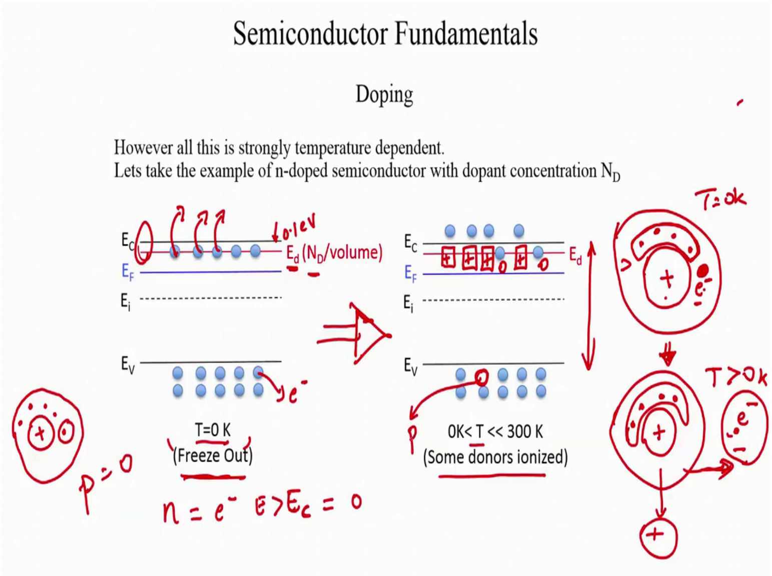

So, what we should do to correctly show these pictures, we will draw static positive charge at the locations at the donor sites, where the electrons have left the donor, whereas these are all still charge neutral these are all charge neutral sites. So, this is the correct picture. And here we have a vacancy, we have got a hole that is left behind, so that is going to contribute to your count P.

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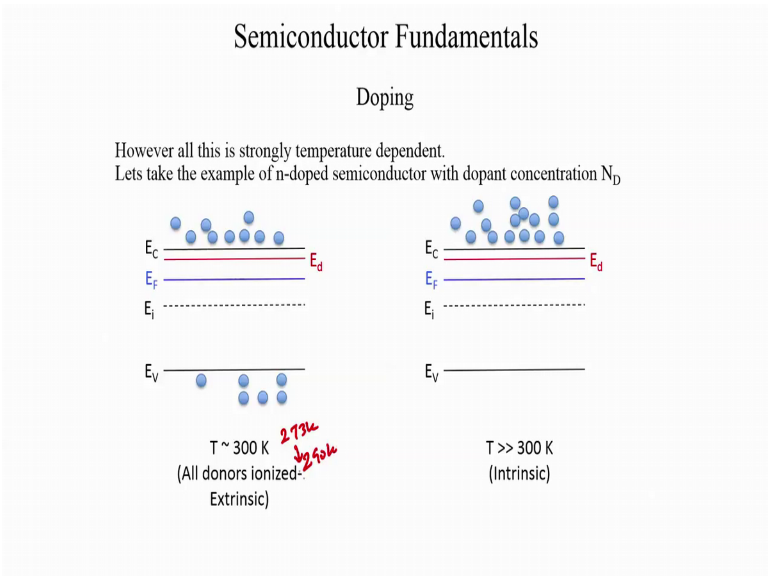

So, as we increase the temperature further, so we let us start approaching 300 Kelvin, you know we hit we hit say 273 Kelvin, and then we start increasing it, and we start approaching 290 Kelvin, and we are in and around 300.

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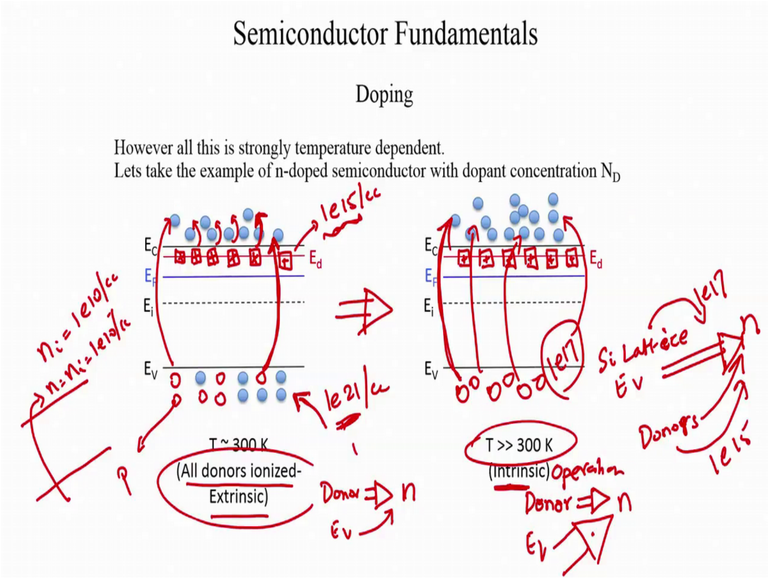

So, in and around 300, we have a large number of electrons that have escaped the valence band, and left behind holes, and these electrons have all migrated to the conduction band. The temperatures now large enough, but this temperature is much more than enough for the electrons in these donor levels to escape the clutch of the donor. And at these temperatures you should find that almost all in fact, all the donors would have ionized, if the doping is done properly. All the donors would have ionized, they would all left behind positive ion cores there. And all these electrons would have escaped. You will find now a lot more electrons from the conduction from the valence band in the conduction band, and all the electrons from these donor sites now in the conduction band.

So, at this temperature, all donors ionized; and the semiconductor is now called extrinsic ok. So, when we say extrinsic semiconductor, it means that as opposed to an intrinsic semiconductor. That means, it is a pure semiconductor without any doping, as opposed to a pure semiconductor. The electron population for the case of N type doping, the electron population is because it is largely, because of the donor contribution, that is all the donors are ionized, and that has that is what is contributing largely to the electron count, and not so much the electrons that have come out from the valence band ok, so that is what you mean by an extrinsic semiconductor. So, an extrinsic semiconductors typically a doped semiconductor with all dopants ionized ok, so that is what is happening at T equal to 300 Kelvin.

Now, let us say we continue increasing the temperature further, you know we push it up, we go from 300 to 400, and maybe even greater than 400 to 500 Kelvin. So, now the temperature is so large, that these donors which were initially ionized, have nothing more to do, there were no more electrons to give up, so they are not going to contribute anything more beyond your 300 Kelvin. These were they already gave up everything all the electrons they had at 300 ok, this is the maximum they could do.

But, now the temperature is so large, that the electrons that were sitting in the valence band, can now significant number can migrate to the conduction band. So, in this condition, it is the electrons from the silicon lattice that is the valence band electrons that are contributing most of the electrons to the n count that is the electrons in the conduction band. The donors have already contributed everything they had, and their contribution now is minimal.

So, just to give you some numbers ok. So, let us say we put donors of 1 e 15 per cc. The intrinsic carrier concentration is about 1 e 10 per cc. And the number of silicon atoms in a silicon lattice is order of 1 e say 21 per cc, I might be an order more or more or less, but so the order of 1 e 21 per cc. So, this is about five times, five orders greater than intrinsic carrier count, and that is about six orders greater than the donor count donor concentration.

So, at T equal to 0 Kelvin; N was 0; P was 0; nobody contributed anything. At T equal to 300 Kelvin in a pure semiconductor intrinsic semiconductor, the n count would have been equal to n i, which is 1 e 10 per cc. But, since we have doped at 1 e 15, the N count is going to be closer to 1 e 15 that is you know five orders of magnitude greater than what an intrinsic carrier count would have been. But, now as we keep increasing the temperature, almost all the silicon atoms that is you know we are talking about 1 e 21 or 1 e 22 silicon atoms (Refer Time: 14:11) going to start giving up their electrons. So, let us say we have 1 e 17 silicon atoms that have given up their electrons ok, so which means that the contribution of the silicon lattice to n is 1 e 17, and the contribution of the donors has not changed after 1 e 15, it had only 1 e 15 to give; it is 1 e 15.

So, at lower temperatures, the donor was contributing more ok. At lower temperatures if you look at the electron count, the donors were giving the bulk of the count towards n, and the valence band was giving very little. But, at temperatures that are much larger, all the donors have already given everything they had to give. So, the donor count has not changed; it is the same ok, it is the same. But, the valence band count is now suddenly increased, it is become much much larger; and this is the one that is contributing more.

So, it is as though the silicon is behaving like an intrinsic material, because it is the electrons that are coming into the conduction band now are coming in from the valence band. And therefore we call this operation at T much much greater than 300 Kelvin as intrinsic operation. It does not mean of the semiconductors intrinsic; this operation is intrinsic; I should call it intrinsic operation ok, intrinsic like operation. The semiconductor is definitely doped; it is not a pure semiconductor. But, if you look at the electron count in the conduction band, it comes largely from E v, because the donors have already given up everything they had ok.

And therefore, we call it as intrinsic operation.

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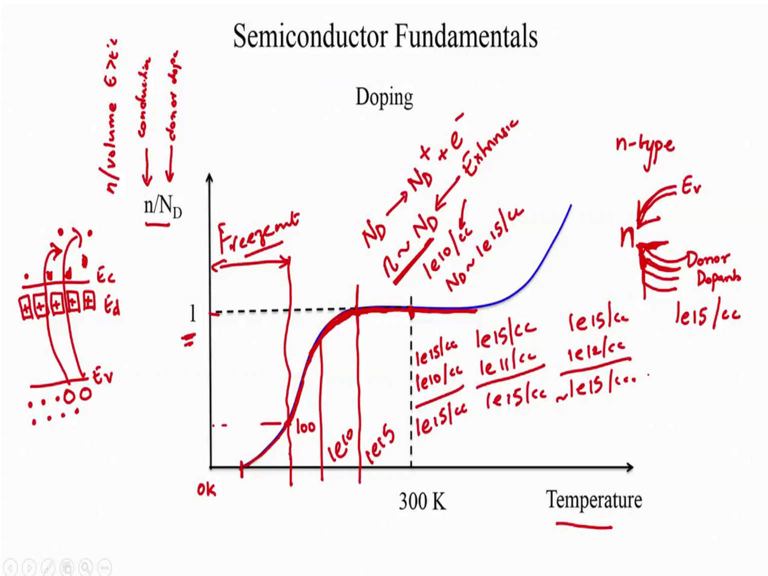

So, here what we plot is the electron concentration in the conduction band divided by the donor dopant concentration. And this is to gauge, how this parameter or how this ratio varies with the temperature. So, as we saw the electron concentration, so at very low temperature. So, let us call this as 0 Kelvin ok; we do not really approach 0 Kelvin, so we start from a very low temperature. At this very low temperature, you have the conduction band edge, you have the valence band edge, and you have your donor levels. And all these donor levels have the electrons bound with the donor atoms. The temperature is too low for these donor atoms to ionize.

Now, as the temperature begins to increase, the temperature is still very low for the electron in the valence band to get to the conduction band ok, so then the electron in the valence band does not make that jump. But, the since the donor level is located so close to the conduction band, the donor electrons can easily make this jump ok. So, we are we are only talking about an n-type semiconductor here, for in this particular plot, and we have assumed that we have doped at with the donor dopant.

So, now as a temperature begins to increase a little, you find that these electrons can easily make this jump, and the electron concentration above E c. So, this is the electron concentration per unit volume at E greater than E c begins to increase. Now, as the temperature increases further, both sites start contributing electrons to the conduction band. So, you have the total number of electrons per unit volume in the conduction band to be n, and it is receiving electrons from the valence band as well as electrons from the donor sites from the donor's donor dopants. So, at T equal to 0, both these were 0. But, as the temperature begins to increase, since the E c minus E d is very low, this contribution was significant. And you find that in all, this region the donor contribution is important.

Now, till a certain point you know since the electron the concentration is very low, we called this as the freeze out region. In fact, freeze out does technically when everything is 0, but we will call this entire region as freeze out. Now, the donors keep contributing. So, more and more donors keep getting ionized. So, let us say we had implanted 1 e 15 donor atoms per cc donor dopants per cc. I would say this temperature let us say 100 donor dopants contributed were ionized, and therefore they contribute 100 electrons to the conduction band.

And as the temperature increases, (Refer Time: 19:59) this contribution significantly start increasing. So, let us say here 1 e 10 donors contributed, and they will reach a temperature, where all 1 e 15 donors will contribute. So, the temperature here is large enough, that all 1 e 15 donors have ionized, and all these electrons have moved to the conduction band leaving behind positively charged donor course ok. So, these are immobile positively charged centers. And all these electrons have now populated the conduction band.

Now, since the temperature is large enough at this point, you will now start seeing a significant contribution from the valence band. So, there will be holes left behind, and there will be some electrons that you know sort of migrated from the valence band to the conduction band ok. So, this as the temperature increases, this contribution will increase, but this contribution will increase dramatically, it will be much much larger.

And beyond a certain point, all the donors would have finished contributing, there are no more donors per unit volume. So, there all the 1 e 15 donors have contributed the 1 e 15 electrons, and the electron count in the conduction band does not increase any further. And at this point, since the n so, basically what happens at this temperature is all the N D donors, they have all ionized, they have all become N D plus, and I have contributed an electron. And therefore, all the n, matches the donor concentration ok.

So, if the intrinsic carrier concentration was say 1 e 10 that is without doping and the donor concentration is 1 e 15, this n is now going to match N D, because the contribution from the valence band states at say T equal to 300 Kelvin is 1 e 10 ok. So, 1 e 10 of these came from valence band states, 1 e 15 came from the donor states, and the summation is close to 1 e 15. Now, in a 1 e 10 is five orders of magnitude less than the donor contribution. And therefore, n is approximately N D. So, this is the perfect extrinsic operation. So, we are in the extrinsic operation region, and therefore n by N D is equal to 1.

And this curve remains flat for a long time, because as the temperature increases, the valence band contribution is increasing. The donor contribution is still it is fixed. The donors have all given up everything they have had ok, so it is always 1 e 15. But, the valence band contribution is increasing, it goes to 1 e 11 per cc, but the total count is still 1 e 15. Then the valence band contribution will increase to say 1 e 12 per cc, but you know it is still thousand times less than the donor contribution. So, the total count is still approximately 1 e 15 per cc.

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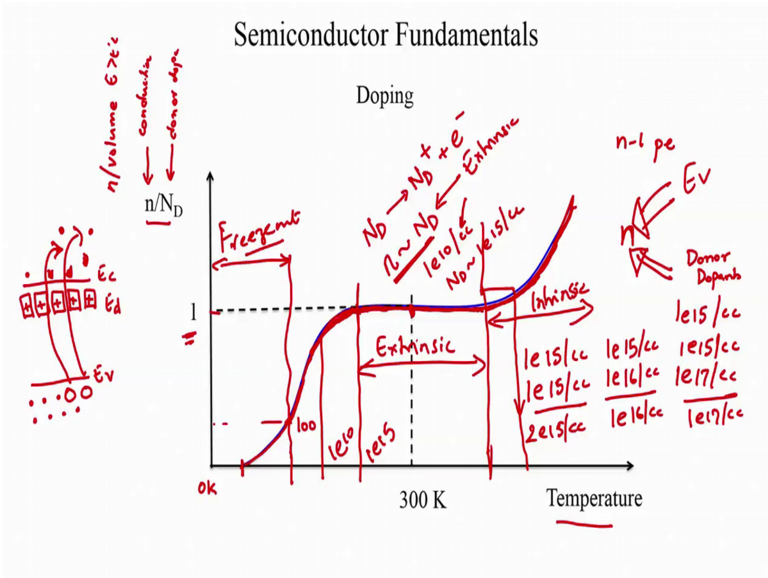

So, this continues for a while, and the curve remains flat, it is completely in this region, it is completely dictated by the donor contribution, and this is all the extrinsic region. The valence band contribution is increasing slowly, but it is still not large enough.

Now, there will be a temperature, where the valence band contribution now starts to match the donor contributions. So, let us say at this temperature, the donor contribution was 1 e 15 per cc, the valence band contribution will match this contribution. And you will start seeing the n by N D starting to get greater than 1. So, the n has increased beyond N D, and the n by N D curve will begin to climb up ok. So, beyond this point, the valence band contribution becomes greater. So, this is the donor contribution is still 1 e 15 per cc, there are no more donors ok, they have given up everything.

But, now the valence and contribution begins to increase dramatically. So, there are many more. So, this is a very badly drawn arrow. So, what I will draw is, the valence band contribution is now going to be much larger than the donor contribution. So, if the donor contribution is 1 e 15 per cc, the valence band into 1 e 16. And at higher temperatures, (Refer Time: 24:58) the donor contribution is still 1 e 15, the valence band will do 1 e 17. And now the count begins to increase. Now, you cannot ignore, you can now begin to ignore the donor contribution. So, this is going to be about 1 e 16 per cc, this is about 1 e 17 per cc and so on. And therefore, n begins to climb once more.

And in this region, since it is the valence band that is contributing to the carrier the electron count in the conduction above the conduction band, this region is called as the intrinsic region, intrinsic like operation ok. It is not that the semiconductors intrinsic as I said, it is the valence band that is contributing to the electron count as opposed to the dopant ok. And therefore it is like an intrinsic semiconductor.

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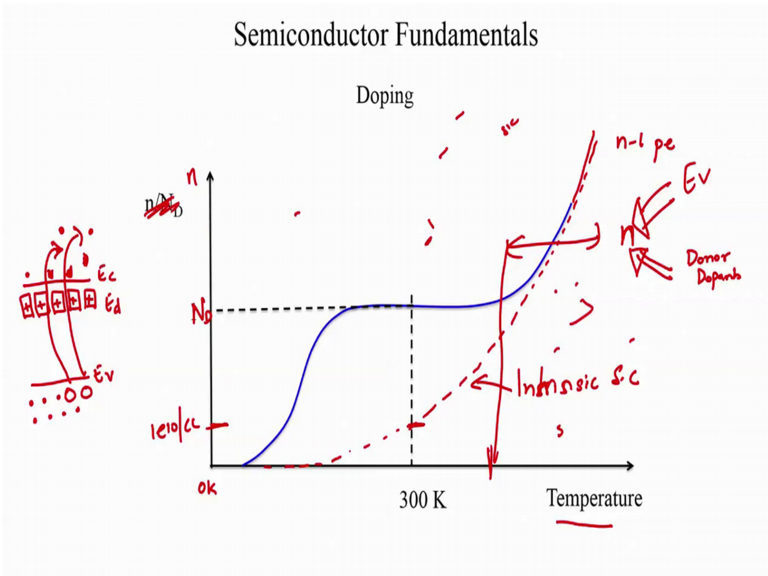

So, if he had no dopant at all, you know if he had let us say for example, the semiconductor was not doped at all, what would the electron count looked like ok, so n by N D does not make any sense. So, let us say we were to plot n, the general shape of n would so, in that case, we will have to redefine the y-axis, let us just do it for the sake of exercise.

We will redefine the y-axis in that case to n, and if we plot n versus temperature in the case of a dopant, this will now become N D. But, in the case of the intrinsic semiconductor, this would have remained very low. And at a certain point, this would have begun to increase. I should have crossed the 1 e 10 per cc mark for silicon here, and it (Refer Time: 26:54) continued to increase and would sort of asymptotically merge with this curve. So, this would this is what a purely intrinsic semiconductor would have done ok. And therefore, in this region, it is as to the doped semiconductor behaves like an intrinsic semiconductor all right, so that is the temperature dependence of doping.

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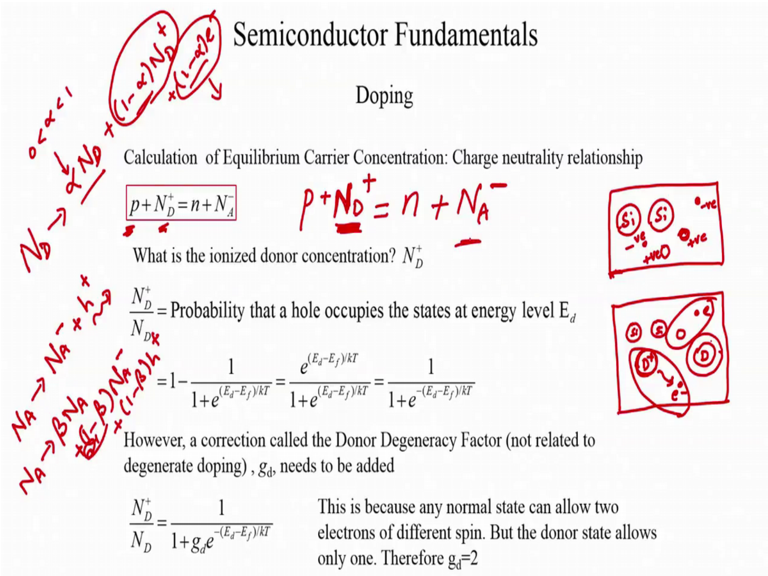

Now, what we do is, we want to now make a more careful count about a mac more careful count of the number of ionized donors, and an more exact count of the electron and hole population ok. And in order to do that, we will start with the charge neutrality relation. So, you know as we discussed the silicon was initially charged neutral ok. You have silicon atoms, some of the silicon atoms have given up an electron, and they have left behind a hole ok, these electrons are left behind a hole. So you do have negative freely moving negative charge, and you have freely moving effective positive charge species, which are holes. And therefore, the entire system is neutral, it is not charged.

And what we did now is we added a dopant, if for example, if we added a donor dopant as we discussed, you have all these silicon atoms that are neutral, we have some free electrons, we have some holes, and we also have about N D per unit volume of donors, and if these donors are all ionized. Let us say some of these donors are ionized, these donors would get a positive charge, and they would contribute an electron.

So, you see this is charge neutral, this donor is not yet ionized, so it is charge neutral, and the entire system is charged neutral right. So, there is there is no charging anyway. Therefore, we can write a charge balance equation. All the positive charges must equaled all the negative charges. And we will take a very general semiconductor, where and we have added some donors, we have added also counted up (Refer Time: 29:31) with some acceptors and so on.

So, all the positive charges are basically the holes that is the mobile positive charge, and the ionized fixed donor charge, not all the donors, only the ionized donors. So, these are the donors, this is the donor concentration that has given up electrons. So, for example, if the semiconductor is not an extrinsic operation, and if the temperature is not large enough, out of N D; let us say alpha donors alpha N D remains as unionized ok, some portion is unionized, and the remaining have ionized.

So, this is the charge neutral neutrality condition for the donors. So, this is a small fraction alpha is less than 1. This is the fraction that has not ionized; this is the fraction that has ionized. So, when we talk about N D plus we are talking about this fraction. So, P plus N D plus is equal to n that is taken into account, all these electrons plus any other existing free electrons in the semiconductor is equal to n, which is going to have negative charge plus the ionized acceptors ok. Just like how we talked about donor ionization, the acceptors will also have to get ionized, which means that an a neutral acceptor specie will take up an electron to complete the bonding.

So, let us say it takes up an electron to say let me write this go one step back. An acceptor will ionize by taking up an electron and giving up a hole, which is free to move about in the lattice. And let us say you know a fraction beta of these acceptors are not ionized, and 1 minus beta of these are ionized, and they gave up 1 minus beta holes. So, just for the sake of argument. So, we are talking about this fraction, when we write N A minus.

So, these are the ionized acceptor like species, and ionized donor like species that are charged. And the ionized donors have got positive charge, because they have given up an electron in the lattice, and the ionized acceptors have got negative charge. And therefore you have this charge balance relation. So, now the question is at some temperature, what is the ionized donor concentration, you know how much of it is N D plus at any given temperature. Can we calculate it? Can we calculated with whatever information we have.

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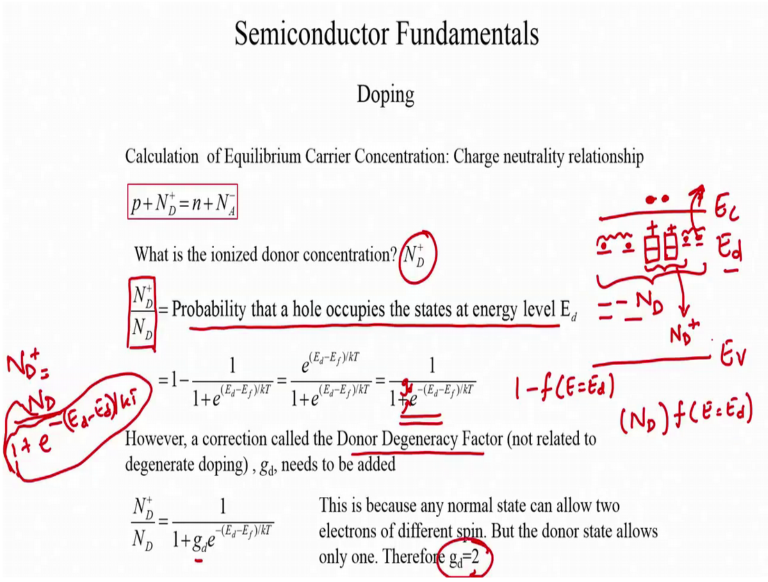

So, if you think about let us draw this energy level let us draw E c, E v, and E d all right, so that is where all the donors are sitting. Now, these have electrons, and let us say these are the ionized species, they have given up electrons. Now, the total concentration per unit volume is N D that is how much we added out of which a fraction of it has ionized, so that is N D plus, and that is what is needed for the charge balance.

So, now the question is what is N D plus, you know how much what percentage of N D plus I mean what percentage of N D is the N D plus, the ionized donors. So, instead what we will do is, we will try to calculate this ratio, you want to make a count, you want to be able to calculate it. So, we want to specifically calculate how much is N D plus by N D that is what is the ratio of the ionized donors to the total donor concentration. Now, N D plus by N D if you think about this diagram ok, these donors are all sitting at some energy level E d.

Now, if you ask the question, what is the probability that an electron occupies these energy levels E d. Now, you have got states inside the gap, and these states are located at E d. And how many states do we have. Since we have you know about N D donors per unit volume, the state sort of scale the number of state scales with this donor concentration.

So, if you ask yourself the question, as to how many electrons occupy the energy level the states at energy level E d, the answer is that it is the number of states available. So, we will say there are N D states available per unit volume into the probability that an electron occupies the state, which is nothing but the Fermi function at E is equal to E d. So, this is the number of electrons occupying number of electrons per unit volume occupying the states at E d ok, which is effectively these states, you see electrons are occupying these states.

We are interested in the states that are empty and therefore, charged ok. We are interested in those states that are positively charged, that is your N D plus. So, we are interested in the probability that an electron does not occupy the state at E d, which means it is the probability that a hole occupies the state at energy level E d, that is your N D plus by N D.

So, what is the probability that hole occupies states at energy level E d, it is 1 minus f of E, it is 1 minus f of E equal to E d, so that is my f at E equal to E d. And 1 minus that is essentially this term, we will divide by that factor there, and you end up with this particular ratio. Therefore, my N D plus is equal to this term here, which is 1 by 1 plus e to the power minus E d minus E f by k T into N D, so that is my number of ionized donors. So, it is this fraction. So, when we earlier mentioned alpha and 1 minus alpha, so this ratio 1 by 1 plus e to the power minus E d minus E f by k T is your 1 minus alpha (Refer Time: 37:05).

So, although this is the number of ionized donors, we need to be a little careful ok, we need have to make a small correction ok, and that correction is something called as the donor degeneracy factor. And this degeneracy factor has got has got little relation to the fact that whether it is a degenerate semiconductor or not. It need not it need not be a degenerate semiconductor ok. We are not interested in degenerate semiconductors in this course I mean de degenerately doped semiconductors. We are only talking about E c minus E f being greater than 3 k T.

But, despite that, while making a calculation of N D plus by N D, we need to attach a correction factor to this term ok. Why do we need that correction factor, we need that correction factor, because if I were to use this argument for any energy level let us say that is some energy level located inside your inside your lattice, I mean inside this energy gap because of some defect ok.

Now, two electrons could have occupied that energy level ok; you could have plus half spin and minus half spin. But, since this is a donor, and the donor allowed only one electron occupancy, and it gave up that one electron occupancy. We have to have a correction factor of 2. And therefore, we add this correction factor by taking this answer, which is come out from pure logic ok, which is the ratio of N D plus by N D is nothing but the probability that the hole occupies the states at energy level E d, which is equal to this term, which is a logically good argument. But, we attach this little correction factor called g d, and you sort of insert that g d in there ok, and that g d takes a value of 2.

And (Refer Time: 39:19) point is that as this as if you have a trap state, that is sort of located. If you have this these states instead of being located so close to the conduction band edge, if they were to be locate the little closer to mid gap, you do not have to worry too much about g d, you can take a value of 1, and you are quite safe with that value ok, so that is the count of the N D plus.

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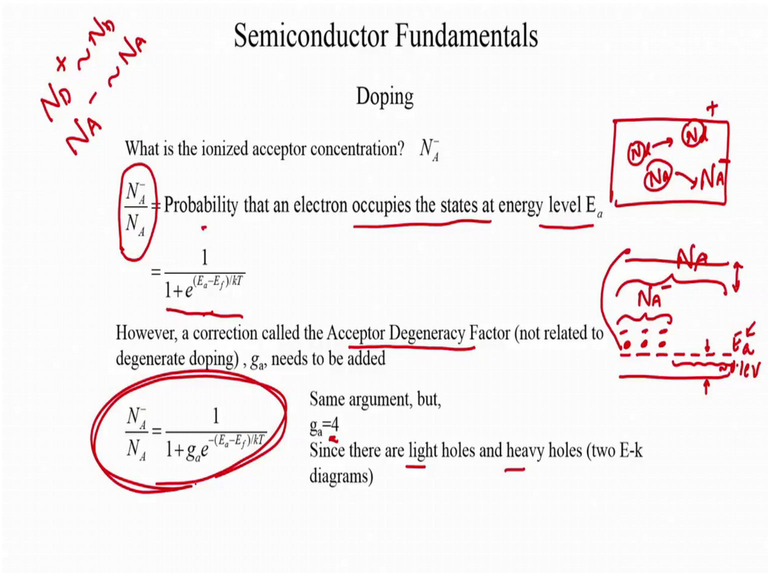

Now, what about N A minus? So, let us say we have counter dope to the semiconductor, we trying to keep things very general right. You have a semiconductor, you have added some N D out of which some of them have ionized, and you have also added some N A out of which a few of them have ionized. So, what is this N A minus count? So, let us make a logical argument there once again. So, if you have N A minus, they are going to sit close to the valence band edge, you know just like how we made in we made a calculation about how E d is very close to the conduction band edge. The acceptor level energy levels are also very close to the valence band edge, so they too will be about say 0.1 electron (Refer Time: 40:36) ok. So, you have these acceptors are also sitting very close to the valence band edge

And these acceptors, when they are charged neutral, they are actually empty, they only had three electrons the valence shell. And by and they get ionized by taking an electron from the lattice. So, by taking an electron from the lattice, these acceptors are now ionized, and they have a negative charge, whereas these are all still charged neutral. So, it is these acceptors that are N A minus ok. And there are a total of N A acceptors per unit volume.

So, we now ask the question what is this ratio N A minus by N A. So, going by the same argument, N A minus by N A is the probability that an electron occupies these states at energy level E a, where E a is the acceptor energy level. And that is given by your Fermi function that is your 1 by 1 plus e to the power E a minus E f by k T. But, just like in the case of donors, we have a correction factor called the acceptor degeneracy factor ok, and that is given by the symbol g a.

Now, logically one might say that g a has to be 2. But, since there are two E-k diagrams for holes, you have as you know these holes have got two different effective masses, and they are called light holes and heavy holes. We use a factor of two times (Refer Time: 42:22) which is g a equal to 4. And we have this to be the ratio of N A minus to N A. So, we have now identified what is N D plus, and what is N A minus for any given temperature T ok. Now, as T keeps increasing, your N D plus will eventually merge with N D, and N A minus will eventually merge with N A ok. But, for any arbitrary T, this is the ratio.

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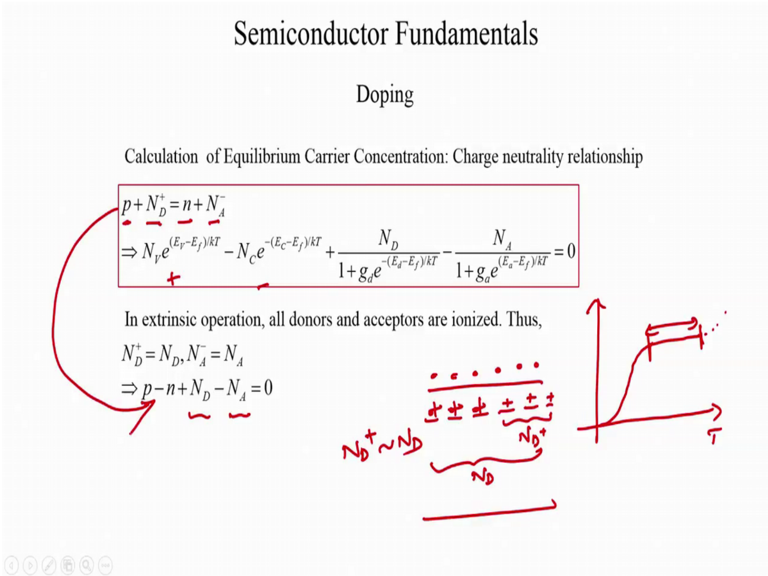

So, now we are all set to write a complete charge balance equation. So, what is p, p is equal to your N v e to the power e to the power e to the power E v minus E f by k T, we have already discussed that. N D plus is your N D plus 1 by g d e to the power minus E d minus E f by k T, where g d is the correction factor. N is nothing but N c e to the power minus E c minus E f by k T; and N A minus is this term. So, what we have done here is just bring all the terms to the left hand side, and say that the left hand side is equal to 0. So, you have the positive charges and you have these negative charges, they must balance out each other to made a charge neutrality.

Now in the case of extrinsic operation that is we are talking about this region of the curve, we have gone past freeze out, and we are an extrinsic operates operation, and we have not yet reached intrinsic operation. So, we are talking about this region, where all the donors have ionized and all the acceptors are ionized. Now, in this case, your N D plus is equal to N D, because this term has become 1. The temperature is so high, the temperature is so large that this term is negligible, and it is mostly 1, and here to the temperature so large that this term is negligible, and it is mostly 1.

So, in extrinsic operation, all the donors have ionized. So, there is no ratio anymore ok. So, for example, sorry: so if I were to draw the conduction band edge and the valence bandage, and let us locate all the donors levels. Initially all the electrons were here during freeze out, then as a temperature increase, some of these electrons moved up and there were some ionized donors that was my N D plus, and that was my N D, and that was the ratio that was N D plus as compared to N D.

But, as temperature increases, all the donors get ionized. And N D plus approaches N D, it becomes equal to N D. So, N D plus is equal to N D, N A minus equals to N A, and the charge neutrality relation instead of having N D plus N A, you might as well just retain N D and N A ok. So, the charge neutrality relation or the charge balance becomes this.

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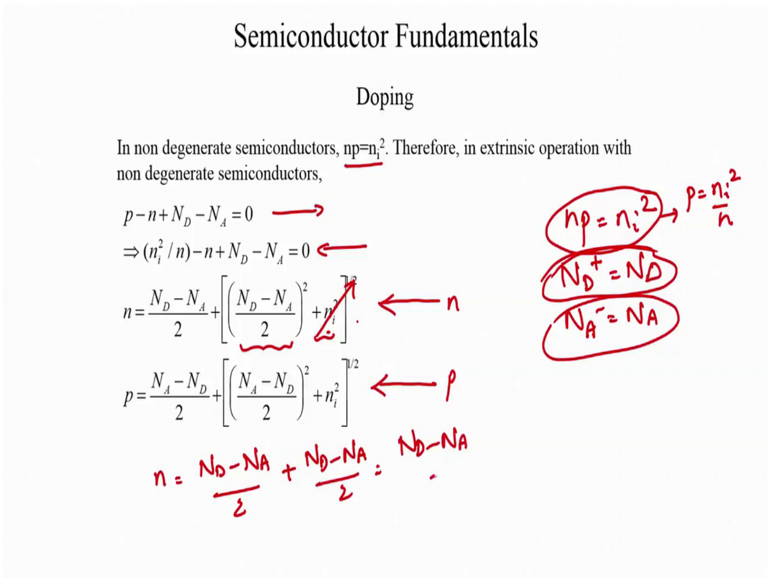

Now, if you use this condition, that n p is equal to n i square, and we are operating an extrinsic region operation that is N D plus is equal to N A N D and N A minus is equal to N A. Then this relation can be rewritten as this, because I am now representing my p as n i square by n. So, now we can establish a quadratic equation with n, we can solve this quadratic equation, and you will end up with the exact electron concentration per unit volume to be equal to this term, and the exact hole concentration per unit volume to be equal to this term ok. So, you just solve this quadratic equation, and I will end up with these two terms.

So, what assumptions have you made here, we have made the assumption the first assumption is all donors have ionized, all acceptors have ionized, cannot happen at low temperatures. This has to be at significantly high temperatures ok, need not be too high, room temperature sufficiently is a sufficiently good case for this assumption. The second assumption is this mass action law holds. And this will hold, when you are in thermal equilibrium, and in the case of non degenerate doping ok. So, this equation will hold. So, under these assumptions, you can say that this is my electron concentration in the conduction band, this is my hole concentration in the valence band.

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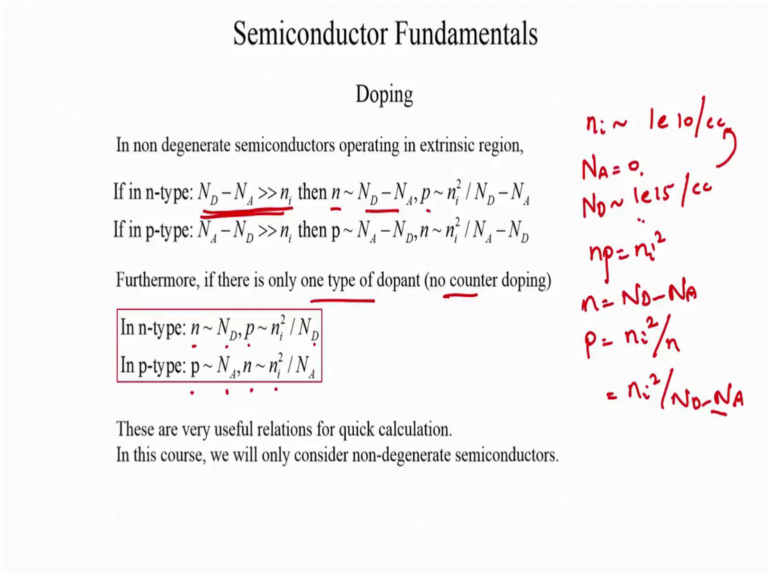

Now, we can make one more assumption if these concentrations are quite large, which is if in the case of n-type semiconductors, your effective donor doping is so large that it goes much greater than n i. So, n i is in the order of the case of silicon you know it is the order of 1 e 10 per cc. If let us say we are doing donor doping, where N A is 0, no acceptor ions, and N D is say 1 e 15, this is a reasonably good case to assume that N D minus N A, which is basically your N D is much greater than 1 e 10 ok.

So, in that case, if you look at this quadratic equation, if you just go back, if you look at these terms. So, let us say let us just take this particular equation there, let us say N A was 0 or essentially N D let us just say N D minus N A is very very large. So, N D minus N A is very large, which means that if you look at these two terms N D minus N A is much larger than n i square. Therefore in this term in the square root the n i square is negligible ok. We ignore that term. And you end up with n is equal to N D minus N A by 2 plus square root of N D minus N A by 2 the whole square, which is basically again N D minus N A by 2, which is equal to your N D minus N A, so that is the assumption we are making here.

If an n-type semiconductors if N D minus N A is much greater than n i, then n is approximately N D minus N A. And p can be calculated from the mass action law, n p is equal to n i square, n is equal to N D minus N A, and therefore p is equal to n i square by n, which is n i square by N D minus N A. And if you are if there are only one type of doping, so you know there is no counter doping that is your N A is 0. Then it is simply that n is equal to N D, p is equal to n i square by N D. And equivalently for holes, if you have accept like doping, if p is approximately N A, n is approximately n i square by N A. So, these are very useful relations for very quick calculations. And this will be very useful for you during these during the assignments or tests in this course ok.

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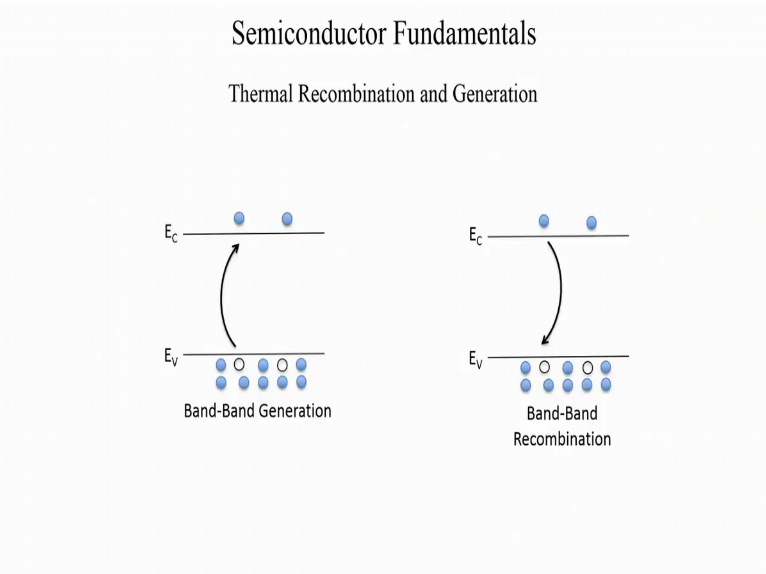

So, with that we will conclude doping. And we will start a new topic, which has got to do with the mechanism by which carriers are generated. The mechanism by which temperature influences care in the free electron and hole generation by thermal excitation.