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Welcome to lecture number seventeen. We want to continue from last lecture, and on this subject of equilibrium carrier densities, this would be the last lecture. After that we will move on to other topics. So, where were we, let us see. So, what we have done in the previous lecture was that, now we are point where if you plot 1 verses T verses log of carrier concentration, carrier concentration on this axis. Then we had that if this is intrinsic carrier concentration something like this; then I use this just not necessary same color code in this lecture but all I am saying is that; and this is the amount of doping.

For example, if it is, if it is N doped material, and this quantity is N D minus N A on this scale; if it is already along scale then you will directly need a read N D minus N A, otherwise you will read, read log of this number. Then, we had said that our behaviour of the actual concentration which we get is something like this- meaning thereby that beyond this temperature, beyond this temperature, on this side of this temperature our material will going

to be, is going to be intrinsic; shown by blue line. And then, on this side material will be what you call as extrinsic or another name is that it is called exhaustion region.

Owing its name this exhaustion going to the fact that, what is happened is that, if we have e c, e v and some dopent level in the all the carriers which were at this level have also gone to the, they have gone to the conduction band, and hence no more carriers can be the, they cannot be anymore carriers, and hence the number of carriers has become saturated. It is in this region that we use these semiconductors; in this region which is, by which I mean this exhaustion region; it is this region, this exhaustion region we use are semiconductors.

And, I and I did by mentioning by, by mentioning that suppose you have a p n junction, a semiconductor in which there is junction- one side is p semiconductor, other side is n semiconductor, what is that mean? That means that if you, well, if you keep increasing the temperature then we know that from this curve here that behaviour or semiconductor is going to become intrinsic. If this is silicon and this is also silicon, in that case what will happen?

While at these temperature regions in the exhaustion region this behaves like a, this region behaves like a p type semiconductor, this region behaves like a n type semiconductor. But, if you keep heating it up and temperature goes really high beyond this temperature, you mean, that means you higher to this region now then this semiconductor is also going to behave like intrinsic, and this semiconductor also going to behave like intrinsic- meaning thereby that since both are silicon then this junction property will be lost; will behave as it is a one big piece of, one big piece of silicon all over, and hence this device will stop functioning.

Ultimately this electronic device is functioned because that there are junctions of p and n or something like that. So, you lose the junction if you go to high temperature. And hence, intrinsic region is not interesting region where we can operate this semiconductor; the region where we can operate is then exhaustion, fine; this is where we were last time.

Now what we going to do is, today's lecture will be what I am showing in green portion. I am going to show to you that if you continue to reduce the temperature that means you continue to move on this axes then the question we want to answer is what will happen to n, when you when temperature starts continues to become lower and lower. I will show it to you that carrier concentrations again began to decrease; and, what is this characteristic of this behaviour, I will wind out to you. But before I do that let me continue on this thought of exhaustion and intrinsic carrier concentration alone; still let me continue on that little bit more before I go to the freeze at still lower temperatures.
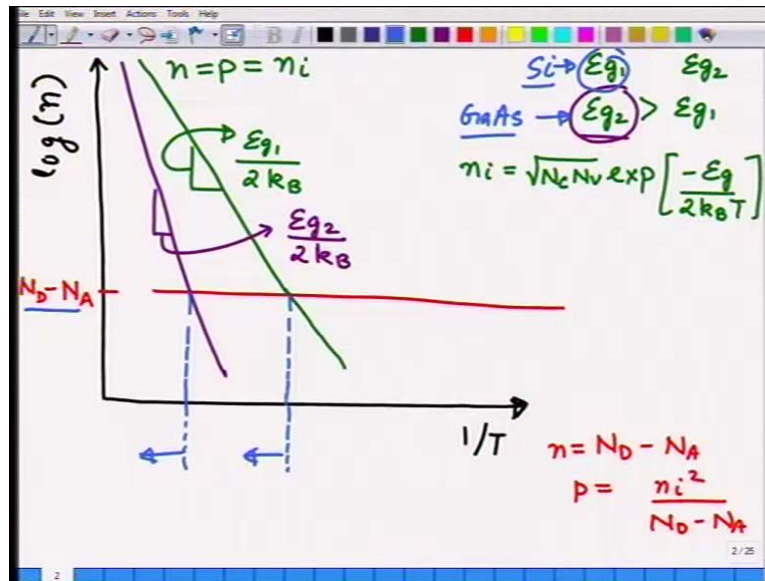
Let me plot this 1 by T one more time; 1 divided by T, I am plotting on this axis; and this is log of carrier concentration, maybe log of n if you wish, if you going to log of n in which we have this, let us say this straight line, something like this; this is the intrinsic carrier concentration that means on this n is equal to p is equal to n i, is the intrinsic carrier concentration. And, the slope gives me, slope gives me minus e g, let me call it 1 for right now k T, that is what the, sorry, not T, by 2 k; all right, drop the minus sign, it is obvious that it is anyway negative slope; so, let me just write, e g 1 by 2 k is a slope.

What I mean is suppose you have 2 semiconductors- one has a band gap of e g 1, other e g 2, and let us say band gap of another semiconductor is, second semiconductor is greater than that of the first semiconductor; then what will be intrinsic behavior? Recall that n i went as square route of N c N v e to power minus e g by 2 k, 2 k B T, that is what n i was. Clearly, then if you increase the band gap then the carrier density will decrease for the, this slope will become greater and greater. I am avoiding minus sign; I am simply saying more negative slope is what it will become then therefore.

If, therefore if I plot, also simultaneously plot the semiconductor for e g 2 intrinsic carrier concentration then I should plot it something like this. If the green line continues like this then this line should be plotted like this, meaning thereby that at any temperature this, since e g 2 is greater than e g 1, the carrier concentration will lower. And, notice the slope that I have drawn is also steeper. This slope of course then will be minus, will be e g 2 by k B T will this slope be then, in that case, ok.

If so, now let us do this. If now, we say that I have a semiconductor which simultaneously has been doped by, let us say we have a semiconductor which has been doped by some net doping of N D minus N A; that means it is permanently more N dope than the, more N dope than p dope; that means more donors than acceptors. So, net doping as we have seen semiconductor is N D minus N A. And, under these conditions the carrier concentration n, the majority carrier concentration; p of course will be much smaller which will be n i square then by N D minus N A will be A smaller number. And, we have given the example on that.

So, if we look at this n which is independent on temperature in the exhaustion region then that would look likes a line something like this. I am again plotting that exhaustion region; here is my N D minus N A of course, N D minus N A. Remember, whatever I am doing; you could plot plot this as log of, instead of plotting log of n you could plot log of p if p is majority carrier; and then you will write N A minus N D, is the same thing. So, whatever I am doing for donors you could do it for acceptors; that does not change anything, all right.

If so, now notice what happens? So, if I look at this behaviour then what do I see? I see that this semiconductor e g 1 which has a band gap of e g 1; for example, let us say this is silicon and let us say this gallium arsenide which has a band gap 1.5 and silicon 1.1, then what will happen? That, beyond this temperature this semiconductor, at this semiconductor, at this temperature semiconductor will start behaving if you increase beyond this temperature right here 1 by T values more than is less than this, then and therefore T is more than whatever corresponds to that point, in that case this semiconductor will start behaving like intrinsic semiconductor, that we have talked about.

If your e g 2, if you take semiconductor which is a higher, which is a higher band gap then that semiconductor would be able to behave like intrinsic semiconductor to higher temperature; of course, have a smaller value of intrinsic carrier concentration; therefore, it takes then greater temperature to reach same value as N D minus N A, whatever is in your system. And hence they can operate in its exhaustion region for, at a, upto a higher temperature. In, sometimes in design consolations you may have to include this as well. So, that is the, another point I wanted to make on, make to you, let you know, want to tell you about, before I move on to what is called as carrier freeze out.

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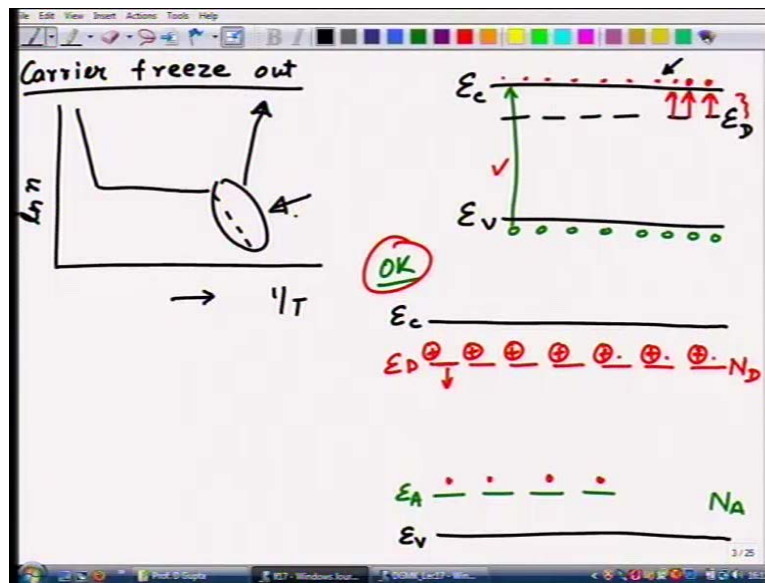
What is saying this; that when temperature was high the dominant mechanism, infact dominant mechanism was the carriers which came because of this reason. The carriers came because of; I am corresponding holes here because these electrons jump over, because these electrons jump over across the band gap therefore we got intrinsic semiconductor, and we plotted out this curve right here like this.

Now, when the temperature became lower, when the temperature is lower that means you moving in this direction, what happened was, at some point of time this, the carrier concentration here what determined by the dopant level; we have e D as a dopant level; and then now what happened was these carriers became, the jumps which became possible toward these jumps. Well, not these jumps became possible, they were always possible; when this jump was happening, this green one, at that time obviously this is small energy gap and hence these jump was happening any ways.

These jumps were anyway smaller jumps across the dopant level happening anyways. Just that the carrier concentration because of these intrinsic jumps was so high that they number because of this was much more smaller. But now, as you lower the temperature intrinsic carrier concentration thus one because, because of this jumps qualitatively at least becomes small; and this particular number because of this which was happening earlier also becomes a more dominant one; and, in that case what happens is micro becomes, starts taking shape of like this, ok.

Now, you also recall that I had given example where I had said that if you have a situation like this, e c, e v, and then let us say I have sort of donor levels like this, and I have some accepter levels like this, and I had said that suppose they are N A of these and suppose they are N D of these, and I had said that; this is e D level and this is this is e A level, this is E A level; then I had said that if you were to look at a picture at 0 k, if you look at 0 k, then what happens?

My electrons I tie, the electrons I tied up to these levels this weight and I am going to erase some of these; and then I had said that at 0 k what will happen, these electrons, some of these electrons will go down here and reach here even at 0 k because that way they lower the energy, so I am going to remove this electrons from here; this 4 electrons; I remove this 4 electrons, but then I am showing you at 0 k these 3 electrons atleast here and still bound to their this three these electrons right here, here and here; these three in this picture is still bound to their phosphorous atom. For example, if phosphorous is a donor in silicon, in that case these three electrons are still bound to the phosphorous, or fifth electrons still bound to the phosphorous atom at 0 k.

Clearly, that means, in this case we know that the carrier concentration would be very low because nothing is there in the conduction band. So, we clearly know that if we continue to go down lower temperature then this carrier concentration must somehow come down, must begin to come down, that we know. What the nature is a straight line, how it come down, that we have to discuss; but that is what is called as carrier freeze out. This is what we mean by carrier freeze out.

That, even at the dopant level, now the carriers will not be able to contribute to conduction, and they slowly and slowly some of these, the fifth electrons of phosphorous and silicon for example will remain; temperature has become so low that there is not enough energy, thermal energy to even extract that fifth electron out to the conduction band and therefore the carrier concentration will again begin to drop down. It is, this is statistics. Now, we are beginning to learn about. So, that is what I am going to do right now.
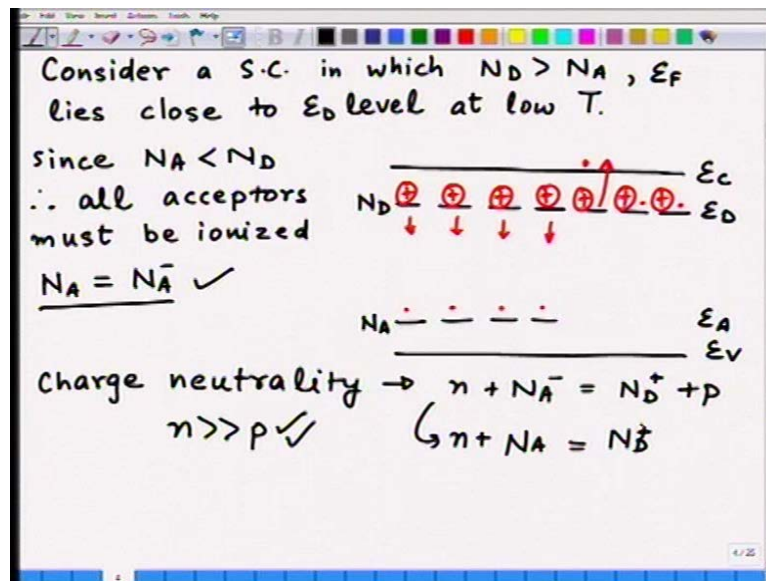
So, again what we will do is, consider a semiconductor in which, in which N D is greater than N A. You are free to consider a semiconductor where, I take example where donors are more than acceptors; you are free to take example where acceptors are more than donor, does not matter. In that case you must talk in terms of p, number of holes but in volume in that, because that is the majority carrier in that case, all right.

If that, if it is so, then formue level lies close to e D level. We have seen this and I gone through everything very clearfully with you that when formue level is exactly at e D level then half of the, half the impurities are ionized. That means, remember this five, at all, in the exhaustion region all the impurities, temperature was high enough, all the impurities were ionized; everything had gone to conduction band. But now, if formue energy was at safe, exactly at the donor level, then what happens? Half of these donors are ionized and half of them are not ionized; that means fifth electron is still tied to the donor, donor atom. So, that is what is going to happen at low temperature. So, is close to e v level at low temperature.

So, what is the low temperature, then what would happen in this case, is what we will like to, try to understand. And, I will draw my picture; again in this case I will again draw the same picture which I draw during the last page, e c, e v, and then I am going to draw those 6, 7 of these, again these acceptor levels; so, N A is smaller than N D, so I have shown 7 lines, 7 segments here for e D level, at e D level; and at e A level I am showing you 4 because that represents N A, number of such sides per unit volume; and this is N D, number of such sides number of phosphorous atoms; so number of boron atoms in case of N A, number of phosphorous atoms in case of N D, phi unit volume of course always.

If so then I have already drawn the picture for you that, what happen is that some of these; now in this picture that I will be ionized; some of the phosphorous atoms not I is ionized, but some of these atoms will be ionized and some will not be ionized; maybe I am showing you one electron due to here, going down here and this is the electron here, here, here; at some low temperature these electrons have gone down here, schematically. That is not necessary exactly how it happens. And, these are the once low temperature is low enough; these have still not ionized that is what is happening.

So, what do we see? Since, N A is smaller than N D; so, first thing we know is since N A is smaller than N D then therefore all acceptors must be ionized; that is N A should be equal to N A minus, all those which ionize; why we can see that is schematically I have shown you; even at 0 k whatever is a, all these electrons would have fallen down to minimize the energy. And therefore, N A would be completely ionized; the boron would have accepted the, for example, a boron in silicon would have accepted these electrons and would have become B minus; that means it is ionized, it is having 4 electrons.

And clearly that will happen because formue energies lying somewhere close to e D level, formue energy somewhere close to e D level. If formue energy is close to e D level then that also says you have your formula N D, N A minus divided by N A, and you can see that if formue energy somewhere here; we have done this exercise, that means all these N D levels would be ionized, ok.

If so then what can, how can I write charge neutrality? If I write charge neutrality then I know, n plus N A minus, should be equal to N D plus; that is what should the charge, that is what the condition for charge neutrality should be. And this is condition were p is much much less than n of course, otherwise I should have, or I should, let me add p, let me add in a p first, and then I am going to say that I am going to use this assumption; I will use this assumption and that n is much much greater than p, since it is n dope semiconductor.

And, we have seen that that N dope semiconductor n per N p is n i square, since n is dominating. Therefore, and since n is dominating, so I am making assumption n is much much greater than p, this assumption I am making. And, in most cases it will be true. So, if that is so then I will write this expression as n plus N A, I replace N A minus by N A, is equal to N D plus, and I will drop this p in favor of N D plus. Anyway N D plus we can imagine is on order of 10 to power 16 or 10 power 17 per centimeter cube. This quantity or N D is and therefore p will be a small number, in comparison therefore, all right.

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If so, now let us substitute this; what is N D? N D plus by N D, you will recall, is of course e to power is equal to e f minus e D by k B T, it is this quantity. So, I will substitute this in here, and therefore n plus N A should become equal to N D times, sorry I made a mistake in this expression right here, so first let me correct this; that is not the expression as we know it; so, that should be equal to 1 divided by 1 plus e to power that factor which I have did now, e f minus e D by k B T.

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So, we substitute this now in there; so that is why it is N D divided 1 e power e f minus e D divided by k B T, all right. Now, I am going to do this little manipulation in here; n plus N A,

I am going to write this as N D divided by 1 plus e to power e f minus e c by k B T; and, I am going to write e to power, e to power e c minus e D by k B T is what I will write this as. Now, you will recognize what this quantity is, you will recognize what this quantity is; this e f minus e c is a factor which appears in n also.

So, I will use this expression n here. And, remember n is equal to N C times e to power e f minus e c by k B T. Therefore, I will use this expression in here. And therefore and, I will write on next page; I will move this, I will substitute this quantity by, n divided by N C, is what I will substitute this as equal to, and then accordingly I will write this expression as, n plus N A should be equal to therefore N D divided by 1 plus N C divided by n, e to power; see what is that, so this quantity will determined as n by N C; so, we substitute it here; so, n by N c, e to power e c minus e D, e c minus e D divided by k B T.

So, what we will do is, now separate these terms in here; and I am going to; so, this way we have we got a rid of e f atleast in these expression. And, what I am going to do is write this as n plus N A plus, n plus N A times, n, e to power e c minus e D by k B T by N C equal to N D; and hence, I will write this as n plus N A times n, e to power e c minus e D by k B T divided by N C as, N D minus N A minus n.

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$$\frac{n(n+N_A)}{N_D-N_A-n} = N_c \exp\left[\frac{\varepsilon_D-\varepsilon_c}{k_BT}\right]$$

Case I $N_A \approx 0$ and at low T $n \ll N_D$

$$\frac{n^2}{N_D} = N_c \exp\left[\frac{\varepsilon_D-\varepsilon_c}{k_BT}\right]$$

$$\Rightarrow n = \sqrt{N_c N_D} \exp\left[\frac{\varepsilon_D-\varepsilon_c}{2k_BT}\right]$$

And, therefore I will write, my final expression will be n, n plus N A divided by N D minus N A minus n as equal to 1 by N c, e to power, e to power e D minus e c by k B T. So, I change the order; e D is here, e c is here, so I will take it down; take it inverted one, inverse of that then in that case if I; I should not write 1 by N c but I should write N c; N c times; so it

should take in there, the another side; so, this is N c times; I take this on the right hand side and take this quantity on the left hand side; so, this is N c times e to power and I have changed the minus sign here. So, this is the expression which we are governing equation, which, using which we will try to understand what the behaviour in freeze out is.
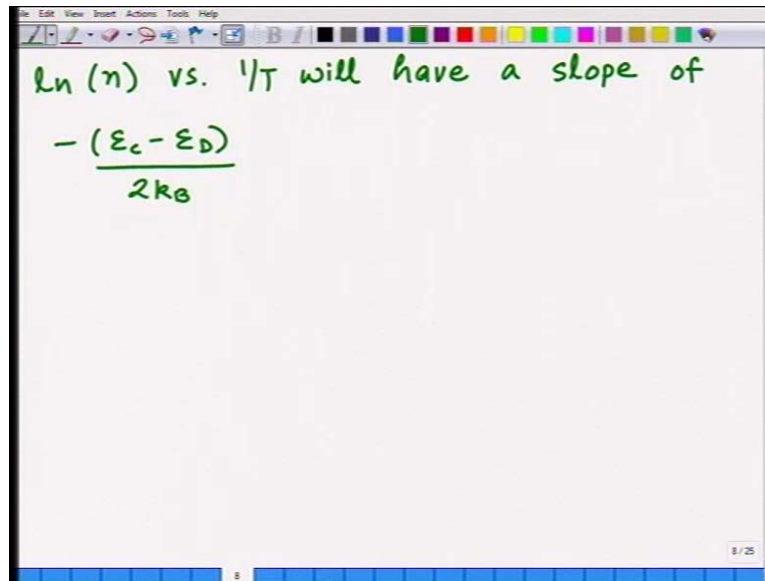
So, what I do is, first we will take a case; three cases we will take. So, case one- this, a green one. Let us consider case one. Let us take N A to be equal to 0, thereby that is we say we have doped only with dope donor atoms, no acceptor atoms are there. And, at low T, answer this that is what we are talking about, low temperature n is, let us assume much much less than, n is less than, that means you are trying to discuss freeze out. So, n has become N D is the most dope, dominant one.

Let me try to explain this to you through this curve, through this curve; where is that curve one, which I want to use. What I am saying is, since this value in that case would represent N D, N D minus N A; and, N A is 0. Then, we are talking about value of n; n values are becoming lower and lower. We are talking about when n values are freezing out, that means the carriers are freezing out; so, n is becoming less and less compared to N D. So, that is the case we are considering- n is less than N D.

In that case, what happens? Now, we are considering case where; so let us see that N A is 0; this quantity N A is 0; n is much much smaller than N D. So, in denominator I am going to only keep N D therefore, and a numerator of course N A is 0, so I am going to leave it as n square; this will make n square equal to N c, e to power e D minus e c by k B T. And, what is e c minus e D? Remember this. Hence, e D level, hence e c level, hence e D level, so it is measuring this difference. It is basically minus of this separation right here; the dopant level measured from the band edge is what we have got, gotten into, all right.

So, if that is the case, then clearly what is implies, what is the value of n; n in that case is equal to, n goes as, in that case N c N D square route, e to power e D minus e c, e D minus e c by 2 k B T, that means n verses temperature.

That means, log of n verses 1 by T, will have a slow of, e c minus e D by 2 k. What does that mean? In intrinsic case, remember this slope was, first of all it will be straight line; first of all you can see, if I take log of n, then I will have a straight line as a function of 1 by T; second, I will have a slope which corresponds to this gap; just like this, how if you wish. So, the way I will plot it out is as follows.
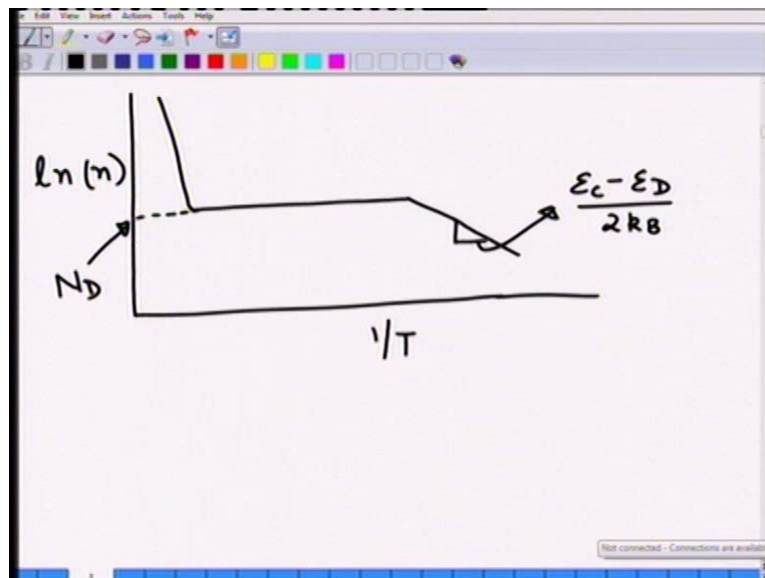
So, we plot it as, carrier concentrations as log of n, now as something like this, this. And then, I am going to plot a straight line like this. And, this value of course will be equal to N D, and N is zero of course; and, this slope will be equal to, this slope will be equal to e c minus e D

by 2 k about this slope D, and carriers is clearly showing that begin to freeze out; the carrier concentration begin to decrease.

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Now, let us take case two. This is the case where N A is not equal to 0; N A is not equal to 0. This leads to another interesting facts, some more interesting facts. Now in this I can, for, or I should not say case two first, let us say if; if N A is not equal to 0 then I have two cases possible, namely that n is less than N A and another case, this is case we will call it two now; and in case three, that means I will call where n is greater than N A, n is greater than less than. And remember, it is always true, always true that N D is a most dominant one, is greater than N A; and, N D is greater than n also.

So, only matter is, this is always given in case two and three then we have a question is between n and N A which one is bigger; n is in one case, in case two we will consider n less than N A, in case three we will consider n greater than N A, I will consider consequence of this. So let us write down all this; N D greater than N A, this given; and N D greater than n, this is understood already; and the case two is basically where n is less than N A or much much less than, we will make it much much less than when you want to make the approximation. So, this is basic is the case two, is what is indicating with.

So, if this is so then remember, let us go back to our expression – n, n plus N A divided by N D minus N A minus n, was equal to N C, e to power E D minus E C divided by k B T. Or, if that is the case, now we are going to make this approximation and we say n is, n is much

smaller than N A; in that case, we will drop this n in favour of this N A. And therefore I am going to write this as n, so we approximate this as n times N A.

Now, numerator will become n times N A, because I am going to drop this n; this n is much smaller compared to N A. And, in denominator I could just simply write N D, because anyway N A and n are, is smaller much much smaller than N A; that we can always do, because N D is the most dominant one; therefore, N c, e to power e D minus e c, k B T.

Again what you observe, log of n verses 1 by T is linear; and slope is e c minus e D by k B, that is the slope now. Earlier we had a slope of 2 k, remember, 2 k; now what has happened, this slope has become, now this slope has become 1 k; slope has changed, all right. So, this is when, when n is less than N A. Before I draw this let us start looking at also the case where when n is greater than N A and then we will draw this case three also, and then we will draw all these together.

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So, now let us look at case three, in which case, n we take as greater than N A; all other things remain same, namely N D is greater than; so, another, another words in this case, the order is n greater than N A; in the previous case of course, the order of things was therefore, the order of things was, N D was, N A will greater than n; n was less than, that was the order of the concentrations. Now, it is N D, n, and then N A.

So, if that is the case, again let us go back to our expression- n, n plus N A divided by, divided by N D minus N A minus n equal to N C, e to power e D minus e c by k B T. If so, then we again make the substitution in here; that in this time, n is greater than N A. Therefore

I am going to drop N A in favor of n. So, I am going to write this numerator as n square again. And of course, denominator is N D because N D anyway is greater than either of these two. So, I am going to write this as N C, e to power e D minus e c by k B T.

Now notice I have n square. So again, if I plot log, log of n verses 1 by T, again what we will notice is linear; second, slope is now again 2 k B again; plus n square, when I take a square root I will get a 2 here, factor of 2 here, so again becomes 2 k b; that is very interesting. That means the slope changes inbetween. So, now we on a position to plot this whole curve. So, I have already plotted the case where N A was equal to 0.

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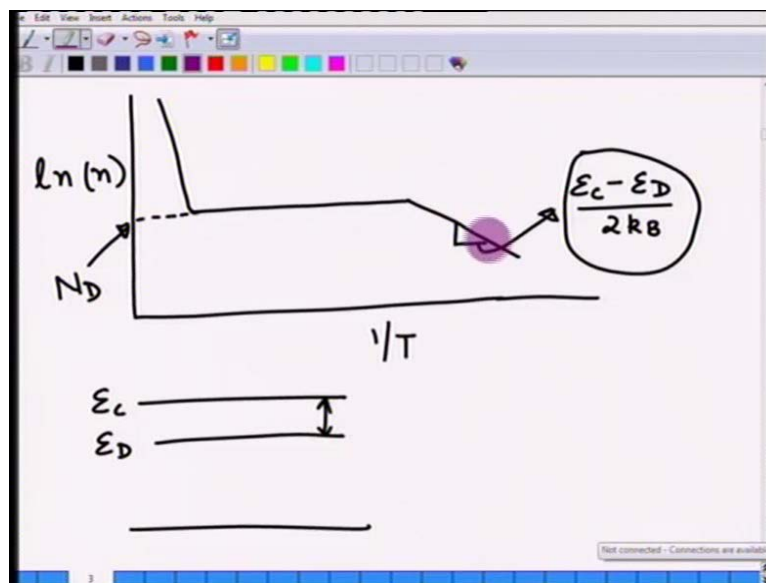
And, you saw the slope was this, whatever this gap, energy gap was; meaning thereby that it is the e c, and have e D, then whatever this gap energy gap was; that gap is written here, e c minus e D, that is written here; the point is more important; this factor 2; this is a factor 2 that was the slope of this line which we had, when N A was equal to 0.
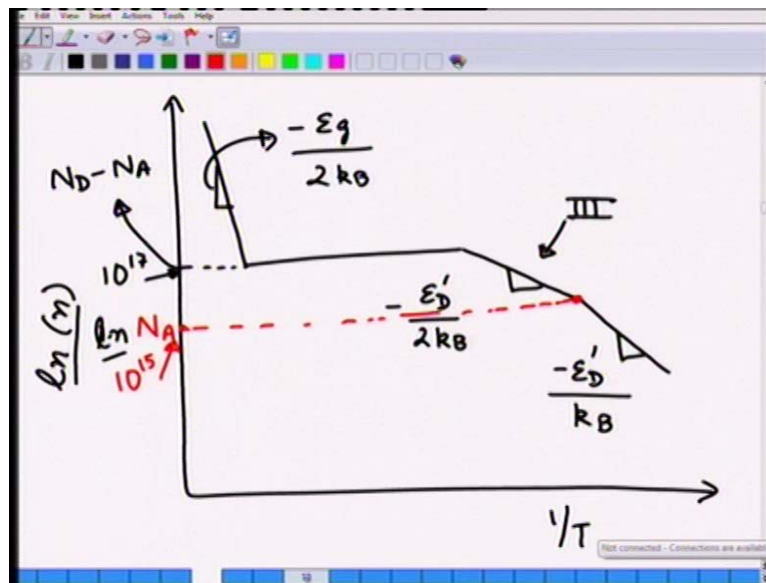
What happens if the n, now I am going to plot what happens when n is not equal to 0. In that case, I will get two cases: one, so log of n, not log; natural log in some plotting in sometime is slope as, all right. Now what will happen? Now, we have two cases where when, let us see, let us repeat it down; when n is less than N A then slope is 1 k here; not two, one is appearing here, when n is less than N A.

So, when n is less than N A then our slope is becoming, then the slope is, in that case slope is e c minus e D by k B, some minus sign here of course. And then, n is; this was case two. And case three was, case three was n greater than N A. In that case, we can see, that when n is greater than N A because of slope which was, which has a factor of two in there. So, we have this as minus e c minus e D by 2 k B. So, when n is greater than; so slope will become half in magnitude, slope will become half when n is greater than N A; and it will become more when, slope become more when n is less than N A.

So, the way I will draw this is something like this, something like this, and then something like this; at some point here it is changing; the slope here is in this case this is, let us give a name because this is become very big. If this is e c, if this is e D, this e D, and this is e v, then let us give this a name; this difference, this magnitude to be equal to, let us call it as, let us give it a name, let us give it e D prime; where e D prime is equal to e c minus e D, that is what this quantity is, that is what this quantity is. So, I am going to plot this as, the slope here is when n is greater than N A; then, I am going to write this as, e D prime by 2 k B, and the slope here is, minus e D prime by k B.

And, what is this point, this point right here, let me use the different pen here, I will say; right here where the slopes break that point should be equal to, on this scale should be equal to N A, right, do you understand this. So, if I label and this entire curve then I will write it this as follows: this quantity is a slope would be e g by 2 k, if you wish I will put a minus sign here; we have understand that is a minus in there; I will not normally writing it. And then, what you, what is it?

This point represents a concentration which is equal to N D minus N A, this represents N D minus N A. Now, upto this point we have region, this is a region case two where, where, the case three sorry; this is case three here which where n is greater than N A. So, now the N which I am plotting here, log n is what I am plotting in this axis; on this axis that number is falling down.

And, by the way keep remembering because I am assuming that we plotting this one a semi log type of graph paper, so the numbers we read out here is N A, number we read out here is N D minus N A. But, otherwise you, if you log when you taken then even you think of this is log, I should write log in front of it also if you wish; depends on how you want to read it, anyways. So, that, I hope you understand that part.

So, if we look at case three then, when then n was equal to N D minus N A; and, N D of course was very large; let us say this is 10 to power 17, this number is 10 to power 17 or something like that; and, this number is equal to 10 to power, let us say 15. So, then n starts becoming less than N D of course; that means it becomes less than, less than 10 to power 17. But it continues to be greater than N A. Let us say it is in 10 to power 17, that means it is more than this quantity N A here; then in that case our slope is e D prime by 2 k.

But, as you can see when n becomes less than N A that means it goes below 10 to power 15, less than 10 to power 15, in that case this slope becomes, slope changes. So the point where slope changes is roughly where n is equal to N A; and hence I use this point to mark as, this value must be that, that means this value must be equal to N A. That's what I am assuming; that is what I am pointed out to you, and then this slope here, all right. So, using this, but this is, now you can see, first physically let us see the whole picture.
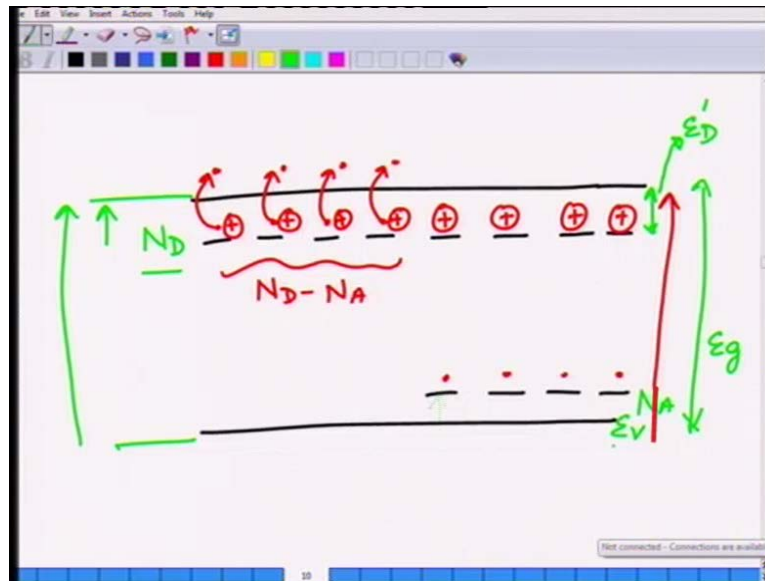
The whole picture looks like this, that I have a system in which I have some electrons which are bound to this level. A very very low temperature, here at very very low temperature, and there are some acceptor levels also. Let us say, acceptors levels few, just some acceptor levels also, which have these have taken their electrons, they ionize; and, I have only, this is a picture at 0 k, this picture at 0 k; and we can add here plus plus also in here.

This is the picture at 0 k; and what has happened is, as we began to raise temperature then I start getting, we start getting some electrons jumping from here to here, and that is what we see in this region here; that is what we see in case two and this is the case two. In case two and three are this regions where some n- I have shown here 2- some of them are started jumping over to this because temperature is slightly increased, and hence this jumps jumps are becoming possible.

As this temperature continues to increase the point comes when all of these electrons have jumped. When all of these electrons jump and that is basically start of this point we reaching here. Now, as we keep increasing the temperature these jumps are still not possible, the temperature is low enough and hence we get into situation a semiconductor is, carrier concentration remains same which is, and this quantity is obviously equal to N D minus N A; this is equal to N D minus N A.

So, we receive, find that carrier concentration remains the same as you continue to increase temperature, and that is N D minus NA, where it remains to; until temperature becomes high enough that these electron jumps also become possible, and then the behaviour becomes

intrinsic like behaviour. That is the big picture of this semiconductor. But, also please notice that this is a very powerful way, this is a powerful experiment. Why I have taught you is this is, this is good, it is a good characterization technique.

What you notice, note; suppose you measure carrier concentration in a full temperature range, from very low to reasonably high temperature, what are the different information can you get? What are the different information you can get out of it? Notice, this is essentially e D prime, you get e D prime, and this quantity is e g, this quantity is e g. If you see, from this you will able to extract just by doing this experiment- measuring carrier concentration as a function of temperature, hole temperature range, things which we can get is you can measure e D. That is if you measure this and calculate this slot, then you will measure this e D; you will able to measure this e D levels.

Second thing you will able to see is that where the slope breaks, when you see a break in slope; in that case, you see, you can measure what N A value is; you can figure out how many of these N A are present in there; what is a number of these acceptor levels present in there. When you see a flat region you can measure out what is N D minus N A, you can measure out what is N D minus N A. And hence, you can figure out what this total number of N D levels are; how many N D are present in there. And finally, when you go down go go higher in temperatures you can also measure the band gap of the semiconductor.

So, in one experiment you can measure in the band gap of semiconductor, you can measure the dopant level with respect to the, measure this dopant level with respect to the relevant band edge, that means e c minus e D that that gap you can measure. And you able to do so, because these are thermally activated jumps. And the two types of thermally activated jumps happening- one across this gap and other across this gap, and that is why you able to measure both these gaps.

So, e D prime, this e D prime you should be able to measure, you should be able to measure the band gap, you should be able to measure N D minus N A, and you should be able to measure N A. This much information you are able to get out of this one experiment. Only one which you are not able to measure a, figure out is what is this energy level. And, this of course you are not able to measure because no transition is, no jumps of electrons are taking place between these valence band and the dopant level, acceptor level are taking place, so how could you measure them. So, that is, that is the only one.

So, hence it is a, this carrier freeze out experiment is a very powerful technique, to be able to measure all these quantities. Of course, you will ask the question, how would you measure n? Measuring n is not an trivial exercise; you could measure n using a hole probe experiment; hole measurement you can do to measure n.

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Alternative is, that you can measure instead of n, you could measure possibly conductivity, you could measure possibly conductivity, and since conductivity is equal to n times number of carrier times, mobility times, the charge, the basic fundamental charge; and if you make a assumption that mobility is not a very strong temperature, function of temperature, then more or less what you measure by sigma is what you measure in n, if you make that assumption. So, this measurement is fairly simple; a 4.4 like measurement will give you conductivity. And, accordingly you can measure n, therefore.

Similarly, by the way I have taken a example where N D was greater than N A, greater than N A, you could have measured, you could have situation where N A is greater than N D; in which case then I would be plotting as a function of 1 by T, I will plotting log of p, and it will be straight forward enough to say that these curves will look something like this where actually I will be measuring N D here, I will be measuring N A minus N D here; N A minus N D, just same analysis you can do; this of course remains the same, it measures e g by 2 k minus if you wish; and, what I will be measuring here, then in this case would be e A minus e v by 2 k, and this will be k B; e A minus e v by k B. So, these are the quantities we will be measuring.

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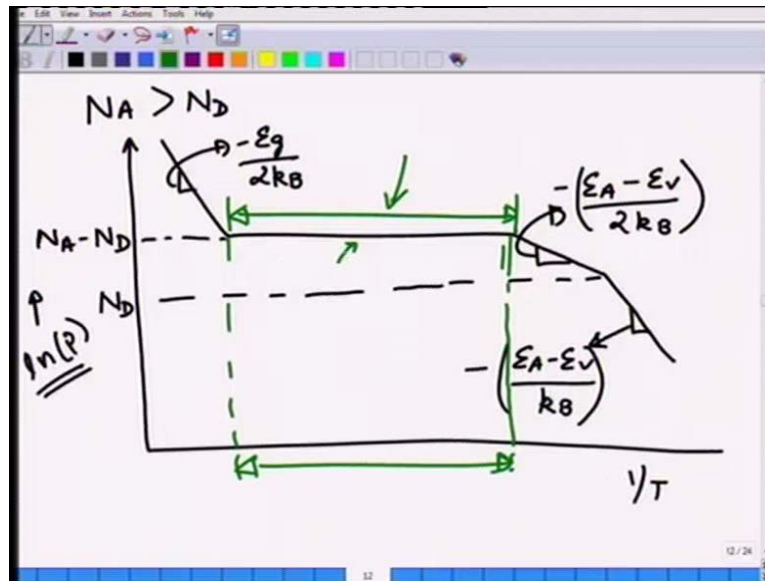
Just by same analysis, now in this case, it will be log of p that will be plotted in this direction. So, you will be able to measure whether it is a, if it is p type semiconductor then this is how you will measure it of n type, then this curve is what will measure out, all right.

So, this brings us to the end of, this brings us to the end of this. I hope you are able to understand this whole equilibrium carrier densities. Why this is taught is as because reason is this; I have mentioned earlier also. These are equilibrium carrier densities. And the, from now on our operation range will we can find between this two temperatures; so, our room temperature must, will choose semiconductors, only those semiconductors whose room temperature lies somewhere between these.

So, room temperature should be between these range; what temperature operation of that semiconductor must be in this range because this is the range in which semiconductor devices will be made; this is the range in which semiconductor devices exhaustion region; we have extrinsic semiconductor will be where with which we will be making these devices. And, now, from now on all assume that this is where we operating, in this condition. In this condition we are reliable to low temperature or high temperature range as far as the devices are concerned, ok.

Now, when you make devices, when you apply voltage, you are disturbing this equilibrium. So, this I had said in the beginning itself, this, to knowing equilibrium carrier density is important because you want to know that when you disturb the system then we will have to watch out how is this system like to come back to equilibrium. So, in order to see the rates of

how fast it comes, tries to come back to its equilibrium then you must know where the equilibrium is, and hence you will describe the equilibrium.

From now on we will start discussing about those processes which disturb this equilibrium, and after that we can start talking about devices. So, let me close this chapter here today with equilibrium carrier concentrations and next time we will start with new topic on, which will lead us to towards devices.

Thank you.