Solid State Physics
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Lecture - 49
Physics of Semiconductor (Contd.)

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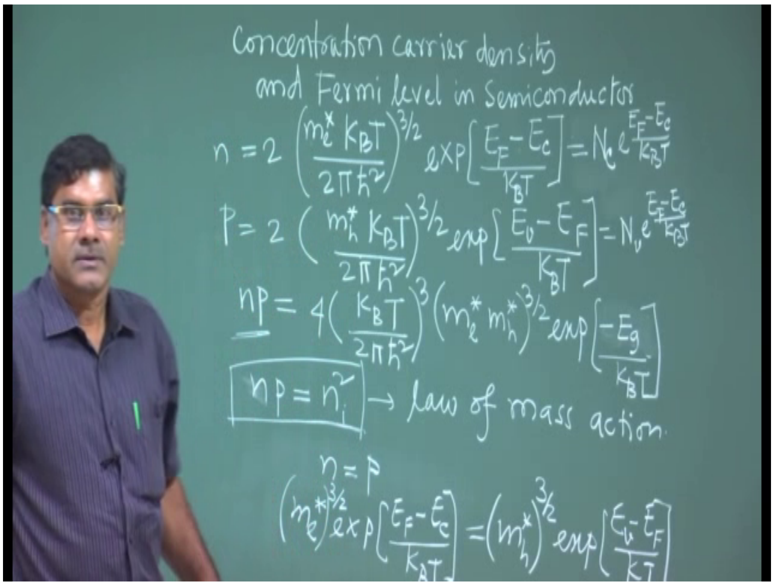

So, we will see today this concentration of carrier density and Fermi level in semiconductor. So, we have seen that this carrier density, the density of electrons n equal to 2 m effective mass of electron and then K B T by 2 pi h cross square to the power 3 by 2 then e to the power or exponential E F minus E c by KT for concentration density of electrons in semiconductor. And for hole concentration P equal to 2 is just m h star K B T by 2 pi h cross square 3 by 2 exponential E v minus E F by. So, somewhere I am writing K, somewhere K B, but it is Boltzmann constant; and also sometimes I am writing m e star or m e star or sometimes not writing, but that is effective mass.

So, then if saw that this n P product of these two is 4 K B T by 2 pi h cross square the cube now m e star m h star effective mass this 3 by 2; and from here you will get exponential E v minus E c by 2 I will get E v minus E c by K B T, so E v minus E c basically band gap E g. It is band gap E g. So, I will get E F minus E c then product so plus E v minus E F. So, minus E F minus E F will go that you will get E v minus E c by K T of course, K B T. So, here you can see that these two term, so this is E v minus E c is basically band gap, these two band valence band conduction band. So, this is E V, this is E C. So, this is band gap E g, and Fermi is in between, this E F in between. So, this I can write E c minus E v or E v minus E c this is basically minus E g, so minus E g. So, in this expression interestingly it is independent of position of the Fermi level, so there is no Fermi level. So, it depends on the separation of valence band and conduction band.

So, this product n P is equal to n P equal to is the n i square; n i is the electron density or hole density in intrinsic semiconductor. So, intrinsic semiconductor this hole density and electron density are equal. So, n i equal to p i. So, n P equal to n i square. So, this is valid for any semiconductor, this is valid for any semiconductor whether it is extrinsic semiconductor or it is intrinsic semiconductor. So, for extrinsic semiconductor, it is p-type or n-type, it can be mixed also both carriers may be there of unequal density, but it will follow these rules. So, this is called law of mass action. So, this is very important law of mass action.

So, this is very important as I told in last class. You see now I have intrinsic semiconductor, now if I put the impurities to make it p-type or n-type, so say for n-type, so number of electrons will increase. When number of electron will increase, so n is basically greater than n i. So, automatically P has to be less than n i P has to be less than n i. So, what does it mean? So, in the intrinsic semiconductor, P i equal to n i, now when I doped the semiconductor with to make it n-type, so electron density is increasing, but simultaneously the intrinsic hole whatever before doping the density was there, so that will decrease.

So, why it happens, it happens because this recombination hole and electron recombination or inhalation, so it is basically proportional to the density of one any type of carrier. So, here density of electrons is increasing. So, probability of recombination will increase and that is happening, and thus the density of p is decreasing. And it is decreasing in such a way that this product has to be constant, so that is the beautiful relation, which gives us very comfortable zone.

Now, we see so here this, so this relation is varied for n i write this relation is very for pi also these are valid for n-type and p-type whatever. So, now, let me take find out the Fermi level. So, here importance you see that I will see here. So, what is happening here. So, this density of electron it depends on this exponentially it is a exponential term is there E F minus E c. So, it depends on the separation between the conduction band the Fermi level, so it depends on temperature also of course. So, for a particular temperature, so it depends on the position of the it depends on the position of the Fermi level between these two E c and E v and here also it depends on Fermi level.

So, position of Fermi level is important because since this product is always constant it is equal to n i square. So, what may happen, so when n is increasing, so p has to decrease. So, n will increase if this E F minus E c decrease right because this is negative this E F minus E c is negative. So, when this will decrease the separation between E F and E c, it is exponential e to the power minus del E, del E is the difference between these E F and E c. So, when del E minus del E e to the minus del E, so del e will decrease, so this will increase. When del e will increase, then this density will decrease.

So, position of the Fermi level is very, very important where it is expected that when n equal to p it is expected that E F this separation this between E F and E c and between E v and E F is it will be more or less equal. So, E F will be at the more or more or less at the middle of the band gap, so that one can see. So, for intrinsic semiconductor. So, I can what I can get I can get n equal to. So, let me tell you that here this term generally we write this like N c e to the power E F minus E c by K B T and this term is in N v to the power E F minus E c by K B T. But N c is this Nc is equal to this, and N v equal to this. So, here N c generally it is called the density of states at the edge of conduction band N v is the density of states at the edge of the valence band.

So, in case of intrinsic semiconductor, so I can write n equal to p, n equal to p. So, n equal to p means what we left n equal to p only I can see in one side yeah, so in one side you will I think this everything will go one side a m e star e to the power or exponential E F minus E c by K B T right. And this to the power 3 by 2 equal to m whole star. Effective mass of this hole effective mass of hole and then exponential you will have E v minus E F by KT, it is going down. So, I think I have to write slightly up.

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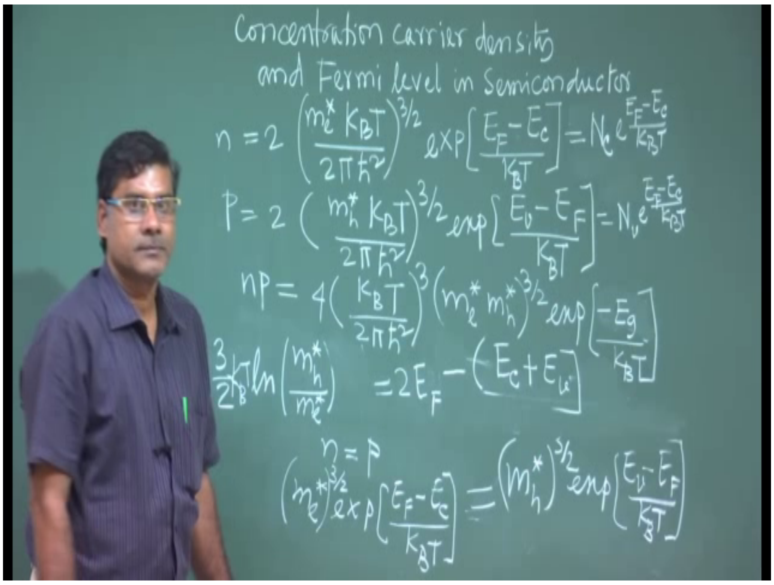

So, this will be equal to m hole effective mass of this 3 by 2 and then exponential E v minus E F by KT right. So, exponential term is there, so I can basically write from here. So, if I just have to write on top. So, from here what I am getting, so this I can write. So, exponential this by this or I think I should write m h by m e star to the power 3 by 2. So, exponential this by this, so exponential E F minus E c by K B T is there this by this means it will go up and then it will mean E plus E F divided by KT of K B T.

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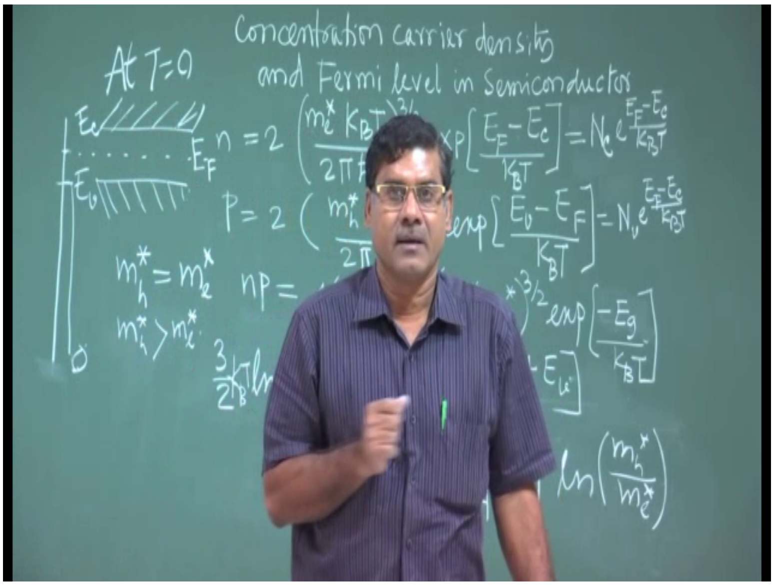

So, just I can write here ln log so 3 by 2 exponential will go K B T will come this side. So, this will be equal to 2 E F if I take minus common then E c plus E v. So, what I am getting, so now what is the E F, E F will be equal to so this plus this, so it will be E c plus E v divided so 2 E F. So, I can divide by 2 and then this plus 3 by 4 K B T ln m hole star over m e star. So, that will be the expression that will the position of the Fermi level. So, now, at T equal to 0, so this part is 0. So, it is E c plus E v by 2, so this E F is will be in the middle of the Fermi level. So, this is E v and this is E c. So, E v plus E c by 2, you see this from somewhere 0 is there right energy.

So, E v means this, this is E v plus E c. So, 0 to E c that is the E c value here, so E c. So, this plus this divided by 2. So, divided by 2 means this is the so two one and then half of it then half of it. So, you see plus E v by 2 means E F is exactly in the middle of the this is the energy right, so at T equal to 0. And if m h this is the whole effective mass of whole equal to effective mass of electron they are equal then what will happen then again this will be zero log one zero, so this part again. So, now, this will be the middle for all temperature it will be independent of temperature. So, for all temperature, it will be in middle, but generally this they are not equal, so this whole mass of effective mass of whole is slightly higher than the effective mass of electron.

So, in that case, so it will contributed and it will be slightly. So, it will add some small value. So, it will be slightly up. So, it is more or less for intrinsic case it is more or less at the middle position of the Fermi level at the middle of the band gap. So, this is fine. Now, let us see the now we see this concentration of carrier in p-type or n-type semiconductor.

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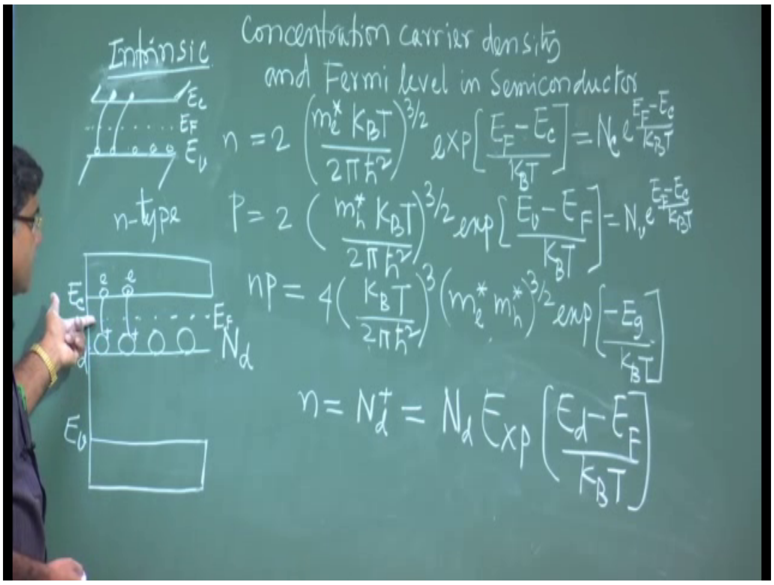

So, let us take n-type semiconductor first n-type semiconductor. So, for intrinsic case what we have seen intrinsic semiconductor what we have seen, so this is a band. So, you see, E v, E c and then its Fermi level is that is E F it is at middle that is what we have seen. Now, for n-type, n-type semiconductor, so what is there see you have conduction band and then you have your valence band. Now, in intrinsic semiconductor, we have to put to get n-type pentavalent atom, it is we tell it is donor that I mentioned earlier.

So, pentavalent by N c after having 5 electrons, so 4 electron is used to for bonding with the other this semi conductor right means not other for this in case of say silicon or germanium. So, they have 4 valences. So, they share 4 electrons with each other. So, this pentavalent, it has 5 electrons. Now, this 4 will be used to make bond with the other atoms and, but fifth one is extra one it will not be used for forming bond with the other surrounding atoms, so that will be additional one and that atom it want to donate to the system, donate to the semiconductor.

So, that atoms is where it is it is in a in its atomic level energy level that electron extra electron it is in energy level of this atom donor atom. So, the donor atom have energy level say here it is a near to the E c, because it is assured that it is near to the E c, because then only it can in election to the system. If it is too far it cannot donate, because to donate to give it needs some energy and that energy is supplied by thermal energy. So, this is the then is the energy level of the donor and this one is E v valence electron.

So, now here in this system earlier here in intrinsic case here the electron was here. So, when this electron jumps to the conduction band then we are getting conduction electron in conduction band and you are getting hole conduction hole conductive hole in valence band. So, here this carrier transport carrier transport between these E c and E v and in between these Fermi level is there. So, effectively so electron from this level, it is going to the other level. So, always you will get this here if you look at these exponential term if you look at this, so with respect to E F, this term comes with respect to Fermi level as if these electrons. It has probability up to this E F and from here it has to go to the E c. So, here as if it is going from E F to E c, it is going to from E F to E c.

And other case that for p-type for getting hole in this case for p getting hole here. So, it is as if this electron has to just it has to go just above this E F. So, it is it will reach to the E c. So, as if this carrier change exchange carrier jump between these E v and E F, so here in case of p, it is E v and E F. So, why I am comparing this one, so now at T equal to 0 temperature, so here what is there here atoms are there donor atoms are there having one electrons, donor atoms are there having one electrons. So, these are neutral atom these are neutral atom. So, this number density of this neutral atom is N d, number density is N d.

So, now electron is there now when it will get thermal energy of that electron will go here will go here. So, when it will go to conduction band then it is free electron. So, it will increase the density of the electron in the system. So, now, here basically electron that is change between. So, this for getting the carrier from one level to another level, now these two level are involved. So, Fermi level must be between these two level, Fermi level must between these two level. So, it is going from here to here. So, we can tell that here it is N d, now when electron are going there, so then it becoming negative sorry positive iron this positive iron and electron is going here electron is going here.

So, what will be the number here, so that will depend on the what is the density of N d of this electron that will be equal to that N that will be equal to N d plus density of these positive irons on this level. So that will be the if N d plus is the density then that density here this electron density here that will be equal, but additional this plus whatever for intrinsic case it was the system initially it was intrinsic. Now, we are additional that electrons we are getting from donor. So, how many electrons are we have got this is the density. Now for intrinsic case whatever earlier, so we can write, so this n dash.

So, N d plus plus n dash, so that will be the middle electron density here. Now, generally n is very, very greater than n this right, so that is why we neglect this intrinsic carrier whatever intrinsic carrier was there. So, we neglect it. So, we clearly write so n equal to N d plus. So, this is the exchange between these two Fermi level is here in between somewhere we do not know. So, that we have to find out in N d f. So, here you see N c e to the power this we have written so in that form you can write. So, this n equal to N d plus equal to this N d. So, density of states or density of this donors here. So, then exponential so it is involved. So, from here it is going here right.

So, between these two as I mentioned this you have to take here the C f. So, as if it is going. So, from here if it go off then it is fine it will reach to the means here. So, we can write it is E d minus E F by K B T. So, yes, so just in comparison one can see this involve this so with respect to E F. So, from here and if it just cross the E F then it is equivalent which in there, so that is why is N d energy of that one E d minus E F by K B T. Similarly, when it is p-type, so acceptor level acceptor level will be here, close to the E v acceptor level so energy is, so I can separately I think there should not be a confusion.

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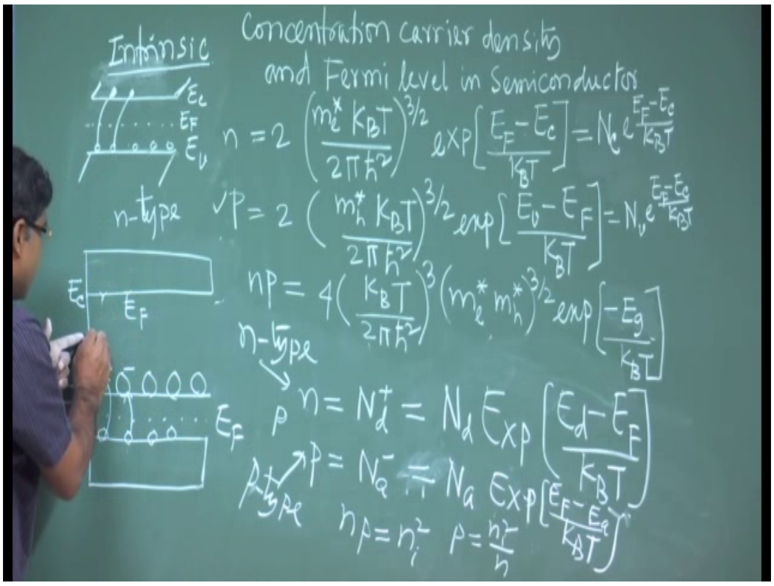

So, this is the energy of the acceptor level doped by the three trivalent atom. So, this atoms are here, it is not ionized. So, now this atom can take electron right, it is accept it can accept electron. So, from where you can get an electron solid from valence band it can get. So, when electron from here when it will go here, so this will be negative, this ion this will be negative ion, this will be negative ion, and here it will be hole because one electron left here. So, it will be equivalent to hole so that means this is a acceptor is accepting electron and giving us hole in the valence band. So, does these hole density will increase in the semiconductor. So, here is the same way you one can find out that here also this that these two energy level is involved to create base carrier to create hole in the system. So, Fermi level must be between this between these two level.

So, if it is E F, so then similarly density of p equal to N a minus. So, how many are ionized ion negative charge accepted right, so that way. So, what is happening electron is going from so here to here. So, as if this electron you have in valence band. So, as if it is available up to this E F, so it is going E F to acceptor level. So, this E F and E a that is two level is involved. So, in this case also this intrinsic this p dash was there, but same way I just we can neglect it because it should be small compared to p so or N a minus. So, this I can write N a exponential E F, E F minus E a by K B T, I do not know whether you can see E F exponential E F minus E a by K B T, so that will be the density of holes in p minus type semiconductor extrinsic semiconductor.

So, from these two you can see that that is energy level of this at donor you know the level of this acceptor that is also important that is also important. So, there is it the difference should not be very, very high then that you need high temperature to get the we get the carrier free career either in valence band or in conduction band. So, now question is, what is the position of the Fermi level, what is the position of the Fermi level in this band gap. So, here also as I shown you earlier that Fermi level for intrinsic densities exactly in middle of the band gap or these two was involve and then that was in middle. So, here you are getting this similar relation you know here in the exponential these and N c exponential these right yes N a exponential these right.

So, now, if we equate this now this is for n-type semiconductor, this is called n-type semiconductors, and this is for p-type semiconductor. Now, in case of n-type semiconductor, if I want to find out what is the position of the Fermi level. So, what I have to do to get the position of the Fermi level, so n-type again instead of what is the density of the p-type type sorry density of holes. So, that say that is p that is p density of holes with this n-types algorithm that is p. Now, n is very, very greater than p because n p has to be equal to n i square, n p has to be equal to ni squares. So, do not do not confuse with this one. So, this is for p-type, but in n-type semiconductor itself there is a hole density of hole is p. So, np equal to ni square; n is very very greater than.

So, what I will get, I will get here p will be ni square by n. So, n is very very high compared to ni so that means, this p will be very, very small. So, here I can take if I can take this p I think then you have to equate for the to get the Fermi level I have to equate basically this yeah these two. So, this is the p and this is the n. So, if we equate these two, so then you will get the position of Fermi level in terms of E v, E d and you will and E F is there. So, from here this if I push it just as I push it earlier, so then you can show that this E F, E F is more or less in middle of this between this E c and E d.

Similarly, for p-type, p is this and there fits n is this n is this. So, if you equate these two then this and this here from this you can find out same way that this Fermi level it will be in the middle of this E v. So, what did does it mean. So, basically Fermi level in case of in case of n-type Fermi in case of ni is above the is close to the is close to the above the conduction band in case send to the conduction band; in case of n-type if Fermi level is close to the valence band. So, just I am not doing just one can so the way I have done for infinity same way. So, this is the expression. Now, just one has to equate n with this p and p with the same then you will get the position of the Fermi level in case of donor.

So, Fermi level the above the donor level and it is more or less in the middle of these two level E d and E c. So, it is E F is closed by E c, so that is why here you can see E F is closed to the E c, so these two terms will be very very small. So, this is the minus term. So, this term will be very, very high exponential minus this small term, it will be not very very high it will be higher right del f is del E is higher compared to that it will be higher. So, n will be higher. And on the other hand, this will be smaller, this will be higher because these difference from E F close to the E c means it is far away from the E v. So, this will be higher. So, p will be lower because this minus negative is there, so that is why from these to this is these two relation is valid for intrinsic case, it is valid for the extrinsic case p-type or n-type.

So, only you can say that if position of the Fermi level where is the position of the Fermi level. So, here from here as I as we saw if we just find out the position of the Fermi level, we can show our power from here itself we can also see that Fermi level is between these two. And if we equate it will get say it is more or less at the middle at temperature T equal to 0. And for other cases, it is middle between these two, so it is close to the of E v. So, other way here also close to the E v this is similar term compared to this one. So, negative it is negatives a smaller means this p will be higher than the same. So, for p-type, its hole densities higher than the electron density. So, there is the concentration of carriers in extrinsic semiconductor and also the position of the Fermi level in band gap in case of intrinsic semiconductor and or p-type and n-type semiconductor that I showed you. So, I will stop here.

Thank you for your kind attention.