Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 09
Semiconductor Basics – II

So, welcome to lecture 9 of the course on Solar Photovoltaics Principles Technologies and Materials. So, let us just recap what we did in the last couple of lectures.

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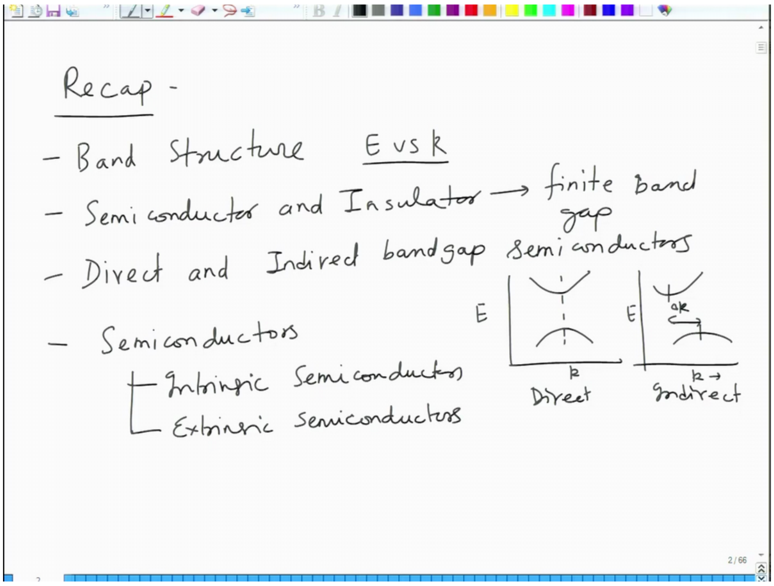

So, we started our discussion on band structure very briefly, I mean without going into any details and basically what happens is that when you plot energy versus wave vector, there is a continuous gap and the E k diagram which is basically the band gap. And semiconductors and insulators have a finite band gap and if it is less than generally 2 2 2 and a half volt E electron volt then it is semiconductor and for band gap higher than 2.5 e b its we define the material normally as insulator.

Now, there was also something called as direct and indirect band gap semiconductor this direct and indirect band gap semiconductors, important to know at least we cannot get into details of this, but basically when the conduction band minima and the valence band minima and the E k space, when they coincides with when they coincide with each other, then it is a direct band gap semiconductor and when then when they do not coincide with each other, when they shift. So, if you have a maxima here minima here maxima there. So, there is a shift in the k space then it is a indirect band gaps in here.

So, this is direct and this is indirect and this has influence on the way carriers are generated and carriers are recombined in semiconductors, we will get back to this later on. And then we moved on to what semiconducting materials are so, we defined intrinsic semiconductors and we define extrinsic semiconductors.

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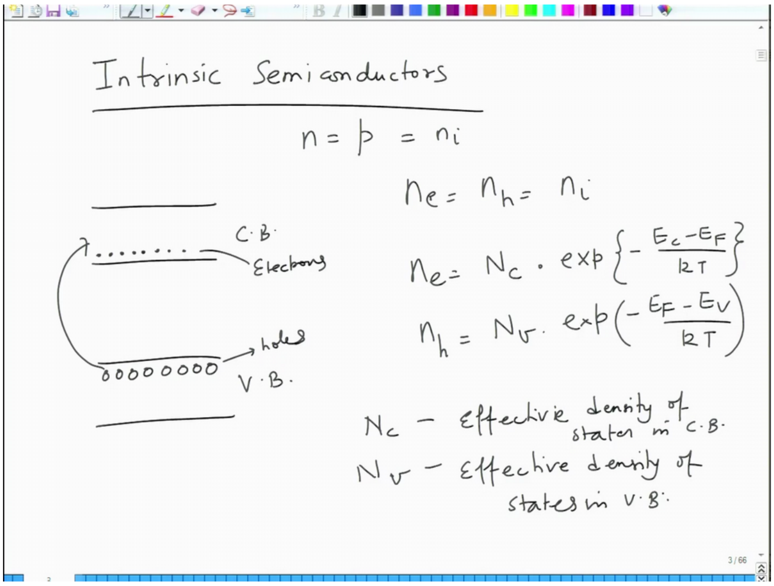

So, moving forward on this discussion intrinsic semiconductors are the ones for which n is equal to p and this is mainly those semiconductor which are where carrier generation is because of thermal excitation.

So, you have conduction band you have valence band, and electrons from this are excited to the conduction band. So, this is conduction band this is valence band leaving rise to so, these are now holes giving behind the hole. So, these are electrons and these are holes so, these are mainly because of thermal excitation and as a result you have n is equal to p which is also called as n i some books also write as n e is equal to n h is equal to n i ok.

Now, the concentration is given as n e is equal to N c into exponential of sorry into exponential of minus of E c minus E F divided by k T and n h is N v into exponential minus of E F minus E v divided by k T where N c and N v are effective density of states in conduction band and this is effective density of states in valence band.

Now, we were talking about where the Fermi levels are Fermi levels will is it the middle of the band gap in case of intrinsic semiconductor whereas, it is closer to, it moves closer to conduction band edge in case of n type semiconductor it moves to valence band edge in case of p type semiconductor. So, let us move ahead with that discussion that we did last time.

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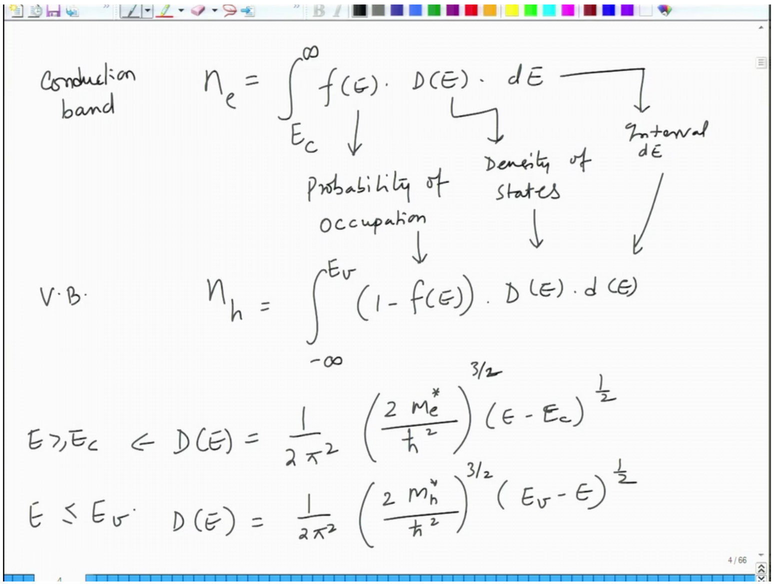

So, the way these carrier concentrations are come about so, the carrier concentrations are basically calculated as so, from E g to in E c to infinity sorry next. So, this is E c to infinity for conduction band. So, this is for conduction band so, this would be f E D E into d E.

So, this is basically you can say probability of occupation D E is density of states and this is over and interval D E. So, interval and we have integrated it from E c to infinity to calculate the carrier concentration in the whole of conduction band for holes so, this is for n e this is for for n h for valence band it would be minus infinity to E v ok. And in this case since we are looking at holes it would be one minus f E D E into small d E again it is probability of occupation of holes density of states and this is the interval D E ok.

So, and we know what Fermi Dirac statistics is and gs and the density of states to be precise is given as for conduction band at least is given as 1 over 2 pi square to m e star which is effective mass of electron we have not gone into effective mass of theory and all that, but I will give you references from which you can read about effective mass E minus E c to the power half.

And that for let me give you also the expression for holes just bear with me for a minute. And density of states for valence band is 1 over 2 pi square 2 M h star divided by h cross square to the power 3 by 2 into E v minus E to the power half so, this is valid for E greater than or equal to E c and this is for E less than or equal to E V. So, now when you make the appropriate substitutions you may you will and if you do the integral and of course, you know the expression for Fermi Dirac statistics.

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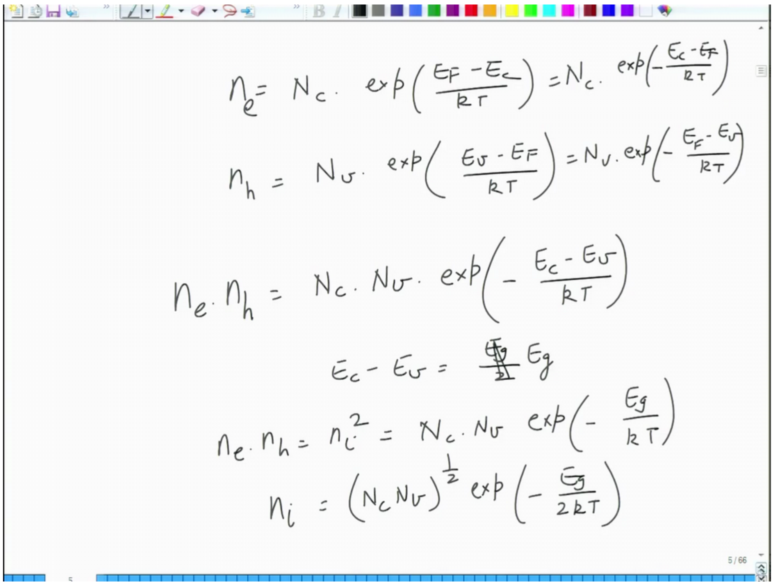

You will get n as N c into exponential of E F minus E c divided by k T and n ne and n h as N v into exponential exponential E v minus E F divided by k T, alternatively you can write is that exponential of minus of E c minus E F divided by k T. And this would be N v exponential minus of E for E F minus E v divided by k T and when you multiply these two together n e into n h, it becomes N c into N v exponential of minus of E c minus E v divided by k T and E c minus E B is equal to E g divided by 2.

So, we get n e into n h which is equal to n i square which is equal to N c into N v into exponential of minus of so, this is sorry E c minus E v is equal to E g this is minus E g divided by k T. And hence n i becomes equal to N c N v to the power half exponential of minus E g divided by 2 k T ok. What is now N c N v?

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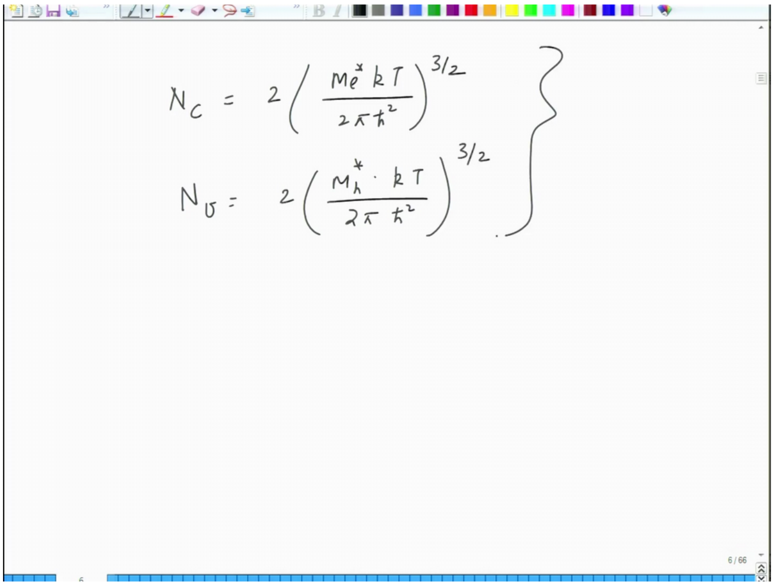

So, this N c N v is basically N c N v is N c is 2 into me star k T divided by 2 pi h cross square to the power 3 by 2 and N v is equal to 2 m h star k T divided by 2 pi h cross square to the power 3 by 2, these are the expressions for N c and N v which we did not look at last time.

These are the expressions for basically, this is the expression for intrinsic carrier concentration, in a intrinsic semiconductor that is how you derive it.

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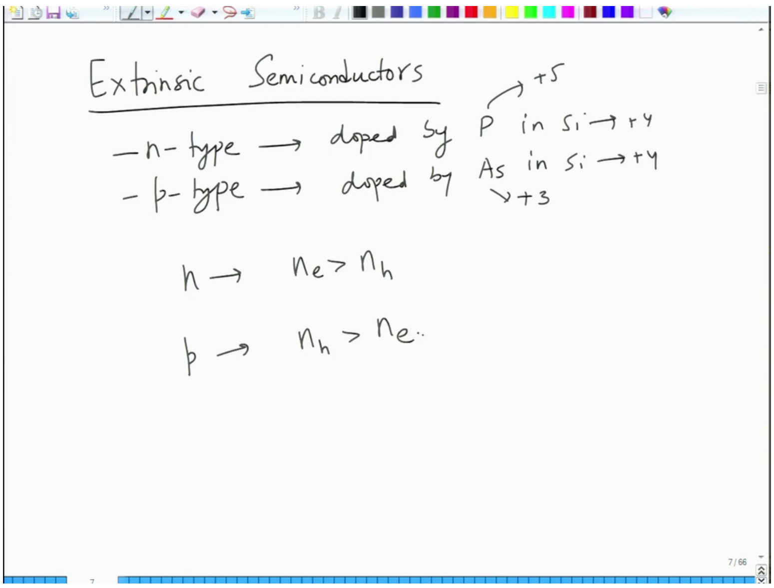

Now, for extrinsic semiconductors we defined last time, extrinsic semiconductors we said there are two types one is n type and second is p type, n type is doped by so if it is in the context of silicon doped by phosphorus and silicon for example, silicon is the base material phosphorus is the dopant and this is doped by things like arsenic in silicon. So, this is plus 5 this is plus 3, silicon is plus 4 as a result they create extra electrons and extra holes.

So, basically since you have in these semiconductor so, n type we said you have n e which is much larger than n h and p type you have n h which is much larger than n e.

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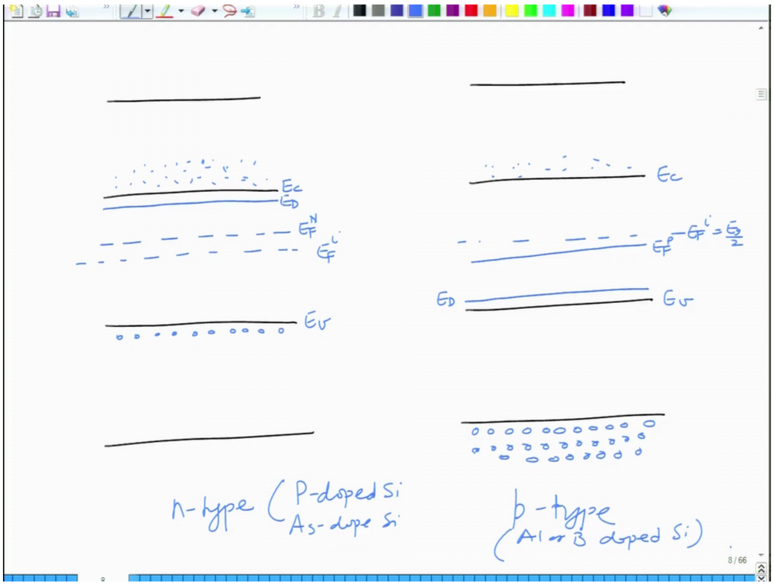

So, if you look at the band diagram of n o p type semiconductor ok. So, for n type semiconductor there are high electron density and very few holes. So, this is n type and the Fermi level lies. So, this is let us say the E F i the Fermi level of n type semiconductor lies little bit ahead, little bit above the E F i and the donor level lies very close to so, this is E c this is donor level.

In this case what happens is that there are more holes and fewer electrons ok. So, here this is E v again the mid gap position is this, but the Fermi level lies here. So, this is E F p this is E F i; E F i is equal to E g by 2, but E F p is little bit lower we will see the expressions of those in a little while this is E c ok. And in this case the acceptor level lies here. So, we said last time that the donor and acceptor level are very close to E c and E v so, that they are completely so that the atom sitting in them are completely donor acceptor and donor atoms are completely ionized.

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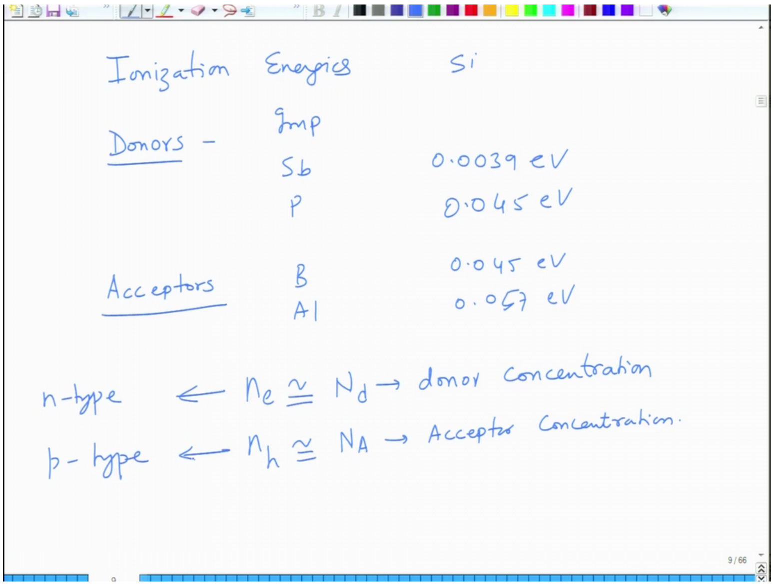

So, ionization energies of these so, for donors we have impurities like antimony phosphorus which have if you put it in silicon for example, and the antimony has a value of 0.0039 sorry am I writing it 0.0039 E v. And for phosphorous this value is 0.045 E v for in this case in case of antimony in case of p type doping let me correct it, it should be boron or aluminum not arsenic, arsenic is plus 5.

So, it should be boron or phosphorus boron or aluminum phosphorous typically antimony, phosphorous antimony is used for n type doping and boron or aluminum or gallium or indium they are used for p type doping. So, let me correct myself there. So, this is p type.

So, this would be phosphorus dope silicon or antimony doped silicon in this case it would be aluminum, or boron doped silicon. And if you look at acceptors in case of acceptors the aluminum common impurities are boron and aluminum for boron the ionization energy is 0.045 electron volt. And for aluminum it is 0.057 E v.

So, you can see that these are very small energies as a result near complete ionization of these is obtained. And since these energies are very small all the extra electrons which they bring are able to get into the conduction of valence, into the conduction band all the extra holes which are created they go they are created in the valence band. So, as a result since their energies are very small they are completely ionized we can write that n e in n type is equal to N d which is the donor concentration and n h in p type is equal to n a which is the acceptor concentration. So, this is for n type and this is for p type.

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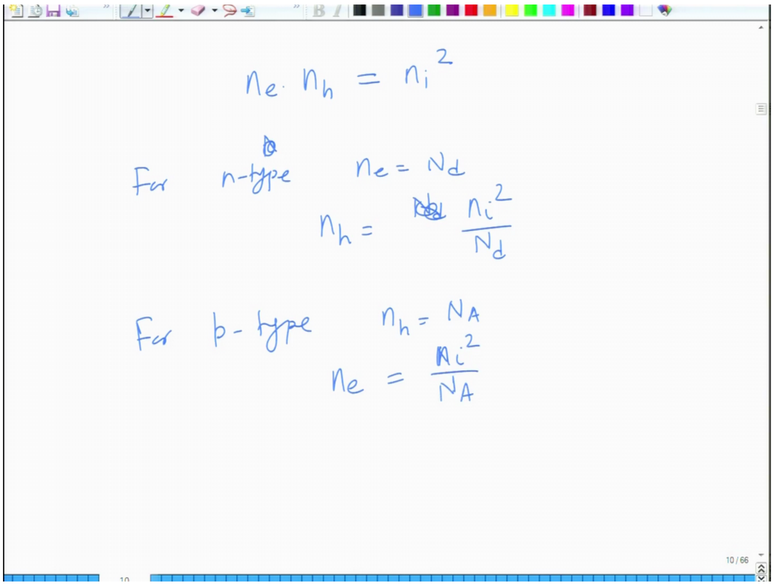

So, when we say that, but at the same time we also make sure mass conservation ensures that n e and n h is equal to n i square ok. Which means for n type n e is equal to N d hence n h is equal to N d n i square divided by N d. For p type in h is equal to N A as a result n e is equal to n i square divided by N A. So, these are the concentration of carriers that we have alright.

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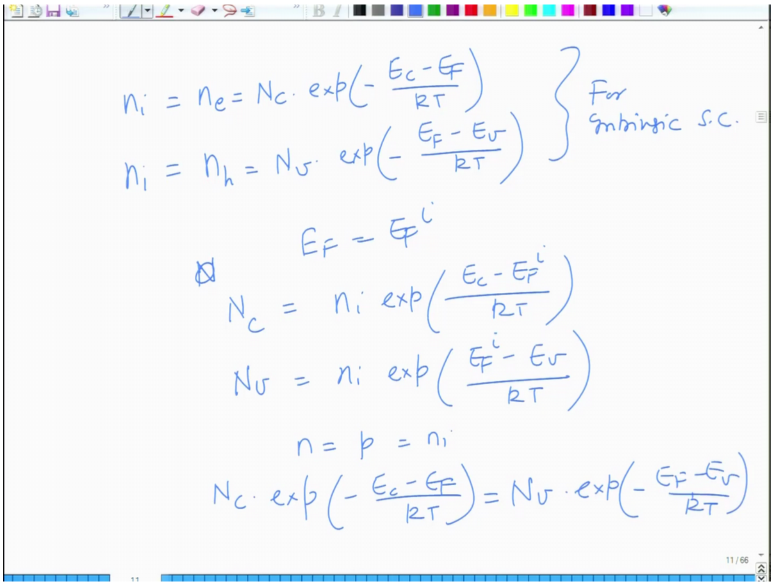

So, we can also write these expressions little bit differently so for example, we said that n i is equal to we said that n e is equal to N c into exponential of minus E c minus E F by k T and n h is equal to N v into exponential of minus of E F minus E v divided by k T ok. We also know that this n e this is equal to n i for intrinsic semiconductors right ok. So, if you just turn the equation upside down and for intrinsic semiconductor E F is equal to E F i then we can write expression for N c as n i exponential of E c minus E F i divided by k T and N v as n i into exponential E F i minus E v divided by k T ok.

So, now for intrinsic semiconductor since n is equal to p is equal to n i. So, which means that N c into exponential of minus of E c minus E F divided by k T is equal to N v into exponential of minus of E F minus E v divided by k T ok.

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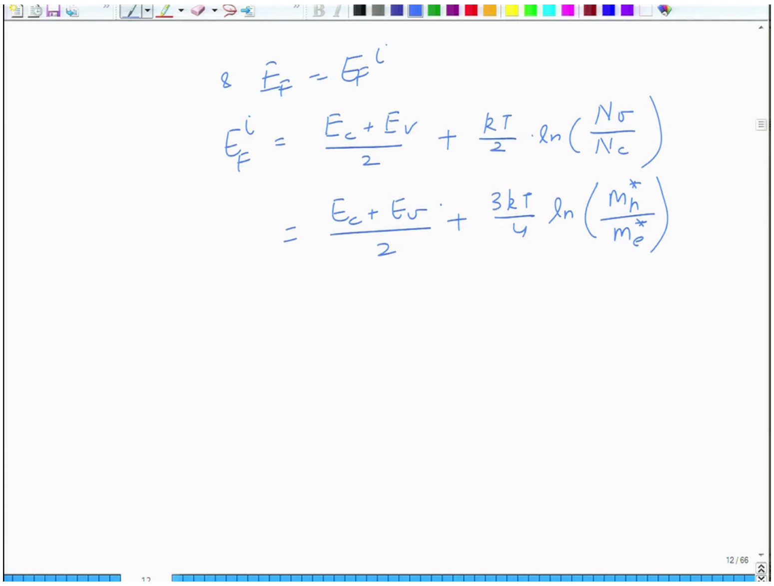

If that is true then we can get the expression for and if E F is defined as E F i, then we can write an expression for E F i; E F i is equal to E c plus E v divided by 2 plus k T by 2 into ln N v by N c and this will turn out to E c plus E v divided by 2 plus 3 k T by 4 ln of m h star divided by m e star effective mass of hole electron.

So, if the effective mass of hole and electron were equal then E F i would be right at the mid gap position; however, if they were different then E F will be different ok. And you can also see there is a strong there is a temperature dependence of E F as well. So, as the temperature changes the Fermi level also goes its increases ok.

Now, another thing that you need to worry about a solid is since, now if you create electron and hole which means you have positive or negative charges, if you dope it with n type impurity you have n type impurities ionized atoms, if you have p type doping you have p type impurities; however, as a solid; solid must remain charged neutral.

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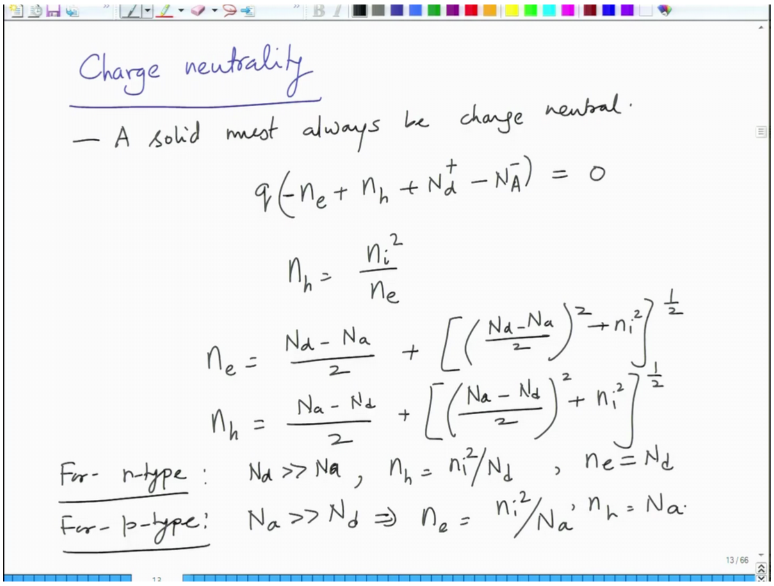

So, which means no matter what happens is that a solid must always be be charged neutral which means that for a given semiconductor q into n e so, minus n e is the negative charge plus holes n h plus N d plus which is the donor atoms minus the acceptor atoms which are negatively charged minus N A minus that overall charge must be equal to 0 and we know that n h is equal to n i square divided by n e.

So, if you substitute in the above equation you can get n e is equal to N d minus N a divided by 2 plus N d minus N a divided by 2 square plus n i square to the power half and n h you can obtain as n t N a minus N d divided by 2 plus N a minus N d to the power 2 to the power to the power 2 plus n i square to the power half.

Now, if we make an approximation that for n type; if N d is equal to is a lot greater than N a which is true for n type semiconductor donor impurities are much larger than the acceptor impurities remember, you will always have some donor and acceptor impurities present in every semiconductor even in intrinsic 1, but the effect is almost effect almost cancels out each other. Because you cannot completely purify a semiconductor to 0 impurity nothing is completely pure on the based on the laws of thermodynamics.

So, as a result you always have some impurity some donor impurity some acceptor impurities. Now, if you intentionally dopar semiconductor to become n type which means N d is a lot greater than n a which means its predominantly p type. And if N d is a lot greater than N a, then if you plug this in the above equation we get p is equal to n i is square divided by N d that is what we said previously also right. And for p type N a is a lot greater than N d which leads to so, sorry let me just not write as p let us write it as n h and in this case N a will be equal to n i square divided by N a ok.

So, and of course, n e will be equal to N d and in this case n h will be equal to N a ok. So, these can also be derived.

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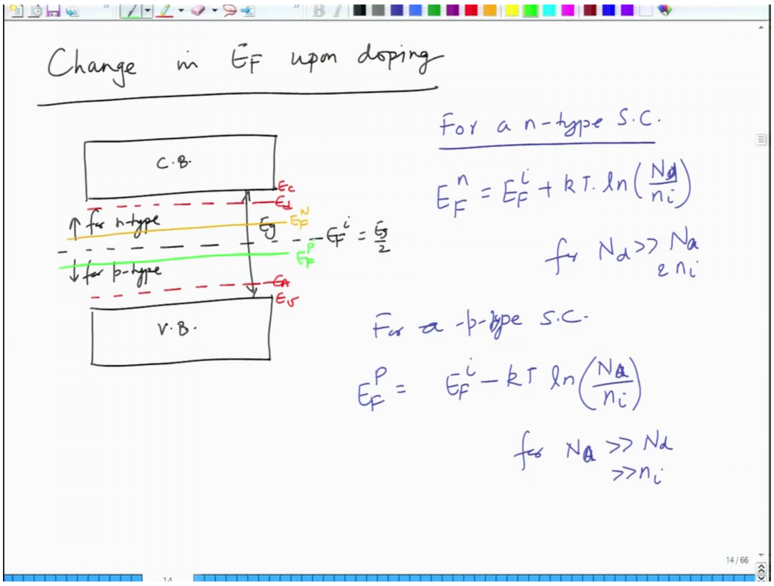

Now let us look at quantitatively the change in E F upon doping so, we said that you have a conduction band you have a valence band ok. So, this is conduction band, this is valence band alright and this is your band gap E g your intrinsic Fermi level is somewhere here. And the Fermi level moves up for n type moves down for p type and this is at E g by 2 for an intrinsic semiconductor alright. And for n type semiconductor you will have this as E d and for p type you will have this as E a this is conduction band edge and this is valence band edge ok.

Now, for a Fermi level of n type semiconductor we can define E F n is equal to E F i plus k T into ln of N d divided by n i. And this is for N d being a lot greater than N a as well as n i ok. And for a p type semiconductor the E F p on the other hand is equal to E F i minus k T into ln N a divided by n i for N a being greater than N d. So, it is getting a small a and it should be greater than n i ok.

So, basically you can see from this expression that as you increase the donor concentration in the first equation, as we increase the donor concentration the term on the right increases right and it is multiplied by k T. So, when your impurity concentration, donor impurity concentration increases it when it is much larger than n i, then E F tends to move up. So, you add something on E F i ok. For a p type semiconductor on the other hand since you have a minus term here as you add more and more to acceptor impurities the Fermi level tends to decrease or go lower with respect to the Fermi level of an intrinsic semiconductor ok.

So, this explained, so if you want if you have a p m type semiconductor your Fermi level will is likely to lie here. So, this is your E F n and if you have a p type semiconductor the Fermi level is likely to lie here so, this is E F p so, this is what we have done so far we have just in this lecture we have looked at the carrier statistics and effect of doping on Fermi level. And some things about the p and n type semiconductors, what we will do in the next class is we will so, this is let me just go through it.

So, we looked at the carrier statistics in intrinsic semiconductors. So, basically simple expression without going through complete derivation. So, this is how you get this n i is equal to N c N v to the power half exponential minus E g by 2 k T. And then we looked at extrinsic semiconductors, the band diagram the ionization energies of donor, and acceptor impurities the relation between the carrier concentration and so, if I just draw these this is for n type and this is for p type ok. And then we looked at some other relations with respect to carrier concentration the Fermi position. And the Fermi position charge internally aspect which gives which ships ties to again carrier concentration expressions and the change in Fermi energy upon doping. So, we will continue with this carrier statistics and carrier mobility carrier motion and semiconductors in the next couple of lectures.

Thank you.