Solid State Devices
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Lecture - 11
Equilibrium Carrier Concentration
(Contd.)

This is the 11th lecture of this course and the last lecture on the topic of Equilibrium Carrier Concentration.

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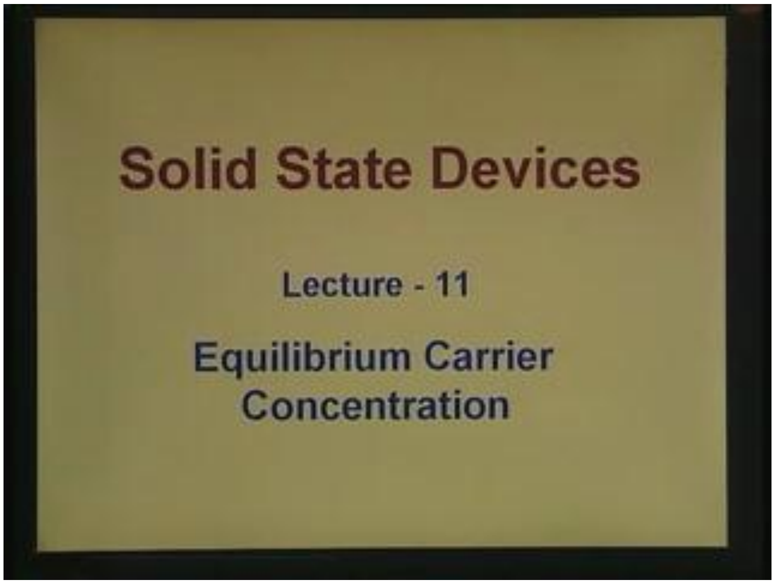
Solid State Devices

Lecture - 11

Equilibrium Carrier Concentration

In yesterday's class, I explained the behavior of concentration in an extrinsic semiconductor as a function of reciprocal of temperature that is the majority carrier concentration.

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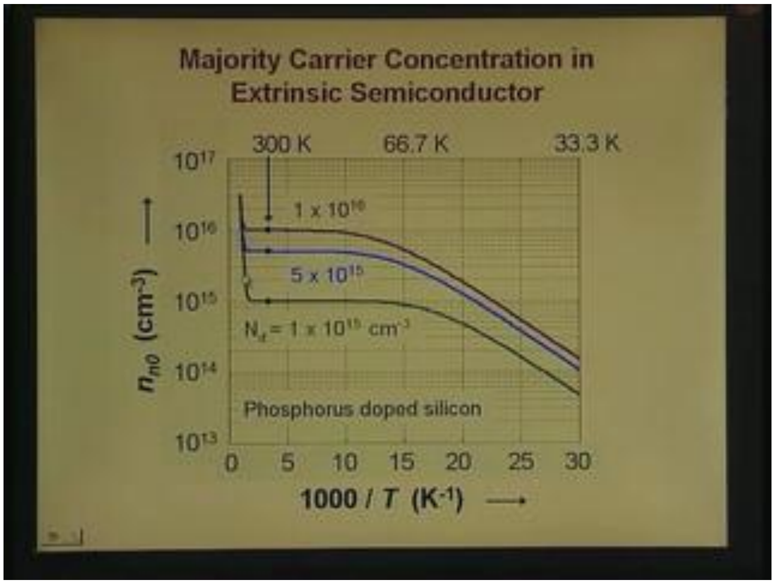

Majority Carrier Concentration in Extrinsic Semiconductor

So we have explained this particular slide. More specifically we have explained how in the different regions here for example, this is extrinsic range, this is the partial ionization range and this is the intrinsic range. How in these three ranges the concentration behaves? We have shown, for example, in the intrinsic range, this range here, your concentration is the same as intrinsic concentration given as square root of N_c N_v e power x minus (Eg by 2KT).

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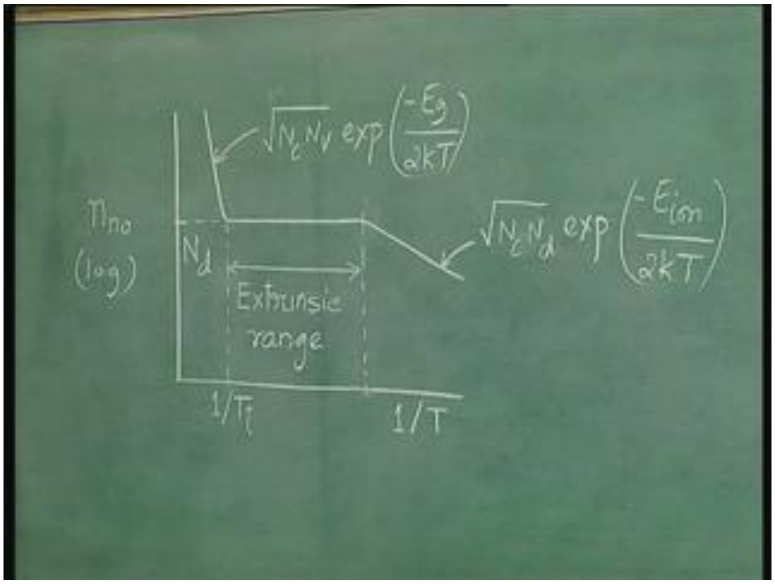

Please note that this formula will hold good in the range where the concentration is exactly equal to the intrinsic concentration. Somewhere near the border obviously this formula will not be valid, we will have to make a more accurate estimation. Similarly, analogous to this range in the partial ionization range which is this particular range the formula is 1 square root of N_c N_d(e power x) minus (Eion by 2KT) where Eion is ionization energy. We have shown this result by considering the band diagram and the analogy between the situation here and the situation in the intrinsic range. Then in the extrinsic range which is a range of interest to us from the point of view of device operation the concentration is equal to the doping level. This is when considering an n-type semiconductor.

Now note that the concentration here is on a log scale and this is on a reciprocal of temperature scale. Today we will see how to calculate the intrinsic temperature and how to calculate the Fermi-level and then we will have a solved example to illustrate how Fermi-level and concentrations can be calculated for specific situations. Let us look at the intrinsic temperature T_i. This particular temperature depends on the border between extrinsic range and the intrinsic range. So how do you define the intrinsic temperature? We can define the intrinsic range temperature using the linear plot of concentration versus temperature.

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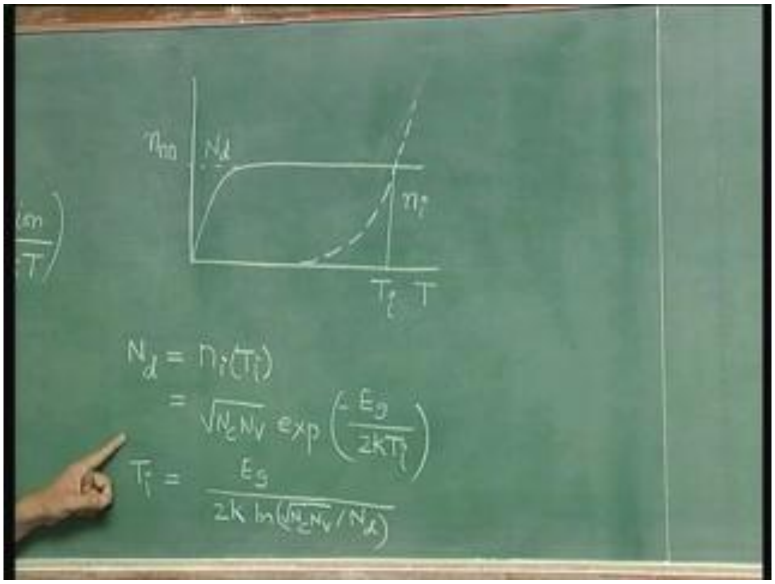

On the linear plot the definition of the intrinsic concentration will be seen much more easily, so this plot is something like this where this is the intrinsic concentration n_i and this is the total contribution because of the thermal generation as well as impurity ionization. I will remove this portion and show only the contribution because of impurity ionization $N_{d.}$ This is the curve representing contribution of the impurity and this is the term representing the effect of thermal generation and more specifically this is intrinsic concentration. Now this is the point where the intrinsic concentration becomes equal to the doping $T_{i,}$ this point is defined as the intrinsic point.

So you define intrinsic point in terms of the doping level and intrinsic concentration where N_d is equal to $n_{i..}$ The formula therefore would be N_d is equal to n_i at T_i is equal to square root of N_c N_v e to the power x(minus Eg by 2KT_i) and when you transform you get T_i is equal to Eg by 2K into ln square root of N_c N_v by N_d. This is obtained from this equation by transformation. Whenever we derive a formula of this type we must check qualitatively whether the formula is correct and whether all these terms are in the correct position. Two important physical parameters on which T_i the intrinsic temperature depends is the energy gap Eg and doping level N_d. According to this formula T_i should increase with energy gap. This is physically correct because if your energy gap is large you must go to higher temperatures to generate the n_i corresponding to the doping level.

Similarly, according to this formula again if your N_d is large the denominator is small and therefore this is large which means that T_i is large. This is also correct because if N_d is large you have to go to higher temperatures to generate n_i. So qualitatively it appears that the formula is correct. In terms of this formula one can calculate the intrinsic temperatures. Let us see what kind of values result.

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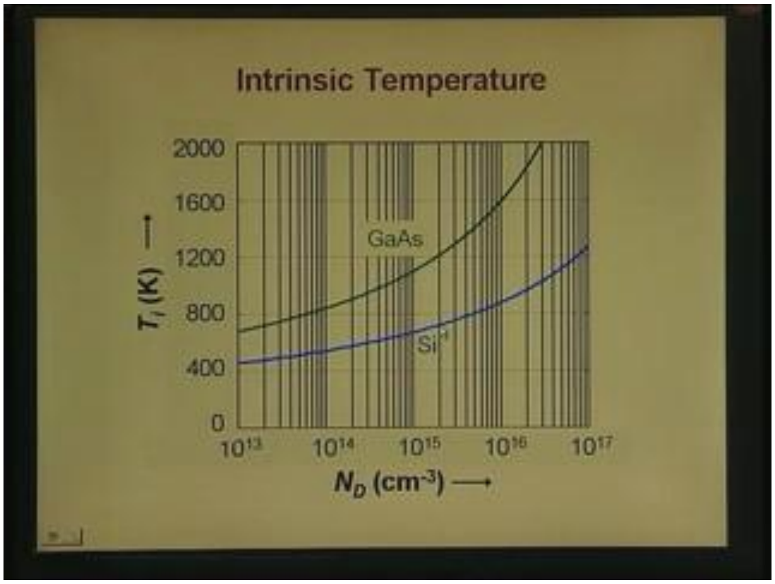

Intrinsic Temperature

Here the intrinsic temperature has been shown for gallium arsenide and silicon. It is because gallium arsenide has higher energy gap of 1.4 electron volts it has higher intrinsic temperature as compared to silicon whose energy gap is 1.1 electron volts.

Let us look at some values at 10 power 13 by cm cube doping level where the intrinsic temperature for silicon is around 450K roughly whereas that of gallium arsenide is about 650K. The gallium arsenide intrinsic temperature is higher by about 200K. You come to about 2(10 power 15) by cm cube doping level, the gallium arsenide intrinsic temperature is 1200K whereas that of silicon is about 700K. That is how the intrinsic temperature depends on the energy gap of the semiconductor and doping level. The intrinsic temperature is important in deciding the extrinsic range. So, if you want to use a device at higher temperatures or for some reason if the device is going to dissipate large amount of power like a power device and therefore its temperature is likely to rise then it is clear that semiconductors with higher energy gap are more suitable for such applications than semiconductors with lower energy gap. This is the importance of intrinsic temperature.

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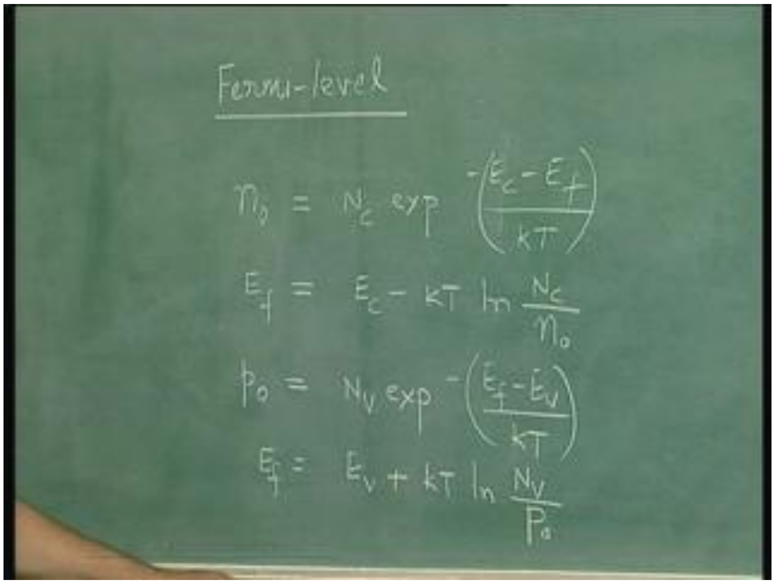

Fermi-level

$$n_0 = N_c \exp -\left(\frac{E_c - E_f}{kT}\right)$$

$$E_f = E_c - kT \ln \frac{N_c}{n_0}$$

$$p_0 = N_v \exp -\left(\frac{E_f - E_v}{kT}\right)$$

$$E_f = E_v + kT \ln \frac{N_v}{p_0}$$

Now let us consider how to estimate the Fermi-level? We know that $n_{0,}$ the equilibrium concentration on electrons is given by N_c exp(minus E_c minus E_f minus by KT). So from here I can get the relation E_f given by E_c minus KT ln N_c by $n_{0.}$ Here n_0 is equal to N_d if there is complete ionization. We are talking of the extrinsic range but more generally this is the relation. So this is how the Fermi-level can be located in terms of the electron concentration. You could locate the Fermi-level in terms of the whole concentration. For that instead of n_0 you will use the formula for p_0 where p_0 is equal to N_v exponential of minus E_f minus E_v by KT which results in E_f is equal to E_v plus KT ln N_v by P_0.

So the Fermi-level is located above E_v by this much value in terms of the whole concentration. Here this formula looks at the Fermi-level with respect to the band edges E_c and E_v. One can also locate the Fermi-level with respect to the intrinsic level of the Fermi-level in a pure or intrinsic semiconductor. This is important because you know that intrinsic semiconductor wwhole concentration is equal to electron concentration and Fermi-level is at the middle of the energy gap.

In a doped semiconductor the concentration will deviate from the concentration in an intrinsic semiconductor depending on the doping and therefore the Fermi-level is deviating. So how much does a Fermi-level deviate from the position in the intrinsic semiconductor because of doping? We can relate E_f to E_i, how we do that? Look at this relation n_0 is equal to N_c exponential minus E_c minus E_f by KT. In addition, we can write the relation n_i is equal to N_c exp of E_c minus E_i by KT it is a negative sign and now we can take the ratio of n_0 and $n_{i.}$

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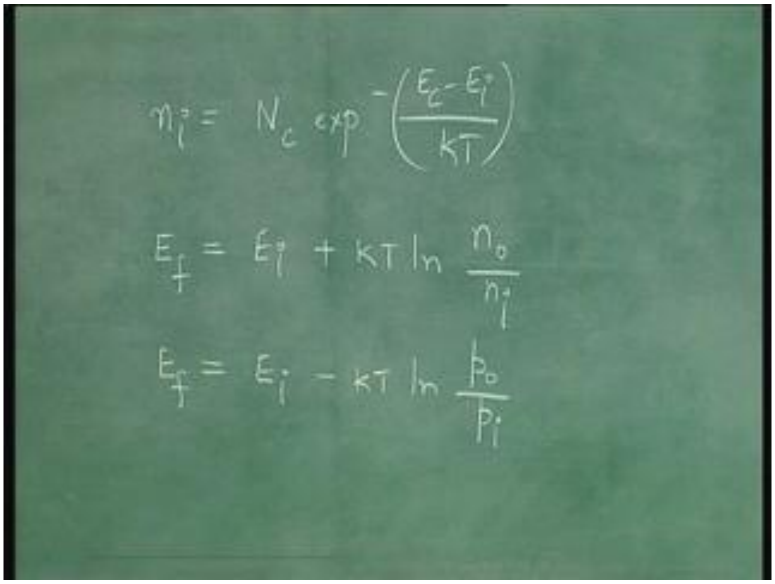

$$n_i = N_c \exp{-\left(\frac{E_c - E_i}{KT}\right)}$$

$$E_f = E_i + KT \ln \frac{n_0}{n_i}$$

$$E_f = E_i - KT \ln \frac{p_0}{p_i}$$

If you take the ratio of n_0 and n_i then you will find that your relationship will be E_f is equal to E_i plus KT ln n_0 by n_i. So if it is an n-type semiconductor then n_0 greater than n_i. The Fermi-level is above E_i; One can similarly do the exercise in terms of whole concentration and you will get E_f is equal to E_i minus KT ln p_0 by p_i. So the Fermi-level in a p-type semiconductor when p_0 greater than p_i is below E_i. This is how we can locate the Fermi-level in terms of the electron whole concentrations. Let us show this on an energy band diagram.

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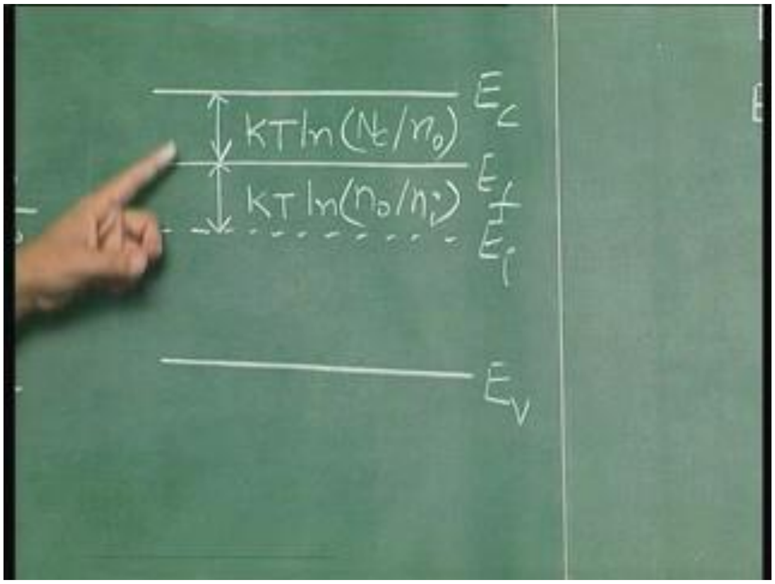

This is E_c, this is E_v and this is E_i suppose it is n-type semiconductor then this will be E_f and it is above E_i. So this difference E_f minus E_i is given by KT ln(n_0 by n_i) is this formula, so E_f minus E_i is equal to KT ln (n_0 by n_i). So alternately you can locate E_f from the conduction band edge and this is given by KT ln(N_c by n_0) which is this particular formula. So E_c minus Ef you shift Ef this side it is KT ln(N_c by n_0), this is n-type. Now you can similarly write relations for Fermi-level in a p-type semiconductor. This is n-type.

Now, using this formula if you estimate the Fermi-levels in silicon for various boron doped and phosphorus doped crystals in the extrinsic range what kind of crystals you will have? So in the extrinsic level you can replace Nn_0 by N_d for phosphorous doped silicon which is the doping level. So this is under the assumption of complete ionization of the impurity and neglect of the thermal generation.

Here n_0 is approximately equal to N_d in an n-type semi conductor in the extrinsic range. So we are interested in estimating Fermi-level in the extrinsic range because that is the range in which the devices operate. Therefore our relations would be E_f is equal to E_c minus kT ln N_c by N_d or alternately E_f is equal to E_v plus KT ln N_v by N_a and this will be in a p-type semiconductor, so this is the n-type, the Fermi-level in extrinsic range and this is for p-type.

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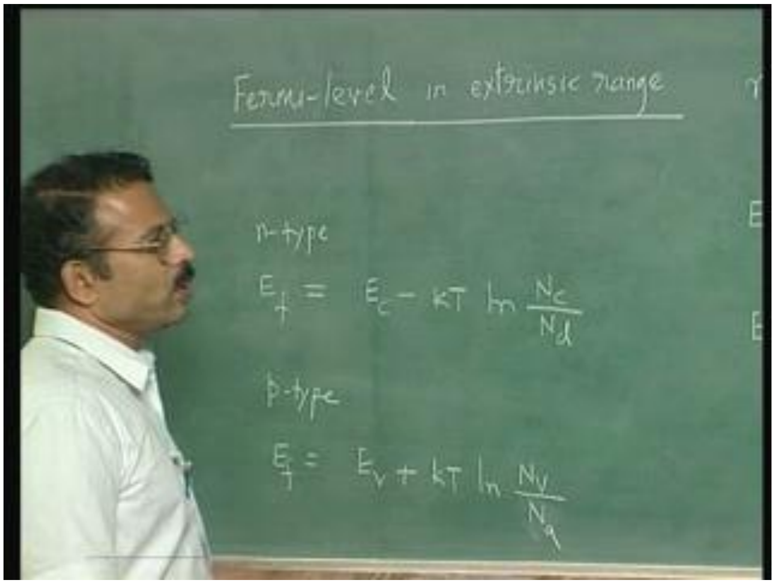

Fermi-level in extrinsic range

n-type

$$E_f = E_c - kT \ln \frac{N_c}{N_d}$$

p-type

$$E_f = E_v + kT \ln \frac{N_v}{N_a}$$

Now you could also use the formula E_f is equal to E_i plus KT ln n_0 by n_i so here n_0 will be replaced by N_d for n-type and here p_0 will be replaced by N_a and p_i is nothing but n_i so we could write p_i or n_i it does not make a difference. This is again n-type and this is p-type so you could use any of this formulae for n-type. When you make an estimation using this at room temperature the calculation looks something like this as shown in the slide here.

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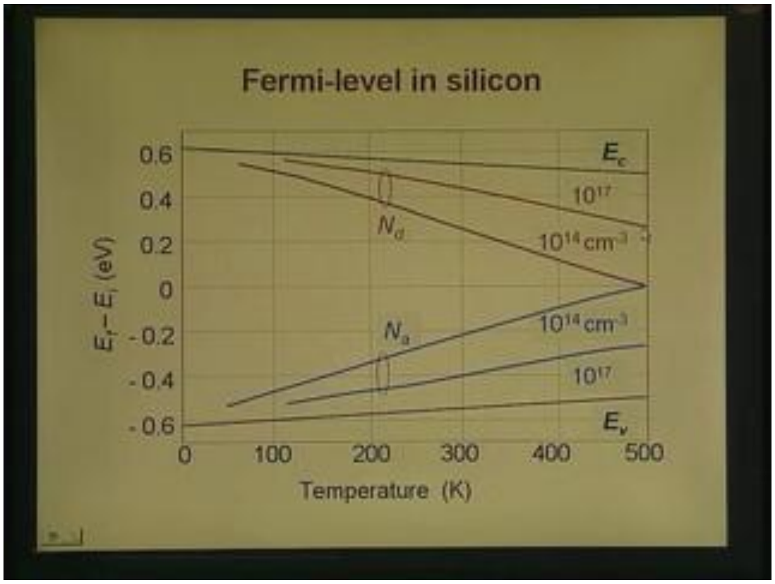

Fermi-level in silicon

So this is the Fermi-level plotted within the extrinsic range. So you find at higher temperatures this is Fermi-level plotted with respect to E_i so E_f minus E_i this is for n-type silicon and this is for p-type silicon and the x-axis is temperature. So you have a behavior both as a function of temperature and doping. You find that in high temperatures the Fermi-level tends to the intrinsic level both for n-type as well as for p-type. The intrinsic temperature is higher for higher doping and that is why this particular Fermi-level here for 10 to the power 17 per cm cube doping has not yet reached the intrinsic level because the doping is higher. At the other end the Fermi-level for all doping levels tends to be at the middle of the region between the conduction band edge E_c and the donor level for the n-type semi conductor. Let us understand this in terms of the diagram below.

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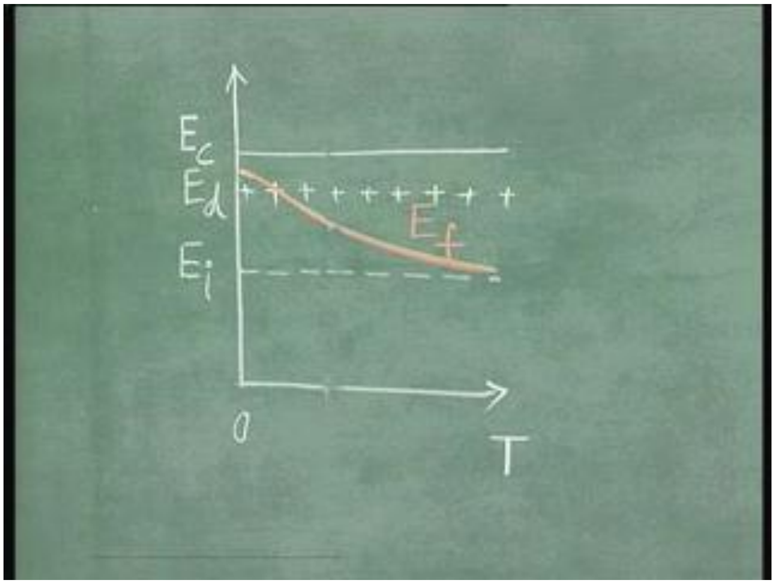

Qualitatively we located the Fermi-level in an n-type semiconductor as per this diagram. So, for T is equal to 0 the Fermi-level is at middle of E_c and E_d, it is at the midpoint of this difference here irrespective of the doping level. Now we did not derive this relation exactly but we showed that the Fermi-level in a n-type semi conductor at T is equal to 0 has to be above E_d but below E_c. Now if you make exact calculations using formulae and so on you will get it at the mid point here. So that is what is being shown here in the slide. Here these lines are tending towards that point.

Now, similarly for p-type silicon they will tend towards these lines, these Fermi-levels will tend towards the middle of the accepted level and the valence band edge. Now, to complete the understanding of this diagram, note that the E_c and E_v have also been shown to vary with temperature. So E_c minus E_v is the difference between E_c and E_v that is the energy gap seems to reduce with temperature. This is true for many semiconductors that the energy gap reduces with temperature.

So what is shown in this slide is the variation for silicon because of the reduction in energy gap the intrinsic concentration that you calculate from the formula square root of N_c N_v e power x (minus Eg by 2KT) will be slightly higher than that you estimate assuming a constant energy gap of 1.12v. Hence that energy gap 1.1v is at 300k and for any other temperature if you want the energy gap you have to use this behavior which is there in some sort of a formula which you are not going to do derive in this course. After considering the Fermi-level now let us look at the topic of compensated semiconductors.

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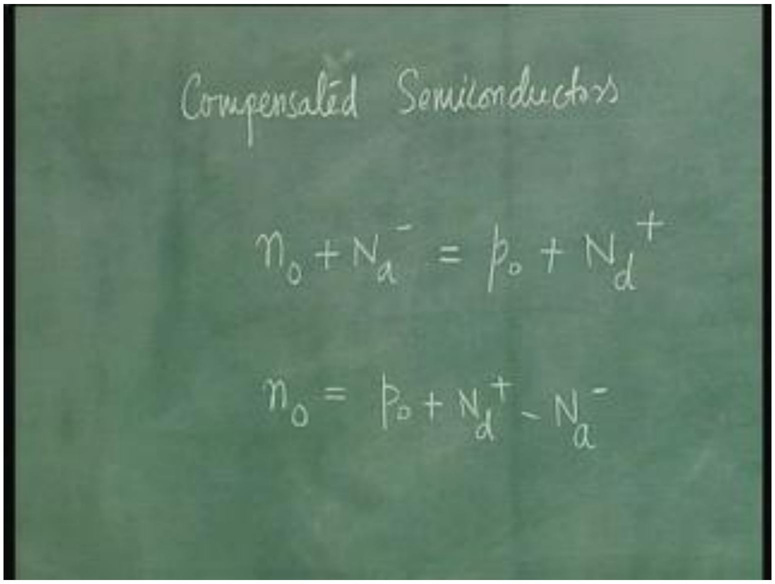
Compensated Semiconductors

$$n_0 + N_a^- = p_o + N_d^+$$

$$n_0 = p_o + N_d^+ - N_a^-$$

Compensated semiconductors: In one of the previous classes in response to a question I had explained how we can predict the behavior of semiconductors in which you have both p-type and n-type impurities using the bond model. That is both phosphorous and boron doping. Now we want to look at the behavior from the energy band point of view. So specifically we had mentioned in that context that for compensated semiconductors your charge balance equation can be written as n_o plus N_a to the power minus is equal to p_o plus N_d power plus, here n_0 is electron concentration, p_0 is whole concentration, N_a power minus is the ionized acceptor concentration, N_d plus is the ionized donor concentration. So, according to this formula supposing you start with n-type semi conductor and you introduce acceptor impurities, so you start with a phosphorous doped semiconductor and you increase the concentration of boron impurity from 0 onwards, now what the behavior is like? You can predict that behavior using this formula n_o is equal to p_o plus N_d to the power plus N_a power minus.

I am rewriting this balance equation like this which we have done in the context of the discussion on compensate semiconductors earlier. This clearly shows that your electron concentration starts reducing as you start raising N_a to the power minus from 0 onwards. Let us understand this particular behavior from the energy band point of view. So what is happening? You have this E_c E_v and these are the donors in an n-type semi conductor.

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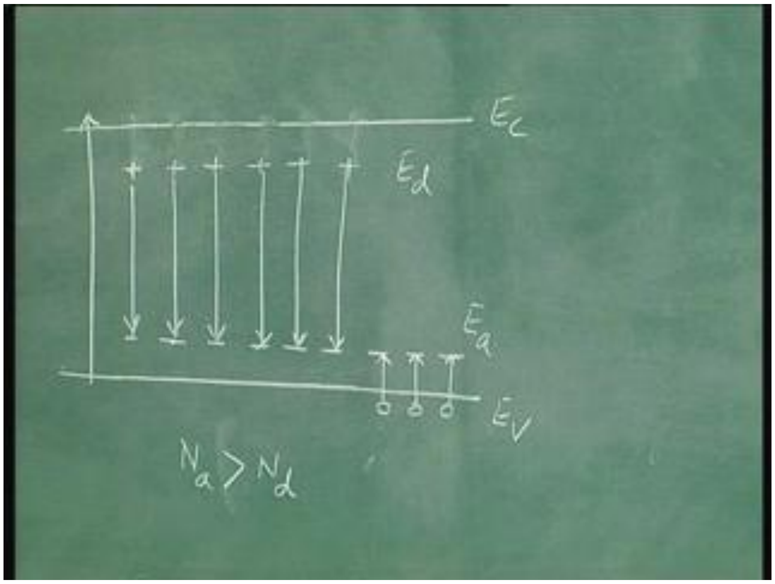

Let us say we are talking of the extrinsic range or we are working around room temperature and these donors are phosphorous so all of them are ionized. So N_d power plus is actually N_d this is shown here by these arrows here. Therefore each of these donors have given away an electron which has gone to the conduction band. Now there is another process that is the process of thermal generation which will be shown as an arrow going from valence band to conduction band and this is thermal generation and this is also present but we know that the contribution of this to the concentration around room temperature is very small so we will not bother about this but concentrate only on the impurity ionization.

Supposing you add acceptor impurities what is going to happen? Here the number of positive signs in some way indicates the concentration of donor impurities. Thus smaller number of negative signs shows that N_a less than $N_{d.}$ Now let us say that we have added these acceptor atoms and what is going to happen? Now, while discussing the energy band model we said that one of the postulates is that electrons occupy the lowest energy states available to them.

The moment you have introduced the acceptor impurities you have introduced allowed states for the electrons here below this donor level. What is going to happen is the electrons from these donor levels instead of jumping up to conduction band they would find it more convenient to jump down on to this acceptor level. So each acceptor level is going to accept an electron from the donor impurity and so these electrons from donor impurity instead of becoming free will get trapped at the acceptors side. This is how the acceptor atoms are reducing the concentration of electrons in the n-type semiconductor.

Now one can extend this logic and show that if N_a becomes more than N_d which means this will correspond to the picture like this. I will explain this line here to show that N_a has become more than N_d. So this is E_c, E_v, E_d and this is E_a the acceptor level. Now what is going to happen is all these arrows will go away so electrons will jump down on to the acceptor side instead of jumping up from the impurity the donor level. So all these impurities have been totally compensated by the acceptor atoms and now these acceptor atoms are there which will accept an electron from the valence band edge and as a result will give raise to holes. Now the semiconductor has changed polarity and it has become p-type rather than n-type because it has now got holes. This is how one can look at the behavior of compensated semiconductors from the energy band point of view and understand the particular phenomenon of compensation.

If your n-type doping is more than p-type doping you get an n-type semiconductor if your p-type doping is more than n-type doping you get a p-type semiconductor. After this we will solve a problem, a numerical example which will show us how carrier concentration is estimated and how the Fermi-level is located.

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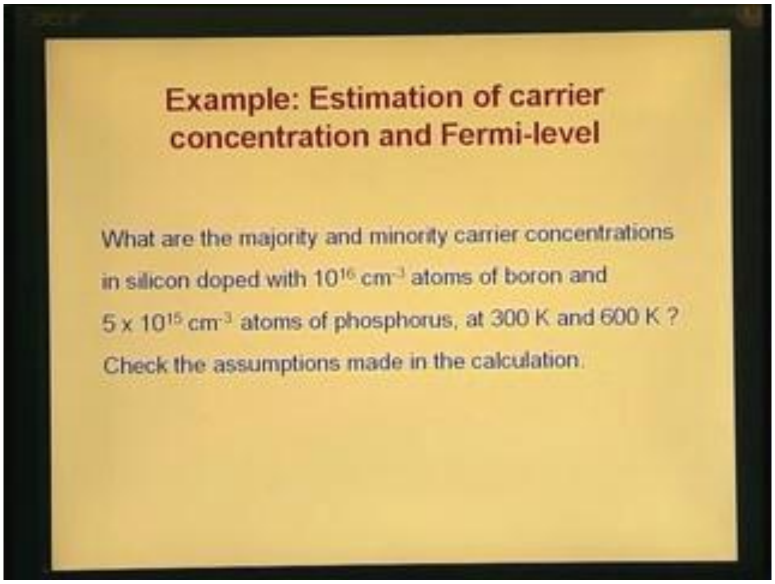

Example: Estimation of carrier concentration and Fermi-level

What are the majority and minority carrier concentrations in silicon doped with 10^{16} cm^{-3} atoms of boron and 5×10^{15} cm^{-3} atoms of phosphorus, at 300 K and 600 K ? Check the assumptions made in the calculation.

Now we shall illustrate some of the ideas related to Fermi-level and carrier concentration with the help of a numerical example. The example is the following: What are the majority and minority carrier concentrations in silicon doped with 10 to the power 16 cm cube atoms of boron and 5 into 10 to the power 15 cm cube atoms of phosphorous, at 300K and 600K? Check the assumptions made in the calculation. So basically we want to estimate carrier concentration in a compensated semiconductor at two different temperatures by checking the assumptions which have been made. Let us see the assumptions which we make.

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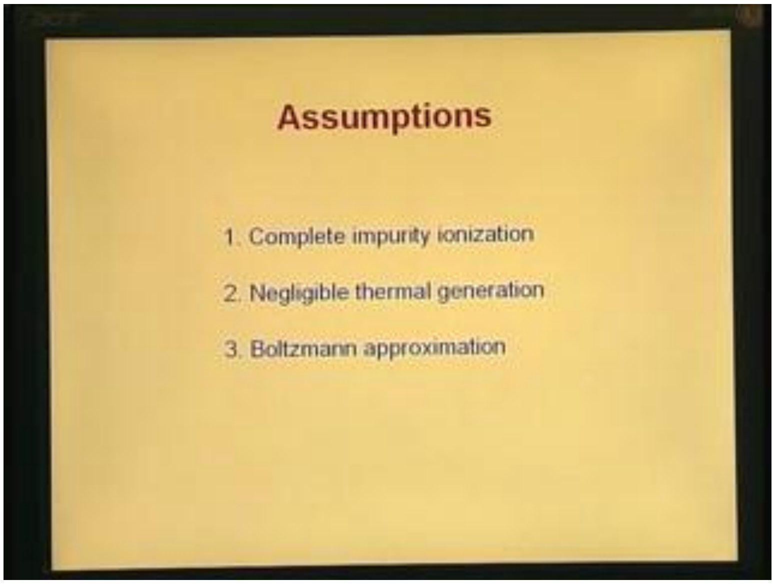

Assumptions

1. Complete impurity ionization
2. Negligible thermal generation
3. Boltzmann approximation

The assumptions that we make normally while estimating carrier concentration are: complete impurity ionization, negligible thermal generation and Boltzmann approximation. Let us see where these approximations or assumptions are made for simplifying the calculation. Let us start with the carrier concentration at 300K.

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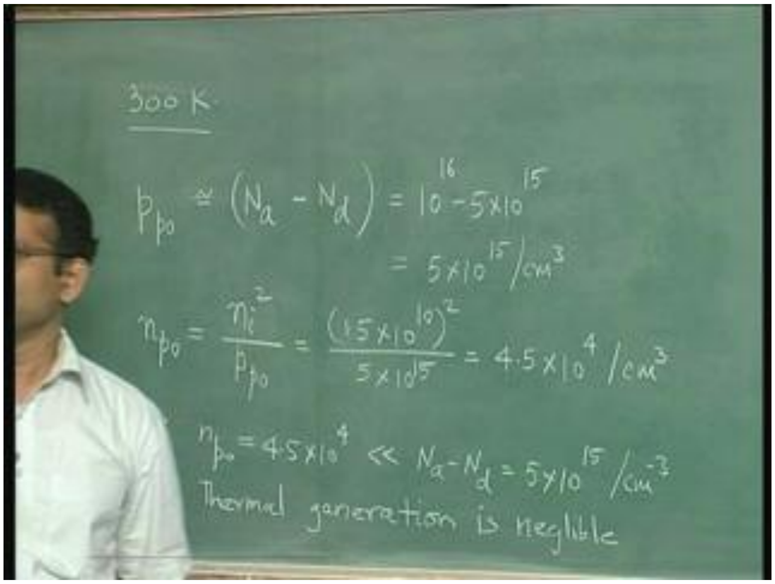

300 K

$$p_{p0} \cong (N_a - N_d) = 10^{16} - 5\times10^{15}$$
$$= 5\times10^{15}/cm^3$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5\times10^{10})^2}{5\times10^{15}} = 4.5\times10^4/cm^3$$

$$n_{p0} = 4.5\times10^4 \ll N_a - N_d = 5\times10^{15}/cm^{-3}$$

Thermal generation is neglible

First we need to estimate the majority carrier concentration and for this we use the charge balance equation. We note that since the boron concentration of 10 to the power 16 cm cube is more than the phosphorous concentration of 5 into 10 to the power 15 it is a p-type semiconductor. We write the charge balance equation as p_{p0} which is the hole concentration in the p-type semiconductor which is equal to N_a minus the ionized acceptor concentration minus the ionized donor concentration plus the concentration of thermally generated carriers which is also the minority carrier concentration (p_{p0} is equal to (N_a minus N_d to the power plus)plus $n_{p0.}$

When you make the assumption of complete impurity ionization this minus and plus signs drop out so that is a simplification. Further when you make the assumption of neglecting the thermal generation that is this particular term n_{p0} is much less than this term N_a minus N_d that is the meaning of neglecting thermal generation so we remove this term also. This is how your equation gets simplified for the majority carrier concentration and so the result is equal to 10 to the power 16 minus 5 into 10 to the power 15 which is equal to 5 minus 10 to the power 15 cm cube so that is the hole concentration. Now the electron concentration n_{p0} is equal to n_i square by p_{p0}. Now n_i at 300K is 1.5 into 10 to the power 10 cm cube so (1.5 into 10 to the power 10) whole square by 5 into 10 to the power 15 and the result is 4.5 into 10 to the power 4 by cm cube which is the minority carrier concentration. Having obtained these concentrations now we must check the assumptions.

For example, supposing we want to check the assumption of negligible thermal generation what does it mean? We need to check whether n_{p0} as obtained here is much less than N_a minus N_d which is obtained here so this is indeed the case. So since n_{p0} is equal to 44.5 into 10 to the power 4 less than N_a minus N_d is equal to 5 into 10 to the power 15 cm cube. Here also the unit is per cm cube hence thermal generation is negligible. We have to check the assumption of negligible thermal generation at 300K. Now how will you check the assumption of impurity ionization? Is N_a to the power minus is equal to N_a? Is N_d to the power plus is equal to N_d? To check that we will have to locate the Fermi-level because we know the fraction N_a to the power minus by N_a is the number of occupied states at the energy level E_a.

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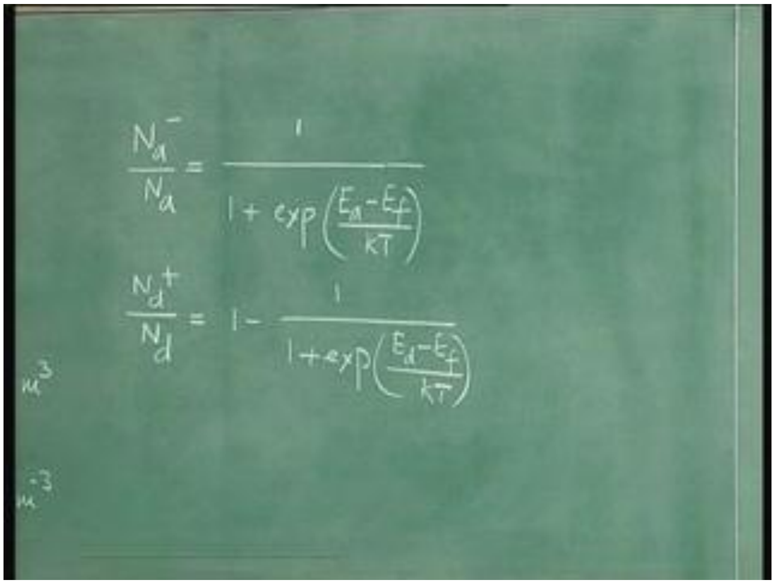

$$\frac{N_a^-}{N_a} = \frac{1}{1+\exp\left(\frac{E_a-E_f}{kT}\right)}$$

$$\frac{N_d^+}{N_d} = 1-\frac{1}{1+\exp\left(\frac{E_d-E_f}{kT}\right)}$$

So this fraction is given by 1 by 1 plus exp (E_a minus E_f by KT). Similarly N_d to the power plus by N_d is the number of unoccupied states at the energy level E_d. This is 1 minus 1 by 1 plus exp (E_d minus E_f by KT). E_d is the donor level corresponding to N_d, E_a is an acceptor level corresponding to N_a. If you know the location of Fermi-level then we can find out these fractions and check whether N_a to the power minus by N_a is equal to 1 and whether N_d to the power plus by N_d is either equal to or close to 1. Let us look at the energy band diagram.

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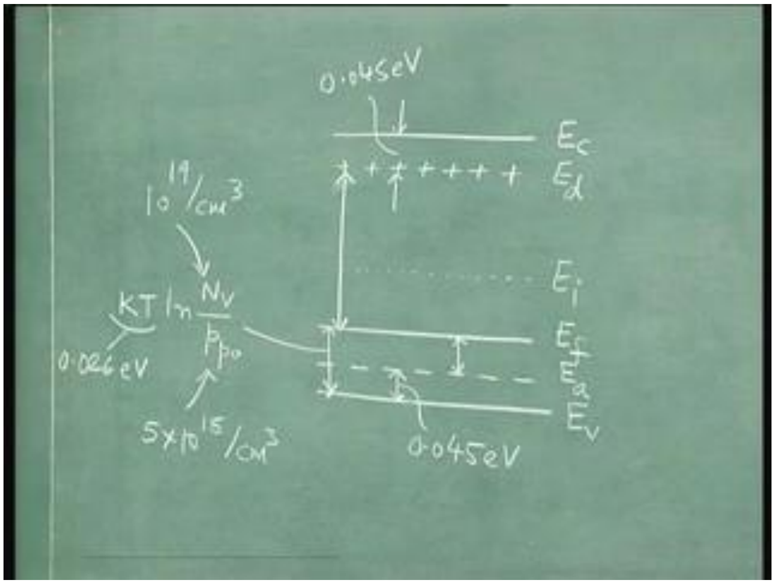

That is something like this, this is E_c and this is E_v and this is E_d donor level, this is acceptor level corresponding to boron so this is E_a. Since it is a p-type semiconductor Fermi-level E_f will be close to the valence band edge than conduction band edge that is away from the intrinsic level and this is E_i. So let us say the Fermi-level is somewhere here, we do not know exactly where it is but we will now locate it shortly, it will be below E_i. Since this is a p-type semiconductor it will be useful to locate the Fermi-level either with respect to the valence band edge or with respect to E_i but not with respect to conduction band edge. So let us locate with respect to valence band edge that is we want to know what is this difference?

From the formula we know that this difference is KT ln N_v by $p_{p0.}$ This is where we are using the Boltzmann approximation now to estimate the location of the Fermi-level. Incidentally the Boltzmann approximation was also used when we estimated the minority carrier concentration from n_i square by majority carrier concentration formula and this is because minority carrier concentration into majority carrier concentration is equal to N_a square or p to the power n is equal to N_a square where this particular relation comes only after we make a Boltzmann approximation.

Coming back here the location of the Fermi-level with respect to E_v can be obtained by using this formula KT ln N_v by p_{p0}. Once we know that we can make the calculation of the ionized impurities because we know these distances E_a minus E_v is equal to 0.045 volt. Similarly this difference is also 0.045 volts. So if you want E_d minus E_f then it will be this difference and if you want E_a minus E_f it will correspond to this difference. These are the two differences we want. Once we know this difference we can estimate the other two. Now what is the value of this KT ln N_v by p_{p0}? p_{p0} we have estimated to be 5 into 10 to the power 15 by cm cube under our assumptions and N_v is 10 to the power 19 divided by cm cube and this KT is equal to 0.026 volts.

So if you substitute all these values and then estimate this particular difference it will turn out to be equal to 0.198 electron volts which is the difference. So as a result this difference is 0.153 electron volts. Now we can try to estimate this relation N_a to the power minus by N_a which will be is equal to 1 by 1 plus exp (E_a minus E_f by KT). This will be 1 by 1 plus exponential minus 0.153 by 0.026 and this works out to 1 minus 2.78 into 10 to the power minus 3. So this 2.78 into 10 to the power minus 3 is very small compared to 1 so N_a to the power minus by N_a is approximately equal to 1 and complete ionization of acceptor impurities is justified.

Now one can similarly do an estimation of N_d to the power plus by N_d. However we need not do a calculation again to check whether this is indeed close to 1 because you see E_d minus E_f by KT where E_d minus E_f is this difference which is definitely much larger than E_f minus E_a which means that this term here E_d minus E_f would be much greater than 0.153 and therefore this term again would be much less than 2.78 into 10 to the power minus 3.

So as a result we can definitely say if the acceptor impurities in a p-type semiconductor like boron doped semiconductor are ionized then definitely the donor impurities present in the p-type semiconductor will also be completely ionized. So we need not do a calculation again for the phosphorus atoms or donor impurities. With that we have checked and justified the assumption of complete ionization. Now is Boltzmann approximation justified because that is a third assumption we have made so that can also be seen very easily as E_f minus E_v is 0.198 electron volts should be three times greater than KT. Now 3KT in this case at room temperature is 0.078 electron volts.

Since 0.198 electron volts is greater than 0.078 electron volts the Boltzmann approximation is justified and is valid. If the boron doping was higher slowly you can see from here that this E_f will start moving close to E_v and then there is a likelihood of the Boltzmann approximation getting violated. But as it is you see that Boltzmann approximation is justified. Now even before actually making accurate calculation of this particular fraction N_a to the power minus by N_a once we have located the Fermi-level here we can get a feel for the fact that the acceptor impurities and the donor impurities are fully ionized because E_f is above E_a, and using the Fermi-Dirac fraction we know that most of the levels below E_f will be occupied and most of the levels which are far away from E_f on the top will be unoccupied. That is how donor impurities are fully ionized and acceptor impurities also are fully ionized once we locate the Fermi-level and even without making a numerical estimation.

Now one can repeat the same procedure for 600 Kelvin. However one thing you must note that we need not check again whether complete ionization will be justified at 600K by calculation because we know that at 300K if the impurities are ionized at 600K they will definitely be ionized. Similarly, even for the Boltzmann approximation one need not check again because you know that as the temperature increases the Fermi-level is likely to move closer and closer to E_i. So this difference between E_f and E_v is likely to increase. Basically the assumption that is likely to be violated is the neglect of thermal generation which is the important assumption that we will have to check.

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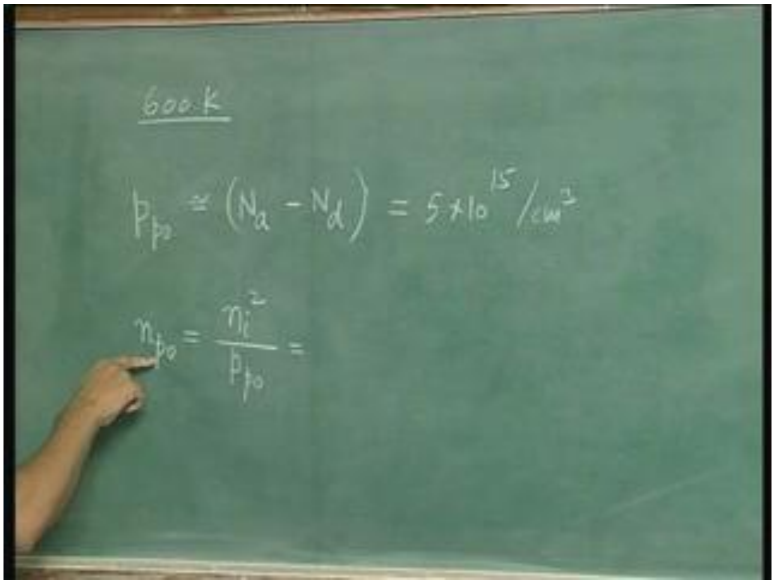

600 K

$$p_{po} \simeq (N_a - N_d) = 5\times10^{15}/cm^3$$

$$n_{po} = \frac{n_i^2}{p_{po}} =$$

Let us do the calculations that 600K. At 600K again neglecting thermal generation and assuming complete impurity ionization you will get p_{po} as same as at 300K and that is 5 into 10 to the power 15 by cm cube. Now, when you want to estimate the n_{po} that is electron concentration you will have to estimate n_i at 600K and that is what we do not know. To estimate this we must estimate n_i so let us estimate n_i at 600K.

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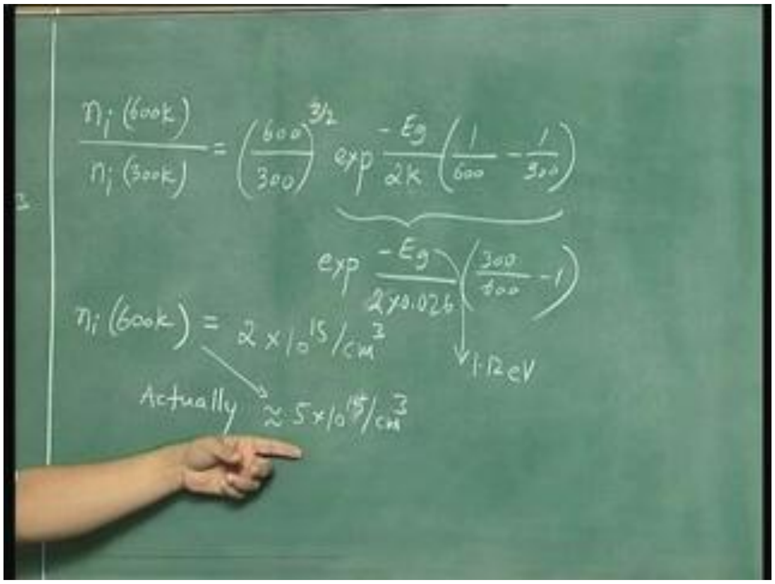

Here n_i at 600K we can estimate in terms of n_i at 300K as follows. So n_i(600K) by n_i(300K) is equal to (600 by 300) power 1.5 exp(minus $E_{g\ \text{by}}$ 2K) into (1 by 600 minus 1 by 300) where we take the 300 out so that 2K(T) corresponding to 300 we know is 0.026 eV. We can write this part as exp minus E_g by 2 into 0.026 ((300 by 600) minus 1). This is the way you must rewrite the term because now this part can be calculated easily instead of calculating this particular term from Boltzmann constant and the temperature of 300K or simply calculating this term by energy gap and Boltzmann constant and then multiplying by this term, you bring that 300K of room temperature out so that 2KT can be written as 0.026.

Now you simplify this and the result would be 2 into 10 to the power 15 by cm cube. Note that we have substituted this particular term Eg as 1.12eV and when you substitute this as 1.12eV you get 2 into 10 to the power 15 by cm cube. In practice however n_i at 600K will be more than this and the actual value will be about 5 into 10 to the power 15 by cm cube if you include the reduction in Eg with temperature so this is a more realistic value. However, we will not use this value but let us continue to use this value where we assume energy gap is 1.12eV. Once you obtain n_i now you can estimate n_{po} as 2(10 to the power 15) whole square by 5 into 10 to the power 15 and the result is 8 into 10 to the power 14 by cm cube.

Now you see that in this case that the n_{po} is not really very small compared to N_a minus $N_{d.}$ In other words, this is definitely more than 1 by 10th of this and thermal generation is not really negligible. In other words we must take into account thermal generation while estimating the majority carrier concentration. In fact as we have said 2 into 10 to the power 15 is an approximate value which neglects the reduction in energy gap at higher temperature. If you take the energy gap reduction in account then n_i will be 5 into 10 to the power 15 and then your minority carrier concentration n_{po} will also turn out to be the same as majority carrier concentration therefore it is almost an intrinsic semiconductor.

So, in that case how do you take thermal generation into account? Here we write n_{po} is not much less N_a minus N_d hence thermal generation should be taken into account.

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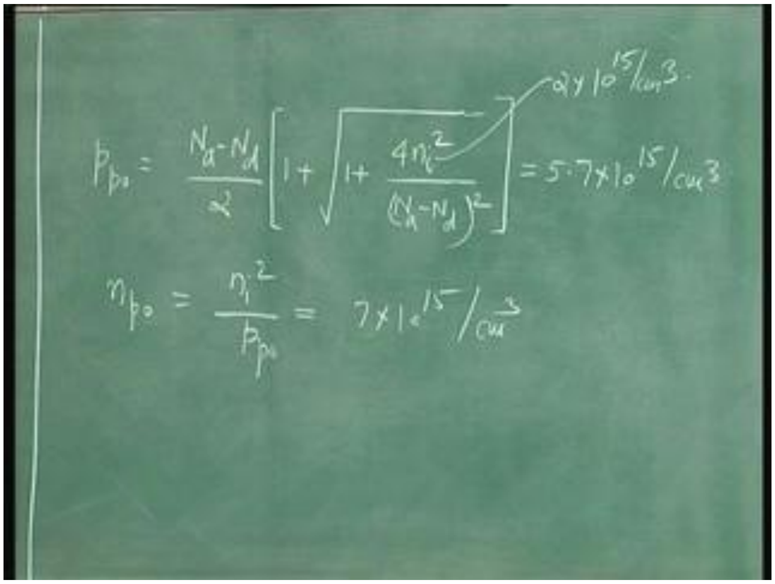

$$p_{po} = \frac{N_a - N_d}{2}\left[1 + \sqrt{1 + \frac{4n_i^2}{(N_a - N_d)^2}}\right] = 5.7\times10^{15}/cm^3$$

$2\times10^{15}/cm^3.$

$$n_{po} = \frac{n_i^2}{p_{po}} = 7\times10^{15}/cm^3$$

So if you want to take that into account then you have to use the quadratic formula that is N_a minus N_d plus here you will have the n_{po} while calculating p_{po} and that quadratic formula is N_a minus N_d by 2(1 plus square root of 1 plus $4n_i$ square by (N_a minus N_d) whole square. So we have written down this particular relation in a slightly different form earlier. If you substitute the various terms the value will turn out to be 5.7 into 10 to the power 15 by cm cube and then if you calculate n_{po} using this value you will get 7 into 10 to the power 15 by cm cube. So here we have used n_i as 2 into 10 to the power 15 by cm cube. This is how one can estimate the carrier concentrations at 600K.

As we have said earlier complete impurity ionization is already justified and we need not check Boltzmann approximation because it will be valid. So this is how one can estimate the Fermi-level and the concentration and derive the information that we want about the semiconductor. Now, before we close this topic it is useful to know that all impurities do not behave like boron and phosphorous. Their ionization energies are not so small as 0.045eV. Let us see the different kinds of ionization energies of other impurities in silicon.

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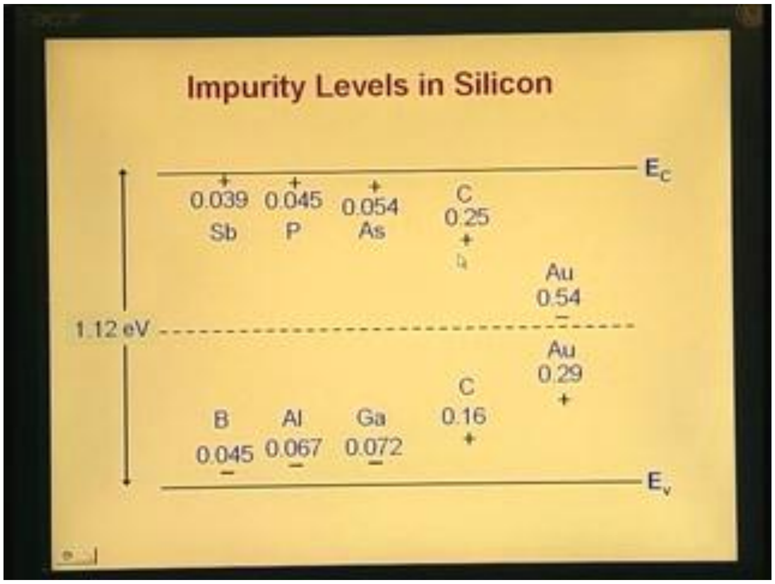

Impurity Levels in Silicon

Here the impurity levels corresponding to different impurities are shown. The impurities shown here are antimony, phosphorous, arsenic, carbon, gold, boron, aluminum and gallium. The positive sign indicates donor impurity or donor level and negative sign is the acceptor level. Further the number here indicates the distance of this particular level from the nearest band edge. So, for example this 0.25 here would mean the distance of this particular carbon level from E_c. On the other hand 0.29 here would mean the distance of this particular level associated with gold from E_v.

Now what you see from this diagram is that some impurities have small ionization energies like antimony, phosphorous, arsenic, boron, aluminum and gallium. So it is donor level close to conduction band edge or acceptor level close to valence band edge. These kinds of impurities can be very useful in changing the carrier concentration because they get ionized very easily and they are used to change the concentration or resistivity of silicon and such impurities are called shallow impurities.

On the other hand, you have what are called deep impurities. These are the impurities such as carbon where ionization energy is large. The word “deep” implies that the impurity is located much inside as compared to the relevant band edge and shallow means it is close to the relevant band edge. So what you see from here is that it is not necessary that donor level should always be close to the conduction band edge. You can have donor level far away from the conduction band edge as it is happening in carbon. And similarly, as it is happening in gold the acceptor impurity is far away from the valence band edge so these are deep impurities. Now what you see further here is that it is not necessary that impurity should give rise to only one level. Here you have carbon which gives rise to two donor levels at two different locations in the energy gap.

Finally it is not necessary that an impurity should be only donor type or only acceptor type. Gold introduces both donor level as well as an acceptor level. So impurities which have both types of levels donor and acceptor are called amphoteric impurities. So deep impurities like gold and many others are useful in altering the transient response of the semiconductor and we will see this in our discussion on excess carriers that cannot change the resistivity because their ionization energy is large but they can change the transient response. Now let us quickly summarize the topics we have discussed in these nine lectures on Equilibrium Carrier Concentration.

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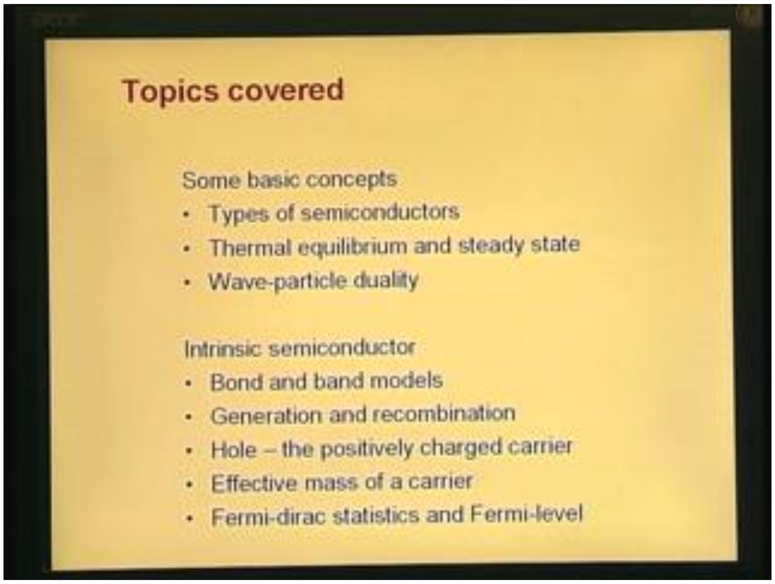

Topics covered

Some basic concepts
- Types of semiconductors
- Thermal equilibrium and steady state
- Wave-particle duality

Intrinsic semiconductor
- Bond and band models
- Generation and recombination
- Hole – the positively charged carrier
- Effective mass of a carrier
- Fermi-dirac statistics and Fermi-level

First we covered some basic concepts such as types of semiconductors, then the concept of thermal equilibrium and steady state and the idea of wave particle duality. Then we went on to discuss intrinsic semiconductor wherein we did the bond and band models, generation and recombination phenomena, then the positively charged carrier or the hole concept, what is the effective mass of a carrier, the Fermi-Dirac statistics and Fermi-level.

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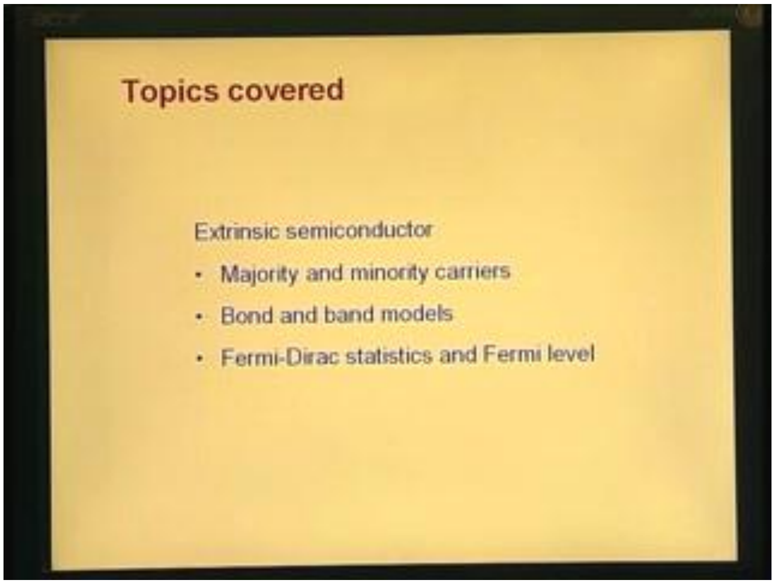

Topics covered

Extrinsic semiconductor

- Majority and minority carriers
- Bond and band models
- Fermi-Dirac statistics and Fermi level

Now this discussion for the intrinsic semiconductor was repeated in a similar manner for extrinsic semiconductors. We discussed the majority and minority carriers, the bond and the band models and the Fermi-Dirac statistics and the Fermi-level.

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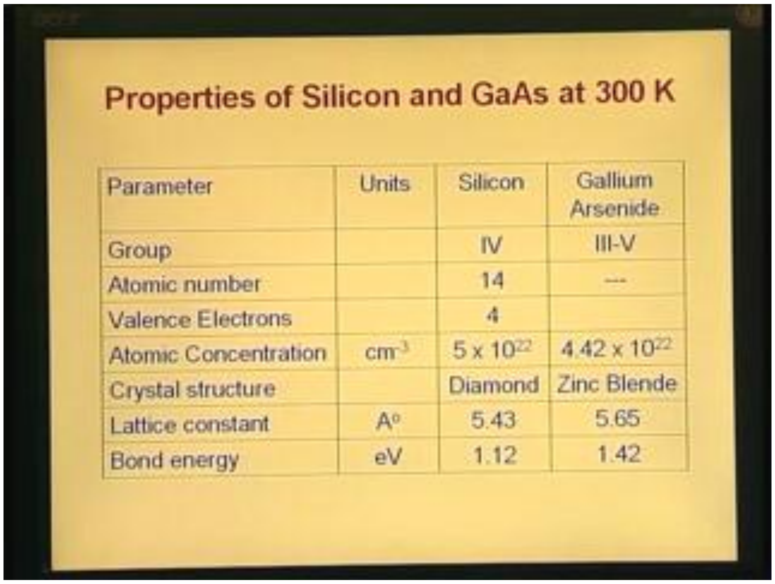

Properties of Silicon and GaAs at 300 K

Parameter	Units	Silicon	Gallium Arsenide
Group		IV	III-V
Atomic number		14	---
Valence Electrons		4	
Atomic Concentration	cm^{-3}	5×10^{22}	4.42×10^{22}
Crystal structure		Diamond	Zinc Blende
Lattice constant	A°	5.43	5.65
Bond energy	eV	1.12	1.42

Now it also useful to see some of the properties of semiconductors that we must remember namely the group of the semiconductor, the atomic number, the valence electrons number, the atomic concentration 5 into 10 to the power 22 by cm cube is a very important number, the crystal structure of a semiconductor, the lattice constant and the bond energy.

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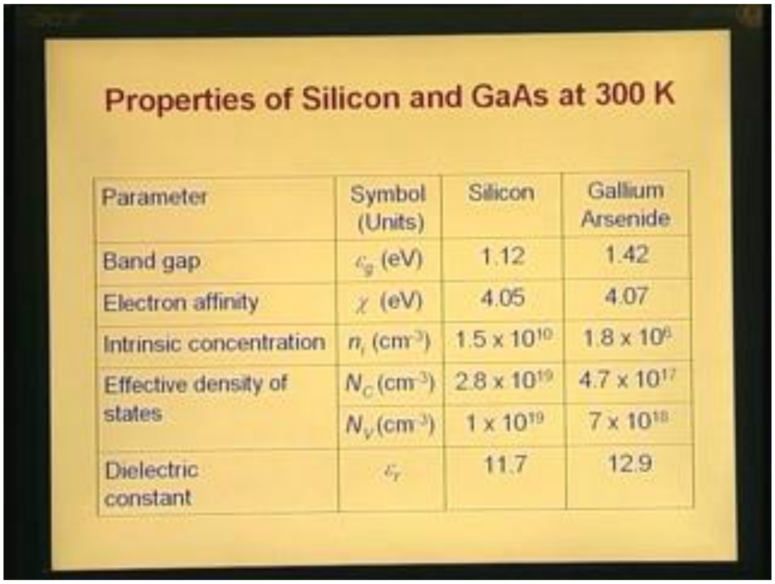

Properties of Silicon and GaAs at 300 K

Parameter	Symbol (Units)	Silicon	Gallium Arsenide
Band gap	ε_g (eV)	1.12	1.42
Electron affinity	χ (eV)	4.05	4.07
Intrinsic concentration	n_i (cm^{-3})	1.5×10^{10}	1.8×10^{6}
Effective density of states	N_C (cm^{-3})	2.8×10^{19}	4.7×10^{17}
	N_V (cm^{-3})	1×10^{19}	7×10^{18}
Dielectric constant	ε_r	11.7	12.9

Further the band gap, the electron affinity, the intrinsic concentration at room temperature, effective density of states in conduction valence bands, the dielectric constant and finally the effective masses of electrons and holes under conductivity and density of states situations.

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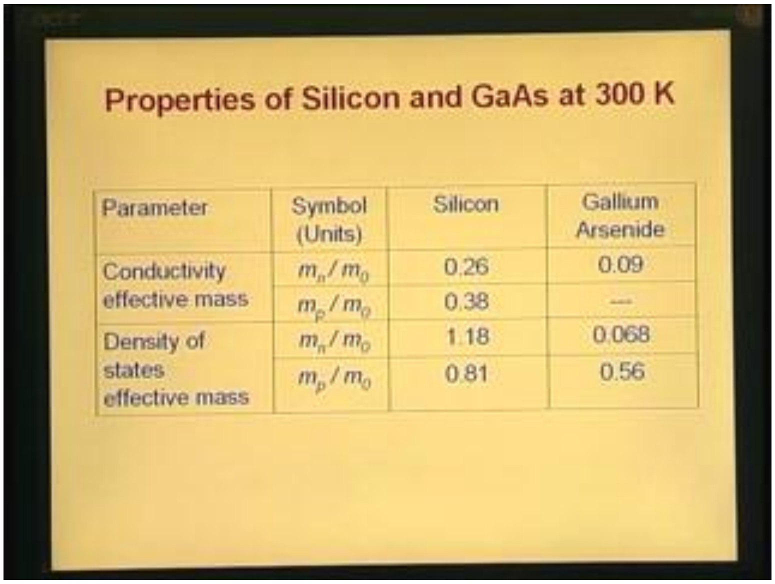

Properties of Silicon and GaAs at 300 K

Parameter	Symbol (Units)	Silicon	Gallium Arsenide
Conductivity effective mass	m_n / m_0	0.26	0.09
	m_p / m_0	0.38	---
Density of states effective mass	m_n / m_0	1.18	0.068
	m_p / m_0	0.81	0.56

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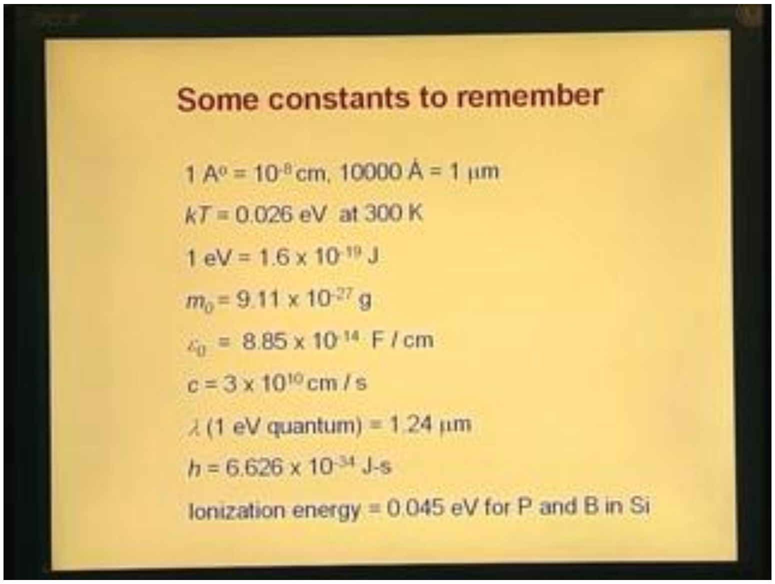

Some constants to remember

$1\ A^o = 10^{-8}$ cm, 10000 Å = 1 µm

$kT = 0.026$ eV at 300 K

1 eV = 1.6×10^{-19} J

$m_0 = 9.11 \times 10^{-27}$ g

$\epsilon_0 = 8.85 \times 10^{-14}$ F / cm

$c = 3 \times 10^{10}$ cm / s

λ (1 eV quantum) = 1.24 µm

$h = 6.626 \times 10^{-34}$ J-s

Ionization energy = 0.045 eV for P and B in Si

Let us also see some constants that we have used and which we must remember. How much is 1 Angstrom in terms of centimeters? How much is a micron in terms of Angstroms? Then what is KT at 300K? How much is 1 electron volt in terms of joules? What is the effective mass of an electron, the permittivity of free space, the velocity of light c the wave length lambda corresponding to 1 electron volt quantum that is 1.24 mm etc. Let us also see the value of the Plank’s constant and finally the ionization energy of shallow donors such as phosphorous and boron which are commonly used for doping silicon. The next topic for discussion would be Carrier Transport.