Solar Photovoltaics: Principles, Technologies and Materials

Prof. Ashish Garg
Department of Material Science & Engineering
Indian Institute of Technology, Kanpur

Lecture - 08
Semiconductor Basics-I

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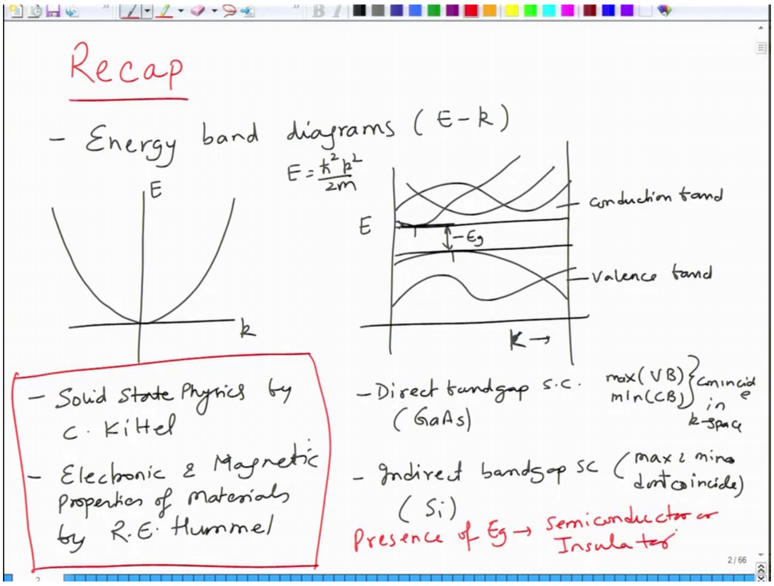

Recap

- Energy band diagrams (E-k)

$E = \frac{\hbar^2 k^2}{2m}$

- Solid State Physics by C. Kittel
- Electronic & Magnetic Properties of materials by R.E. Hummel

- Direct bandgap S.C. (GaAs) max(VB) min(CB) } coincide in k-space
- Indirect bandgap SC (Si) (max & mins don't coincide)

Presence of Eg → Semiconductor or Insulator

So, welcome to this lecture number-8 of Solar Photovoltaics course Principles, Technologies and Materials. So, we will first do a bit of recap of last lecture, and then move onto the contents of this lecture. So, in the last lecture, we learned about energy band diagrams, which are basically E-k diagram. E is the energy, and k is the wave vector.

So, these diagrams for a single electron the curve is like this. So, this is the parabolic curve, because E is equal to h cross square k square divided by 2 m. Then you plot it for a lattice, the situation changes for a lattice you have to plot this energy on all the reciprocal lattices space points. This is you can say capital K, which is the reciprocal lattice spaced points. And then you get a kind of many curves for different zones. So, you have curves like these, and you know you can have curves like these, and then we have this curve, this curve, and so on and so forth.

Now, here what is important is that you so basically material if these band, if these lines or curves are continuous across the space, and you can always jump from one state to another without having a discontinuity, then it is not a insulator or semi-conductor. However, if you have a gap like what you see here, across the k-space there is a gap, there are no energy states present within this state, then this represents what we call as a semiconductor or insulator with the energy gap E g.

And if this maxima and minima of conduction band and valence band this, the band on top is called as conduction band, on the band at the bottom is called as valence band. And if the maxima and minima of valence in conduction band coincide with each other, then it is called as a direct band gap semiconductor. So, maxima and minima maxima of valence band, and minima of conduction band, they coincide in k-space.

And if the maxima's and second one is indirect band gap semiconductor, if these two do not if maxima and minima do not coincide ok. So, for example, direct band gap semiconductor is like gallium arsenide is about direct band gap semiconductor, indirect band gap semiconductor is a but you like silicon, you can read the details from other books such as solid state physics by KiHel. This is a very nice physics book.

You can also read electronic and magnetic properties of materials by R.E Hummel. These are a few good books, which you can consider for building background on these topics. We have not covered them in full detail. So, as a result you need to get better exposure, if you want to learn more about these things.

So, key thing is if you have energy states which are continuous across the E-k space, and you can always find energy state any at any given energy level that means, it is a continue it is a conductor. But, if you have a forbidden energy gap, where you do not find energy state, then it is a semi-conductor insulator depending upon the magnitude of Eg ok. So, presence of Eg presence of a forbidden gap will mean it is a semi-conductor or insulator.

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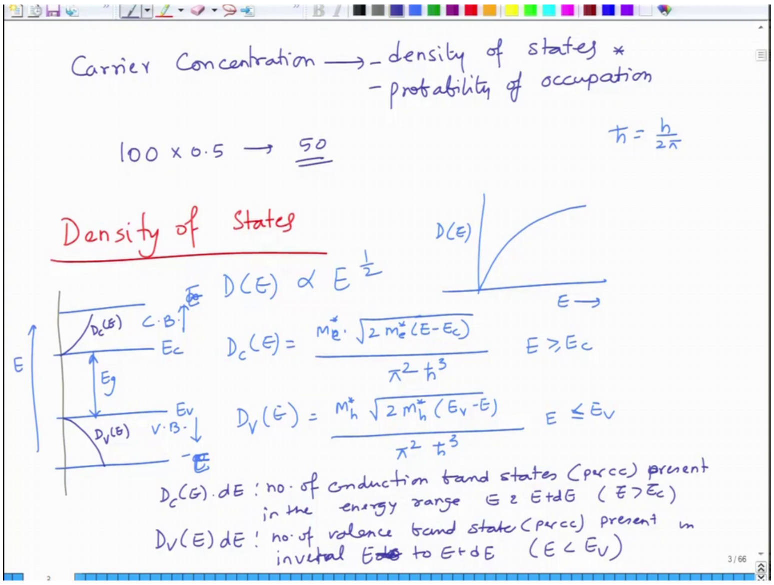

Carrier Concentration → - density of states *
- probability of occupation

$100 \times 0.5 \rightarrow \underline{\underline{50}}$

$\hbar = \frac{h}{2\pi}$

Density of States

$D(E) \propto E^{\frac{1}{2}}$

$D_c(E) = \frac{m_e^* \cdot \sqrt{2m_e^*(E-E_c)}}{\pi^2 \hbar^3}$ $E \geq E_c$

$D_v(E) = \frac{m_h^* \sqrt{2m_h^*(E_v-E)}}{\pi^2 \hbar^3}$ $E \leq E_v$

$D_c(E).dE$: no. of conduction band states (per cc) present in the energy range E & $E+dE$ $(E > E_c)$

$D_v(E)\,dE$: no. of valence band state (per cc) present in invetal E~~dE~~ to $E+dE$ $(E < E_v)$

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Now, having known this now next thing we want to know is what is the so in order to calculate that in order to work out the carrier concentration. So, carrier concentration, we require first thing is density of states, so which means how many energy states are available per unit volume let us say.

And then what is the probability of occupation, the product of these two will give you what is the number of carriers, because suppose you have 100 energy states ok, but probability of occupation is only 0.5 which means, there are 50 carriers which are there alright. So, that is what we need to do we need to find out first what is density of states and what is probability of occupation.

So, let us first look at what is density of states. So, density of states in a semiconductor, so density of states is given as we write it as D E, which is proportional to E to the power half ok. However, for a semiconductor we can write it in a little bit more precisely. So, for semiconductor the band structure is like this, you have conduction band, you have valence band. So, this is conduction band, this is valence band. And we have a forbidden energy gap ok.

So, if you plot just D as a function of E, and it will it is basically a parabolic sort of behavior basically my square root relationship D E goes as E in this fashion alright. Now, when you plot it now for a semiconductor, you have a conduction band, and you have a valence band, so you need to plot that density of states in both the bands.

So, density of states in a conduction band is given as D c E is given as we write it as M n star or we M e star rather into square root of 2 M e star into E minus E c, so this is E c. So, here it goes from E c to infinity, and here it goes from E v to minus infinity or some negative energy; so, basically E c to negative energies and E v, E c to positive energies, and E v to negative energies basically ok.

So, this goes from the equation is M e star into square root of 2 M e star into E minus E c divided by pi square and h cross q, where h cross is nothing but h divided by 2 pi h is the Planck's constant. And this is valid for energies E greater than or equal to E c. So, of course at E c this will become equal to 0. So, you have 0 density of states at E c, and higher density of states at higher energies. So, the energy so states increase in number as you go to higher energies and then D v E is analog of it.

So, this is basically m h star 2 square root of m h star into E v minus E divided by pi square into h cross cube this is for energies E less than or equal to E v ok. So, if that is the case, then you can plot these. So, if let us say this is E ok, then if I make a Y axis here, let us say this is the Y axis, then in this direction it goes as this, and in this direction it goes as this ok. So, these are you can say this is D v E and this is D c E. So, we have found the density of states.

Now, the next thing we want to find out is so this comes from the quantum mechanical analysis, and we have not gone into details of that, but basically we want to find out. So, basically you can say that D c E d E what would that be, that would be number of conduction band states per cc right, which are in the present in the range present in the energy range what is the energy range here, energy range will be E and E plus d E were in that energy range right.

Similarly, you can say D v E would be into d E would be number of valence band states per cc present in interval d E to sorry E to E plus d E ok. So, here we say that E is greater than E c. And here we say that E is less than E v all right. So, basically these are and they are numbers number of energy states per unit volume. So, we can say that numbers per centimetre square E per E v ok. So, we can you can do energy distribution in that fashion.

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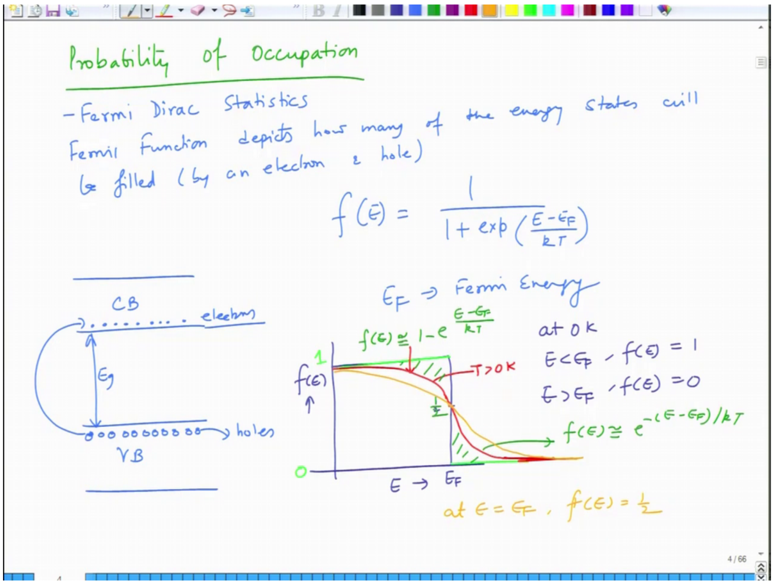

Probability of Occupation

- Fermi Dirac Statistics

Fermi Function depicts how many of the energy states will be filled (by an electron & hole)

$$f(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

$E_F \Rightarrow$ Fermi Energy

at 0 K

$E < E_F$, $f(E) = 1$

$E > E_F$, $f(E) = 0$

$f(E) \cong 1 - e^{\frac{E-E_F}{kT}}$

$f(E) \cong e^{-(E-E_F)/kT}$

at $E = E_F$, $f(E) = \frac{1}{2}$

Now, what we need to know next is: what is the probability of occupation. This comes from what we call as Fermi Dirac statistics Fermi ok. So, basically here Fe so we write a function here. This basically the Fermi function, we can say this basically is a function. Fermi function depicts how many of the energy states will be filled by an electron or in the case of a valence band we can call it as a hole.

What happens in semiconductors is basically, when you have so this is conduction band, this is valence band, you have energy gap Eg, these are electrons which are present. So, at 0 k you will not have any electron in the valence band, all of them are filled up to here, because they do not have energy to cross over. But, as you increase the energy, some of them will cross over. And they go to conduction band, and then leaving empty states behind, and these empty states behind are called as holes. So, these are electrons, and these are holes. Holes are also carriers, because they provide states for conduction of electrons.

So, f E f E the probability the probability with which an electron probability of occupation of energy state by an electron is given as 1 over 1 plus exponential of E minus E F divided by k T, where E F is a reference energy which is called as Fermi energy. And k is the Boltzmann constant, T is the temperature. So, if you plot this now here, so this function as a function of temperature if you plot it, for example at 0 k, when you plot f E as a function of E at 0 Kelvin for temperatures for energy less than E F.

When E is less than E F at 0 Kelvin, then this will be e to power minus infinity. So, this will be equal to 0. So, probability of occupation will be 1.

However, when E is greater than E F, then this will be equal to E to the power infinity basically right. And E to power E infinity is a very large number, which means it will become 0. So, at temperature at energy is greater than E F, so this is energy E F. So, at energy greater than E F, the probability of occupation is 0. So, this is 0 at energy less than E F, the probability of occupation is 1.

And for of course, the function is sort of undefined at E is equal to E F, because it becomes E exponential 0 by so you can say that every energy state up to E F is filled when so you can take this as sort of one. So, but the mean value will come at half. So, this function is this asymptotic around half. So, however so what this tells you is that at 0 Kelvin for E less than E F, the f E is equal to 1. For E greater than E F, f E is equal to 0, which means all the energy levels are filled up to Fermi level, and at 0 Kelvin, and above E F all the energy levels are empty.

And as you increase the temperature as you increase the temperature, this curve goes in this fashion. So, as you increase the temperature, the curve becomes like this. So, this is at T greater than 0 Kelvin. So, basically what happens is that this curve on this side follows the relation f E is equal to 1 minus so basically you can say approximately equal to 1 minus e to the power E minus E F divided by k T. And at these energy levels, it follows f E is approximately equal to e to power minus E minus E F divided by k T ok.

So, now this number becomes negative, so the Fermi energy at these so the probability at these energy levels reduces, and probability of these energy levels arises. So, basically what it means is that the state that carriers in this range have left, and they have gone here. Now, this is what, so basically essentially you can say that this function and the function changes around half the function changes around a value half. So, if you raise the temperature further, this will this curve will go in this fashion ok, so it is node it is node is that half. Now, if this is the case, then so at E is equal to E F, you can say the f E is half. So, at E is equal to E F, you can say f E is equal to half.

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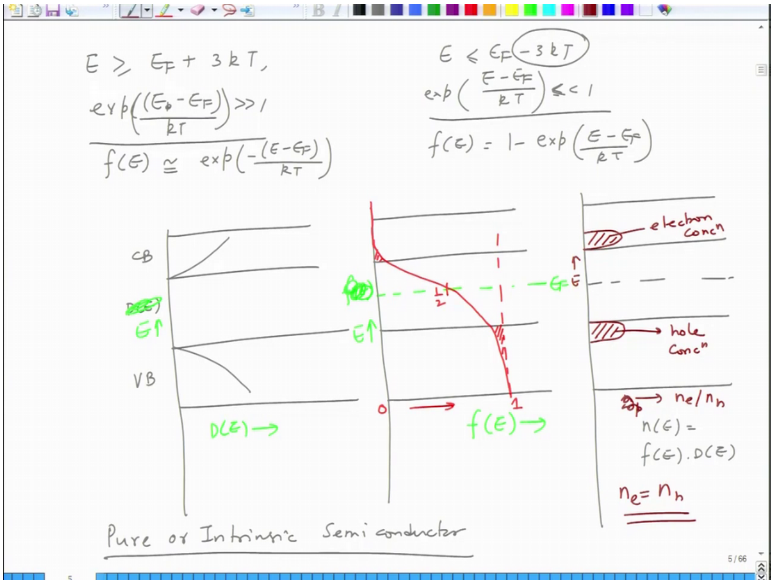

$E \geq E_F + 3kT,$

$\exp\left(\frac{(E_\phi - E_F)}{kT}\right) >> 1$

$f(E) \cong \exp\left(-\frac{(E - E_F)}{kT}\right)$

$E \leq E_F \boxed{-3kT}$

$\exp\left(\frac{E - E_F}{kT}\right) \leq < 1$

$f(E) = 1 - \exp\left(\frac{E - E_F}{kT}\right)$

$n(E) = f(E) \cdot D(E)$

$n_e = n_h$

Pure or Intrinsic Semiconductor

And then if another observation that you make is when E is greater than equal to f E F plus 3 k T, then you can write exponential of E minus E F divided by k T is much larger than 1. And f E is generally given as exponential of minus of E minus E F divided by k T. And for E less than or equal to E F minus 3 k T, this exponential of E minus E F divided by k T, this becomes less than one. As a result you can write f E as 1 minus exponential of E minus E F divided by k T, and this is what we have written there right.

So, if you recall that is what we have written here, this is the behaviour. So, this energy is so at these temperature, these temperatures of the temperature which depict the energy, which is E less than E F minus 3 k T's with this 3 k T sort of a number beyond which you start having significant changes in the curve on the both sides. And you can approximate this function, because this value becomes significantly higher as at these magnitudes.

So, now if you want to find out the carrier concentration now, the carrier concentration is for a given semiconductor, we say that this is our conduction band, this is our valence band that de goes as this so this is D E ok. So, this is C B, and this is V B ok. And our for a intrinsic semiconductor, so this is for a pure semiconductor pure or intrinsic semiconductor.

For a pure or intrinsic semiconductor, the Fermi level right lies right at the middle. So, this is the position of Fermi energy this is f E ok. So, you can you can see that so this is a so the if you if you if you now plot the, let us say this is the value of f E, and this is the value of sorry this hang on this is E, and this is D E in this direction. So, y axis is energy ok. This is f E. So, if I now plot f E, this is one here. So, the f E will go as something like at a finite temperature, it will go in this fashion right.

So, this value is approximately this is 1, and this is 0 on the y axis ok. So, basically this region, and this region they are equal in area its it is symmetric around, this value that is half. Now, what is n E? So, if you want to now plot n E, this is conduction band, this is valence band, this is Fermi energy, so n E is now equal to f E into D E. So, when you plot these, you get these lobes which show you. So, this is energy, and this is n r p, so electron hole concentration. So, this is basically the hole concentration, and this is electron concentration.

And in an intrinsic semiconductor n is equal to you can say a n e or n h instead of n and p. So, we can say n e is equal to n h, because the Fermi function is symmetric around the Fermi energy. And Fermi energy lies right in the middle of the band gap ok, this changes when you make a p or n type semiconductor. So, we would do that when we come back again to this.

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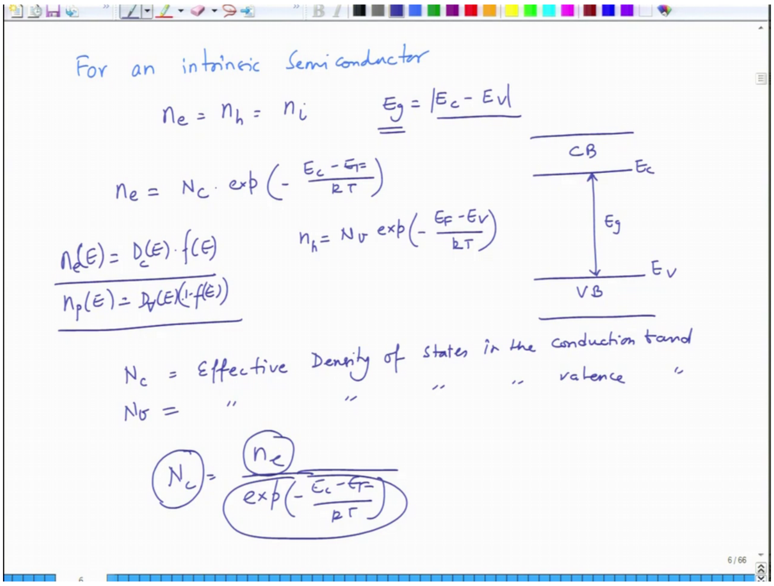
For an intrinsic Semiconductor

$n_e = n_h = n_i$ $\quad \underline{\underline{E_g}} = \underline{|E_c - E_v|}$

$n_e = N_c \cdot \exp\left(-\frac{E_c - E_F}{kT}\right)$

$n_h = N_v \exp\left(-\frac{E_F - E_v}{kT}\right)$

$\underline{n_e(E) = D_c(E) \cdot f(E)}$

$\underline{n_p(E) = D_v(E)(1 - f(E))}$

N_c = Effective Density of states in the conduction band

N_v = " " " " valence "

$$\boxed{N_c} = \frac{\boxed{n_e}}{\boxed{\exp\left(-\frac{E_c - E_F}{kT}\right)}}$$

So, now what we do is that we go to essentially so we say that for an intrinsic semiconductor. For an intrinsic semiconductor, n e is equal to n h, this is taken as n i ok. And e and E g is equal to taken as the difference of E c minus E v ok, we can take mod of this basically. So, if this is your conduction band edge, this is your valence band edge, this is valence band, this is conduction band, this is E c, this is E v; then whatever reference you take the E g is the difference between E c and E v.

So, this is your band gap. And this is given as this n e is equal to n h for operant for operant intrinsic semiconductor, this n e is given as N c into exponential of so we can calculate using quantum mechanical calculations same density multiplied density of a states basically, you will calculate n e E as a function of D E into f E. So, this is what will give you the electron concentration.

Similarly, you can calculate the hole concentration n p E as D, so this is D c E, this is D v E into one minus f E, because we are looking at the other side that is 1 minus f E. So, if you do that, then we get n e is equal to N c into exponential of minus E c minus E f divided by k T. And we get n h as N v into exponential of minus of E F minus E v divided by k T, where N c is essentially effective density of a states density of states in the conduction band, and N v is equal to effective density of a states in valence band.

And you can see this from this expression, if you look at this N c is equal to nothing but n e divided by is some exponential function this is E c minus E f divided by k T. So, basically this is the probability function ok, you can take this upstairs you can take this up and it becomes exponential E c minus E f divided by k T. So, this is the probability function one over exponential whatever and this is nothing and this becomes the concentration. So, essentially the concentration divided by probability function is nothing but the defective density of a states, so that is why this N c is taken as effective density of a states in conduction band, and N v is taken as effective density of a states in the valence band.

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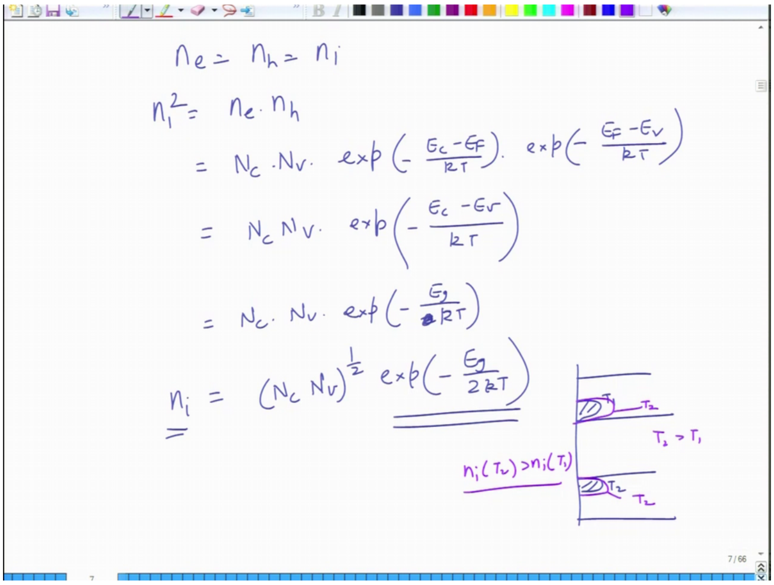

$$n_e = n_h = n_i$$

$$n_i^2 = n_e \cdot n_h$$

$$= N_c \cdot N_v \cdot \exp\left(-\frac{E_c - E_F}{kT}\right) \cdot \exp\left(-\frac{E_F - E_v}{kT}\right)$$

$$= N_c N_v \cdot \exp\left(-\frac{E_c - E_v}{kT}\right)$$

$$= N_c \cdot N_v \cdot \exp\left(-\frac{E_g}{\cancel{2}kT}\right)$$

$$\underline{n_i} = \underline{\underline{(N_c N_v)^{\frac{1}{2}} \exp\left(-\frac{E_g}{2kT}\right)}}$$

$$T_2 > T_1$$

$$\underline{n_i(T_2) > n_i(T_1)}$$

Now, so we say that n e is equal to n h is equal to n i. So, we can also say that n i square is equal to n e into n h, which means it will be N c into N v into exponential of minus E c minus E f divided by k T into exponential of minus of E F minus E v divided by k T. And if you put them together, it becomes N c N v into exponential of so this becomes exponential minus of E c minus minus E v divided by k T. And E c minus E v is equal to E g. So, this becomes equal to N c into N v exponential of minus E g divided by 2 k T. So, n i is N c N v to the power half exponential of sorry two will not be here, now the two will come ok.

So, basically you can see that intrinsic carrier concentration is an exponential function of temperature and band gap. So, as the band gap decreases, the n i will increase for a given temperature. And as the temperature increases, the n i will increase. So, the lobes that you saw there, they will so this is at let us say temperature T 1. So, this lobe will be let us say at temperature T 1. If the temperature t 2 is higher, then this will become bigger. So, this will be at T 2, but they will remain equal in size. So, T 2 is greater than T 1. So, you can say that n i at T 2 will be higher than n i at T 1 ok. So, this is what will happen for intrinsic semiconductor.

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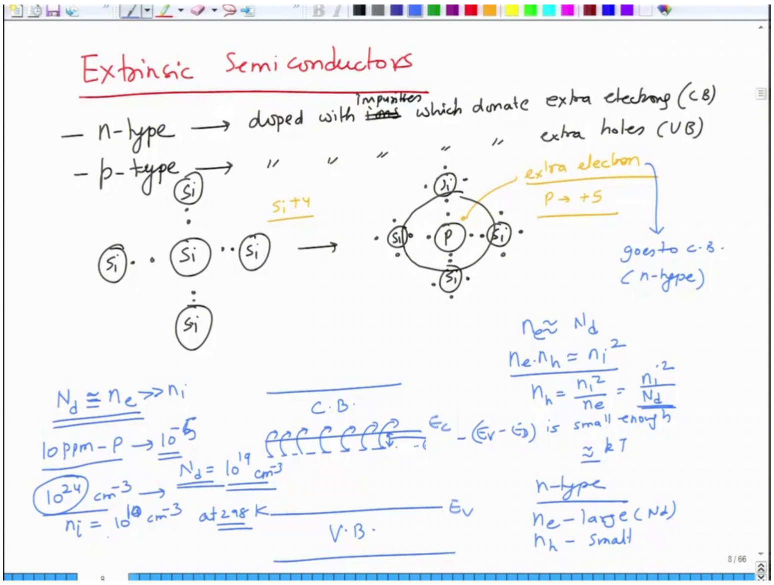

Extrinsic Semiconductors

– n-type → doped with impurities ~~ions~~ which donate extra electrons (CB)

– p-type → " " " " " extra holes (VB)

$n_e \approx N_d$

$n_e \cdot n_h = n_i^2$

$n_h = \frac{n_i^2}{n_e} = \frac{n_i^2}{N_d}$

$N_d \cong n_e >> n_i$

10 ppm – P → 10^{-5}

10^{24} cm^{-3} → $N_d = 10^{19}$ cm^{-3}

$n_i = 10^{10}$ cm^{-3} at 298 K

$(E_c - E_D)$ is small enough $\approx kT$

n-type

n_e – large (N_d)

n_h – small

Now, intrinsic semiconductor is has lower conductivity and to make devices generally we dope the semiconductor with a dopant. And these doped semiconductors are called as extrinsic semiconductors. And these extrinsic semiconductors have two types; one is of n-type, and second is of p-type. n-type is the one, where you have doped with ions which donate or doped with impurities which are also called as dopants, which donate extra electrons. And these are doped with impurities which donate extra holes. So, these electrons will go in conduction band, and these holes will go in valence band.

So, generally for as far as some for something like silicon, if you have silicon, silicon has 4 of these electrons. And so you have multiple silicon atoms, and these silicon atoms are coordinated in such a manner, so that each silicon is coordinated by 4 silicon atoms. So, you have one silicon atom here, another silicon atom here, another silicon atom here, another silicon atom. This is a simplistic design, although the tetrahedral coordination is not like this So, this is silicon, this is silicon, this is silicon, this is silicon. So, it has fourfold coordination from each silicon so that you have covalent bonding and you have a s p 3 hybridization.

Now when you replace this silicon with phosphorus let us say so this is silicon, this is silicon, this is silicon, this is silicon, these have four extra. So, this electron, this electron, this electron, this electron, they are all they all are shared, but phosphorus brings an extra electron because phosphorus is plus 5 impurity, silicon is plus 4. So, this extra electron is the one which is because of phosphorus atoms. And this extra electron goes to conduction band and it makes with a n-type semiconductor. So, this extra electron is in goes to conduction band leading to a n-type behaviour.

So, what it leads to in terms of band representation is, we have silicon whose valence band is here, we have conduction band here. This is E v, this is E c. When you dope it with phosphorus; phosphorus creates an energy level which is called as donor energy level E D. And phosphorous for each phosphorous atom if you are able to ionize all of them, then these electrons cause to conduction band provided this donor ionization energy the difference between E v minus E D is a small enough of the order of k T, so which is generally the case and phosphorus will ionize and give rise to give all its electrons extra electrons away to conduction band.

So, in this case the number of carriers basically N d becomes equal to almost equal to n e. So, if you for example, dope with 10 ppm phosphorous, 10 ppm will become 10 to the power minus 6 parts per million right, so one part per million which means 10 to the power minus 6 for every part. So, basically if in a million you have one 10, 10 of phosphorus atoms, so based on the concentration of phosphorus atoms, you will have the carrier concentration.

So, in a given lattice, if the number of atoms is 10 to the power of 24 per centimetre cube, and electron instant an intrinsic carrier concentration is about 10 to the power let us say I do not know 14 per centimetre cube at a given temperature let us say at about 298 Kelvin. So, let me get the exact numbers. So, n i is about 10 to power 10 for silicon. For silicon it is about 10 to power 10 per centimetre cube at 298 Kelvin ok. Now, this number can increase to if you if you dope phosphorus with 10 to power minus 10 ppm, then ppm is 10 to the power minus 5 ok.

If you have 10 to the power 24 atoms per centimetre cube, this becomes so N d will become 10 to the power 19 per centimetre cube. So, you can see that N d is much higher than n i. And if all the N ds are able to contribute to electrons which means N d is almost equal to n e, and this is much more larger than n i. So, for a n-type semiconductor n is equal to N d. However, because of mass conservation n e into n h is always equal to n i square. When we increases, when the electron concentration suddenly increases, then recombination also decreases increases.

So, when the recombination increases, then of course the hole concentration also tends to decrease in the valence band. So, as a result this relation has to be always followed. So, for a n-type semiconductor this n h is equal to n i square divided by n e or it is equal to n i square divided by N d. So, for an n-type semiconductor some in summary you have n e is large almost equal to N d, and n h is small as against the intrinsic semiconductor.

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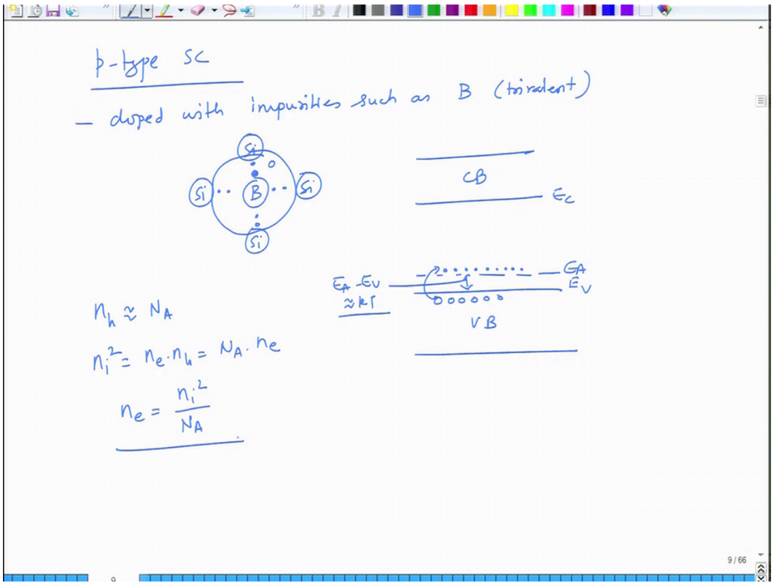

p-type SC

– doped with impurities such as B (trivalent)

$n_h \approx N_A$

$n_i^2 = n_e \cdot n_h = N_A \cdot n_e$

$n_e = \frac{n_i^2}{N_A}$

If you take for an of p-type semiconductor, p-type semiconductors are doped with impurities such as a boron which are trivalent impurities ok, phosphorous - pentavalent, these are trivalents. So, when these are trivalents, then if you make the same configuration you have these silicon atoms, silicon, silicon, and then you have boron. So, boron comes with only 3 electrons; silicon has 4 electrons to share. So, this boron atom now it basically you can say now where does it need to bring an electron from, it does not it cannot bring an electron it short of electrons right. So, this creates a hole in the valence band.

So, in the in the in the so this will be basically you can say 3 electrons are shared and this is basically you can say there is a hole there. So, basically what happens is that in the band diagram perspective, this is conduction band, this is valence band this is E c, this is E v, the p doping will causes energy will create energy level E, E A accepted energy level which will take the electron from here to here to fulfil its configuration for the bonding and leaving a hole. So, it will take a electron some from somewhere here, leaving a hole in the lattice somewhere ok.

So, to make this fourfold to make this covalent bonding, it will create a hole somewhere else. So, this is the hole that is created. It is taken electron away from some silicon ok. So, essentially it will create holes because these electrons will go here to the so this is acceptor energy level. So, this is again this energy level as E E A minus E v is of the order of k T and that is how p-type doping will work. For a p-type doping in the analogous manner, this n h is equal to N A as a result n i square is equal to n e into n h, we can write this is equal to N A into n e. So, n e is equal to n i square divided by N A.

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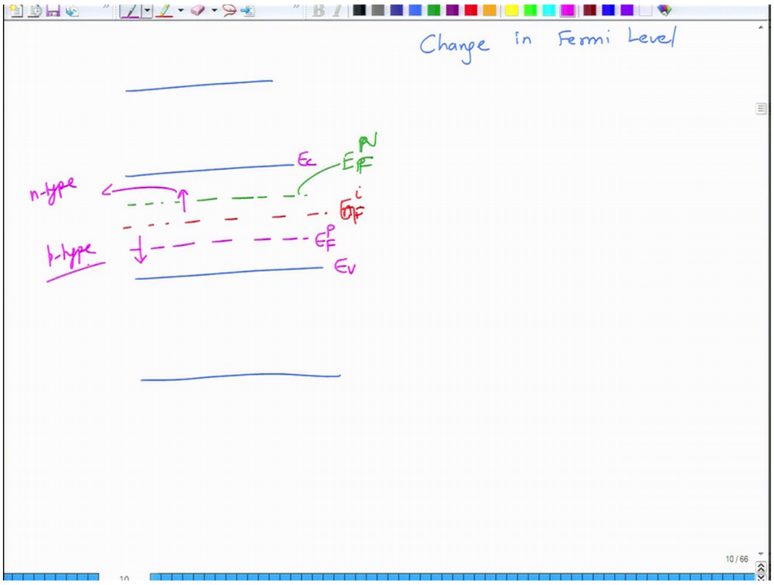

Change in Fermi Level

Another thing that happens in these semiconductors p and n-type is the Fermi level tends to shift. So, change in Fermi level. So, the Fermi level for a intrinsic semiconductor is here; this is E F i. For a p and n-type semiconductor; so, this is E F p sorry E F E F N, and this will be E F p. The Fermi level tends to ship shift up for a n-type towards the conduction band, this is E c, this is E v, and Fermi level tends to shift down for a p-type semiconductor ok. Now, this has repercussion in terms of what we do earlier the energy band diagram.

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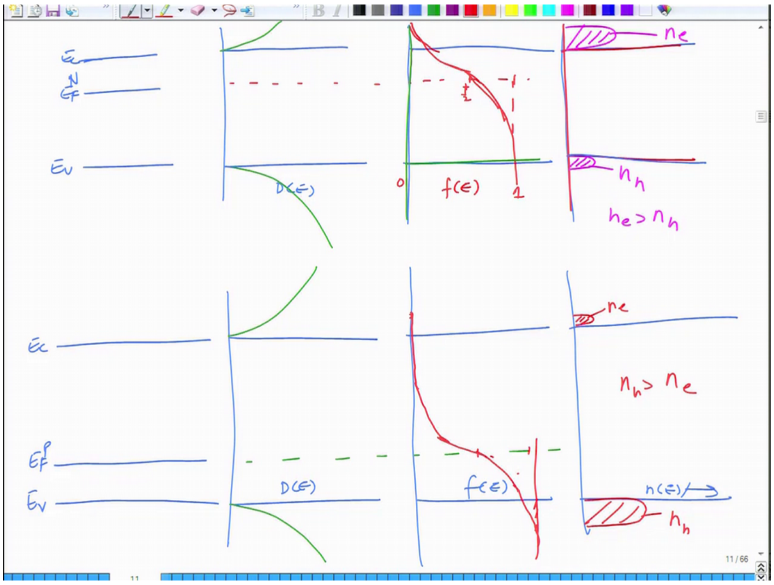

Now, you can also you can do the similar energy band diagram picture that we did earlier for a we drew that. So, now if I draw this in this fashion, let us say this is E c, this is E v, and for a n-type semiconductor this is E F somewhere on top. This is E c; this is E v. If you plot density of states D E, D E will go in this fashion on this side like this on this side in this fashion. If you now plot the Fermi energy, the Fermi energy would be, the Fermi energy will go. So, this is so this is from energy.

Now, we want to plot the probability of occupation. Probability of occupation will go as if this is 0, this is 1, this is half, it will be symmetric around this point. So, essentially you can say it will go in this fashion. So, this is 1, this is 0, this is f E. So, the center point has shifted to top now. So now, if you want to plot the electron concentration, so electron concentration I can use the same color for lines, these are the blue lines here, again the blue lines here.

Now, if I want to plot the electron concentration since there is more area here this gives a bigger lobe and this gives a smaller lobe much smaller lobe. So, this is n e and this is n h. And you can see that n e is much larger than n h. And this is because the Fermi function has shifted. So, it is not drawn very nicely, but it is sort of little just like this ok. For a p-type, on the other hand, you can draw it in a different manner for a p-type if this is E c, this is E v, the Fermi level is now here E F p, this is E F n.

Again I want to make the same things. So, here I want to plot D E, I want to plot f E and I want to plot n e or p e right n e or n h your basically carrier concentration. So, if I want to plot for this, this will remain same the same behaviour. In this case, now the Fermi level is come here. So, Fermi level has come here. Now, you can see that the Fermi level will sorry if this is let us say 0, this is 0, this is half this is 1 ok. It will go something like this in this fashion ok. So, it will have more area. So, this is one. So, it will have more area here, but it will have no area on the other side. If it is in fact, I am not drawn it very well, but it would be something like this. So, there will be some area on this side.

Let me see if I can draw it a little better [music] ok. Basically you can say this curve will go something like this and it will go something like this on the other side touching 0 here. And now if you plot electron and hole concentration, the hole concentration will be bigger, and the electron concentration will be smaller. So, this is n h and this is n e. And n h will be much larger than n e. So, this is the difference between the p and n-type semiconductors in terms of their concentration. Now, so this semiconductor last thing I would come to what is n c and n v. So, expression for n c and n v we will see in the next class and, but we will just see how the semiconductor behavior changes as a function of.

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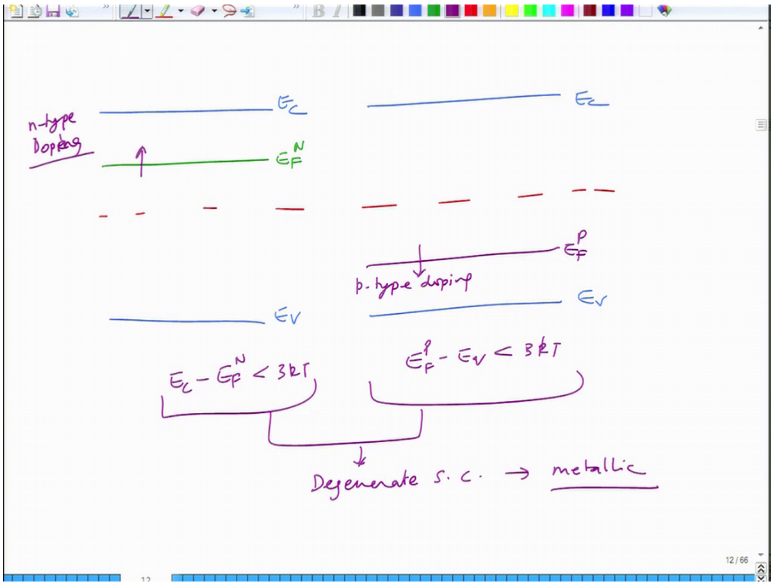

So, what happens is that when so this is your n-type, this is your p-type. This is E v; this is E c. For a n-type semiconductor, if this is the intrinsic level, for a n-type semiconductor, this Fermi level is somewhere here; and for p-type the Fermi level is somewhere here. This Fermi level keeps shifting to upside as you dope more and more. So, with doping, it increases F. So, n-type doping right and this will shift towards E v with more p-type doping. And if you keep doping them, they will keep shifting up or down. So, when the difference between E c and E F n is less than 3 k T or when the difference between E F p and E v is less than 3 k T, then they tend to become what we call as degenerate semiconductors, they become degenerate semiconductors or more like a metallic behaviour, they become more and more conducting.

So, you will see in certain circumstances n-type is heavily doped, p-type as a heavy dope which means their Fermi levels are very close to conduction band or valence band. So, this is what we are done today we have looked at the carrier concentration and the reason behind having higher and lower concentrations and the expressions. And, this on this we will further dwell in the next class to look at little bit more analytical treatment of a carrier concentration and Fermi energy in the next lecture ok.

Thank you.