Solar Photovoltaics :
Fundamental Technology and Applications

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Lecture - 08
Charge Carrier Dynamics in Semiconductors

Welcome everyone. In our last lecture, we have learned that why first like some materials are metals some of them are semiconductor and some of them are insulator. And just in the previous lecture, we have learned that the different classes of semiconductor based on the doping, based on the band gap, on the positions of the periodic table.

So we have now a fairly good idea about the semiconductor and very often we are talking about the charge carriers. But the question is how can we calculate this charge carriers. Because this charge carriers plays a very important role in photovoltaic devices. So today we will calculate the number of charge carriers in a semiconductor. And from there, we will find out the charge carrier concentrations in a pure semiconductor and in extrinsic semiconductor.

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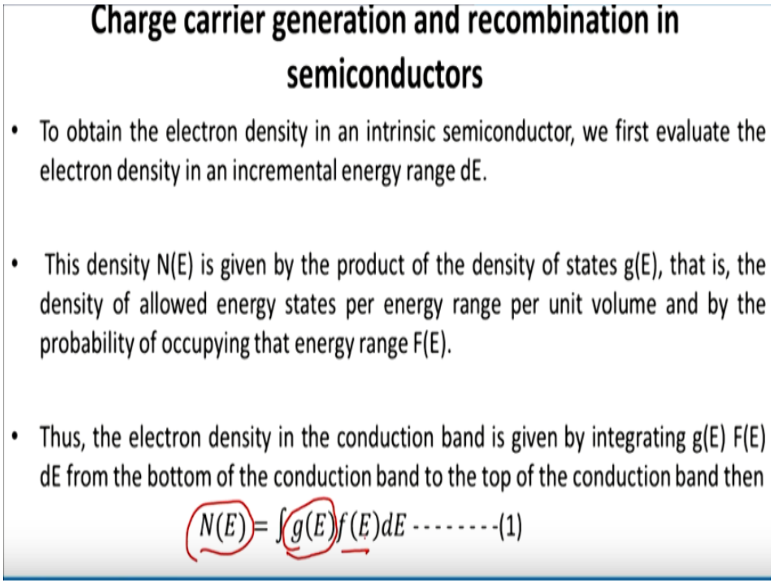

Charge carrier generation and recombination in semiconductors

- To obtain the electron density in an intrinsic semiconductor, we first evaluate the electron density in an incremental energy range dE.
- This density N(E) is given by the product of the density of states g(E), that is, the density of allowed energy states per energy range per unit volume and by the probability of occupying that energy range F(E).
- Thus, the electron density in the conduction band is given by integrating g(E) F(E) dE from the bottom of the conduction band to the top of the conduction band then

$$N(E) = \int g(E) f(E) dE \text{ --------(1)}$$

So charge carrier generation and recombination in semiconductors. To obtain the electron density in an intrinsic semiconductor, we first evaluate the electron density in an incremental energy range dE. This density N(E) is given by the product of density of states g(E) that is the density of allowed energy states per unit energy range, per unit volume and by the probability of occupancy that the energy level that is called the Fermi distribution function F(E).

So if N(E) is the total number of the electron, so how can I get this N(E) by multiplying the density of states which I have written as g(E). You can as well right as dE or rho E. Different textbook use different version of this, but here we are using g(E) times the Fermi-Dirac probability functions. So it is somewhat like that. Like let us say like you know in a classroom, there are total of 50 students.

Or for example there are a total of 60 students are there and there are 30 benches in that classroom and each benches can occupy maximum of two students. So if I say or if someone say that in that class there are 60 students is there and there is a class happening on Monday from let us say 10 to 11 o'clock, and in the classroom A there are 30 benches are there. So then how many students are there present at this class?

So we cannot say unambiguously there are 60 students in the class. So basically, it depends upon what is the probability of turnover of the students in the class and how many chairs or how many benches are available to them to sit down. So if I know the number of available benches, so let us say there are 30 benches in the class. So the number of available bench is 30.

And if I know that the class is very popular or the subject is very interesting then the all the students turn out to the class, then the probability of turning out all the students is maximum that is hundred percent, and each of the bench can occupy two students, then we can say that the maximum number of students in the class today is 60.

So it depends upon first the number of available bench, here the number of density of states and it depends upon the probability of coming the students in the class, here the Fermi-Dirac distribution functions. And just like if you multiply the number of available benches in the class times the probability of the student coming that is equal to the total number of students.

In this case of semiconductor the density of states, which is giving you the number of available energy states per unit energy range per unit volume times the probability of occupancy that is Fermi-Dirac distribution function f(E), when I multiply these two things together, that gives the number of students. Here the number of electrons N(E).

Thus the electron density in the conduction band is given by integrating g(E) and f(E) over an energy interval dE from the bottom of the conduction band to the top of the conduction band. So I can write N(E) is equal to integration g(E) times f(E) into dE. Now previously we have calculated what is the expression for g(E).

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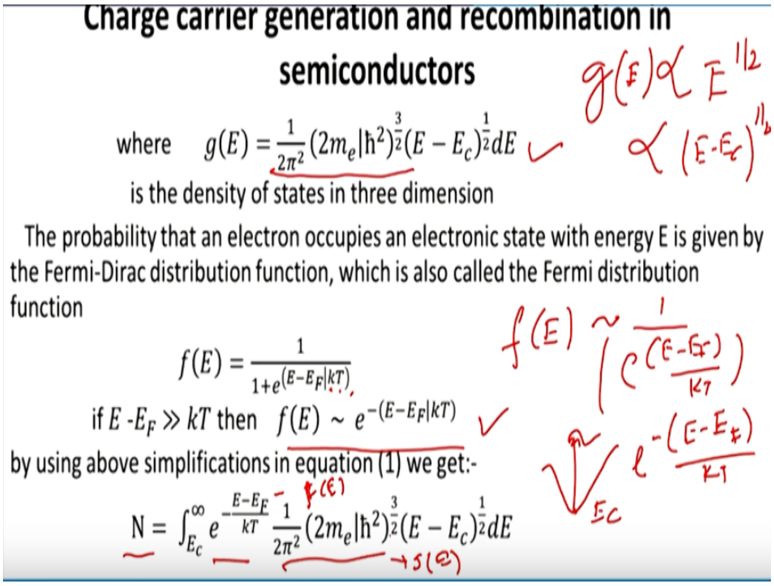

Charge carrier generation and recombination in semiconductors

where $g(E) = \underbrace{\frac{1}{2\pi^2}(2m_e|\hbar^2)^{\frac{3}{2}}}(E - E_c)^{\frac{1}{2}}dE$ ✓

is the density of states in three dimension

$g(E) \propto E^{1/2}$

$\propto (E-E_c)^{1/2}$

The probability that an electron occupies an electronic state with energy E is given by the Fermi-Dirac distribution function, which is also called the Fermi distribution function

$$f(E) = \frac{1}{1+e^{(E-E_F|kT)}}$$

$f(E) \sim \frac{1}{\left(e^{\frac{(E-E_F)}{kT}}\right)}$

if $E - E_F \gg kT$ then $f(E) \sim e^{-(E-E_F|kT)}$ ✓

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

E_c

by using above simplifications in equation (1) we get:-

$$N = \int_{E_c}^{\infty} \overset{f(E)}{e^{-\frac{E-E_F}{kT}}} \underbrace{\frac{1}{2\pi^2}(2m_e|\hbar^2)^{\frac{3}{2}}}_{\to g(E)}(E - E_c)^{\frac{1}{2}}dE$$

And we know that for a three dimensional case, this density of g(E) is proportional to E the power half for a three dimensional material. For a two dimensional material, it was constant E to the power zero and for a one dimensional material it was E to the power minus half. And for a zero dimensional material it was a delta function. But we are considering real semiconductor which is a three dimensional material.

So density of states is proportional to E to the power half. And the proportionality constant was this. One over 2 pi square 2m e by h bar square to the power 3 by 2. And if we consider E c is the bottom of the conduction band, so then we can modify this equation E as proportional to E minus E c to the power whole half. And that is what we have written here with the constraint in the beginning.

So g(E) is one over 2 pi square 2m e by h bar square whole 3 by 2 E minus E c to the power half dE. That is that density of states in three dimension. Now what is the probability of occupancy? The probability that an electron occupies an electron state with energy E is given by the Fermi-Dirac distribution function, which is also called the Fermi distribution function. And what is that Fermi distribution function?

F(E) is equal to 1 divided by 1 plus e to the power E minus E F by kT where k is the Boltzmann constant T is the temperature and F is the Fermi energy. Now if we consider that E – E F is very very greater than kT so then what will happen? this terms e to the power E – E F by kT that will be higher than 1 or much greater than 1. So we can approximate f(E) in this limiting situations as 1 by e to the power E minus E F by kT or we can write this if it goes up e to the power minus E by E F divided by kT.

That is what we have written here f(E) is e to the power –E – E F by kT. So now our next job is to multiply this terms and this terms and integration over the all available energy range. So N the total number of electrons is integration E c to the infinitive. Why is it to infinity. Remember, if this is my conduction band, so this is the E c the bottom of the conduction band.

And for the sake of argument, we are integrating it towards the infinitive. So we are going upward directions. And my first factor is e to the power minus E minus E F by kT, that is the Fermi function and then the density of states. This is f(E) and this is your g(E) times dE. Now we need to integrate this equation. Looks like probably like you know very nasty integration to do it.

But we will see that is not so difficult to do it. So some of the terms are constant. Let us look at the previous equation once again. So you have one over 2 pi square 2m e by h bar square to the power 3 by 2 that is all are constant. So we can take all these terms outside the integrant. That is what we are doing here.

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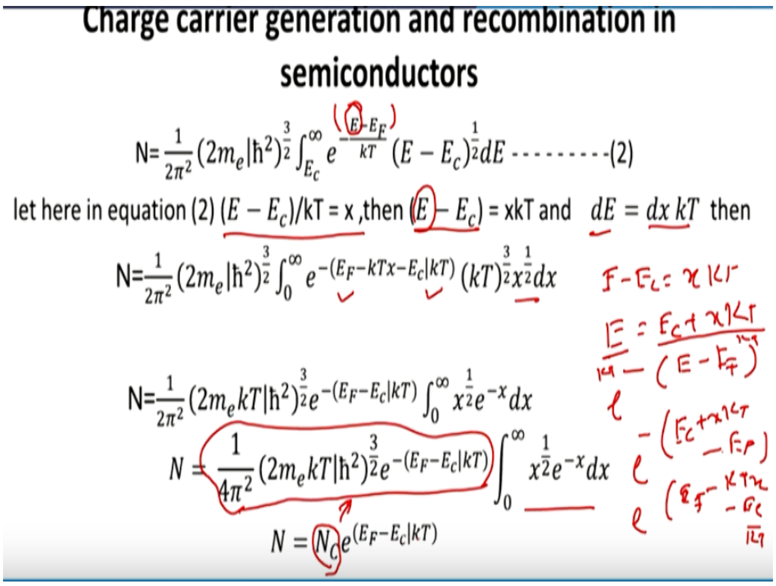

Charge carrier generation and recombination in semiconductors

$$N=\frac{1}{2\pi^2}(2m_e|\hbar^2)^{\frac{3}{2}}\int_{E_c}^{\infty}e^{-\frac{(E-E_F)}{kT}}(E-E_c)^{\frac{1}{2}}dE \text{ - - - - - - - - -(2)}$$

let here in equation (2) $(E-E_c)/\text{kT} = \text{x}$,then $(E-E_c) = \text{xkT}$ and $dE = dx\,kT$ then

$$N=\frac{1}{2\pi^2}(2m_e|\hbar^2)^{\frac{3}{2}}\int_{0}^{\infty}e^{-(E_F-kTx-E_c|kT)}(kT)^{\frac{3}{2}}x^{\frac{1}{2}}dx$$

$$N=\frac{1}{2\pi^2}(2m_ekT|\hbar^2)^{\frac{3}{2}}e^{-(E_F-E_c|kT)}\int_{0}^{\infty}x^{\frac{1}{2}}e^{-x}dx$$

$$N=\frac{1}{4\pi^2}(2m_ekT|\hbar^2)^{\frac{3}{2}}e^{-(E_F-E_c|kT)}\int_{0}^{\infty}x^{\frac{1}{2}}e^{-x}dx$$

$$N=N_ce^{(E_F-E_c|kT)}$$

$F - E_c = x\,kT$

$E = \frac{E_c + xkT}{kT}$

$-(E-E_F)$

$e^{-(E_c+xkT-E_F)}$

$e^{(E_F-kTx-E_c)/kT}$

We are taking one over 2 pi square 2m e by h bar square 3 by 2 outside the integrant and integrating from integration E c to infinity, e to the power E – E F by kT into e to the power E – E c to the power half dE. Now we will do some simple approximation. So let us consider E – E c by kT = x. That is a favorite tool we do when we do the integration. So then E – E c will be xkT. The kT at the bottom will go up.

And then if I integrate it, E c is a constant that is a value, the bottom of the conduction band. So it will be zero if I differentiate it, so only giving dE that is dx into kT because kT is a constant. So then you can write N is equal to 1 over 2 pi square 2m e by h bar square 3 by 2 integration. Now since I am changing the integration limit, I can also write integration E c to infinity as zero to infinity.

E to the power minus, now I have considered E - E c by kT = x or E – E c = xkT. So then this terms here E has to be replaced from the expression here, right? Because now your E – E c = xkT. Or your E = E c + xkT, right? So that is what we have written here. So E - E F instead of E we have written E c + xkT okay? So the bracketed expression, if you write this bracketed expression.

So this is E to the power minus what was there E – E F so that we can write e to the power E c plus xkT minus E F, right? Or this minus, minus plus. So we can also write this as e to the power E F – kTx – E c by kT. Because we have one more terms kT here at the bottom. So basically when you do e is equal to E c + xkT then we have to divide it by kT.

So you have to also divide it by kT and that is what we are doing it here. So again you look that this term is a constant, this term is a constant. So if this comes out, so N is equal to 1 over 2 pi square 2m e by kT h bar square 3 by 2 e to the power minus E F – E c by kT integration 0 to infinity. Now x square x to the power half e to the power – x dx. X to the power half e to the power minus x dx looks like a standard integral, right?

So N is 1 over 4 pi square 2m e kT by h square 3 by 2 e to the power E F minus E c by kT. All these terms see it looks like a constant. And then integration zero to infinity raised to the power half e to the power minus x dx. Life becomes more simple. Integrating these terms is easier. Now instead of all these constant all these things, if I call all this constant term by N c so this is N c then I can write N is equal to N c e to the power E F minus E c by kT.

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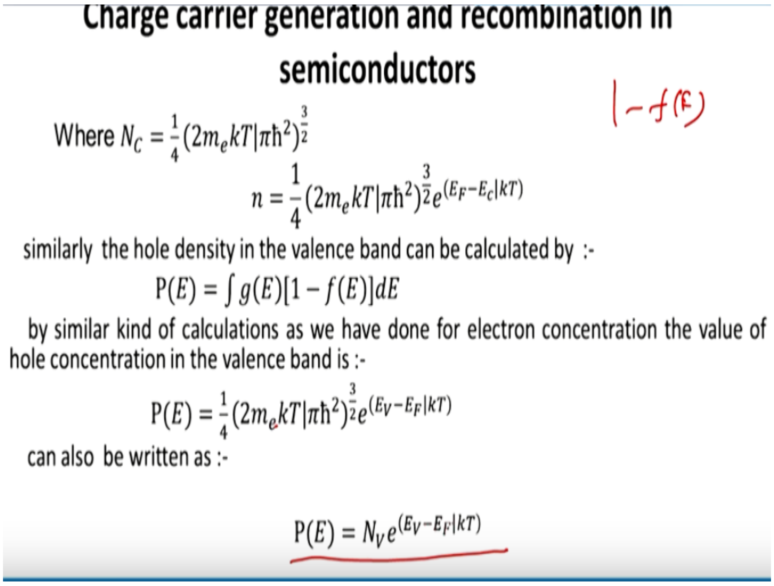

Charge carrier generation and recombination in semiconductors

$1-f(E)$

Where $N_C = \frac{1}{4}(2m_e kT|\pi\hbar^2)^{\frac{3}{2}}$

$$n = \frac{1}{4}(2m_e kT|\pi\hbar^2)^{\frac{3}{2}} e^{(E_F - E_c|kT)}$$

similarly the hole density in the valence band can be calculated by :-

$$P(E) = \int g(E)[1 - f(E)]dE$$

by similar kind of calculations as we have done for electron concentration the value of hole concentration in the valence band is :-

$$P(E) = \frac{1}{4}(2m_e kT|\pi\hbar^2)^{\frac{3}{2}} e^{(E_V - E_F|kT)}$$

can also be written as :-

$$\underline{P(E) = N_V e^{(E_V - E_F|kT)}}$$

Where N c is 1 by 4 2m e kT pi h bar square 3 by 2 and n is 1 by 4 2m e kT by pi h bar square 3 by 2 e to the power E F minus E c by kT. Now this was the electron density. Similarly we can find the hole density. Now the total probability density is 1 so the probability of occupancy of an energy level by an electron and hole is one. So if the electron probability density or the occupancy of the probability of an electron at an energy E is f (E).

Then the probability of occupancy of a hole of occupying the same energy level will be 1 – f (E). So for calculating the hole density in the valence band one can calculate P (E) is equal to integration g (E) 1 – f (E) dE because that gives the probability of occupancy of a hole times the density of states. And by approaching or by following the same treatment as you have done in the case of the electron, we can also find out the concentration of the hole in the valence band.

And whereas P (E) is 1 by 4 2m e by kT pi h bar square to the power 3 by 2 e to the power E V minus E F by kT. It can also be written as P (E) is equal to N V e to the power E v minus E F by kT. So you look that in the last slide, we have written N is equal to N c e to the power E F minus E c by kT and how it was coming from?

We have considered these as a constant and this was a standard integral which was like gamma function and from the gamma function value we have substituted this standard integral value here and doing by simple calculations and simplifications we got the value of the electron density like this is N is equal N c e to the power E F minus E c by kT.

And we got the hole density in the following slide P (E) is equal to N v e to the power E v minus E F by kT. So now we have the electron concentration in the conduction band and we have the hole concentration in the valence band.

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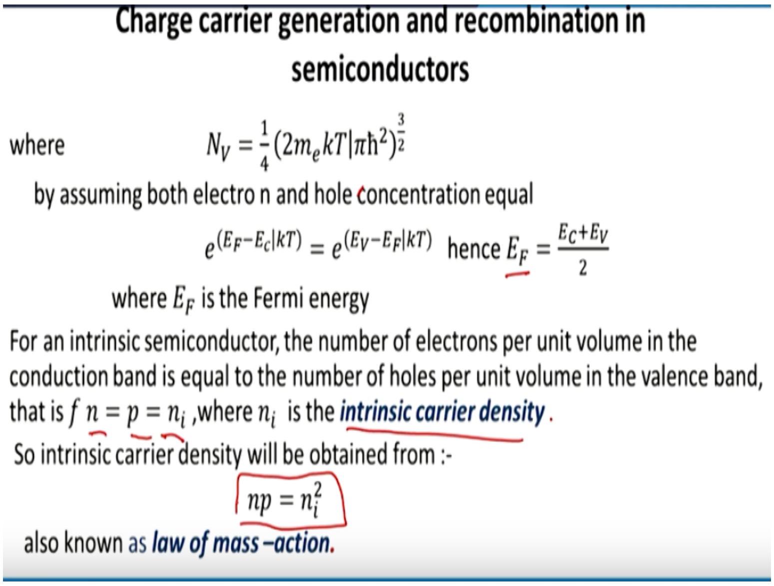

Charge carrier generation and recombination in semiconductors

where $N_V = \frac{1}{4}(2m_e kT|\pi\hbar^2)^{\frac{3}{2}}$

by assuming both electro n and hole concentration equal

$e^{(E_F - E_c|kT)} = e^{(E_V - E_F|kT)}$ hence $E_F = \frac{E_C+E_V}{2}$

where E_F is the Fermi energy

For an intrinsic semiconductor, the number of electrons per unit volume in the conduction band is equal to the number of holes per unit volume in the valence band, that is f $n = p = n_i$,where n_i is the **intrinsic carrier density**.

So intrinsic carrier density will be obtained from :-

$\boxed{np = n_i^2}$

also known as ***law of mass –action.***

Whereas the constant N V was 1 by 4 2m e kT by pi h bar square to the power 3 by 2. So by assuming both electron and hole concentrations are equal, we can write that e to the power E F minus E c by kT is equal to e to the power E V minus E F by kT because at equilibrium the number of electrons should be equal to a number of holes. Hence, you can write the Fermi energy E F as E c plus E V by 2.

So for an intrinsic semiconductor where you have the same number of electrons as the number of holes the Fermi energy lies in between conduction band and valence band. For an intrinsic semiconductor the number of electrons per unit volume in the conduction band is equal to the number of holes per unit volume in the valence band.

That is the n = p and you can also write that the number of electrons or number of holes in an intrinsic semiconductor as n subscript i, where i stands for intrinsic semiconductor. So n i actually intrinsic carrier density. So intrinsic carrier density n i that is equal to n = p. So since there are both electron and both hole so we can write that n i times n i or n i square is equal to n into p.

So n i square is equal to np or np = n i square. That is called the law of mass action, very important law in the case of semiconductor.

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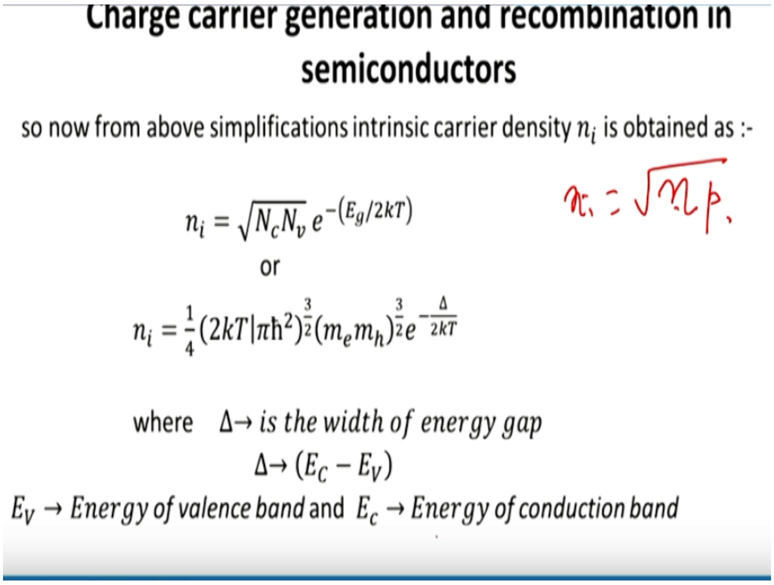

Charge carrier generation and recombination in semiconductors

so now from above simplifications intrinsic carrier density n_i is obtained as :-

$$n_i = \sqrt{N_c N_v}\, e^{-(E_g/2kT)}$$

$n_i = \sqrt{np}$.

or

$$n_i = \frac{1}{4}(2kT|\pi\hbar^2)^{\frac{3}{2}}(m_e m_h)^{\frac{3}{2}} e^{-\frac{\Delta}{2kT}}$$

where $\Delta \rightarrow$ *is the width of energy gap*

$\Delta \rightarrow (E_C - E_V)$

$E_V \rightarrow$ *Energy of valence band* and $E_c \rightarrow$ *Energy of conduction band*

So from the above simplification for the intrinsic carrier density n i, it is obtained as n i square is equal to np or n i is equal to the it will be square root of electron density times hole density, okay. So if I write n i so we have already calculated what is n what is p so that is square root of N c into N v e to the power minus E g by 2kT where n i is equal to 1 by 4 2kT by pi h bar square to the power 3 by 2 m e m h to the power whole 3 by 2 e to the power minus delta by 2kT.

Where delta is the width of the energy gap and delta is equal to E c minus E v where E v is the energy of the valence band and E c is the energy of the conduction band. Once we are able to calculate what is the intrinsic carrier concentration, then let us move to how does the current density and mobility change in an intrinsic carrier.

Because for constructing a solar cell device, both the current density and the mobility of the material plays an important role. When a small electric field is applied to a semiconductor sample, each electron will experience a force. And they will be accelerated along the field during the time between the collisions. So you apply an electric field to the electron, so they will be accelerated.

In which direction they will be accelerated? They will be accelerated along the field direction. Therefore, an additional velocity component will be superimposed on the thermal motion of the electrons. So the thermal motion of the electron has a particular velocity, its random. Now due to the external perturbation which is the electric field here, there is an induced velocity.

So that will be superimposed with the velocity due to the thermal motion. This additional component is called the drift velocity. So the drift velocity so that depends upon the external electric field. If I increase the electric field, drift velocity will increase. If I decrease the drift velocity, drift velocity will decrease.

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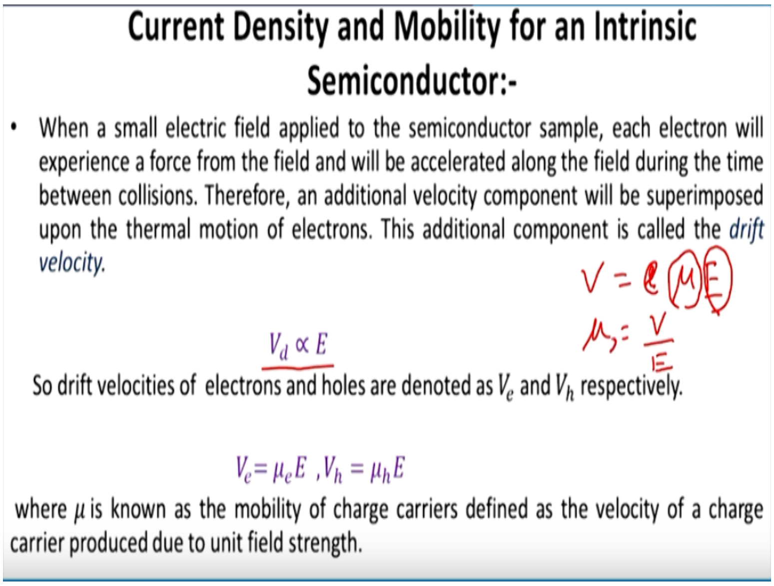

Current Density and Mobility for an Intrinsic Semiconductor:-

- When a small electric field applied to the semiconductor sample, each electron will experience a force from the field and will be accelerated along the field during the time between collisions. Therefore, an additional velocity component will be superimposed upon the thermal motion of electrons. This additional component is called the *drift velocity.*

$V = e\,\boxed{\mu}\,\boxed{E}$

$\mu, = \frac{V}{E}$

$$\underline{V_d \propto E}$$

So drift velocities of electrons and holes are denoted as V_e and V_h respectively.

$$V_e = \mu_e E \;, V_h = \mu_h E$$

where μ is known as the mobility of charge carriers defined as the velocity of a charge carrier produced due to unit field strength.

So another way we can write that drift velocity is proportional to the electric field E, right? So drift velocity of the electrons and hole if you denote as V e and V h respectively then V e can be written as mu times e and V h can be written as mu h times E where e is the electric field and mu is a quantity which is called the mobility of the charge carriers, which is from this equation can be defined as the velocity of the charge carrier per unit electric field.

You look at this genetic expression of both of this electron and hole case. So we can write that V e is equal to which will be mu times electric field. So mu is the mobility and e is the electric field. So what is mu? Mu is equal to V divide by E. So the definition of the mobility is the velocity per unit electric field. Now for the case of electron you put a subscript e, for the case of hole you put a subscript h.

So that is what we have written here. V e is equal to mu e times E; V h is equal to uh times E. Now in the case of semiconductor we know both type of charge carrier exist; electrons and hole. So the conduction happens due to the both type of charge carriers. So that is why the semiconductor had two different kinds of mobility, mobility due to the electron mobility due to the hole or electron mobility and hole mobility. There are experimental methods to measure this mobility also.

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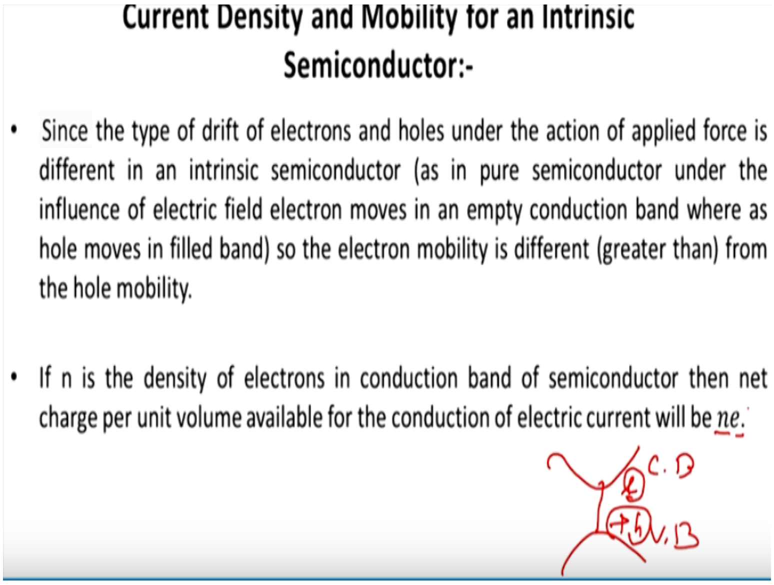

Current Density and Mobility for an Intrinsic Semiconductor:-

- Since the type of drift of electrons and holes under the action of applied force is different in an intrinsic semiconductor (as in pure semiconductor under the influence of electric field electron moves in an empty conduction band where as hole moves in filled band) so the electron mobility is different (greater than) from the hole mobility.

- If n is the density of electrons in conduction band of semiconductor then net charge per unit volume available for the conduction of electric current will be *ne*.

Since the type of drift of electrons and holes under the action of the electric field or the applied field is different in an intrinsic semiconductor or in a pure semiconductor, under the influence of electric field, moves in an empty conduction band where this holes moves in a field band so the electron mobility is different or greater than from the hole mobility.

So what we are saying here that for a pure semiconductor or an intrinsic semiconductor we know that under the influence of an electric field the electron moves in a empty conduction band. So if this is your valence band and this is your conduction band, this is your valence band and this is your conduction band, right? So the electron moves from the valence band to the conduction band.

And there is a vacancy is being created here. That is hole and that is electron and this is hole. Now the conduction band is usually empty and valence band is hole. So electron is moving in an rather emptier band whereas the holes is moving in a filled band. So that is why the mobility of the electron is usually higher than the mobility of the hole.

If n is the density of electrons in a conduction band of semiconductor, then net charge per unit volume available for conduction of the electric current will be n times e; n is the density of electrons and the charge carrier or the elementary charge carrier is e. So if I multiply n times e, so that will give you the amount of charge per unit volume which is available for conduction in the unit volume.

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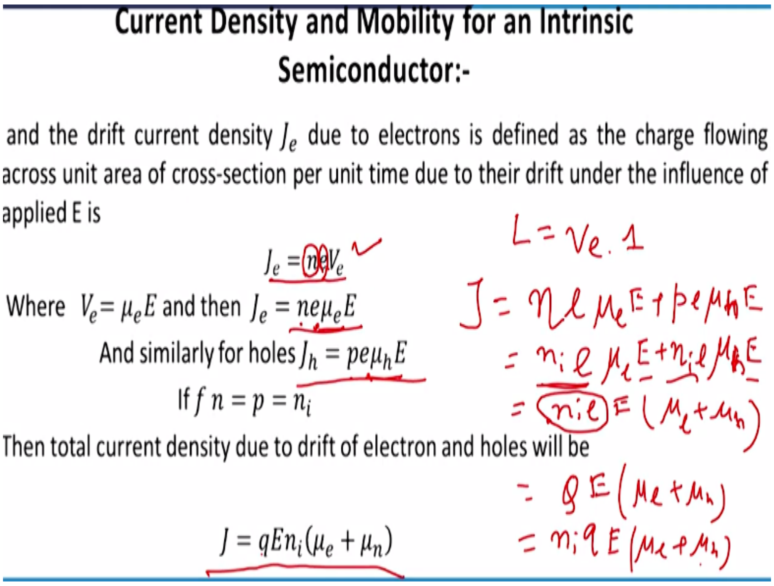

Current Density and Mobility for an Intrinsic Semiconductor:-

and the drift current density J_e due to electrons is defined as the charge flowing across unit area of cross-section per unit time due to their drift under the influence of applied E is

$$J_e = neV_e$$

Where $V_e = \mu_e E$ and then $J_e = ne\mu_e E$

And similarly for holes $J_h = pe\mu_h E$

Iff $n = p = n_i$

Then total current density due to drift of electron and holes will be

$$J = qEn_i(\mu_e + \mu_n)$$

$$L = V_e . 1$$

$$J = ne\mu_e E + pe\mu_h E$$
$$= n_i e \mu_e E + n_i e \mu_h E$$
$$= n_i e E(\mu_e + \mu_h)$$
$$= qE(\mu_e + \mu_h)$$
$$= n_i q E(\mu_e + \mu_h)$$

So the drift velocity J e, which is due to the electron that is defined as the charge flowing across the unit area of cross section per unit time, due to their drift under the influence of applied E can be defined as J e is equal to ne times V e. So remember ne here n is the electron concentration e is the charge carrier. So that gives you the charge carriers or the total amount of charge per unit volume.

When I multiply it by the drift velocity so that in an unit times so drift velocity if it is V e if the time is unit like one second, so that gives me the distance L. So if I multiply that drift velocity with the charged amount per unit volume, that gives me the drift current density J e. Where V e was mu times e and if we substitute these values of V e in this particular expression, I will get the drift current density J e is equal to ne instead of V e I put mu e into E.

So it will be ne mu e E. Similarly for hole we can write the drift current due to the hole is pe mu h e. Look, both of the equation are same. Both of the current density is proportional to the electric field because now electron the drift velocity is due to the application of the electric field and due to the electric field, there is a mobility of the electron.

In the case of electron it is the electron mobility, in the case of hole it is the hole mobility. But either electron or hole both of them the charge is the same, only difference is the sign. One of them is negative another is positive. So if you take the absolute values of the magnitude, so I can write the magnitude of the charge here also e and here also e.

And in the case of the electron you put n the charge carrier concentrations here you put the p that the hole carrier concentrations. But in intrinsic case, we know n is equal to p is equal to n i. Both of them are equal to the intrinsic carrier concentration. So the total current density due to the drift of the electrons and holes will be j is equal to qEn i.

So if I take this quantity n and p is equal to n i so I can write that total current density is due to the electrons and hole ne mu e E plus p e mu H E, right? But you can write that n and p in an intrinsic carrier as n i. So basically this is n i e mu e E plus n i e mu H E, right? Now what is the n i times e? That is the intrinsic carrier concentration times the charge. So that is the total charge.

So if I write the total charge both of this expression has n i times e. So I can take n i times e as a common. I can take also the electric field as common. So what is left inside the bracket is mu e times mu H. This is the capital H. You can also write it as a small h. Let us change it for the consistency to the small h where h stands for hole; n i times e that is Q.

So Q or you can also write small q whatever you prefer QE mu e plus mu h. That is what we have written here. The total current density due to the drift is QE n i into mu e plus mu h. So either you can put a small qEn i or you can replace this q into n i as a big Q or some people also prefer to write it as a n i and then instead of E you write it as a q so that it represents both the electron and hole charge E mu e times mu h, clear?

Now once we have a concept of what is a P-type semiconductor and what is an N-type semiconductor and we have learned that semiconductor has two different types of charge carriers, namely electrons and hole. Now we can go forward and construct a p-n junction devices. When light shines on solar cell photo voltage is generated.

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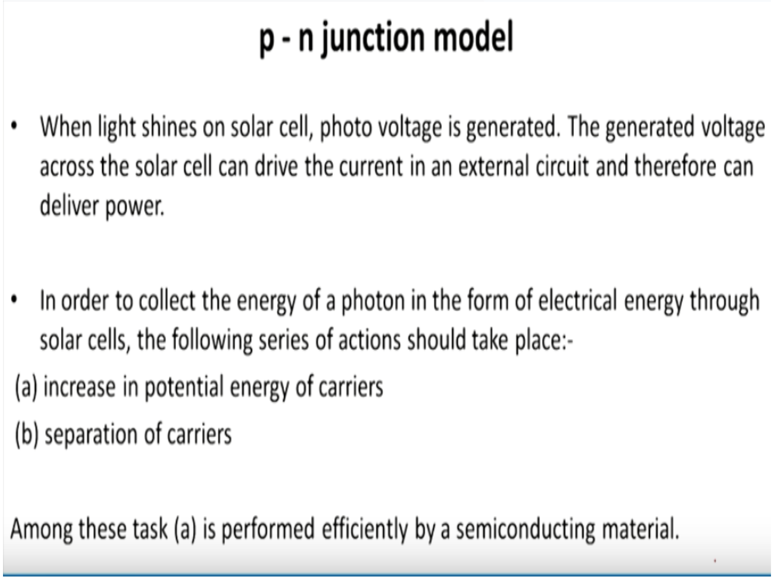

p - n junction model

- When light shines on solar cell, photo voltage is generated. The generated voltage across the solar cell can drive the current in an external circuit and therefore can deliver power.

- In order to collect the energy of a photon in the form of electrical energy through solar cells, the following series of actions should take place:-

(a) increase in potential energy of carriers

(b) separation of carriers

Among these task (a) is performed efficiently by a semiconducting material.

The generated voltage across the solar cell can drive the current in an external circuit and therefore can deliver power. In order to collect the energy of a proton in the power of electrical energy through solar cells the following series of action should take place. First increase in potential energy of carriers, separation of carriers. Among this task a is preferentially efficient by a semiconducting material.

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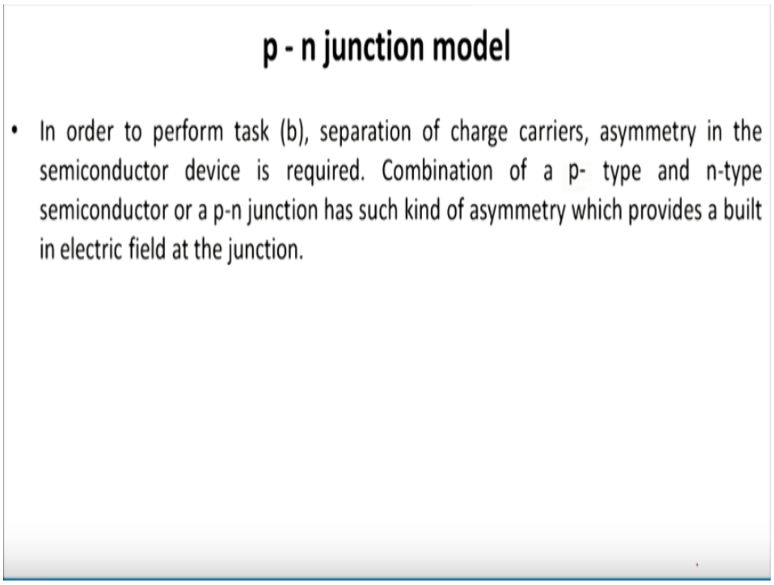

p - n junction model

- In order to perform task (b), separation of charge carriers, asymmetry in the semiconductor device is required. Combination of a p- type and n-type semiconductor or a p-n junction has such kind of asymmetry which provides a built in electric field at the junction.

In order to perform the task b separation of charge carriers asymmetry in the semiconductor device is required. Combination of a p-type and n-type semiconductor or a p-n junction has such kind of asymmetry which provides a built in electric field at the junction. So to construct a solar cell devices, there are two properties has to be satisfied. What are those two properties? Let us once look back.

One of them increase in the potential energy of the carriers and that a semiconductor can do efficiently. And the second thing is that separation of charge carrier. Because unlike in the case of conductor where the electron was the dominant charge carrier, here I have two different type of charge carrier. One is electron another is hole. Now they can be bound.

And you remember we have defined them earlier as an exciton and the binding energy which bound them together they are called excitonic binding energy. Now they can be bind. Now this unless until this bound charge carrier separates and available for the pre conduction, I do not get a current in the external circuit. So it is very important to separate this charge carriers.

Now how can you separate this charge carrier? We can separate the charge carriers only if we introduce asymmetry in the devices. And the only way we can introduce asymmetry in the devices by constructing a p-n junction devices. And that is why we make a p-n junction device and if I simplify a solar cells basically this is nothing but a p-n junction device with a particular geometry. So introduction to a p-n junction device in equilibrium condition.

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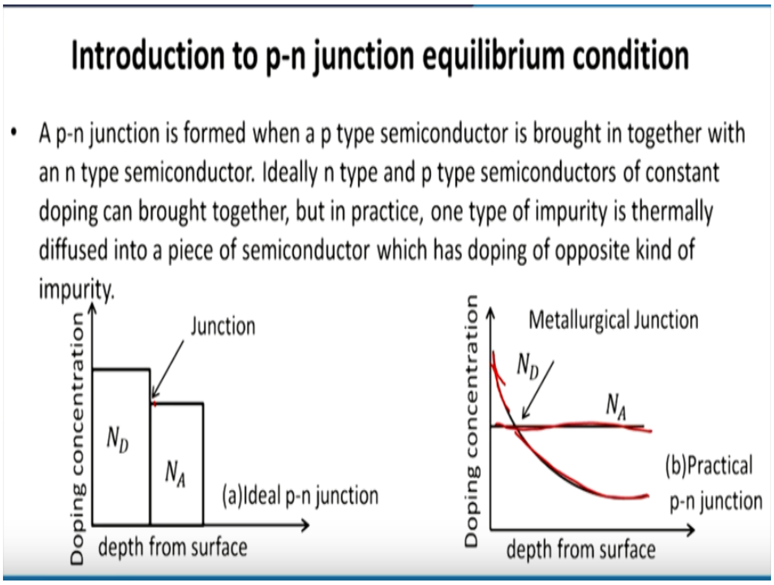

Introduction to p-n junction equilibrium condition

- A p-n junction is formed when a p type semiconductor is brought in together with an n type semiconductor. Ideally n type and p type semiconductors of constant doping can brought together, but in practice, one type of impurity is thermally diffused into a piece of semiconductor which has doping of opposite kind of impurity.

A p-n junction is formed when a p type semiconductor is brought in together with an n type semiconductor. Ideally n type and p type semiconductors of constant doping can be brought together, but in practice one type of impurity is thermally diffused into a piece of semiconductor which has doping of opposite kind of impurity. So let us say I have a p type semiconductor and I have a n type semiconductor in hand.

And the question is, if I just fuse them together should I make a p-n junction diode? The answer is no. What it is told here, although ideally we expect that n type and p type semiconductor the constant doping can be brought together in reality what is done that one type of impurity is thermally diffused in an already existing impurity.

We start with p type impurity or n type impurity and then diffuse the p type impurity in that material. Because later on we will learn that the construction of the band gap or the depletion region at the p-n junction plays a very important role. That is why we simply cannot stitch a p type and n type semiconductor to make a p-n junction diode.

So here like you know we are plotting the doping of the semiconductor on the y axis and the depth from the surfaces x axis. So basically, if we start with an N A which is an acceptor impurity, then you put the donor impurity and you form a metallurgical junction at the boundary. That is the ideal p-n junction, which is like a step function.

But in a real p-n junction the doping of the concentration and depth from the surface is not as straightforward like that. Here you have an acceptor and you have a donor but there is a changing or the gradient here. The metallurgical junction is here. This is the n type. This is the acceptor impurity, this is the donor impurity and that is not as rectangular nicely shaped function like that.

Because you grow that semiconductor and very often it is very controlled. Although it is nowadays because of the improvement of the technology it is precisely possible to grow the semiconductor very nicely. And you can control even the width of this p type and n type layer.

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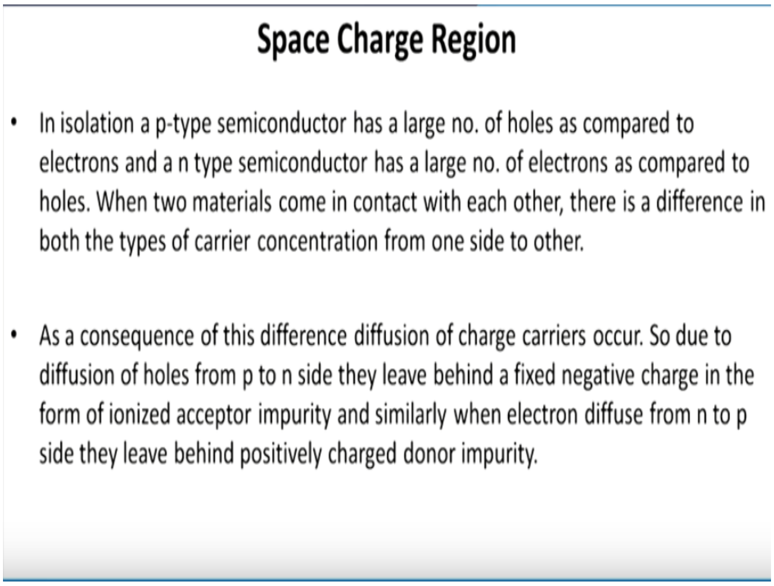

Space Charge Region

- In isolation a p-type semiconductor has a large no. of holes as compared to electrons and a n type semiconductor has a large no. of electrons as compared to holes. When two materials come in contact with each other, there is a difference in both the types of carrier concentration from one side to other.
- As a consequence of this difference diffusion of charge carriers occur. So due to diffusion of holes from p to n side they leave behind a fixed negative charge in the form of ionized acceptor impurity and similarly when electron diffuse from n to p side they leave behind positively charged donor impurity.

So what is a space charge region? It is, in an isolation a p type semiconductor has a large number of holes as compared to electrons. An n type semiconductor has large number of electrons as compared to holes. When two materials come in contact with each other there is a difference in the both type of carrier concentration from one side to another. As a consequence of this difference, diffusion of the charge carriers occur.

So due to the diffusion of holes from the p to n side they have behind a fixed negative charge in the form of ionized accepted impurity. And similarly, when electron diffuse from n to p side they leave behind positively charged donor impurity. But how it happens, how it exactly form and how it can influence the energy momentum diagram or the potential energy diagram that we will learn in the next class. Thank you.