Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 12
Carrier Transport, Generation and Recombination

So, we begin with lecture 12 of the Solar Photovoltaics course.

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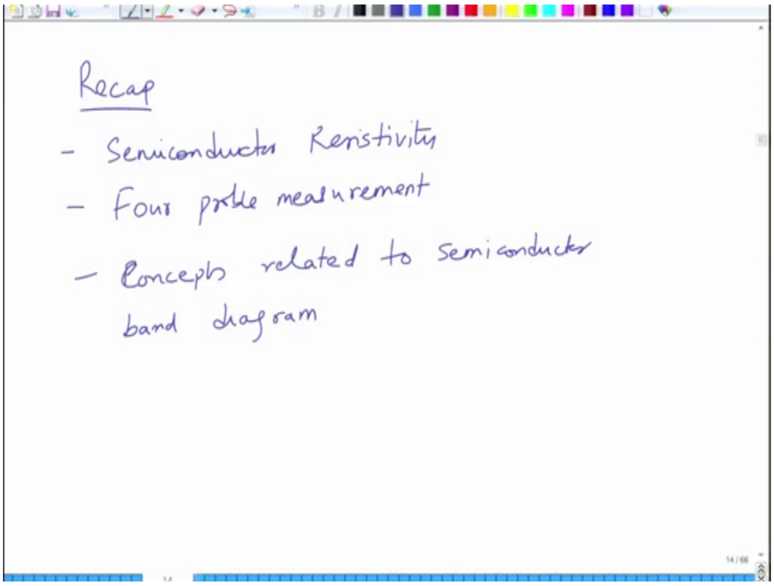

Recap

- Semiconductor Resistivity
- Four probe measurement
- Concepts related to Semiconductor band diagram

So, just brief recap. So, in the last lecture we learnt about semiconductor resistivity, four probe measurement to measure the resistivity and then concepts related to semiconductor band diagram ok. So, basically what is the direction in which energy changes, in what sense the sign of energy is important, how does the band bending occur and how do you plot electric field potential and charge density in a semiconductor. This will come useful when you learn about the junctions. Now, next topic that we take up is the carrier diffusion.

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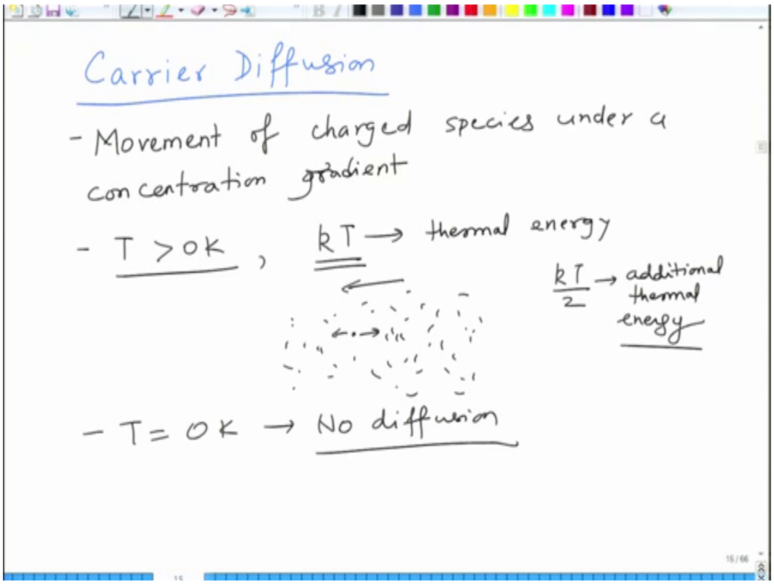

Carrier Diffusion

- Movement of charged species under a concentration gradient
- $T > 0K$, $kT \rightarrow$ thermal energy

$\frac{kT}{2} \rightarrow$ additional thermal energy

- $T = 0K \rightarrow$ No diffusion

So far we seen carrier drift which is the movement or charges under the electric field. This is movement of charges under a concentration gradient by enlarge, do you get ok. So, diffusion is basically physical process in which carriers move from one place to another and as a result they need to have thermal energy.

So, at T greater than 0 Kelvin every carrier has some thermal energy, so, thermal energy is k T, is a thermal energy. And if you take the, if have species like these and generally you will not have such a ordered straight so, let me just draw. So, we have situation like this, where let us say on this side you have more carriers than on this side ok. So, carriers would move like to move in this direction overall, but since diffusion is a random process the they could be overall carrier can move in this direction as well as in this direction right, but there is a net flux in one direction because of concentration gradient.

Now, since the any species at a given location has probability of moving either right or left. So, we say that the thermal energy which is available to species to move in the one direction is k T by 2. So, its k T by 2 is the additional thermal energy which drives the diffusion process ok. So, of course, at T greater at, T is equal to 0 k you have no diffusion because you have no thermal energy available it is only at energies higher than 0 Kelvin, you have thermal diffusion taking place.

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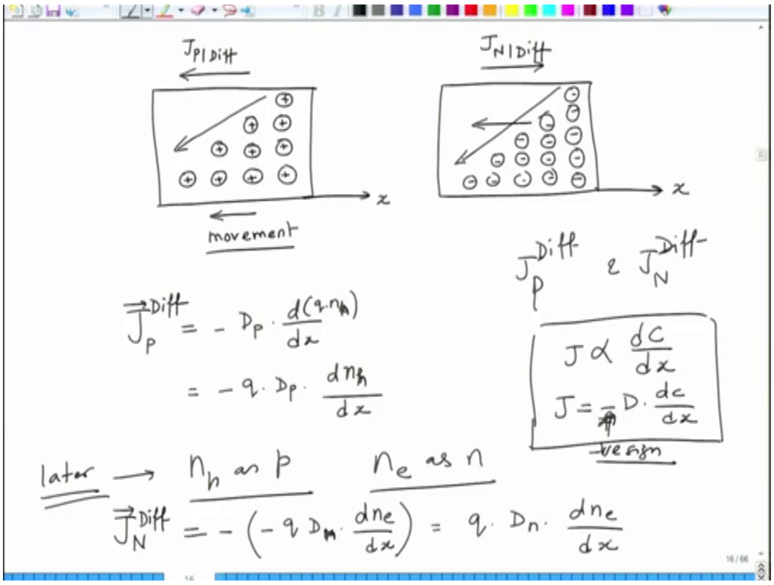

J_P^{Diff} & J_N^{Diff}

$$\vec{J}_P^{Diff} = -D_p \cdot \frac{d(q \cdot n_h)}{dx}$$

$$= -q \cdot D_p \cdot \frac{dn_h}{dx}$$

$$J \propto \frac{dc}{dx}$$

$$J = -D \cdot \frac{dc}{dx}$$

-ve sign

later → n_h as p n_e as n

$$\vec{J}_N^{Diff} = -\left(-q D_n \cdot \frac{dn_e}{dx}\right) = q \cdot D_n \cdot \frac{dn_e}{dx}$$

So, the scenario is something like this. Let us say you have a picture like this in which, so very simplified diagram of how a concentration gradient may look like. So, these are let us say the positive charges ok. So, we have net concentration gradient in this direction, all right, let say this is x.

So, in this direction we have what we call as J P diff ok. Similarly, you might have a scenario in which you may have concentration gradient like this, so, these are let us say negative charges. So, in this case the movement will also be same, so movement of carriers will also be same in this direction this is the direction of movement and the same will be the direction of current, all right.

In this case the movement will happen in this direction, this is for negative carriers if this is x the distance is scale. So, you have a concentration gradient like this the diffusion will take place in this direction, but the current will be measured in this direction. So, this will be J N diff, you can also write it as J P diff and J N diff ok. Now, of course, these are taken as vectors also, so, we can write them in vectorial form we will, in fact eventually write them in vectorial form, all right.

So, basically we have J P diff as minus of q. Now, we know that from the Fick's law the flux J is proportional to dc by dx that is the concentration gradient. And we write this as J is equal to minus of D into dc by dx, all right. This is the Fick's first law with and this minus sign is because of concentration gradient because charge is moving from higher concentration to lower concentration regions, so that is why you have this negative sign.

Now, if you now correlate the flux of charges, flux of charges is essentially is equal to. So, let me just write this expression in a slightly different form. So, for positive charges it would be minus of D p or you can D p into D dx that charge concentration, charge concentration gradient basically gradient of charge concentration and this is nothing, but you can say q this is the total charge right q multiplied by n h right ok. So, this will be minus of q D p into d n h divided by dx ok.

You can also write, so we will have to make some simplified language later on we will have to later we will write n h as p and we will write n e as n. We will write that later on because the when we write the equation it becomes it becomes very simple, but that we will do later. So, this is the diffusion current for hole, J diff is equal to minus of D p minus of q into D p into d n h over dx.

Similarly, J N diff, now since J N diff is in the opposite direction as to the concentration gradient that is the flux of the carriers the sign is opposite. So, essentially the sign is now minus of minus q D n d ne by dx so, this becomes q into D n d ne by dx.

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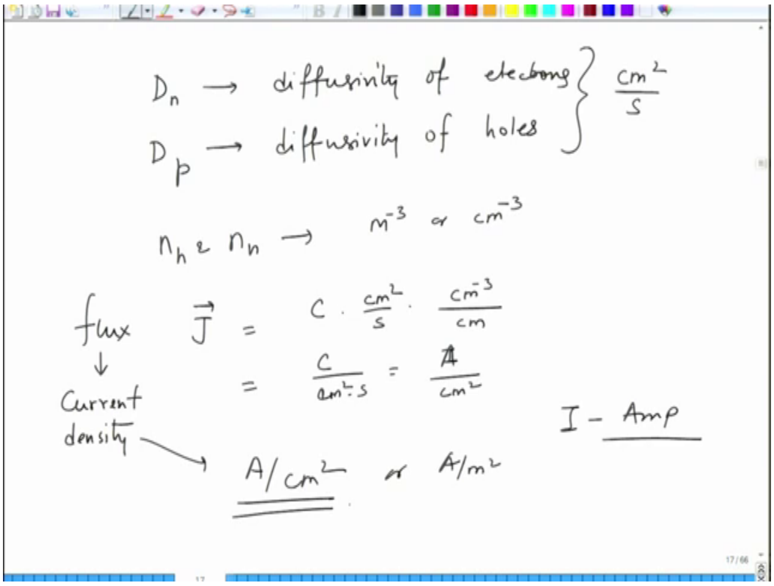

$D_n \rightarrow$ diffusivity of electrons

$D_p \rightarrow$ diffusivity of holes $\Big\}\ \frac{cm^2}{s}$

n_h & $n_n \rightarrow m^{-3}$ or cm^{-3}

flux ↓ Current density → $\underline{\underline{A/cm^2}}$ or A/m^2

$$\vec{J} = C \cdot \frac{cm^2}{s} \cdot \frac{cm^{-3}}{cm} = \frac{C}{cm^2 \cdot s} = \frac{A}{cm^2}$$

I - $\underline{\text{Amp}}$

You can write them in more general form where D, all right; so D n is diffusivity of electrons so, D p is diffusivity of holes. The units of these are in centimetre square per second whereas, the units of n h and n e are in per meter cube or centimetre cube, so, in this case we will take per centimetre cube, all right.

So, if look at the flux now, the current will be so you have q in coulomb in to centimetre square per second into you have n as per centimetre cube and this will be centimetre. So, if you look at the units now this is coulomb per centimetre square per second. So, essentially its coulomb per second is ampere, ampere per centimetre square, so, basically the number of amperes passing through per unit area, all right.

So many charges, so much charge in coulomb passing through a unit area per unit sec time, this is what the flux says basically. And this is nothing, but current density because current density is always represented in ampere per centimetre square or ampere per metre square whereas, current is given in ampere only ok. So, essentially this is what it means, number of charges passing through per unit are per unit time.

So, now having look at the diffusion current what is total current? Total current is J P, ok. Let me before we write this let us just write the general form of these equations.

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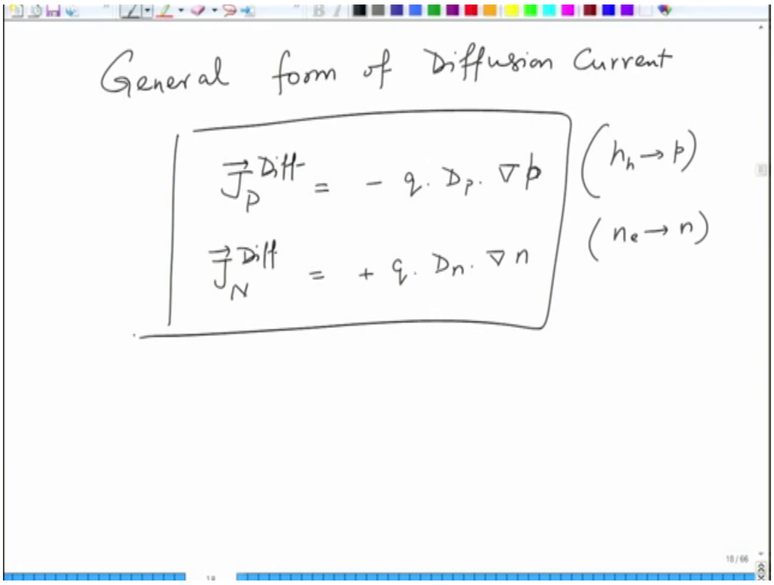

General form of Diffusion Current

$$\boxed{\begin{aligned} \vec{J}_P^{\,Diff} &= -\,q \cdot D_p \cdot \nabla p \\ \vec{J}_N^{\,Diff} &= +\,q \cdot D_n \cdot \nabla n \end{aligned}}$$

$(n_h \rightarrow p)$

$(n_e \rightarrow n)$

The general form of these equations, general form of diffusion current you can write that this as. So, J P diff can be written as minus of q D p into del of p and J N diff can be written as minus a plus of q D n into del of n. So, instead of writing del of n h, I have now shifted it to del of; so essentially what we have done is n h is represented as p and n e is represented as n ok. So, there will be they look a little bit more simpler later on ok, so, this is what these general expressions for diffusion currents are.

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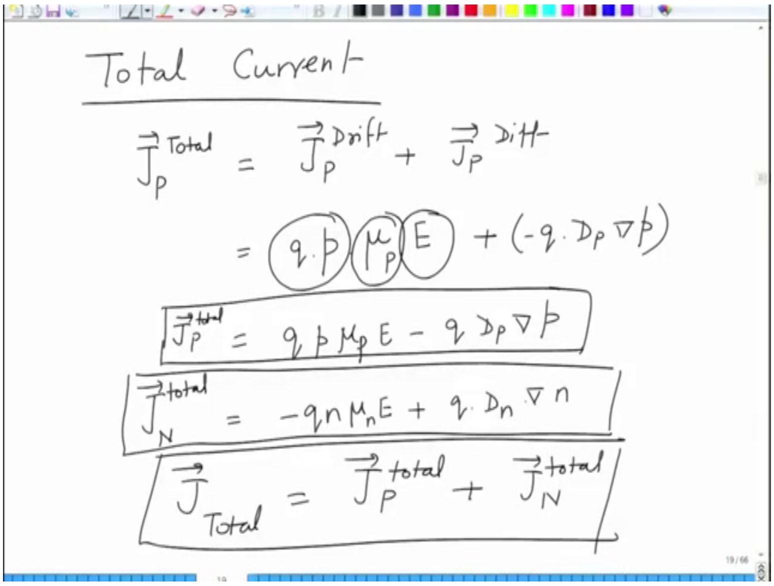

Total Current

$$\vec{J}_P^{Total} = \vec{J}_P^{Drift} + \vec{J}_P^{Diff}$$

$$= q\cdot p\, \mu_p\, E + (-q\cdot D_p \nabla p)$$

$$\boxed{\vec{J}_P^{total} = q\, p\, \mu_p E - q\, D_p \nabla p}$$

$$\boxed{\vec{J}_N^{total} = -q n \mu_n E + q\cdot D_n \nabla n}$$

$$\boxed{\vec{J}_{Total} = \vec{J}_P^{total} + \vec{J}_N^{total}}$$

So, the total current now, so J P total is equal to J P drift plus J P diffusion and this is basically equal to q, so I replace n h by p into mu P into E remember that ok. So, this is the total amount of charge per unit volume, this is the mobility and this is the electric field. Plus, what is J P diff? It will be minus of q D p into del of p, all right. So, this becomes q p mu p E minus of q D p del of p. Similarly, for electrons J N total will be equal to for electrons you can take the charge as minus of q n mu n E plus q into D n del of n ok.

So, this we have taken this we have now replace n e and n h by p into q right. So, here we have replaced this by n into q. So, essentially and since for electrons its charge is negative, so, we have taken it negative ok. So, J total for a given semiconductor will be equal to J P total plus J N total, all right. So, this is the you can say J P and this is J N.

These are the 3 expressions which are important. Later on you can see that for a holes the diffusion current is negative in sign, it will become because you have this for holes the holes move in the same direction and the current is calculated in same direction. Whereas, for electrons the current I measured in the opposite direction as compared to the flow of electrons, all right. So, these are the two expressions that are important for you to understand.

So, far what we have; what we have seen in a semiconductor have carrier, carriers move under the influence of electric field or they move under the influence of concentration gradient. So, this is about the movement of carriers, carrier action. There are few more things that are happened in semiconductor which are important from the perspective solar photovoltaics, generation of carriers and loss of carriers ok.

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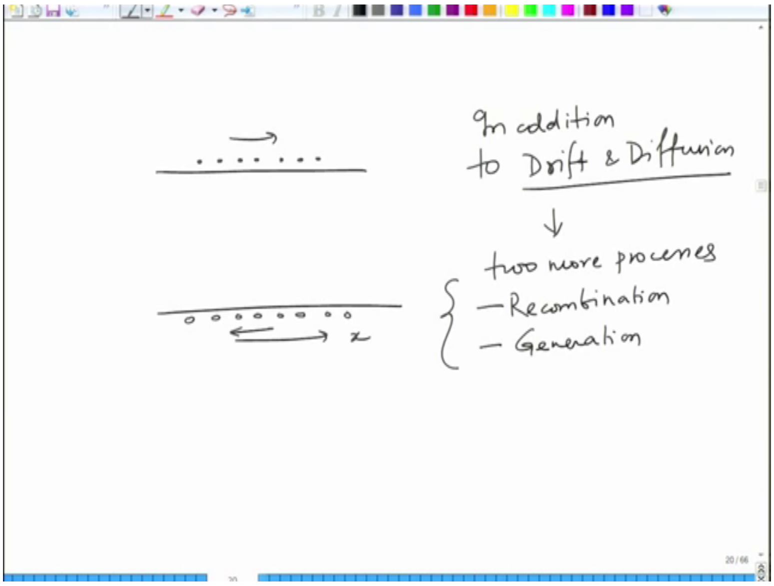

So, this is called as, so you have you can say this is a semiconductor x, so here you have electrons, holes, so they move, but the now the question is do they move with the same concentration or do they get lost at the different places or do they get increased at various under various conditions. For example, what will happen if you shine light on semiconductor? You expect that carrier concentration will increase, if light has sufficient energy to excite more carriers. Or what will happen if you have impurities if you have defects in the semiconductors you might the carriers might face the green boundary, carriers may fight traps or something like that they will get lost.

So, this process other than in addition to drift and diffusion which is about the carrier action you have two more processes. So, they will determine the net flux, but the flux is also effected by two more processes which is called as recombination and generation. So, it is these four processes together which will generate the net change in carriers concentration as a function of time or distance in a semiconductor ok. So, let see what these things are.

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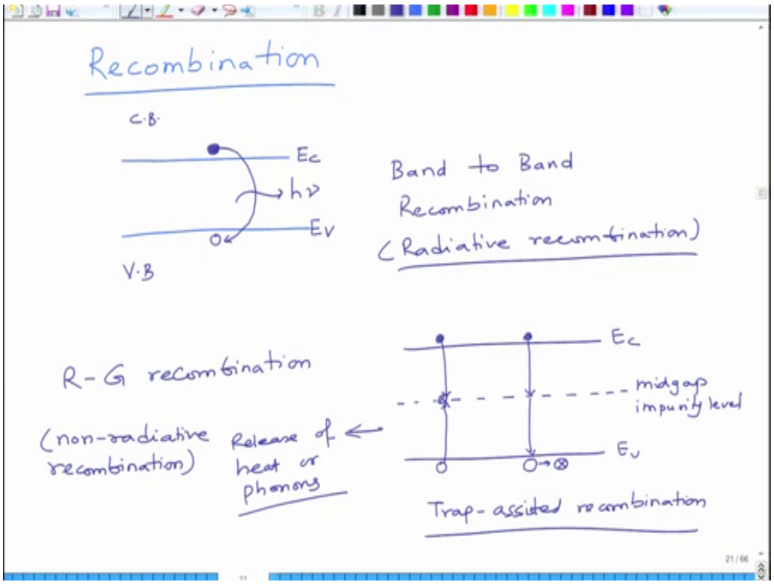

Recombination

Band to Band Recombination (Radiative recombination)

R-G recombination

(non-radiative recombination)

Release of heat or phonons

Trap-assisted recombination

So, now we focus our attention on recombination first. So, let us not, we will talk about the generation in the second half, let us first look at the recombination. So, recombination as a name itself suggest in a semiconductor charges can recombine, which means electrons and holes being equal and opposite charges to each other they can they have the tendency to recombine.

So, the first mechanism that is operated when the semiconductor is called as band to band recombination. What happens in this case? You have a hole, you have a electron, ok, this electron may move. So, this is conduction band, so this is E c this is E v, so here you have conduction band, here you have valence band, the electron and may relax from conduction to valence band to combine with the holes in the process it will lead to a photon of energy E. So, this is band to band recombination which is called radiative recombination. So, it has emission of a radiation of energy h nu corresponding to the energy which is released.

Another process which is called as R-G recombination or it is called as recombination generation recombination or you can say that trap assisted recombination what happens in this case is you have a band. So, you have a so this is E c, this is E v, you have a trap somewhere sitting in between, so this is a mid-gap impurity level.

So, you have a impurity which is neither closed to conduction band nor closed to valence band it is not able to ionise itself, what happens in this you have a electron sitting here, you have a hole sitting here sorry. The electron and hole may reach here and they may recombine and this kind of recombination is called; this kind of recombination is called as trap assisted recombination. This is a very common mode of recombination because impurities are present in, so this could be impurity, it could be defect something like that. For example, it could be vacancy, it could be dislocations, all of them they create at the middle of every defect has a certain energy level. So, when you map that energy with respect to conduction and valence band it is often in the mid gap position and that allows that helps in carrier recombination.

So, electron may come hole may go there recombine, alternately electron may go here first and then it may go there first and then it will combine with hole leading to recombination ok. So, this leads to generally release of heat or phonons. So, this is called as non-radiative recombination ok.

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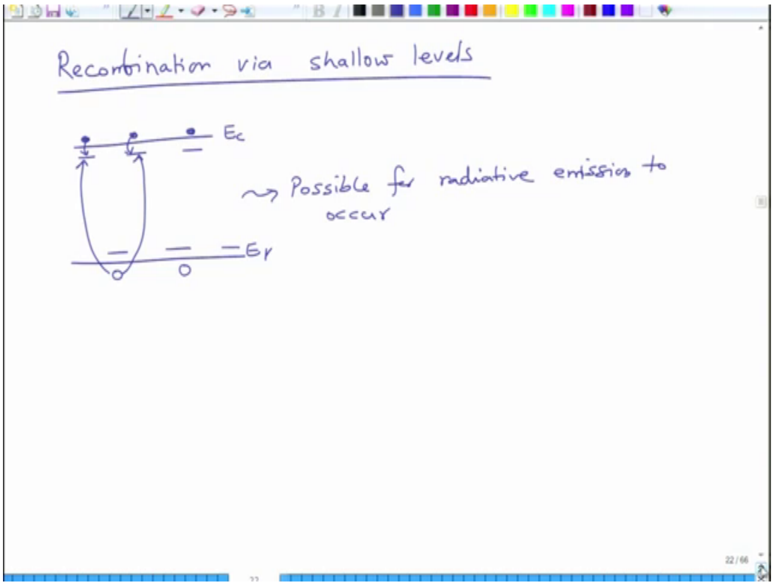

Recombination via shallow levels

~> Possible for radiative emission to occur

And the third common mode is recombination via shallow levels. In this case what happens is that you have you have band E c E v, you have trap levels which are sitting close to conduction or valence band edge, you might have something here ok, these are shallow levels. Shallow means they are closer to conduction valence band edge, so you have electrons sitting here, you have holes sitting there. So, what might happen is that you have electron coming here and hole going there or you might have electron coming here, hole going there ok.

So, it happens via shallow levels. So, again you have in this case you may have some radiation coming out of appropriate because this energy released is quite large. So, as result it could it is possible to have this in a radiated manner, so, possible for radiative emission to occur, so, this is a via trap levels.

So, these are the three known main causes of recombination. However, the most common cause in semiconductor is rate this trap assisted recombination where impurity and defects the lead to recombination in semiconductors. And of course, band to band recombination is also very common. This is especially true when your carrier density becomes large, when your carrier density becomes very large, then the energy level also becomes very high, when the energy is becomes very high so more the carriers are created, more the carriers are combined thermally. So, this is basically thermal recombination, they just come to valence band to combine because carrier concentration is very high.

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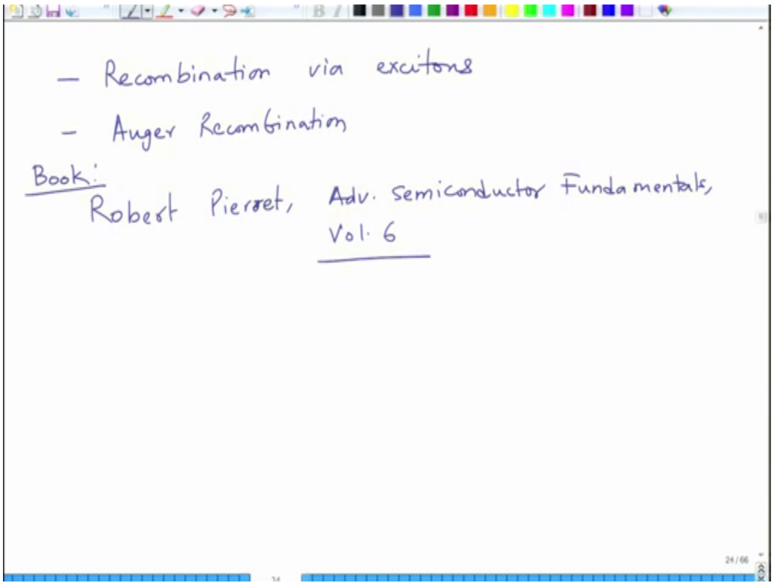

- Recombination via excitons
- Auger Recombination

Book:
Robert Pierret, Adv. Semiconductor Fundamentals, Vol. 6

So, this is the recombination process that happens in semiconductor and you can also have other recombination process such as recombination via excitons. You can have other you can have other auger recombination. So, there are various recombination processes which are there, we cannot get into details of everything, but if you want to read more about recombination I would recommend you to go through Robert Pierret, Advanced Semiconductor Fundamentals, Volume 6 ok. Go to this book, so, this is about recombination.

But, the main methods for recombination are band to band recombination and trap assisted recombination. There are other methods as well, but they are less common as compared to the first two.

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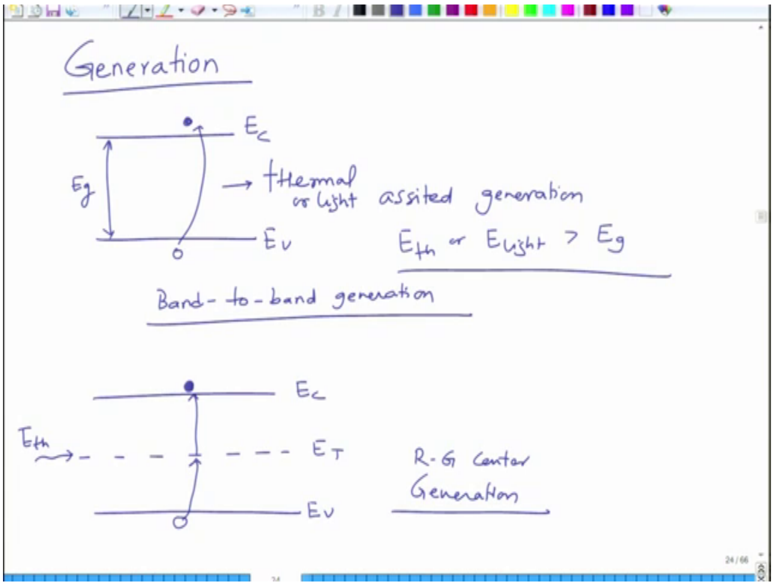

And then we have generation, so, first we just look at the processes and then we quantify them ok. So, generation happens first because of thermal generations. So, you have E c, E v for a band diagram of semiconductor. So, a electron here gets excited creating an electron leaving a hole ok. So, this is thermal excitation, thermal or light assisted generations, this is what happens is solar cells. You have a radiation of energy, so basically energy E thermal or E light is greater than E g ok. So, this is the band gap, you need to overcome this energy to thermally excite or photo excite the carriers.

So, what it requires is that energy of radiation and energy of heat the thermal energy should be larger than the band gap. So, this is called as band to band generation, very common mode of generation in semiconductors. Second generation mechanism is which is because of defects. So, you have E c, you have E v, you have trap, somewhere here. So, you provide some thermal energy, this thermal energy leads to the creation of carriers in this fashion, so you create a; so electron from here it first goes to this, then it goes to this stage so, energy provided in parts. You do not get like all of the energy in once at once. So, this is called as R-G centre generation, not very common, but it is possible.

And then of course, you can have a photo emission from band gap centres and impact ionisation that can also cause, but these are made to measure modes of generation.

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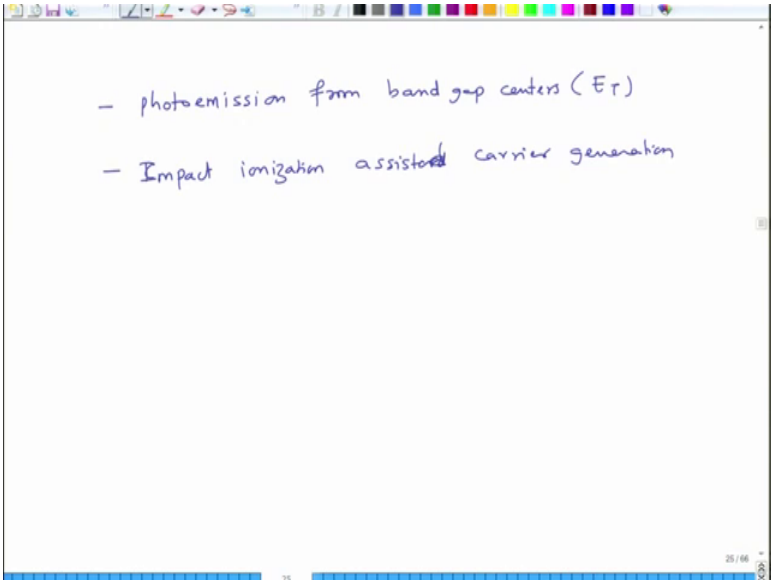

- photoemission from band gap centers (E_T)
- Impact ionization assisted carrier generation

The other modes are photo emission from band gap centres such as traps, energy levels and then you can have carrier impact ionisation assisted carrier generation. So, again if you want to read more about this go to the same book which I recommended Advanced Semiconductor Fundamental by Pierret. So, these are the main methods of recombination and generation. How do you quantify them?

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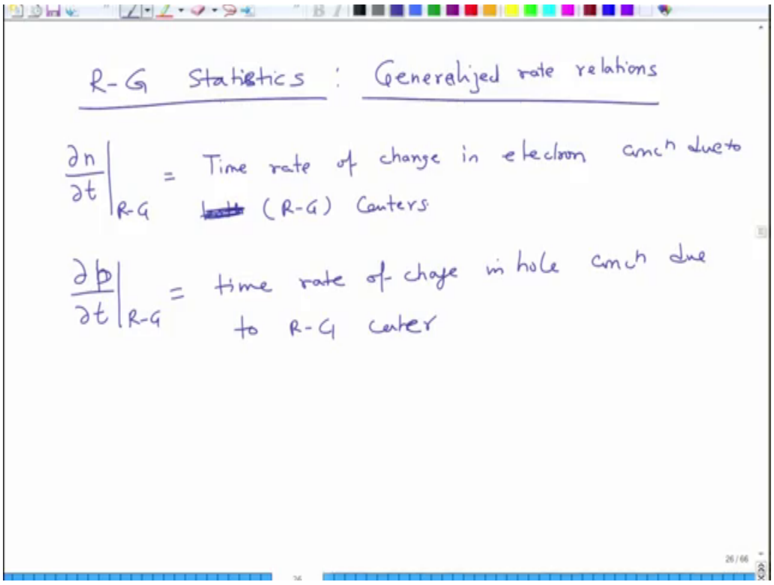

R-G Statistics : Generalized rate relations

$\left.\frac{\partial n}{\partial t}\right|_{R-G}$ = Time rate of change in electron conc^n due to ~~both~~ (R-G) Centers

$\left.\frac{\partial p}{\partial t}\right|_{R-G}$ = time rate of change in hole conc^n due to R-G center

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So, for quantifying them we have what we called as R-G statistics which give us generalised great relations because these things and bring sometime dependence into the picture.

So, basically, we say del n by del t R-G is time rate of change in electron concentration due to both R-G centre ok. So, its negative if the electrons are lost and its positive if its electrons are created, similarly due to R-G centres not both, but R-G centres. And then we have del p by del t R-G which is time rate of change same, in hole concentration due to R-G centre. Again, this is positive if holes are created and negative if holes are lost and this includes both capture and emission ok, so, negative means captured, emission means its positive.

So, we will quantify this we will couple these with a term that we have seen from drift and diffusion and then come to the final equations of carrier rate of change of carrier concentration in semiconductor. So, we will finish here today what we have learnt is about recombination generation and some diffusion aspects in semiconductors and we will take it a further in the next class ok.

Thank you.