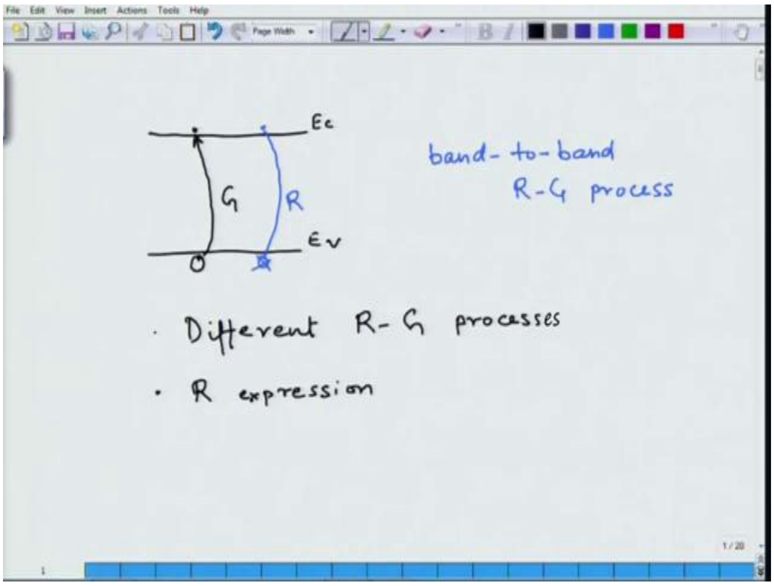
Optoelectronic Materials and Devices
Prof. Dr. Monica Katiyar
Department of Material Science and Engineering
Indian Institute of Technology, Kanpur

Module - 3
Optoelectronic Device Physics
Lecture - 22
Carrier recombination-generation-II
Other mechanisms

Continuing our discussion on semiconductor device physics. In the last lecture, we started our discussion on carrier generation. We looked at three ways of generating carriers thermal optical generation and electrical generation. We also looked at recombination where it could depending on whether the material is direct semiconductor or indirect semiconductor. It can lead to radiative emission in other words light emission or non-radiative emission. Characteristics of all the generation recombination processes that we discussed so far was that they were band to band transition.

(Refer Slide Time: 00:56)

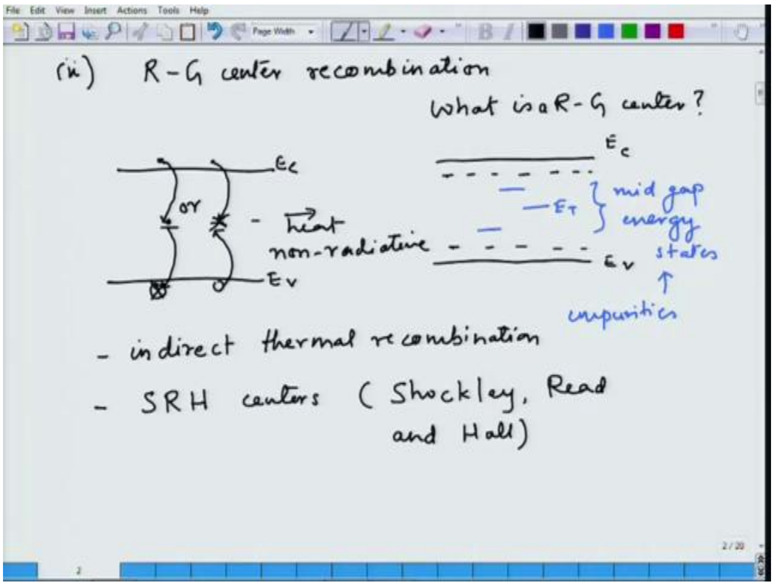


- Different R-G processes
- R expression

Basically, so far we discussed that if I have a semiconductor, which has conduction band and valence band then we talked about a electron being promoted to the conduction band and leaving behind a hole, this is a generation process. We also talked about combining with the hole in the valence band and this is the recombination process. We saw how it can happen, that is basically by thermal generation or optical generation or recombination, which result in light emission or non-radiative emission, which is basically heat. The characteristics of this was that we were talking about all transition, which were band to band from valence band to conduction band or vice versa band to band recombination generation processes.

But this is not the only way to generate a electron hole there or to recombine a electron hole pair. There are many more ways of doing it and today's lecture is about talking about different ways of having recombination generation processes. So, today we are going to talk about different processes for a different R G processes that different form band to band transition. Then we will look at we have already looked at the generation rate. In the case of thermal or optical generation, we will also look at what would be a recombination rate expression in couple of a special cases of electron hole pair generation and recombination. So, let us start with different r-g processes it will first start with recombination processes and then find the equivalent of a generation process for each of the recombination mechanisms that exist. So, assuming that the first process is already discussed band to band transition.

(Refer Slide Time: 03:09)


(ii) R-G center recombination

What is a R-G center?

- indirect thermal recombination
- SRH centers (Shockley, Read and Hall)

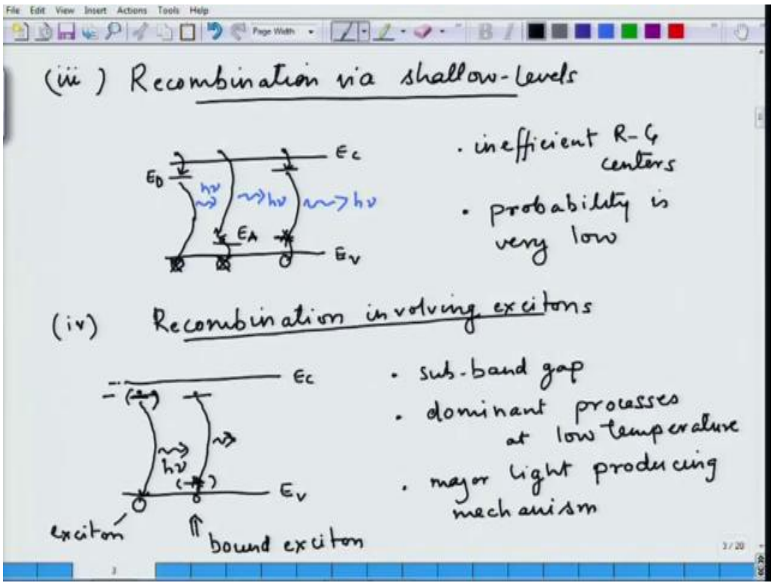
Let us look at the second way of having in a semiconductor and that is known as R-G centre recombination. Now, before I answer that I think it requires that we explain what is a R-G centre. What is a R-G centre? You have already studied in earlier modules that in order to make a intrinsic semiconductor extrinsic we put some dopants, which act either as donors or acceptors. They contribute electrons and holes by a thermal excitation to conduction or valence band R-G centres are also impurities, but the difference between R-G centre. Donor and acceptors is that donors and acceptor exist very close to the respective band edge on the other the impurity is which create a states rather deep in the mid gap, which create mid-gap energy states.

Now, these impurities which exists in the semiconductor cannot act as dopant, because the difference between the energy level and the band edge respective band edge is too large. but, they act as R G centre. They act R G's as recombination or generation centre. How do they act as recombination centre? If he see this only R G centre in this case, then a R G centre which exist in the middle of the band gap an electron can come to the defects state from where it can further go down and analyte a hole.

So, it is a two step process now, which was earlier one step from conduction band to valence band. Now, it has become from conduction band to the a recombination R G centre, which is a impurity energy level. Then to the valence band, this process can also be seen as in two steps in one which is it is basically same thing. How you write it a electron comes to the defect state or R G level? A hole also combines at this level and there that is where they analyte each other. So, this defect state the impurity state acts as a intermediary in the recombination process. This process in general does not give out light, it will give out heat or it will be non-radiative. For this reason that it is a indirect thermal recombination, this process is also called as indirect thermal recombination.

Direct thermal recombination being the process where band to band transition takes place, it also has another name it is often called S R H centres R G centres are also called S R H centres. S R H stands for the name of the three scientists (( )). They were the first one to explain this a mechanism of recombination. Earlier we knew about the recombination from the conduction band to the valence band. They propose that the impurity centres, which are in the mid-gaps can act as recombination generation centre and create a path which will be non radiative for recombination. Then we can talk about other process for recombination.

(Refer Slide Time: 07:41)



(iii) Recombination via shallow-levels

- inefficient R-G centers
- probability is very low

(iv) Recombination involving excitons

- sub-band gap
- dominant processes at low temperature
- major light producing mechanism

This is known as recombination via shallow levels as you know shallow levels are same as your donor or acceptor levels. They can also contribute to the R G processes to a recombination process. So, if you have for example, a donor a sitting very close to the conduction band. It is possible that the electron first comes to the donor level and then from there it interacts with the hole in the valence band and has a recombination process. Another option for that is also possible that one has acceptor level E A and that can participate in the recombination where electron first comes to the acceptor level. From here it goes to the valence band and there is the recombination process taking place. This way there can be other combinations of it is also possible where you have two levels the electron is captured here.

The hole is captured by the acceptor level and then finally, there is a recombination event taking place here. So, there can be many combinations of involvement of the shallow levels which are basically your donor acceptor levels, which contribute to the carrier concentration in the semiconductor. This in this process compared to the mid gap is that many of these recombinations in the shallow levels is going to be radiative in nature. They can all these large energy transitions can have radiative emission.

So, a shallow level centres in general are may be one can call them inefficient R G centres in terms of providing recombination. So, they are inefficient R G centres. Why are they inefficient? Because the chances that a electron which is captured by a donor level it has two possibilities. It can either go back because of thermal fluctuations go back to the conduction level or it can recombine with the valence band. This is this level difference is very, very small, it is very lightly that it will come out of the donor level and be part of the conduction band. Hence, the probability that it does the recombination via this root is very, very small. That is why we are calling it a very inefficient R G centres, which are if if an electron is trapped in a mid-gap level would generally recombine.

We also find that it is radiative, as we have already mentioned and but these processes generally, which involving shallow levels their probability is very very low at room temperature. So, the rates are not very high probability for this recombination via shallow levels probability is very low. So, this is not a dominant recombination process its we are looking at the recombination of carriers. Now, in the same series, then the next recombination mechanism is known as recombination involving excitons.

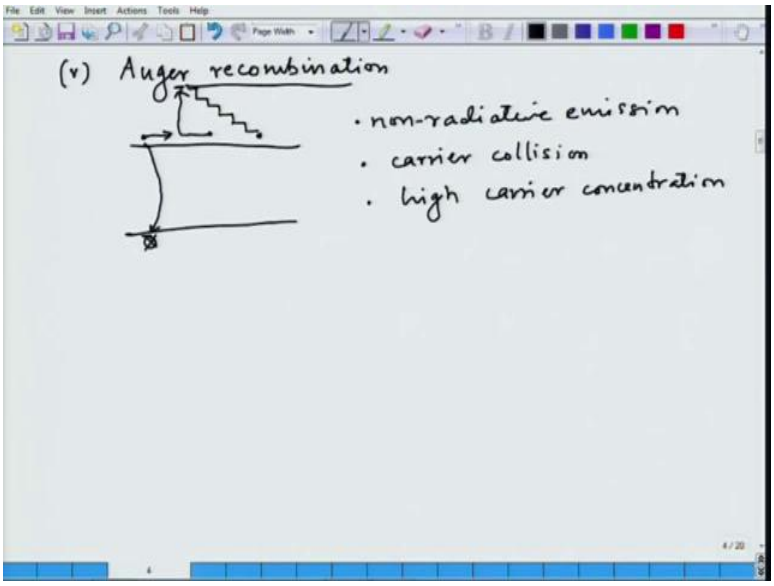
Now, again before we explain this behaviour. It is important to realise what are excitons. So, once again, if we look at free electron in the conduction band and free hole in the valence band. They can move on their own they are not bound to each other, but it can happen that a electron in the conduction band gets bound to a hole in the valence band. In that case they they are no more independent. Rather they move as a hole and that a entity a electron hole pair, which is bound to each other is called exciton. To represent this exciton, we say that this is a electron which has a electron which has become part bound to the hole its level is slightly lower that the band edge of the conduction. We since this is not a real level this is a level created because of formation of exciton, it is normally represented as in the bracket. Remember all the levels, which were there due to impurities were shown as the energy levels in the band gap.

Now, this electron which is bound to to this hole can recombine and give emission once again, this emission is generally radiative in nature. It can also participate through shallow levels. In other words, I can be a shallow level and hole bound to not the electron here but, the electron in the shallow level or in the donor level. In this case, this exciton which is bound to the electron and the donor level is known as the bound exciton as oppose to the exciton, which is by bonding of the free electron and free hole in the valence band. This one is bound to the particular donor level and it cannot move freely.

So, there are two type of excitons; one is free exciton, which will move together a electron hole pair will move and the second type which is a bound bound exciton. which cannot move freely in the material, but it can still recombine and the electron will recombine with the the hole here. There will be an halation and again this will be radiative in nature. This way one can think of more permutation combinations for recombination involving excitons. What are the observations about these recombination using excitons. That is we can see because of this binding energy of exciton the emission. That we get is not going to be equal to the emission of the band to band transition. It is going to be a emission, which is going to be in sub band gap.

So, the energy of emission is going to be in sub band gap and this is also another way of trying to figure out what is a binding energy of exciton is? Normally these processes through the exciton formation are important. These are the dominant processes at low temperature not at room temperature and majority of LED’s which one sees today. This this is the major light producing mechanism.

(Refer Slide Time: 15:34)



(v) Auger recombination

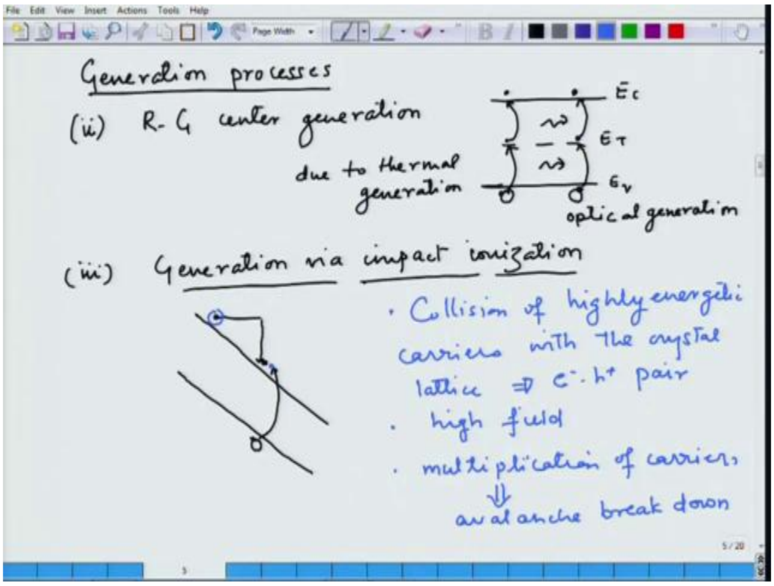
- non-radiative emission
- carrier collision
- high carrier concentration

So, that brings us with the the next recombination mechanism and this is called auger recombination. The R is silent and it is spelled as o j. In this process basically we have a electron and a which is which is at a very high energy. It has a collision with another electron. At the same time, it recombines with the hole and the energy that it generates in this process of recombination. It gives to the other electron and the energy of that electron goes to a higher kinetic energy level. That energy than will get reduced in steps basically being lost as heat to the lattice. Then then the second electron comes back to its ground state.

In this process the recombination energy is given to the second electron that is having a collisions simultaneously with the recombination process. It takes the energy of the recombination process and losses it to the heat. So, the energy is lost in a in a non radiative emission. In this case we do not get any light here it is basically taking place because of carrier collisions. Hence, the process is a a normally occurring where you have a high carrier concentration. Then these processes have to be accounted for high carrier concentration basically means very high level of doping in the, a device. Then this has to be accounted for in this case.

So, in summary what we have shown is in addition to band to band transition you can have recombination of carriers through various radiative or non radiative mechanisms. First one being recombination via R G centres, which are impurity centres second one being recombination via shallow impurity levels. Third one being recombination due to excitons, fourth one being recombination due to excitons and the fifth one being a recombination due to auger processes which are again non radiative. Now, equivalent of this recombination process because generation is exactly opposite of recombination, one can then talk about generation processes, which can also occur in the material.

(Refer Slide Time: 18:23)



Generation processes

(ii) R- G center generation

(iii) Generation via impact ionization

- Collision of highly energetic carriers with the crystal lattice $\Rightarrow e^- \cdot h^+$ pair
- high field
- multiplication of carriers
  $\Downarrow$
  avalanche break down

So, if we look at these generation processes just like we have R-G centre recombination, we can have R-G centre generation. So, after band to band generation this would be R-G centre generation. What do we have here is reverse of recombination taking help of the R G centres.

So, a hole a electron which is in the valence band first goes to the R-G centres, then from here it goes to the conduction band leaving behind a hole. This is the generation process, this can happen just like in the band to band transition. It can happen due to thermal generation, it can also happen due to light absorption light absorption can also take a electron to the R-G centre level. Then another light absorption can take it to the conduction level leaving behind a hole.

So, there are two ways that one can have a generation of electron hole pairs through R-G centre; this would be example of optical generation. So, the process as you can see is exactly reverse of R-G centre recombination. The next recombination process that we had was through the shallow centres. Now, if we think of generation through the shallow centres it is nothing but same as creating a n or p type material. So, there is no specific generation process through the shallow centres. They, if you it is basically contributing to changing the the electrical conductivity of the material same thing about excitons.

Since, there are no we are creating e h pairs, there are no existing e h pair. There is no concept of exciton generation to start with. Excitons are created only after electron holes pairs are existing and they bind with each other to form an exciton. But we do have the opposite of the process which is auger process. We call it generation via impact ionization. This is opposite with the auger process because in the auger process the collision of two electron led to the recombination energy of one electron being given to the second electron. Then that particular energy is lost in heat. In this case, we talk about the the energy, the the high kinetic energy of a electron having a collision with another electron.

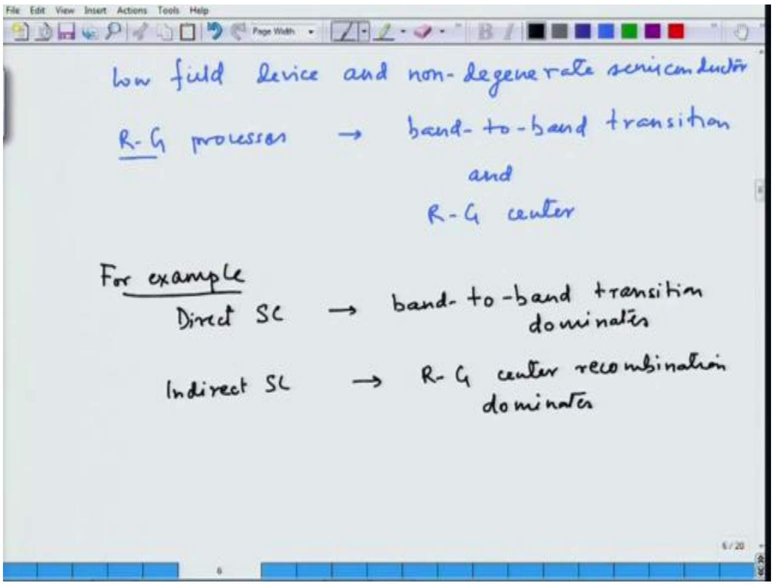
It loses its energy and the second when it has a collision with the carrier, it creates, it takes the electron in the valence band and takes it to the conduction band thereby creating a hole here. So, this particular electron has a collision with the you can say the the material lattice or another carrier in which it loses its energy. This energy is given to the electron in the valence band and that is moved to conduction band creating a hole.

So, by this impact of carriers with each other or with the lattice we have created a electron hole pair and this is why it is called generation by impact ionization. This is a very important process because this is the key process for where you have collision basically depend on collision of highly energetic carriers with the crystal lattice. Discs generates a electron and hole pair.

Now, this process is normally occurs at high field because you need highly energetic carriers. It occurs at high field and this is a process by which one can have multiplication of carriers a single carrier when it is been excited to high energy have a collision with the lattice. It creates more carriers, so this is a process by which you can have multiplication of carriers by impact ionization. This is what leads to then eventual what is called as an avalanche breakdown, which we will see later in device devices. Basically, it is there that a single carrier is generating, multiple carriers and those multiple carriers then generate more carriers. Thereby you suddenly have a high leakage current and the device fails.

So, this process of generation via impact ionization is important from that point of view now all these processes that we have discussed. In addition to we discussed in the last lecture can occur in a semiconductor, all at the same time. But it is not important that how many are occurring? What is important is what the rate at which they are occurring is? They will all be occurring at a different rate. Generally, if we look at our discussion earlier what one finds is that, if you have a known a device which is a low field device. You have a low field device and non-degenerate semiconductor.

(Refer Slide Time: 24:49)



low field device and non-degenerate semiconductor

R-G processes → band-to-band transition
and
R-G center

For example
Direct SC → band-to-band transition dominates

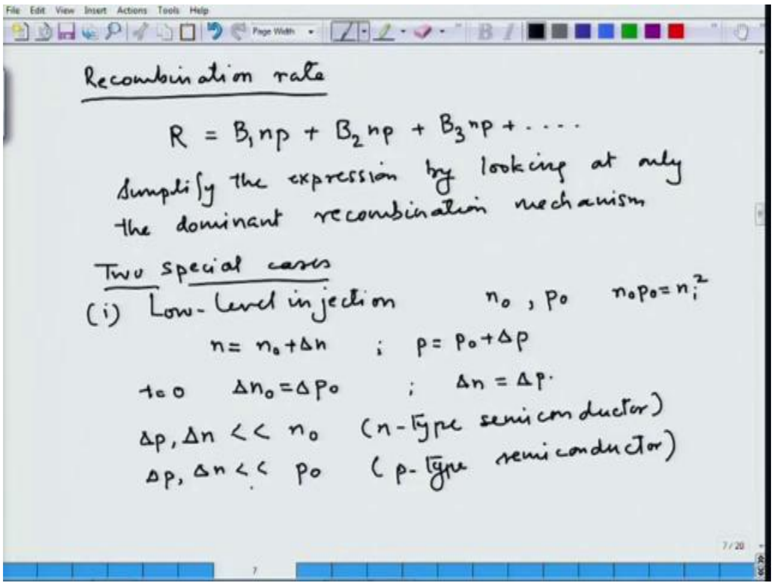
Indirect SC → R-G center recombination dominates

So, basically we have ruled out auger processes here and generation impact ionization then the dominant R-G mechanisms in such devices is going to be and we are talking about room temperature processes. The R-G processes that dominate are band to band transition and R-G centre. Now, depending on the situation and the device one will also have to see which one of this is dominant. For example, if we have a device, which is direct semiconductor device. then the rate for band to band transition is much much higher as discussed earlier.

Because there is no requirement for momentum conservation while having this transition band to band transition dominates. That does not mean that R-G centre is not taking place, all it says is that the rate at which band to band transition is taking place is higher than the R-G centre. On the other hand, if I have a indirect semiconductor, in that case R-G centre recombination generations dominate. This is required because band to band transition as we discussed earlier looking at the e k diagram is a very much less probable compared to the band to band transition. Sorry transition through the R G centres in indirect semiconductors.

So, the dominant process which we commonly see among all the R G processers that are discussed in devices is band to band. R G centre now, let us see what kind of recombination's rate we are going to get? So, in the last lecture, we got an expression for generation rate if it is a thermal generation rate. Then it is a constant value only dependent on the temperature, if it is a optical generation rate, then we can calculate it depending on what is the wavelength of the light coming in. What is the absorption coefficient of the material? You can calculate what would be the generation rate? Now, let us see if we can give some values to the recombination rate.

(Refer Slide Time: 27:56)



Recombination rate

$$R = B_1 np + B_2 np + B_3 np + \cdots$$

Simplify the expression by looking at only the dominant recombination mechanism

Two special cases

(i) Low-Level injection n_o, p_o $n_o p_o = n_i^2$

$n = n_o + \Delta n$; $p = p_o + \Delta p$

$t = 0$ $\Delta n_o = \Delta p_o$; $\Delta n = \Delta p$.

$\Delta p, \Delta n << n_o$ (n-type semiconductor)

$\Delta p, \Delta n << p_o$ (p-type semiconductor)

So, what would be the recombination rate in a semiconductor, so we have discussed many processes and we have also said there may be one or two will dominate and rest may not be dominant in a particular material. So, in general if I want to write the total recombination rate in a semiconductor, I can say that it will be addition of all the processes discussed. So, my combination rate from the last lecture is something some constant because of first mechanism.

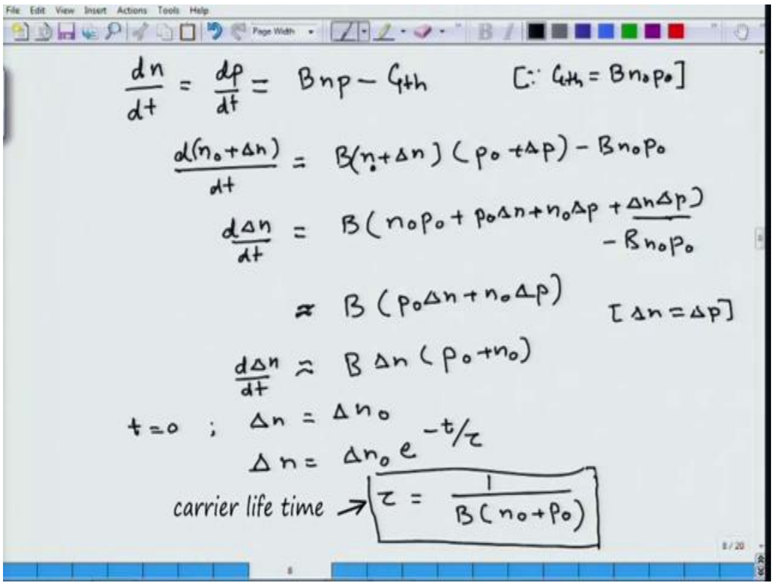
Let us say it is band to band transition multiplied by the carrier concentration in the conduction and valence band plus the rate due to the second process through R G centre. For example, again n p plus the third process may be due to excitons and so on. I can add all the recombination generation processes that I have talked about or maybe there are more. I will get the total recombination rate. Now, as we discussed also that not all of them will play a dominant part so often, what is done is one looks at only just the recombination the dominant recombination mechanism and simplifies the expression by looking at only the dominant recombination mechanism.

But this does not mean that I am limiting myself, because since each of the mechanism is independent of each other I can always add the rates as I have shown here. So, I am I am going to derive equation only for a simple one mechanism, but if I have more than one mechanism, I will just add the rates for each one individually. So, let us look at this situation, we will look at two special cases which occur very often in the device physics and try to get a expression for R. The first case is which is often seen which is known as low level injection. A low level injection basically means that in equilibrium you have the material, which has equilibrium concentration of electrons and holes. We know that this is basically n naught p naught is equal to the intrinsic carrier concentration e square.

We create excess electron and holes we generate excess electron and holes by any process may be optical first that the new carrier concentration is n naught plus delta n. This is p naught plus delta p and if you are doing it by thermal or optical generation, we know that if the excess carries are generated at t is equal to 0. Then del n naught is equal to del p naught and then in the recombination process at every instant you are going to recombine one electron with one hole, which basically also means that delta n is always going to be delta p in this process. If there is no other process taking place, there is no loosing of carriers by another means. Then this should always be true, so low level injection.

Basically, then means that the excess carriers, which are generated at anytime the maximum being at t is equal to 0 is always less than delta n or delta p is always less than the majority carrier concentration . So, delta n p is always going to be less than p naught this is majority carrier concentration for n type semiconductor and this is for p type semiconductor. So, in this condition if I try to see how, what what would be the recombination rate? In this condition, I can write my equations so at t is equal to 0, I have created excess electrons and excess holes by a. Let us say optical excitation process such that the two concentrations are same.

(Refer Slide Time: 32:42)



$$\frac{dn}{dt} = \frac{dp}{dt} = Bnp - G_{th} \qquad [\because G_{th} = Bn_0p_0]$$

$$\frac{d(n_0+\Delta n)}{dt} = B(n_0+\Delta n)(p_0+\Delta p) - Bn_0p_0$$

$$\frac{d\Delta n}{dt} = B(n_0p_0 + p_0\Delta n + n_0\Delta p + \underline{\Delta n\Delta p}) - Bn_0p_0$$

$$\approx B(p_0\Delta n + n_0\Delta p) \qquad [\Delta n = \Delta p]$$

$$\frac{d\Delta n}{dt} \approx B\Delta n(p_0+n_0)$$

$$t=0 \;;\quad \Delta n = \Delta n_0$$

$$\Delta n = \Delta n_0 e^{-t/\tau}$$

$$\text{carrier life time} \rightarrow \boxed{\tau = \frac{1}{B(n_0+p_0)}}$$

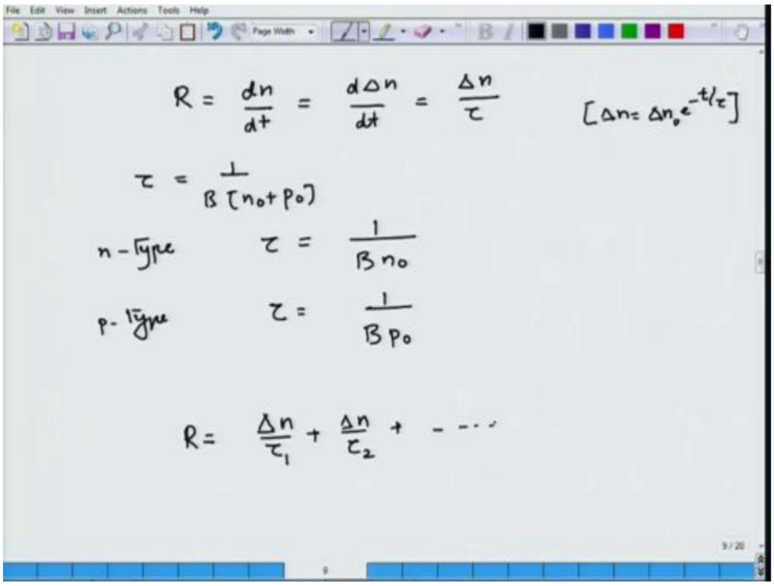
Then at any time t i I am trying to look at how is the concentration of electrons changing with time t i could always write it as how is the concentration changing of holes, because one electron will recombine with one hole. Now, this rate is going to be equal to the recombination whichever mechanism does not matter. It is the constant will change so a general any one mechanism B times n times p minus the generation rate. If I only put in excess carrier at t is equal to 0 after that the generation rate is g thermal. Now, from our earlier discussion we know that g thermal due to thermal means is nothing but if this is the only mechanism taking place due to in this process is going to be n naught p naught.

So, then I can write my expression and I will expand this the carrier concentration at any time is carrier concentration in equilibrium plus the excess carrier concentration. The change in that as a function of time is equal to B n can be x generate further in terms of n naught plus delta n p naught plus delta p. From here I get this as B n naught p naught. Now, I can simplify this n naught n p naught being two constants here. So, this would just reduce to change in the excess carrier concentration due to recombination process will be B, now this can as you can easily simplify, this will cancel with the thermal generation. This particular expressions since we have taken the assumption of a very very low level of injection, it is going to be very very small compared to these two expressions.

So, we can drop that since this is negligible and this will then reduce to with our low level injection will reduce to be p naught delta n plus n naught delta p. Since, we have optical excitation and then recombination we know that delta n at any time is equal to delta p, I can write this as B delta n p naught plus n naught. Now, this now this is a familiar equation, I can this is a first order differential equation, which is a very well known solution. We know at the condition at t is equal to 0 delta n is equal to delta n naught with that the solution for the above equation is delta n is equal to delta n naught exponential minus t over a time constant, known as lifetime for the carriers tau is nothing but 1 over the recombination rate constant times n naught plus p naught.

So, this this entity is known as the carrier life time and it is very important in devices. It gives it is defining the rate of recombination for a. In this case we have taken any one particular process, if we have more than one recombination process we will just add tau one the recombination rate for first and second and third process. So, this is what would be the the equation for change in the excess carrier concentration.

(Refer Slide Time: 37:06)



$$R = \frac{dn}{dt} = \frac{d\Delta n}{dt} = \frac{\Delta n}{\tau} \qquad [\Delta n = \Delta n_0 e^{-t/\tau}]$$

$$\tau = \frac{1}{B[n_0 + p_0]}$$

n-type $\tau = \frac{1}{B n_0}$

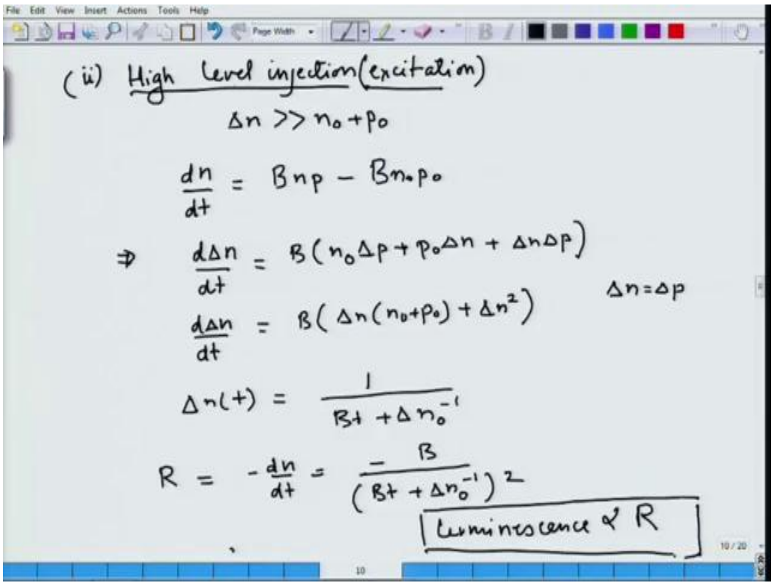
p-type $\tau = \frac{1}{B p_0}$

$$R = \frac{\Delta n}{\tau_1} + \frac{\Delta n}{\tau_2} + \cdots$$

So, in this low level injection regime than recombination rate which is d n d t, which in this case is going to be d delta n over d t can see is nothing but delta n naught over tau. Because delta n is delta n naught exponential minus t over tau delta, sorry delta n over tau, so this is our recombination rate, one can further simplify this equation what is life time a tau here? For a general case is 1 over B n naught plus p naught, but if we take majority carrier n type device, you can see that p naught is going to be very very small. Then the life time for carriers that is going to be 1 over B n naught. If it is a p type semiconductor, then this life time will reduce to 1 over B p naught because n naught is going to be very very small compared to p naught.

So, this is the example of recombination rate when we have low level of injection. This basically means if I am going to put in recombination rate due to different processes in any equation, I can write r is equal to delta n over tau. If I have more than one process then I would write delta n over tau 1 plus delta n over tau 2 and so on so forth. So, this would be the recombination rate due to various processes in a semiconductor. Now, let us look at the second situation and that would be a high level of injection.

(Refer Slide Time: 39:02)



(ii) High level injection(excitation)

$$\Delta n >> n_o + p_o$$

$$\frac{dn}{dt} = Bnp - Bn_o p_o$$

$$\Rightarrow \frac{d\Delta n}{dt} = B(n_o\Delta p + p_o\Delta n + \Delta n\Delta p)$$

$$\Delta n = \Delta p$$

$$\frac{d\Delta n}{dt} = B(\Delta n(n_o+p_o) + \Delta n^2)$$

$$\Delta n(t) = \frac{1}{Bt + \Delta n_o^{-1}}$$

$$R = -\frac{dn}{dt} = \frac{-B}{(Bt + \Delta n_o^{-1})^2}$$

$$\boxed{\text{Luminescence} \propto R}$$

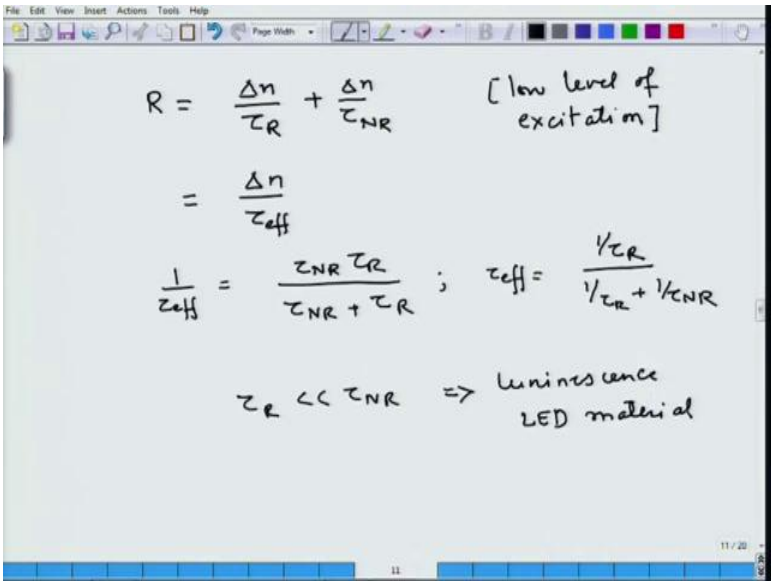
So, if you have generation that leads to high level of excess carrier present in the material than the condition. There is for high level injection one can also talk about it ex injection or excitation. Normally injection is used when you have electrical generation, but if the other means then one would call it high level excitation. In this particular case the situation is such that the excess carriers that are generated are much much greater than the total carrier concentration in equilibrium. Now, if this is the case we start with our equation that was there earlier, so d n over d t is equal to r times n p minus, sorry B times n p minus B times n naught p naught and in...

Now, if I have this condition you can easily see that I cannot neglect delta n times delta p the excess carrier concentration is very high, what I can neglect is n naught p naught and in in that situation. Then this will result in if I am looking only in terms of excess carrier concentration d delta n d t is going to be equal to B times n naught delta p plus p naught delta n plus delta n delta p. Now, earlier we neglected this this cannot be neglected anymore. This is going to remain in the equation and so the rate of change we put in the condition delta n is equal to delta p is going to be B times delta n n naught plus p naught plus delta n square. Now, this is our equation that needs to be solved, then for finding out what would be delta n?

In case of high level injection and the solution for this equation exist as delta n as a function of t is nothing but 1 over B t plus delta n naught inverse. So, this is for high level injection and then the rate for high level injection will be given by negative of d n d t or negative of B over B t plus delta n naught inverse square. Now, we have two recombination rates to be used in our equation, one for low level of injection and the other one for high level of injection. If we are talking about a LED, you can see that this injection rate luminescence from the material is proportional to the recombination rate.

If it is radiative recombination process, then how much light you will get is going to be proportional to these three combination rate? So, this is a application point of view, but now we have two general expressions for recombination rate. If you have only a single process existing, now what will happen if I have more than one processes existing? Some of them we know are radiative and others are non radiative. We have already looked at the processes, which make them radiative and not non radiative.

(Refer Slide Time: 43:18)



$$R = \frac{\Delta n}{\tau_R} + \frac{\Delta n}{\tau_{NR}}$$ [low level of excitation]

$$= \frac{\Delta n}{\tau_{eff}}$$

$$\frac{1}{\tau_{eff}} = \frac{\tau_{NR}\,\tau_R}{\tau_{NR} + \tau_R} \; ; \quad \tau_{eff} = \frac{1/\tau_R}{1/\tau_R + 1/\tau_{NR}}$$

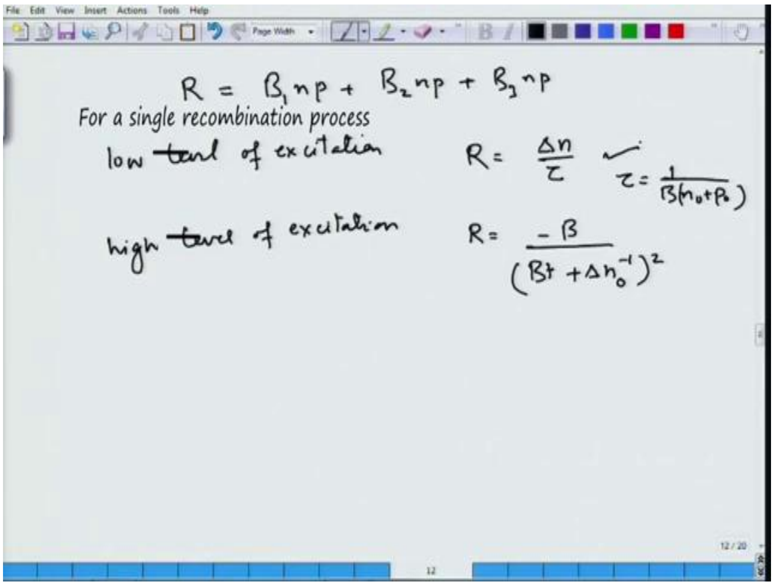
$$\tau_R << \tau_{NR} \Rightarrow$$ luminescence LED material

In that case my recombination rate as I have just discussed is going to be equal to... Let us say I am talking about two type of processes; one being overall radiative, one being non radiative. Looking at a low injection level low excitation level will be delta n over tau radiative process plus delta n over tau non radiative process looking at the rate equation for low level of excitation. Now, this is often people equate it to an effective life time an make it call it tau delta n over tau effective, where basically 1 over tau effective is equal to tau n r tau r over tau n r plus tau r or if you want to reverse it. This is this is sometimes also written as the effective life time is 1 over tau r over 1 over plus 1 over tau n r. Now, this is an interesting equation to observe becausen what it says is that if I have two processes in which the radiative process is equal to the non-radiative recombination process, then I am going to lose some of the light in a heat and some will come out as light.

But if for some reason the processes which are non radiative become much much faster. Then I may have overall recombination rate which is which is going to give any radiative emission. Hence, this is the tau effective is a interesting parameter to tell about the efficiency of luminescence. If tau r is much much less than the tau n r, then this is good for our for luminescence and this would be a good LED material. So, far what we have, I will just summarize, what we have learnt about generation recombination processes? We have looked at generation of electron and hole pairs through various mechanisms semiconductor. It could be transition when electron goes from valence band directly to conduction band being band to band transition. It could be a transition where electron goes two valence band via R G centre.

R G centres are basically impurities or impurity defect complexes which are somewhere giving energy levels in the mid-gap of the semiconductor. It can do recombination through excitons or through auger process. Similarly, you can have generation via impact ionization or you can have generation via R G centres. Then we looked at, we have already looked at generation rate. In earlier lecture today, we looked at in a special cases what would be the recombination rate, a general expression for recombination rate is was given as B times n p.

(Refer Slide Time: 46:52)



$$R = B_1 np + B_2 np + B_3 np$$

For a single recombination process

low ~~level~~ of excitation $R = \frac{\Delta n}{\tau}$ ✓ $\tau = \frac{1}{B(n_0 + p_0)}$

high ~~level~~ of excitation $R = \frac{-B}{(Bt + \Delta n_0^{-1})^2}$

Then we will we will defined for each recombination process a different rate constant and then for two special cases, we have shown for low level of excitation. That recombination rate is nothing but delta n over tau and where tau is given by 1 over B n naught plus p naught. For high level excitation R will be given by negative of B over and anytime we need to use the recombination rate depending on which situation is there. We can use these equations directly or use a general expression. If you do not know whether the level of excitation is low or high, generally in most of the device physics examples we will take up here in simple devices. We take the case of low level excitation and solve the equations. Now, at the end of this lecture, we have expressions for generation rate for electron.