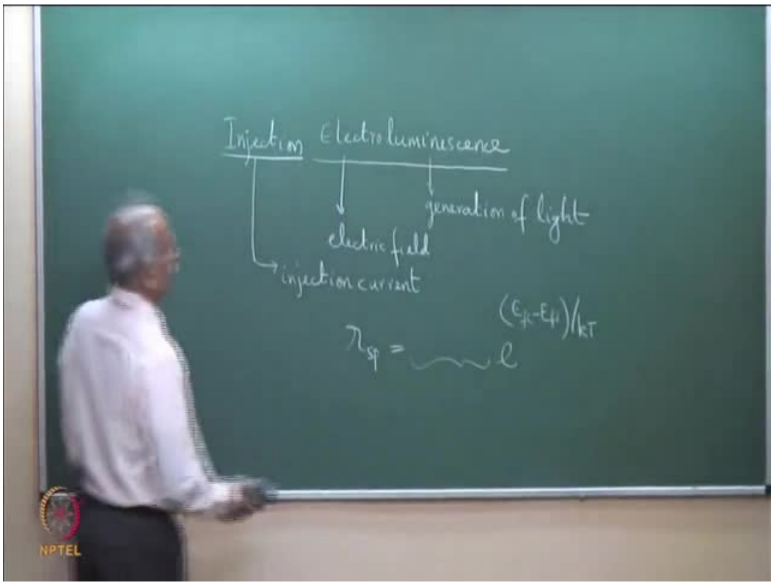
Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 27
Injection Electroluminescence
Part-III, Semiconductor Light Sources

(Refer Slide Time: 00:52)



In this part three of this course, we are primarily discussed about semiconductor light sources a structure, device structure, principle of operation characteristics and output characteristics; this will be mainly covered in this part of course. So, we started with the injection electroluminescence, injection electroluminescence.

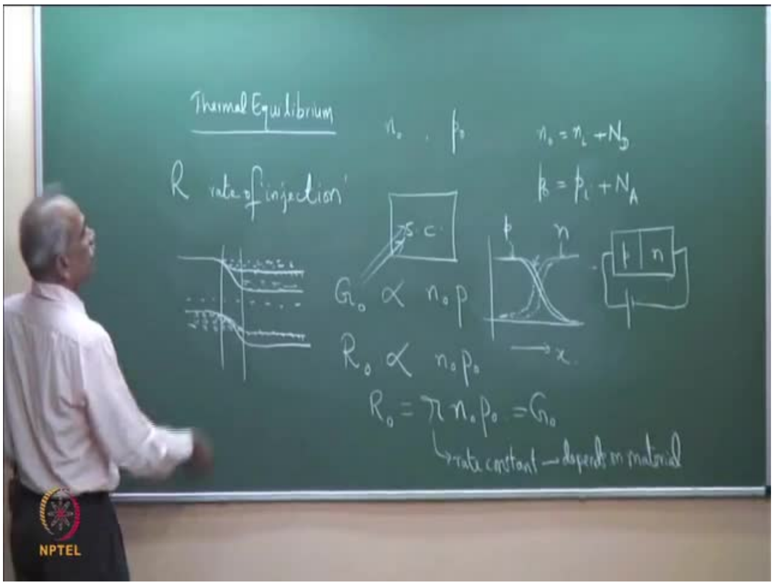
So, electroluminescence, electroluminescence refers to luminescence in the presence of the electric field luminescence. That is generation of light, of light in the presence of electric in the presence of electric field and injection electroluminescence, injection electroluminescence refers to generation of light in the presence of an injection current this injection refers to injection current.

So, generation of light in the presence of an injection current is injection electroluminescence. We are primarily concerned with injection current in forward bias p n junction in the junction area; we are interest in junction area or active region because we will have when you forward bias. We will have Quasi Fermi levels and difference separation between Quasi Fermi levels can be controlled for the forward bias. This will determine or this will enhance the emission efficiency or if you recall the rate of spontaneous emission.

We had an expression for rate of spontaneous emission this expression whatever expression that you had will get multiplied by e to the power E f c minus E f v by k t. If you forward bias the junction where E f c minus E f v will be is a separation between the Quasi Fermi levels. So, by choosing appropriate separation here you can change the rate of spontaneous emission which is nothing but the number of emission per unit time per unit volume from the material can be increased by order of magnitude so that you can have significant emission of light. So, we are interested primarily in injection electroluminescence.

Let us recall some amount of because we are now discussing generation of light and light generation comes from recombination of electrons and holes in a semiconductor. Let us first start with discussion brief discussion on the rate of generation and recombination of carriers in a semiconductor rate of generation to recombination.

(Refer Slide Time: 03:45)



If you consider is semiconductor acting the thermal equilibrium, we are looking at thermal equilibrium. Let n 0 are p 0, the carrier concentration in this piece of semiconductor. This is a semiconductor n 0 and p 0 is the steady state carrier concentrations in this semiconductor. This semiconductor may be p doped or n doped or as in the case of the junction it would be p and n. So, n 0 here refers to n i plus N D, if it is n doped where n is the donor concentration intrinsic plus donor concentration and p 0 is pi which is equal to n i intrinsic concentration plus the acceptor around concentration.

So, n 0 and p 0 are the carrier concentration in thermal equilibrium, then the rate of generation the rate of generation. If I want to call it as G 0 rate of generation is proportional to n 0 into p 0 and rate of recombination R 0 is the same as the rate of generation. So, this is n 0 and p 0 we see n 0 and p 0 are the carriers available in the semiconductor.

In a semiconductor, as we discussed earlier there is continuously carriers are generated because of thermal energy carriers continuously make upward transition, but also they make downward transition, which means electrons keep recombining with holes. But at any at steady state there is n 0 is number of carriers here, the concentration of carriers and p 0 is the concentration of hole. Therefore, the rate of this is generation of carriers, absorption of energy or may be thermal energy because we are in thermal equilibrium that generation rate of generation and rate of recombination.

The rate of recombination is proportional to n 0 and p 0 which we can write as a proportionality constant rate constant R into n 0 p 0, since it is in thermal equilibrium, rate of recombination must be equal to rate of generation. Therefore, R 0 is equal to R into this must be equal to G 0 rate of recombination, R 0 is rate of recombination is proportional to this R is rate constant. This is rate constant proportionality constant which depends on the property of the material depends on the material when I say material. It will depend on the whether it is a direct band gap material or indirect band gap material.

It will also depend on the defect density in the material traps and defects in the material. So, it depends on the material the rate constant, so R 0 rate of generation is equal to the rate of recombination. Assume that now we put a beam of light separate from outside, which creates additional electrons and holes. We are now moving to quasi equilibrium somehow if we create additional electrons or holes or if R is the rate of injection rate of injection. That is generation of carriers additional not thermal additional rate of injection or generation of carriers why do I use the word injection, because, normally we have this additional carriers injected through a forward bias p n junction, that is why we used the word injection.

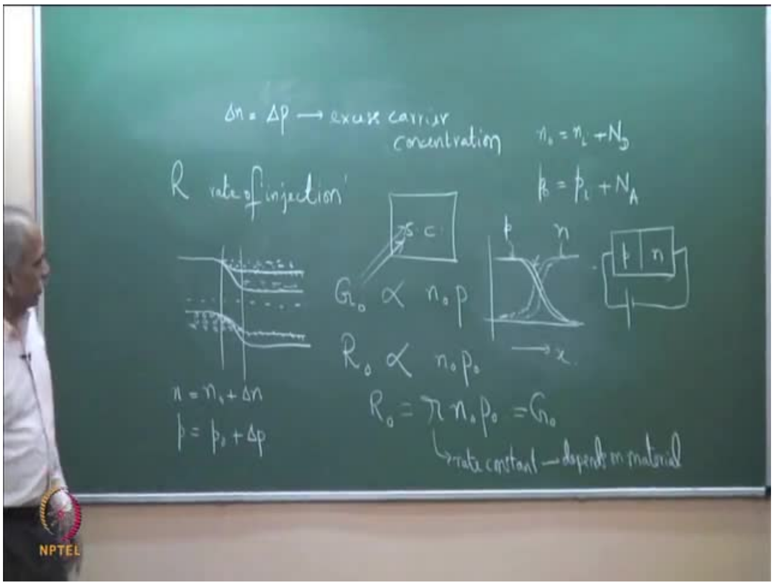
So, you take a p n junction and forward bias this p n then as you as we have seen this carrier concentration and how the profile changes. So, if you plot the p and n concentration, so this is p side and this is n side, so p concentration varies like this and drops down as you go across the junction and this is the electron concentration. So, this is n and this is p carrier concentration if you inject, if you forward bias the diode then that there will be more carriers injected into the junction region here. So, this is with forward bias this is with forward bias and similarly, there will be more electron injected into the junction region.

So, if you look at the junction region you recall again from the various pictures whichever picture is convenient to you, you can look at that. So, this is the band diagram, energy band diagram of the p n structure before forward biasing, once you forward bias this raises up this also comes up. So, let me differentiate this part to show that this is the forward bias region and then we have earlier electron were up to this.

Now, electron has come up to this here, they have moved to this side you can see here and earlier originally holes were up to this. Now, because this band has moved forward holes have come up to this, which means the junction region here, where we have excess carrier concentration excess of electron and holes, excess because of the injection.

Therefore, if I look at the junction region then if R is the rate of injection which means if delta n and delta p. So, delta n equal to delta p is the rate of delta n equal to delta is the rate of carrier injection that is excess carrier concentration excess carrier concentration. This is quite simple let us just speeding because we have covered all of these basics earlier.

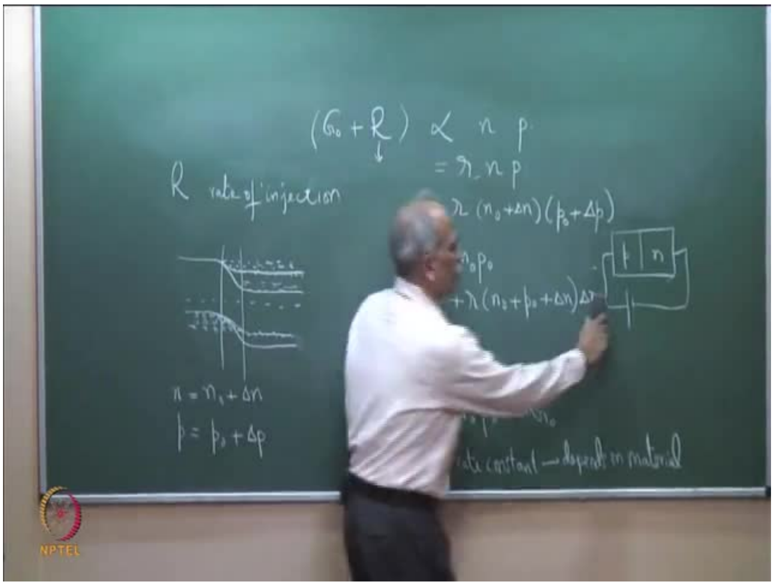
(Refer Slide Time: 11:15)



Then, I have n is equal to n 0 plus delta n and p is equal to p 0 plus delta p delta p is equal to delta n. If you think of right generative then also for every electron generated here, one hole will be left behind. Similarly, when you inject current for every electron which is coming from the negative side here a hole will be released here. Therefore, delta n is equal to delta p always whether it is by illumination or by current. Therefore, n is equal to n 0 plus delta n p is equal to p 0 plus delta and therefore, we now have rate of generation G 0 plus R.

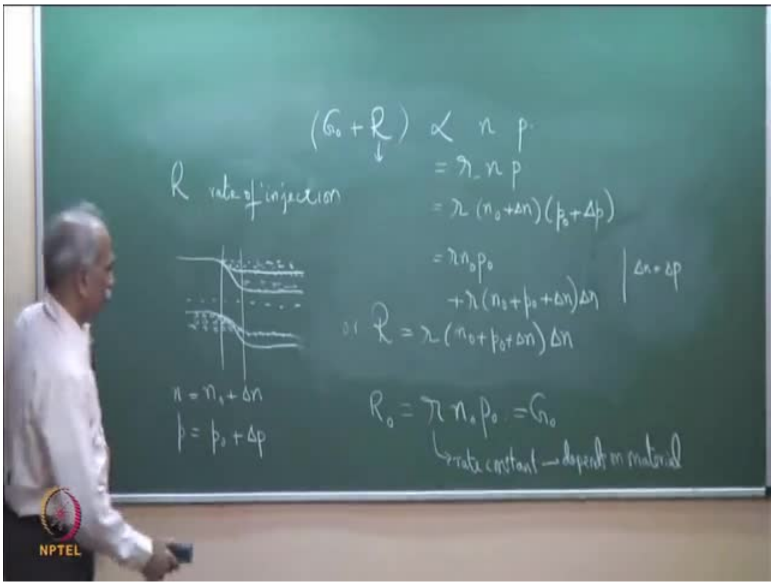
This is R is the rate of injection, we see rate of generation due to thermal energy was G 0 plus R is the rate of injection of carrier. Therefore, G 0 plus R this is proportional to n into p or this is equal to the rate constant into n into p what is n, n is n 0 plus delta n excess carrier concentration p is p 0 plus delta p. Therefore, this is equal to R into n 0 plus delta n plus into p plus delta p 0 plus delta that is equal to R into n 0. So, n 0 p 0 just multiply this p 0 plus R into n 0 plus p 0 plus delta n into delta n, delta n is equal to delta p. So, simply multiply 4 terms n 0, p 0, n 0 delta p delta n p 0 and delta n into delta p, so I have taken one delta n here.

(Refer Slide Time: 13:56)



Recalling that delta n is equal to delta p delta n equal to delta p, what is the first term R n 0 p 0, R n 0 p 0 is nothing but G 0, therefore G 0 plus R is equal to this or R, the rate of injection is related to this. So, R into n 0 plus p 0 plus delta n into delta n, what is the unit of delta n carrier concentration, this is concentration means the unit here is per cc or meter cube.

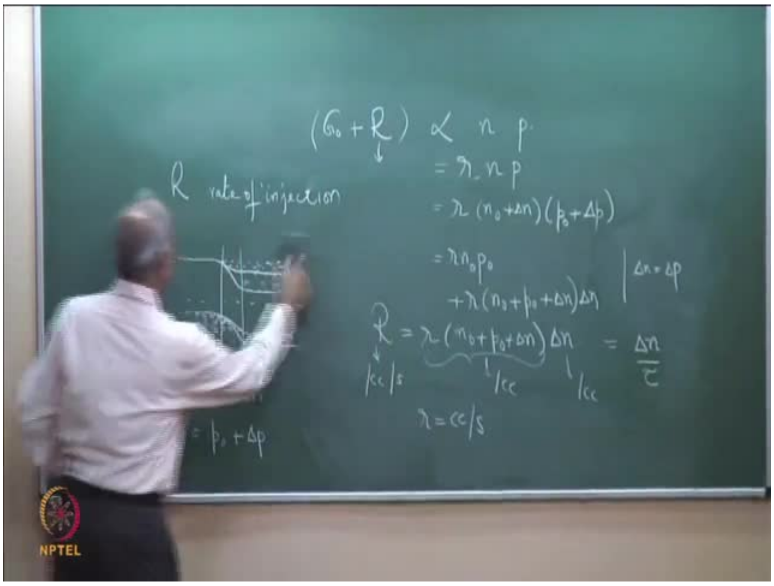
(Refer Slide Time: 14:44)



This is also per cc this whole term in the bracket, rate of injection is number of carriers injected per unit time per unit volume. So, this is number per cc per second, the rate of injection here therefore, what is the unit of R.

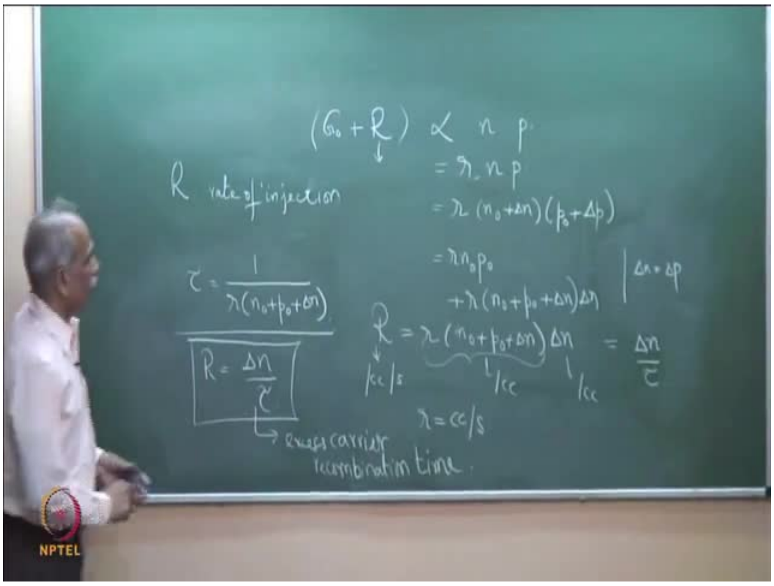
So, one cc cancels with one cc, so R will have rate of injection, so this is per cc therefore, the rate constant R here, is unit of cc per second. This R is equal, so this I write as delta n into tau delta n into tau where this whole thing. So, this is the unit of R and this is the unit of cc. Therefore, this whole quantity has unit of per second, we see this quantity is unit of per second. Therefore, this I am writing this as delta n by tau because this is per second, so denominator there is tau no confusions R is equal to this.

(Refer Slide Time: 16:49)



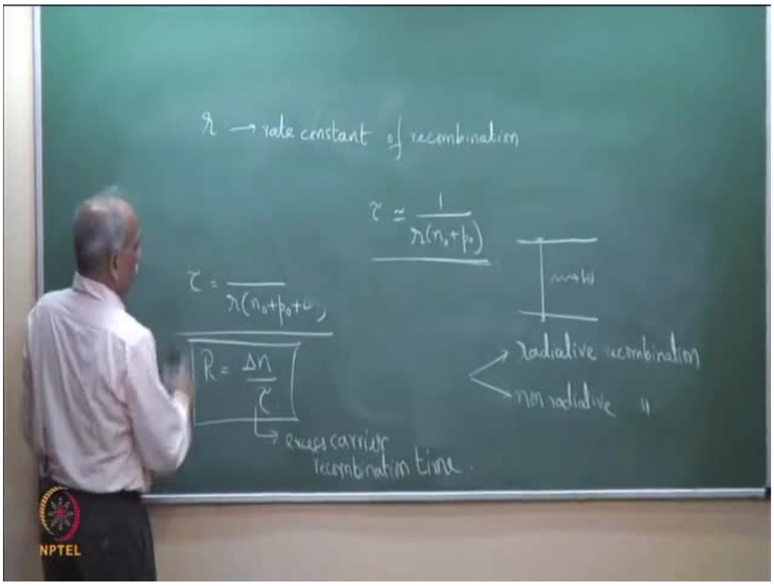
I am writing this expression as delta n by tau where, tau is equal to 1 divided by R into n 0 plus p 0 plus delta n.

(Refer Slide Time: 16:46)



If I call this quantity as 1 by tau it is delta n by tau, but I wrote all these units just to say that yes indeed this as units of inverse time. Therefore, it is this can be represented as some 1 by tau this tau, so R is equal to delta n by tau this is an important expression. This tau is called the excess carrier recombination time, excess carrier recombination time, if the injection rate delta n is relatively small injection rate R is relatively small.

(Refer Slide Time: 17:58)



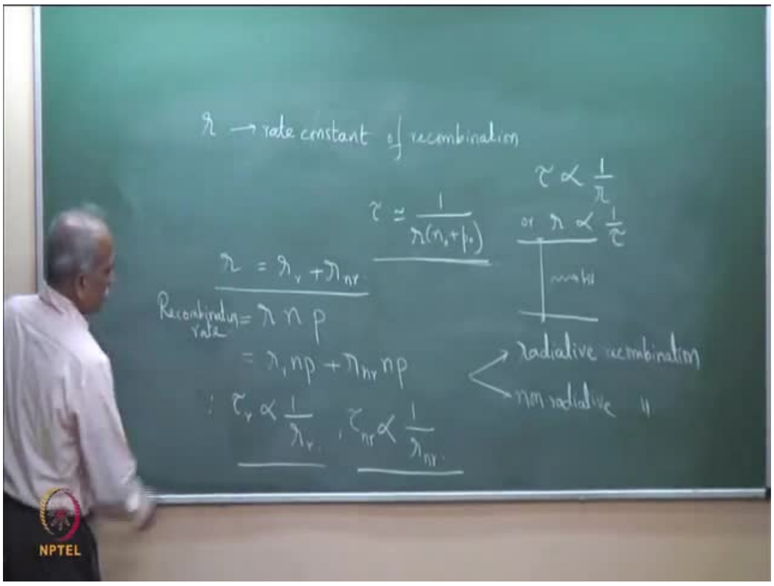
So, delta n if delta n is much less than n 0 and p 0, then this can be written as tau is approximately equal to 1 divided by R equal into n 0 plus p 0, R is a material parameter, why we are interested in bring tau is because time is a measurable parameter. That is life time of carriers is a measurable parameter experimentally. You can measure this was just a rate constant, proportionally constant, but tau is a recombination time, which is a measurable parameter before I proceed further this is approximately equal, but as you will appreciate that if delta n is very large then the life time here. Excess carrier recombination time tau will depend on delta n, when the delta n becomes large in the denominator here.

Then it can no more be neglected with respect to these and then you will indeed see that tow is also a function of delta n. The recombination time will depend on the injection carrier rate for higher injection rates for moderate or low injection rates when delta m is much less compared to n 0 and p 0.

It is almost independent and you talk of a carrier recombination time delta tau, recombination time tau in a given material, because it depends only on the material its carrier concentration equilibrium carrier concentration and the rate constant tau. Now, R is a rate constant for recombination it is a rate constant of recombination, there are two types of recombination possible.

We have seen that transition and electron making a downward transition in and making a recombination electron and whole recombination here, mainly two emission of a photon in this case, the transition is called radiative transition. So, radiative transition, radiation recombination or the electron may make a recombination without the emission of any photon and in that case it is called non radiative recombination.

(Refer Slide Time: 21:26)

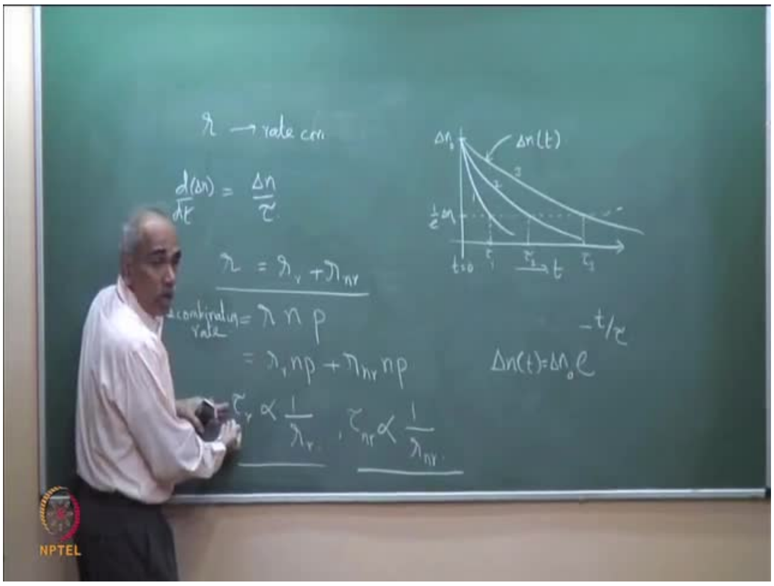


So, the recombination has radiative part and a non radiative part accordingly the total recombination. Therefore, will have radiative part and non radiative part and we have R is equal to r plus r n r, recombination r. We see this recombination r is proportional to r into n into p generation or recombination is proportional to if the recombination comprise of radiative and non radiative then I will have to write this as r r into n p plus r n r into n p. So, this means when I write like this that the rate constant will comprise of a radiative part and non radiative part so do not use r here, you can write recombination because r I have used specifically for injection rates, so recombination.

So, recombination rate recombination rate is proportional to n and p recombination rate is proportional to the number of electron and number of holes that is why it is proportional to the product and proportionality constant is r. The recombination comprise of radiative part and a non radiative part and if I call r r as the radiative rate constant and r n r as the non radiative rate constant then I can write like this. Now, from here you can see that tau is inversely proportional to one by r or r is inversely proportional to 1 by tau. Therefore, I can define a life time or a recombination time tau r, which is proportional to 1 over r r and a tau n r which is proportional to 1 over r n r.

We see this, it will all became clear when we reach the required results right. Now, what we know is recombination comprises of a radiative part and non radiative part accordingly I have split r into r r plus r n r.

Since, the rate constant is inversely proportional to a time constant, therefore, we define a radiative recombination life time tau r and a non radiative recombination time tau nr. They may be very different and so this is what I have defined, why we have define, it will become clear. Now, before I proceed, let me again give you an idea about this lifetime. I am sure many of you know this and some of you have measured also minority carrier life time in semiconductors and so on.



So, what is this life time, what it means is life time at t is equal to 0. So, this is at t is equal to 0 if you inject a certain carrier concentration delta n 0 here delta n 0 that is you have a material in this. Let us say a burst of light has created delta n 0 and delta p 0.

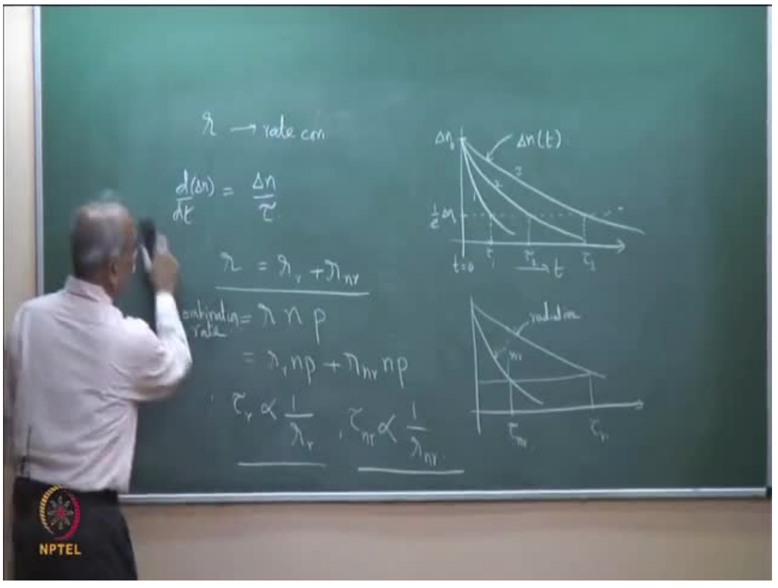
Then it is only instantaneous it is like and impulse it his created delta n 0 and delta p 0, then with time because of recombination this continuously drops down like this. The excess carrier drop goes on reducing because they had recombining if they recombine faster, then this rate will fall faster. If they recombine slowly, then this will go very slowly and the tau that you have you can find this from this expression delta n by tau.

So, this is nothing but d by d t of delta n which is a function of time this is delta n 0, but whatever we are plotting is delta n with time. How the excess carrier concentration is changing with time in the material, so, this is and where it falls to 1 by e. So, this is 1 by e of delta n because if you differentiate this then d of delta and bring delta n here and integrate then you will get this as dropping as e to the power minus t by tau.

So, the rate at which it will drop you will get a function here delta n of t is equal to delta n 0 into e to the power minus t by tau, and what is the tau. So, 1 by e of delta n 0 if you draw these line then you will get this is tau so tau 1 so this is case 1, case 2, case 3 this is tau 2.

Just to recall, the picture what is the picture of this time constant recombination life time, what it means is if tau is very small, which means the recombination rate is very fast they are recombining very fast. Therefore, the life time is very small if tau is very large, it means the recombination rate is very slow this is slow recombination rate. This is important because now we have defined a radiative recombination life time and a non radiative recombination lifetime. In certain materials these two are indeed of the same order and in certain materials they are highly different, very different. You will see that the radiative life time is very large, but non radiative life time is very small.

(Refer Slide Time: 28:03)



For example, if a material, if a particular material has variation like this that the delta n the radiative time is very large, so this is tau r and the non radiative time is very small. So, this is tau n r, do not worry how we will differentiate because this is non radiative nr. This is radiative, radiative ground, radiative recombination here I have plotted the total recombination. So, it is referring to tau here, how I have done that I am looking that only non radiative recombination. Only radiative recombination, radiative recombination are very slow and non radiative are very fast, but whether it is radiative or non radiative one electron and one hole is lost that carriers are lost in recombination.

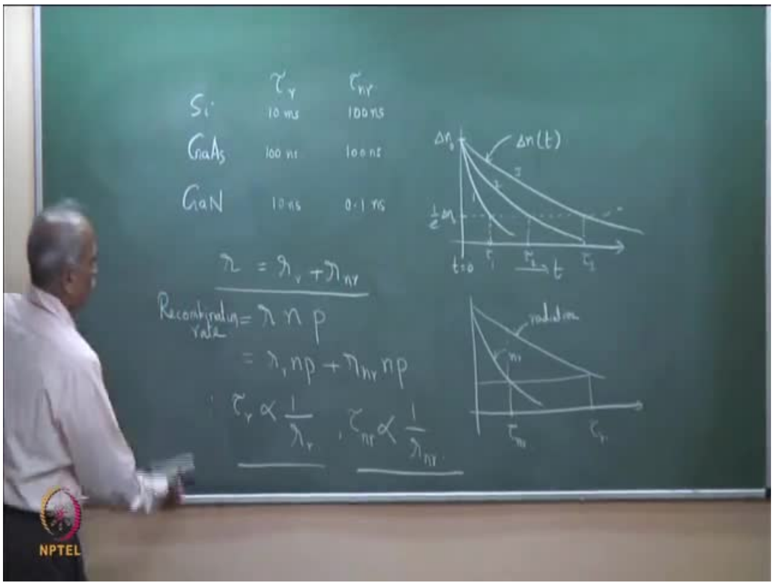
Therefore, in a particular material if non radiative life time is very short which means the carriers combine very quickly mostly by non radiative. Therefore, within this time very few radiation transitions have taken place, most carriers are already lost by non radiative transition. Therefore, the contribution of radiative transitions will be very little in the case of a material which has a very small tau n r. You will appreciate this now if I write the typical example.

Let us take silicon gallium arsenide and if you want gallium nitrate what is tau r and what is tau n r typical material. It will depend on defect density and carrier concentration and so on. A material where let us say n 0 and p 0 is of the order of 10 to the power of 17 per cc.

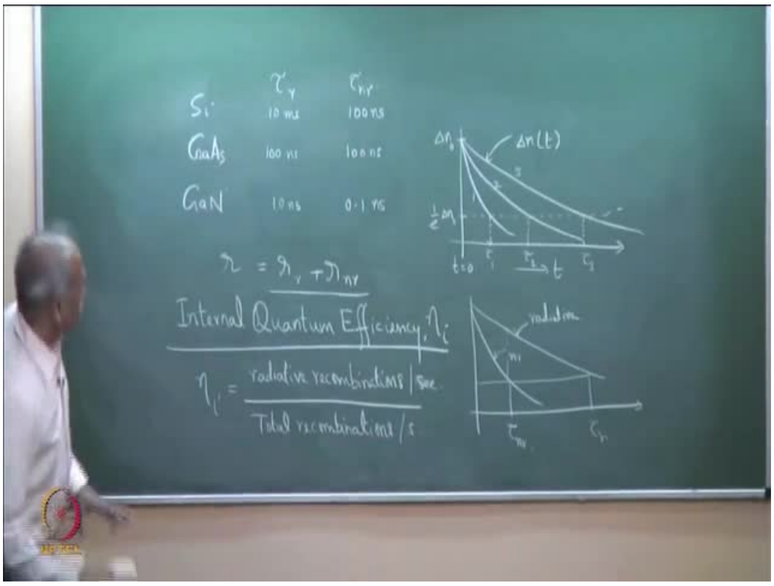
In silicon the radiative recombination of the order of 10 milliseconds non radiative is of the order of 100 nanoseconds, in gallium arsenide this is of the order of 100 nanoseconds this is of the order of 100 nanoseconds. If you go to gallium nitrite this is of the order of the 1 second for gallium arsenide it is approximately tau r is 10 nanoseconds and this is 10 to the power minus 1 or 0.1 nanoseconds. Let me see if I have the values for gallium nitrate tau r is 10 nanoseconds and this is 0.1 nanoseconds that of tau n r. You see for gallium arsenide both radiative and non radiative are equally probable.

The time is same recombination, time is the same which means the rate at which recombination is taking place is the same if you take silicon the rate for radiative is much larger 10 millisecond, this is 100 nanoseconds. So, the non radiative life time is much smaller here, which means if I have 1 million recombinations taking place, primarily most of them will be by non radiative and very few will be radiative, do you follow the importance of the life time.

One is non radiative, another is radiative whichever life time is short which means that is the reaction which takes place very fast or that is the recombination which is taking because small life time with large rate constant they are inverse. So, the rate constant is very large for that now why did I discussed all of these is very simple that we are interested in a parameter which is most important called Internal Quantum Efficiency.

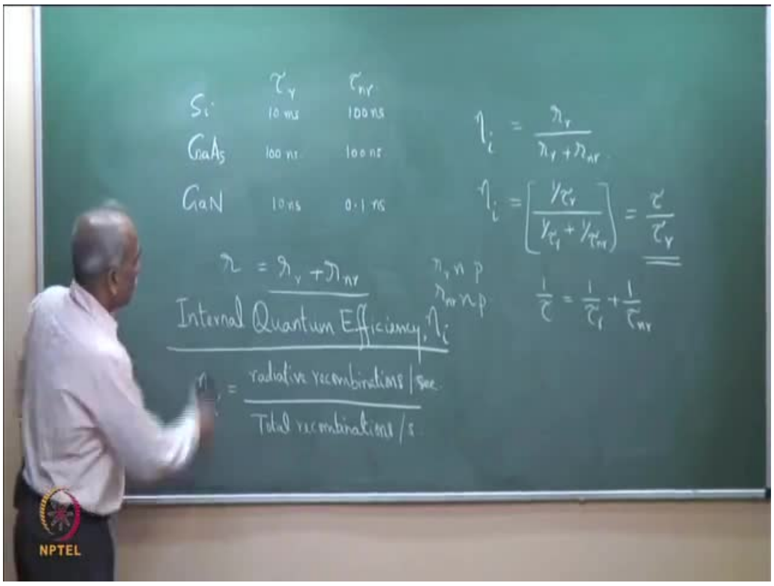


(Refer Slide Time: 32:29)



Internal Quantum Efficiency in all semiconductor sources, this is the most important parameter which generates, which determines the efficiency of generation of light efficiency of generation of light. What is internal quantum efficiency? It is very simple definition, it is out of the total recombination it is the ratio of radiative recombination to the total recombination. So, eta i is equal to ratio of radiative recombination, if you want you can write per unit time that is per second divided by total recombination total recombination per second. Let me erase this if time permits, we will discuss a technique to measure the life time, let us now continue.

(Refer Slide Time: 34:02)

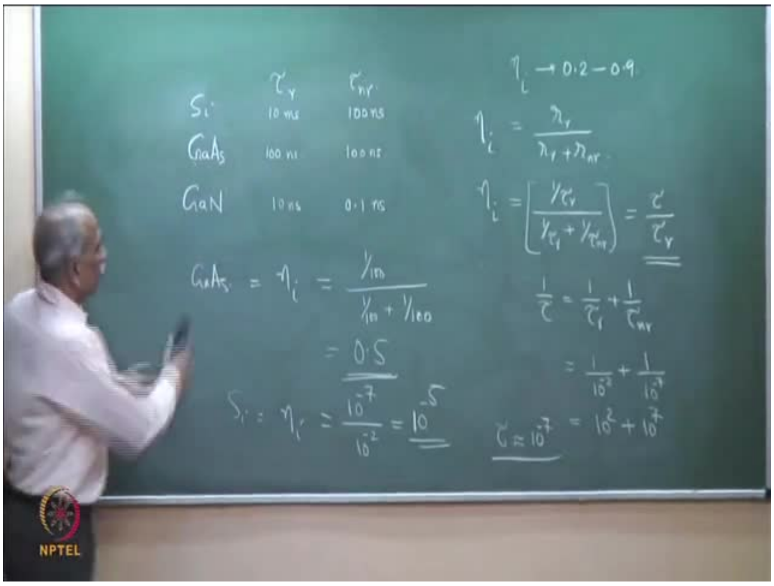


That means eta i is equal to r r divided by r r plus r n r, you agree because radiative recombination, where r r into n into p n n radiative recombination, where r n r into n into p. Therefore, total is r r n into p plus r n r n into p, so, n p is common in all the places. Therefore, this is the ratio, but we have something here or this total, this is equal to r r is proportional to inversely proportional to tau r, which means 1 divided by tau r divided by 1 over tau r plus 1 over tau n r because the proportional constant is same for the given material. This is 1 over tau r plus 1 over tau n r is 1 over tau is equal to 1 to 1 over tau r plus 1 over tau nr right r is equal to r r plus this.

Therefore, this is inversely proportional, so 1 over tau r is equal to 1 over tau r plus 1 over tau nr 1 over tau equal to 1 over tau r plus 1 over tau n. That is what I have written denominator is nothing but 1 over tau so this is equal to tau divided by tau r eta i is equal to tau divided by tau r, what is this means, what have I written here. If there are this tells us if there are 100 recombination taking place. If 10 of them lead to the generation of photon and 90 of them do not lead to the generation of photon.

Then this ratio is 10 divided by 100 which is 0.1 eta i is 0.1 means 10 percent of the total recombination lead to generation of photon if eta i equal to 0.5. It means 50 percent out of all the recombinations 50 percent will lead to the generation of photon, while 50 percent do not they are non radiative recombination.

I have put same numbers here, so which is interesting therefore, to see what is eta i for this material, so you can take let us take gallium arsenide first of gallium arsenide.



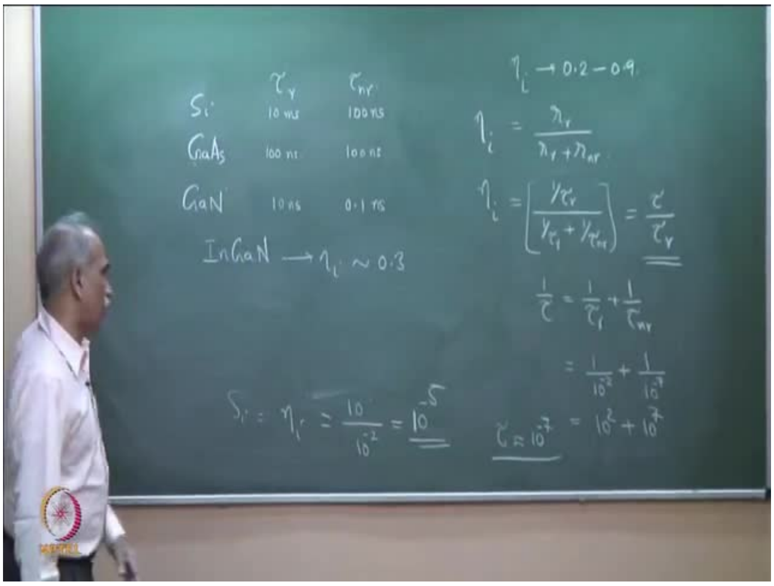
So, eta i is equal to 1 over tau r divided by 1 over tau r plus 1 over, so this is 1 over 100 nanosecond all are nanosecond, so I do not have to write 1 over 100 plus 1 over 100, how much is this. So, x divided by 2x whatever be the 1 over 100 is 0.5 if you look at silicon. So, for silicon eta i is equal to if you want we can use this directly, see this is the expression 1 over tau is equal to 1 over tau r this is 10 millisecond. So, 10 milliseconds is equal to 10 to the power of minus 2 second plus 1 divided by 100 nanosecond 10 power minus 7 here. So, this is equal to this is a very large number because one over 10 power minus 2 this is 10 power 2 plus 10 power 7 which is approximately 10 power 7 of 10 power 2 is negligibly small.

Therefore, tau is equal to approximately equal to 10 power minus 7 because this number is 1 over tau is about 1 10 to the power of 7. Therefore, tau is approximately this therefore, tau r, so 10 power minus 7 divided by tau r tau r is 10 milliseconds. So, 10 to the power minus 2 is this is approximately equal to the internal quantum efficiency for silicon is 10 power minus 5 which means out of 100,000 recombination, one will generate photon are the rest do not generate photon. Similarly, you can find out for gallium nitrate here, this is 10 nanoseconds, this is 0.1 nanosecond.

I think this will came out to be 10 power minus 2 approximately 10 power minus 2 check what you get for this so the efficiency is relatively lower here, but, see that gallium arsenide, so this is an indirect band gap material this is a direct band gap material. In general direct band gap materials have eta i in the range 0.2 to 0.9 and indirect band gap material have generally very low internal quantum efficiency 10 power minus 3 minus 4 minus 5 minus 6 very small numbers, what does this tell you.

If you want to realize a source we should choose a material which is direct band gap which has a large eta i incidentally gallium nitrate is also a direct band gap material, but this does not have large eta i. Therefore, whenever sources are node this wide band gap semiconductor when people make source like for the blue e d.

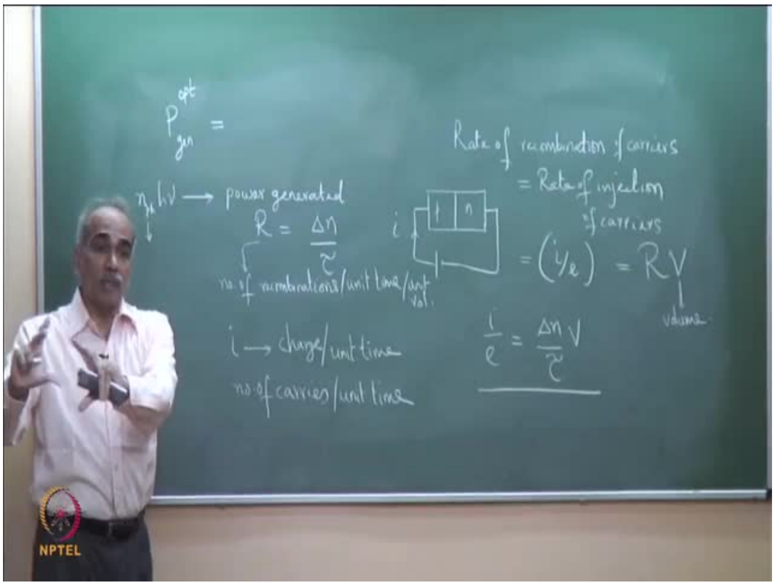
(Refer Slide Time: 40:24)



It is indium gallium nitrate which is used the ternary compound indium, gallium nitrate this has a eta i of approximately 0.3 this is very small eta i of gallium nitrite, but indium gallium nitrate the ternary compound has a very large internal quantum efficiency. So, the first point i when you choose a material choose to realize sources. Now, we are discussing in this part only about sources eta i the internal quantum efficiency should be as large as possible. So, that there are more radiative transitions non radiative recombination which lead to the generation of photons.

Let us, discuss little bit more about injection electro luminescence. So, one pair of radiative recombination life time and non radiative recombination life time and internal quantum efficiency. Please put some numbers of tau r and tau n r and how to calculate internal quantum efficiency in practical devices, when we say injection we talk in terms of current i if i is the current. We want to relate this to the power generator.

(Refer Slide Time: 41:52)



Now, we want to go to the device what is the power generated so for we have been talking about recombination rate and so many things. Now, we want to came to the device engineers prospective he passes a current I wants to know, what is the optical power generated and how much is available to him. So, if i is the current, let us consider a p n junction we use p n because it is very easy to inject current. So, a forward biased p n junction current there is a current i which flows through the diode, what is the power generate r is equal to delta n into tau, what is r number of carriers recombination.

That is number of recombination per unit time per unit volume this is, how number of recombination per unit time and per unit volume what is i, i is current is charge per unit time rate of change of so charge per unit time. So, what is the number of carriers per unit time, so number of carriers per unit time carriers per unit time please see rate of recombination why a current through.

This because carriers are recombining at the junction region the rate of recombination here is equal to the rate of injection because it is the recombination, which is responsible for current flow. So, everyone recombination here leads to injection of an electron and a hole. So, rate of recombination equal to rate of injection this is the important point rate of injection rate of recombination of carriers equal to rate of injection of recombination of carriers equal to rate of injection of carriers.

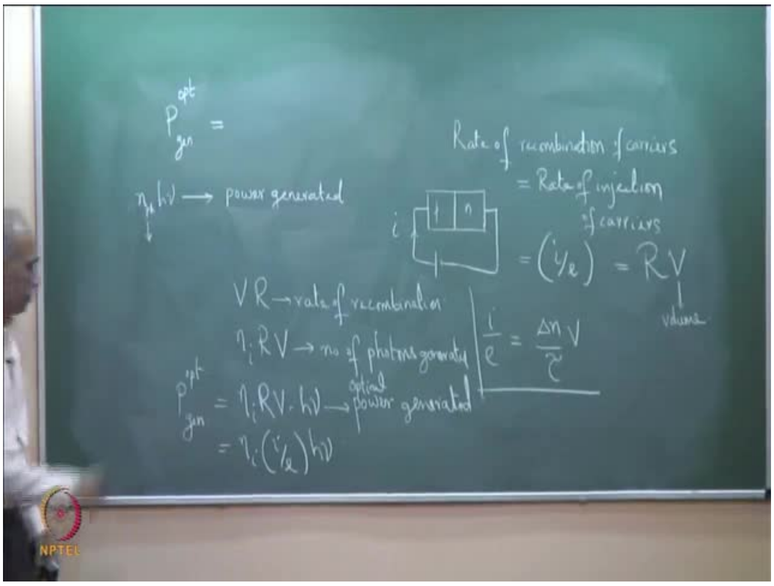
So, let me add the recombination of carriers, please see this the basic definition injection of carriers i is the rate at which the charge flows, what is the number of carrier. That will flow per second, so rate of injection of carrier is equal to I divided by e charge of 1 carrier is e. So, i divided by e will give you rate of injection of carrier, this is equal to rate of recombination of carrier, what is the rate of recombination of carriers. This is unit per volume in the current; there is no unit volume, so r into V where V is the volumes please see the logic.

If r is the rate of recombination then r into v will give you rate of recombination in the volume, because r by definition is rate number of recombination per unit time per unit volume. Therefore, r into V will be number of recombination per unit time which is rate of recombination. So, rate of recombination of carrier is equal to r into V V i by V is equal to r into V, what is r. So, i by e is equal to r is delta n into tau, so delta n by tau into V every recombination. So, what is power generated optical power we are interested in optical optical power generated every recombination radiative recombination.

Every radiative recombination will give us one photon generation, we are interested in power generation if n is the number of photons generated per unit time, what is the power generated n into h nu. The power is generated if n is the number of photons generated per unit time n h nu. The power generated power generating n is the number of photon this n is number please I have also used earlier n for carrier concentration, but this n is number of photon.

If you want you can put n p h for the time being because it was all disappears in a short while finally what you will get is just optical power. How it is related to current that is the device engineer one, but it is to be linked from the basic because all these while we have been talking of carrier recombination. Photon generation, radiative transitions and non radiative transitions which does not mean anything to a device engineer. So, n p h into h n u give you the power generate number of photon is determined by radiative recombination out of all the radiative recombination eta i times radiative recombination eta i times R will give you all.

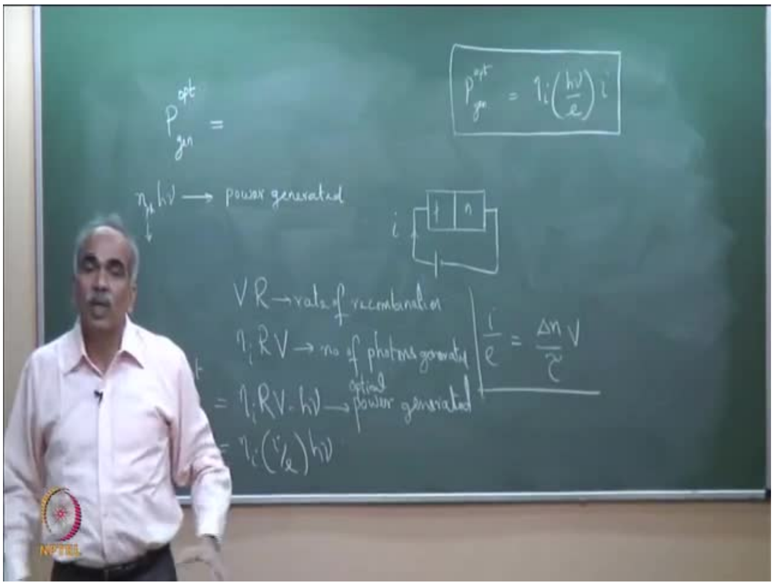
(Refer Slide Time: 48:39)



R is the rate of recombination, so R into v is the rate of recombination out of this eta i is the fractional generation this is rate of recombination, which means number of recombination per unit time in the volume V. So, eta i into r into V is the number of photons generated number of photons generated eta i, because out of all the recombination a fraction eta i will lead to generation of photons eta i into r into V.

This is the number of photon generated multiplied by h n u will give me power n i R V into h n u is the power generated optical power R into V is equal to i by e, so this is equal to p optical p optical generated. So, R V is replaced by i to e so eta i into i by e into h n u eta i into i by e into h n u is the power optical, power generated p optical.

(Refer Slide Time: 50:38)



So, I have got the expression that p optical I am right now writing afterwards we will draw we will deal means, we are dealing with optical power only, just that this point I am writing p optical generated. Therefore, is equal to eta i something can be simplified here h is constant n u is c by lambda and h c by e is 1.24. Anyhow let me keep it as it is, i by e, so h n u by e into i.

So, this is the optical power generated, if you know a material the internal quantum efficiency of the material like any material be calculated for silicon gallium arsenide. If you know what is the band gap h n u is close to e g, so you know this you know e you know the current because current is the one, which you are passing. So, for a given current you can calculate what is the power generated.

So, we are now coming to after how much optical power is generated at this point I am giving emphasis on generation because it only generation you have not yet got output, we have to see what is the output power that we are going to get. So, with this expression I will stop here and continue in the next class, we will see there are different efficiencies which are generated which are defined because all of the generated power does not come out.

Therefore, we have to see an extraction efficiency there is a parameter called extraction efficiency and finally, there is a parameter called wall plug efficiency, which means if you are supplying. So, much of electrical power what is the optical power that you are getting, so p optical divided by p electrical is called the wall plug efficiency. Wall plug because you take the electrical power from the wall plug this is called wall plug efficiency.