Semiconductor Optoelectronics

Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology – Delhi

Lecture - 26
Injection Electroluminescence

So, in this part 3 of this course, we will primarily discuss about semi conductor light sources, structure, device structure, principle of operation, characteristics and output characteristics. These will be mainly covered in this part of the course. So, we start with the injection electroluminescence.

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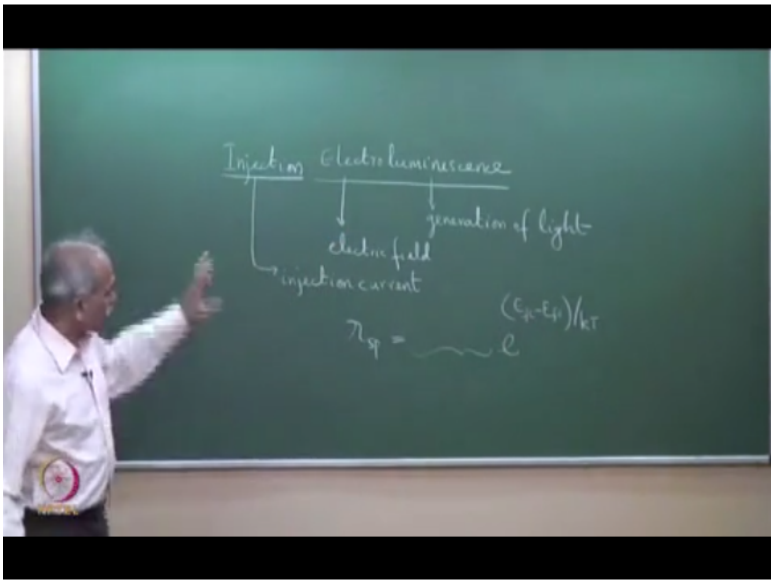

Electroluminescence refers to luminescence in the presence of an electric field. And injection electroluminescence refers to generation of light in the presence of an injection current, this injunction refers to injection current. So, generation of light in the presence of an injection current is injection electroluminescence. We are primarily concerned with injection currents in a forward biased PN junction in the junction area.

We are interested in the junction area or active region because, when you forward biased, we will have Quasi fermi level and the difference separation between the Quasi fermi levels can be controlled by the forward biases and 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 Efc-Efv/KT.

If you forward biase resumption, where Efc-Efv is the 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 emissions per unit time per unit volume from the material can be increased by orders of magnitude and 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 the recombination of electrons and holds in a semi conductor. So, let us first start with a brief discussion on the rate of generation and recombination of carriers in a semiconductor. If you consider a semiconductor at thermal equilibrium, so, we are looking at Thermal equilibrium.

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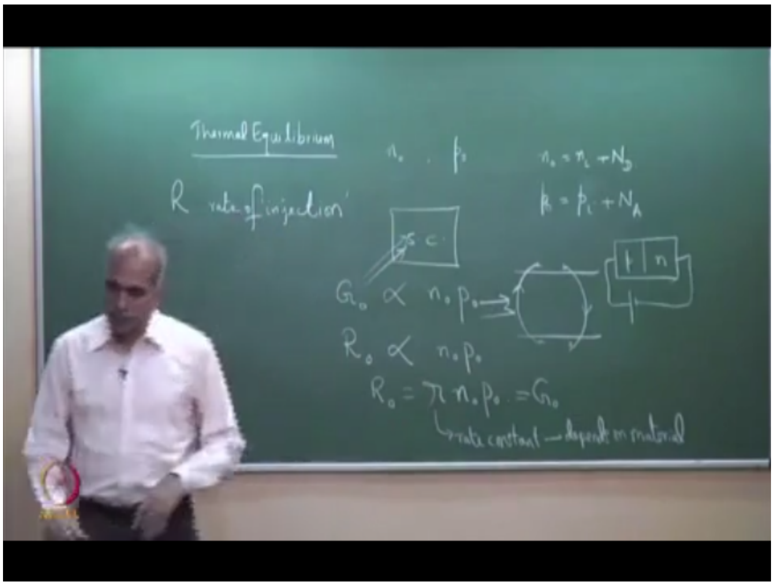

Let n0 and p0 be the carrier concentration in this piece of semiconductor, this is a semiconductor, n0 and p0 are the steady state carrier concentrations in this semiconductor. This semiconductor may be (()) (04:03) or as in the case of the junction, it could be p and n. so, n0 here refers to ni+ND, if it is n doped where N is the donor concentration, intrinsic plus donor concentration and p0 is pi which is = ni, intrinsic concentration plus the acceptor ion concentrator. So, n0 and p0 are the carrier concentrations in thermal equilibrium.

Then the rate of generation, if I want to call it as G0, rate of generation is proportional to n0*p0. And rate of recombination R0, is the same as rate of generation. So, this is n0 and p0. We see n0 and p0 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 holds but at steady state. There is n0 is the number of carriers here, that is called concentration of carriers and p0 is the concentration of force. Therefore, the rate of, this is generation of carriers, absorption of energy or may be thermal energy because we are in thermal equilibrium, that rate of generation and rate of recombination.

The rate of recombination is proportional to n0 and p0, which we can write as a proportionality constant, rate constant r*n0p0. Since it is in thermal equilibrium, rate of recombination must be equal to rate of generation. Therefore, r0 = r*this, must be = G0. Rate of recombination R0 is rate of recombination is proportional to this r, is a rate constant, this is a rate constant, proportionality constant, which depends on the property of the material.

When we say material, it will depend on 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, R0 rate of generation = rate of recombination. Assume that now we put a beam of light separate from outside, which creates additional electrons and out, that is we are now moving to quadric equilibrium.

So, somehow if we create additional electrons or force or if R is the rate of injection, that is generation of carriers additional, not thermal, rate of injection or generation of carriers, why do I use the word injection? Because normally we have these additional carriers injected through a forward biased pn junction. That is why we use the word injection. So, you take a pn junction and forward biased this pn, then as we have seen these carrier concentrations and how the profile changes.

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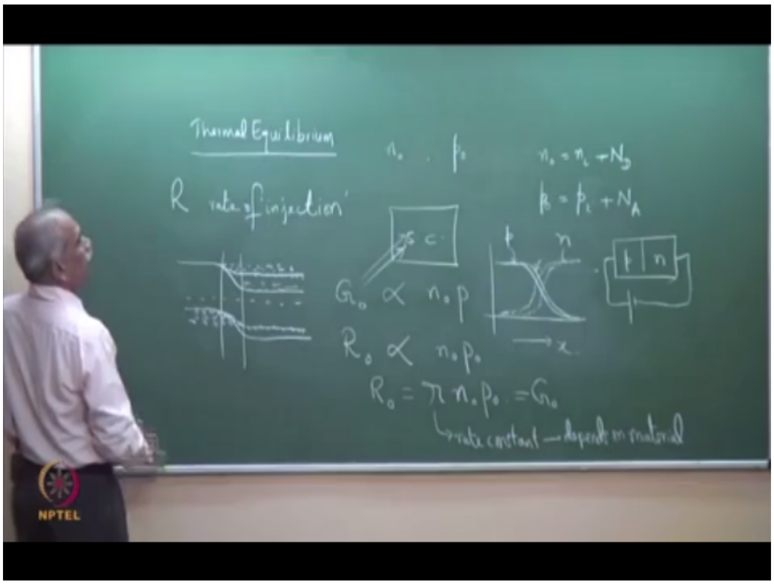

So, if you plot the p and n concentration, so this is p side and this is n side. So, p concentration varies like this and drops down as you go across the junction and this is the electron concentration. So, this is n and this is p, carrier concentration. If you inject, if you forward biase the diode, then there will be more carriers injected into the junction region here. So, this is with forward biase, and similarly, there will be more electrons 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 energy band diagram of the pn structure before forward biasing, once you forward biase, this raises up, this also comes up. So, let me differentiate this part to show that, this is the forward biase region and then we have earlier electrons were up to this.

Now, electrons have 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 electrons and holes, excess of the injection and therefore, if I look at the junction region then, if R is the rate of injection, which means if delta n and delta p.

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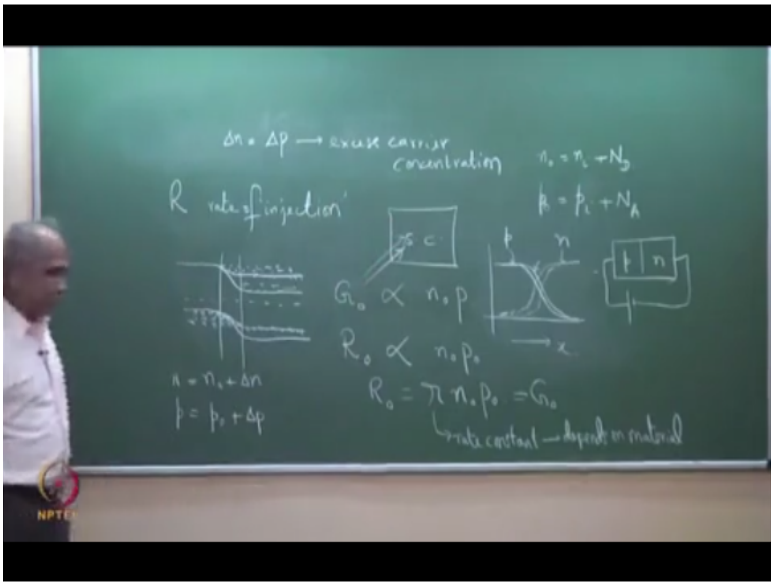

So, delta n = delta p is the rate of delta n = delta p is the rate of carrier injection, that is excess carrier concentration. This is quite simple that is why I am just speeding up because we have covered all of these basics earlier, then I have n=n0+delta n and p=p0+delta p. delta p=delta n. If you think of light generating, 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=delta p always. Whether it is by elimination or by current. Therefore, n=n0+delta n, p=p0+delta p. And therefore, we now have rate of generation G0+R, this R is the rate of injection, please see rate of generation due to thermal energy was G0, R is the rate of injection of carriers. Therefore, G0+R, this is proportional to n*p or this = the rate constant * n*p, what is n? n is n0+delta n, excess carrier concentration, p is p0+delta p.

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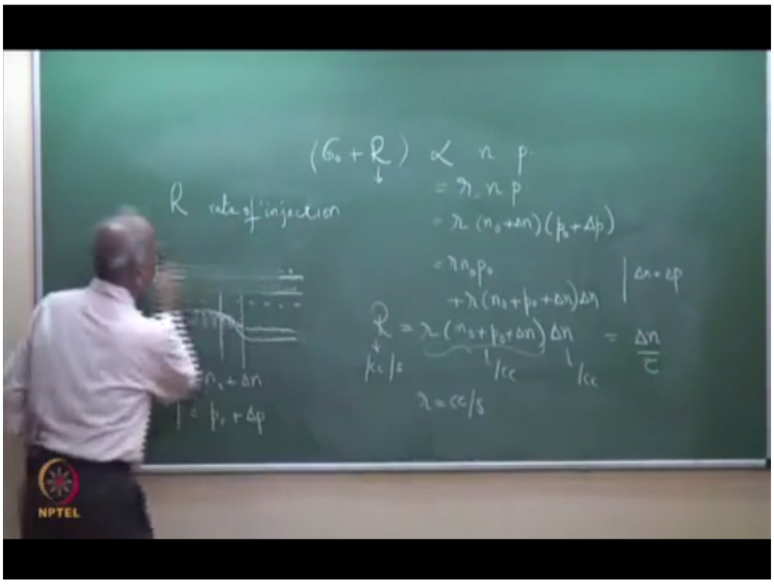

Therefore, this = r*n0+delta n*p0+delta p, that = r*n0p0+r*n0+p0+delta n*delta n, delta n=delta p. so, simply multiply terms n0, p0, n0 delta p, delta n p0 and delta n*delta p. So, I have taken one delta n here outside recalling that delta n=delta p. what is the first term? Rn0p0 is nothing but G0, therefore G0+R=this, or R, the rate of injection is related to this, so r*n0+p0+delta n*delta n.

What is the unit of delta n? carrier concentration, this is concentration means, the unit here is per cc or meter cube, 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, this is per cc, therefore, the rate constant r here is unit of cc per second.

This r=this, I write as delta n*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. Please see, this quantity is unit of per second and therefore, write this as delta n/tau, because this is per second. So, denominator there is tau, no confusions r = this, I am writing this expression as delta n/tau.

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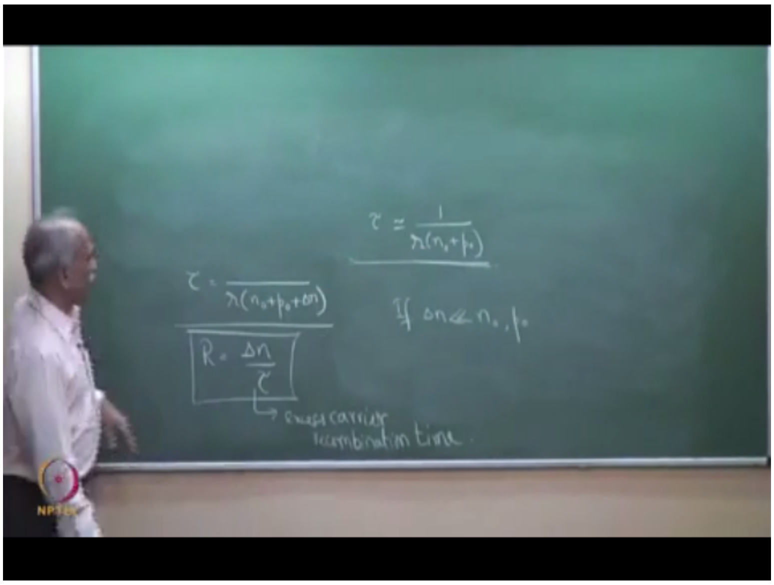

Where tau=1 divided by r*n0+p0+delta n. if I call this quantity as 1/tau, it is delta n/tau, but I wrote all these units just to say that, yes indeed this has units of inverse time. Therefore, it can be represented as some 1/tau. This R=delta n/tau. This is an important expression; this tau is called the excess carrier recombination time. If the injection rate delta n is relatively small, injection rate r is relatively small so that delta n, if delta n is much < n0 and p0. Then this can be written as tau is approximately = 1 divided by r*n0+p0, r is a material parameter.

Why we are interested in bringing tau is because time is a measurable parameter. That is lifetime of carriers is a measurable parameter, experimentally you can measure, this was just a rate constant, proportionality constant. But, tau is a recombination time, which is a measurable parameter. Before I proceed further this is approximately equal to, but, as you will appreciate that if delta n is very large, then the lifetime here, excess carrier recombination time tau will depend on delta n.

When delta n becomes large in the denominator here, then it can no more be neglected with respect to this, and then you will indeed see that tau 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 n is much < compared to n0 and p0, it is almost independent and you top of a carrier recombination time tau in a given material.

Because it depends only on the material, its equilibrium carrier concentrations and the rate constant tau.

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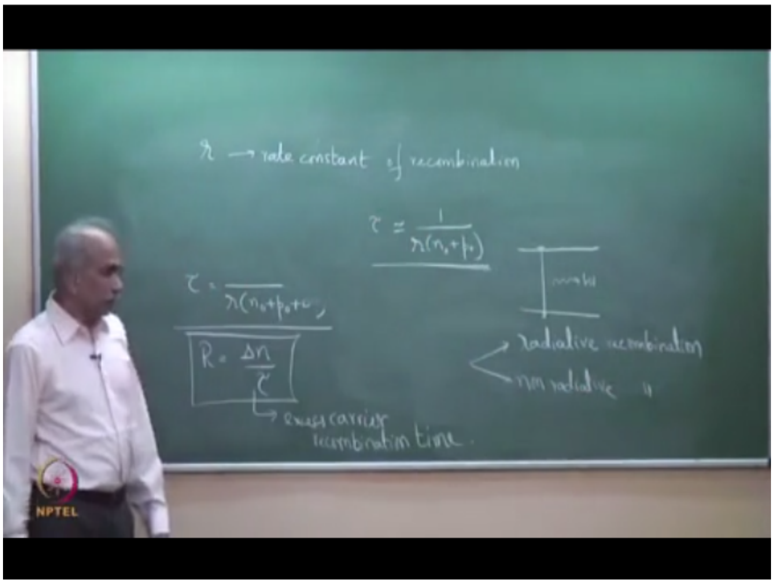

Now, r is a rate constant for recombination. There are two types of recombination's possible, we have seen that transitions and electron making a downward transition in and making a recombination electron and whole recombination here merely to emission of a photon, in this case, the transition is called radiative transition so, radiative recombination or the electron may make a recombination without the emission of any full photon.

And in that case, it is called non-radiative recombination. So, the recombinations have a radiative part and a non-radiative part. Accordingly, the total recombinations therefore will have a radiative part and non-radiative part.

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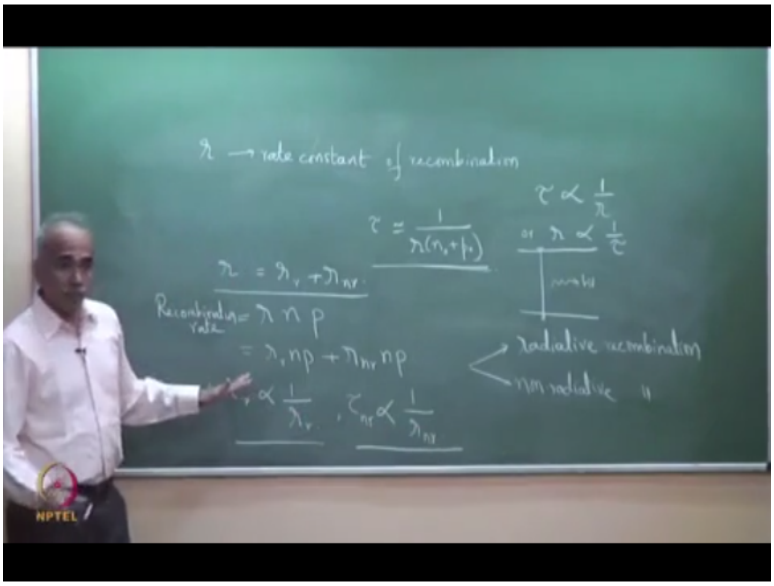

And we have r=rr+rnr, please see this recombination r is proportional to r*n*p generation or recombination is proportional to if the recombinations comprise of radiative and non-radiative, then I will have to write this as rr*np+rnr*np. So, this is the meaning when I write like this, that the rate constant will comprise of a radiative part and a non-radiative part, so not use r here, we can write recombinations because, r I have used as specifically for injection rate.

So, recombination rate is proportional to n and p, and proportional to the number of electrons and number of holes that is why it is proportional to the product and proportionality constant is r, the recombinations comprise of a radiative part and a non-radiative part and if I call rr as the radiative rate constant and rnr as the non-radiative rate constant, then I can write like this okay. Now, from here you can see that, tau is inversely proportional to 1/r or r is inversely proportional to 1/tau.

Therefore, I can define a lifetime or a recombination time tau r, which is proportional to 1 over rr and a tau nr, which is proportional to 1 over rnr, please see this. It will all become clear when we reach the required result. Right now, what we know is recombinations comprise of a radiative part and a non-radiative part accordingly I have split r*rr+rnr and also, 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 defined? 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 lifetime in semi conductors and so on. So, what is this life time?

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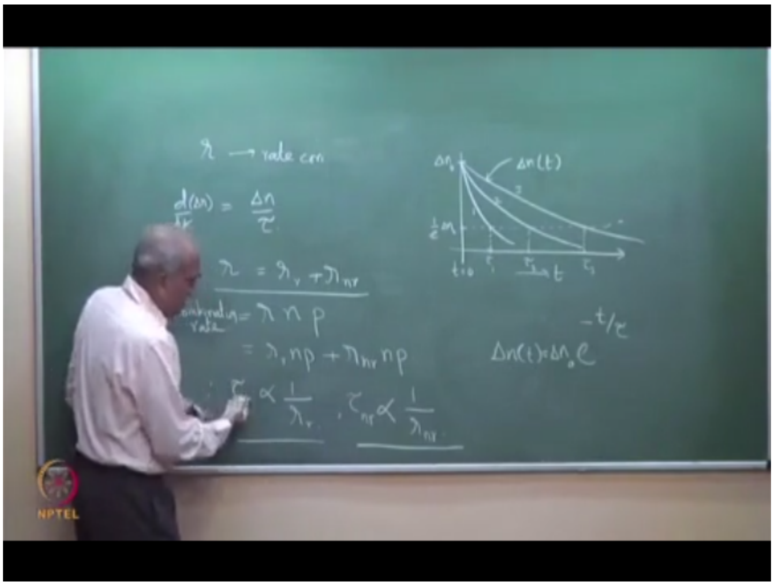

What it means is, lifetime at t=0, if you inject a certain carrier concentration delta n0 here, that is you have a material, in this let us say a burst of light has created delta n0 and delta p0, then it is only instantaneous, it is like an impulse, it has created delta n0 and delta p0, then with time, because of recombination, this continuously drops down like this. The excess carriers go on reducing because they are recombining.

If the 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 from this expression delta n/tau. So, this is nothing but d/dt of delta n, which is a function of time, this is delta n0, but ever 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/e? So, this is 1/e of delta n, because if you differentiate this, then d of delta n, bring delta n here and integrate, then you will get this as dropping as e to the power -t/tau. So, the rate at which it will drop, so, you will get a function here delta n of t = delta n0* e to the power -t/tau. And what is the tau? So, 1/e of delta n0, if you draw this line, then you will get, this is tau. So, tau1, so this is case 1, case 2, case 3.

This is tau 2, just to recall the picture that, what is the picture of this time constant, recombination lifetime. What it means is, if tau is very small, which means the recombination rate is very fast, we are combining very fast. Therefore, the lifetime is very small. If tau is very large, it means the recombination rate is very slow. It is a slow recombination rate. This is important because, now we have defined a radiative recombination lifetime 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 and you will see that the radiative lifetime is very large, but non-radiative lifetime is very small.

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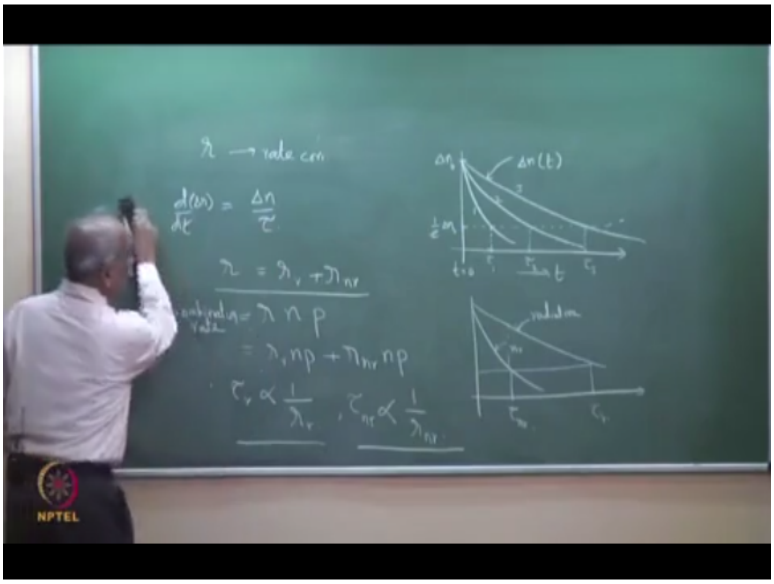

For example, if a particular material has variation like this that the delta n, the radiative time is very large, so, this is tau r and the non-radiative time is very small. So, this is tau nr. Do not worry how we will differentiate between, this is non radiative nr, this is radiative dowm, radiative recombination. Here I have plotted the total recombination. So, it is referring to tau. Here how I have done do not worry about it right now, that I am looking at only non-radiative recombinations and only radiative recombinations.

Radiative recombinations are very slow, non-radiative are very fast. But, whether it is radiative or non-radiative, one electron and one hole is lost. The carriers are lost in recombination, therefore, in a particular material, if non-radiative lifetime is very short, which means the carriers combine very quickly mostly by non-radiative, therefore, within this time, very few radiative transitions have taken place. Most carriers are already lost bu non-radiative transitions.

And therefore, the contribution to radiative transitions will be very little in the case of a material which has a very small tau nr, you will appreciate this now. If I write the typical example.

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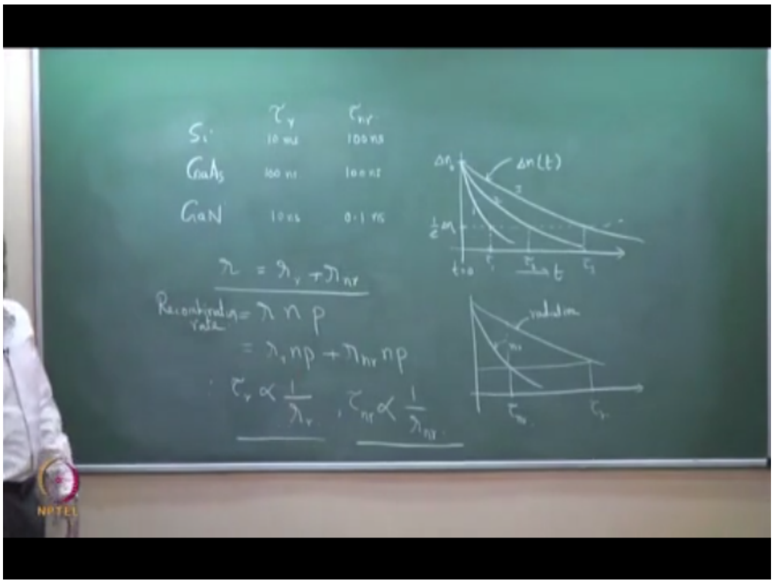

Let us take silicon gallium arsenate and if you want gallium nitrite, what is tau r and what is tau nr typical material okay. It will depend on defect density and the carrier concentration and so on okay. A material where let us say n0p0 is of the order of 10 to the power of 17 per cc. in silicon, the radiative recombination is of the order of 10 millisecond. Non-radiative is of the order of 100 nano second. In gallium arsenate, this is of the order of 100 nano second, this is of the order of 100 nano second.

If you go to gallium nitrate, this is of the order of the one second, for gallium arsenate, it is approximately tau r is 10 nano second and this is 10 to the power of -1 or 0.1 nano second. Let me see if I have the values. For gallium nitrite, tau r is 10 nano second and this is 0.1 nano second that is okay tau nr. You see, for gallium arsenate, both radiative and non-radiative are equally probable. The time is the 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 milli seconds, this is 100 nano seconds. So, the non-radiative lifetime is much smaller here, which means if I have 1 million recombination taking place, primarily most of them will be by non-radiative and very few will be radiative. Do you follow the importance of the lifetime? One is non-radiative another is radiative, which ever lifetime is short, which means that is the reaction which takes place very fast.

That is the recombination which is taking because small lifetime means large rate constant, they are inverse. So, the rate constant is very large for that. Now, why did I discuss all of these is very simple that we are interested in a parameter which is most important called internal quantum efficiency.

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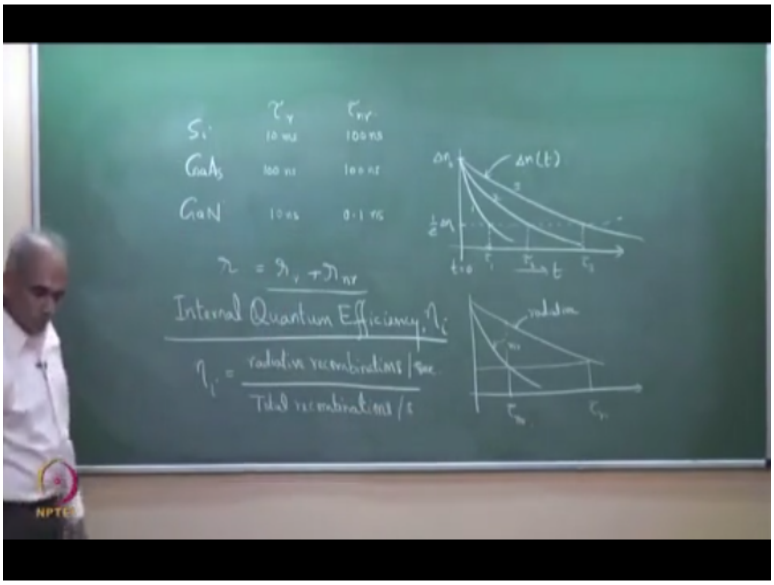

In all semiconductors sources, this is the most important parameter, which generates, which determines the efficiency of generation of light, efficiency of generation of light. What is internal quantum efficiency? It is very simple definition. It is out of the total recombination; it is the ratio of radiative recombinations to the total recombinations. So, eta i=ratio of radiative recombinations, if you want you can write per unit time, that is per second divided by total recombinations per second.

This means, okay let me erase this. If time permits we will discuss a technique to measure the lifetime but, let us right now continue.

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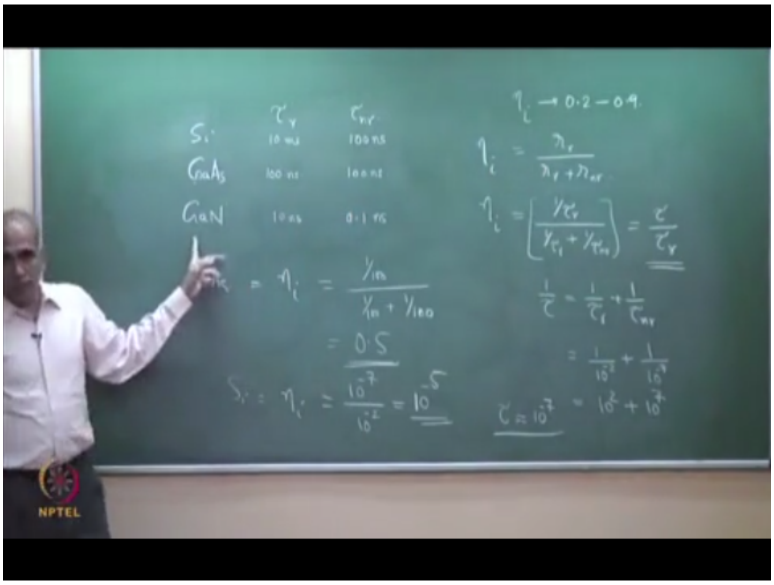

That means eta i=rr divided by rr+rnr, we agree because, radiative recombinations were rr*n*p, non-radiative recombinations were rnr*n*p. therefore, total is rrn*p+rnr n*p. so, np is commonly in all the places, therefore, this is the ratio. But, we have something of here r, this is the total. This = rr is inversely proportional to tau r, which means 1 divided by tau r divided by 1 over tau r+1 over tau nr. Because, the proportionality constant is the same for a given material.

What is 1 over tau r+1 over tau nr? Is 1 over tau = 1 over tau r+ 1 over tau nr right. R = rr+this therefore, this is inversely proportional. So, 1 over tau r = 1 over tau r+ 1 over tau nr. 1 over tau = 1 over tau r+ 1 over tau nr. That is what I have written here. The denominator is nothing but 1 over tau, so this = tau divided by tau r. Eta i=tau divided by tau r.

What does this mean? What have I written here? This tells us, if there are 100 recombinations taking place, if 10 of them lead to the generation of photo 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% of the total recombinations lead to generation of photons. If eta i=0.5, it means 50% out of all the recombinations, 50% will lead to the generation of photons, while 50% do not.

They are non-radiative recombinations. I have put some numbers here, so it is interesting therefore to see what is eta i for these materials. Let us take gallium arsenate first, so, eta i= 1 over tau r divided by 1 over tau r+ 1 over tau nr. So, this is 1 over 100 nano second, all are nanoseconds, so I do not have to write. So, 1 over 100+1 over 100. How much is this? Okay. So, x divided by 2x, whatever be 1 over 100 is 0.5.

If you look at silicon, so for silicon, eta i=if you want, you can use this directly see this, what is the expression 1 over tau=1 over tau r, this is 10 millisecond. So, 10 millisecond is 10 to the power of -2 seconds+1 divided by 100 nanosecond, 10 power -7 here. This is a very large number, because 1 over 10 power -2 is this is 10 power 2+10 power 7, which is approximately 10 power 7, because 10 power 2 is negligibly small alright. And therefore, tau is approximately=10 power -7.

Because this number is, so 1 over tau is about 10 to the power of 7 and therefore, tau is approximately this. Therefore, tau r, so 10 power -7 divided by tau 7, tau r is 10 milliseconds, so 10 power -2. This is approximately = 10 power -5. The internal quantum efficiency for silicon is 10 power -5, which means out of 1000 recombinations, 1 will generate photon, all the rest do not generate photon. Similarly, you can find out for gallium nitrite here, this is 10 nanoseconds, this is 0.1 nanoseconds.

I think, this will come out to be 10 power -2 approximately. Check what you get for this. So, the efficiency is relatively lower here but, see that gallium arsenate, 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 materials have generally very low internal quantum efficiency. 10 power -3, -4, -5, -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 nitrite is also a direct band gap material. But, this does not have a large eta I, therefore, whenever sources are made, this is a wide band gap semiconductor. When people make sources, like for the blue LED, it is indium gallium nitrite which is used.

The ternary compound indium gallium nitrite, this has eta of approximately 0.3. this is very small, eta of gallium nitrite, but indium gallium nitrite, the ternary compound has a very large internal quantum efficiency. So, the first point is 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, no radiative recombinations which lead to the generation of photons. Let us discuss a little bit more about injection electroluminescence. So, radiative recombination lifetimes and non-radiative recombination lifetimes and internal quantum efficiency. Please put some numbers and be familiar with the numbers of tau r, tau nr and how to calculate internal quantum efficiency.

In practical devices, when we say injection, we talk in terms of current I.

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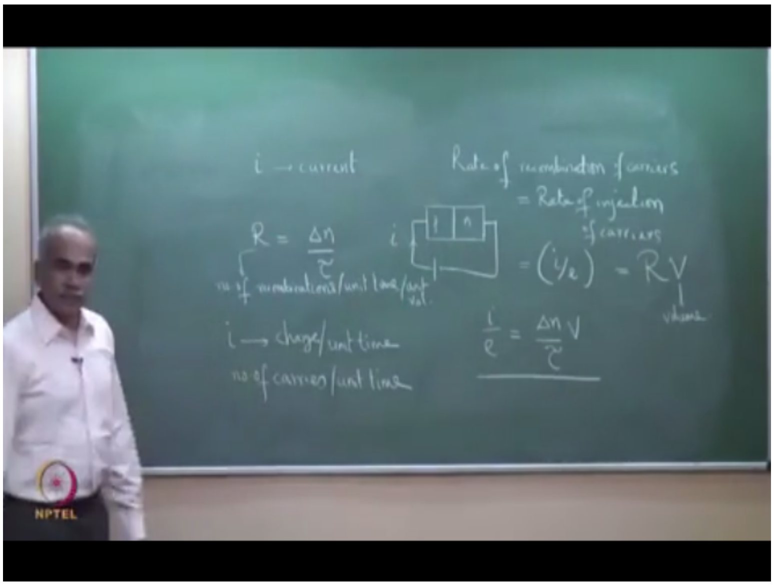

If i is the current, we want to relate this to the power generate. Now, we want to put the device, where what is the power generated. So far we have been talking about recombinations, rate and so many things. Now, we want to come to the device engineer’s perspective, he passes a current I want to know, what is the optical power generated and how much is available to heat. So, if i is the current, let us consider a pn junction diagram.

We use pn because it is very easy to inject current. So, a forward biased pn junction current, there is a current i, which flows through the diode, what is the power generated? R=delta n*tau. What is R? number of carrier’s recombination, that is number of recombinations per unit time per unit volume this is all. Number of recombinations per unit time per unit volume. What is i? i is current, current is charge per unit time.

So, what is the number of carriers per unit time? So, number of carriers per unit time, please see rate of recombination, why a current flow through this? Because, carriers are recombining at the junction region. The rate of recombination here = the rate of injection. Because, it is the recombinations which is responsible for current flowing. So, every one recombination here leads to injection of an electron and a hole.

So, rate of recombination=rate of injection. This is the important point, rate of injection. Rate of recombination of carriers=rate of injection of carriers. So, let me add recombination of carriers, please see this, this is the basic definitions injection of carriers. I is the rate at which charge flows. What is the number of carriers that will flow per second? So, rate of injection of carriers=I divided by e. Charge of one carrier is e. so, I divided by e will give you rate of injection of carriers.

This = rate of recombination of carriers. What is the rate of recombination of carriers R? but, this is per unit volume. In the current, there is no unit volume. So, R*V, where V is the volume. Please see the logic, if R is the rate of recombination, then R*V will give you rate of recombination in the volume. Because R by definition is number of recombinations per unit time per unit volume. Therefore, R*V will be number of recombinations per unit time, which is rate of recombination.

So, rate of recombination of carriers=R*V, i/e=R*V. What is R? so, i/e=R is delta n*tau, so delta n/tau*V. Every recombination, so what is power?

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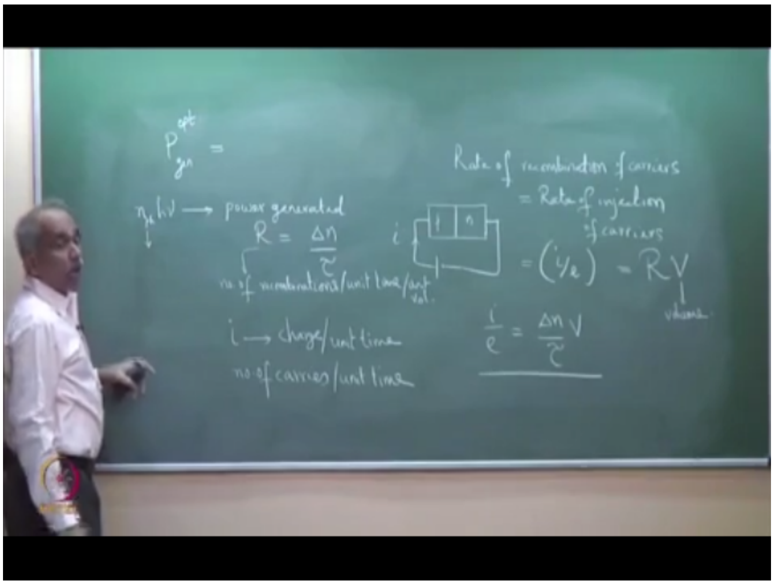

Our interest is power generated, that is power generated, optical power, we are interested in optical. Optical power generated, every radiative recombination will give us one photon generation. We are interested in power generation. If n is the number of photons generated per unit time, what is the power generated? n*h nu is the power generated, if n is the number of photons generated per unit time, nh nu is the power generated, n is the number of photon.

I have also used earlier n for carrier concentration, but this n is number of photons. If you want you can put nph, for the time being, because it will all disappear in a short while. Finally, what we will get is just optical power how it is related to current. That is all the device engineer want. But, it is to be linked from the basics because all these while we have been talking of carrier recombination, photon generation, radiative transitions, non- radiative transitions, which does not mean anything to a device engineer.

So, nph*h nu gives you the power generate. Number of photons is determined by radiative recombinations. Out of all the radiative recombinations, eta i times radiative recombination, eta i times r will give you R.

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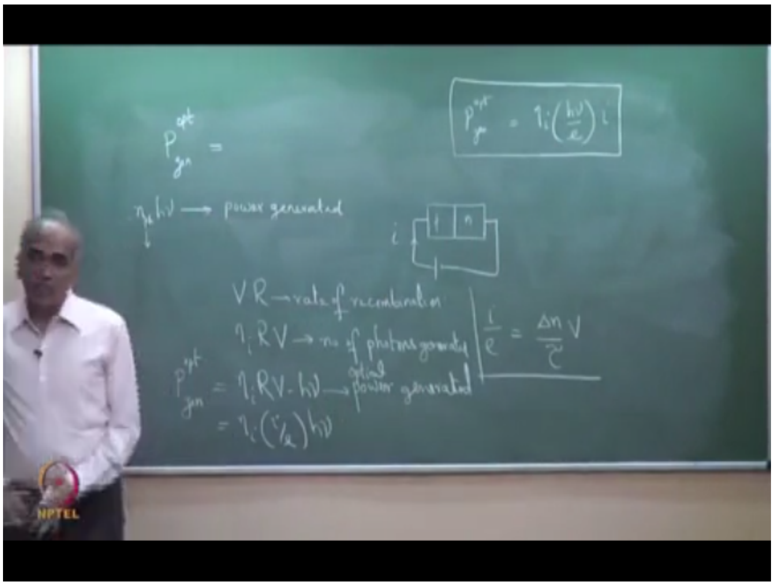

R is the rate of recombinations. So, R*V is the rate of recombinations. Out of this, eta i is the fractional, this is rate of recombination, which means number of recombinations per unit time in the volume V. so, eta i*R*V is the number of photons generated. Because, out of all the recombinations a fraction eta i will lead to generation of photons, eta i*R*V. this is the number of photon generated, multiplied by h nu will give me power. niRV*h nu is the optical power generated.

R*V=i/e, so, this = P optical generated. So, RV is replaced by i to e. So, eta i*i/V*h nu is the optical power generated, P optical. So, I have got the expression that P optical, I am right now writing, afterwards we will drop. P means we are dealing with optical power only. Just at this point I am writing P optical generated, therefore = eta I, something's can be simplified here. H is constant, nu is c/lambda and hc/e is 1.24. anyhow, let me keep it as it is i/t.

So, h nu/t*I, so, this is the optical power generated. If you know a material, the internal quantum efficiency of the material like any material, we calculated for silicon gallium arsenate. If you know, what is the band gap, h nu is close to eg. 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 opt how much optical power is generated. At this point, I am giving emphasis on generation, because, it is 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 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. So, it is called wall plug efficiency. We will discuss this in the next class.