Fiber Optics

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Lecture – 34
Optical Sources and Detectors – II

Let us continue our discussion on semiconductors and semiconductor based optical sources in this lecture. So, what we were discussing was the probability of occupancy of an energy state, which is given by a function which is known as Fermi function is defined $f_E = \dfrac{1}{1+\exp(\frac{E-E_f}{k_B T})}$.

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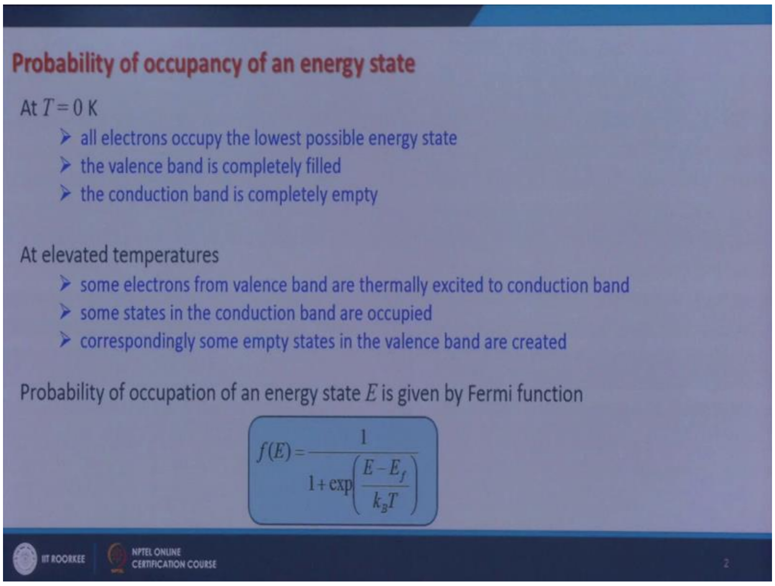

Let us look at intrinsic semiconductor and the probability of occupation of energy states in an intrinsic semiconductor.

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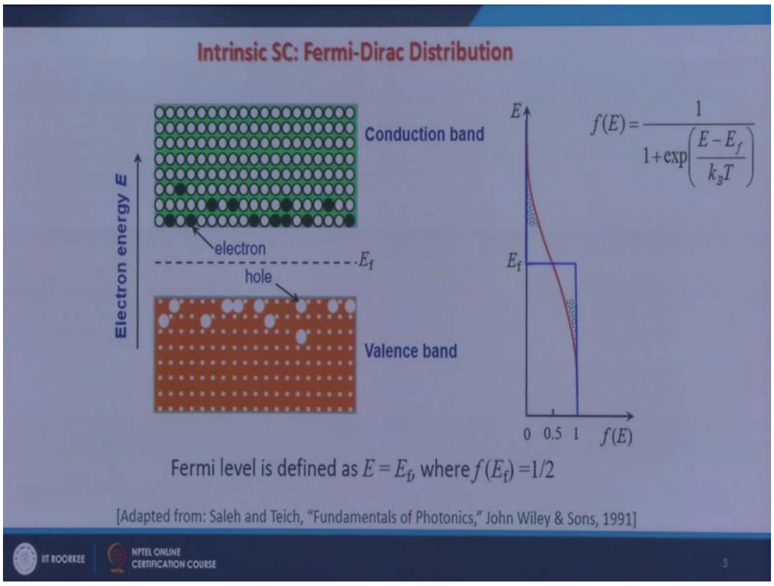

This kind of distribution is defined by this Fermi function is known as Fermi Dirac a statistical distribution. So, in an intrinsic semiconductor I have valence band and I have conduction band, then at absolute 0. I know that valence band is completely filled and the conduction band is completely empty. That is the probability of occupation of energy states here in the valence band is 1 while the probability of occupation of energy states in conduction band is 0. So, if I look at this function and I put T = 0 here then for $E = E_f$, what I have this is as $1 + e^{\infty}$. So, $f(E) = 1$. So, I have the probability of occupation 1. While for energies larger than E_f I have this because of T = 0 this becomes infinity. So, $f(E) = 0$. So, what I see that at absolute 0 up to this level the probability of occupation is 1 while above this level the probability of occupation is nil.

At elevated temperature what happens some of the electrons go here. So, there are some states which are occupied by the electrons, then and there are some vacancies created here. So, the probability of occupation in the valence band goes down a little, and the probability of occupation in the conduction band increases from 0. At $E = E_f$; however, what I find that it is e^0. So, it is half. So, I define Fermi level as $E = E_f$ where $f(E) = 1/2$, at some finite temperature *T* the level which has 50% probability of occupation it is a Fermi level, and at absolute zero the level up to which the probability of occupation is one.

And above which the probability of occupation is nil. So, this is known as Fermi level. In an intrinsic case semiconductor the Fermi level lies in the middle of the gap. If I have *n* type semiconductor then there are large number of electrons here. So, large number of states are occupied here. So, the Fermi level shifts up; correspondingly the Fermi Dirac distribution looks like this, you have more electron states occupied here. So, you have a larger value of *f(E)* here. While in *p* type semiconductor you have large number of holes here. So, the Fermi level shifts down. Now if you make a junction using this *p* type material and *n* type material then what happens is this.

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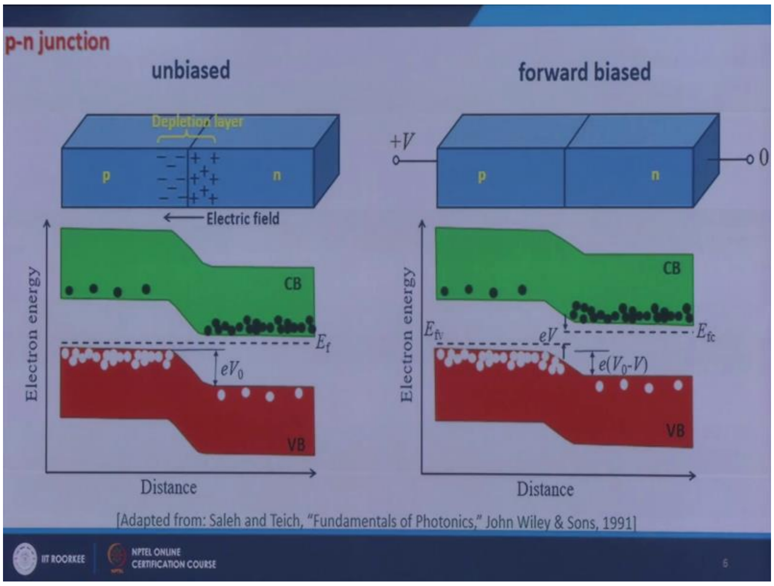

When you join them together then you know in *n* type you have electrons excess carrier as electrons, which are around the positive ion core and the holes in excess which are around the negative ion core. When you join them together then electrons from here will move towards the *p* side and will recombine with holes fill the vacancy and will leave behind the positive ion core while here they will combine the hole. So, they will leave behind these negative ions, and this will happen on until an equilibrium is reached.

So, in equilibrium position near the junction I have positive ions on this side and negative ions on this side this sets up an electric field from *n* to *p*, this electric field creates a potential energy which looks like this. So, this is the electric potential; if I plot here the energy of the electron as a function of distance, now what happens is that in equilibrium you see in *n* type your E_f is near the conduction band, and in *p* type your E_f is near the valence band. When equilibrium is reached then this E_f is somewhere here and there is banding of this. So, this shifts downwards this shift upwards and there is a potential created here because of this electric field.

So, what happens is that this potential or this electric field prevents electrons going from here to there, and holds from here to there. Remember that this is electron energy that is energy of electron is increasing in this direction, correspondingly the energy of hole is increasing in this direction. So, this is a barrier for electrons and this is a barrier for holes. So, you have a potential barrier created here and the height of the barrier is eV_0. If you forward bias it that is if you apply the positive field here.

So, a positive potential here and 0 or negative potential here then you are basically decreasing this potential barrier. Then electrons some of the electrons can now flow from here to the from *n* type to the *p* type, and holes can flow from *p* type to *n* type and there would be conduction. So, this is forward bias *p*-*n* junction. If you reverse bias it that is if this is negative and this is positive then you will further enhance this, and there would be no current flowing in the circuit or very small current will be flowing in the circuit.

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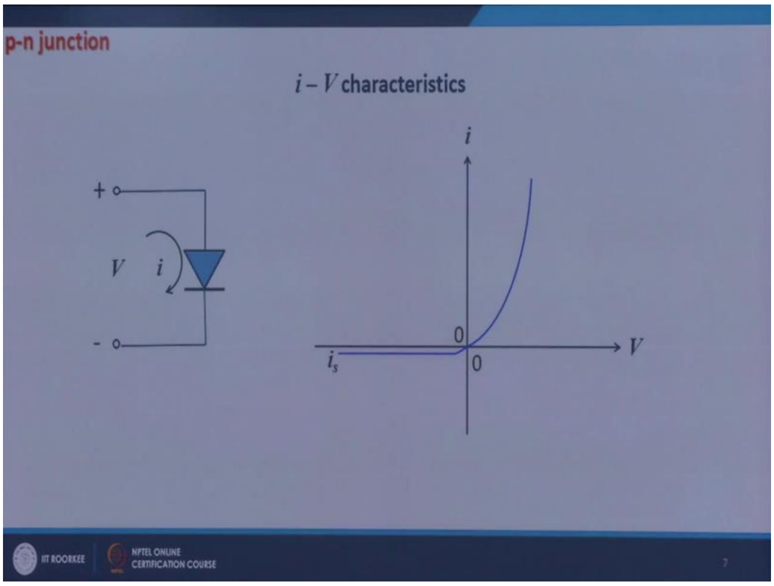

So, if you look at the *i*-*V* characteristics of a p-n junction. So, in forward bias if you increase the voltage the forward current will increase; however, if you apply the negative voltage and increase this then you will have a reverse saturation current flowing very small in amount and if you apply very large voltage then there would be breakdown.

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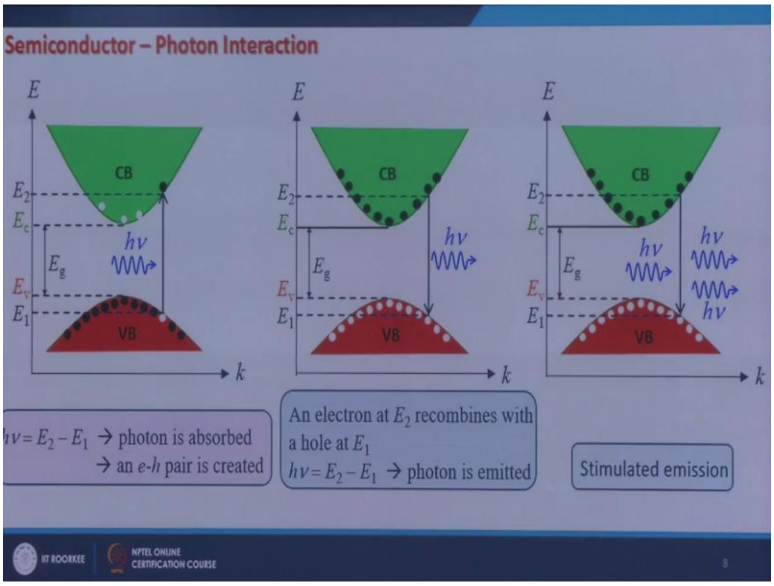

The important thing now, is to understand how photons interact with semiconductors because this will form the basis of our optical sources and optical detectors right. So, if I have a semiconductor which has got valence band and conduction band, there are large number of electrons available here and there are states available here in conduction band for electrons. Now if a photon interacts with this semiconductor and the energy of the photon is such that it is the difference of an energy state here and an energy state available here, then this electron in this energy state will absorb this energy of the photon and will go to this state in this conduction band.

In this way it will leave it will leave behind a vacancy here and an energy state here is occupied. So, in this way it will create an electron hole payer; a photon would be absorbed if the energy is larger than the bandgap then only it will be absorbed. So, absorption of a photon by a semiconductor will create an electron hole pair, and this electron here and hole here can now contribute towards conduction if you apply an appropriate electric field. So, such kind of interaction is responsible for photo detection process to make photo detectors. There is another way in which there can be interaction between a semiconductor and a photon, and that is if some electrons are already there in conduction band that is the states here are occupied, and holes are available in the valence band the vacancies are there in the valence band, then there is a natural tendency of electrons to go back to the lowest energy state to the lower state.

So, an electron can go from here to the valence band and recombine with hole, and it can do it at its own spontaneously, if the lifetime of these states is very small. Then there would be recombination between electron and hole spontaneously, and as a result of photon of energy difference between these two states will be emitted. This kind of emission of photon is known as spontaneous emission, this process is responsible for light generation in light emitting diodes.

There is another process a process similar to this you already have electrons available in the conduction band and holes in the valence band. So, the electron will recombine with the hole in the valence band, but if the energy states of the electrons here are such that they are long lived they are known as metastable states. Then this recombination from here to here transition of electron from here to the valence band is triggered by another photon if this transition is triggered by another photon, then the emitted photon is in the same phase and in the same direction as the triggering one, then this kind of emission is known as stimulated emission, this emission is responsible for light generation in lasers.

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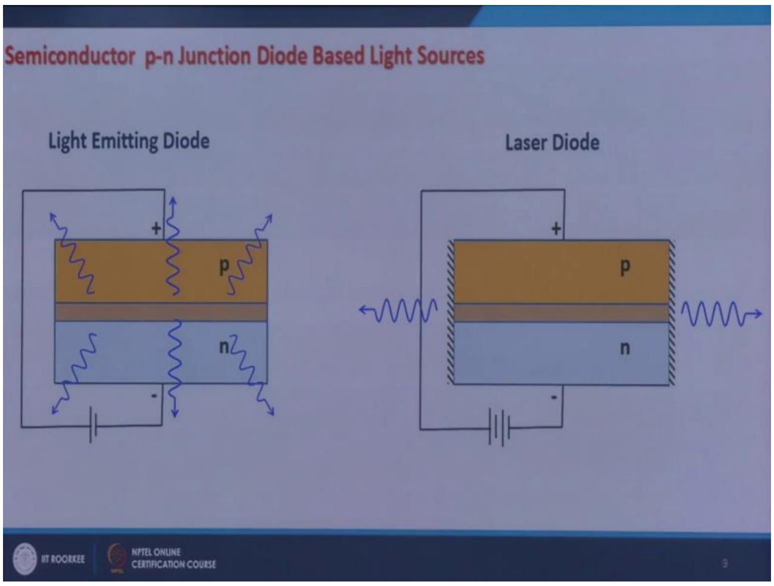

So, we have semiconductor *p-n* junction diode based light sources is light emitting diode where the light generation is via the process of spontaneous emission. So, what you do you forward bias a *p-n* junction diode by forward biasing it, you are basically injecting the carriers that is electrons in the conduction band and holes in the valence band. So, since you have now electrons available in conduction band and holes in the valence band.

So, this recombination of them is in is spontaneous manner will give you light output, and this light is incoherent and this is the process responsible for generation of light in light emitting diodes. However, if the light emission is via the process of stimulated emission, then you amplify the radiation and if you place two mirrors here and provide feedback in the k_BT then you can make it a laser from amplifier you can make the oscillator and that is basically a laser. So, this is the process responsible for light generation in laser diodes. So, let us now look at light emitting diodes. So, these are various forms of light emitting diodes available commercially available, the process responsible here for light emission is injection electroluminescence.

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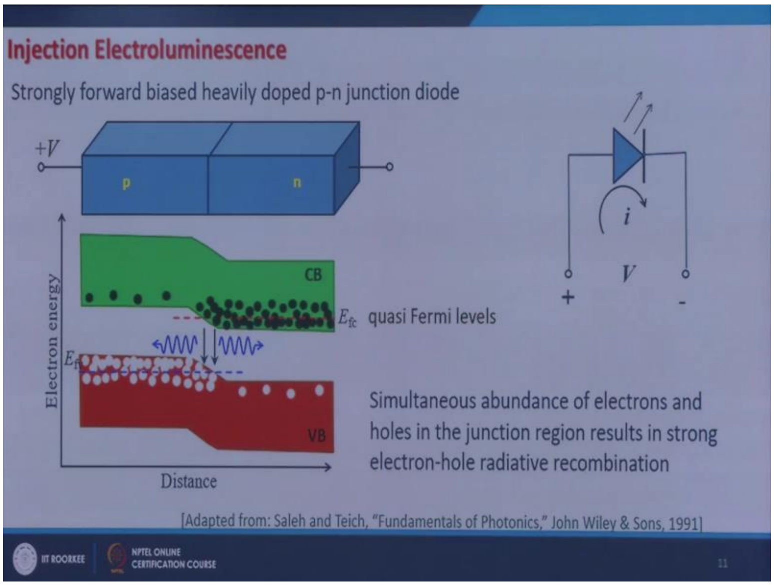

So, I explain this with the help of a strongly forward biased heavily doped *p-n* junction diode. So, if this *p-n* junction is heavily doped, then there are large number of electrons in the conduction band and large number of holes in the valence band such that this Fermi level goes even inside the conduction band and this Fermi level shifts to inside the valence band and these are known as quasi Fermi levels.

The consequence of this heavy doping and strong forward bias is that we are injecting lot of carriers, and lot of carriers are available here now. So, if I look at in the junction region then in the junction region there is simultaneous abundance of electrons and holes. Then these electrons will make transitions will recombine with holes and give you light output. Photons coming out light radiation and in this way an LED will work LED will emit light.

So, if you have a *p*-*n* junction diode you forward bias it and you get light out of it. A very important parameter of a light emitting diode is its efficiency quantum efficiency, how efficient it is in generation of light. To understand this let us go back to the very basic phenomenon of light emission in such devices, I have just seen that light is emitted by radiative recombination of electrons and holes. So, electron is in the conduction band hole is in the valence band, electron recombines with hole there is a radiative recombination. So, photon comes out, but this electron can recombine with hole.

By another process also, that is by releasing heat by releasing thermal energy instead of releasing the photon such kind of combination is known as non-radiative recombination. So, I now have two kinds of re-combinations one is radiative recombination where photon comes out, another is non radiative recombination where the energy is released in the form of thermal energy. But I know that light is generated by the process of radiative recombination. So, when I inject current in a *p*-*n* junction, I create electron hole payers then not all the electron hole payers recombine radiatively, some of them are recombined non-radiatively, and this gives me some finite quantum efficiency, because some part is lost in heating up the device.

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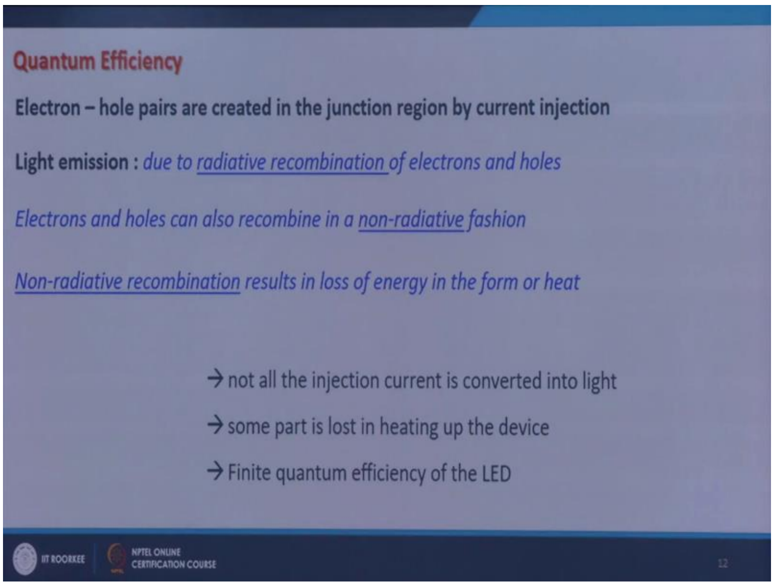

So, it will give me finite quantum efficiency of the LED, I cannot have 100% quantum efficiency in an LED in such a way. So, to work out the expression for quantum efficiency, let us look at the carrier concentration how the carrier concentration decreases with time because electrons recombine with holes. So, the number of electrons decrease in the conduction band and number of holes decrease in the valence band.

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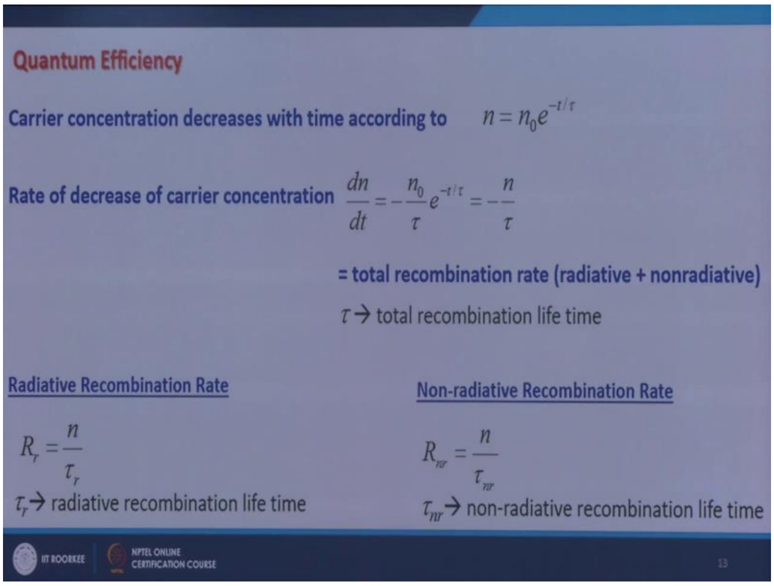

So, the number of carriers decrease according to $n = n_0 e^{-t/\tau}$, where n_0 is the number of carriers at $t = 0$, this tau is known as lifetime. I can find out from here what is the rate of decrease of carrier concentration by simply doing $\frac{dn}{dt} = -\frac{n_0}{\tau} e^{-t/\tau} = \frac{n}{\tau}$. Minus simply indicates that the carriers are decreasing.

So, where τ is recombination lifetime and this is total recombination rate it involves radiative as well as non-radiative. I do not know which process is responsible here in what proportion, and tau is basically total recombination lifetime. Now if I say that R_r is the rate which is due to radiative recombination, then $R_r = \frac{n}{\tau_r}$ I drop the minus sign because it only indicates the decrease in the number of carriers then $R_r = \frac{n}{\tau_r}$, where τ_r is the radiative recombination lifetime and you can also have decrease in the concentration of carriers by non-radiative recombination. So, I define radiative recombination rate as $R_{nr} = \frac{n}{\tau_{nr}}$, where τ_{nr} is the non-radiative recombination lifetime.

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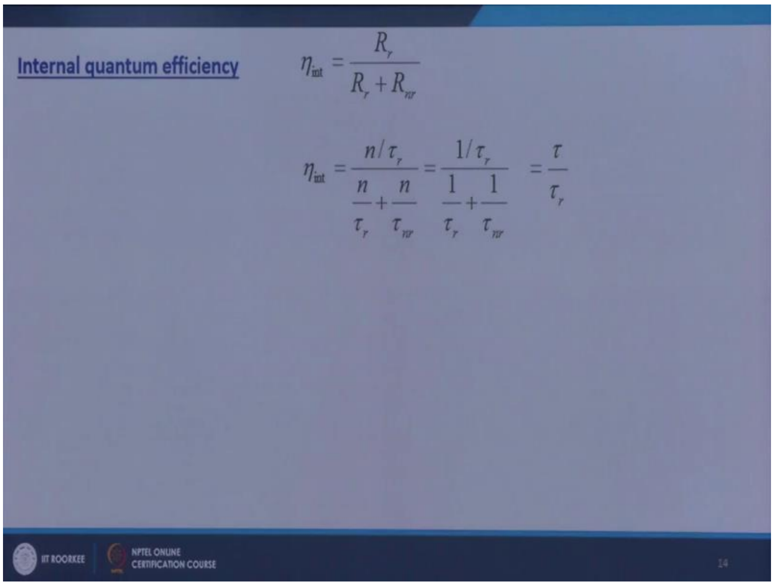

So, the internal quantum efficiency I can now calculate because the light in LED is coming out only because of radiative recombination. So, the internal quantum efficiency is given by $\eta_{int} = \frac{R_r}{R_r + R_{nr}}$. That this what fraction of re-combinations is via the process of radiative recombination. Since $R = \frac{n}{\tau}$. So, if I put it there. So, I can write it down as $\eta_{int} = \frac{\tau}{\tau_r}$, where τ is the total recombination lifetime and is given by $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$ because $R = R_r + R_{nr}$. In general, this τ_r and τ_{nr} are comparable for a direct bandgap semiconductor such as GaAlAs or InGaAsP.

So, if they are comparable then eta internal is typically 50% this is for homo junction LEDs homo junction means the junction between the same material you know p type and n type materials are the same. However, for double hetro junction LED you can increase it up to 80% 60 to 80%, how much power is generated in the device.

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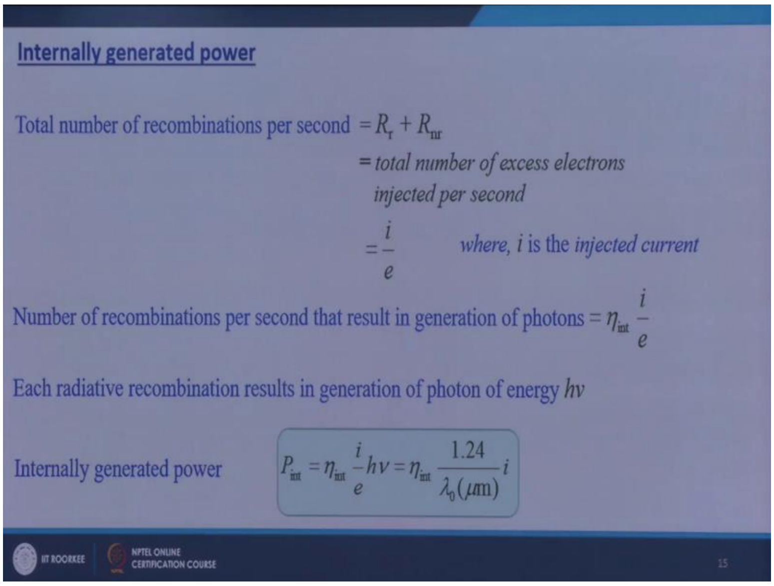

I know that total number of re-combinations per second are $R = R_r + R_{nr}$ which is the total recombination rate and this is nothing, but the total number of excess electrons injected per second.

So whatever excess electrons are injected per second they are getting recombined. So, the number of electrons injected per second should be equal to the number of re-combinations per second. How many excess electrons are injected per second? Well if *i* is the current then *i/e* is the number of electrons injected per second. Now how many of these re-combinations result in generation of photons well the fraction, which is corresponding to radiative recombination, and that fraction is eta internal.

So, the number of re-combinations which are radiative are now eta internal and then the number of re-combinations that result in generation of photons would be $\eta_{int} i / e$ and each recombination these are the re-combinations per second and each of these re-combinations will give you one photon, and I know the energy of one photon is $h\nu$. So, if I multiply this by $h\nu$ I will get the energy per unit time that is power. So, the internally generated power would simply be $\eta_{int} ih\nu / e$, and I can convert this into this particular fashion for convenience, because $h\nu = hc / \lambda$.

So, your $P_{int} = \eta_{int} ih\nu / e$.

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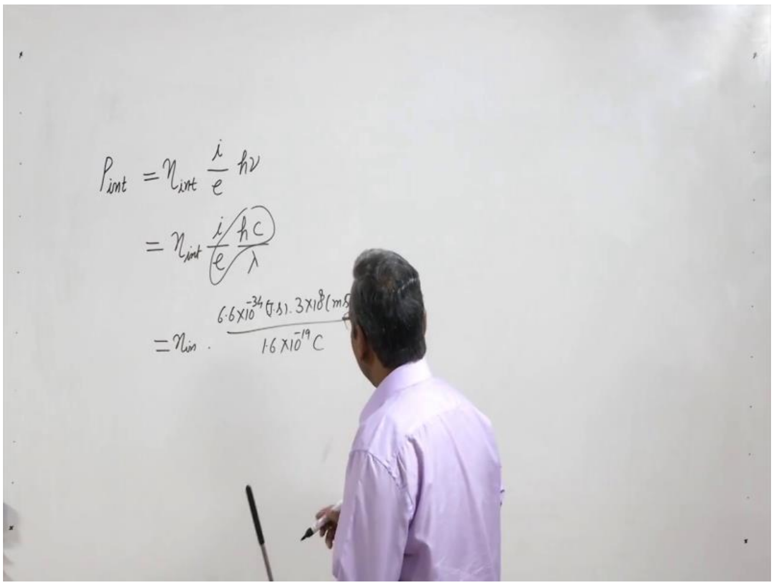

So, this is $P_{\text{int}} = \eta_{\text{int}} ihc/e\lambda$; if you look at *hc* over *e* then *h*. So, this is simply $P_{\text{int}} = \eta_{\text{int}} \frac{6.6\times10^{-34}\times3\times10^{8} i}{1.6\times10^{-19}\lambda}$. So, this we had worked out previously also. So, this comes out to be 1.24×10^{-6}. So, you can write it down like this. So, this is the internally generated power.

In the next lecture I would look into some more characteristics of a light emitting diode and I will also look into a laser diode.

Thank you.