Advanced Optical Communications
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Lecture No. # 13
Light Emitting Diodes - I

We are discussing optical sources for communication. In the last lecture, we described the characteristics which we are looking for in an optical source, and then we found that the sources which are semiconductor base, they are most suitable for optical communication. Because these sources they are compatible with optical fiber, and at the same time they also compatible with the electronics. Then we saw that in a semiconductor source, you can have what is called light emitting diode or LED s or the Injection laser diodes, and then we started discussing the basic principles of light emitting diode.

The basic idea there was to see, if we take a semiconducting material. What kind of radiation we get from a semiconducting material. That is, what are the spectral characteristics of the radiation, which we receive from a semiconducting material, and then what is the efficiency with which the radiation can be emitted from a semiconducting material. So, we took a simple semiconducting material, and then we had a very simple model which says that if you are having electrons, and holes in conduction and valence bands respectively. Then any electron can combine with any hole and can give a corresponding photon out.

At this point of time, we are assuming that every electron which is recombining with the hole is going to give a photon out. So, we are assuming that efficiency is 100 percent, and then we ask a question that when the electrons and holes are distributed in the conduction and valence band. Then what kind of spectral distribution we will get from a source, so we took a very simple model and then we said that the energy level diagram.

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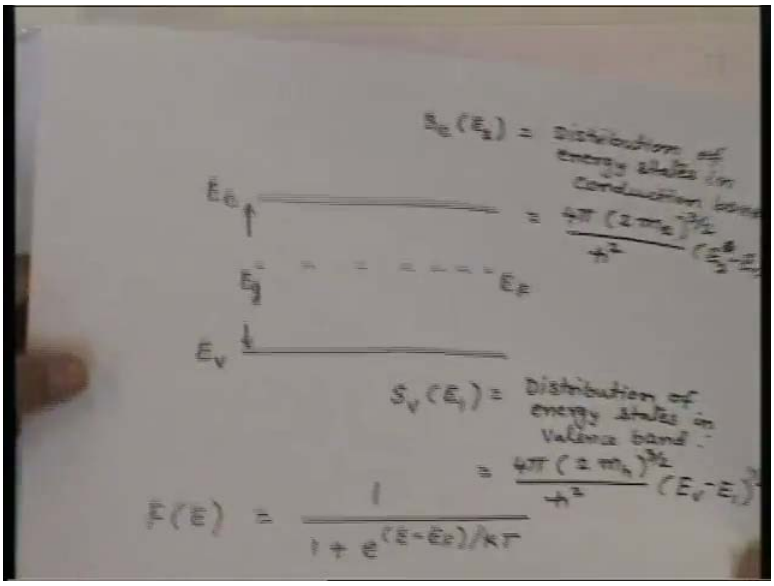

And then we said that the energy level diagram for a semiconducting material will be. There will be a conduction band here there will be valence band here this is the energy band gap.

And if you take a Intrinsic material then you have a Fermi level which is midway between the two and then availability of electron. In the conduction band will depend upon two things that is availability of energy state which is given by this distribution of energy state function and then occupancy of that energy state per electron which is given by the Fermi function which is this similarly, In the valence band the availability of a hole will depend upon the available energy state. In the valence band which is again given by this energy density function and then non occupancy of that energy level which is given by 1 minus this form of function.

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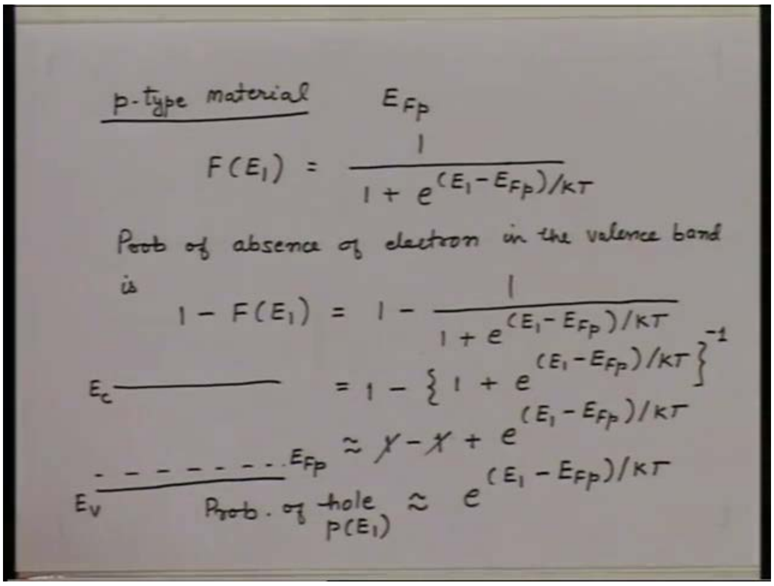

p-type material E_{Fp}

$$F(E_1) = \frac{1}{1 + e^{(E_1 - E_{Fp})/KT}}$$

Prob of absence of electron in the valence band is

$$1 - F(E_1) = 1 - \frac{1}{1 + e^{(E_1 - E_{Fp})/KT}}$$

$$= 1 - \left\{1 + e^{(E_1 - E_{Fp})/KT}\right\}^{-1}$$

$$\approx \cancel{1} - \cancel{1} + e^{(E_1 - E_{Fp})/KT}$$

$$\approx e^{(E_1 - E_{Fp})/KT}$$

Prob. of hole $p(E_1)$

So, by taking a simple model then we wrote down essentially the probability of having a hole. In the valence band in a p type material and then making certain approximations that the energy levels which you are talking about are much smaller compared to the Fermi energy level. We got the probability of a hole which was approximately given by this quantity similarly; we did the exercise for the n type material.

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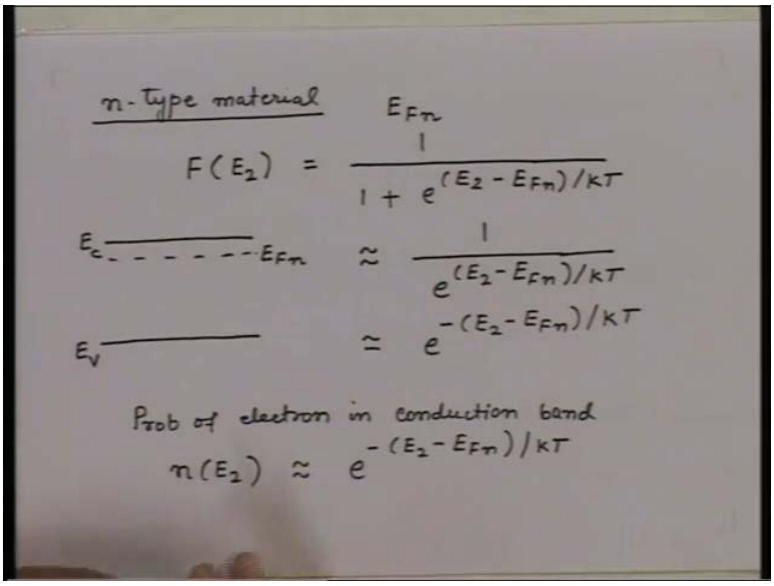

n-type material E_{Fn}

$$F(E_2) = \frac{1}{1 + e^{(E_2 - E_{Fn})/KT}}$$

$$\approx \frac{1}{e^{(E_2 - E_{Fn})/KT}}$$

$$\approx e^{-(E_2 - E_{Fn})/KT}$$

Prob of electron in conduction band

$$n(E_2) \approx e^{-(E_2 - E_{Fn})/KT}$$

And then we said that probability of having an electron, in the conduction band that is approximately given by again this function, which is the exponential function while doing this if you recall? We have to assume that the variation of the density of energy states is assumed constant. In the conduction and valence band and that is with the understanding that this function is a very slowly varying function of energy. So, over a small range of energies where electrons and holes are primarily confined near the edges of the bands the function can be assumed more or less constant. So, under these assumptions essentially, we got the probability of electrons in conduction band and probability of a hole in the valence band and then we said if you have if you take a material now.

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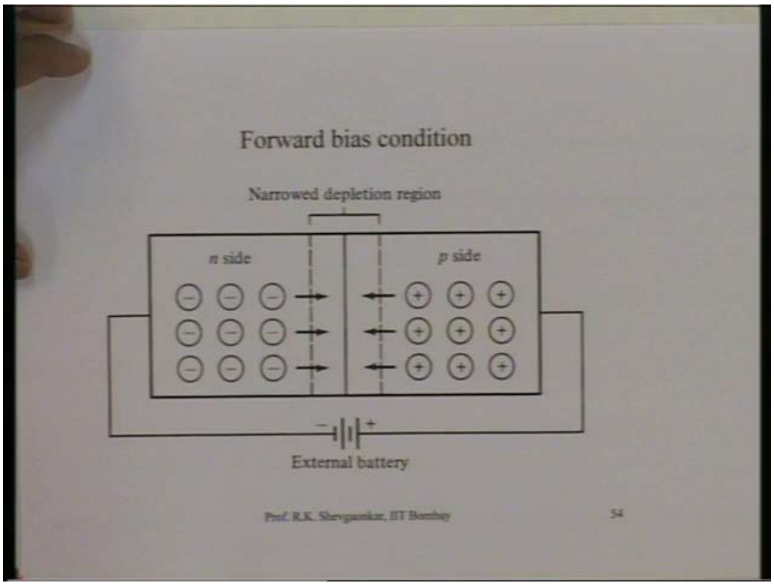

Forward bias condition

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And make a junction out of it which is the p n junction or nothing but a diode and If you make this diode forward bias then holes and electrons are Injected. In the depletion region where the recombination between the electron and hole will take place and every recombination will give a photon out. So, you will get a light which will be coming out of this.

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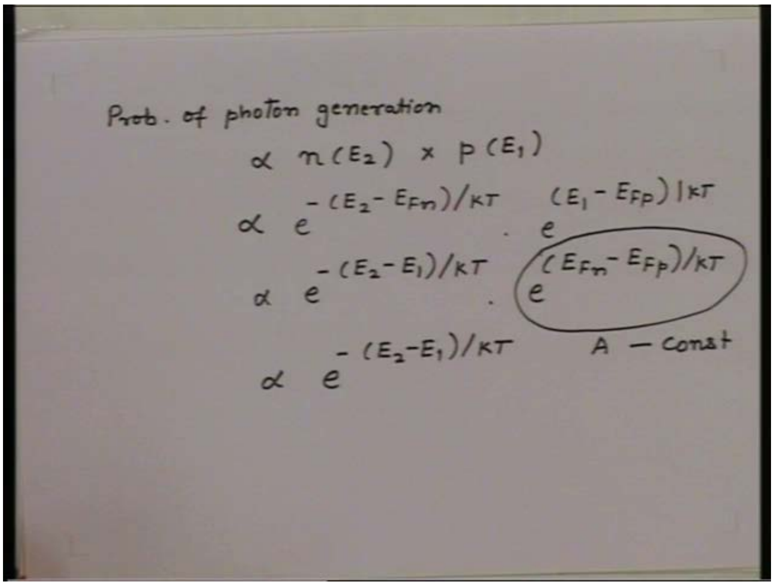

Prob. of photon generation

$$\propto n(E_2) \times p(E_1)$$

$$\propto e^{-(E_2 - E_{Fn})/kT} \cdot e^{(E_1 - E_{Fp})/kT}$$

$$\propto e^{-(E_2 - E_1)/kT} \cdot \boxed{e^{(E_{Fn} - E_{Fp})/kT}}$$

$$\propto e^{-(E_2 - E_1)/kT} \qquad A - \text{const}$$

So, then saying that if the photon is generated, now we are now asking. What is the probability of a photon generation once we know that probability of electron in the conduction band in n type material and probability of hole, in the valence band in p type material?

So, we say the probability of photon generation is proportional to the density of electrons as a function of energy level and in conduction band; we are representing energies by E 2 multiplied by the probability of hole. In the valence band and their energy is represented by E 1 so substituting now for these two probabilities of electron, and hole we get the probability of photon generation which will be essentially given by this and then by separating out the terms. We get a term to the power minus E 2 minus E 1 divided by k T multiplied by this quantity which is a constant.

Because, for a given doping of the junction the E F n which is a Fermi energy for n type material and E F p which is the Fermi energy for p type material are constant. So, this quantity is constant for a given device, so then we see the probability of photon generation is proportional to e to the power minus E 2 minus E 1 divided by k T and k is the Boltzmann constant and T is the absolute temperature of the device.

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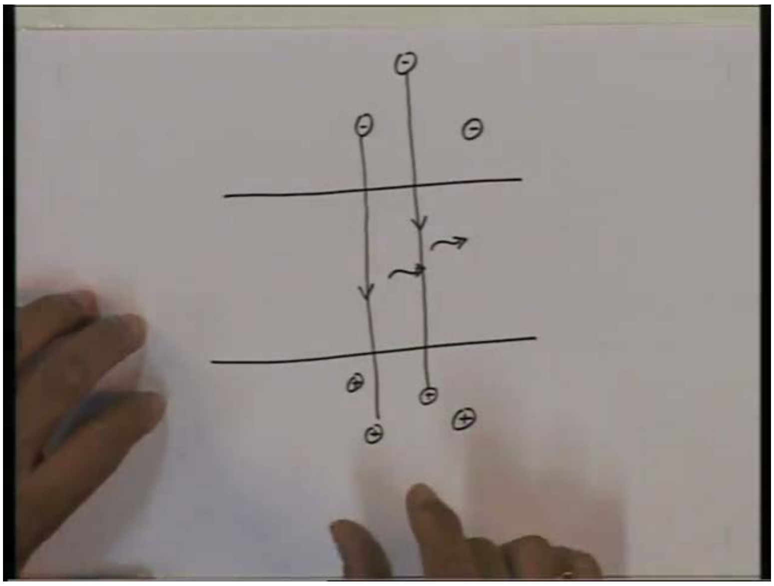

Now if you look at again the energy diagram, we will say that we have a conduction band here and we have a valence band here, and now you are having holes, which are distributed in this region and then we are having electrons which are distributed in this.

And as we said any electron can recombine with any hole and can give me a photon out. So, essentially if I consider this electron and If I consider this hole this recombination which is going to take place from here to here will give me a photon out similarly. If I consider a whole here and if I consider an electron here this difference between these two energies is exactly same as this difference, so this way also will give me a photon out and this photon will have a same energy as the energy of this photon.

And as we saw the energy of the photon is proportional to the frequency of the photon. So, frequency of these photons will be same now if you want to find out what is the spectral density of the emission from this p n junction or from the semiconducting material then essentially we have to add up all the electron hole pairs, which have a energy difference same as the photon energy in which we are interested so what that means is that this quantity here now E 2 minus E 1 is nothing but the photon energy or the frequency of the photon which we were looking for.

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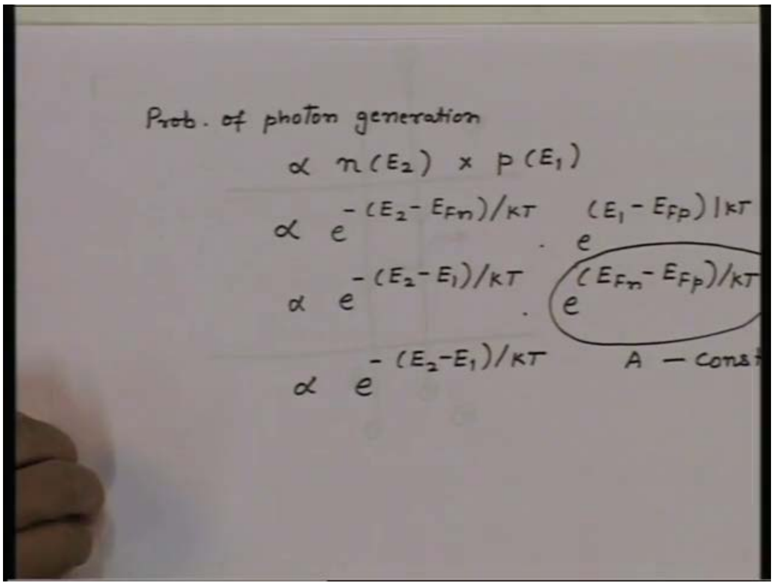

Prob. of photon generation

$$\propto n(E_2) \times p(E_1)$$

$$\propto e^{-(E_2 - E_{Fn})/kT} \cdot e^{(E_1 - E_{Fp})/kT}$$

$$\propto e^{-(E_2 - E_1)/kT} \cdot \boxed{e^{(E_{Fn} - E_{Fp})/kT}}$$

$$\propto e^{-(E_2 - E_1)/kT} \qquad A - \text{Cons}$$

So, this quantity E 2 minus E 1 essentially is constant but then we are having all possible pairs which we have to now add to find the total number of photon, which are going to be generated or in other words essentially we have to Integrate this quantity for all possible energies for which this difference E 2 minus E 1 is equal to energy of the photon E p h.

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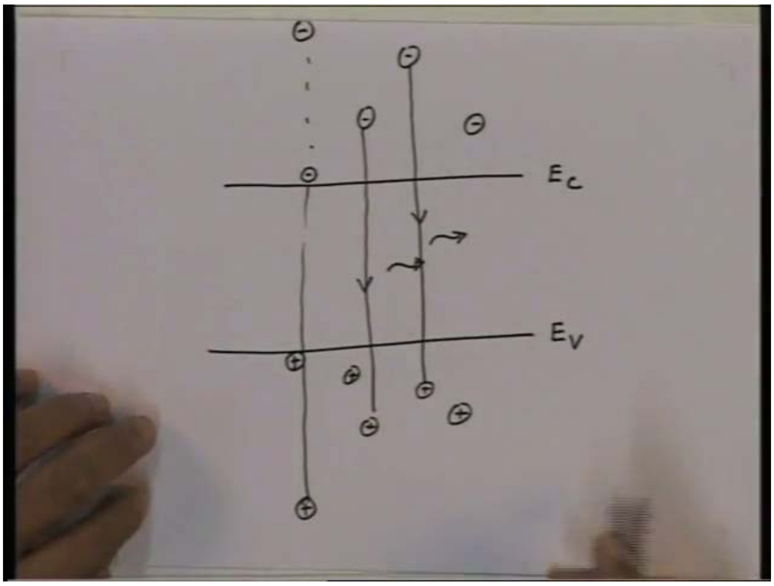

So, what essentially we are saying is all electrons starting from here and for which the corresponding hole will lie somewhere here, so we can go all the way up till this hole will lie on this edge and then you have corresponding electron here.

So, for integrate this is the energy which is E C, this is the energy which is E v and the energy is in the conduction band is given by E 2. So, if I integrate this quantity here for all values of E 2 going from E C to E V plus the photon energy in which we are interested.

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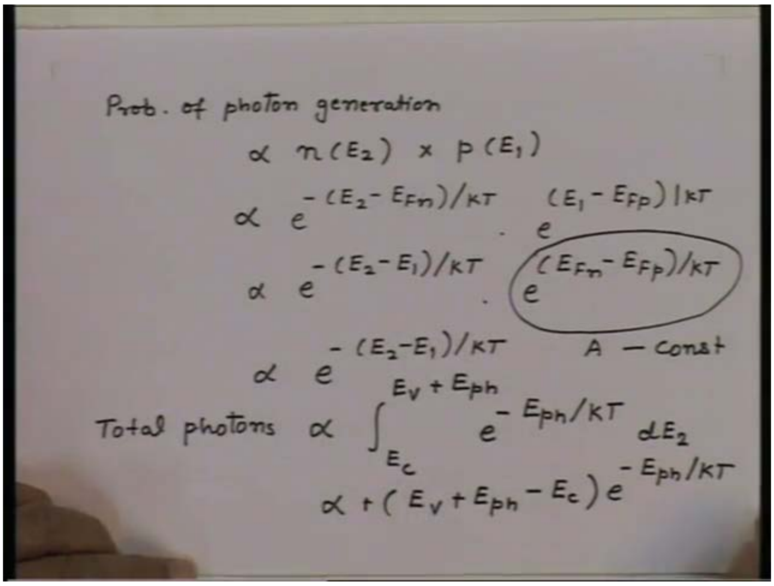

Prob. of photon generation

$$\propto n(E_2) \times p(E_1)$$

$$\propto e^{-(E_2-E_{Fn})/KT} \cdot e^{(E_1-E_{Fp})/KT}$$

$$\propto e^{-(E_2-E_1)/KT} \cdot \boxed{e^{(E_{Fn}-E_{Fp})/KT}}$$

A — const

$$\propto e^{-(E_2-E_1)/KT}$$

$$\text{Total photons} \propto \int_{E_c}^{E_v+E_{ph}} e^{-E_{ph}/KT}\, dE_2$$

$$\propto (E_v+E_{ph}-E_c)\, e^{-E_{ph}/KT}$$

Then we will get the total number of photons, which will be emitted for a given frequency or for a given energy. So, while integrating this essentially we are doing as follows, we are finding out now the total number of photons that is proportional to integral and if you are integrating for E 2 then as we said this goes from E C to E V plus E photon which is E p h. We are integrating this quantity there is a constant here which goes in to this proportionality constant.

So, this is e to the power minus E 2 minus E 1 which is E p h divided by k T we are integrating with E 2 so this quantity is constant which we can take out.

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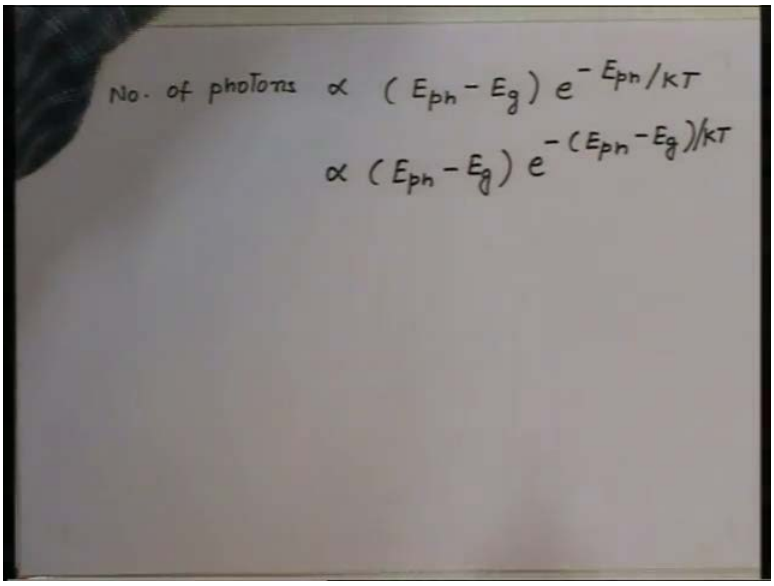

$$\text{No. of photons} \propto (E_{ph} - E_g)\, e^{-E_{ph}/kT}$$

$$\propto (E_{ph} - E_g)\, e^{-(E_{ph} - E_g)/kT}$$

So, essentially the total number of photons emitted at a given frequency or at a given energy which is E photon are essentially given by E V plus E p h minus E C minus e to the power minus E p h divided by k T.

Now this quantity here E C minus E V, we can put as the band gap, which is E g, so essentially we get the total number of photons that will be proportional to the quantity, which Is E p h minus E g the band gap energy e to the power minus E p h divided by k T so firstly the model, which you have discussed here is valid for the energies which are more than the band gap which is E g so if the energy is less than the band gap energy then there is possibility of recombination so the model is not valid, because the photon is not going to be emitted.

So, essentially this number of photons which you are calculating, this is only true for the energies which are greater than each now. If I look at this quantity here you will see that initially when E p h is equal to E g then this quantity is zero. So, there are no photons emitted for the energy which is equal to the band gap energy as E p h increases this quantity increases and this quantity is still very small, because E p h is a small quantity then after sometime the exponential function starts dominating and then again the function start decreasing. So, you have a sort of a local maximum for this function at which the number of photons will be maximum.

In fact you can just add one term here minus E g which is a constant quantity for a given material. So, you can write down this quantity here as E p h minus E g to the power minus E p h minus E g divided by k T and e to the power plus E g you can multiply and since E g is constant for a given material. That can again be absorbed in to this proportionality constant so if I now plot this function that is number of photons and the function of the photon energy and that essentially gives me the spectral distribution of light emitting diode.

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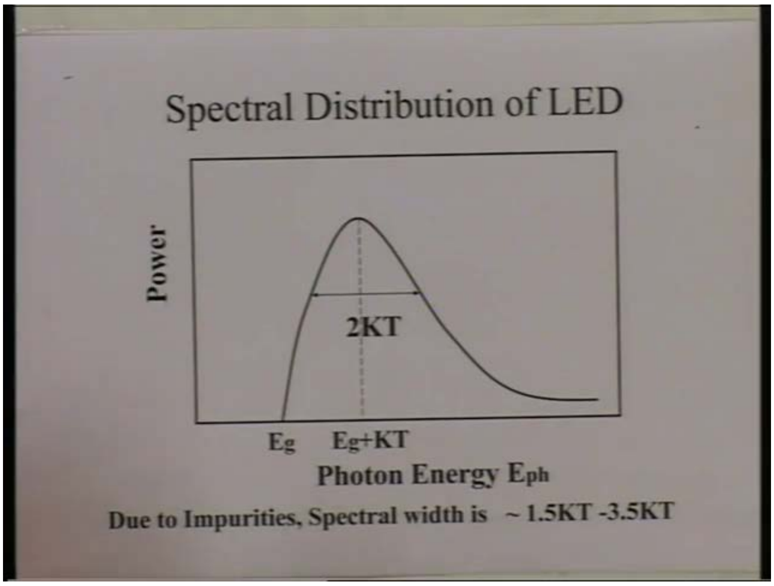

Spectral Distribution of LED

Due to Impurities, Spectral width is ~ 1.5KT -3.5KT

Then we get a typical curve which will look like that now as I mentioned when the photon energy is equal to E g then the power of the number of photon which are emitted is zero as the energy increases photon energy increases the number of photon increase or the power increases. It reaches to the maximum when photon energy is E g plus k T and then again it start decreasing exponentially and for large photon energy. The power is practically zero, so we get a spectral distribution which looks a asymmetric kind of distribution.

The maximum power is received not corresponding to the energy which is the band gap but is little more than that of course, this quantity k T is a very small number compared to E g typically the band gap energy for semiconducting material is of the order of about 1 E V whereas, this quantity k T if the order of about 0.025 E V at room temperature. So, this quantity is very-very small compared to E g nevertheless the maximum power is not received for energies equal to the band gap energy but for the energy which is little higher than the band gap energy.

The second important aspect however for this analysis is that this quantity here if I measure the effective width of this function that gives me the spectral width of the light emitted by the LED, and if I see approximately if I take this function and find out the width of this function you will see that this width is approximately 2 k T. So, when we go for one semiconducting material to another this quantity E g change but as far as the width of this spectrum is concerned that is 2 k T and has nothing to do with the band gap energy E g.

Or In other words when I go from one semiconducting material to another material the peak wavelength or peak frequency will change because E g would change, but the spectral width is independent of the material as long as the material is having a temperature which is T the spectral width is 2 k T in energy and this is not a very good feature, because what this means is that the spectral width which is one of the very crucial parameters for optical communication is not in our control at all.

So, if we use a light emitting diode as the source for optical communication then spectral width is decided purely by the operating conditions, which is equal to 2 k T in the priors of impurities in the material, this may range over a range of 1.5 k T to about 3.5 k T but again the thing to note here is that this number is independent of E g so depending upon the operating conditions you may have a spectral width and this spectral width will be independent of the material or the wavelength at which the emission is taking place.

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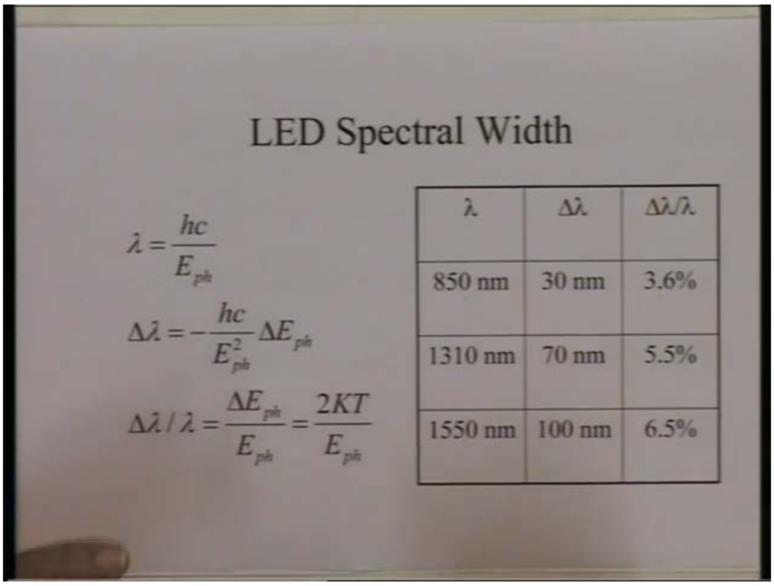

LED Spectral Width

$$\lambda = \frac{hc}{E_{ph}}$$

$$\Delta\lambda = -\frac{hc}{E_{ph}^2}\Delta E_{ph}$$

$$\Delta\lambda / \lambda = \frac{\Delta E_{ph}}{E_{ph}} = \frac{2KT}{E_{ph}}$$

λ	$\Delta\lambda$	$\Delta\lambda/\lambda$
850 nm	30 nm	3.6%
1310 nm	70 nm	5.5%
1550 nm	100 nm	6.5%

Now I can ask quantitatively having understood this what is the spectral width, which the LED typically has when the LED is operating at 850 nanometer or 1310 nanometer or 1550 nanometer. So, we know the relation that the lambda is equal to h c divided by E photon. We are looking here for the spectral width that means the change in the wavelength so we can delta lambda that is equal to I can differentiate this with respect to E p h so I get minus h c upon E p h square into delta E p h.

So, this is the spread in the energy of the photon from the spectrum. This is the corresponding change or the spread in the wavelength which we will get in the spectrum. You can take h c upon E p h which is nothing but lambda so you can take this quantity lambda and bring it down so you get delta lambda upon lambda all the relative spectral width for the source that is delta E p h divided by E p h now delta E p h as we saw is approximately 2 k T and this is the photon energy if you substitute that then you get now the relative spectral width of a source.

And this is essentially tabulated here so we have got a lambda which is the operating wavelength of the LED. This is the spectral width delta lambda and this is the quantity delta lambda by lambda which essentially gives me the percentage spectral width. So, if I take a semiconducting material for which the band gap corresponds to 850 nanometer which is gallium arsenide then we will have a spectral width approximately about 30 nanometer or 3.6 percent.

Whereas if I go to other ternary or quaternary materials for which the spectral width is 70 nanometer and emission wavelength is 1310 nanometer the percentage spectral width is about 5.5 percent and if I go to the third window of emission, which is 1550 nanometer then the spectral width will be as large as 100 nanometer or the relative spectral width will be 6.5 percent now remember when we are discussing different windows for optical communication. We went from 850 nanometer to 1310 nanometer, because that is why the dispersion is going to be lesser.

But that was under the assumption that other parameters of the system remain same what, we find in this case now is that as you go to longer and longer wavelengths the spectral width of the source increases and therefore, the dispersion in the optical system increases so dispersion for 1550 nanometer will be almost three times compared to what dispersion you will get at 850 nanometer so LED has one of the major problems and that is, It has a very large spectral width.

And that is a reason if we use a LED as a source for optical communication then the data rate is very small. It could be only of the order of about 10 of megahertz or may be 100 megahertz but beyond that the dispersion will be unmanageable, because the spectral width for this source will be very large.

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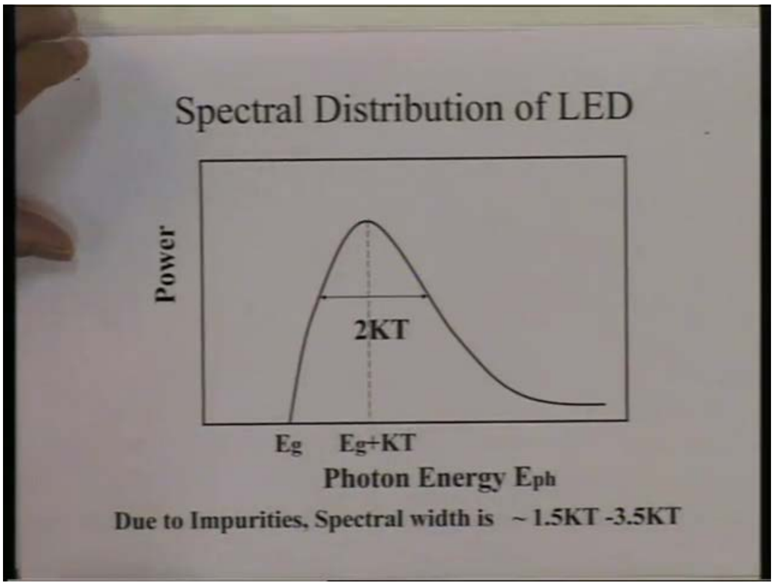
Spectral Distribution of LED

Due to Impurities, Spectral width is ~ 1.5KT -3.5KT

The second Issue which is there for LED well before that let us look at this LED spectrum again which is this and as you note here that the LED spectrum ,what we have calculated theoretically looks highly asymmetric. It has a very rapid cut off at E g and this tail extends very smoothly on the higher energy side. Whereas if you take a typical LED spectrum in practice, you will realize that the spectrum does not look that asymmetric the spectrum look more or less symmetric.

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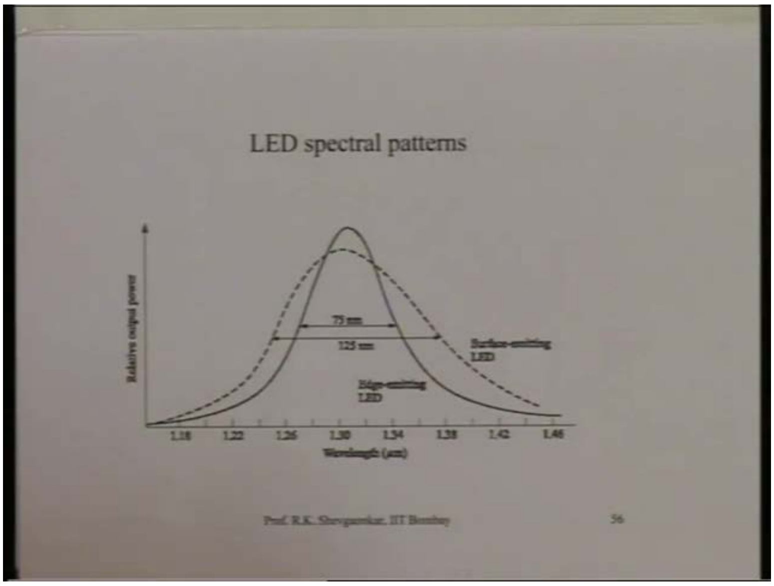

LED spectral patterns

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So, if I take a typical LED and if I look at the spectral distribution of a typical LED, it will look something like that this are the high very rapid cut off on one side, and tail extending on the other side and this has something to do with the practical conditions of LED.

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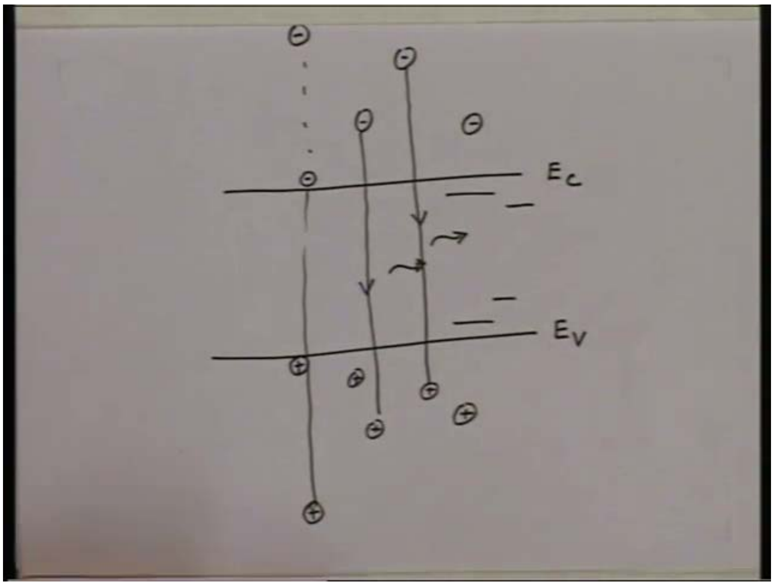

And that is when we talked about the energy level diagram, we said there is no electron hole recombination possible, because there are no energy levels present between the forbid and back Whereas in the presence of impurities. One will see that there are certain energy levels which now also exist within the forbid and back so there is a possibility of recombination even for the energy differences which are less than E g. So, you would get some light for the energies energy of the photons which will be less than E g which theoretically we said that they sharp cut off at E g because there is no recombination possible for the energies less than E g.

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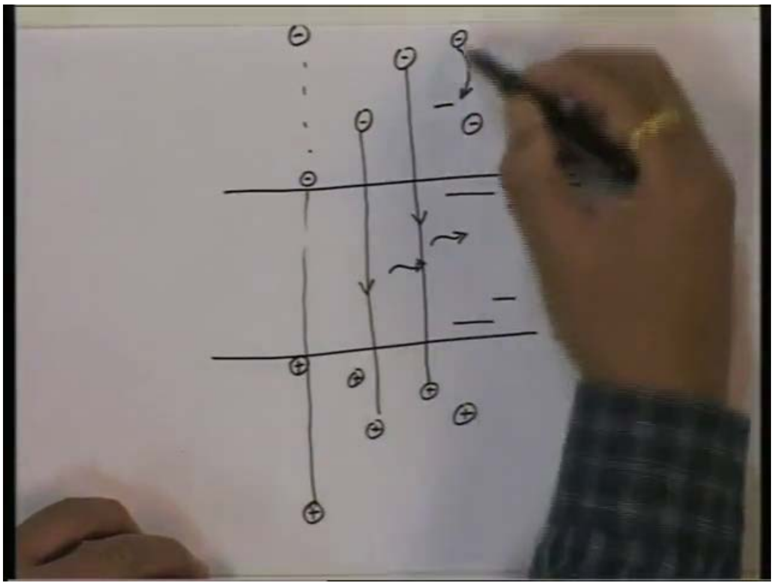

Second thing what will happen is that if the electron is here at a very high energy compared to E C, and if the energy level is available here within the conduction band itself then the electron may jump from here to here, and can share away certain energy. So as the recombination of these electrons around the peak takes place with the holes the high energy electrons can jump down to fill those energy states or in other words the electron hole pairs which has a very large energy difference they will be depleted.

So, you will have a less photons corresponding to the very high photon energies and you will have little higher photons for the energy which are less than band gap energy.

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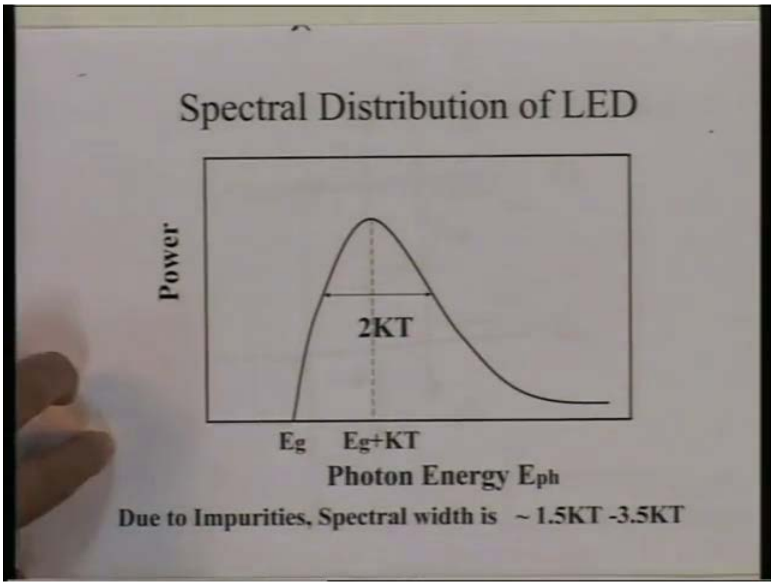

Spectral Distribution of LED

Due to Impurities, Spectral width is ~ 1.5KT -3.5KT

So, the distribution which we have got here it say that this function dies down little more rapidly either then extends that smoothly for a very long energies similarly, you have a function now there is a some photon can be emitted even in this region so this function extends little something like this.

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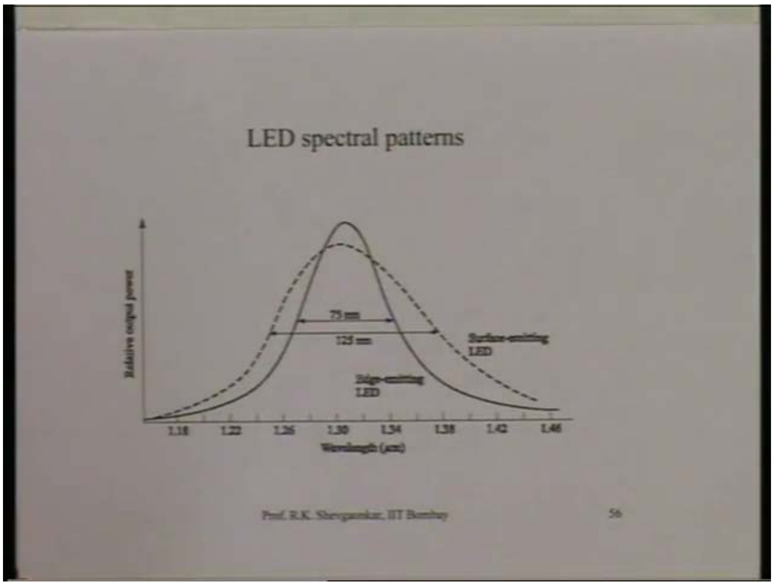

LED spectral patterns

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And this function dies down little more rapidly, as a result we get the spectrum which looks more symmetric spectrum and that is what is shown here. So, in practice if you look at LED, it does not have an asymmetric spectral distribution as we have got theoretically, but it has much more symmetric distribution in terms of frequency or wavelength.

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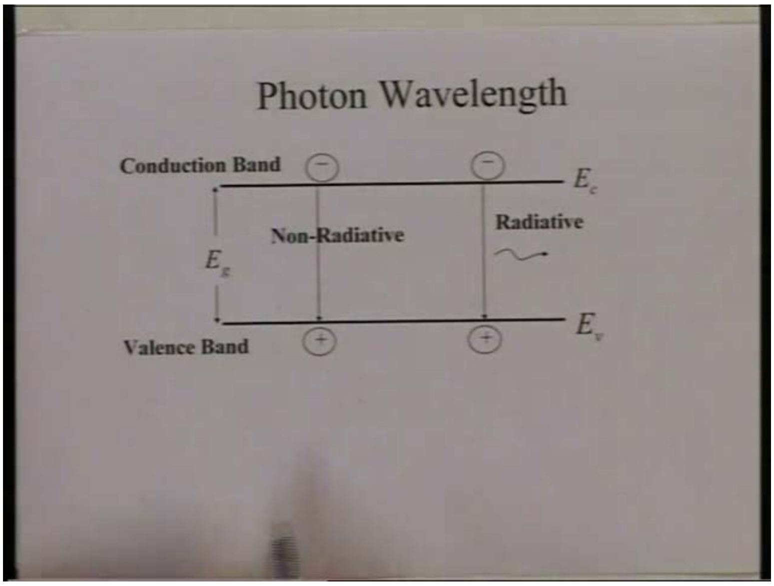

Photon Wavelength

The second aspect of the emission from semiconducting material is the efficiency issue, we saw that when the electron hole recombination takes place, there are two processes which are there one is what is called the non radioactive recombination process and other one is the radioactive recombination process.

And we have seen that when the electron hole recombination takes place the photon may be emitted or the photon may not be emitted. If the photon is emitted then that radioactive recombination process is the useful process, because we got light out but when the electron hole recombination takes place and if the energy has gone in some other form like lattice vibration or something like that then the photon is not emitted and the light has not come out.

So, when we create a p n junction and when the electron and holes are injected in to the depletion region the recombination takes place, but for every recombination we may not get a photon out and that is the quantity is captured by what is called the quantum efficiency.

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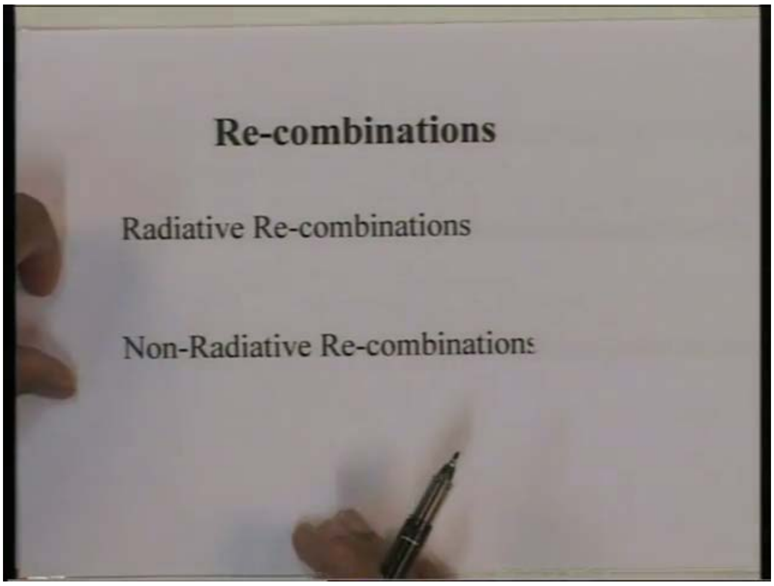

Re-combinations

Radiative Re-combinations

Non-Radiative Re-combinations

So, what we have seen we have got for the recombination two processes the radioactive recombination process and the non radioactive recombination process and for emission of light. This is the process which is the responsible process and this process is essentially is a wastage of recombination, because this recombination does not give any photon out.

So, then one can define now quantitatively what is called the quantum efficiency which is conversion of the electrical energy to photons now.

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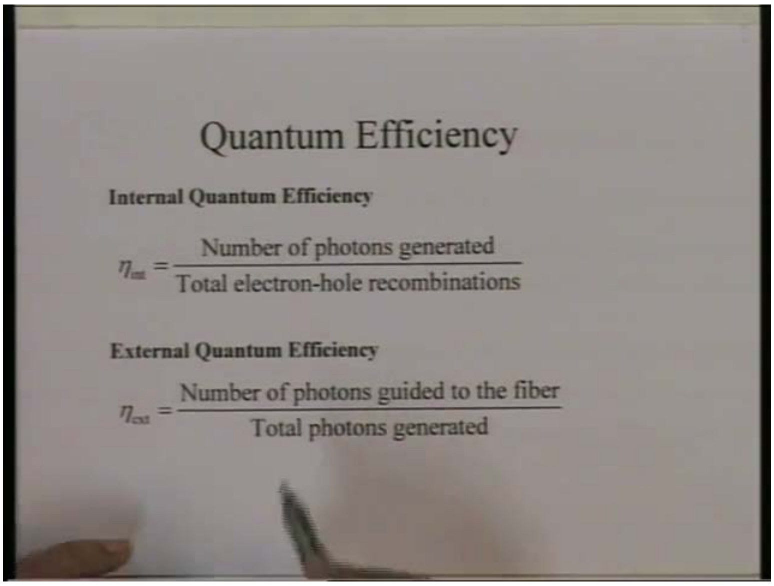

Quantum Efficiency

Internal Quantum Efficiency

$$\eta_{int} = \frac{\text{Number of photons generated}}{\text{Total electron-hole recombinations}}$$

External Quantum Efficiency

$$\eta_{ext} = \frac{\text{Number of photons guided to the fiber}}{\text{Total photons generated}}$$

The quantum efficiency is divided in to two parts one is what is called the internal quantum efficiency, which is something to do with the photon generation process the second quantity is, what is called the external quantum efficiency which is something to do with the capturing of the photon which is generated?

So, I can define now these quantities the internal quantum efficiency and the external quantum efficiencies are as follows. The internal quantum efficiency is the total number of photon generated inside the device divided by the total electron hole recombination’s or in other words internal quantum efficiency is a ratio of radioactive recombination to total recombination’s and this process is something to do with intrinsically with the material the impurity level and so on.

So, you will see that the internal quantum efficiency will be decided by the intrinsic properties of the material and may be the fabrication process the external quantum efficiency, which has something to do with the collection of photon, that is defined as the number of photons guided to the fiber divided by the total number of photons generated so the photons are generated, but what process the photon has to go through till it becomes finally, available for communication or reaches inside the optical fiber that quantity is given by this external quantum efficiency. So, total efficiency will be essentially the product of these two the internal quantum efficiency and the external quantum efficiency.

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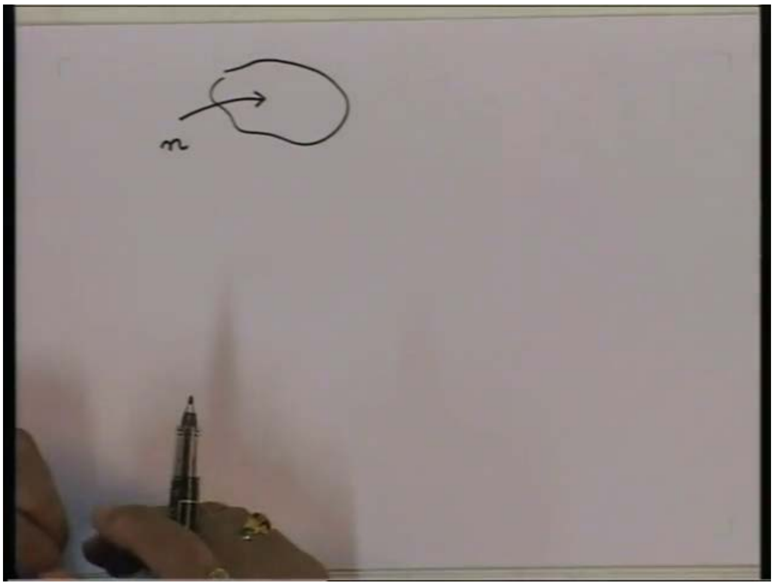

So, let us see now what are the factors which are responsible now for this efficiency, Firstly when we are having a region and in which some carriers are injected, and let us say some and carriers are injected inside this the rate of change of recombination are disappearance of this carrier would be proportional to the carrier density.

So, we can write the equation that is d n by d t minus which says that, because of the recombination the carrier density is reducing as a function of time that is proportional to the carrier density n. Now this is a very simple equation we can solve this equation, and we get the n as a function of time that will be equal to the initial injected carrier density e to the power minus t divided by tau where tau is called the lifetime of this injected carrier against recombination, so this quantity is the lifetime of carrier.

So, essentially the recombination process now can be characterized by this parameter tau, which is the lifetime of a carrier against recombination from here we can also see that d n by d t minus that is equal to n by tau.

Now we have seen that there are two processes which are responsible for this recombination. So, each process now can be characterized by the corresponding lifetime against recombination, so we have a radioactive process and we say the lifetime against recombination against the radioactive process is denoted by the lifetime tau r r.

Whereas if the recombination is non radioactive then the parameter tau is denoted by tau n r so we have tau r r, which is lifetime against radioactive process recombination similarly, we can say tau n r is lifetime against non radioactive process, so if the both the processes are acting simultaneously then the depletion of the carriers injected in a region will be the disappearance due to a radioactive process and due to the non radioactive process.

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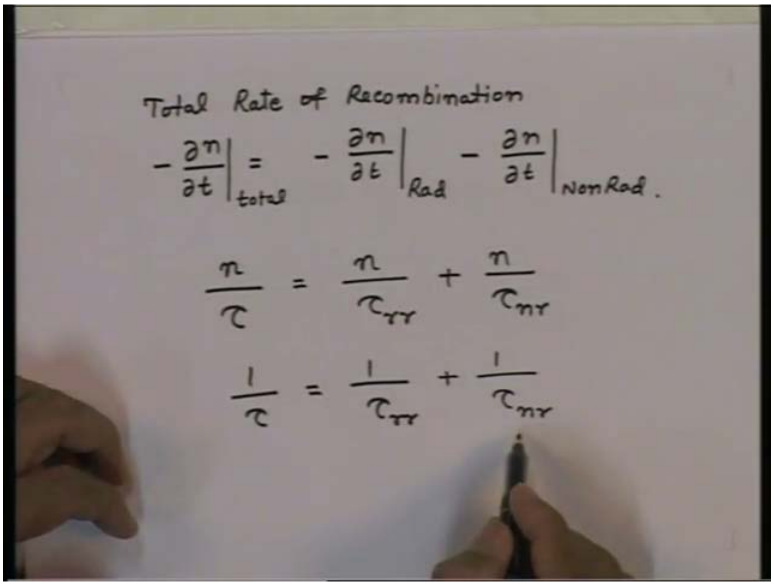

Total Rate of Recombination

$$-\frac{\partial n}{\partial t}\Big|_{total} = -\frac{\partial n}{\partial t}\Big|_{Rad} - \frac{\partial n}{\partial t}\Big|_{Non\,Rad}.$$

$$\frac{n}{\tau} = \frac{n}{\tau_{rr}} + \frac{n}{\tau_{nr}}$$

$$\frac{1}{\tau} = \frac{1}{\tau_{rr}} + \frac{1}{\tau_{nr}}$$

So, if I say that the total recombination which is going to take place is characterized by the total lifetime, then we can say that the n upon tau will be equal to n upon tau r r plus n upon tau n r.

So, rate of recombination total rate of recombination is equal to sum of the recombination’s due to radioactive process and sum of the recombination due to the non radioactive process. So, we can say here now that the total rate of recombination that is minus d n by d t that is equal to I will just write this total that is equal to minus d n by d t due to radioactive process minus d n by dt due to non radioactive process and as we saw here minus d by dt is equal to n upon tau, so you can substitute here say, you say this is n upon tau where tau is the total effective lifetime of the carrier that is equal to n upon tau r r plus n upon tau n r.

N is common so essentially, we get one upon tau that is equal to one upon tau r r plus 1 upon tau n r so what that means is that the effective lifetime will be decided by smaller of the two If the tau r r is much smaller compared to tau n r. Then the effective lifetime will be same as tau r r whereas, if tau n r is much smaller than tau r r then effective lifetime will be more or less as tau n r, so smaller of the two essentially will decide. What is the effective recombination lifetime of the carriers when they are injected in the depletion region once we get this?

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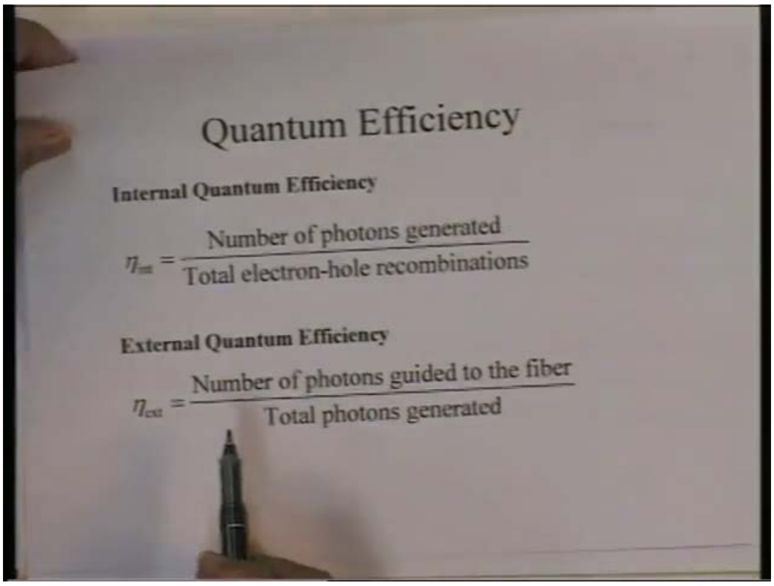

Quantum Efficiency

Internal Quantum Efficiency

$$\eta_{int} = \frac{\text{Number of photons generated}}{\text{Total electron-hole recombinations}}$$

External Quantum Efficiency

$$\eta_{ext} = \frac{\text{Number of photons guided to the fiber}}{\text{Total photons generated}}$$

Then now I can talk about the internal quantum efficiency and that we saw that is equal to total number of photon generated. So this quantity is nothing but the rate of radioactive recombination divided by the total number electron hole recombination, so that is the total rate of recombination.

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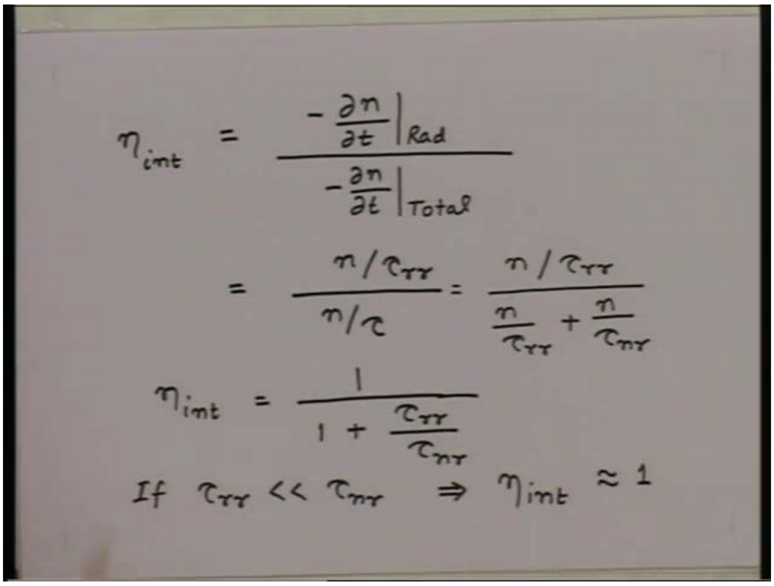

$$\eta_{int} = \frac{-\frac{\partial n}{\partial t}\Big|_{Rad}}{-\frac{\partial n}{\partial t}\Big|_{Total}}$$

$$= \frac{n/\tau_{rr}}{n/\tau} = \frac{n/\tau_{rr}}{\frac{n}{\tau_{rr}} + \frac{n}{\tau_{nr}}}$$

$$\eta_{int} = \frac{1}{1 + \frac{\tau_{rr}}{\tau_{nr}}}$$

If $\tau_{rr} << \tau_{nr} \Rightarrow \eta_{int} \approx 1$

So, from here we get now Internal quantum efficiency which is internal that is equal to minus d n by d t radioactive divided by minus d n by d t total substituting now for d n by d t radioactive, and total we get is equal to n divided by tau r r divided by n divided by tau.

So, which is equal to n divided by tau r r divided by n by tau r r plus n by tau n r, so we get internal quantum efficiency that is equal to one upon all the n will cancel, we can divide it by tau r r you get 1 plus tau r r by tau n r so what we see from here is that if tau r r is much-much smaller compared to tau n r then this quantity is negligibly small and internal quantum efficiency is almost equal to one, so we say that if tau r r is much-much less than tau n r that gives me the internal quantum efficiency almost 1.

But if tau r r becomes comparable to tau n r or larger than this then the efficiency drops very rapidly. What that physically means is that when the both the process are operating and when the electron holes are injected for recombination, if tau r r is much smaller compared to tau n r before the electron holes can recombine against the non radioactive process they have already recombined, because of radioactive process and photon is emitted now the non radioactive process does not have a chance to show its effect, because before it starts showing it effect the electron holes are already recombined and the photon has been emitted.

So, what we want for good internal quantum efficiency. This quantity radioactive recombination should be much smaller compared to the non radioactive recombination lifetime however what happens is that this quantity which is tau r r is intrinsic parameter of the material used for making this device whereas, this quantity tau n r depends upon various factors. It depends upon the impurities the energy level which is created the artifacts where recombination can take place. So, this quantity is the one which it will depends upon fabrication process the impurity levels and various things whereas; this is the quantity which is a intrinsic parameter of the material.

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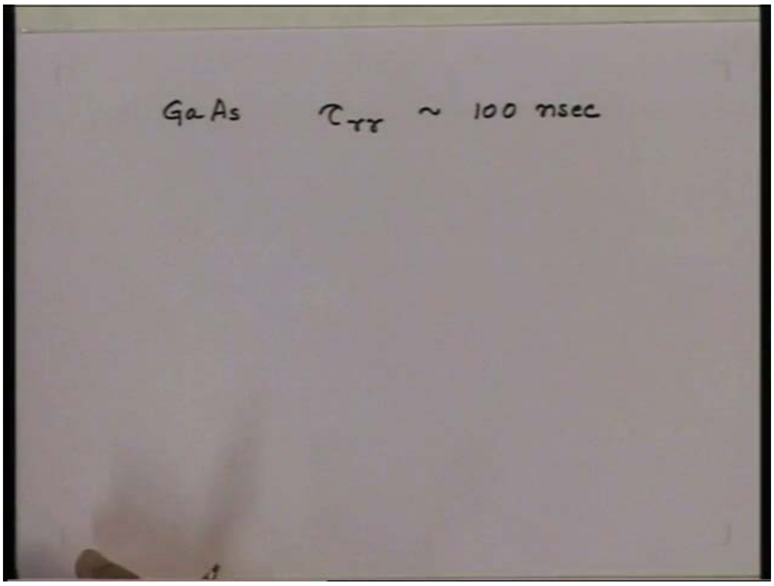

GaAs $\tau_{rr} \sim 100$ nsec

So, if I consider gallium arsenide then tau r r for this is of the order of about 100 nanosecond and if I consider the tau n r- tau n r will depend upon the impurity level and if you take very pure material then tau n r will be very-very large and most of the recombination would take place because of radioactive recombination and you will get efficiency but in practice tau n r also is of the order of about 100 nanosecond so due to impurities tau n r is also of the order of about 100 nanosecond.

As a result you get the internal quantum efficiency of the order of about 0.5 that means whatever electron hole pairs are recombining approximately 50 percent of that give you photon out and this number is not a too bad a number for simple reason that whenever, we talk about the conversion of energies anything which is more than about 2030 percent is considered to be a good efficiency. So, from that angle conversion of the electrical energy which is in the form of electron hole pairs in to an optical energy which is a photon is a fairly efficient process because 50 percent of this recombination's give you a photon out.

The second efficiency which is external quantum efficiency, that is the one probably, which is much more problematic, and that depends upon various factors, so here we are saying that the external quantum efficiency which is number of photons.

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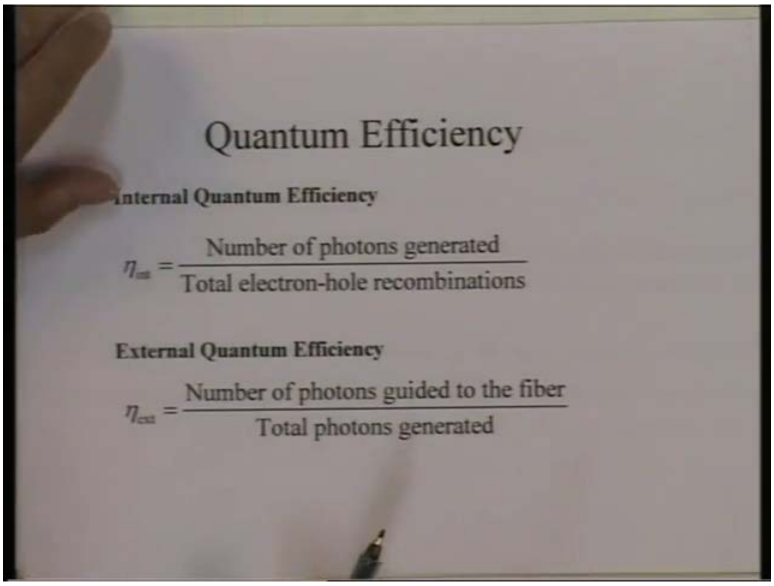

Quantum Efficiency

Internal Quantum Efficiency

$$\eta_{int} = \frac{\text{Number of photons generated}}{\text{Total electron-hole recombinations}}$$

External Quantum Efficiency

$$\eta_{ext} = \frac{\text{Number of photons guided to the fiber}}{\text{Total photons generated}}$$

Now guided to the fiber divided by the total number of photons generated so here photon is generated now only thing, now we are trying to get this photon finally, guided inside the optical fiber so let us look at the journey of the photon after it is emitted.

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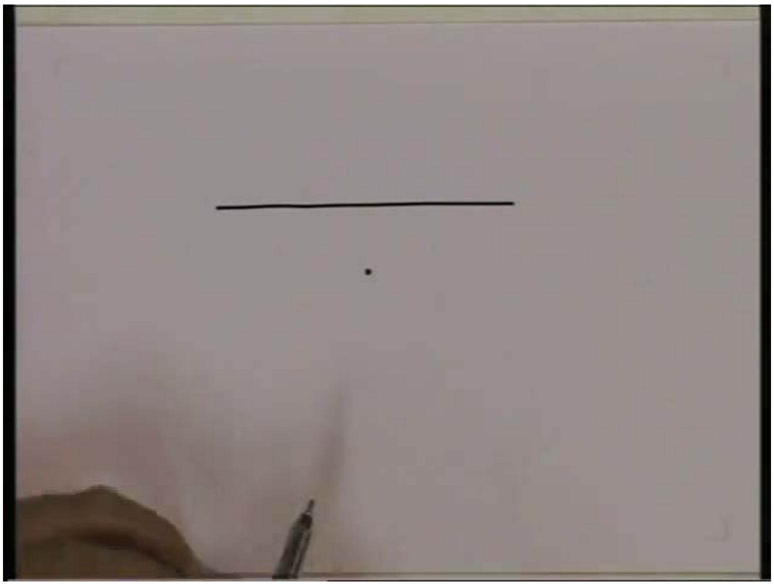

So, let us see we are having a semiconducting material here where the photon is generated now note here. When the recombination is taking place the recombination is not taking place on the surface of the semiconducting material the recombination will take place somewhere deep inside this material. Somewhere here and the photon is born here at this location now since the photon is born it does not have any history and photon is nothing but a packet of light which starts moving with velocity of light.

But since it does not have any history, it does not know which direction it should go definitely. So, there is a equal probability of a photon which is generated, because of this recombination to travel in different directions or what it means in other words is that as soon as the photon is born it is scattered with equal probability in all directions.

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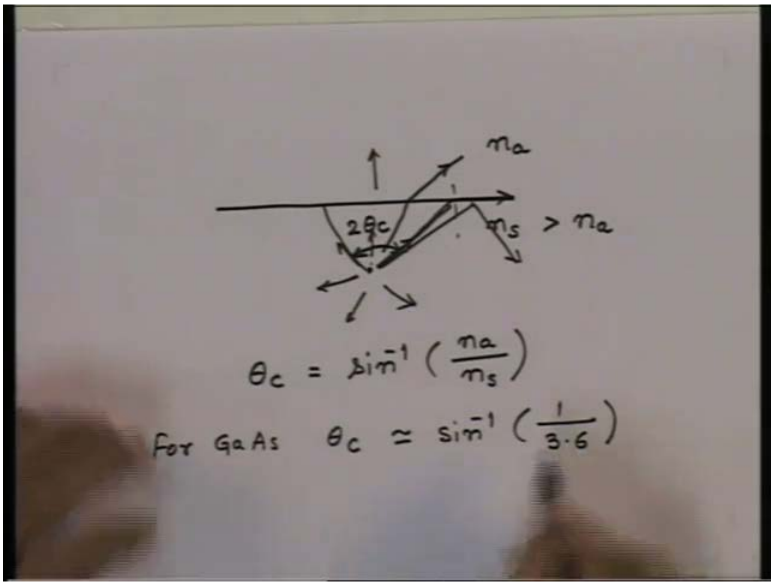

$$\theta_c = \sin^{-1}\left(\frac{n_a}{n_s}\right)$$

For GaAs $\theta_c \simeq \sin^{-1}\left(\frac{1}{3.6}\right)$

Now, we are saying that when the photon is born here it can either go this way or it can go this way or it can go this way or I can go this way this way this way and so on. Now note here that the semiconducting material typically has a refractive index, which is quite hard so let us say the refractive index for this was n s and the refractive index here is let us say n of a and typically n s is greater than n a. So the photon essentially is trying to go from a denser medium to a rarer medium and as a result there may be a possibility that when it is incident on this interface at an angle which is greater than the critical angle the photon is reflected back inside the material again.

So, what is happening is that the photon which is going like this will come out the photon, which is going this way will get reflected like this the photon which go like this may be if this angle is equal to the critical angle. It will start moving like this but if the angle os more than this angle then the photon will be reflected back inside the semiconducting material. So, what we are saying is although the photon generation is isotropic that means there is equal probability of photon emitted in all directions when at the point of generation of photon the photon which can escape out will correspond to a cone this cone which is two times the critical angle two times theta c.

So you can calculate what is the angle which is theta c because we know the refractive index of the material, we know the refractive index outside, so theta c will be equal to sine inverse of n a upon n s and if I consider a material like gallium arsenide this quantity is three point six and if I say that the photon is getting emitted in air this is n a is equal to1e. So, you have for gallium arsenide theta c is approximately equal to sine inverse of 1 upon three point six, so if I take approximately this quantity let us say four so one upon four.

So theta c will be of the order of about fifteen degrees if I take accurately it will be about eighteen to twenty degrees. So what that means is that although the photons are bond with spherical symmetry only photon which are lying within a cone of only plus minus twenty degrees from this direction can escape out all other photon essentially will get reflected back inside the device and ultimately they will again give the energy to the carriers and the energy will get thermal zed so essentially. What we are saying is the fraction of the total number of photon, which were bond which can escape from here or which lies within this solid angle correspond hat is the one factor affecting the external quantum efficiency.

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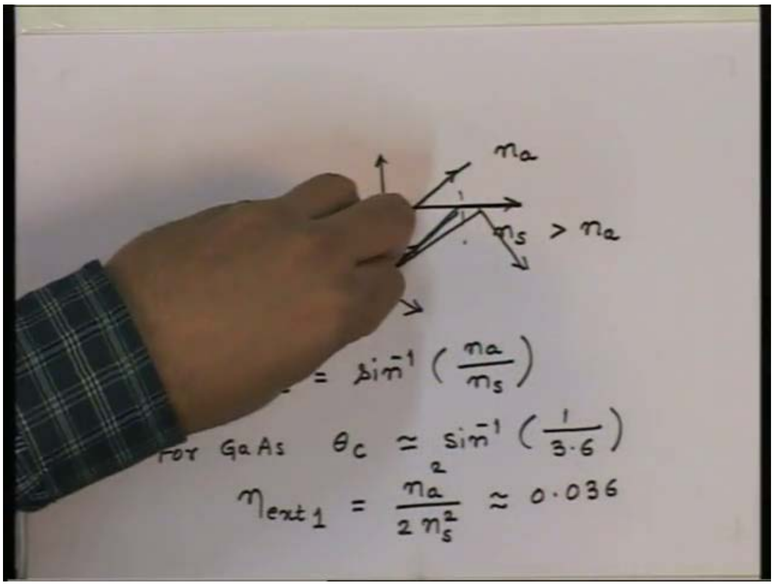

$= \sin^{-1}\left(\frac{n_a}{n_s}\right)$

For GaAs $\theta_c \simeq \sin^{-1}\left(\frac{1}{3.6}\right)$

$\eta_{ext\,1} = \frac{n_a^2}{2 n_s^2} \simeq 0.036$

And if I just do a simple calculation to find out what fraction will come out of this. So, I calculate solid angle corresponding to this and divide by total four pass solid angle. I will get the eta external one due to this total internal reflection, that is equal to n a square divided by 2 n a square and approximately again for gallium arsenide. If I substitute this numbers it will turn out to be 0.036. So it is Interesting now to note that if 100 photons were born here inside the material like gallium arsenide only about three point six photons on average would be capable of coming out of this device or there is a loss of ninety six photons.

So major efficiency loss takes place right here in escaping the photon from the device, so photon generation process is a very effective process but capturing the photon and bringing it out of the device and guiding it inside the optical fiber is probably far most difficult process so we will continue with this discussion. We will see that there are many factors, which will now contribute to ultimately capturing the photon and guiding in to the optical fiber but just from the view point of taking the photon out of device you will see that we have efficiency which is hardly about four percent.

So, the external quantum efficiency is much more important parameters for a device then the internal quantum efficiency, because internal quantum efficiency is fifty percent but capturing the photon is more difficult and that is why external quantum efficiency is much smaller compared to the internal quantum efficiency. So, in the next lecture we will see other factors which will contribute to the external quantum efficiency.