Fundamentals of Semiconductor Devices

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Lecture - 51

Basics of LED

Welcome back. So, if you recall we are discussing LED, in the last class we are introduced what LEDs are, how they work, the basic operational principle and so on. So, today we shall continue the discussion. So, LED is the reverse of photo detectors and solar cells you convert electrons and holes or electrical energy into light energy. We have to make a distinction between visible LED is that our eyes can perceive and IR or UV LEDs that our eyes cannot perceive, but those are useful for other application. When we talk about things like brightness, colour rendering and other things we talk about only the visible LEDs which human eyes can you know sense right.

In general many of the electrical and optical properties of LEDs will remain same whether we human eye can sense or not. But only the things like brightness, colours, chromaticity all these things are related to the white LEDs or the coloured LEDs which human eyes can perceive ok; please remember that. So, in the last class I told you that in the ending of the last class I told you that LEDs are not mono chromatic which means LEDs do not emit only a single wavelength. There is a range you know, it is a distribution of wavelengths and that spread of the wavelength will depend on lambda.

Shorter wavelength LEDs like blue or UV will emit will have a shorter spread and higher wavelengths will have a higher spread, if you recall that right. So, LEDs not a strictly a monochromatic light although eye perceives to be it to be like a monochromatic light and this spread in its wave length comes from the Fermi distribution and the density of states. If you recall I had introduced joint density of states that takes into account both electron and hole effective masses together as a harmonic mean, that is called reduce effective mass and from there we derive this expression for you know the intensity versus the wavelength and we saw that there is a spread in that right.

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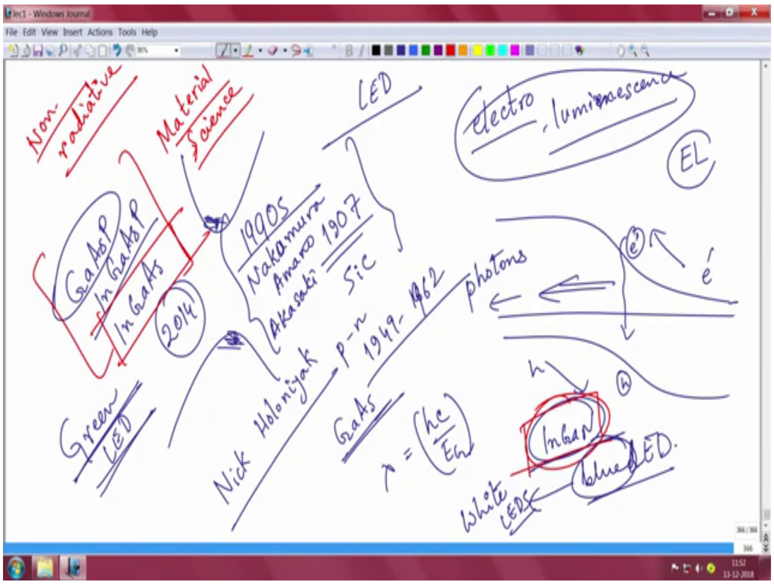

So, let us come to white board now and we will continue with what where we had left yesterday. So, I told you that LED you know the process is called electroluminescence, I hope you remember that. Electroluminescence is the process of emission of light from LED. What happens is that if you have a p-n junction you know and then you are injecting electrons and you are injecting holes, then the recombined and that energy that is lost is given out as photons. If the energy is recombine this electrons and holes are recombining radiatively from band to band ok.

This photons will come out at an energy corresponding to the band gap; ideally it should come out at a la wavelength of lambda equal to h c by E G. But I told you it comes out slightly more than that because, there is a distribution you know in the E K diagram the electrons will be like that, holes will be like that. So, there will be a small distribution here because of that the peak will be slightly shifted.

Now, it needs not necessary that it is always a p-n junction all the p-n junction will give you efficient LEDs, but somehow if you can basically make electrons and holes recombine the emission of light that process is called electroluminescence or EL ok. Please keep that in mind electroluminescence or EL; I told you the first electroluminescence was observed in 1907 which is more than 110 years back.

And it was actually observed in a material that you even cannot expect it to you know exhibit EL, it was in silicon carbide which is in indirect band gap material. So, it of course, it was very in efficient very poor; nevertheless first p-n junction LEDs based on you know gallium arsenide and other things they came out in the range of 1949 to 1962. In this range gallium arsenide although gallium arsenide wave length is not exactly in the visible spectra towards the tail of the red you know near IR. But p-n junction an LED on gallium arsenide was you know this invented by this person called Nick Holoniyak right; who Holoniyak who also wanted a Nobel Prize, but he did not get it of course ah.

So, anyways and then the work on LEDs has started a lot in 1970's-80's and all many companies in Japan and US were very much into big time R and D development of LEDs of different materials. People realise that this gallium arsenide phosphide you know, in indium gallium arsenide phosphide, InGaAs all these LEDs were you know they were taking place. They were they were the research was going on not only for visible, but also other applications you know. But, gallium arsenide phosphide LEDs were pretty dominant in a way because they were able to get all this red, yellow and other emissions, but green was a problem, blue was a problem.

So, only in 1990's you know this Japanese team of Nakamura and you know Nakamura and this three gentleman Amano right Akasaki. These guys got the Nobel Prize in 1990 and in 2014 they got the Nobel Prize for a work that they did in 1990's, they essentially enable the InGaN LED they enable it is a p-n junction essentially. So, they got the InGaN blue LED which you can convert to white by using a phosphor coating and that is why that makes possible our white LEDs that are used in our homes and garages and streets and all.

So, that LEDs are eventually done, but there is a lot of history, lot of historical research you know accounts are there as to how this research was going on. How many set backs were there, how people had fired them from companies and all these things are there. You can read up in the internet ok, that is an important thing, but we should be aware that this was the track of development of LEDs. And even today there is a lot of research going on specially in green LED because, green LED green is not very easy to emit even for gallium nitride technology.

Green emission efficiency is an our actually not as close to blue emission efficiencies because, for green you need a higher indium competition InGaN and higher indium composition in InGaN is difficult to grow material wise.

Please remember that all these materials are not silicon, these are compound semiconductor gallium arsenide, phosphide, indium gallium nitride, InGaAs and so on. And whenever I say compound semiconductor there is a lot of material science that has to go in to it in terms of the lattice mismatch, in terms of the structural quality, terms of the strain. It is a humongous amount of material science structure research that goes into enabling this layers because, whatever layer you grow InGaAs, InGaAsP whatever this have to be growns crystalline very high quality crystalline solid.

If they are not then non-radiative recombination centre will be large; that means, if there are defects; if there are defects and other kind of material imperfections you will get non-radiative recombination that will kill your efficiency ok; that will reduce your efficiency and even make your device not emit any light.

So, your material has to be of superior quality, superior material structural quality and so, there is a lot of material science that make sure that this layers that you are growing are very high quality ok. You should remember that making something emit light is more difficult than making something absorb light in give photoconductivity. So, it is easier to do research on photoconductivity then to do an LED because light emission is a very complicated process and very difficult ok.

So, you need very best quality of material there anyways. So, apart from you know white light LED giving us you know all these lightings and all there are many applications of LEDs you know applications of LEDs of course, lighting is the most important application now.

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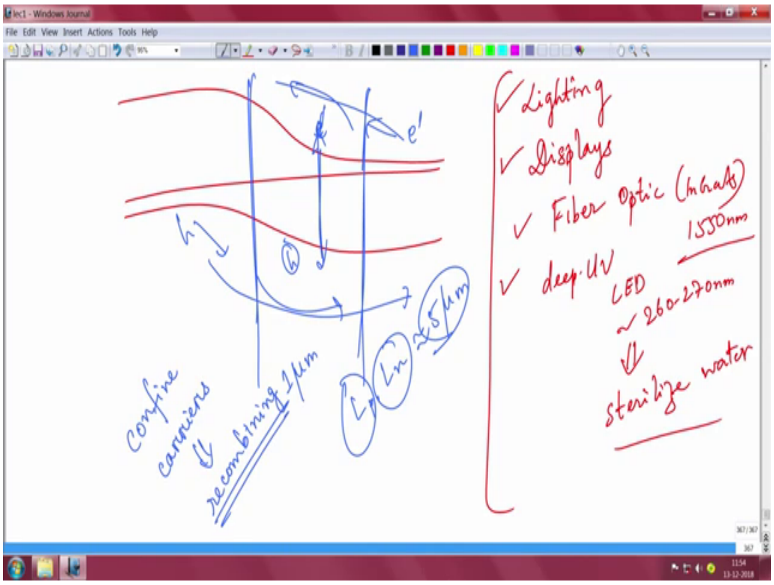

Because, everywhere you see white light LEDs, you also have a lot of applications in displays. This bill boards, computers, games, automobiles you know clocks and everywhere the backlight, the back panel mobile phone all this place displays depend heavily on la LEDs ok. Also you have to remember that things like fibre optic communication they use they use LEDs that are not visible to human eye, InGaAs LEDs they use for mid in air higher you know 1550 nanometre communication optical fibre communication. You also can use deep UV LED; deep UV LED which emits at around 260, 270 nanometre that is also the emission of mercury lamp by the way to kill bacteria and sterilize water.

So, there are many applications that we many applications are valid. So, it is a very vast and growing field, but you should know what is the hot area? Now if you want do any research. And all in all cases the LED is basically a I keep telling you it is basically a p-n junction, but the problem with a simple p-n junction is there when electrons and holes are you know injected by a forward bias; the electrons and holes are expected to combine here and emit light.

But they might move very fast and they might not get time to recombine, then they you will not get a very bright LED. And, secondly this diffusion of holes and electrons might be very long. If the if this depletion width is for example, 1 micron suppose I am sell telling you and the hole diffusion length L p and L n the diffusion lengths are say 5 microns suppose. Then in 5 micron 1 electron and 1 hole will recombine to give 1 photon.

But your depletion is so, narrow 1 micron that you have very less chance that electrons and holes will recombine so, the emission will not be there. So, you want the you want to confined the electrons and holes you want to confined the carriers. So, that they get to spend more time in terms of the recombining ok. So, that they can spend more time and they have a more probability of recombining with each other to emit light and that is why you confined them and the confinement is enabled by a quantum well I keep telling you this.

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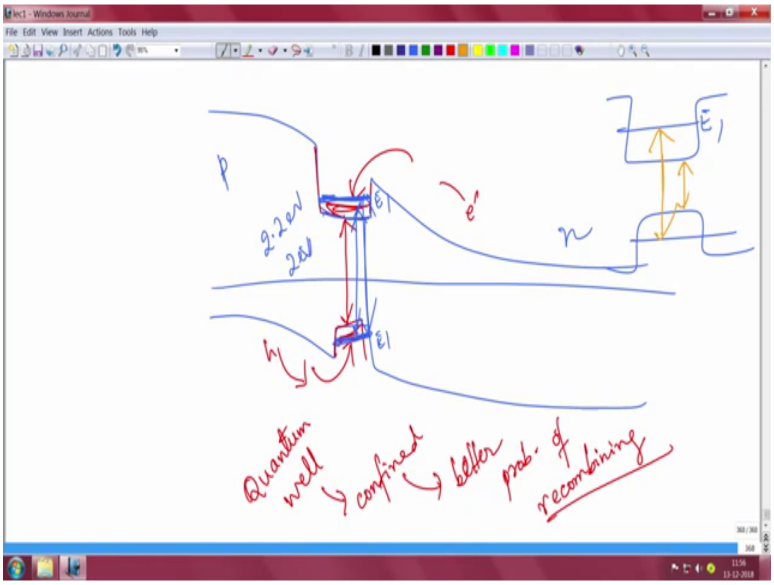

So, it is your right this is your n type, this is your p type. So, when you inject holes from here, when you inject electrons from here if electron falls down here a holes falls down here, then the electrons and holes will not be able to come out because there is a barrier. It is a quantum well see it is called a quantum well in case you have forgotten. This is call a quantum well, carriers are confined here and because they are confined the carriers are confined here and because they are confined you are not able to move out no.

So, they will get a better probability of recombining, now better probability of recombining and of course, the material has to be direct band gap material in all these. So, that when they recombine they will recombine radiatevely and you know band to band until emit a wavelength corresponding to this.

But in reality they will be like a sub band level here; so it will come recombine from the first sub band E 1 to first sub band E 1 here. So, it will be slightly more than the band gap of InGaAs or whatever you are using here, you see my point right. If the band gap of this quantum well is suppose 2 e v, the emission of the light will be slightly more maybe 2.2 e v or 2.3 e v because, there is a it is a quantum well.

In a quantum well you have sub band levels if you remember high school physics. So, the sub band of the electron quantum well sub band of the hole quantum well it will recombine from sub band to sub band and so, it will be slightly more like you have this and you have the whole here.

So, it will basically recombine from this to this from this to this is. So, that energy slightly more than this, that is why you will get a peak at a slightly lower wavelength or higher energy. This is the reason why you have quantum well LEDs so, that you come recombine you confine them you increase the probability of them recombining well.

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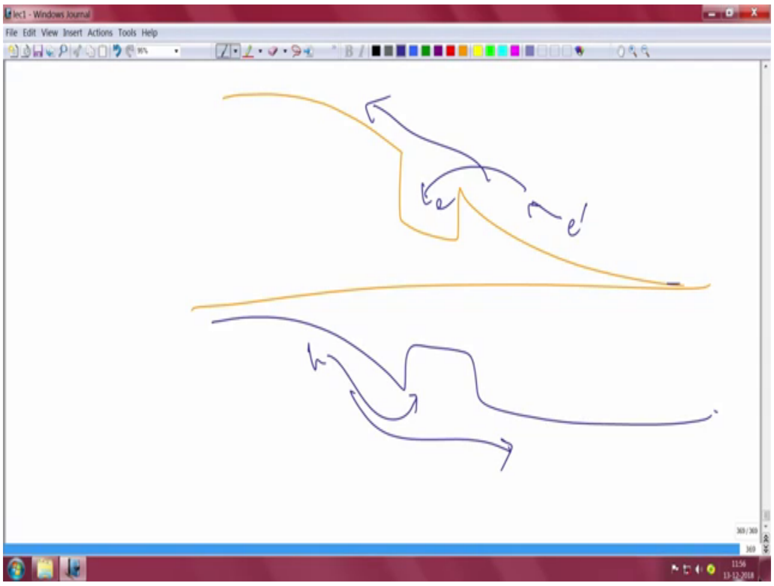

In reality of course, people what they do it that; suppose you have 1 quantum well like that this is your whatever. So, you have 1 quantum well then when you are injecting electron some electron might fall here, but some might go actually. Some electron might fall here, some holes might go some might go because, they also you are injecting and high energy. So, what many people do is that they I have multiple quantum well.

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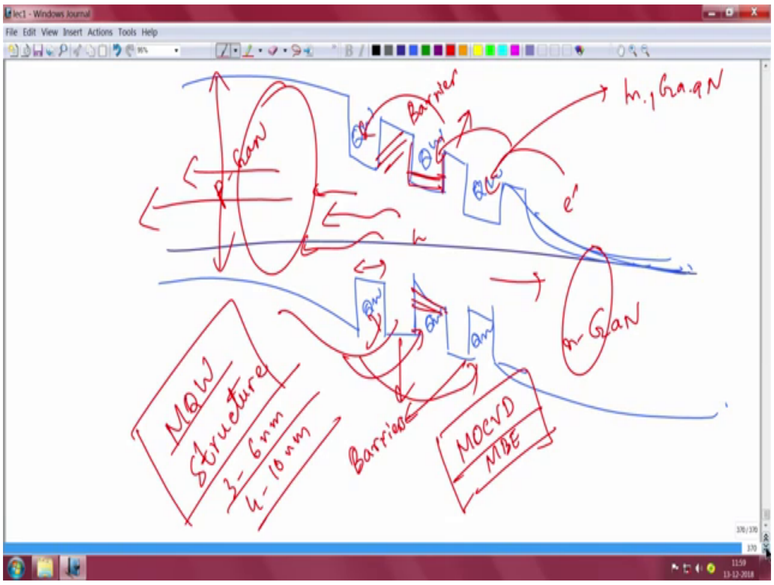

So, what I mean by do that is that we will have 1 quantum well then you have a barrier again another quantum, well another barrier again another quantum well another barrier and go like that right or maybe it will go like that ok.

So, then you will have like that you will have a quantum well, you will have a barrier, you will have a quantum well barrier like that you see. So, this is one quantum well, this is one quantum well, this is one quantum well for electron. Similarly, quantum well for hole, quantum well for hole, quantum well for hole these are barriers. The barrier can be a little wider band gap material of course, these are barriers, these are barriers ok.

So, what you do is that by increasing the number of quantum well, when you are injecting electron you make sure that they fall ok; you make sure that they fall and you have a better chance of making them recombine. This is called a Multiple Quantum Well: MQW structure ok, most of the LEDs are like that multiple quantum well structure.

So, you cannot give 3 quantum well or 5 quantum wells are more than enough; it is no need to grow like 10 quantum well or 100 quantum well because there is no improvement eventually. I mean only 1 in 3 for quantum well you will get some improvement and also material wise growth wise there are some challenges, but this is what people do.

And in some case these are all the interesting things that you should be generally aware of in terms of designing. So, for example, if you are using a gallium nitride you know blue LED InGaN, blue LED you are using an n type gallium nitride, a p type gallium nitride. So, it is quantum wells this quantum wells could be InGaN 10 percent which is a lower band gap material to emit blue right. And the light that comes out the photon that comes out will corresponding to correspond to the band gap of InGaN; the quantum well slightly more because of the sub band level, but still substantially lower than the band gap of GaN.

So, the photos that come out will not be observed in this p type or n type GaN because, the p type or n type GaN is a wider band gap material compared to the photon energy of InGaN which is a smaller band gap material. So, the photons can come out without getting absorbed which is a beautiful thing of quantum well. If you do not use a quantum well just the p-n junction then the photon that comes out has the same energy as the p type and n type layer. So, they get absorbed in the p type and n type layer they do not come out so, that is not good.

So, quantum well offers two advantage one is that it confines, hence in increases the chance of recombination and increasing the brightness of LED or efficiency. Secondly, the light that comes out will not be absorbed. So, you can extract the light as you know better in a more efficient way [FL]. So, this is these are 2 main advantages of using quantum, well people use a multiple quantum well structure. Typically 3 to 5 quantum wells and each of the quantum well layer could be you know the range could differ.

It could be between 3 to 6 nanometre could be even slightly more slightly less depends and the barrier could be also you know in the same range maybe 4 to 10 nanometre depends; so in the typically in few nanometre. So this kind of precise precision will need you MOCVD or MBE to grow MOCVD or MBE systems. These are epitaxial tools very sophisticated epitaxial tools to grow these materials one layer by one layer while maintaining a super high crystalline quality of the layers.

So, that the non radiative recombination does not take place. So, these are very lot of things that you know are there going behind LED production and LED research. So, that I told you about the quantum well LED multiple quantum well LED to get high radiative efficiency right.

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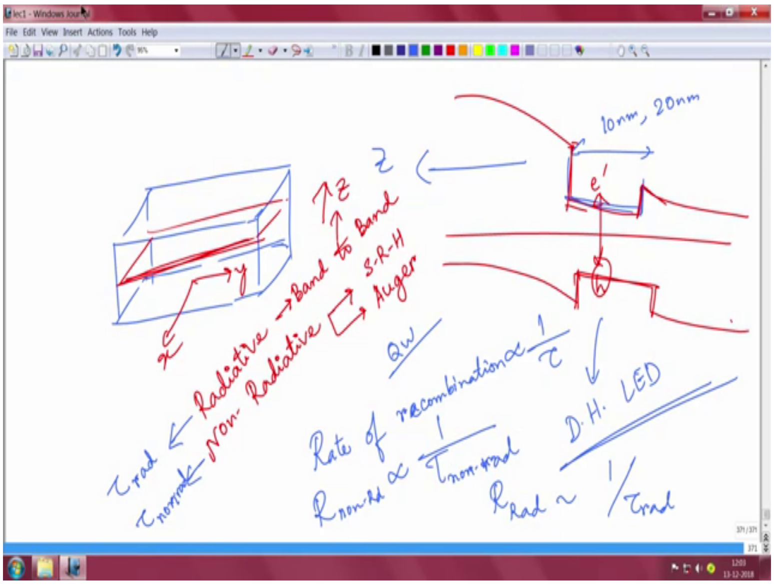

So, now that I was talking about efficiency I will talked at there are two kinds of life recombination. Even if I take a quantum well or a non-quantum well LED, I am just drawing 1 quantum well that is also fine.

Sometimes what happens is that this quantum well can be little typically its arounds at 3 to 6 nanometre or so, but some people do you know what they only have one sort of structure like this where, they do not have a very thin layer. They will have a slightly thicker layer may be it is not a exactly a quantum well and this thickness could be may be you know depends, it could be maybe 10 nanometre or may be even 20 nanometre and only one of these will be there, no non-multiple.

This is not exactly a quantum well, this is called a double hetero structure LED ok. The one of the first blue LEDs was made on this kind of structure only. It is little wider [FL] it is not too thin to be quantum well, a quantum well is such that your electrons or holes will only can move only in x y direction not in the z direction, this is the z direction of growth. So, your con carriers that are confined cannot move in the z direction. What I mean is that in actually when you grow the layers you will grow like these no you will grow like this right. So, this is your layer stacks that you are growing maybe in between you have an InGaN layer or whatever.

Then the confinement if it happens here this is your z direction, carriers cannot move in this direct direction. They can only move in x and y direction that is why it is called quantum well you are confining in you confining it to two dimension. In the third dimension it cannot move because of the barrier [FL], but in double hetro structure LED it is not exactly a quantum well, because you give it wider.

You know typically that thickness of the quantum well t should be in the order of De Broglie wavelength of the electron, in that case you call it a quantum well anyways. So, these are also call double hetro structure LED, but in general whether you talk about the multiple quantum well LED or a p-n junction without any quantum well we are talking about double hetro junction anything you can talk about.

But, eventually there are two types of recombinations that carriers will have take place. The electrons and holes need to recombine right, there are two types I told you of course; one is called radiative recombination which is the band to band radiative recombination. And one is called the non-radiative recombination that cont does not contribute to light that kills your efficiency.

This non-radiative recombination could be Shockley Hall Read recombination that is the trap assisted or at high injection density it can be Auger recommendation that I have discussed. And the radiative recombination is typically band to band recombination ok; now each of these categories of re recommendation has its own life time.

So, radiative recombination has a lifetime of tau red and non-radiative recombination will have a life time of tau non-red ok. These are life times ok; these are life times. Now, the question the problem you interesting thing is that the rate of you know recombination the rate of recombination, the rate of recommendation is actually inversely proportional to the lifetime. So, the rate of radiative recombination is inversely proportional to the radiative lifetime. Similarly, the rate of non-radiative recombination is proportional to 1 by the non-radiative lifetime.

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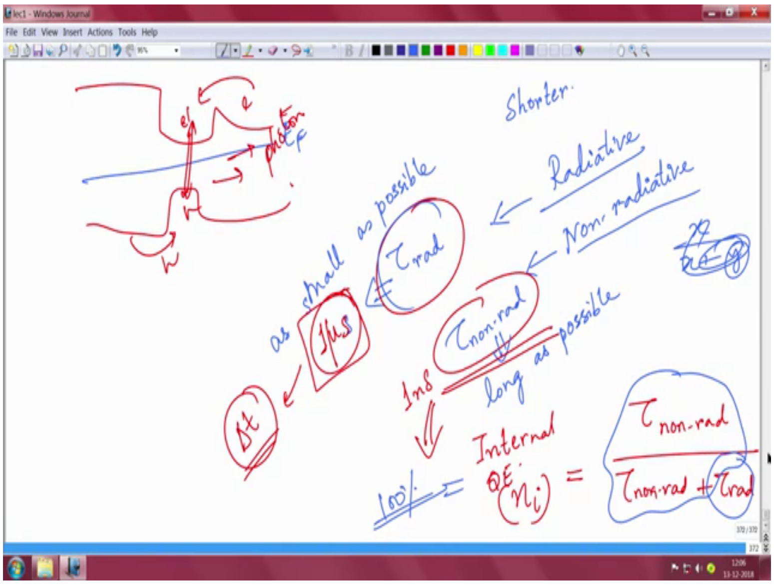

So, what does it mean ok? It means that if you have a shorter lifetime you recombine more. Now, there is a radiative recommendation, there is a non-radiative recombination both will take place in a material. You want that most of the recommendation should be radiative very few are almost nothing should be non-radiative which means, you want the radiative recombination rate to be higher right.

And you want that non radiative recommendation rate to be lower which means you want the radiative recombination lifetime to be as short as small as possible ok. Because, is inversely proportional now and you want the non-radiative lifetime you want them to be as long as possible or as large as possible. So, when I say if you have a radiative lifetime suppose your radiative lifetime is 1 nanosecond; that means, after every 1 nanosecond carriers electrons and holes this is a Fermi level whatever.

I am not drying very well ok, your electrons and holes are coming, electrons and holes are recombining here to emit photon that is radiative recombination. So, every 1 nanosecond your electrons and holes are recombining radiatively to emit light that is a good thing. And suppose your non-radiative recombination is 1 microsecond; that means, after every 1000 nanosecond or 1 microsecond you have 1 electron, can recombine with some defect or holes non-radiatively whatever that is good. If on the other hand the reverse happens which means every 1 nanosecond your carriers are re recombining non-radiatively to defects.

And in 1 microsecond every 1 microsecond your carriers will recombine radiatively to emit light then practically you will get no light because, in the time duration delta t that you recombine 1 electron and 1 hole to give you 1 photon; in that already 1000 electrons and 1000 holes will recombine not to give light. So, if you have a fixed number of electrons and holes that you are injecting by applying a voltage then you see in every delta t time you will have 1 electron and 1 photon emit light. And 1000 electrons 1000 holes not emit light; that means, your at your efficiency of LED emission has gone to the dogs, there is no admission there ok.

So, internal quantum efficiency; internal quantum efficiency or n i this I QE is defined in a way as the non-radiative lifetime divided by non-radiative lifetime plus radiative lifetime, you want the radiative lifetime the radiative lifetime to be as small as possible. So, that electrons and holes recombine very fast radiatively so, that you get most of the emission as acceptable light ok.

So, if you are no radiative recombination rate e you know life time sorry, if the radiative recombination lifetime is as small as possible then this quantity will approach 1 because, it is like x by x plus y where, y is very very small, then it will become 1 you know that is same thing. Then your internal quantum efficiency will become 100 percent.

So, you want done radiative recombination lifetime to be as small as possible compared to non-radiative lifetime ok; please keep that in mind. When I say non-radiative lifetime it includes Shockley Hall Read and Auger recombination both ok.

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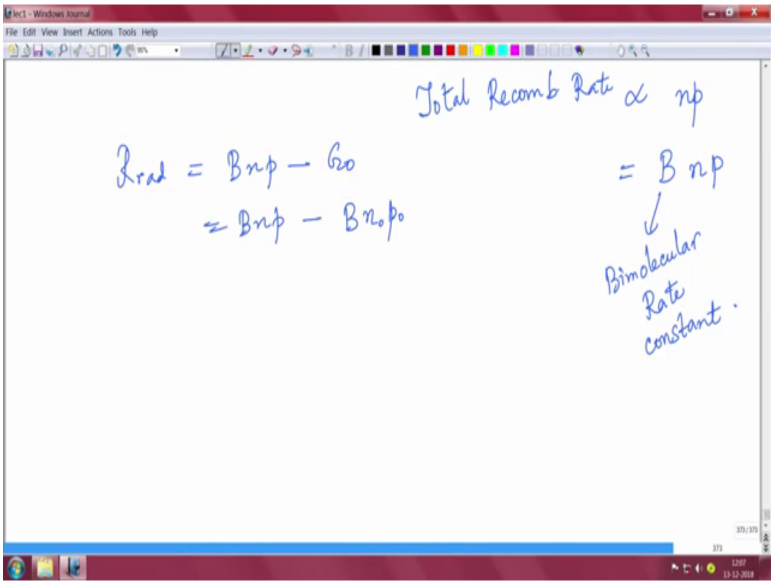

Total Recomb Rate $\propto np$

$= B\,np$

Bimolecular Rate constant.

$R_{rad} = Bnp - G_0$

$= Bnp - Bn_0p_0$

The total recommendation rate; the total recombination rate is proportional to the number of entire number of free electrons and number of free holes. And it is the proportionality constant is given B into n in to p, this B is actually a constant it is called the bimolecular because the 2 molecular spaces; bimolecular rate constant; bimolecular rate constant.

So, the radiative recombination rate ok; the radiative recommendation rate is actually the total recommendation rate minus the thermal generation. Now, the actually the thermal generation is nothing, but this bimolecular rate constant in to equilibrium electron in to equilibrium hole ok, equilibrium before your injecting anything.

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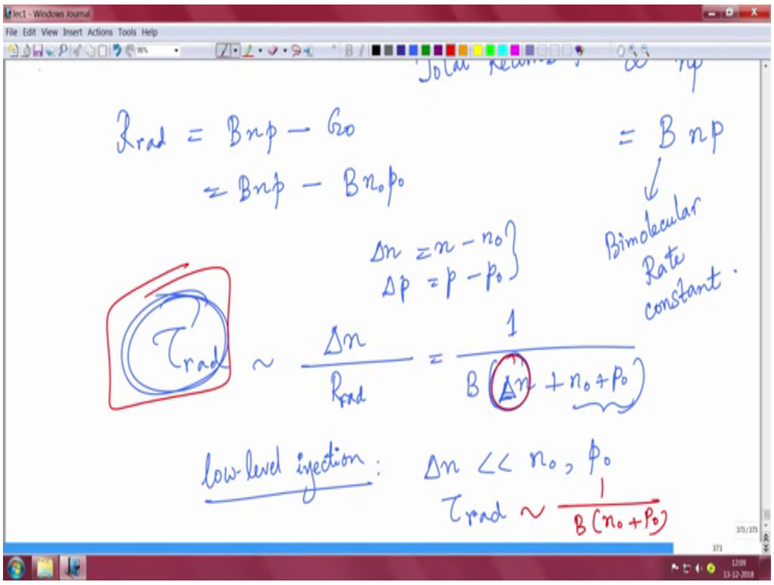

$$R_{rad} = Bnp - G_0$$
$$= Bnp - Bn_0p_0$$

$$= B\,np$$
$$\downarrow$$
Bimolecular Rate constant.

$$\left.\begin{aligned}\Delta n &= n - n_0\\ \Delta p &= p - p_0\end{aligned}\right\}$$

$$\boxed{\tau_{rad}} \sim \frac{\Delta n}{R_{rad}} = \frac{1}{B(\Delta n + \underbrace{n_0 + p_0}_{})}$$

low-level injection: $\Delta n << n_0, p_0$

$$\tau_{rad} \sim \frac{1}{B(n_0 + p_0)}$$

So, and you know that delta n the excess electron is nothing, but total electron minus equilibrium electron; excess hole is nothing, but totally holes minus the equilibrium holes right.

So, essentially your radiative life time is given by the total I mean this quantity is same by the way, excess electrons that you are injecting divided by the radiative lifetime that is your radiation lifetime ok. And it comes out to be 1 by a bimolecular rate constant, delta n that is the excess electrons you have or holes whatever it is the same quantity plus equilibrium electron plus equilibrium hole. This gives you the radiative life time, this gives you the radiative life time.

So, higher radiate radiative recombination rate will give you shorter radiative lifetime and that is better ok. And it depends if you have higher equilibrium concentration also you will become, you will get lower radiative lifetime. You have to also inject excess carriers by the way ok, this is just you should keep that in mind. For low level injection; low level injection [FL] your biasing the LED as a lower voltage so, that your current is little low.

So, at lower level injection your delta and the excess carrier is much lower than your equilibrium carrier concentration. In which case your radiative recombination lifetime, this quantity, this quantity will be proportional to 1 by B into n naught plus p naught because, this delta n will be much smaller please remember that.

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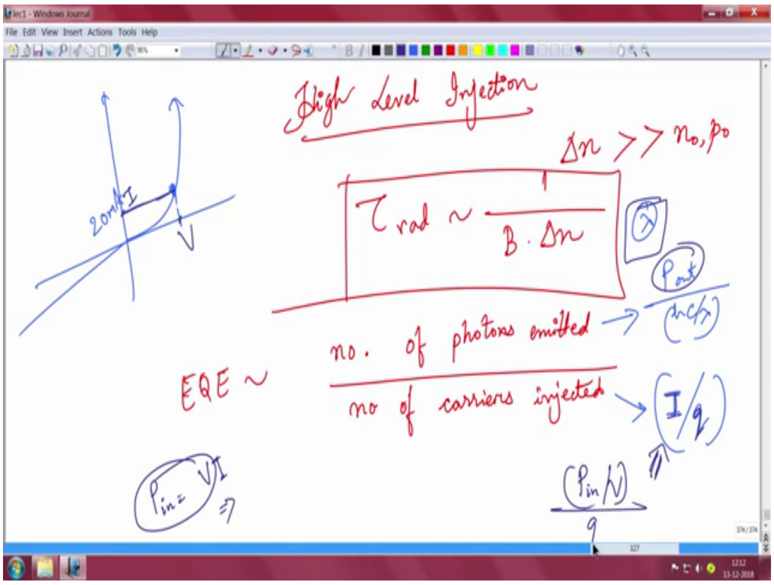

And of course, if you are talking about high level injection; if you are talking about high level injection which means you are biasing the LED at very high voltage, you are getting a lot of injection. Then your excess carrier concentration is much larger than your equilibrium concentration and then you are radiative lifetime is almost proportional to 1 by B times delta n. So, you just to keep in mind just in case anyways. So, does good about it so, I talked about I Q E and then there is of course, you know E Q E I will just quickly finish the efficiency part.

E Q E is essentially given by the xl quantum efficiency similar to photo detectors is the inverse. In photo detectors it was the number of electron hole pairs coming out of the circuit device divided by the number of photons falling on the device. Here it will be number of photons coming out of the device which is emitted that is coming out of the device. You do not care how many photons are generated in the quantum well or a in the active layer because, many of the photons may not come out. They might get absorbed or lost or whatever, your concern is how many number of photons are emitted and what is the number of carriers you are injecting to the device.

You do not care how many of these carriers actually reach the active region the quantum well. When if the carrier you are injecting by applying the voltage may not even reach the quantum well, it might get lost in metal contact and so, another things. But, your external control efficiencies how many photons you are emitting from the device divided how many divided by how many carriers you are injecting ok. So, of course, the number of photons that is emitted here, this number of photons that is emitted here per unit time. If your emitting at a particular wavelength lambda is P out that is the output optical power you are getting, remember output optical power divided by h c by lambda.

And the number of carriers that you are injecting is nothing, but the current that you are supplying that you actually the current voltage, LED is a forward bias junction by the way. So, you will look like this right, it is looking like this. So, you will bias at some forward voltage no. So, what is the current here? Maybe 20 milliamp or whatever that 20 milliamp or whatever current you are pushing is the I. And I by q is actually the number of carriers per unit time is then unit time. But now of course, please remember that your m LED is not emitting at a single wavelength, it is a range of wavelength. I am talking about the peak wavelength here ok, most of the power will be near the peak wavelength only.

Now, because your applying some voltage here V you are getting some current here, I may be 10 milliamp 20 milliamp. The input electrical power you are giving is V times I, you agree? V that is the voltage you applying maybe 5 volt, 3 volt who knows and the current you are getting maybe 10 amp milliamp, 20 milliamp whatever. The product is the electrical power you are getting, this is different from the optical power output you are getting remember that ok.

So, if this is the case then you know it is number of carriers, this number of carriers injected is the total current coming out of the device divided by q which I can write as from here I can write I equal to P in by V right P in by V that is current right by q.

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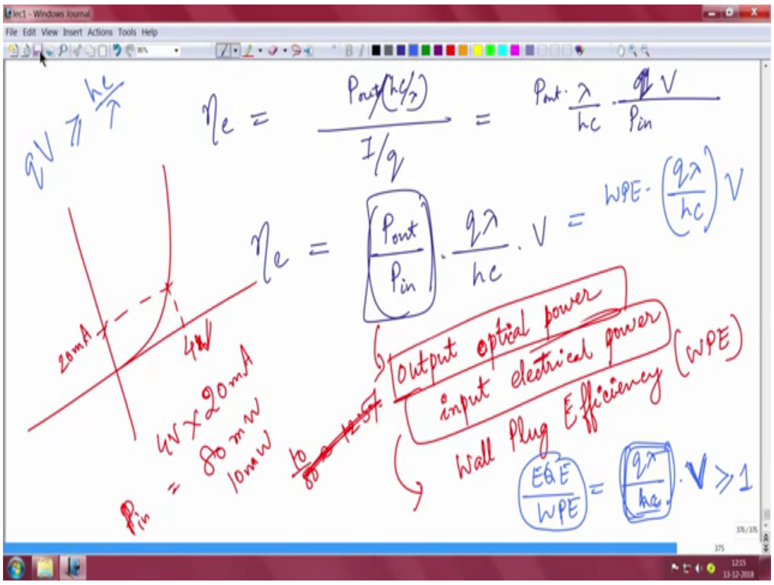

So, this is your P in by V by q is your so, what I can do is that external quantum efficiency is number of photons emitted P output by h c by lambda divided by I by q. So, I can write that as P out by you know into lambda by h c into 1 by q by I, I is nothing but P in by V so, we can go up right. So, essentially your external quantum efficiency is P out which is the optical output power by input electrical power times q lambda by h c into V ok. Now, this quantity the output optical power this quantity this is external quantum efficiency by the way E Q E.

This quantity is output optical power output optical power divided by input electrical power divided by input electrical power is called; this quantity is called wall plug efficiency; wall plug efficiency ok. It is a very important quantity in LED literature, wall plug efficiency is defined as then output optical power you are getting by the input optical power you are supplying. Suppose you have this I V know; you have this I V, suppose you are applying a voltage of say 4 volt sorry 4 volt.

And you are getting a current of say 20 milliamp and the LEDs emitting bright blue light suppose. Then the input power you are giving is 4 volt into 20 milliamp which is nothing, but 80 milliwatt of power you are giving input.

Now, what is the brightness of the LED? You can measure it in a integrating sphere, there is a tool to measure how much power is coming out in terms of optical power. If the power that is coming out is 10 milliwatt of optical power then your wall plug efficiency will be 10 by 80, which will be how much? Very low you know it will be like 12 percent or 12.5 percent ok. So, like that so, that is wall plug efficiency and now from this you can say that you know this is equal to wall plug efficiency times q lambda by h c into V.

In other words I can say that external quantum efficiency by wall plug efficiency is equal to q lambda by h c into V ok; q lambda by h c into V ok, wall plug efficiency. Now, the problem is that your wall not problem the statement is that your external quantum efficiency divided by wall plug efficiency, this ratio will always be greater than equal to 1 which means external efficiency will be always slightly higher than wall plug efficiency.

The reason is this energy that you are pumping as a photon that q h c by q, you know sorry h c by lambda h c by this, this energy can never be actually greater than the voltage you are applying; equivalent voltage because the some of the voltage will anyways get wasted somewhere right.

So, anyways what is try to say is that a law of conservation of energy says that the energy that you are supplying q V will always be greater than equal to the energy of the light you are emitting. That is why your wall plug efficiency will be always slightly lower than the external quantum efficiency. So, we will end the class here today. We have covered a law portion of the LED, we have discussed about radiative, non-radiative recombinations and a rates. I told you about a bimolecular rate constant, introduce the different efficiency terms, the quantum wells, double hetro junction LEDs.

So, these are important concepts in LED literature that we should be familiar with. We have one more class of LED remaining what we will do is that we will go through some of the laws mechanism like escape cone and total internal reflection losses. Little bit on the may be the brightness and the chromaticity and how human eye perceives the bar bright coloured LED ok. All those things we will touch base in the next class. So, that will conclude the optoelectronic section of this course ok.

Thank you for your time.