Semiconductor Optoelectronics

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Lecture - 30
Light Emitting Diode-III
Output Characteristics

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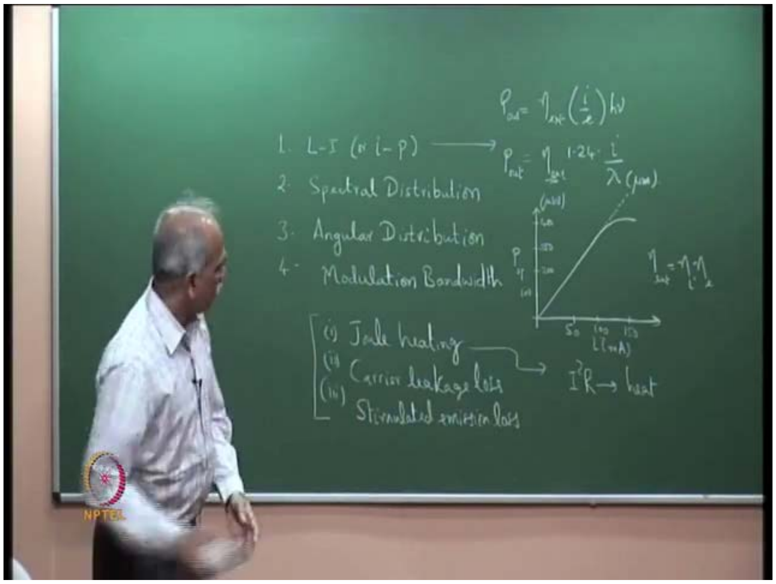

In the last class we had started with the device characteristics or the output characteristics. So, I had written a few characteristics, the first one was L I light current characteristics or i p, i p characteristics, the second one, L I light current characteristic and wavelengths distribution or spectral distribution, wavelengths spectrum or spectral distribution. Angular distribution or radiation pattern and just recalling, are radiation pattern and the fourth one is modulation bandwidth, these are some of the important ah device characteristics modulation bandwidth.

We started discussion on the L I characteristics and we have, we know that the optical power generated given by an expression p output, p out, optical is equal to eta external into i by e into h v, which you can also write, eta external into h new is c by lambda so h c by lambda is by, e is 1.2 4, so 1.2 4 into i by lambda where lambda is in micrometres. The output power p out is equal to eta external into 1.2 4 i by lambda, i is the current and p is the optical power, p naught. So, which obviously means that the optical power is proportional to the current so if you plot i versus p optical here, then we are expected that a linear curve, but as I said in practice it deviates at higher currents, at higher currents it deviates from the linear relation and we were discussing why this nonlinear behaviour or deviation from the linear characteristics.

So, typical numbers may be 50, 100, 150 milli amperes, we should always be familiar with the typical numbers, i in milli amperes and p, optical power this could be 100, 200, 300, 400 micro watts. This is micro watts of course there are LED switch are which can give milli watts of power also, but typical LED’s would give this kind of variation. So, we were interested to see what is the reason for this. I had listed 3 different reasons, one joule heating and quickly recalling what we had discussed, joule heating, second carrier leakage loss, so carrier leakage and the third 1 is stimulated emission loss, stimulated emission loss.

So, these are the three major reasons, joule heating, we have discuss is quiet clear that as you pass higher current here, as you pass higher current the i square r loss, i square r loss leads to heat generation or heating of the device. Heating of the device leads to availability of much more phonons in the material and therefore the non radiative recombination start dominating over radiative recombination’s and consequently eta external which contains, recall that this eta external contains, eta external is equal to eta i into eta extraction efficiency. So, eta i drops down exponentially with temperature and therefore, eta external drops down and therefore, eta i drops down exponentially and therefore the power generated or power output drops. So, these are the, so that is joule heating.

The second one, carrier leakage. So, today we will discuss carrier leakage and the stimulated emission loss and then go over to the spectral distribution and angular distribution, some of these characteristics I discuss in little bit more detail because similar considerations are valid for laser diodes.

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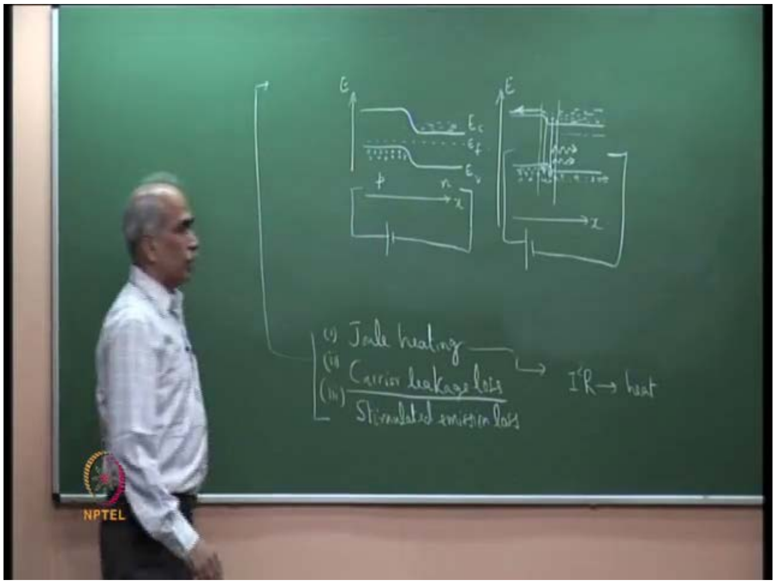

So, what is this carrier leakage, second point, carrier leakage. If I take a p n junction, then the band diagram, p n or you could take the hetero structure also is one and the same. So, before biasing this is E x E v E c and E f, before biasing. So, there are plenty of electrons here and plenty of holes here, when you forward bias when you forward bias this device that means to the p n, so p n to the p n you apply, you forward bias the device. Which means you have lifting this band up, so I draw this again, just if we redraw it, the dotted lines indicate the original position. So, you have carriers coming here, plenty of carriers and plenty of holes here, which means in the same position, physical position x. So, this axis is x this axis is E, in the same physical position you have plenty of electrons and holes, which recombine that leads to an external current. However, as you forward bias this stronger, that is as you increase the injection current, which means you are biasing it stronger, the carriers here, electrons do not see any more barrier.

Please see, this is the potential barrier which was blocking the electrons, now when you lift this up, that is when the injection current becomes large the carriers can simply go over from here like this. This means, please see here there are plenty of vacant states and there is no barrier therefore and remember that this end we have applied positive bias, which means this end is positive. So, the electrons here just get collected by the electrode at the other end, they do not recombine with the holes, because there are plenty of vacant states here and there is no potential barrier and therefore the electrons simply rush to the other end. Because that the positive end and get collected, exactly same thing happens here the holes can simply go to the other end.

When do we get photons photons we get if the electrons combine with holes, so when you forward bias electrons combine with holes leading to generation of photons, but if the electrons are directly collected by the electrode at the other end there is no generation of photon this is call carrier leakage leakage of carrier. So, carrier leakage from this end, though although you are passing a higher current, although you are passing a higher current recombinations are taking place generation of light is taking place, but some amount of carriers leak without leading to recombinations and therefore without contributing to generation of photons and that leads to the saturation, Second effect carrier leakage loss which leads to saturation is this.

We go to the third very quickly stimulated emission loss, this is technically different. Stimulated emission loss is a loss for surface emitting LEDs, but it is a gain for edge emitting LEDs, we will see what is this stimulated emission loss, let me erase this. So, recall the structures device structures of surface emitting LED and edge emitting LED, in edge emitting LED you have a channel where optical confinement is taking place.

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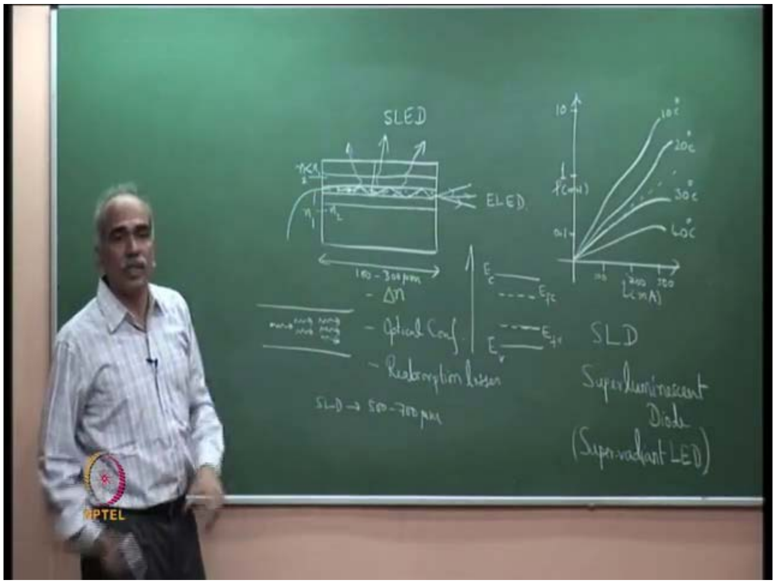

So, stimulated emission loss, I come to the next point stimulated emission loss very quickly, if you recall the structure of the LED, the cross section that I am showing, I am not showing all the layers. So, just let me show the active layer here, so here is the active layer, in surface emitting LED, light which is coming out is, what is the output. The output that we get is the light which is coming out like this, where as in edge emitting LED, the light which is generated and trapped inside because of optical confinement, is the output that we get, the edge emitting LED the output that we get is the optically confined output. It is, optical confinement is because this material is a lower band gap material. Therefore, the refractive index n here is higher compare to the cladding layers which have refractive index a little lower, n 2 less than n 1. They are, recall that they are high band gap materials on the side because they formed double hetero structures. So, these are the cladding materials this is the active material.

So, light is confined because of total internal reflection, so we get output from the edges. So this is ELED, edge emitting LED and this is SLED, both of them are double hetero structures. Double hetero structure is required because we want to minimize the reabsorption losses, one, please see recall the points, why do we need double hetero structure, 3 basic points are carrier confinement because to get larger delta n so that the fermi level can move up, the separation between the fermi levels can be large for a given current. Second point is optical confinement because light can be trapped, this is not useful for surface emitting LED because you do not want any confinement you want it to come out. So, this is optical confinement is useful for edge emitting LEDs and as we will see later, semiconductor lasers.

The third point is reabsorption losses, to minimize reabsorption losses. So, this 2 points are very important for both the LEDs and therefore you have to use a hetero structure, but there is optical confinement, as you pump harder, you are pumping harder, increasing the injection current means you are increasing the separation between the quasi fermi levels E f c and E f v. This is E c this is E v. What I am drawing is the energy band diagram in the active region so this is in the active region, okay let me draw this, because fermi level we normally draw with dash line, so let me draw. So, if I draw the energy band diagram in the active region there is a separation of the fermi level because of injection current of forward biasing.

If you pump harder means if you inject more then fermi level separation increases and you know that when the separation between the fermi level is larger than E g then stimulated emission will take over absorption, the probability of emission will be more than that of absorb, absorption and stimulated emissions will take over. As you start increasing this separation stimulated emission starts slowly increasing, although it as not a taken over, but it is increasing and therefore a photon which is travelling in this direction, light generated and travelling in this direction, will start stimulating additional photon. So, if I zoom this portion, just zoom that portion, light which is a photon which is travelling like this will stimulate, further stimulated emission and therefore this will start building up, it will further build-up.

This is exactly the laser action, so almost a laser like action stimulated emission has started increasing as E f c minus E f v separation increases, it is still not reach the stage where it is dominant, but it has increased. So, in the case of an edge emitting LED, what would happen is stimulated emission will also lead to, there is spontaneous emission due to which light is coming that is the LED operation, but stimulated emission is also contributing to the light generation and therefore the net generation would increase with increase in separation between these and therefore, what would you expect in the case of an edge emitting LED. We should expect, if this is the case then, I should expect it to go like this, this is p versus i.

I have not shown that yet, because there are 3 reasons why it was saturating, the 2 reasons which we discussed are still dominating and therefore we are not see this, even in an edge emitting LED. I will return to this, but as far as SLED is concerned, SLED surface emitting LED concerned this stimulated emission is definitely a loss because now more and more photons are generated in this direction and light is going to sides. So, the total amount of light coming out reduces, it is not proportional to the current that you are injecting and this is called stimulated emission loss. To summarise, stimulated emission loss is a loss for surface emitting LED, but is a gain for edge emitting LED. However even in an edge emitting LED normally you will see saturation is doing this, normally you would not see this, but you will see this if you go to low temperature. If you reduce the temperature you will indeed see a graph like that.

So, what I am now plotting is characteristic temperature dependent output, characteristics of a super luminescent diode. These are experimental curves reported in the literature, I will first draw the graph and then explain. The current that I am plotting are now hundreds of milli ampere, 100 milli ampere, 200 mill ampere, 300 milli ampere, the power here is typically. So, this is log scale 0.1 power in milli watt, 0.1 which means 100 micron, micro watt, 1 micro watt and 10, 1 milli watt, 10 milli watt. Power in milli watt, 1 milli watt, 0.1 milli watt which is 100 micro watt, 1 milli watt and 10 milli watt.

These are typical numbers for super luminescent diode SLD, this is SLED surface emitting light emitting diode, this is ELED and this is SLD, super luminescent diode or sometimes it also called as super radiant LED, super radiant LED. The structure of a super luminescent diode is the same as that of an LED, almost the same as that of a of a ELED, except that typically this length is little longer. In the case of a, so that this effect become dominant.

Please see, the stimulated emission gain will be more if the length over which the photons are travelling it larger, in a gain medium or in a medium where there are photon generation taking place if you have sufficient length then the amount of light accumulated, generated and accumulated because of stimulated emission will be more. Please see, in the case of a surface emitting LED, even though a photon which is travelling like this induces stimulated emission, within atom it is out of the active region. Whereas a photon which is travelling in this direction it has plenty of time to, time in the sense plenty of medium that active medium available to create more stimulated emission. That is why this one you see more stimulated emissions possible and therefore if you increase this length then stimulated emissions can be very significant and therefore a super luminescent diode is primarily an edge emitting LED.

Typically LEDs have 100 to 300 micro meter, typical LED length, but if you take super luminescent LEDs, SLD typically have 500 to 700 micron l, the l length is typically large 300, 500, 600, because that will enable a longer optical path where you can have stimulated emission. So, this is a super luminescent diode, please see at normal temperature it is still saturating or the power is deviating from the linear behaviour just like in an LED. However, when you cool the phonons go down and therefore you have kept the device at 20 degree centigrade, therefore the joule effect is not there, joule heating effect is not there because you have maintained the temperature at 20 degree centigrade. So, even if the current is increasing the joule effect, joule heating effect is not there and you can see a curve which is increasing in an upward direction because of the stimulated emission gain.

These are measured curves in super luminescent diodes you can have power increasing upward, you can see a chain in slope here because of stimulated emission gain, but normal surface emitting LEDs and edge emitting LEDs at normal temperature will have always a nonlinear behaviour which is reducing or deviating away from the linearly.

So, I hope the 3 points are clear that stimulated emission gain for ELED, stimulated emission is a loss for SLED and we are making use of that to generate super luminescent diodes. The structure of the super luminescent diode and or an edge emitting LED in general is almost the same as the semiconductor laser except that there are no clewed surfaces at the ends which act as mirrors, mirror like ends in the case of a semiconductor laser to provide the necessary feedback. You do not need that feedback in the case of LEDs because if feedback is there, then it will start oscillating. So, we will discuss the semiconductor lasers in more details at later stage.

Let me come to the next characteristic that is spectral distribution or wavelength spectrum. Because we would come across somewhere super luminescent diodes and you saw that the current that is passing through are relatively large 100, 200, 300 milli amperes because the device is long. Therefore, there is lower current which is flowing through the device, current is flowing from the top because the electrodes are here and because the device is longer there is more current which has to flow to create the same delta n , the same concentration because it is a volume is larger length is larger therefore volume is larger.

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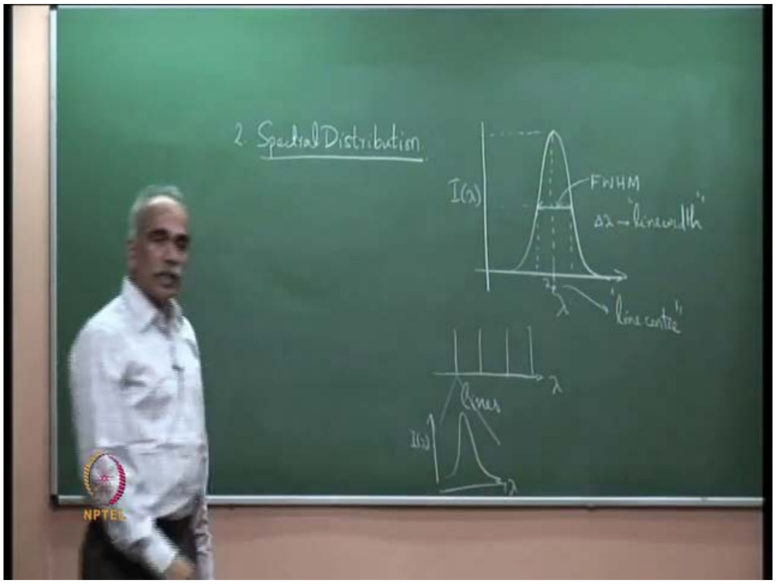

So, we will come to wavelength spectrum, spectral distribution or wavelength spectrum. Any source, if you plot the intensity distribution of a source you generally see that it has a finite width and the full width at half maximum FWHM, so FWHM full width at half maximum that is this is the maximum then half of it, full width in lamda. So, this is called delta lamda, is called the line width and this is called the line centre, the lamda 0 or lamda p is sometimes called line centre.

This is the line, why is this call sometimes line because traditionally if you see the spectrum of any substance, any material, gas, you will see spectral lines. If you see under normal spectrometer you will see, if you take for example mercury mercury lamp you will see lines blue violet, green, yellow, different lines you will see so what we call then a spectral lines. So, this is what I have plotted is lamda versus the position, we are not measuring in a spectrometer we do not measuring intensity, what we are measuring is the angle theta where it comes because our objective is to determine the wavelength. So, then we use the d sin theta equal to n lamda and determine the wavelength. So, these are call spectral lines so this is line, if you now resolve 1 line under a high resolution spectrograph then you will see that this line is actually, it is like zooming, so this line is actively like this. So, the same thing in wavelength you are zooming now and then you will see that lamda versus i of lamda, if you measure the intensity lamda then you see this, this is what I have plotted and therefore the centre of that line is called line centre.

So, this intensity distribution is a line which is expanded in the wavelength scale and therefore this is the line centre, this is the line width, is a width of the line. This is the reason why we used these terminologies line width and line centre. So, we want to see what is the spectral distribution of an LED, recall what we have studied, the spontaneous emission light generation in an LED is primarily due to spontaneous emission and the rate of spontaneous emission will indicate the rate at which photons are emitted and therefore, the intensity is determined by the spontaneous emission spectrum, spontaneous spontaneous emission rate.

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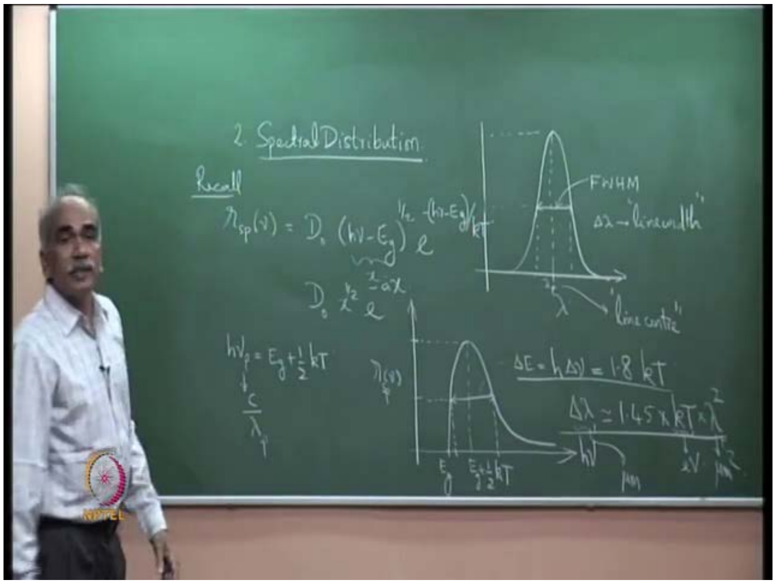

So r s p of mu you recall just we have derived already, recall r s p of mu is equal to D 0 into h mu minus E g to the power half into e to the power minus h mu minus E g h mu minus E g by k t, an expression of this form then we said let this be x. So, that we wrote this as D 0 into x to the power half e to the power minus a x, where a is 1 by k t, write this a kind of variation and then we plotted this and we got a variation which. So, what I have plotted is h mu versus r s p of mu. Every spontaneous emission generates 1 photon and therefore the rate at which spontaneous emissions are occurring will also be the rate at which photon generation takes place and therefore the spectrum is, spectrum output, spectrum is basically determined by r s p of mu and we have seen that this peak here, so this is starting point is E g and the peak corresponds to E g plus half k T half k t, capital t, temperature here and the line width here, we had an exercise, so this line width because this is energy axis delta E is equal to h into delta mu, was equal to approximately equal to 1.8 times k t.

From this you could determine what is delta lamda. So, delta lamda is approximately equal to 1.45 into k T into lamda p square, lamda p lamda p was corresponding to this peak, so this E g. So, h mu p is equal to E g plus half k t, so mu p here is c by lamda p that is the peak at which the wavelength at which the peak occurs. So, this this gives you the line width, in this expression please remember that this delta lamda is in micro meter, this k T is in E v and this lamda is also in micro meter, so micro meter square.

The question is how did we get this expression, we had an exercise for come which you have to find out the full width at half maximum here okay. So, this was the maximum here so you had to find out what is the full width at half maximum, so if you find this out what is the full width at half maximum you will get this, how to find this out this is not analytically solvable, you have to numerically solve this either graphically or numerically. So, you can find out that this separation here, this axis is energy this you call as E 2, this you call as E 1 then delta E, E 2 minus E 1. Which is also equal to h into delta mu is equal to this, this you have to determine numerically and then in this you simply substitute for delta lamda because delta mu is c by lamda square into delta lamda and that lamda is corresponding to the peak and this is the expression okay. If you still find it difficult we can discuss about this.

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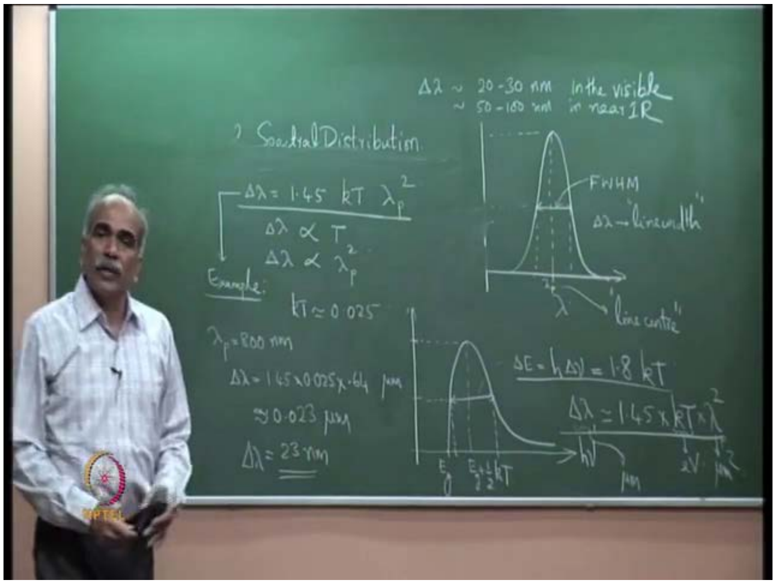

So, the line width, the point is delta lamda is given by. So, delta lamda is equal to approximately 1.45 into lamda p square. Two two things you note here, delta lamda here is proportional to T, the width is proportional to temperature line width, second delta lamda is proportional to lamda p square and let us take an example what kind of numbers that we get here, let us see example at room temperature, so k T is equal to 0.025. Let us say a Gallium Arsenide LED is emitting at 800 nano meter, that is lamda p is 800 nano meter. I am just taking an example Gallium Arsenide LED is emitting at 800 nano meter, then you find out what is delta lamda, just you have an idea about what kind of numbers that we have is 1.45 into 0.025 into, this has to be in micro meter therefore 0.8, 0.8 square, so 0.64, lamda p square is 0.64 and check how much is this, so many, so many micro meters.

So, this if I say 1.5 approximately, which means this is, how much is this, we can simplify this 0.6 4 into 1.5 is approximately 1 approximately 1 and therefore this is 0.025 approximately equal to 0.023, so he has calculated 0.023 micro meter that is 23 nano meters. So, delta lamda is equal to 23 nano meters. Typically in the visible region, of course you can see that instant of lamda p at 800 if you take a visible LED, 600 nano meter or 630 nano meter then you will have you even less, so typically, typical values of delta lamda is of the order of 20 to 30 nano meter, in the visible in the visible and is of the order of 50 to 100 nano meter in near IR that is 11.5 micron, typically this is the kind of numbers that you would get for LED.

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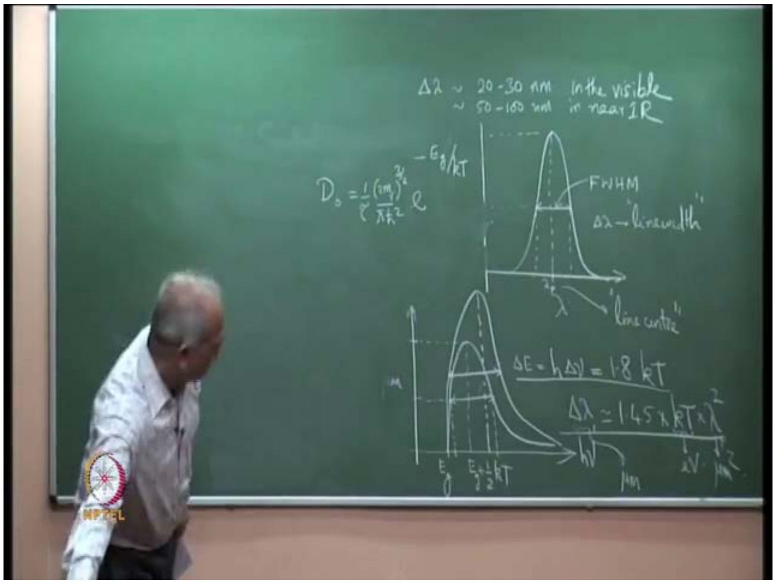

Alright so, I come back to this graph, if this is the spectral distribution that we are plot if you increase the temperature what we expect we expect that let me first plot and then you see whether what I would plotted is right. So, we expect this to shift to right because E g plus half k T. T is temperature therefore has a increase temperature the peak is shifted to the right and what else do we expect, the delta lamda will also increase because it is proportional to temperature. Therefore the full width at half maximum, now you see the full width at half maximum it will be more than the original, full width at half maximum is shifting to the right and the amplitude is also increasing, why did they show that the amplitude is increasing because this D 0 if you see the expression for D 0, this has some terms, into E to the power minus E g by 2 k T. The D 0 contains some terms here, I can give exactly the expression for D 0, so D 0 is given by 1 over tow here and 2 m r. We have derive this 2 m r to the power 3 by 2 divided by pi h cross square into E to the power, (( )) E to the power E g by k T, E g by k T. So, temperature increases exponent decreases, E to the power minus exponent which is smaller, which means D 0 is larger. Temperature increases tow decreases therefore D 0 is larger, so D 0 is larger that is why it is going like this, you expect an LED if you increase the temperature to go up like this, means more radiance if you increase the temperature. In practice this is not what you see, so what if I were to plot this in the wavelength scale. Let me plot this is an important point, I had to make an important point here that is keep active.

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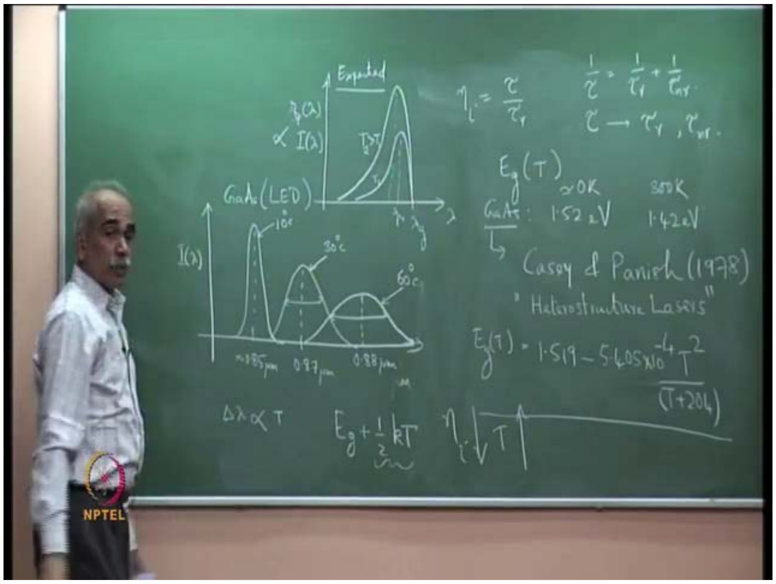

So, if I convert this into wavelength, this is lamda versus i of lamda or r s p of lamda, which is proportional to i of lamda, which is proportional to i of lamda in10sity. We should expect corresponding to lamda g here, so this is lamda g, lamda g corresponds to E g, band gap. So, if I want to plot with respect to lamda. I expect that, theoretically we should expect a curve like this and at a higher temperature, we should expect a curve like this. So, this is lamda p 1 corresponding to this is at temperature T 1, this is at temperature T 2, which is greater than T 1.

Is this graph clear, it is the same graph, it is in the frequency domain, it is in the wavelength domain, higher energy corresponds to lower wavelength so that is all and the peak is shifted to lower wavelength, peak is shifted to lower wavelength, but the peak, this is expected expected from what we have done, the theory that we have done, but this is not what you get, in practice what you get this here and we need some explanation that is why I am plotting this now.

This is one of the experiments reported in literature, I do not remember the reference, this is for Gallium Arsenide LED. So, this is at 10 degree centigrade, this is at 30 degree centigrade and this is at 60 degree centigrade, measurements this wavelength here is about 0.85 micro meter approximately, this is 0.87 micro meter and this is 0.88 micro meter or 8 8 5 something like that approximately, approximated number. So, what I have plotted is I of lamda versus lamda wavelength at 3 different temperatures for a typical Gallium Arsenide LED. So, what do we see, 1 the peak wavelength is shifting shifting to lower energy, here it is shifting to higher energy which means we expect it to shift to lower wavelength, smaller wavelengths, but it is shifting with temperature to higher wavelength 1, second the peak we expected the peak to go up, this is at higher temperature, this is at lower temperature as per the theory that we have, but this is what you actually see in practice.

What could be the reasons obviously our theory has not taken into account several things and that is why you are seeing this completely opposite behaviour this is going up, but actually the peak is coming down. Which is shifting to lower wavelength with higher temperature, but this is measured practical, we have obviously missed something and this is what I want you to keep in mind and this an important lesson in this and that is in certain derivations we make certain approximations or we do not take into around certain aspects the result could be completely opposite when you take care of those aspects and this is what the simple experiment demonstration. 1 first point, band gap of a semiconductor E g is a function of temperature, we have not taken care of this, band gap decrease for example, if you take Gallium Arsenide band gap is 1.52 E v around 0 K and 300 K room temperature this is 1.42 E v.

So, the band gap is temperature dependent, you can find there are empherical expressions which are given, you can see it is a very good book, Casey and Panish this unit refer to this. Casey and Panish, it is there in our library, Panish, hetero structure lasers. There are 2 volumes volume part a and part b. The temperature dependence of gallium arsenide, let me write E g for Gallium Arsenide which is for temperature dependent, it listed for almost most of the useful semiconductors, but I am writing only for Gallium Arsenide it is given as 1.519 minus, is an empirical formula 5.405 into 10 to the power of minus 4 into T square divided by T plus 204, T plus 204.

So, what you see is as temperature this is at 0 K put T equal 0 and this is 1.519 that is what I have written here, approximately 1.52. So, what you see is the band gap decreases with temperature for a semiconductor, as temperature increases band gap decreases means the energy decreases that is why the wavelength is increasing, this peak is shifting because peak comes at E g plus half k T, remember k T is a very small quantity from 10 degree. So, 30 degree it is 300, 303. 10 degree it is 283 and 60 degree it is 233. So, it is a small difference in change in this T, but E g changes quite a bit. E gas a dependence which is more compare to this k T. Therefore, although k T was shifting to higher energy, but the band gap E g itself is decreasing, E g is a function of T which is decreasing that is why the net effect is it shift to the low, higher wavelengths or lower energy.

Why the peak is going down second question we expected this, but the peak is going down, peak is going down primarily because of as temperature increases, eta i drops down exponentially as temperature increases eta i drops down and eta i drops down means thus rate of spontaneous emission goes down rapidly.

Rate of spontaneous emission which leads to generation of photons please see, recombination takes place, tow in the expression there, this tow contains tow r and tow n r and the relation is 1 over tow is equal to 1 over tow r plus 1 over tow n r. As temperature increases tow decreases rapidly because tow n r decreases and therefore eta i is equal to, we have this expression tow by tow r, tow decreases rapidly because tow nr decreases rapidly. Why tow nr decreases rapidly there are non radiative transitions which increase rapidly as temperature increases because phonons are in much larger number and therefore this decreases leading to a decreasing this and therefore eta i decreases and therefore the generated photons go down if the increase in temperature and therefore you have this decreasing.

We have not taken care of the dependence of eta i, in our earlier derivation we did not take care of dependence of eta i on on the intensity. The third point is you see that this is spreading, this is as per our finding because this spread as because the delta lamda is proportional to T, this you absorb in practice. What is the physical reason for this, mathematically we see that delta lamda is proportional to T, but physically what is happening.

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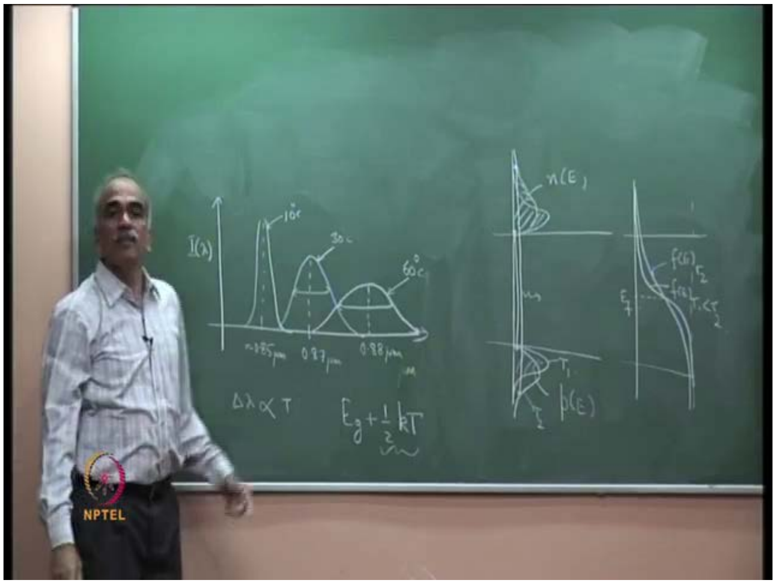

Let me quickly show this is the carrier distribution the physical variation and therefore I (( )). At a particular temperature we have carrier distribution, which is this. There are different ways of illustrating this 1 of the ways is what I am showing, at a particular temperature, this is what I have plotted n of E recall this is what we had discussed in the first part of the course carrier distribution which was a product of density of states multiplied by the probability of occupation f of E, recall that f of E itself, at a particular temperature if f of E varies like this, then if you increase the temperature this distribution. So, for a lower temperature it will be like this, so this is the fermi energy E f, this is f of E at temperature T 2, this is f of E at temperature T 1, which is lower than T 2 and this leads to a spread in the carrier.

So, this distribution here spreads like this this distribution here spreads like this, at a higher temperature so this is T 2 this is T 1. When the distributions spreads, the distribution over which photons emitted will also become wider because a photon, an electron sitting here can combine with the hole sitting here giving a photon of energy h mu, this gap an electron which is sitting here. Now, electrons are given here, electron which is sitting here can combine with the hole sitting here and can give a higher energy, which means the spread has increased, that is why you have a larger spread at higher temperature.

This is the physical reason because of carrier spread in that 2 bands. So, this is about the wavelengths spectrum, is very important characteristic of any source, so expected and when you do an experiment if you find the result is somewhat different than what is expected then one has to give a thought that why it is different and what is it that you have not included. So, now we are able to explain with the inclusion of E g as a function of time we are able to explain this which was not as we saw earlier. I think I will stop here and we will continue in the next class.