# Semiconductor Optoelectronics

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## Lecture - 29
## Light Emitting Diode-III Output Characteristics

So in the last class we had started with the device characteristics or the output characteristics so I have written a few characteristics.

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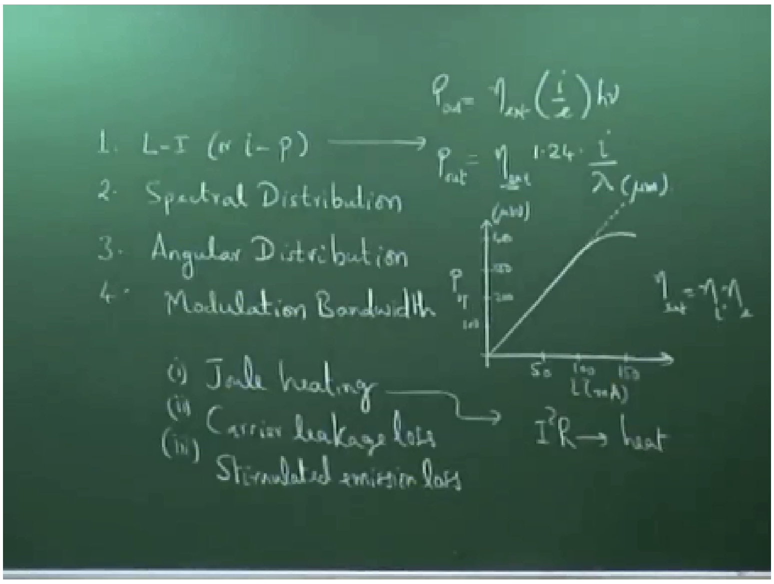


The first one was L-I light current characteristics or i-p characteristics. The second one L-1 light current characteristics and wave length distribution or spectral distribution. Wave length spectrum or spectral distribution. Angular distribution or radiation pattern. I am just recalling radiation pattern and the fourth one is Modulation bandwidth. These are some of the important device characteristics Modulation bandwidth.

We started discussion on the L-I characteristics and we know that the optical power generated is given by an expression p out optical= eta external*i/e *h nu which you can also write eta external * h nu is c/lambda. So h c/lambda is by e is 1.24. So 1.24* i/lambda where lambda is in micrometer. The output power p out=eta external * 1.24 i/lambda I is the current and p is optical power po out.

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 here a linear curve, but as I said in practice it deviates at higher current. At higher current it deviates from the linear relation and we were discussing why this non linear behavior or deviation from the linear characteristics. So typical numbers maybe 50, 100, 150 milliampere.

We should always be familiar with the typical numbers i in milliampere and p optical power this could be 100, 200, 300, 400 microwatts this is microwatts. Of course there are LEDs which can give milliwatts of power also, but typical LED would give a kind of variation. So we were interested to see what is the reason for this. I had listed 3 different reasons. One joule heating.

I am quickly recalling what we had discussed joule heating. Second carrier leakage loss and the third one is stimulated emission loss. So these are the 3 major reason joule heating we have discussed it is quite clear that as you pass higher current here the 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 and consequently eta external which contains recall that this eta external contains eta external=eta i* eta extraction efficiently. So eta i drops down exponentially with temperature and therefore eta external drops down. Eta i drops down exponentially and therefore the power generated or power output blocks. So that is joule heating.

The second one is 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 have discussed in little more detail because similar consideration are valid for laser diode.

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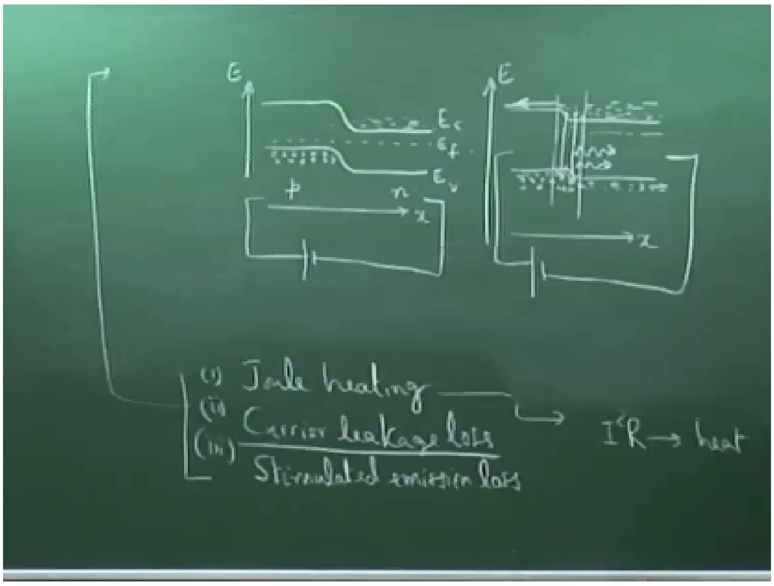


So what is this carrier leakage second point carrier leakage. If you take a PN junction, then the band diagram PN or you could take the heterostructure also. So before biasing this is E X Ev Ec and Ex before biasing. So there are plenty of electrons here and plenty of holes here. When you forward biased this device that means to the pn. So pn you apply you forward bias device which means you are lifting this band up. So I draw this again just re-draw it.

The dotted lines indicate the original position. So you have carrier coming here plenty of carrier 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 biased stronger that is as you increase the injection current which means you are biasing it stronger.

The carrier here the 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 space 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 space here and there is no potential barrier and therefore the electrons simply rush to the other end because that is a 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 called carrier leakage. So although you are passing a higher current recombination start taking place generation of light is taking place.

But some amount of carrier leak without leading to recombination and therefore without contributing to generation of photons. And that leads to the saturation the second effect carrier leakage loss which leads to saturation with this. We go to the third very quickly stimulated emission loss. This is completely different. Stimulated emission loss is a loss for surface emitting LEDs, but is a gain for edge emitting LEDs. We will see what is this stimulated emitted loss. Let me erase this.

So recall the structure device structures of surface emitting LED and edge emitting LED. IN edge emitting LED you have a channel where optical confinement is taking place. So stimulated emission loss.

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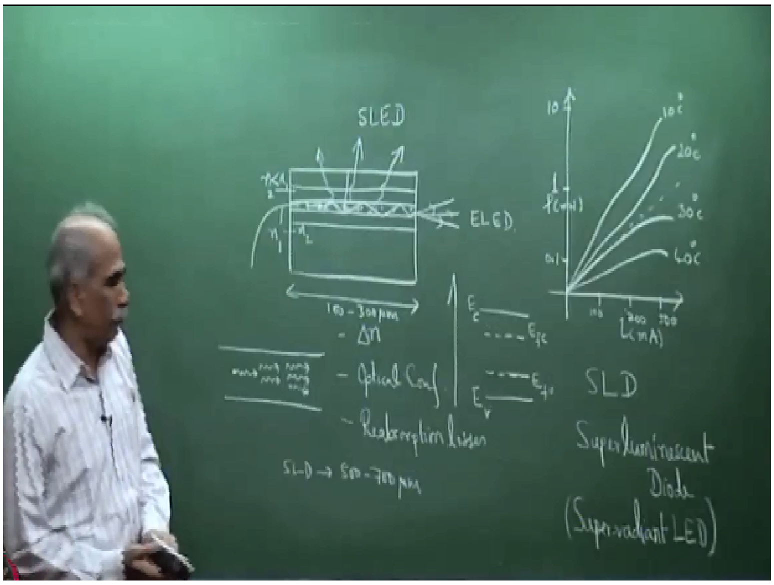


I come to the next point stimulated emission loss. Very quickly if you recall the structure of the LED the cross section that I am showing. I am not showing all the layers. So just let me show the active layer here. Here is the active layer in surface emitting LED light which is coming out is what is the output. The output that we get is the light which is coming out like this whereas 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 because this material is a lower band gap material therefore the refractive index n here is higher compared to the cladding layer which have refractive index a little lower $n2<n1$. They recall that they are high band gap materials on the side because we formed double heterotructures.

So these are cladding materials that 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 heterostructures. Doubles heterostructure is required because we want to minimize the re-absorption losses one. If we recall the point why do we need a double heterostructures.

Three basis 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 it. So this is optical confinement is useful for edge emitting LEDs and as we will see later semi conductor lasers.

The third point is re-absorption losses to minimize re-absorption losses. So these 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 level Efc and Efv this is Ec this is Ev. What I am drawing is the energy band diagram in the active region.

So this is in the active region. Let me draw this because Fermi level we normally draw with the 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 or forward biasing. If you pump harder means if you inject more than Fermi level separation increases and you know that when the separation between the Fermi level is larger than Eg then stimulated emission will take over absorption.

The probably of emission will be more than that of absorption and stimulated emission will takeover. As you start increasing this separation stimulated emission starts slowly increasing. Although it has not yet 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 Efc-Efv separation increases. It has 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 very 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 will 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 able to see this even in an edge emitting LED. I will detail to this but as far as SLED is concerned surface emitting LED is concerned this stimulated emission is definitely a loss because now more and more photons are generated in this direction and light is going to the 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 summarize stimulated emission loss is a loss for surface emitting LED, but is 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 temperatures.

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 superluminescent 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 milliampere 100 milliampere, 200 milliampere, 300 milliampere.

The power here is typically so this is log scale 0.1 power in milliwatt 0.1 which means 100 microwatt, 1 microwatt and 1 milliwatt, 10 milliwatt power in milliwatt. 0.1 milliwatt which is 100 microwatt 1 milliwatt and 10 milliwatt. These are typical numbers for super luminescent diode SLD. This is SLED surface emitting light emitting diode. This is ELED and this SLED.

Super luminescent diode or sometimes it is also called super radiant LEDs. The structure of the super luminescent diode is the same as that of an LED almost the same as that of an ELED except that typically this length is little longer in the case so that this effect becomes dominant. We will see the stimulated emission gain will be more if the length over which the photons are travelling is 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 generated and accumulated because of stimulated emission will be more. Please see in the case of surface emitting LED even though a photon which is travelling like this induce a stimulated emission within no time it is out of the active region whereas a photon which is travelling in this direction it has plenty of time, time in the sense plenty of active medium available to create more stimulated medium.

That is why you see more stimulated emissions possible and therefore if you increase this length then stimulated emission can be very significant and therefore a superluminescent diode is primarily an edge emitting LED. Typically LED have 100 to 300 micrometer typical LED length, but if you take superluminescent SLDs typically have 500 to 700 micron.

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 superluminescent diode. Please see at normal temperature it is still saturating or the power is deviating from the linear behavior 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 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 superluminescent diode. You can have power increasing upward you can see a change in slope here because of stimulated emission gain.

But normal surface emitting LEDs and edge emitting LEDs at normal temperature will have always a non-linear behavior which is reducing or deviating away from the linear region. 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 superluminescent diode. The structure of a superluminescent diode or an edge emitting LED in general is almost the same as a semiconductor laser.

Except that there are no cleaved surfaces at the ends which acts as mirror like end in the case of a semiconductor laser to provide the necessary feedback. You do not need that feedback in the case of LED because if feedback is there then it will start oscillating. So we will discuss the semi conductor lasers in more detail at a later stage. So let me come to the next characteristics that is spectral distribution or wave length spectral.

Because you would come across somewhere superluminescent diode and you saw that the current that is passing through are relatively large 100, 200, 300 milliampere because the device is long. Therefore, there is more current which is flowing through the device. Current is flowing from the top because the electrodes are here and because the device is longer that is more current which has to flow to create the same delta and the same concentration.

Because if the volume is larger, length is larger therefore volume is large.

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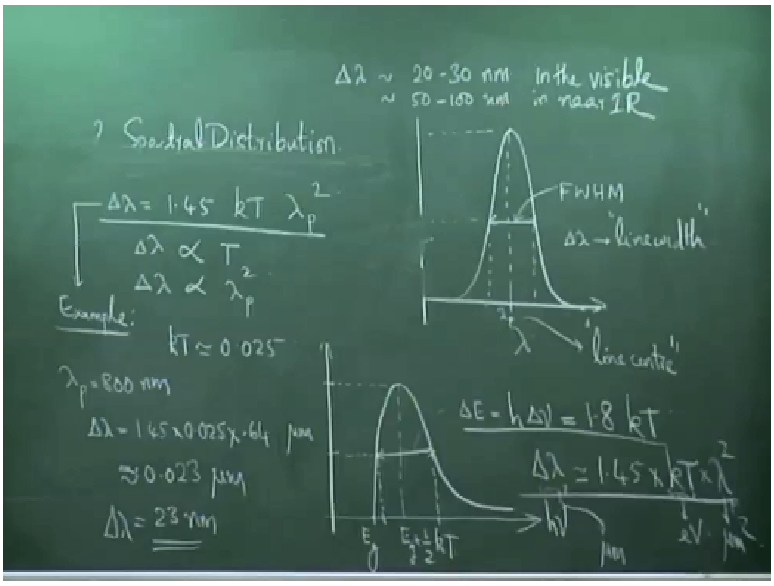


So we come to wavelength spectral. Spectral distribution or wavelength spectral. Any source if you plot the intensity distribution of a source you generally see that it has a finite width and the full width at half maximum FWHM. So FWHM full width and half maximum that is if this is the maximum then half of width full width in lambda. This is called delta lambda is called the line width.

And this is called the line centre lambda 0 or lambda p is sometimes called line center. This is the line why is this called sometimes line because traditionally if you see the spectral of any substance, any material gas you will see spectral lines. If you see under a normal spectrometer you will see if you take for example mercury lamp you will see lines blue, violet, green, yellow different lines you will see.

We called them as spectral lines. So this is what I have plotted is lambda versus the position. We are not measuring in a spectrometer we do not measure intensity what we are measuring is the angle theta where it comes because our objective is to determine the wavelength. So then we use (()) (27:16) theta=n lambda and determine the wavelength. So these are called spectral lines so this is lines.

If you now resolve one line under a high resolution spectrograph, then you will see that this line is actually it is like assuming. So this line is actually like this. So the same thing in wavelength you are assuming now and then you see that lambda versus i of lambda if you measure the intensity lambda then you will see this. This is what I have plotted and therefore the center of that line is called line centre.

So this intensity distribution is a line which is expanded in the wavelength (()) (28:05) and therefore this is the line centre this is the line width. So this is the reason why we use 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 spectral. Spontaneous emission rate of rsp of nu you recall. This we have derived already we call rsp of nu=D0*h nu-Eg to the power ½ * E to the power –h nu-Eg/kT then expression of this form. Then we said this be x so that we wrote this as D0* x to the power ½ E to the power –ax where a is 1/kT.

And then we plotted this and we got a variation which what I have plotted is h nu versus rsp of nu. 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 output spectrum is basically determined by rsp of nu and we have seen that this peak here. So this is starting point is Eg and the peak corresponds to Eg+1/2 kT temperature.

And the line width here we had an exercise. So this line width because this is energy x delta E=h* delta nu approximately=1.8 times kT. From this you could determine what is delta lambda? So delta lambda is approximately=1.45*kT* lambda p square. Lambda p was corresponding to this peak. So h nu p= Eg+1/2 kT. So nu p here is c/lambda p. There is a peak at which the wavelength at the peak occurs. So this gives you the line width.

In this expression please remember that this delta lambda is in micrometer this kT is eV and this lambda is also in micrometer square. So how did you get this expression? The question is how did we get this expression? We had an exercise from which you have to find out the full width at half maximum here.

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. Then you can find out that this separation here this axis is energy. This you call this E2 this you call this as E1 then delta E2-E1 which is also= h* delta nu= this.

This you have to determine numerically and then in this you simply substitute for delta lambda because delta nu is c/lambda square *delta lambda and that lambda is corresponding to the peak and this is the expression. If you still find it difficult we can discuss about this. So the line width the point is delta lambda is given by so delta lambda= approximately 1.45 * lambda p square.

Two things you note here delta lambda is proportional to T the width is proportional to temperature line width. Second delta lambda is proportional is lambda p square and let us take an example what kind of numbers that we get here let us see example at room temperature. So kT=0.025. Let us say a gallium arsenide LED is emitting is 800 nanometer that is lambda p is 800 nanometer.

I am just taking an example gallium arsenide LED is emitting at 800 nanometer then you can find out what is delta lambda just to have an idea about what kind of numbers that we have is 1.45*0.025* this has to in micrometer therefore 0.8 square so 0.64 lambda p square is 0.64 and check how much is this so many micrometers. So this if I see a 1.5 approximately which means how much is this.

We can simplify this 0.64*1.5 is approximately 1 and therefore this is 0.025 approximately= so he has calculated 0.023 micrometer that is 23 nanometer. So delta lambda=23 nanometer. Typically, in the visible region of course you can see that instead of lambda p at 800 if you take a visible LED 600 nanometer or 630 nanometer then you will have a less. So typical values of delta lambda is of the order of 20 to 30 nanometer in the visible.

And is of the order of 50 to 100 nanometer in near IR that is I, 1.5 micron typically this is the kind of numbers you would get for LEDs.

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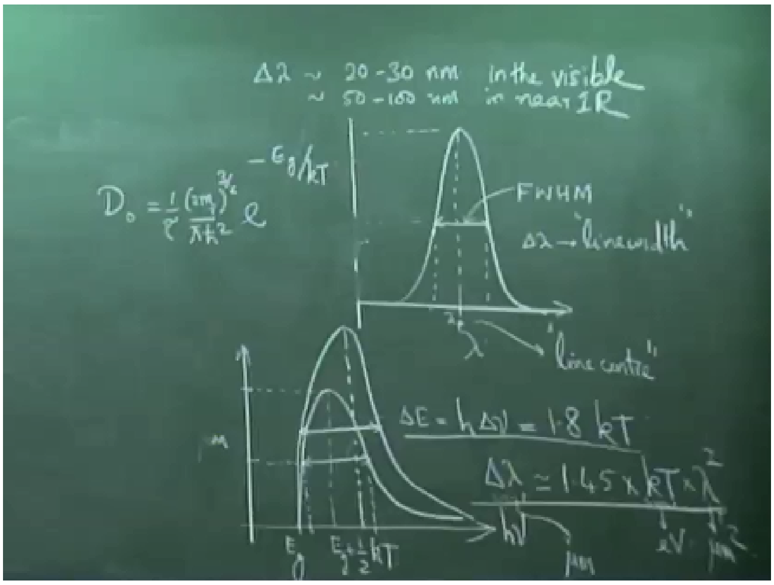


So I come back to this graph. If this is the spectral distribution that we had talked if you increase the temperature what do we expect? We expect that let me first plot and then you see whether what I have plotted is right. So we expect this to shift to right because Eg+1/2 kT T is temperature. Therefore, as I increase temperature the peak is shifted to the right and what else do we expect.

The delta lambda 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 and half maximum is shifting to the right and the amplitude is also increasing why did I showed that the amplitude is increasing because this D0 if you see the expression for D0 this has some terms into E to the power –Eg/2 kT.

The D0 contains some terms here I can give you exactly the expression for D0. So D0 is given by 1/tau here and 2 mr we have derived this 2 mr to the power 3/2/pi h cross square (()) (38:17) * E to the power Eg/Kt. So temperature increases exponent decreases E to the power –an exponent which is smaller which means D0 is larger. Temperature increases tau decreases therefore D0 is larger. So D0 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 if I were to plot this in the wavelength scale let me plot.

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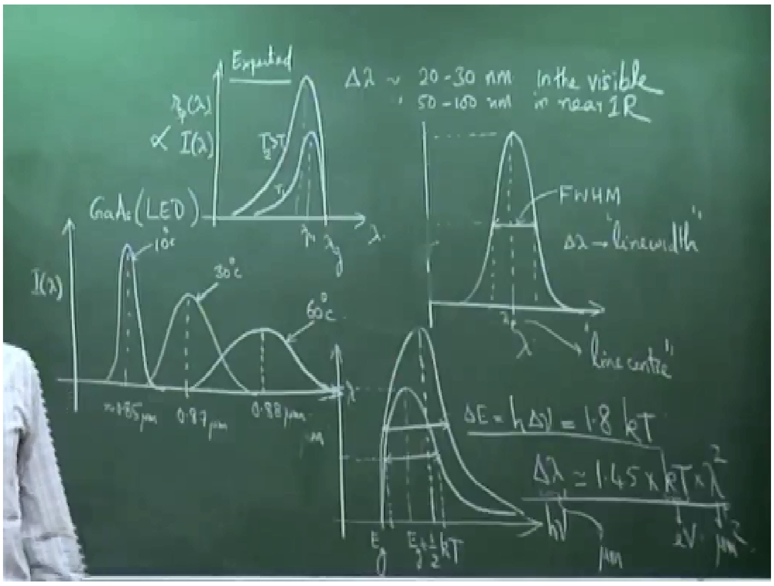


This is an important point I had to make an important point here that is in practice if I convert this into wave length this is lambda versus I of lambda or rsp of lambda which is proportional to I of lambda intensity. We should expect corresponding to lambda g here. So this is lambda g. Lambda g corresponding to Eg band gap. So if I want to plot with respect to lambda 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 lambda p1 corresponding to this is at temperature T1 this is at temperature T2 which is >T1. 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, but this is 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 micrometer approximately this is 0.87 micrometer and this is 0.88 micrometer or 885 something like that approximately numbers.

So what I have plotted is I of lambda versus lambda wavelength at 3 different temperature for a typical gallium arsenide LED. So what do we see? One the peak wavelength is shifting to lower energy. Here it is shifting to higher energy which means we expect it to shift to lower wavelength. Smaller wavelength, but it is shifting with the temperature to higher wavelength. Second we expected the peak to go up this is at a higher temperature.

This is at a 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 behavior. This is going up, but actually the peak is coming down. This is shifting to lower wavelength with higher temperature, but this is measured practically.

We have obviously missed something and this is what I want you to keep in mind and there is an important lesson in this and that is in certain derivations we make certain approximation or we do not take into account certain aspects. A result could be completely opposite when you take care of those aspects and this is what this simple experiment demonstrates.

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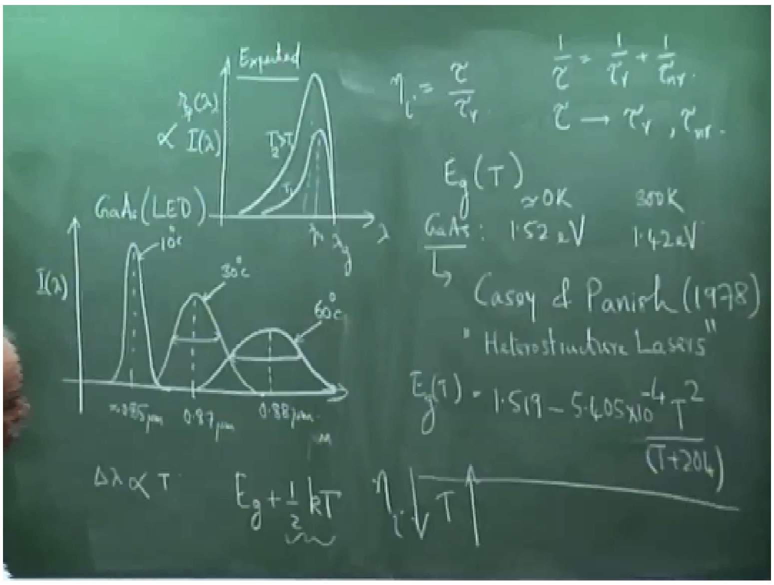


One first point band gap of a semiconductor Eg is a function of temperature. We have not taken care of this. Band gap decrease for example if you take gallium arsenide band gap is 1.52 eV around 0 k and at 3300 k room temperature this is 1.42 eV. So the band gap is temperature dependent you can find there are empirical expressions which are given. You can see a very good book by Casey & Panish please you may refer to this Casey and Panish is there is our library heterostructure lasers.

There are 2 volumes part A and part B. There is a temperature dependence of gallium arsenide. Let me write Eg for gallium arsenide which is for temperature dependent. It is listed for almost most of the useful semiconductors, but I am writing only for gallium arsenide it is given as 1.519-this is an empirical formula 5.405* 10 to the power of -4 * T square/ T+204. So what you see is this is at 0 k put T=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 Eg+1/2 kT. Remember kT is a very small quantity from 10 degree. So 30 degree it is 303. 10 degree it is 283 and 60 degree it is 233.

So it is a small difference in change in this T, but Eg changes quite a bit. Eg has a dependence which is more compared to this Kt. Therefore, although kT was shifting to higher energy, but the band gap Eg itself is decreasing. Eg is a function of T which is decreasing that is why the net effect is it shifts to the higher wavelength 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 the rate of spontaneous emission (()) (47:42) rapidly. Rate of spontaneous emission which leads to generation of photons please see recombination takes place. Tau in the expression there this tau contains tau r and tau nr and the relation is 1/tau=1/tau r+1/tau nr.

As temperature increases tau decreases rapidly because tau nr decreases. And therefore eta i= we have this expression tau/tau r tau decreases rapidly because tau nr decreases rapidly why tau 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 decrease in this and therefore eta i decreases.

And therefore the generated photons go down with 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 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 lambda is proportional to T. So this you observe in practice.

What is the physical reason for this? Mathematically we see that delta lambda is proportional to T, but physically what is happening?

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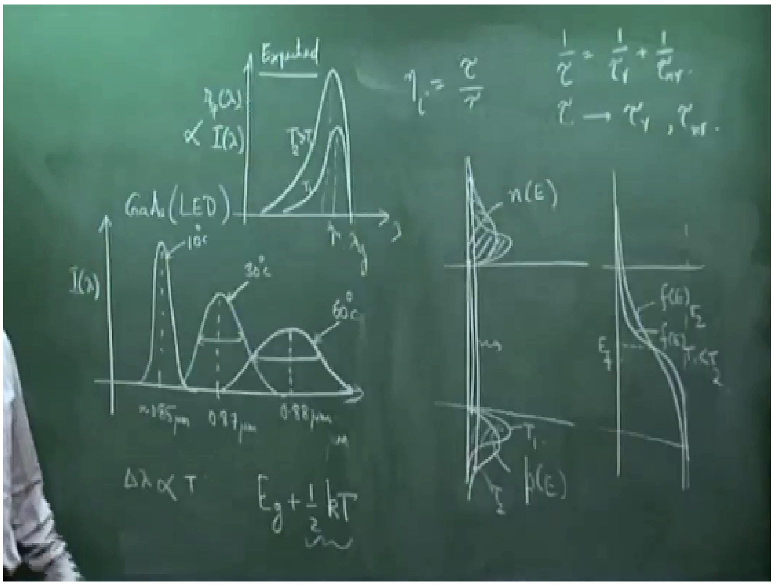

Let me quickly show this carrier distribution the physical variation and (()) (49:55). At a particular temperature we have carrier distribution which is this. There are different ways of illustrating this. One of the ways is what I am showing at a particular temperature. This is what I have plotted n 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 for a lower temperature it will be like this. This is the Fermi energy. This is f of E and temperature T2 this is f of E at temperature T1 which is lower than T2 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 T2, this is T1. When the distribution spreads the distribution over which photons emitted will also become wider because an electron sitting here can combine with the hole sitting here giving out photon of energy h nu this gap and electron which is sitting here now electrons are given here. Electron which is sitting here can combine the hole which is sitting here and can give the 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 the 2 band. So this is about the wavelength 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.

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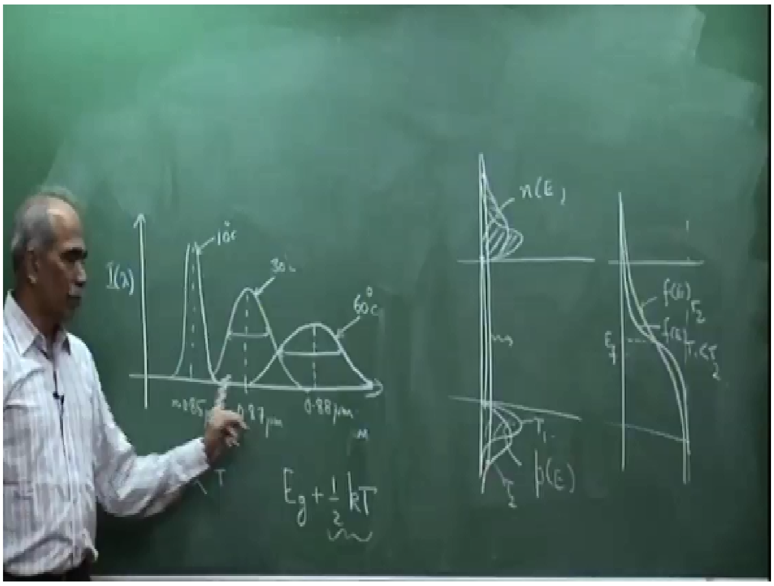

So now we are able to explain with the inclusion of Eg a function of time. We are able to explain this which was not as we saw earlier. I think I will stop here and we will continue in the next class.