Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
India Institute of Technology - Delhi

Lecture - 28
Light emitting diode-II Device Characteristics

Today, we will discuss about the Device Characteristics of Light Emitting Diodes, before I proceed with the device characteristics, let us recall in the last class we had looked at the device structure.

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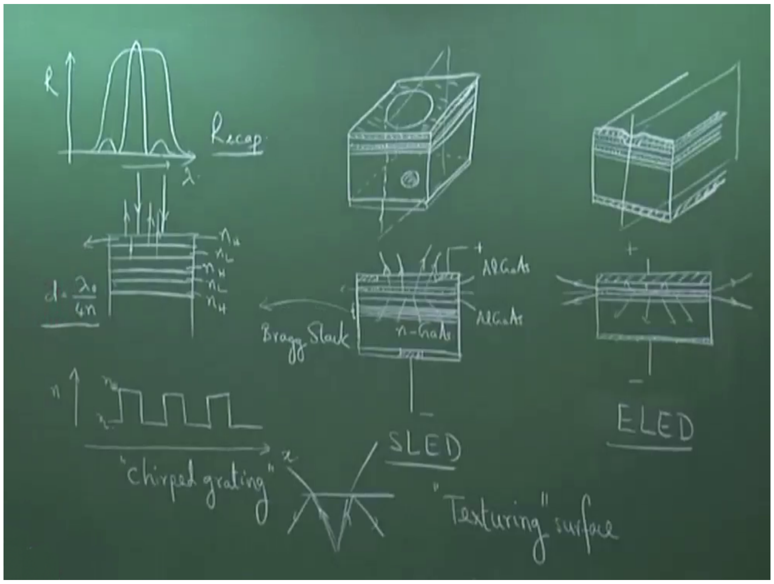

And broadly there were 2 classification surface emitting LED and edge emitting LED, the abbreviation ELED edge emitting LED, and surface emitting LED. The structure in 3d looks like this, so the dotted region here is the layer is the active region everywhere the dotted region is the active region, and the shaded region is the metallic electrode. In surface emitting LED since the light, so this is what is shown here is the cross section a segment if you take a segment in the along these lines, so this is what you see the cross-section.

Similarly, if you take a segment longitudinal segment along this line then this is what you see, so what is shown here is the longitudinal section of this, and here this is the section. So that is why you see this here it is actually a circular electrode there, and an annular electrode at the top, and we have already discussed that the annular region is because the emitted light has to come out, so the generated light has to come out here.

So that is why we have usually there is a window dielectric window there, and an annular electrode, so I had taken for example gallium arsenide substrate and so on, so n gallium arsenide substrate and then you have AlGaAs layer the cladding layers which are aluminium gallium arsenide in this particular case, and an active layer in between which would be a different composition aluminium gallium arsenide or gallium arsenide, so that is the active layer.

So the structures look almost similar, and there is a window here and the light comes upwards here, there was a question that the light which goes below that is into the substrate so this is usually lost it is a waste, in both the cases light that comes down here is a waste, in this case of course light which is going here is also lost, because we are from primarily collecting light from the edges that is why it is edge emitting LED making use of the optical confinement property of a double heterostructures light which is coming out here in the form of a cone from the edges.

In this case it is coming the edges the light which is coming here in the edges are lost that is not made use of, but in both cases the light which is going down into substrate is lost, there were some efforts to there are some designs where one can make use of this. For example, there are designs in which you have a Bragg reflecting stack here in the cladding, a Bragg reflecting stack, so this is called a Bragg stack, so let me zoom in and show you, what is this Bragg stack?

So the Bragg stack is basically a interference filter high reflection low reflection periodic, high index low index structure, so n high, n low, n high, n low, so it is a periodic medium and low and so on n high. And you know that such a structure if chosen properly that is if you choose the thickness of this d=lambda/4 n, then such a structure acts as a high reflecting, so if the incident light which is here is reflected back resonantly, this is the interference filters.

So the light which is incident gets reflected back, so if you choose this as lambda/4 layers the thickness of lambda/4 alternatively, high index low index, high index low index, a particular wavelength that satisfies this. For example, lambda 0/4 n will get lambda 0 will predominantly be reflected back, so if this radiation is at a particular wavelength, then all of them can be reflected back, you can make this high low high low layers again by a combination of gallium arsenide aluminium gallium arsenide.

It is a Bragg stack comprising of gallium arsenide aluminium gallium arsenide, because the refractive indices are different aluminium gallium arsenide has higher refractive index, we will discuss more about this later when we discuss big cells that is vertical cavity surface emitting lasers which are designed on the basis of Bragg stack, so we will discuss this about later. But for the time being I would I wanted to mention that there are designs where the light which is going into the substrate can also be reflected back.

So that overall efficiency is higher, this is for particular wavelength you can make a range of wavelength because we know that light emitted from LED is not monochromatic at 1 wavelength, there is a range of wavelength that is emitted, and you can make this stack reflecting for a range of wavelength by chirping the period by choosing d of, right now if you take a periodic structure the refractive index variation would look like this.

So this is what I have plotted n versus x the depth direction, so n this is higher index this is lower index n L, lower index higher index, lower index, but it is a periodic refractive index variation. But you can change the period which is called a chirped grating, so we will discuss about this later chirped grating which simply means the period is changing with x, and you can design chirped gratings which reflected over a wide band.

If you see those of you who are familiar with Bragg gratings, if you see a perfectly periodic reflectivity of perfectly, so what I am plotting is R here versus wavelength lambda, then the reflection curve looks like this for a perfectly periodic square wave. But if you chirp it then this band can get widened and you can it is possible to design wideband reflectors using chirped grating, so some designs also include this.

But one has to see whether one would like to go for this or not depends on the application, if the application demands then only one would go, otherwise the cost of the device will go up any additional layers any additional fabrication process will add to the cost of the device. Therefore, only in such cases where you really need very high efficiencies one goes for such designs.

One last point which I wanted to mention here was that as you can see we have discussed this that light that is coming out comes only up to a cone, because beyond that it undergoes total internal reflection, light within this cone will only come out rest of it will get totally internally reflected. There is a technique which is called texturizing, this was discovered much later texturizing the surface.

In surface emitting LEDs the efficiency can be enhanced by texturizing the surface, what is this texturizing? So this is basically making the surface uneven in simple terms it is nothing but making the surface uneven texturizing, and that increases the efficiency.

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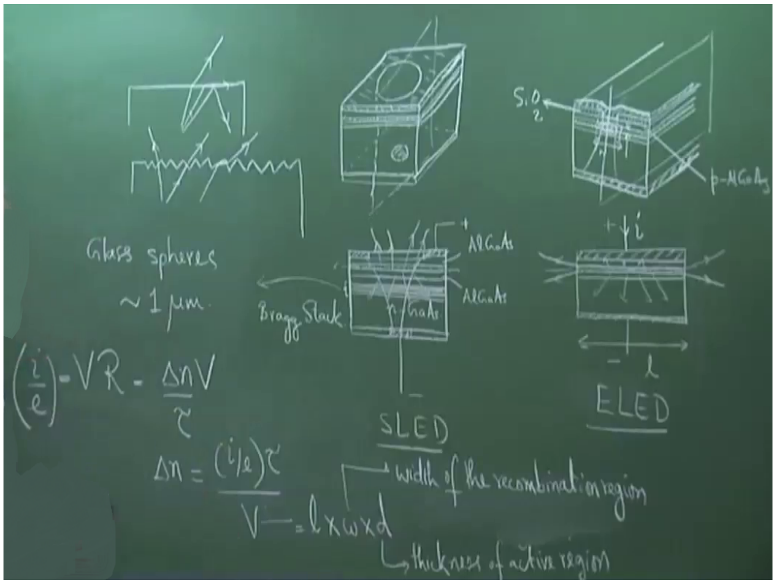

So you have let me show this, so here is a plane surface then you have light which is coming up to this goes grazing, which means any angle which is higher than that will get totally internally reflected, and an angle lower than this will come out that is considering a perfectly plane surface. Suppose, I damage the surface texturing I mean deliberately I make the surface just I am exaggerating, so let us say I have a surface which is like this.

In this case this is not true because a ray of light in this particular case, see here it is hitting this interface not at critical angle because the surface itself is like this, and therefore, this can simply pass through, because of the nature of the surface because of the corrugations in the surface most of the light will get scattered and pass through. So you could have light passing very easily through such a substrate.

For example, this particular one may get reflected here it may undergo total internal reflection here, but from here it will come out, so by texturizing the surface how this is done? This is done by using sandblast of glass spheres using a technique which was using glass spheres approximately diameter 1 micrometer blasting the semiconductor surface that causes texturization, it is a sphere therefore, it is not spoiling the surface but it is texturizing the surface.

So using this it has been shown that the emission efficiency extraction efficiency increases the reflection losses can be reduced by using such structures. In fact, now currently there is some research going on in using photonic crystal structures periodic photonic crystal structures on the surface to enhance the extraction efficiency alright, so I hope the structures are now clear edge emitting LED and surface emitting LED.

One other point which I wanted to mention is here we know why the dimension of the electrode is reduced, because we wanted that the carriers flow like this, so that the recombination takes place in the central region and light can come out, if the electrode was fully up to this carrier should have also flown here, and that is why we are using such an electrode. What about here, why this was reduced? You see this layer here is a dielectric layer it is a blocking layer SiO2.

And metal is only here, so the carriers flow like this, it is a strip the metal is in contact with a semiconductor this is semiconductor, so this is p-AlGaAs let us say that layer, and the next one is n-AlGaAs and in between is the active region. The metallic strip is like a strip it is not the whole it is not a layer which is in contact with the entire layer of the semiconductor, it is only here, why is this? What is the reason? If carriers go from here, you can see the light is generated only in this region.

Because the recombination takes place only here, so that when light comes out here you get cone of light which is coming or a beam of light, otherwise light would be generated over the entire sheet, so you would get a sheet of light, one reason but that is not the primary reason. What is the reason? Why this has been the width of the electrode has been reduced? Recall that we had an expression recombination is= delta n*tau.

And we had seen that this multiplied by volume is= the charge which is flowing i/e if i is the current that is flowing then by i/e is the number of carriers which is entering the semiconductor which is=rate of recombination multiplied by the volume of the region where it is a recombining V is the volume of the region where recombination takes place, so this expiration we have. So therefore please see this.

So this therefore if I multiplied by V here I should be multiplied by V here also to the right R= delta n/tau V*R= delta n by tau*V which is also =i/e I could written here, so we have delta n=i/e*tau/V. Now I am taking the last 2 here and delta n=i/e*tau, what is V? V is the volume of the active region where recombination is taking place, so this volume this V= length*width*thickness, what is l? Let me show here l is the length of this region.

Please see, current is flowing here there is a current i which is flowing through the device, I can show with respect to this or with respect to this, the current is flowing there i, this is the length of the device, what is the width of the device if I reduce the electrode then effective width is only this, this is the width of the device so this is w the width of the device, because V here stands for the volume where recombination is taking place.

Therefore, recombination is taking place only here, so the length of the region multiplied by width and what is d? d is the thickness of this region the active region, so d is thickness of the active region that is thickness of the active region, w is the width of the region of the recombination region which is approximately= the width of the electrode which is in contact here the width of the electrode which is in contact approximately equal to.

And l is of course the length of the region, now when we talked about double heterostructures I have already discussed the importance of the d, by taking a small d of 0.1 micrometer or 0.2 micrometer you are able to confine the carriers to a small region, and therefore, you could increase the density current the carrier density delta n by reducing d.

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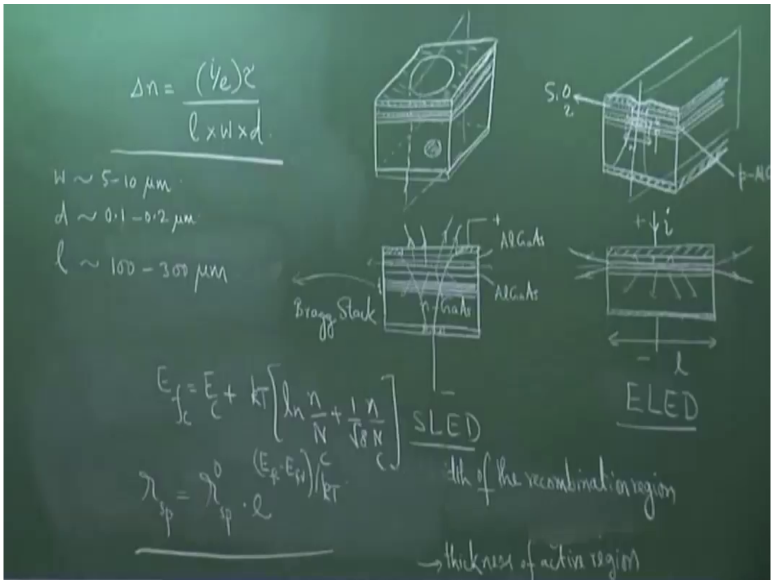

If that is the case, so let me write this again expression here delta n= i/e*tau/l*w*d, for a given current i delta n can be large if any of these 3 ore all these 3 could be as small as possible. So d we have reduced thickness of the active region that is reduced therefore, delta n increases for the same current, in comparison to homojunction, homojunction LEDs w is the width of this here, and by reducing the transverse dimension of the electrode we have effectively reduced w.

And therefore, delta n can become larger, we could of course reduce l also, if we reduce l the volume where light is generated becomes very small, and therefore, you have to strike a balance in general you could reduce all the 3 to get a large delta n for the same current, but d and w can be reduced without losing much, whereas if you reduce l the entire volume reduces, w reducing will also help us to get a beam from this LED.

Otherwise, you will get a strip over which emission takes place, normally in applications you would like to have a beam, and therefore, w is reduced this w is typically 5 to 10 micrometer, so w is typically 5 to 10 micrometer and d I already discussed is about 0.1 to 0.2 micrometer in a double heterostructures. And in an edge emitting LED l is typically so l here is typically 100 to 300 micron, so some idea about the real numbers of dimension of the devices.

So these 2 have been reduced, why are we interested in a large delta n? A large delta n because the fermi level Ef moves up if delta n becomes large, you recall the expressions for fermi level Ef=Ec+ kT*ln n/Nc+1/square root of 8 n/Nc, and what is this n, n is n0+ delta n, larger the delta larger will be this and therefore, Efc, so Efc when in quasi equilibrium this is Efc and Efc the separation between Efc and Efv will increase if delta n becomes large, it depends on delta n not the current.

And therefore, for a given current even by passing a small current you can achieve a large value of delta n, so that the separation between the fermi levels can be large, and as we know that separation between fermi level why do we want larger separation between fermi levels, because the probability of emission would go up and we know that the rate of spontaneous emission here is proportional to it depends on if you have.

So it depends on some number RSP at 0 that is thermal equilibrium multiplied by so this 0 is standing for thermal equilibrium multiplied by e to the power Efc-Efv/kT for thermal equilibrium Efc= Efv, so this term is e to the power of 0 which is 1, but in quasi equilibrium the rate of spontaneous emission gets multiplied by this factor, this factor will be large if the separation is large, the separation is large if delta n is large, delta n is large if dimension are small for a given current.

So this is the logic why the strip width has been reduced, so we in a given structure by now we know what is that need for having such a structure such layers such combinations, why do we need this? We now completely understand this structure, why such a structure is used in realizing LEDs light emitting sources. We now proceed to the characteristics of light emitting devices, just before I proceed one last small point here that is I have written like this.

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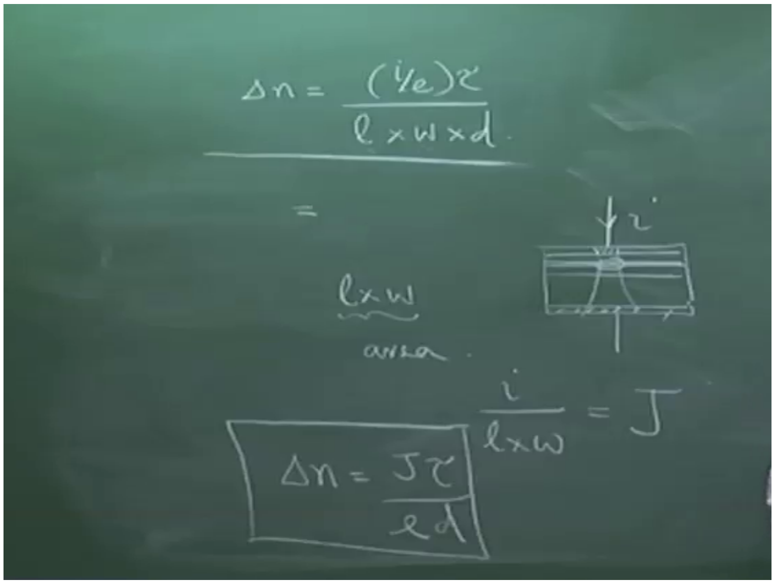

So this if you recall l*w, what is l*w? Length*width gives you the area of the strip, l*w gives you recall the active region, so before erasing I should have checked. So this is now front view okay cross-section, so here is the strip metallic strip and under this so many layers are there alright, let me know the layers again very quickly okay, so the carriers are flowing like this and this is the active region here, this width is w and l is the length.

So you have a strip of area l*w is the area through which current is flowing current is going from top, please see this this line current is flowing through an area l*w is there strip width, strip area of the strip, l*w is the area of the active region through which current is flowing. Therefore, i/l*w is what the current density J, therefore, delta n=J*tau/e*d this is an expression we would need later, delta n=j tau/e*d, d is the thickness of the double heterostructures active layer, tau is the access carrier recombination time, J is the current density.

Because when we go to semiconductor lasers you will see that normally it is discussed in terms of J the current density that expression has come right from here. So we will use directly this expression later when we get it, I would not again derive and show you from where we have got it, so this is from where we have get this expression delta n=J tau/e*d.

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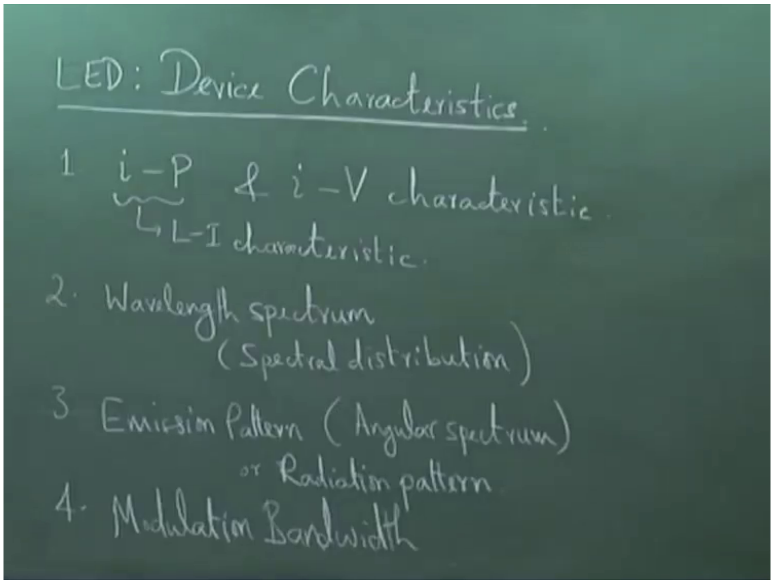

LED: Device Characteristics.

1 i-P & i-V characteristic.
↳ L-I characteristic.
2. Wavelength spectrum
(Spectral distribution)
3 Emission Pattern (Angular spectrum)
or Radiation pattern
4. Modulation Bandwidth

So device characteristics, there are some important device characteristics which we need to discuss about 1 the i-P and i-V characteristics it is a diode, this i-P is current versus power this sometimes also called as L-I characteristics light current characteristics, some literature some books may write it as light current characteristics, this is i versus current versus optical power L-I characteristics. Wavelength spectrum or sometimes this is called as spectral distribution.

Emission pattern, so when any user wants to use an LED, he has to know all these emission patterns, it is also called angular distribution, angular spectrum, emission pattern it is also called as angular spectrum sometimes radiation pattern, normally with antenna people use radiation pattern. And 4th modulation bandwidth, we will discuss these important characteristics one by one.

Let me take up the first one, and i-P so let me erase this, we will discuss the first one and then come to one by one all the four characteristics. Now this is completely from the user point of view, we have seen the physics of the device the design and the structure of the device, so i-P characteristics.

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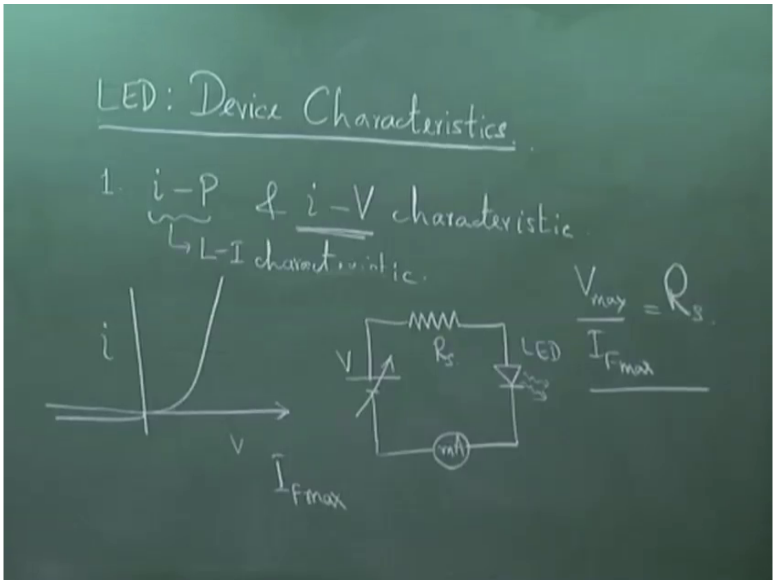

First, i-V characteristics i-V is LED is a light emitting diode, it is a forward biased diode and therefore, the i-V characteristics if you want to measure these i-V characteristics so V versus i, of course you can also measure the reverse characteristic, so it is the same it is a diode so it is the same diode characteristics. If you measure the i-V characteristics you will see the same diode characteristics, so typically here is a cell and there is a serious resistance Rs and here is the diode LED.

You can vary the voltage, and you can measure the current, so i mA and Rs the series resistance simple i-V characteristics, and LED gives out light. So vary the voltage and you can see that the current increases, if the same the forward diode characteristics and the backward reverse diode characteristics important point when in practice is to know that you have to put a resistance Rs, every device is characterized by IF max the maximum forward current through the diode.

If you see the data sheet of a LED there will be IF max the maximum current, so if V0 or Vmax is the maximum voltage here, then you have to choose IF max=Rs the series resistance, the series resistance before you start measuring this experiment before you do this experiment first calculate If we are using a supply with maximum voltage Vmax, and if IF max is the device forward current maximum forward current, then use the resistance Rs in series.

So that by mistake you do not exceed the current so that the diode does not get damaged, so the series resistance is to protect the LED, this is the i-V characteristics one can measure it very easily. And I am sure some of you are doing this experiment to measure the i-V characteristics. I come to the next characteristic i-P or L-I characteristic light current characteristics of a diode, this is very important.

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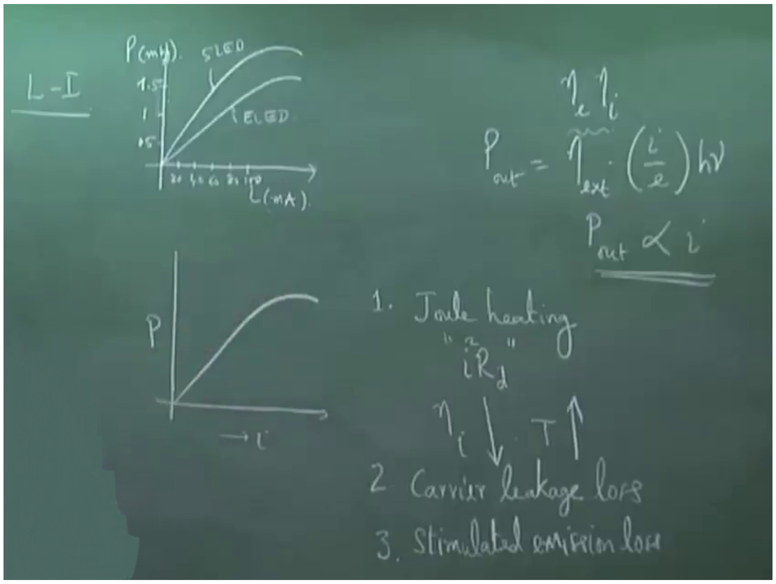

So L-I characteristics, L-I or i-P okay, so what do we expect so current I through the diode versus optical power, so P optical. What do we expect? We expect a linear curve because we have already derive the expression that P out=eta external quantum efficiency*i/e*h nu, therefore, P is proportional to P out is proportional to i. So we expect a linear characteristic here, so do we get linear characteristics many of you have measured this, this is not wrong.

So we should get linear characteristics, yes you do get a linear characteristic. So if you take a surface emitting LED you get a linear characteristic up to some region, so this is SLED, if you take the edge emitting LED it will also so almost similar characteristics, edge emitting LED has a for the same current in general ELED is a little bit less power because only the light which is trapped on the strip is what is coming out, whereas in surface LED it is the radiation is emitted over a wider cone.

And therefore, the power is slightly high, but the characteristics look the same which is output is proportional to input optical power P optical is, so why does it saturate here so what are the reasons for saturation, this is fine the initial portion. So typical numbers if I were to put so this may be so 20, 40, 60, 80, 100 so around 100 milliampere this is i milliampere, and this could be say 0.5, 1, 1.5 what is the unit milliwatt.

So typically 1 milliwatt optical power around 60, 50, 80 milliamperes of current maybe 100 milliamp of current. So typically this is the kind of numbers that you get or maybe 100s of microwatt for 10s of milliampere generally you will get about this. So after sometime you can see that it saturates, so what is the reason for this saturation, so let us focus on the saturated region, so this is going straight and then it starts saturating.

And even starts coming down as current increases, now this is i versus P, there are several reasons for this. The first one is joule heating it is a diode, the diode has an internal resistance, current is flowing through the resistance, so there is i squared R heat. So joule heating is because of this i square R, this R is the diode resistance so there is heating of the diode in fact If you touch the diode you can feel that the diode is getting hotter as the current increases.

So i square R joule heating, so why should the heating bring it down, because as the device starts getting heated eta i the internal quantum efficiency goes down, this eta external contains eta extraction multiplied by eta i, so this product is eta external eta extraction depends on the device structure. So in the previous discussion, we had how to maximize the extraction that is what we had discussed.

Now eta i is a material parameter which tells you the fractional recombinations that lead to the emission of photons, the rest of it is by non-radiative transition, but as the device starts getting heated there are the phonons in the lattice become very large, and eta I start going down most of the recombinations become non-radiative recombinations. So eta i is in fact exponential dependence, so if temperature goes up eta if T goes up eta i drops down almost exponentially.

The internal quantum efficiency drops down because of the existence of large amount of lattice energy for phonon energy which is responsible for non-radiative recombinations, and the fraction of non-radiative recombinations increase over radiative recombinations, radiative recombinations are responsible for giving light, non-radiative recombinations do not lead to generation of light. And therefore, this is one of the first reasons.

Let me write the reasons and then I will stop here and continue in the next class. The second reason is carrier leakage loss. And a third reason which is applicable to SLEDs, but not for ELEDs is stimulated emission loss. I will discuss these point in the next class, because we have to take a quiz. The quiz has been pending for quite some time, so we will discuss these and see, what do we mean by carrier leakage loss and stimulated emission loss?

Today's quiz is 1-minute quiz, it is fill in the blanks, you should not take more than 1 minute okay, so take out your answer sheet write your name and keep ready, I will put the quiz and in 60 seconds you must close and give it, just fill in the blanks very, very easy, do not let your eyes run this side or that side just on your sheet okay, everyone ready? 1 minute 60 seconds no more.

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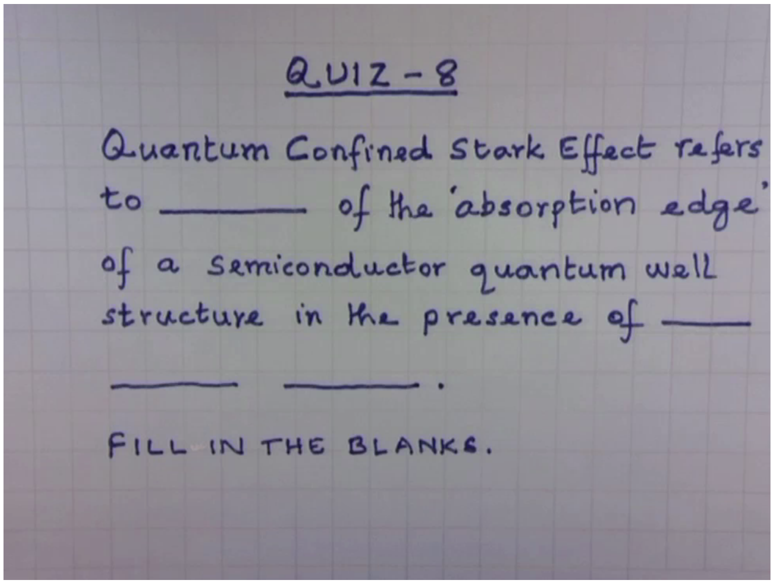

QUIZ - 8

Quantum Confined Stark Effect refers to ______ of the 'absorption edge' of a semiconductor quantum well structure in the presence of ______ ______ ______.

FILL IN THE BLANKS.

Quantum confined stark effect refers to dash of the absorption edge of a semiconductor quantum well structure in the presence of dash dash dash. Fill in the blanks, your time starts now, fill in the blanks with appropriate words. The only unique words will fit in their okay, let me the answer is let me give you the answer also, so what is the answer here nothing else will fit. Red shift of the absorption edge of a semiconductor quantum well in the presence of applied electric field.