Semiconductor Optoelectronics

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Lecture - 29
Light Emitting Diode-II
Device Characteristics

Today, we will discuss about the device characteristics of light emitting diodes.

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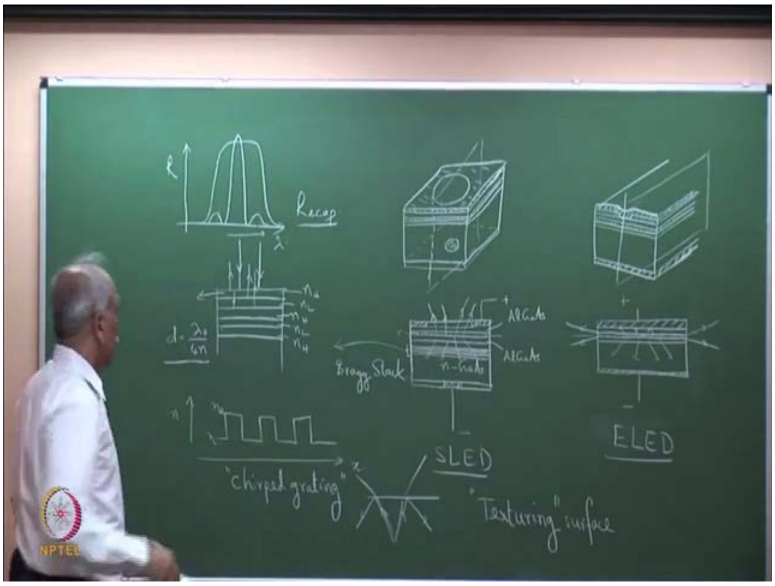

Before I proceed with the device characteristics, let us recall in the last class we had looked at the device structure and broadly there were two classifications; surface emitting LED and edge emitting LED. The abbreviation ELED edge emitting LED and surface emitting LED. The structure in 3D looks like 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 we shown here is the cross section a segment, if you take a segment in the along this line, so this is what you see the cross section. Similarly, if you take a segment, a 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, a electrode there and an annular electrode at the top and we have already discuss 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, and gallium arsenide substrate and then you have l gas layer the cladding layers, which are aluminum gallium arsenide in this particular case and a an active layer in between which could be a different composition aluminum 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 a 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 waste. In this case suppose light which is going here is also lost because we are primarily collecting light from the edges. That is why it is edge emitting LED, making use of the optical confinement property of double hetero structure, 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 it the edges are lost that is not made use of. But in both cases the light which is going down into the substrate is lost there are, 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. 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 n 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 is equal to lamda divided by 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 lamda by 4 layers, the thickness of lamda by 4 alternatively high index, low index, high index, low index a particular wavelength that satisfies this, for example, lamda 0 divided by 4 n will get lamda 0 will predominantly be reflected back. So, if this radiation is that the 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, aluminum gallium arsenide. Be it is a bragg stack comprising of gallium arsenide and aluminum gallium arsenide because the refractive indices are different. Aluminum gallium arsenide has a higher refractive index. We will discuss more about this later, when we discuss vec cells that is vertical cavity surface emitting lasers, which are designed on the basis of Bragg stacks. So, we will discuss about this 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 a particular wavelength. You can make a range of wavelengths because we know that light emitted from a LED is not monochromatic at one wavelength thus a range of wavelength which is emitted and you can make this stack reflecting for a range of wavelengths 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 the up, what I have plotted is 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, 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 a chirped grating which reflects over a wide band. If you see the, those of you are familiar with the Bragg ratings, if you see a perfectly periodic reflectivity of a perfectly. So, what I am plotting is r here versus wavelength lamda, then the reflection curve looks like this for a perfectly periodic square wave. But, if you chirp it then this band get widened and you can it is possible to design wide band reflectors, using chirped grating. So, some designs also include this but, one has to see whether one would go for this or not depends on the application. If the application demands, 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 discuss 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 texturing. This was discovered much later. Texturing the surface, texturing the surface. In surface emitting LED the efficiency can be enhanced by texturing the surface.

What is the texturing? So, this basically making the surface uneven. In simple terms it is nothing but, making the surface uneven. Texturing and that increases the efficiency.

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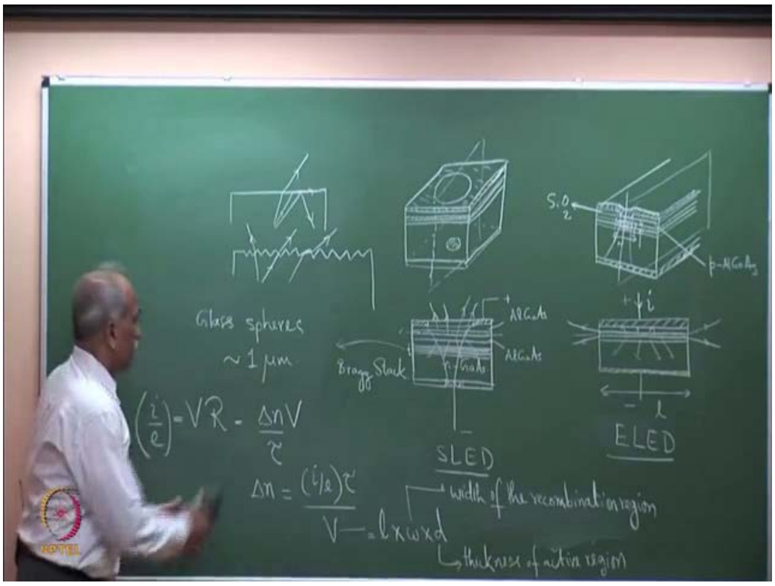

So, you have let me show this so here is a plain surface then, you have light which is coming up to this goes gracing which means, any angle which is higher than that will get totally internally reflected and an angle lower than this will come out. That is considering a perfectly plain surface. Suppose, I damage the surface, texture I mean deliberately. I make the surface. Just say 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 reflect here. It may undergo total internal reflection here, but from here it will come out. So, by texturing the surface. How this is done? This is done by using sandblast of a glass spheres, using a technique which was using glass spheres, glass spheres, 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 texturing 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 ah some research going in using photonic crystal structure, 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 carriers should have also flow in 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 is a blocking layer, S i o 2 and metal is only here. So, the carriers flow like this. It is a strip. The metal is in contact with the semiconductor. This is semiconductor. This is p Algas let us say, that layer and the next one is n Algas 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 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 recombination takes place only here. So, that when light comes out here you get a 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 equal to delta n into tau delta n into tau and we had seen that this multiplied by volume is equal to the charge which is flowing i by e. If i is the current that is flowing then, by i by e is the number of carriers which is entering the semiconductor which is equal to rate of recombination multiplied by the volume of the region where it is recombing, recombining. v is the volume of the region where recombination takes place. So, this expression we have. So, therefore, please see this.

So, this therefore, if I multiplied by V here, I should multiply by V here also to the righ R is equal to delta n divided by tau, V into R is equal to delta N divided by tau into V which is also equal to i by e. I could written i by e here. So, we have delta N is equal to i by e into tau divided by V. Now, I am taking the last two here and delta N is equal to i by e by V into tau. What is V? V is the volume of the active region where recombination is taking place. So, this volume this V is equal to length into width into 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, 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. This is the width of the device because the v here stands for the volume where recombination is taking place. Therefore, recombination is taking place only here.

So, length of the region multiplied by width and what is d? d is the thickness of this region, the active region. So, l so, d is thickness of active region. That is thickness of the, thickness of active region, thickness of the active region; v w is the width of the region of the recombination region, which is approximately equal to 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 hetero structure I have already discussed the importance of d. By taking a small d of 0.1 micrometer or 0.2 micrometer you are able to confined the carriers to a small region and therefore, you could increase the density current the carrier density delta n by reducing d. If that is the case so, let me write this again expression here.

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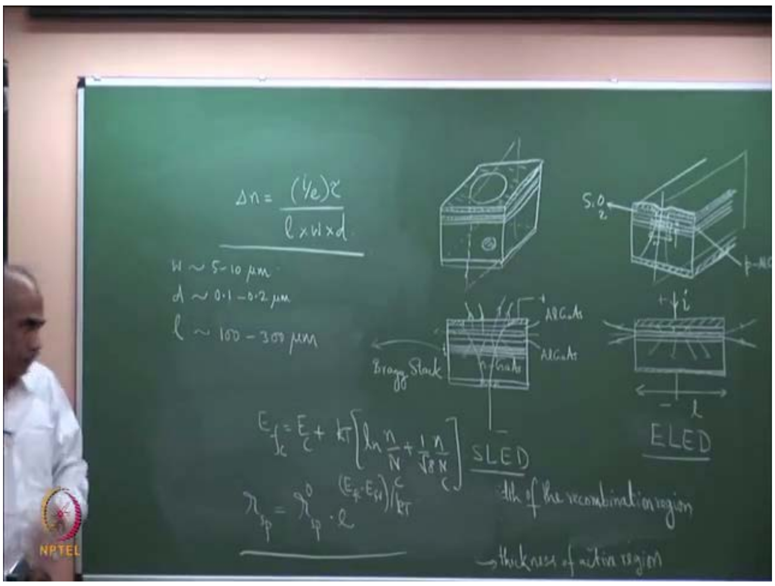

Delta n is equal to i by e into tau divided by l into w into d. For a given current i delta n can be large if, any of this three or all these three would be as small as possible. So, d we have reduced thickness of the active region. That is reduced therefore, delta n increases for the same current in comparison to homo junction. Homo junction LED's; w is the width of this here and by reducing transverse dimensions of the electrode, we have effectively reduce w and therefore, delta n can become larger. We could of course, reduce l also if you 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 three 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 the this LED, otherwise you will get a strip over which emission takes place.

Normally an 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 discuss is about 0.1 to 0.2 micrometer in a double hetro structure and in an edge emitting LED, l is typically so, l here is typically 100 to 300 micrometers. So, that some idea about the real numbers of dimension of the devices. So, these two have been reduced. Why, why are we interest in a large delta n? A large delta n because the Fermi level E f moves up, if delta n becomes large. You recall the expression for Fermi level E f is equal to E c plus k t into l N. N divided by n c plus 1 over square root of 8 N divided by N c. And what is this N? n is N 0 plus delta N. Larger the delta N, larger will be this and therefore, E f c so, E f when in quasi equilibrium this is E f c and E f c the separation between E f c and E f v 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 you want larger separation between 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 r s p at 0 that is thermal equilibrium multiplied by so, this 0 is standing for thermal equilibrium multiplied by E to the power E f c minus E f v by k t. For thermal equilibrium, E f c equal to E f v. 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 dimensions are small for a given current. So, this is the logic why that 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 LED’s light emitting source. 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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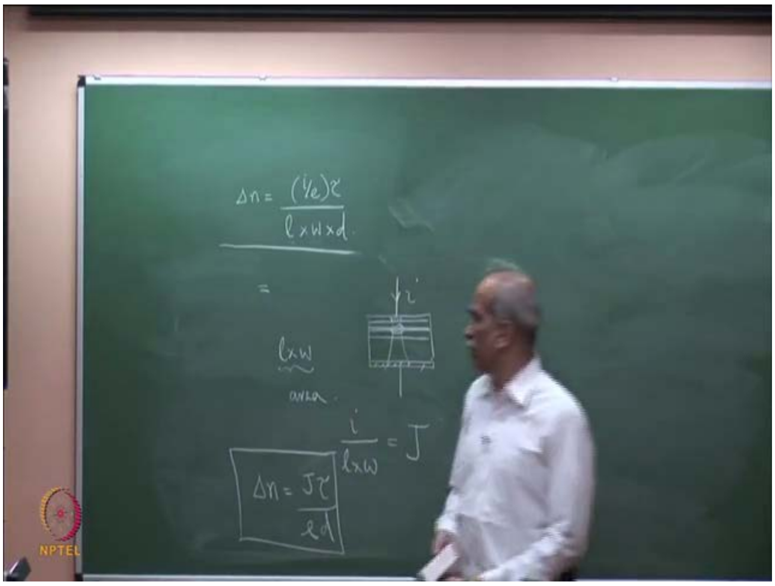

Just before I proceed one last small point here, that is I have written like this. So this, if you recall l into w. What is l into w? Length into width gives you the area of the strip. l into w gives you, recall the active region before erasing I should have checked. So, this is now front view okay. The cross section. So, here is the strip, metallic strip and under this so many layers are there. Let me draw the layers again, very quickly. 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 into w is the area, through which current is flowing. Current is going from top. Please see this, this is i current is flowing through an area l into w. l into w is the strip width. Strip area of the strip, l into w is the area of the active region through which current is flowing. Therefore, i divided by l into w is what the current density J. Therefore, delta N is equal to J into tau divided by E into d. This is an expression, we would need later. Delta N is equal to J tau by E into d. d is the thickness of the double hetro structure, active layer. Tau is the excess 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 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, we get this expression delta N is equal to J tau divided by E into d. So, device characteristics.

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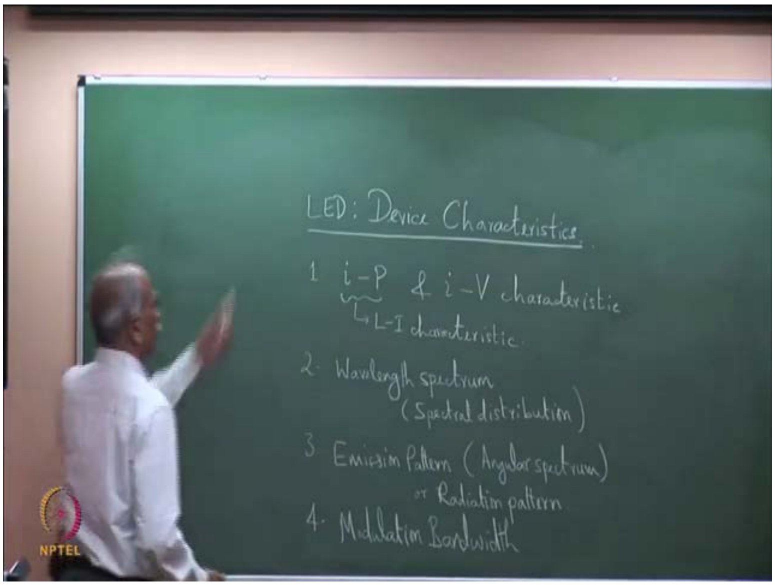

There are some important device characteristics which we need to discuss about one, the i p and i V characteristic, is diode. This i p is current versus power, these sometimes also called as L i characteristics. L i characteristics, light current characteristics. Some literature, some books may write it as a light current characteristics. This is i versus current versus optical power. L i characteristics. Wavelength spectrum or sometimes it is called as spectral distribution. Emission pattern so, when any user want to use an LED, he has to know all these emission patterns. Is also called angular distribution, Angular spectrum emission pattern.

This also called as angular spectrum sometimes radiation pattern or radiation pattern. Normally with antenna people use radiation pattern and fourth 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 discuss first one and then come to one by one all the four characteristics.

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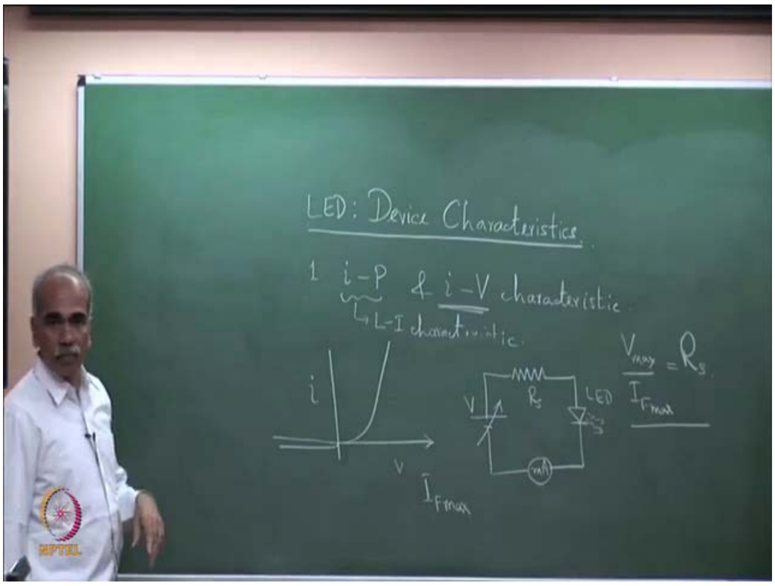

Now, this is completely from the user point of view. We have seen the physics of the device, the design and the structure of the device. So, i P characteristics; first i V characteristics i V is LED is a light emitting diode, it is a forward biased diode and therefore, the i V characteristics. If you want to measure this i V characters. So, V versus i of course, you also measure the reverse characteristics. So, it is the same, it is a diode so it is a same diode characteristics. If you measure the i V characteristics, you will see the same diode characteristics. So, typically here is the cell and this is series resistance R s and here is diode LED. You can vary the voltage and you can measure the current.

So, i m A and R s a series resistance. Simple i V characteristics and LED gives out light. The LED. So, vary the voltage and you can see that the current increases if the same the forward diode characteristic and the backward reverse diode characteristics. Important point when in practice is to know that, you have to put a resistance R s. Every device is characterized by I f max, I f max.

The maximum forward current to the diode. If you see the data sheet of a LED there will be I f max, the maximum current. So, if V 0 or V max is the maximum voltage here then, you have to choose I f max equal to Rs. The series resistance before you start measuring this experiment before you do this experiment, first calculate if you are using a supply with maximum voltage V max and if I f max is the device forward current maximum forward current then, use the resistance R s 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 doing this experiment to measure the i V characteristics.

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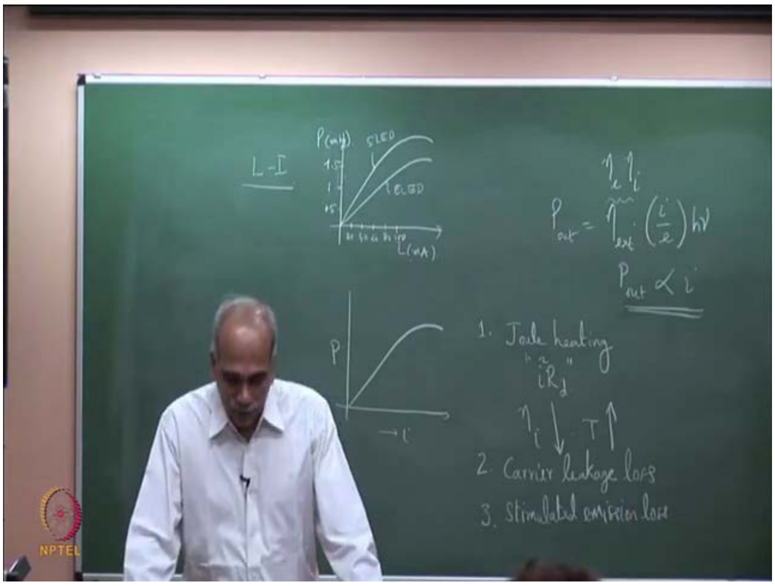

I come to the next characteristic. i p or L i characteristics, light current characteristics of a diode. This is very important, so L i characteristics. L i or i p, okay. L i. So, what do we expect? So, current i through the diode versus optical power. So, p optical power. So, what do we expect? We expect a linear curve because we have already derived the expression that p out is equal to eta external, external quantum efficiency into i by E into h. Therefore, p is proportional to p out, is proportional to i. So, we expect a linear characteristic here. So, do we get a linear characteristics. Many of you have measured this, this is not wrong so we should get a linear characteristics.

Yes, you do get a linear characteristic. So, if you take a surface emitting LED, you get a linear characteristics, characteristic up to some region so this is SLED. SLED. If you take a edge emitting LED, it will also show 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 emitted over a wider cone and therefore, the power is slightly high. But the characteristics look the same. It is output is proportional to input optical power p optical is. Why does it saturate it here? So, what are the reasons for saturation?

This is fine. The initial portion so, typical numbers if I have to put. So, this may be so 2, 40, 60, 80, 100. So, around one 100 milli ampere this is i milli ampere and this could be say 0.5, 0.5, 1, 1.5. What is the unit? Milli watt. So, typically 1 milli watt optical power around 60 50 80 milli amperes of current. May be 100 milli ampere of current. So, typically this is the kind of numbers that you will get or may be 100 of micro watts, for tens of milli ampere generally you will get about. So, after some time you can see that it saturates.

So, what is the reason for the saturation? So, let us focus on the saturated region. So, this is going straight and then it start saturating and even starts coming down as current increases. And this i versus P. There are several reasons for this. The first one is joule heating. Joule heating. It is a diode. A diode has a internal resistance, current is flowing through the resistance. So, there is i square R heat so joule heating is because of i square R. So, 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. 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 are discussing. Now eta i is a material parameter, which tells you the fractional recombinations that lead to the emission of the photons.

The rest of it is by non radiative transition, but as the has device starts getting heated there are the phonons in the lattice become very large and eta i starts 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 or 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 recombination do not lead to generation of light and therefore, 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 SLED's but, not for ELED's is stimulated emission loss, stimulated emission loss. I will discuss these points 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 one minute quiz. It is fill in the blanks. You should not take more than one minute. So, take out your answer sheet write your name and keep ready. I will put the quiz and 60 seconds you must close and give it. Is just fill in the blanks. Very very easy. Do not let your eyes run this side or that side, just on your sheet. Okay.

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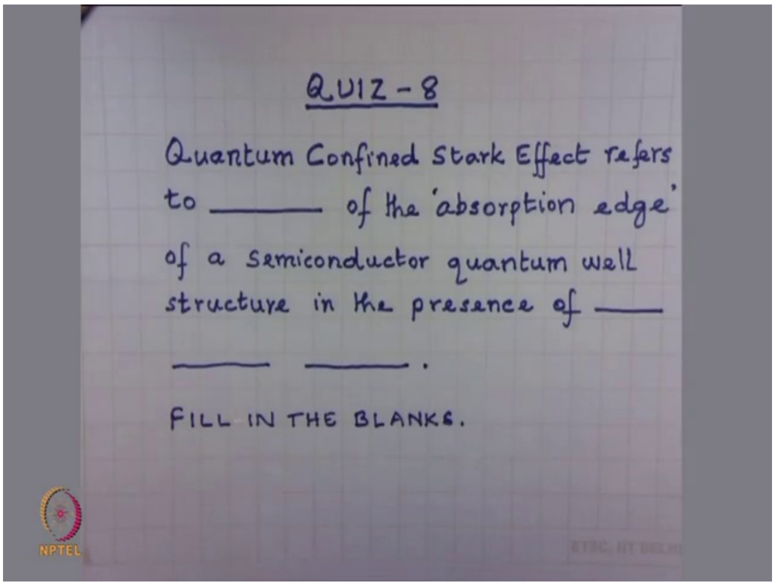

Everyone ready? 1 minute, 60 seconds. No more. Quantum confined stark effect refers to dash of the absorption edge of a semiconductor quantum well structure in the presence of dash dash dash. Fill in the blanks. Your time starts now. Fill in the blanks with appropriate words. The only unique words will fit in there. Quantum confined stark effect refers to of the absorption edge of a semiconductor quantum will structure in the presence of. Let me a, the answer is. Let me give you the answer also. So, what is the answer here? Nothing else will fit red shift. It is the red shift of the absorption edge of a semiconductor quantum well in the presence of applied electric field.