Semiconductor Optoelectronics
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Lecture - 27
Light Emitting Diode – 01 Device Structure and Parameters

So, today we will discuss about light emitting diodes, the first device and second device, we already discussed about the modulator. Let me recall first what we have, we have rate of recombination which is given by delta n/tau, where tau is excess carrier lifetime. Delta n is excess carrier concentration and this is rate of injection or rate of recombination. We also have 1 over tau = 1 over tau r + 1 over tau nr.

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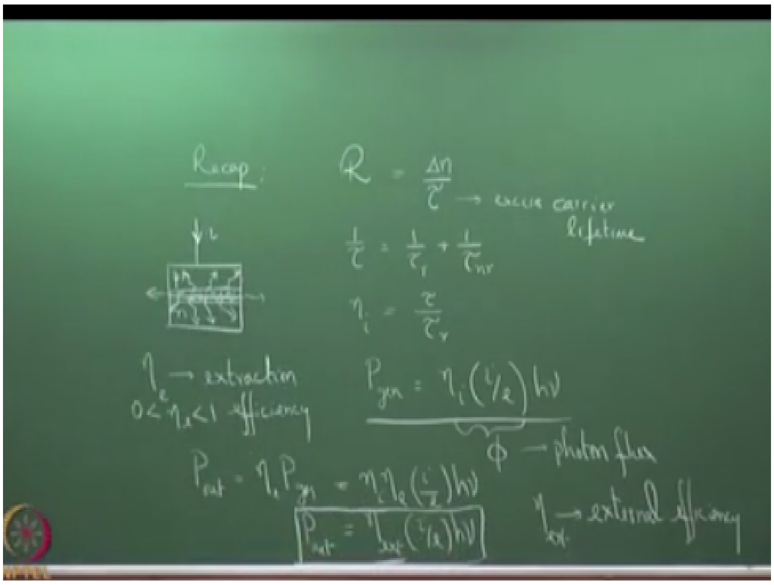

Recap:

$R = \frac{\Delta n}{\tau}$ → excess carrier lifetime

$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$

$\eta_i = \frac{\tau}{\tau_r}$

η_e → extraction efficiency

$0 < \eta_e < 1$

$P_{gn} = \eta_i \underbrace{(i/e)}_{} h\nu$

ϕ → photon flux

$P_{out} = \eta_e P_{gn} = \eta_i \eta_e (\frac{i}{e}) h\nu$

$\boxed{P_{out} = \eta_{ext} (i/e) h\nu}$

η_{ext} → external efficiency

Tau r is the radiative recombination lifetime and tau nr is the nonradiative recombination lifetime and we have written the internal quantum efficiency eta i as the fraction tau divided by tau r. Basically, it is the ratio of radiative transitions to the total number of transitions, radiative recombination to total number of recombinations and then we have found out an expression for the optical power generator which = eta i * i/e * h nu.

Note that this is nothing but the photon flux power generated is photon flux multiplied by energy of one photon. So this is photon flux, i/e is actually electron flux. I is charge per second and i/e is number of charges per second and therefore, this is the carrier flux multiplied by eta i gives you the photon flux, photon flux multiplied by energy of photon gives you the optical power generator.

This is the optical power generator. So, if you take the semiconductor here at p-n junction, as I said, the easiest way of current injection is a forward biased p-n junction here. In the junction region, we now that in the junction region we have recombinations taking place and light generated. So, spontaneously recombinations are taking place and light is generated. So, the generated light is coming out in all directions.

Because it is primarily spontaneous emission because stimulated emission will dominate only when efc - ef will becomes greater than h nu. Otherwise, you are in the domain of spontaneous emission. So, the light generated is emitted, we want to know so this expression refers to the light generated, but what is the output power and root when the proton is coming out, when radiation is coming out, there can be losses.

And therefore, the actual power output will be less than the power generated. If eta e is the extraction efficiency, which means out of the generated power, the fractional power that is being extracted out, then the power output p out will be = eta i eta e * p generated, I would drop the optical because we are taking of optical power only and therefore, this = eta i * eta e * i/e * h nu.

This is the power output, where eta e is the fraction, so this eta e is < 1 is the fractional power, which is coming out of the total generated power. This quantity is written as eta external * i/e * h nu, where eta external is called external efficiency. So, we have several efficiencies here, eta i is internal quantum efficiency, is property of the material. Eta e is the extraction efficiency as you will see it will depend on the device structure eta e.

That is what we will be discussing now, eta e is the device extraction efficiency depending on the device structure and eta external is called eta external efficiency, so internal quantum efficiency and external efficiency. External efficiency determines what is the power output. So p out = eta, so this is the expression that we need. P out = eta external * i/e * h nu. A little bit of simplification here.

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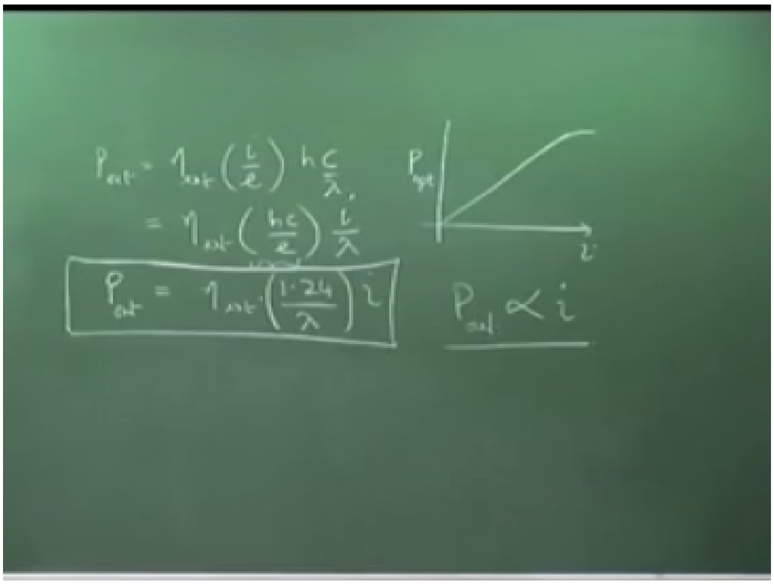

So, p out = eta external * i/e, i is the current and h nu, I can write as hc/lambda h nu, so this = eta external * hc/e, all are constant, Planck's constant, velocity of light and charge * i/lambda. This quantity if you put lambda in micrometers, you can put all the constant, this will come out to be 1.24, so we have eta external * 1.24/lambda * i. So, p out = eta external * 1.24/lambda * i.

An important point you will see immediately is that p out for a given device, it emits around a certain wave length lambda here, so p out is proportional to i, which means as you increase the current output power will go on increasing. As you will see later that and some of you would have done this experiment that if you plot i versus p optical for an LED, you get a linear variation like this.

Up to some current later on, it saturates, we will discuss the reasons for the saturation and so on, but you can see that p optical is proportional to the current i, which is directly visible in this expression. So in the remaining part, we will discuss about the device structures and how eta e can be maximized. Because if eta i is property of the material, eta e can be maximized by choosing appropriate device structure.

Basically, there are two types of the devices are broadly classified into two categories, one is called the surface emitting LED and other one the edge emitting LED. We will see the device structure and depending on the applications, one would choose either a surface emitting LED or an edge emitting LED. There are further variance of this, but broadly LEDs are classified into two categories.

So LEDs device structure, we have surface emitting LED or this is written as SLED, surface emitting LED and edge emitting LED, which is called ELED. As the name indicates, one of the devices emits from the surface and another one emits from the edge. So, depending on the application one would choose either surface emitting or edge emitting, both are used. For example, in all display applications, we use surface emitting LEDs.

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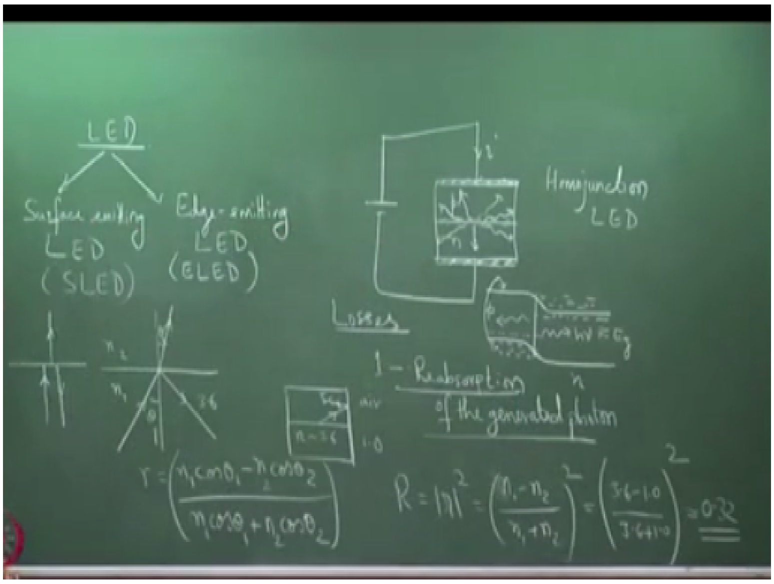

Whereas if you have applications where you need relatively (()) (10:14) beam in one particular direction, then you use edge emitting LEDs. Now let us see, the basic structure of an LED, it is a p-n junction, if you take a simple homojunction p-n junction, a current I pass through this a forward biased homojunction. In the junction region that is the active region here, light is generated and light when you forward biased because of recombination light propagates in all directions.

It is spontaneous emission; therefore light is emitted in all directions. As light propagates, if you take a homojunction so homojunction LED that is it could be a p type early p-type gallium arsenide and n-type gallium arsenide and doped gallium arsenide homojunction. What you see is that if I plot the band diagram, forward biased LED, so the EFC and EFV have split.

So, this is p type and this is n type, I am drawing the band diagram of the forward biased device. Recombinations, there are plenty of electrons here and plenty of holes here, the holes and electrons combine and h nu is given, we know this. The energy h nu here is approximately = eg > r - eg approximately = eg. The quasi Fermi levels are in the junction region only.

And the light is generated, there are some recombinations taking place here also, they are negligible compared to the recombination which are taking place here. The recombination is taking place here and light is generated. The generated light is now propagating to the rest of the semiconductor beyond the active region. When it is passing through here, let us say light is propagating like this, an electron which is sitting here.

There are plenty of holes here, but still there are electron also and electron from here can make an upper transition and create more holes and electrons that is the generated photon can be reabsorbed by the same material, so this is a major loss, re-absorption loss. So, losses and I am seeing, we have to first understand that extraction efficiency eta e, it is less than 1, so what are the factors which are contributing to that small value of eta e.

Ideally if eta e was 1, it was wonderful generated all the generator light would have come out, but eta e is < 1, so the losses are first one, re-absorption of the generated photon outside the active region as it comes out, it can get absorbed. This is a major loss. What are other losses can be think of? This diagram let me draw it again here, so this is the junction region, light is traveling in this direction here.

Let us say, it is traveling here, these are metal electrodes, light which is traveling here meets this interface here. This is an interface between semiconductor and air outside. The refractive index of the semiconductor is approximately 3.6, if you take gallium arsenide. Others are also 3.5, 3.24, so very large refractive index, n is of the order of 3.6, outside refractive index is 1.0.

So if you take an interface, a ray of light which is incident like this, so this is n1, this is n2, this is n1, then a part of it will be reflected and the part of it will be transmitted. The fraction, which is the reflection coefficient r is given by n1, if you call this as theta 1 and this as theta 2, then is n1 cosine theta 1, Fresnel reflection coefficients, you would have studied in optics. Reflection coefficient is n1 cosine theta 1 - n2 cosine theta 2 divided by n1 cosine theta 1 + n2 cosine theta 2.

This is for one polarization, for the other polarization, there is a small change, this is the amplitude reflection coefficient and the energy reflection coefficient r = mod r square which = the whole thing which is square, you simply square this. For the simple case, you can see that you can put thetas and find out what is the reflection coefficient and the energy reflectivity, r is the reflectivity.

The fractional power which is reflected back is r. If you consider a normal incidence here like this, then theta = 0 and you will get n1 - n2 divided by n1 + n2 and the reflectivity r = n1 - n2, these are n, not eta, so n1 + n2 whole square. If you substitute n1 is 3.6, so this is 3.6 because light is coming from inside here 3.6, n2 is air outside, so if I substitute values, 3.6-1.0 divided by 3.6+1.0 whole square and this is approximately = 0.32.

That means the reflectivity is 32%, even for normal incidence, if it is at an angle, it will be more. So for normal incidence, it is 32%. So above 32% of the light, which is coming out, it is trying to come out is reflected at this interface. So first one is here, re-absorption losses. The second one is reflection losses at the semiconductor air interface. So, the light which is trying to come out is again reflected back, only a part of it is coming out.

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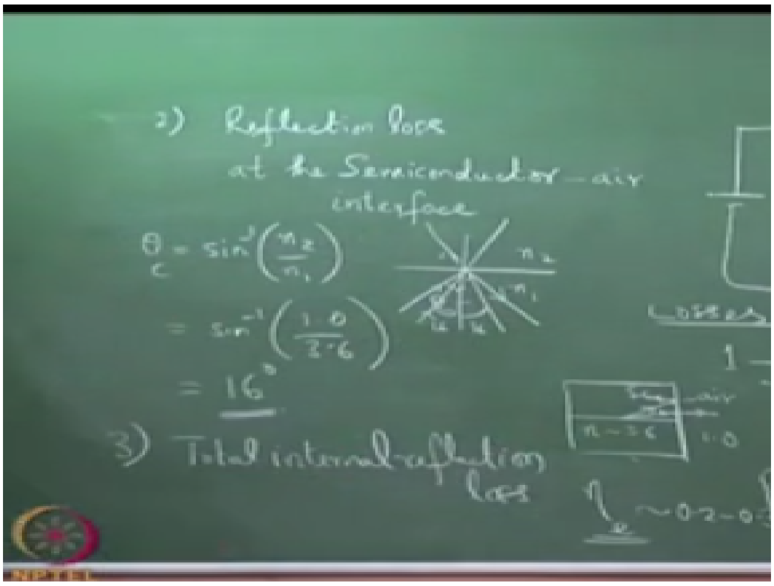

Now, more importantly you see light is coming from a denser medium to rarer medium, this is the denser medium, outside is a rarer medium, so there is a possibility of total internal reflection and what is the total internal? So, if light is incident like at an angle theta and this is n1, this is n2, then the critical angle theta c is sine inverse of n2/n1, if theta is > theta c, then it will be totally reflected.

There is no light coming out, so light is trying to come out here, we saw that even if total internal reflection is not taking place is significant fraction, let us say light was going like this. It is getting reflected back and only a small 68% is going out, 32% is coming back. Now, I also want to see what is the cone within which light can come out. What is this angle theta? Look at the angle theta, theta c = sine inverse of n2 is air outside, so 1 divided by 3.6.

This is 16 degrees, which means to the interface here, if it makes an angle more than 16 degree like this, a little bit more than 16 degree, it will get totally reflected, which means the cone that is coming out is only within that 16 degree. So, this is totally reflected only if theta, all the rays which tried to go within the angle of 16 degree here, 16 degree and 16 degree these will only come out.

In other words, a major portion of the generated light will get totally internally reflected from the semiconductor interface. There is very little light which is able to come, only within 16 degree cone, the light which is incident at the interface will come out, rest is reflected back and this is the third loss which is called, so let me write the third one here, total internal reflection losses at the semiconductor air interface.

As we will see some things can be reduced by having outside instead of air, if you put a proxy interface, you can reduce and so on, we will see, but these are three important losses, which we see without considering any defects or anything, we assume that the material is pure, everything is fine. There are additional losses if the material is impure, there are defects, then there are also losses because of carrier losses due to trap.

So these are optical losses that you see, re-absorption of the generator photon, reflection losses, reflection is not a loss as far as semiconductor is concern, but as far as the user is concern, it is not coming out. So, reflection is a loss for him. Similarly, the total internal reflection will also be a loss. Usually, we think total internal reflection is good, those who have studied optical waveguides, you know that the light is getting guided by total internal reflection.

And here we are saying total internal reflection is loss. No, we will see that we will make use of this for our gain, so these are the losses, major losses of the generator photon, which contributes to eta e. The extraction efficiency becomes small, only a small fraction typically this number is about 0.2 to 0.3, extraction efficiency is of the order of 0.2 to 0.3 because of these losses.

How to minimize the loss? How to reduce this loss? These losses are reduced by use of double heterostructure. So, double heterostructures will significantly reduce these losses. So, today's LEDs all structures are double heterostructures. The edge emitting and surface emitting LEDs which we have today are double heterostructures. So, we wanted to discuss this before drawing the actual structure.

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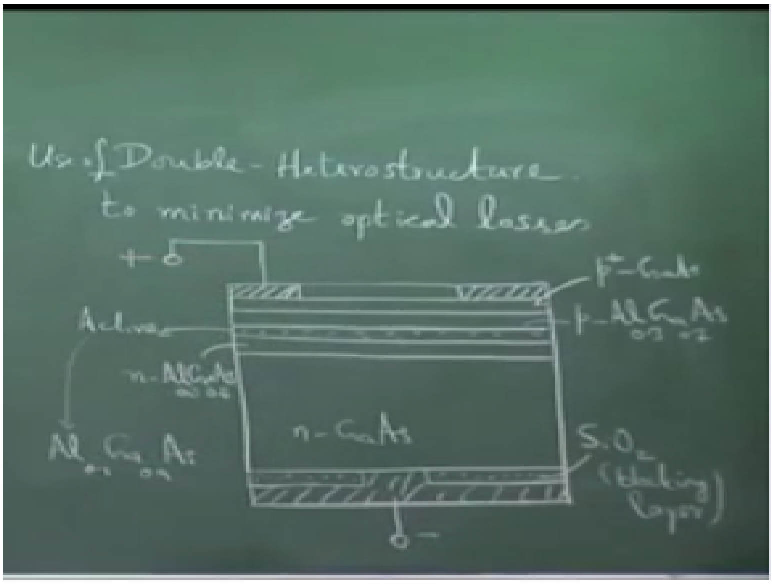

So, use of double heterostructures to minimize losses, optical losses. How would double heterostructure, okay let me first draw a structure. Let me first draw structure of a surface emitting LED, draw it along with me and then we will discuss about every layer, what is the purpose of this layer? So, this is n gallium arsenide substrate on which a layer of n aluminum gallium arsenide is deposited over which an active region is deposited.

This is active, active could be gallium arsenide, active could be aluminum gallium arsenide, but with the different composition. For example, if I put this as Al0.3, gallium will be 0.7 arsenic, then this active could Al0.1 gallium 0.9 arsenide or it could be pure gallium arsenide also. So the active region and above this, we have let me write it to the other side, p aluminum gallium arsenide, Al0.3 gallium 0.7, the numbers I am taking only as an example.

And usually above this, there is a p layer, okay let me draw this p, p+ gallium arsenide, you would know why and then we have, I will draw the structure and then I will explain what are the roles of each of these layers and where is the heterostructure and how it is going to help as. This is SiO2 silicon blocking layer. This is called blocking layer. This is the contact electrode.

So, let me show it like this, n side, so this is negative - and we have the positive contact electrode here and this is the dielectric window, it could be silicon nitride many times people used silicon nitride which is transparent dielectric window. The dielectric window is required for light to come out. Carriers are flowing here, so see this structure, this is a vertical section. So the LED is like this, so we have put taken out a section of this.

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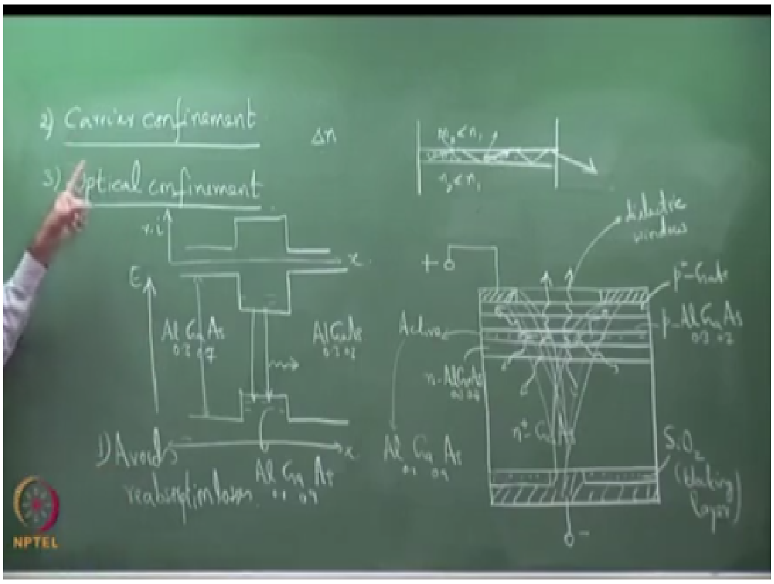

These are nonconducting silicon blocking layer and here is the window. So the carriers, when you forward biased, the carriers flow towards this, these series. The carriers are flowing here like this. What I have shown, this is flow of carriers. Electrons and poles, flow of carriers. Because there is no current which can flow here, there is a insulating layer silicon, the metal is here, semiconductor is here.

So, it is making contact here and the carriers are flowing in this way. When it flows in this region, this is our active region. There are recombinations taking place in the active region and therefore, light is generated here and light comes out, not just here, it also tries to go in different direction as before. First thing we see is the band diagram of the active region. So, what I have shown is the typical surface emitting SLEDs, a typical structure.

So, start with the n or n+ gallium arsenide. The n+ gallium arsenide with this metal contact forms a nearly good ohmic contact. The p+ gallium arsenide here forms a good ohmic contact with this metal here. This is an annular electrode. It is an annular electrode means with a slot in the middle open slot from where light come out, otherwise the metal will block, the light which is coming out, so it is a annular electrode.

Please see the picture, it is a annular electrode. It is a vertical cross-section like this. This is the substrate, starting substrate on which a layer of n aluminum gallium arsenide is deposited and therefore, the band structure you have is this of the active region. So this is active region, which is aluminum 0.1 gallium 0.9 and arsenide that I have shown here active. This is larger band gap.

This is aluminum 0.3 gallium 0.7 and arsenide, same here AlGaAs, 0.3, 0.7 and arsenide. Light is generated by recombinations which are taking place here, so the photons of energy h nu which are generated here as they come out, they are seeing material which has a larger band gap. It has a larger band gap here and therefore; it will not be absorbed. So, the double heterostructure, first point it does is it avoids re-absorption losses.

The top gallium arsenide layer here is very thin in fact gallium arsenide it would get absorbed, but that is a very thin layer, p+ layer. So, this avoids re-absorption losses. In the homojunction recall, that outside everywhere it was the same material and it could have absorbed again. Here, it avoids re-absorption losses. This is the first point it does.

Second thing, we have already seen that when you forward biased it, the carrier density becomes very large in this area, you recall we have discussed the energy band diagram and that time, I had mentioned that one important advantage of double heterostructure is carrier confinement for the same. So, this is avoiding re-absorption losses. The second important advantage of double heterostructure is carrier confinement.

We already discussed two times, so I am not again going into that. What it simply means is, for the same given current, excess carrier concentration delta n can become very large because the carriers are confined to a small dimension in space. Therefore, carrier concentration is charge per unit volume will become very large for the same amount of charge which is reaching the junction region, so that is carrier confinement.

A third thing is optical confinement. For a given material system, a region which has a higher band gap, has a lower refractive index. This is a fortunate coincidence in nature. For a given material system that a region which has higher band gap has a lower refractive index, which means in the same way if I were to plot refractive index profile, it would have been like this. So what I am plotting now, refractive index ri versus x.

Here, this was E versus x band gap variation. This is refractive index versus x, which means if I see this, let me show only the active region for the entire structure. So, what you have is this is the active region, which has a smaller band gap has a larger refractive index, so it is like refractive index n1 here and n2 here, which is < n1, so n2 < n1. So, the light which is generated here, light that is generated.

Of course, those which come at a larger angle than the critical angle will go out like this, but those which are travelling at an angle which is smaller than the critical angle, they will get trapped inside and they will behave like an optical wave guide and light comes out from the edges and this property is made use of in realizing edge emitting LEDs, optical confinement.

So, optical confinement refers to the optical energy which is generated in the active region that is confined because of optical wave guiding action and why do we have wave guiding action, because the region outside has a higher band gap. This has a lower refractive index compared to this and the optical wave guiding action confines the optical energy. There are three, why I have written three?

What is the importance of double heterostructures? Double heterostructures have three important advantages. There are more in terms of design flexibility, but three important advantages. You can call this as one, this two and this three or any order, but these are the three most important advantages of the double heterostructure. One, carrier confinement; two, optical confinement; and three lower re-absorption losses, reduced re-absorption losses.

This is the surface emitting LED. In this, the third one is of no use. Because we want light to come out, the light which is trapped here will come out on the sides, which we are not able to make use of. We are able to make use of only the light, which is coming here. So, I have explained the advantages of all the layers. These are blocking layers, you see if I did not have this blocking layer, the carriers would have gone like this, which means it will be generating here, at this end light.

And that light cannot come out because the electrode is blocking. For we want the light is generated in the center, so that it is coming out from here. That is why these ends are blocked. Do you follow. So, this is a typical structure of a surface emitting LED. Now, the edge emitting LED has a similar structure which makes use of the third point namely the optical confinement.

The other two points are any how made use of, but it also makes use of the third point. The other LED, the surface emitting LED does not make use of that point. In other words, whatever light trapped which goes to the sides is a waste as far as surface emitting LED is concerned. So, the edge emitting LED structure looks like this. So, now you can draw very quickly.

So we have the metal electrode, always minimum three layers are required to form the double heterostructure. So, this is the active layer, the cladding layers or the high band gap layers and the substrate and here. So, this is if you start with n or n+ gallium arsenide substrate and then, you have the aluminum gallium arsenide or the materials we will discuss, there are number of materials depending on the wave length of interest.

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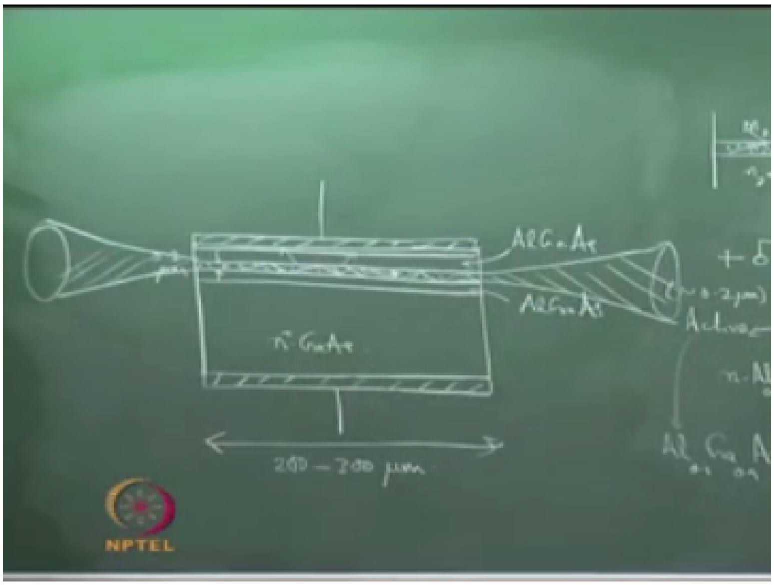

We will discuss this separately, aluminum gallium arsenide. Right now, I am choosing this because we have already studied that (()) (39:35) and that is the active. The edge emitting LED looks like this, typical dimension here is of the order of 200 to 300 micrometer, the length here. Here, this thickness is approximately 60 micrometers, the substrate. Each of this layers, the active layer is typically about 0.2 micrometer, is the thickness of active layer, 0.2 micrometer.

The outside cladding layers are typically 0.5-0.6 micrometer, the outside cladding layers. So, this whole thing is only one micron. This substrate is about 50 micron, the whole thing is only about 1 micron, so same thing here. Length is here about 200 micron, this is 0.2 micrometer. In the edge emitting LED, the light which is going like this will be lost, just like in the surface emitting LED, light which is going to the sides is lost that is not being used.

But in this case, the light which is going in this direction that all the light that is generated in this direction will get trapped optically, they will not be lost and therefore, they will come out in this fashion here. So, the light comes out here. This is the light cone which is coming out from the ends, both the ends. We will discuss about its characteristic, how does the cone look like etc, a little later when we discuss the device characteristics.

But right now, I am focusing on device structure on device structure. This is called an edge emitting LED because light is emitted from the edges. This is a surface emitting LED, as the name indicates light is emitted from the surface. There are applications where you need light to come out like a torch light, directional light. You want to couple this for example to an optical fiber.

Then, you would light to come directionally. Of course, you will need a little bit of focusing lens or whatever to couple into the device that you want, but edge emitting light LEDs give directional light, not parallel. Surface emitting lights give LED over a wide range of angles. This is required for displays because in a display, if light is coming only like this, those who are sitting on the other side would not be able to see because light is going only in this direction.

So in the display, you would like light to come out over a wide region that is why you can see all those red LEDs which are displayed on which we are used as display LEDs on instrument panels. They are surface emitting LEDs because light has to come out, so that one can see from the sides also. But edge emitting LEDs have more directional output, more directional. It is not parallel because it is already diverging.

Why is it diverging? Because this angle, this layer thickness here is very small. We will discuss the characteristic a little later. I hope the picture is clear that surface emitting LED and edge emitting LED, both are double heterostructure LEDs. Both the devices are double heterostructure. Double heterostructure primarily to avoid re-absorption losses. In this case, the third property of double heterostructure namely optical confinement to the wave guide is also made use of.

So that light is coming from an edge with more directionality. A little bit, a different version of this also is used which is called superluminescent diode. We will discuss about this when we come to the characteristics. So, LEDs broadly have two device structure, surface emitting LEDs and edge emitting LED. The surface emitting LED further has different variations. For example, you see the typical display LED that we have, the display LED. What does it have?

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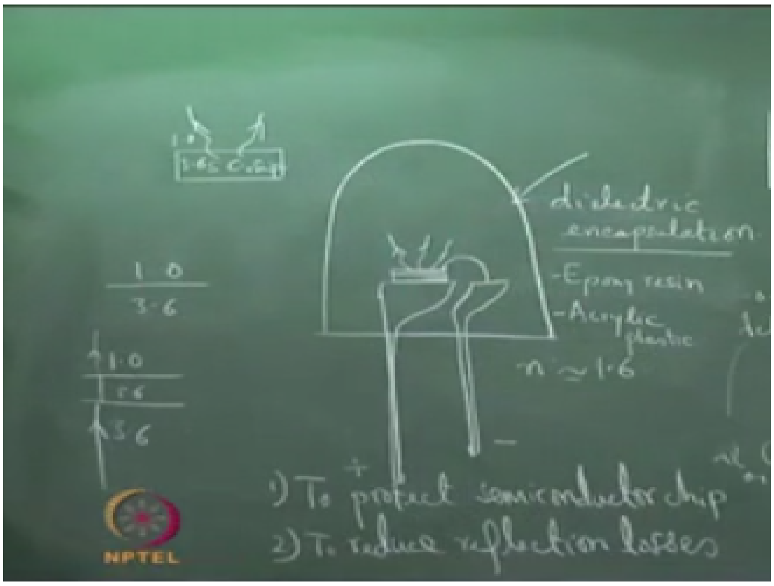

It has the chip, the semiconductor chip which is emitting light into the surface here, sitting on a metal electrode and another electrode here. The display LEDs that we have the cheap one the red colored LED, this has the contact. This annular electrode from the top, this is the semiconductor chip that I have shown here, the whole thing, which I have shown is this small chip here sitting and this is the lead.

Which is positive in this? The longer one. This is positive and this is negative. This is dielectric encapsulation. This dielectric encapsulation could be, this they used epoxy resin which solidifies epoxy resin or also acrylic plastics. Typically, the refractive index of this is of the order of 1.6 n of the outside dielectric. This is the display LED where this whole thing, please remember, I said that this is only 60 micron.

So it is a small chip that is this which is sitting here and this is the leads that you see and this is our typical display LED. The dielectric encapsulation helps one to protect the semiconductor chip; second, it also helps no explanation is required, right to protect the chip because it is a dielectric encapsulation, so to protect the chip from ambient exposure to air and damage.

So, it is now so (()) (47:26) that you can simply throw it, nothing happens because it is now protected fully into encapsulate. The second one to reduce reflection losses. What is this second part? Reflection losses. In this case, light was coming out here and you see, this still has of course there is a silicon nitride window, you can use the dielectric window, this will also reduce, but otherwise if you have a semiconductor chip.

Let us say this is the semiconductor chip from where light is coming, this is the sc chip, okay. I am not drawing again all the layers from where light is coming out to air and again it will meet this interface. There are reflection losses because you are coming from semiconductor 3.6 to 1.0, this is what the reflection loss that we were talking about. If you put the dielectric encapsulation, now it is like this.

Earlier we had 3.6 and 1.0 air interface, between 3.6 and 1.0. Now, we have 3.6, 1.6 and 1. If you calculate the reflection which is coming, so there is a light going from here, you find out the reflection that is coming with the two interfaces and one interface, you will see that the reflection loss is reduced. Here 32% is reflected, which means 68% is transmitted. You apply the same formula for these two interfaces this is not interference, because it is a bulk big layers.

These are not interference layers, not multilayer interference, this is bulk. But even in bulk, you first find out the reflection coefficient here. Find out what is the reflectivity? Find out the reflection coefficient here and take the product of the two. If r1 is the reflectivity here, r2 is the reflectivity, the net reflectivity will be r1 * r2, the product, you will see that this will be align almost 82%, put some numbers and see, the output here will be 82%.

Here output will be 68%. So, it has already reduced the reflection loss. So, the dielectric encapsulation helps into protect the chip, but also to reduce the reflection losses. So, this is the structure of the surface emitting LED. More of the details about what are the characteristics, how does this structure and the edge emitting structure affect the characteristic, we will discuss in the next class that is device characteristics. We have discussed the device structure, next we will discuss device characteristics. I will stop here.