Semiconductor Optoelectronics
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Lecture - 28
Light Emitting Diode-I Device Structure and Parameters

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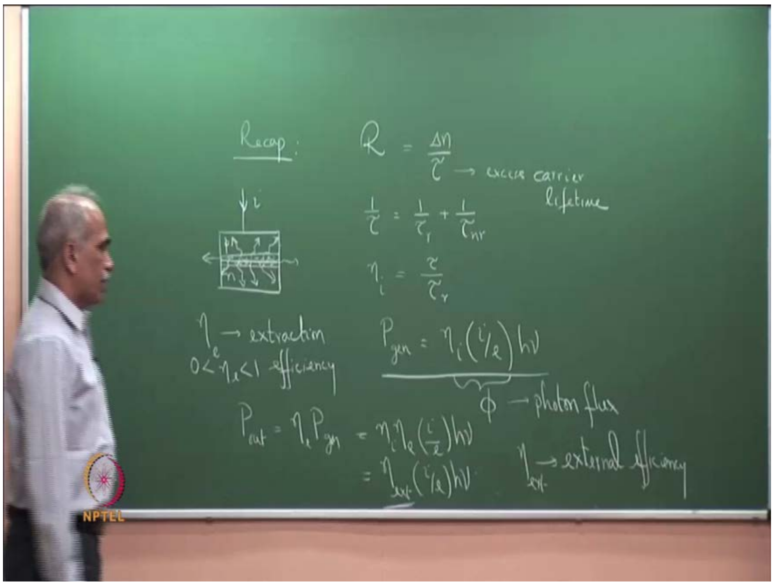

So, today we will discuss about the light emitting diodes the first device and second device, we already discussed about the modulator. Let me recall first what we have, we have rate of recombination which is given by delta n by tau, where tau is excess carrier lifetime. Delta n is excess carrier concentration, and this is rate of injection or weight of recombination. We also have 1 over tau is equal to 1 over tau r plus 1 over tau n r, tau r is the radiative recombination life time, and tau n r is the non-radiative 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 is equal to eta i into i by e into 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 by e is actually electron flux; i is charge per second, and i by 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 is multiplied by energy of photon gives you the optical power generated; this is the optical power generated. So if you take semiconductor here, a p n junction as I said easiest way of current injection is forward biased p n junction here. In the junction region, we know that in the junction region, we have recombinations taking place and light generated, so spontaneously recombination are taking place and light is generated. So, the generated light is coming out in all direction, because it is primarily spontaneous emission, because stimulated emission will dominate only when E f c minus E f v 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 refer to light generated, what is the output power, and the route when the photon is coming out when the radiation 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 equal to eta i eta e into P generated, have drop the optical, because we are talking optical power only, and therefore, this is equal to eta i eta e into i by e into h nu. This is the power output, where eta e is the fraction, so this eta e is less than one, is the fraction, fractional power which is coming out, out of the total generated power.

This quantity is written as eta external into i by e into h nu. This is called where eta external, is called 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 depends on the device structure eta e; that is what we will be discussing now, and eta e is the device extraction efficiency, depending on the structure, and eta external is called eta external efficiency. So, internal quantum efficiency and external quantum efficiency, external efficiency determines what is the power output. So, P out is equal to eta, so this is the expression that we need, P out is equal to eta external into i by e into h nu.

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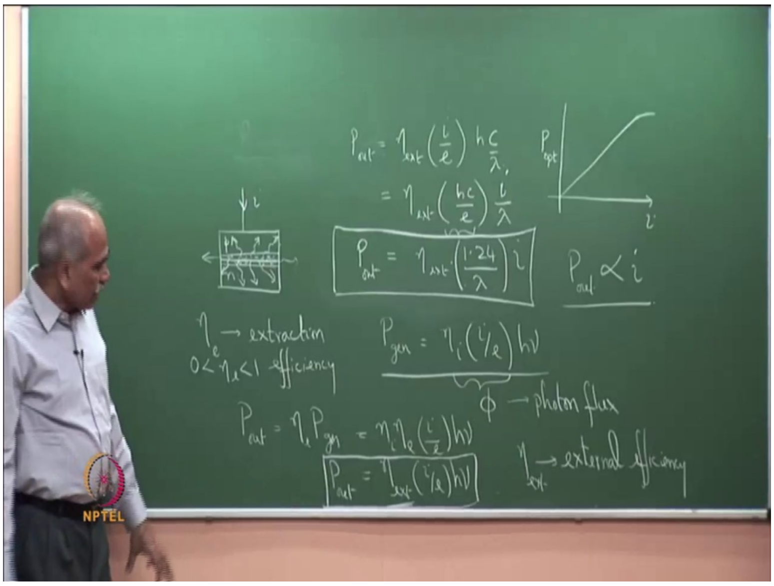

A little bit of simplification here, so p out equal to eta external into i by e, i is the current. And h nu i can write as h c by lambda h nu. So, this is equal to eta external into h c by e all are constant, plank's constant velocity of light and charge into 1 by lambda, i by lambda. This quantity, if you put lambda in micrometer, you can put all the constants, this will come out to be 1.24, so we have eta external into 1.24 by lambda into i.

So, P out is equal to eta external into 1.24 lambda by into i. An important point you see immediately, is that P out for a given device, it emits around a certain wavelength lambda here, so P out is proportional to i, which means as you increase the current, output power will go on increasing. As we will see later that, and some of you would have done this experiment; that if plot i verses p optical, p optical for an LED you get a linear variation like this, up to some current later on it becomes it gets saturates. We will discuss the reasons for this saturations and so on, but you can see the p optical is proportional to 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 the property of the material, eta e can be maximized by choosing appropriate device structure.

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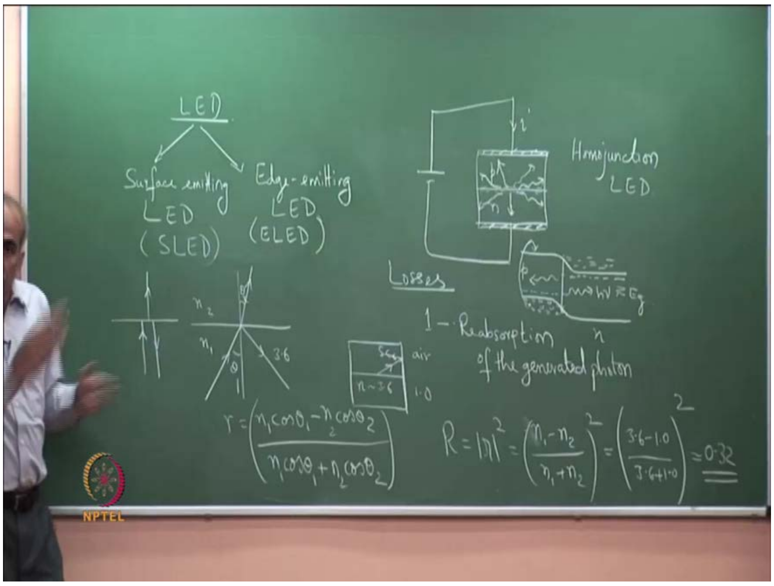

Basically there are two types of. The devices are broadly classified into two categories; one is called the surface emitting LED, and the other one the edge emitting LED. We will see the device structure, and depending on the applications one would choose either surface emitting LED, or energy emitting LED. There are further variants of these, but broadly LED’s are classified into two categories; one is. So, LED’s structure device structures we have surface emitting LED or this is written as SLED; surface emitting LED, and edge emitting LED edge emitting, which is called ELED. As the name indicates one of devices emits from surface, and the 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 you use surface emitting LED’s.

Whereas if you have applications where you need relatively collimated beam in one particular direction then you use edge emitting LED. Now let us see the basic structure of a LED, it is a p n junction, if you take a simple homo junction p n junction. The current i passed through this, a forward biased homo junction. 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 direction, is spontaneous emission; therefore, light is emitted in all directions. As light propagates if you take a homo junction, so homo junction LED; that is, it could be a p type gallium arsenide and n type gallium arsenide, and opt gallium arsenide homo junction. What you see is if I plot the bend diagram forward biased LED, so the E f c and E f v have split, so this is p type, and this is n type. I am drawing the bend diagram of the forward biased device. Recombination; there are plenty of electrons here, and plenty of holes here the holes here. The holes and electrons combined and h nu is given, we know this.

The energy h nu here is approximately equal to e g greater than or equal to e g, approximately equal to e g. The quasi fermi level, are in the junction region only, and the light is generated at the recombination majority. There are some recombination taking place here also, they are negligible compared to the recombination region which are taking place here. The combination is taking place here and light is generated. The generated light is now propagating through the rest of the semiconductor, beyond the active region. When it is passion through here, lets us say light is propagation like this, and electron which is sitting here. There are plenty of holes here, but still there are electrons also. An 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 reabsorption losses, so losses.

I am seeing, we have to first understand; that extraction efficiency eta e, it is less than one, so what are the factors which are contributing to that small value eta e. Ideally if eta e is 1 it was wonderful, generated all the generated light would have come out, but eta e is less than one. So, the losses are; first one, reabsorption of the generated photon outside the active region, photon outside the active region, as it comes out it can get absorbed, this is a major loss. What other losses can be think of. This diagram, let me draw it again here, so this is the junction region. Light is travelling in this direction, let’s say its travelling here. These are metal electrodes; light which is travelling here meets this interface here. This is an interface between semi conductor and sir 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 hence n is the order of 3.6. Outside refractive index is 1.0.

So, if take an interface, a ray of light which is incident like this. So, this is n 1, this is n 2, this is n 1, then a part of it will be reflected, and part of it will be transmitted. The fraction which is the reflection co efficient are r, is given by n 1, if you call this as theta 1 and this as theta 2, then this is n 1 cos theta 1, final reflection co efficient reflection, you would have studied in optics, refraction co efficient is n 1 cos theta 1 minus n 2 cos theta 2 divided by n 1 cos theta 1 plus n 2 cos theta 2. This is for one polarization, for the other polarization there is a small change. This is the amplitude reflection co efficient, and the energy reflection co efficient are, r is equal to mod r square which is equal to the whole thing which is square. For the simple case, you can see that you can put theta and find out what is the reflection co efficient? And the energy reflectivity; r is the reflectivity. The fractional power which is reflected back is r.

If you consider normal incidence like this, then theta is equal to 0, normal incidence then theta is equal to 0, and you will get n 1 minus n 2 divided by n 1 plus n 2, and the reflectivity r is equal to n 1 minus n 2, these are n not eta, so n 1 plus n 2 whole square. If you substitute n 1 is 3.6. So, this is 3.6, because light is coming from inside here 3.6, n 2 is air outside. So, if I substitute values 3.6 minus 1.0 divided by 3.6 plus 1.0 whole square, and this is approximately equal to 0.3; that means, the reflectivity is 32 percent, even for normal incidence, if it is an angle it will move. So, for normal incidence it is 32 percent. So, about 32 percent of the light, which is coming out, which is trying to come out, is reflected at this interface. So, first one is here, re-absorption losses, the second one is reflection losses.

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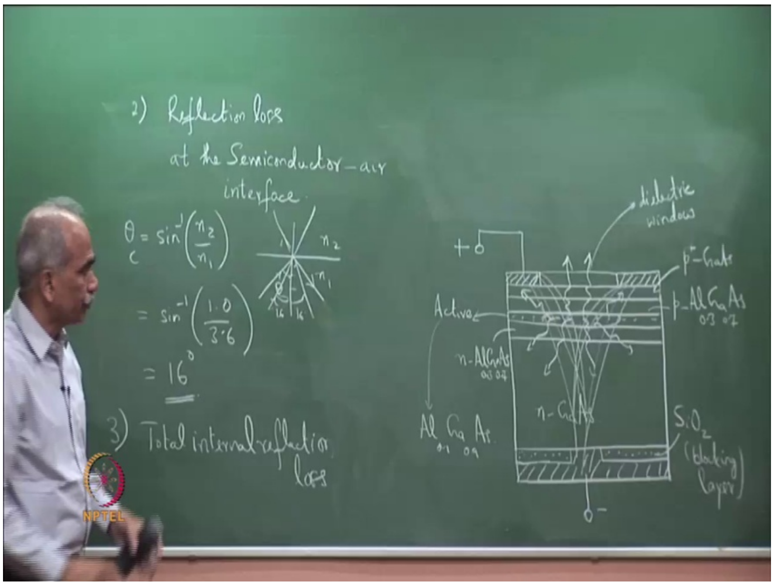

So, first one is re-absorption loss, second one is reflection loss at the semiconductor air interface. So, the light which is trying to come out, is again reflected back, only a part of it is coming out. Now more importantly you see, light is coming from a denser medium to rarer medium. This is the denser medium, outside is the rarer medium. So, there is a possibility of total internal reflection, and what is the total internal reflection. So, if light is incident like this at an angle theta, and this is n 1, this is n 2, then the critical angle theta c is sine inverse of n 2 by n 1. If theta e is greater than theta c then it will be totally reflected, there is not light coming out. So, light is trying to come out here, we saw that even if total internal reflection is not taking place, is signification fraction. Lets us say light was going like this, it is getting reflected back, and only small 68 percent is going out and 32 percent is coming back. Now I also want to see what is the cone with in which light can come out, what is this angle theta.

Look at the angle theta; theta c is equal to sine inverse of n 2 is our outside, so 1 divided by 3.6. This is 16 degrees, which means to the interface, here interface, if it makes an angle more than 16 degrees like this, a little bit more than 16 degrees 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 try 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 incidented the interface will come out, rest is reflected back, and this is the third loss which is called. Let me write the third one here; total internal reflection loss, at the semiconductor air interface.

As we will see some things can be reduced by having outside instead of air, if you put a epoxy 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 and everything is fine. There are additional losses if the material is impure, there are defects and there are also losses, because of carrier losses due to traffic. So, these are three optical losses that you see; re-absorption of the generated photon, reflection losses, reflection is not a loss as far as semiconductor is concerned, but as far as the user is concerned 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 wave guide you know that the light is getting guided by the 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 our. So, these are the three losses, major losses of the generated 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 losses, how to reduce this loss? These losses are reduced by use of double heterostructures. So, double heterostructures will significantly reduce these losses. So, today's LED's all structures are double heterostructures. The edge emitting and surface emitting LED's which we have today are double heterostructures. So, we wanted to discuss this before drawing the actual structure, so use of double heterostructure, so use of double hetero structures to minimize optical losses.

How would double hetero structure. So, first let me draw a structure, let me first draw structure of surface emitting LED, draw it along with me, then we will discuss about every layer, what is the purpose of this layer. This is n gallium arsenide substrate, on which a layer of n aluminum gallium arsenide is deposited, aluminum gallium arsenide, over which an active region 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 Al 0.3, I hope you can see this Al 0.3, gallium will be 0.7 arsenic, then this active could be Al 0.1, gallium 0.9 arsenic, 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 a 1,3 gallium 0.7. The numbers I am taking only as an example, this one, and usually above this there is a p layer. Let me draw this p, p plus 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 hetero structure, and how it is going to help us. This is Si 02 silica 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 minus and we have the positive contact electrode here positive, and this is a dielectric window. It could be silicon nitride; many times people use 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 we have taken a section of this. These are non conducting silica blocking layer, and here is the window. So, the carriers, when you forward biased, the carriers flow towards this, you see this; the carriers are flowing here like this. What I have shown, this is flow of carriers, electrons and holes flow of carriers, because there is no current which can flow here, there is a insulating layer silica. 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 recombination 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 it tries to come out in different direction.

First thing we see, is the bend diagram of the active region, so what I have shown is a typical surface emitting SLEDs; a typical structure. So, start with the n or n plus gallium arsenide. The n plus gallium arsenide with this metal contact forms a nearly good omic contact. The p plus gallium arsenide here forms a good omic contact this metal here. This is an annular electrode, it’s an annular electrode, means with a slot in the middle open slot from where light can come out, otherwise the metal will block the light which is coming out. So, it’s a annular electrode, please see the picture annular electrode, it’s a vertical cross section like. This is the substrate, starting substrate on which a layer of n aluminum gallium arsenide is deposited.

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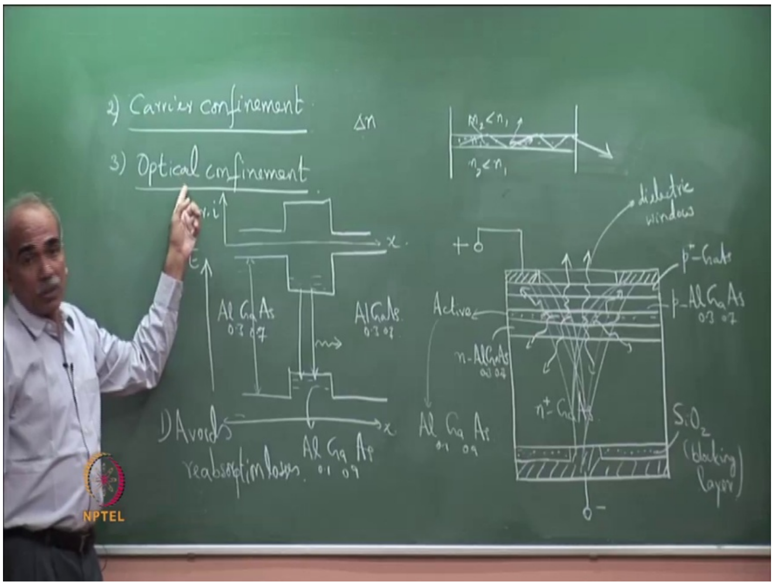

And therefore the band structure you have, is this, of the active region, I am showing the band structure of the double hetero structure. So, this is active region which is aluminum

0.1, gallium 0.9, and arsenide that I have shown here active. This is larger band gap, this is aluminum 0.3, gallium 0.9 0.7 and arsenic same here 0.3 0.7 and arsenic. Light is generated by recombinations which are taking place here. So, the photon of energy h nu which are generated here, as they come out they are seeing material, which has a larger band gap here. It has a larger band gap here, and therefore it will not be absorbed. So, the hetero structure, the double hetero structure, first point it does is, it avoids re-absorption losses. The top gallium arsenide layer here is very thin, in fact, in gal gallium arsenide it would get absorbed, but that is very thin layer p plus layer. So, this avoids re-absorption losses in the homo junction recall that outside everywhere it was, the same material and it could have been 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 bias, it the carrier density becomes very large in this area, you recall we had discussed the energy band diagram, and that time I had mentioned that one important advantage of double hetero structure, is carrier confinement, for the same carrier confinement is the. This is avoiding the re-absorption losses. The second important advantage of double hetero structure is carrier confinement, we have already discussed two times, so I am not again going into it. What it simply means is for the same given current. The carrier concentration is 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. 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 have to plot refractive index profile, it would have been like this. So, what am I plotting now refractive index r i, refractive index verses x. Here this was e, e verses x band gap variation, this is refractive index verses x, which means if I see this.

Let me show only the active region not 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 n 1 here and n 2 here, which is less than n 1, so n 2 less than n 1. 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, if what is the importance of double hetero structures? Double hetero structures have three important advantages, there are more in terms of design flexibility, but three important advantages. You can call this as one, this as two, and this as three or any order, but these are the three most important advantages of a double hetero structure; one carrier confinement two optical confinement, and three lower re-absorption losses, reduced re-absorption losses. This is a 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, so that the.

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 right, and that light cannot out, because the electrode is blocking. So, we want that 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 point whatever light trapped, which goes to the sides is a waste as far as surface emitting LED is concerned. So, the edge emitting LEDs structure looks like this.

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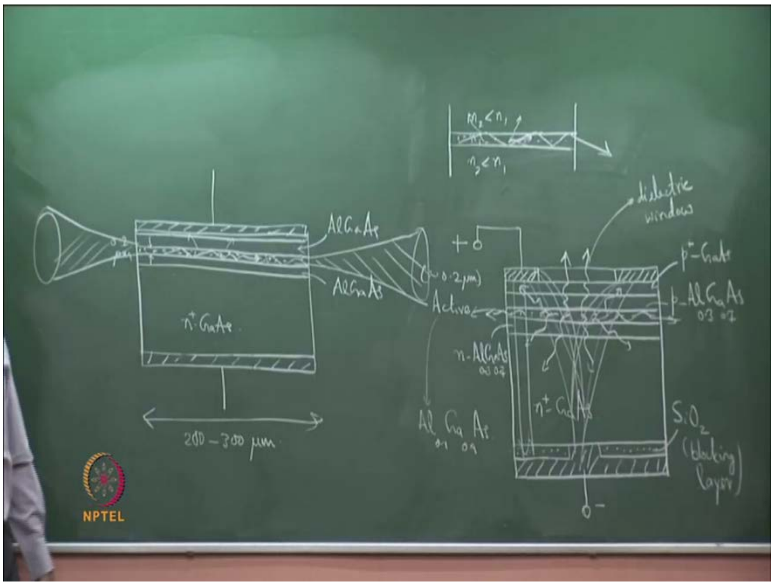

So, now you can draw very quickly, so we have the metal electrode, always minimum three layers are required to form the double hetero structure, so this is the active layer, the cladding layers, or the high band layers and the substrate and here. So, this is if you start with n or n plus gallium arsenide 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, we will discuss this separately, aluminum gallium arsenide. Right now I am choosing this we have already studied the details of this, 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 micro meters the substrate each of this layer, is the active layer is typically about 0.2 micrometer is the thickness of the active layer. The outside cladding layers are typically 0.5 0.6 micrometer, the outside cladding layers.

So, this whole thing is only 1 micron, this substrate is about 50 micron, the whole thing is about 1 micron. So, same thing here, length is here about 200 micron, this is 0.2 micron, 0.2 micrometer. In the edge emitting LED the light which is going out 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, that is not 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 all will come 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 etcetera a little later, when we discuss the device characteristics, but right now I am focusing on device structure. This is called an edge emitting LED, because the 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, optical fiber, and then you would like light to come directionally.

Of course, you will need 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, but directional. Surface emitting lights give LED over a wide range of angles. This is required for displace, 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 a 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 you are used as display LEDs on instrument panels, they are all surface emitting LEDs, because light has to come, so that one can see from sides also. But edge emitting LEDs have more directional output, more directional, it’s not parallel, because its already diverging, why it is 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 hetero structure LEDs, both the devices are double hetero structure, double hetero structure primarily to avoid reabsorption losses to avoid reabsorbtion losses. In this case the third property of double hetero structure, 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 super (( )) diode, we will discuss about this when we come to the characteristic. So, LEDs broadly have two device structures; surface emitting LEDs, and edge emitting LEDs.

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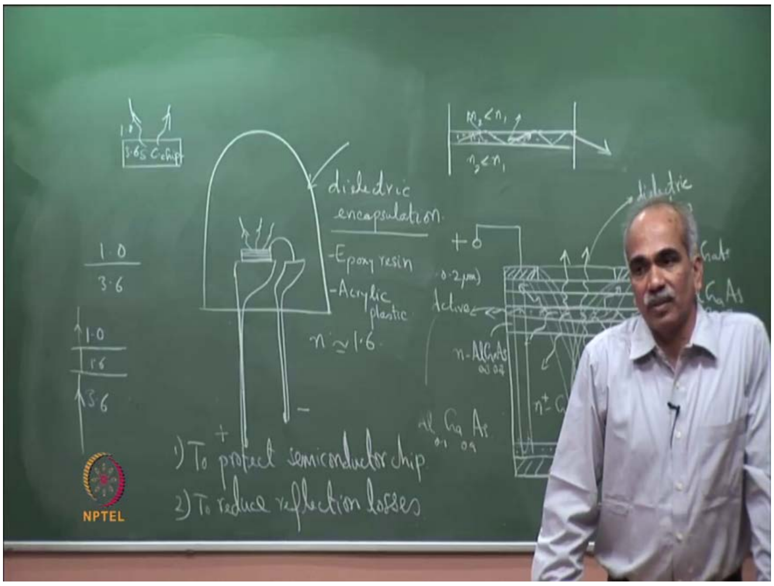

The surface emitting LEDs further has different variations; for example, you see the typical display LEDs that we have. The display LED, what does it have, it has the chip the semiconductor chip, which is emitting light into the surface here, sitting on a metal electrode, and another electrode here. The display LEDs the 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 has shown here, whole thing which I have shown chip here sitting, and this is the lead, which is positive in this, the longer one; this is positive, this is negative. This is dielectric encapsulation; this dielectric encapsulation could be this, the use epoxy resin, which solidifies epoxy resin, or all acrylic plastics. Typically the refractive index of this is of the order of 1.6 n of the dielectric, outside dielectric. This is the display LED, where this whole thing.

Please remember I said it is only 60 micron, so it’s very 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 chip, to protect the semiconductor chip. Second, it also helps no explanation is required right to protect the chip, because it’s a dielectric encapsulation, so to protect the chip from ambient exposure to air, and damage it is now so rugged that you can simply throw it, nothing happens, because now it is protected fully into encapsulated. 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 if you can use a 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 se chip, I am not drawing again in all the layers, from where the light is coming out to air, and again it will meet this interface, there are reflection losses, because you are coming from a semiconductor 3.6 to 1.0, this is what is the reflection loss that we were talking about. If you put a 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, so 3.6 1.6 and 1. If you calculate the reflection which is coming, so there is 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 percent is reflected which means 68 percent is transmitted. You apply the same formula for these two interfaces. This is not interference, because it is bulk 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 co efficient here, and take the product of the two, if r 1 is the reflectivity here, r 2 is the reflectivity, the net reflectivity will be r 1 into r 2, the product. You will see that this will be allowing almost 82 percent, put some numbers and see, the output here will at 82 percent, here output will 68 percent, 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.