Fundamentals of Semiconductor Devices

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Lecture - 52
LED: light extraction and design issues

Welcome back. So, we are discussing LED, Light Emitting Diodes. You remember in the last class I had introduced the concepts of efficiencies. External quantum efficiency and wall-plug efficiency which are very important terms in LED; we derived the expressions, I told you that wall-plug efficiency is always slightly lower than external quantum efficiency.

And most of the LED manufacturers will try to coat wall-plug efficiency only because that is what you are interested in. How much optical power you are getting divided by how much electrical input power you are supplying right. That quantity stays, that definition stays you know valid for all kinds of LED whether it is visible or UV,IR LED and so on. I told you what heterojunction, why heterojunction is important you know and different kinds of LED's that are there.

Today we shall discuss a little bit on the loss. What are the losses in LED because extracting light out from LED is a very important task and it is not very obvious that you will be able to get all the light out because of many loss mechanisms that take place. If time permits we shall also go through some electrical properties of LED's which is essentially a pn junction diode kind of a thing. But there are certain aspects, you know in LED that we have to take care when even we are discussing a p n junction ok. So, we will come to the white board here.

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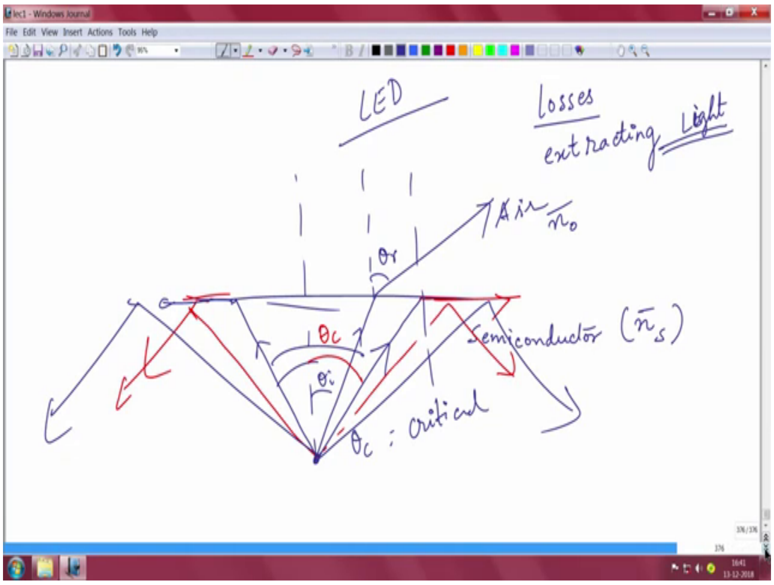

So, we have discussed the efficiencies and if you recall the last lectures, discuss the efficiencies and then also the recombination the bimolecular recombination rate. And I have discussed you know how the access carrier concentration is there important and for high level and low level injection.

The internal quantum efficiency is given by the ratio of the; you know the radiant non radioactive and radioactive life time sort of thing. So, all these things we have covered. So, today we shall discuss about an important thing and that is called the losses. Extracting light out, extracting light out from a LED is actually a quite difficult task. I mean, if you have an LED we will definitely we will be able to see glowing. If you have a blue LED or a red LED on a wafer of gallium nitride. A blue LED on a gallium nitride wafer or a red LED on a gallium arsenide phosphide wafer. You will be able to see that there is a red glow or a blue glow with your eye.

But that is only a fraction of the light that is emitted. You actually lose or a lot of the light. So, one of the very important loss mechanism you know, you will see very well is that suppose you take a case where this is your semiconductor. It can be GaN, a gallium arsenide anything ok. It is a semiconductor and this is your air; this is your semiconductor, this is your air.

So, if you think of light coming out from here from any of the point here, then you know there is a critical angle because there is a refractive index difference. This is a refractive index of n naught this is refractive index of say n s.

So, you know when the light comes out. When the light comes out within a critical angle, you know from high school physics that is it can come out with an angle of refraction like that right. There will be you know the angle here and then there is an angle of refraction here. The angle of refraction is larger because the refractive index of air is lighter, lower right.

So, at a particular critical angle, at a particular critical angle theta c, your light rays will get total internally reflected and above that your light ray will get bounce back inside. So, only those light rays can come out of the semiconductor crystal which are emitted within this angle of, you know theta c the critical angle. Because all the light rays emitted otherwise will basically get bounce back within the crystal and then this is I am talking about the top emission. You can also think of side and edge another emission. But essentially you are going to get emission within only a cone.

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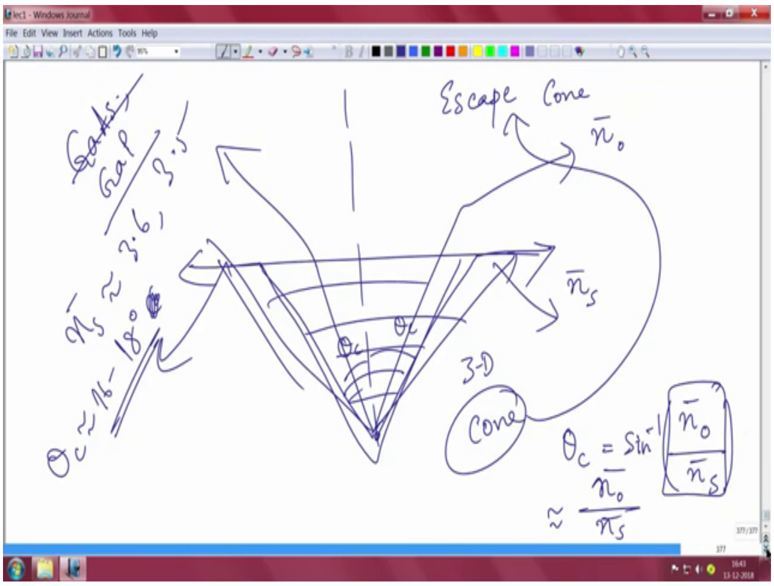

And that is called escape cone because the light can escape only within that cone you see my point. This is a semiconductor and this is your air, because of this mismatch in the refractive index, a light ray can only come out within this, within this angle. I mean this angle is theta c this angle also is a theta c of course. So, if you talk about a 3-D, 3-D visualization, this is a 2-D but if you talk about 3-D visualization, then this whole thing will be like a cone. That is call your escape cone because light can come out only within that cone. All the light that is emitted at a angles higher than that will actually bounce back within the substrate itself. So, that is a huge loss that you have actually. You recall that this critical angle, this critical angle is equal to sin inverse of the refractive index of air by refractive index of the semiconductor right. And if these quantity is small then you can almost write it as refractive index of air by refractive index of semiconductor.

So, you will see that actually for typical gallium arsenide for example, or gallium phosphide for example, this numbers this refractive index, indices are around 3.6 or 3.5. So, gallium nitride is also maybe 2.5 or so. So, the critical angle will be around 16 to 18 degree. What it mean, degree. What this means is that your light will be able to only come out within that angle. So, there is a large amount of light which cannot come out ever because of this total internal reflection.

That is a huge loss actually for your light right, that is a limiting mechanism for your light right. So, you know even if you have a wide band gap semiconductor on a p n junction even if you have a wide band gap.

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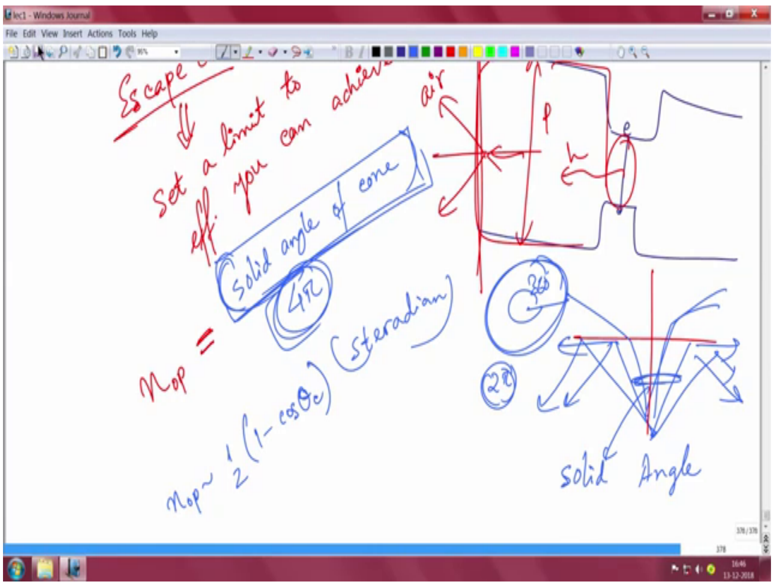

Semiconductor like that this is not the absorption when the photon electrons and holes are made, you know recombined the photons that is emitted the energy of the photon is less than the p type or n type layer. This absorption, this the photon will not get absorb in this layer there is different from this refractive index, refractive index is this is air, this is whatever.

So, at this interface it will get this refraction know. So, total internal reflection will basically limited. So, you know there is a loss and that escape cone loss; that escape cone loss will basically set a limit. It will set a limit to the efficiency you can achieve, to the efficiency you can achieve. So, that is a very sad thing because now you will lose a lot of light out there and. So, you call this efficiency of o p. That is the optical loss due to this critical angle this is due to this is total internal reflection because of light travelling from one media to another media. So, essentially you can think of this as the efficiency that is limited is that light is coming out within that cone right.

I told you there is a cone there right you know. The light can only come out to a cone be a after that light will not come out after that it will get bounce back. So, light will come out to this cone.

So, this cone basically is the solid angle. In a 3-D. you don't talk about single angle you just talk about solid angle in steradian. If you remember your 10 plus 2 maths. So, essentially that efficiency limited by the escape cone because most of the light will get reflected within inside and law with loss you know a very fraction of this will come out. This is basically defined as the ratio of the you know the solid angle; this defined as the solid angle of that cone.

Solid angle of the cone divided by the total solid angle of the; of a 3-D which is 4 pi steradian. Remember this is all in steradian, by the way 4 pi steradian is like the solid angle of a complete sphere you know like in how many direction just like in a 2-D. If you have a circle then the angle of the circle is 2 pi radian. Remember that 2 pi 360, 0 degree you know; this is 360 which is 2 pi. Similarly in 3-D in a sphere spherical thing you can think of the total solid angle as 4 pi. So, this is the solid angle of the cone with which is the light escapes.

This is only the light that will contribute to light coming out and then this is 4 pi is the total solid angle it. So, happens that you can do the math here. You know the math can be done and this comes out this n op comes out to be around half 1 minus cos of theta c. Theta c is the solid angle of the theta c is the solid angle of the this, sorry the critical angle of the of the semiconductor.

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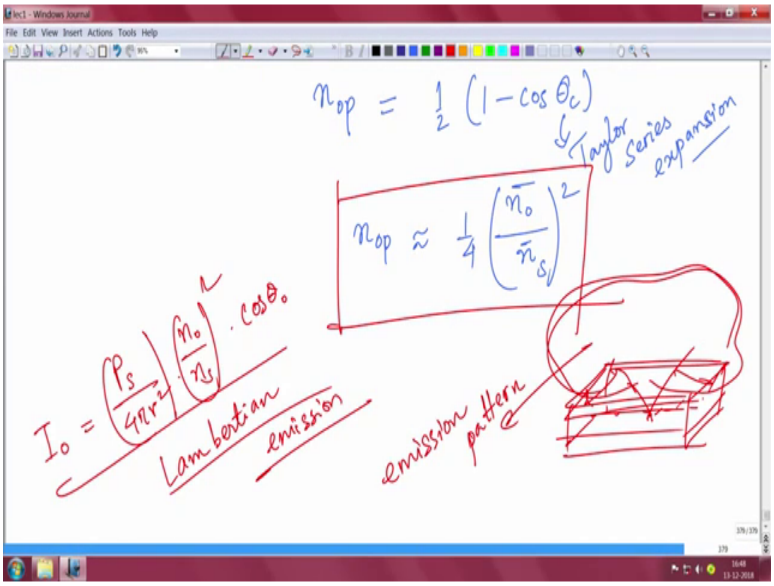

So, this n o p the efficiency limited by the of total internal reflection is half 1 minus cos of theta c. That is the limitation you will get actually and you can if this theta is very small then you can do a Taylor series expansion. A Taylor series expansion can be done if you remember your maths from your 10 plus 2 and maybe your undergraduate first year.

You can do a Taylor series expansion to do some approximation if theta c is low; then you will get n o p as equal to 1 by 4 refractive index of air divided by refractive index of semiconductor whole square. This is your efficiency that is limited by the escape cone. This is the efficiency that you will limit by escape cone [FL] and then if you take a planar structure you know if you take a planar structure like that this is your LED. For example, this is just like a planar structure [FL].

If you take a planar structure and that light is coming out and getting reflected whatever then there is an emission pattern light will come out in certain pattern know that is called emission pattern. Emission pattern, in what pattern is the light coming out because everywhere light will get emitted from every each and every point right and so if you look at that angle theta then you know you can say that the total light power, the intensity that is emitted is equal to the power the power that is emitted by 4 pi r square. r is the distance from the you know the wafer you can say point. And this is n naught by n s square the refractive index square into cos of theta naught; the angle theta naught is the angle at which you are looking.

Essentially in a way you can say that this is the emission pattern and the typical emission pattern is called a Lambertian emission pattern. Lambertian emission pattern; this is the pattern of emission of light from a planar LED; Lambertian emission pattern will come. Now, this is a huge loss by the way this efficiency that you are getting.

It is a; there is a huge loss that is you know because of total internal reflection and most of the LED's are planar. You know you have a wafer which is a plane right, it is not like a whatever thing, it is a plane and because of the planer wafer if you look at a 50 or 60 degree angle your intensity will drop by maybe 50 percent for example.

Now, how do you beat this problem; this problem of total internal reflection that is killing your effort.

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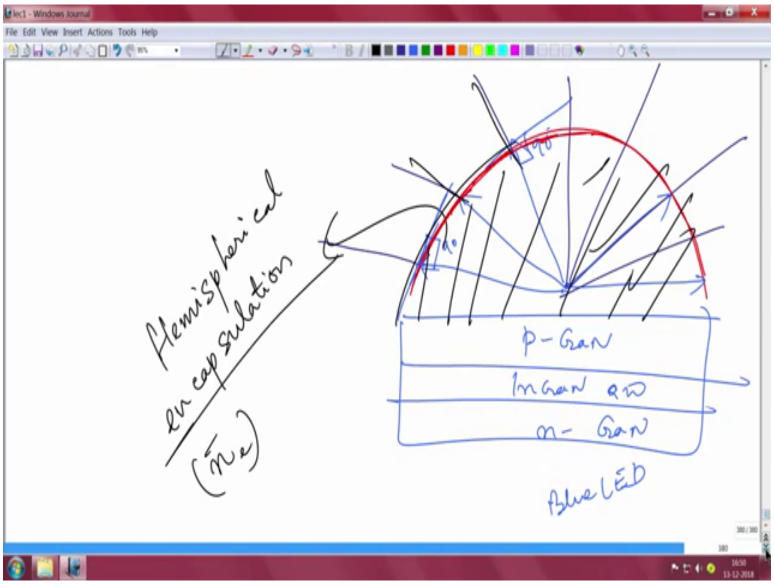

What you do is that you know this total internal reflection will not take place on a hemi spherical surface. Suppose I have a point light here then no matter whatever direction the light goes, no matter whatever direction the light goes in any direction the light goes what will happen. The surface of a sphere; if you draw a tangent; the tangent is always perpendicular to this radius.

At any point the tangent is 90 degree and if it is 90 degree then absolutely there will be no total internal reflection. It will come out straight; it will come on straight there will be no problem. So, what you do of course, it is impossible or almost very difficult to make an gallium nitride or gallium arsenide wafer which is spherical like this. So, what you do is that you have your wafer.

This is your p-gallium nitride, this is your indium gallium nitride quantum well, this is your n type gallium nitride, suppose blue LED what do you do is that you put a hemispherical coating like that. This is a hemispherical coating. There is a hemispherical cap. You can say hemispherical encapsulation; hemispherical encapsulation of a material whose refractive index of the semi spherical encapsulation n e for example, is absolutely adjusted so that you know you get minimum total internal reflection even with 90 degree here.

So, that there is no you know the perfect sort of thing and you will essentially able to extract it out like better. So, this hemispherical encapsulation is of course, given in commercial LED’s;. so that you you do not lose the light because of total internal reflection right, it will eliminate your critical angle limitation.

So, you put a hemispherical coating and this could be n e any polymer or any other kind of material that people can suitably you know figure out based on the application. And apart from this loss there could be also other loss you know in terms of; so light extraction is a very you know complicated business official light extraction.

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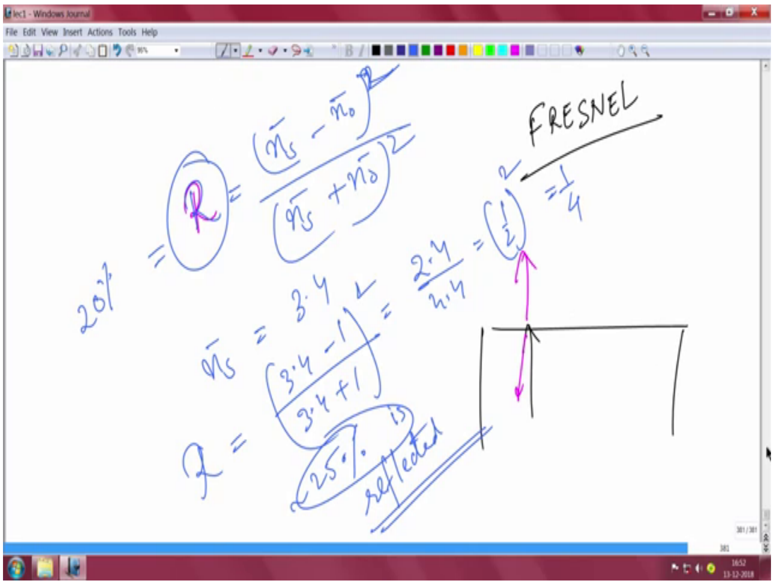

thus another loss and that loss is called Fresnel loss, s is actually silent Fresnel. You might have seen the Fresnel reflection. Whenever light travels from one medium to another medium there is a loss because of reflection at the interface. Light is coming out ven if it is coming out perpendicularly there is a fraction that will actually come out, a small fraction might get reflected.

So, the Fresnel loss is basically about a mismatch in the refractive index and so there is a reflection that takes place. This reflection coefficient the reflection that take place here can be said as semiconductor refractive index minus the air refractive index to which it is going square whole square divided by semiconductor refractive index plus a refractive index whole square [FL].

So, this loss; this is a reflex this quantity is reflected. So, whatever intensity you have this fraction of that diffraction, this fraction of this quantity can be say 20 percent if you put say n s of gallium arsenide is 3.4. So, what you can do is that the amount of light reflected at the interface of gallium arsenide and air will be 3.4 minus 1. Air is refractive index of 1. 3.4 plus 1 whole square. So, this is 2.4 by 4.4 which is almost like you know 1 by 2 which is square is 1 by 2; 1 by 4.

So, you can say that almost 25 percent of the light is reflected unnecessarily. I mean this is not unnecessarily, this is you something you cannot control. So, this is loss basically. Whatever intensity of putting of that 25 percent is loss because of Fresnel reflection.

They are waste actually reduce it by doing some kind of surface texturing, making the surface rough, anti reflection coating and all these things are more of the technologies associated with liar extraction.

So, those are important things that we should be aware of generally and then an LED is an electrical device of course. So, these are a loss mechanisms I have talked about. I will quickly tell you about LED as you know as a electrical device. So, I told you that any LED you can if you can simplistically think of this as a p n junction. The forward biased current even if it is a quantum well there will always be a forward biased current right.

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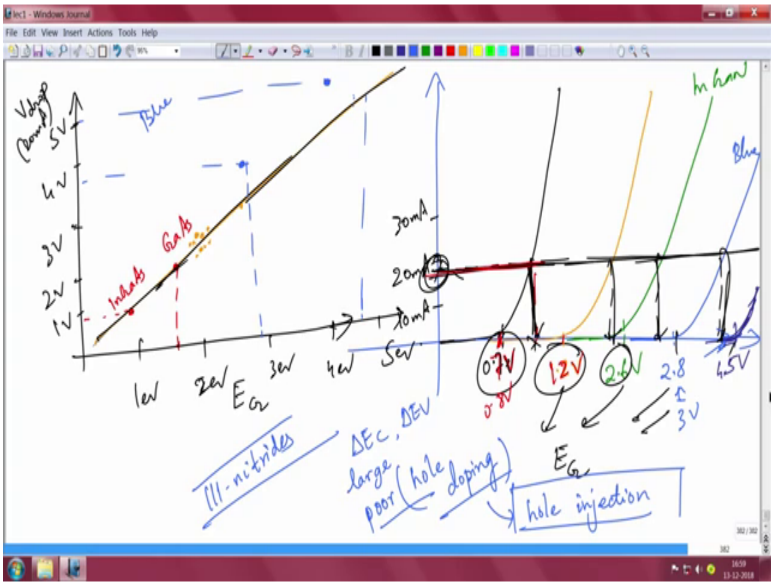

It can be quantum well, multiple quantum well, double hetrojunction who cares; they will always be there right. So, if you have a silicon for example, if you take just the silicon p n junction it is not an LED by the way you will forward current like this and this cut in voltage is probably around 0.7 Volt right. Then if you take gallium arsenide; you take gallium arsenide and the cut in voltage will be around 1.2 Volt.

You can take probably InGaAs you know; you can take InGaAs. It can be also less than that because you know it can be less than silicon InGaAs photodiode.You can take maybe you know In GaN green LED a green LED would probably be here In GaN green LED. The cut in voltage would probably be around 2.6 Volt or so and then there is a blue LED that is the blue LED In GaN classic blue LED that will be around say 2.8 Volt may be 3 Volt depends how good it is right DPUV LED I could not show it here DPUV LED.

A DPUV LED would be much more you know. Maybe 5, this scale is not correct may be 5 Volt. At 5 Volt only the UV will turn on or 4.5 Volt because the band gap is also high and so.

So, what you see here is that to get the same current say this is 20 milliamp 0. 20 milliamp is the standard that is why I keep mentioning that. 10 milliamp, 30 milliamp and all. So, to get say 20 milliamp of current for a lower wavelength light and LED you know blue, green and all; you actually have to apply a higher voltage to get the same because this cut in voltage all these cut in voltage depends on band gap E G. So, if your band gap is large which means the emission wavelength is low.

As you go low and lower wavelength green, blue near UV deep UV as you keep going short and shorter wavelength you are going larger and larger band gap. What happens is that you need to spend more energy. You have to bias at a higher voltage to get the same; to get the same current; injection current. To get same injection current you have to go to a higher voltage. You are losing more actually, you have to apply more voltage that is why you know you get you have to apply more electrical energy that is one thing. To get a UV or a blue LED.

You have to apply more electrical energy input than getting for example, a red or a orange yellow right and if you talk about this what is the voltage; if you have a constant area if you talk about all the devices having the same area so that there is no problem with the normalization of area. If I say 20 milliamp [FL]; for 20 milliamp of current how much is the voltage that I am dropping; as a function of band gap. So, on the x axis I have band gap of different material.

So, I have a band gap of 1 ev, band gap of 2 ev for example, band gap of 3 ev, band gap of 4 ev, band gap of 5 ev. And this is the voltage on the y axis is the forward voltage drop; this voltage drop is this is turn on, but I will talk about this voltage drop. This voltage drop at 20 milliamp what is the voltage you are dropping here; hat is the voltage your drop what is the voltage you are dropping for different LED’s.

So, I will call this is the forward voltage drop at 20 for getting 20 milliamp of current. So, this is 5 Volt, 4 Volt, 3 Volt; voltage 2 Volt, 1 Volt and 0. Ideally it should have been a linear line like almost like a linear line like that.

So, one to one correspondence 2 Volt [FL] you will get 2 electron volt and s on and so forth, but actually is not so easy. So, your InGaAs; your InGaAs will have a band gap of you know 1 point the if your emitting at 1.3 micron it is probably less than here. So, you will InGaAs get here this is InGaAs. So, it is less than 1 electron volt of band gap and you also drop less than 1 volt to get 20 milliamp.

You have gallium arsenide that 1.4 ev at around 1.4 ev your band gap is 1.4 ev you also have to drop around 1.4 ev to get the 20 milliamp because cut in is typically low for gallium arsenide. Cut in voltage the turn on voltage will be 1.2 Volt for silicon. It may be 0.7, 0.8 Volt, but the band gap is 1.1 Volt. So, at 1.1 volt you might be getting a actually 20 milliamp of current you following my point right, but the problem is these are almost on the line, but the problem is with green and blue with green and blue; with green and blue the problem is you will have to go much higher.

For example, you know for example, if I take about red and orange they will be in the range here only. All will be here 2.3, 2 point not 3 actually sorry ideally it should be like sorry ideally it should be like this. So, all your orange and yellow and everything will be a hovering around this point 2, 2.1, 1.9 and all this red and all right, but the moment you talk about green and blue you are going to have a little problem.

So, blue actually you know it will be here you should ideally get 2.8. Your; the band gap should be 2.8 or 2.9 electron volt, but you are in fact dropping more than 3 Volt for example, to get the same. Similarly you know algane at 4.5 Volt you should be able to get this 4.5 ev band gap, but you would have voltage that you have to drop is more than 5 Volt here.

So, typically III-nitrides for III- nitrides the voltage that you have to drop is actually more than the band gap equivalent band gap by q unlike l gas, n gas and all. The problem is because there is a problem in you know this in LED there is always a delta E c, delta E v because of the hetero structure these are called band discontinuities. And these are large in III-nitrates, smaller in l gas that is why when you inject a current this also play a role. This will limit the thing and also III-nitrates have a poor hole doping.

It is very difficult to dope them hole you do get hole doping, but that hole doping is very inefficient; that is why the efficient; the first demonstration of successful hole doping lead to the invention or the development of high efficiency LED which is why they got the obel prize. This hole doping is still very challenging it is done, but it is very poor, it is not 100 percent ionized. So, that is one reason and because of this poor hole doping, your hole injection is very difficult a very poor. And as you go higher and higher band gap l again for UV, DPUV your p type doping becomes worse and worse and. So, your hole injection suffers more and more and you have poor p type connectivity, poor p type contact. This is why you have to apply more voltage then what is needed theoretically to get the same in this input this milliamps of current.

Now, this is of course, you know generic LED that I was talking about, but I mean this is about the p n, but electrically there is also another important thing to understand.

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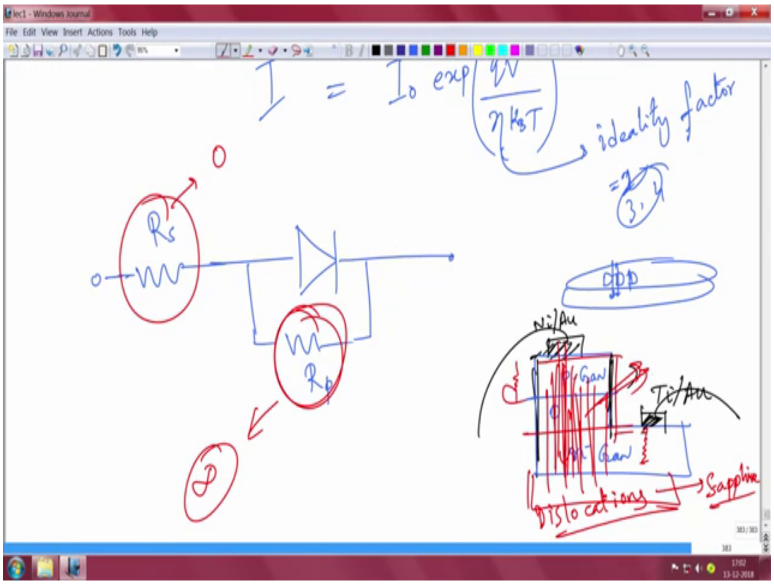

You see the idea it basically p n junction even if it is a quantum well or a double heterostructure; it is a eventually p n junction diode that you can explain the equation.

So, you can say that the diode equation holds true; ideal diode equation which is I equal to I naught exponential of qV by eta or nKT. This is Boltzmann constant this is of course, ideality factor if you remember ideality factor tells you how close to ideal diode equation your devices. If you ideality factor is 1, it means it is an ideal diode if it is true it means a one deviating its recommendation dominator. I told you in gallium nitride LED you can even have 3 or 4 if you have not done it well it can be even 10, 20 you know that is terrible.

If are you know for gallium nitride yeah your material quality is not good your ideality deviation will be there and you have a large ideality factor. Now, ideally a diode should be able to this is a LED of course, ideally a diode should be able you know you can schematically you can say this is the diode. But the problem is the problem is that there is always some series resistance; what is series resistance.

Series resistance is all the parasitic resistances in the contacts in the neutral p and n region. Those are extra voltage that you will drop there. So, this is a series resistance that comes and then there is a shunt resistance that comes. Shunt resistance is always in parallel. It basically is you know it is the dislocation or any other parallel leakage part; surface leakage you know like you have this LED wafer.

Suppose, this is your LED wafer on which your making many many LED’s is here, but the current will be top down flowing top down actually as I told you the way it looks like is that this is your p-GaN. For example, this is your quantum well and n-GaN and other things, this is your n type GaN. You basically make a contact on the top p-GaN typically with nickel and gold contact this is the metal then you etch down in (Refer Time: 23:33) in plasma chemistry you will etch down and you will come to n type GaN and can you make a contact here which is called which is typically titanium and gold.

When you apply voltage and this contact then the current will flow and essentially the emissions will come out from here the quantum well; the quantum well will emit. So, this is like a structure here and the current has to flow vertically, but the material quality of gallium nitride and you know such things is not so high.

So, you have a lot of material problems. So, you have dislocations going like this from the substrate this is some substrate that you have to grow sorry ok. I have clicked on something else here yeah. So, you have many dislocations coming out. This dislocations are basically missing line of atoms these are crystal imperfections and defects and because you grow on some substrate like sapphire or whatever right. There is no native gallium nitride substrate easily available.

So, because of this dislocations and all you can have leakage through this dislocations even if you do not apply you know even if you have a reverse bias; ideally your device should not leak, but it will leak because of this dislocations. These are like parallel paths you can think of these as like parallel leakage paths that will always occur that is captured by this. Ideally you would like this to be infinity; that means, the parallel path should have infinite resistance. Which means they should not be there; that means, the top down current should be dictated by the diode behaviour not this parallel path. So, you want this infinite do you need you want the parallel paths the leakage paths to infinite resistance which means current should not flow them any one the series resistance should be 0.

So, that no voltage unnecessarily drops across this series resistance or the contact resistance here right. This is the use useless voltage drops that you will have otherwise. Now the question is how will the ideal diode behaviour change in an LED in the presence of the series resistance and the shunt resistance you know it is important to know in general because we are discussing LED here.

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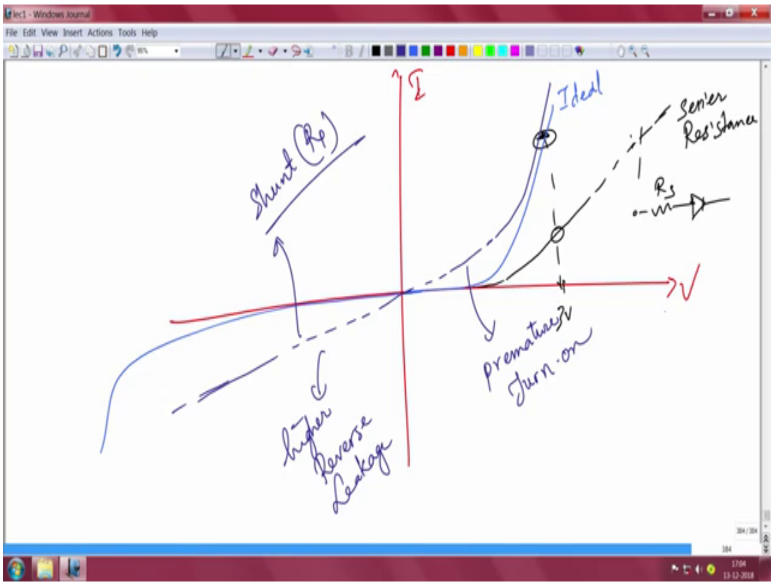

So, ideally I told you; know this is your I versus V what happens is that you know ideal diode equation should look like this. And then it should look like this; ideal diode equation ah, but in the presence of this thing what will happen is that your extra series resistance will dominate

If your series resistance dominates this extra series resistance that you are dropping then the of course, this is your ideal; this is your ideal. Then series resistance will dominate to, it will increase the resistance like this it will go like this is your series resistance dominating and this series resistance typically starts dominating when your voltage is high and you are having a large voltage drop across the series resistance. This excess parasitic resistance it will look like that. It will not affect the reverse bias, forward biased will be affected you will get low current at the same voltage say 3 Volt or 5 Volt you are supposed to get this value of current.

But instead you will get lower current because of the series resistance and now what about the shunt resistance. Shunt resistance is a parallel leakage part. So, what it does is that it increases the leakage; it increases the leakage even on the forward bias it will screw up your turn on; it will go like this which is very bad. It will screw up your turn on and you will have essentially a premature turn on; you will have a premature turn on; a premature turn on voltage and a higher reverse leakage higher reverse leakage.

So, these are the characteristics of your shunt resistance R p; shunt resistance. So, those also affect your devices badly. So, if you look at the circuit now you can actually find out the this is the p n junction things only, but in the context of LED I am talking about because you will see that in practical LED's these are important.

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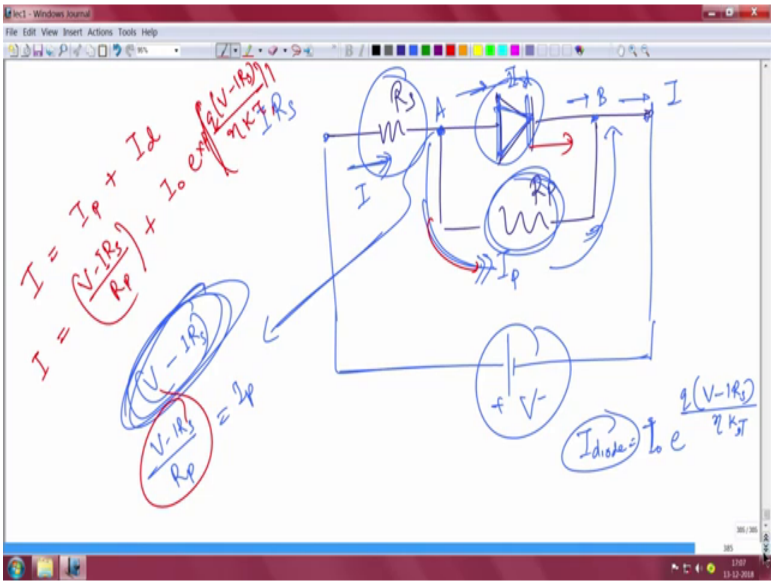

So, if you look at this circuit again this is your series resistance, this is your diode and this is your shunt resistance R p. Then if you have a current is going here. There is a current that is going here; some current will go through the diode, some current will go here through the parasitic resistance. They will again combine here and flow out here as I. So, you are actually applying a voltage here. Your voltage is applied here because this series and shunt resistance will always be there. So, if this is the current that is flowing here and this is the voltage your applying then the voltage that is dropping here is given by I times R S; that is the voltage that is dropping here. So, the voltage at this point A will be given thus the voltage at this point A will be given by V minus I R S;that is the voltage that is at this point right of course.

So, V minus R I S. So, this voltage actually between A and B the voltage between A and B that is dropping across the diode and across this shunt resistance is actually V minus I R SS and this V minus I R S if you divide by R P which is this resistance. Then you get the current flowing through here which is I P. You get the current right and you know your diode equation; if you recall your diode equation pure diode equation. It is actually the diode current that is flowing here I diode is equal to I naught which is the reverse saturation current e to the power; e to the power what; e to the power the voltage that is dropping across the diode which is nothing but this quantity.

So, that is q this quantity V minus I R S by eta KT. This is your current that is flowing through the diode. So, essentially what is happening is that the total current is equal to the current flowing through the shunt resistance which is I P plus the current that is going to the diode. So, the total current is equal to I P is this which is V minus I R S by R P plus I naught reverse saturation current exponential of q of course, q V minus I R S by n KT. Can you believe; can you see the point; let me write it on again.

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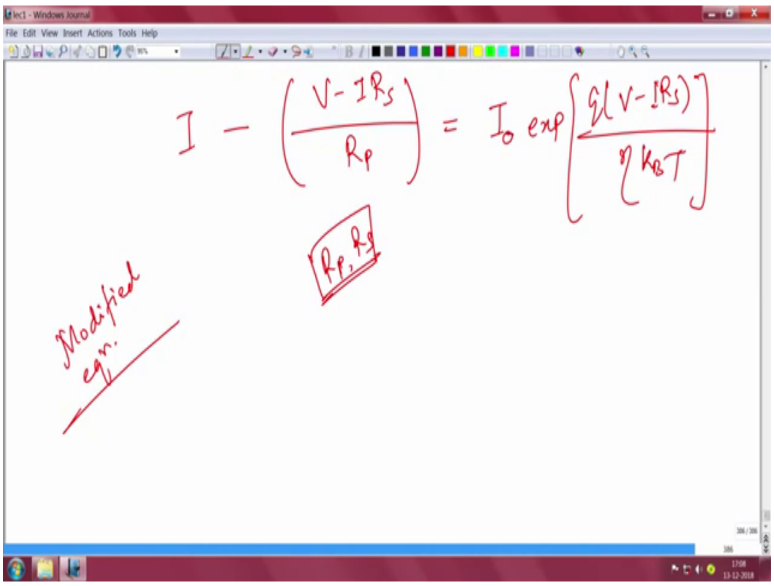

The total current that is flowing minus V minus the total current I R S by R P; series resistance and shunt resistance it is a; we want to find out the series resistance and shunt resistance, this is your I naught; saturation current reverse saturation current e to the power q V minus I R S by eta KT. This gives you the modified diode equation in the presence of series and shunt resistance.

This is your modified equation of the diode in the presence of series and shunt resistances because R S and I P are there. And you can actually find out you know this series and shunt resistances R P and R S can be found out from this equation by doing some fitting and other things. We will not going to the do that right now, but you can actually find out the series and shunt resistance from this equation if you do a fitting and you do some derivative and other things.

Those are part of the advanced you know syllabus; we will not cover them right now here. So, what we will do is that we shall wrap of the lecture here. We are almost done with most of the important aspects of LED. The electrical properties, the efficiencies, the escape cone losses and other things. There is a small portion of LED remaining at that we shall try to cover in the next lecture. And that is about the LED is that are visible which are which our eye can sense you know.

Then we can talk about brightness, colors, color rendering and chromaticity and other things. We shall try to briefly discuss those in context of white LED's or LED's that can emit light that are perceptible to human eye that because then that is a human eye related things.

So, we will talk about that a little bit and then we have few more lectures on transistors. We are again coming back to transistors; transistors on different aspects. That is the final concluding part of the course. Transistors for high speed application, transistor for high power applications, logic, memory and so on. We shall go through them little carefully so that you are aware which applications need what kind of transistors and what are the materials, what are the technologies needed for that.

What are the figures of merit, how do you compare one category, another category and so on. Those should be in a part of the curriculum because that gives an idea and calibration as to what kind of devices are used in the different applications in electronic gadgets that are around you. So, let us end the class here and the next class we shall quickly touch base upon sound the LED aspects with respect to visible LED.

Thank you for your time.