Introduction to Photonics
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Semiconductor Light Source and Detector: Light Emission

Welcome to yet another session of Introduction to Photonics so yesterday we started discussion on semiconductor light sources and detectors so we understood that carrier transport which is specifically important from the perspective of light emission and detection is different for semiconductors compared to what we have so far discussed in terms of dilute atomic systems. So we realize that there is something called conduction band and a valence band and we go to the point where we realize that you could have carriers being transported from the jumping from the valence band to the conduction band that is in the case of an electron jumping from valence band to the conduction band that put constitute a light absorption.

So if you have a light with energy greater than the band gap energy then that could get absorbed leading to a electron hole pair generation which we will come back and discuss little more detail when we get into semiconductor light detectors.

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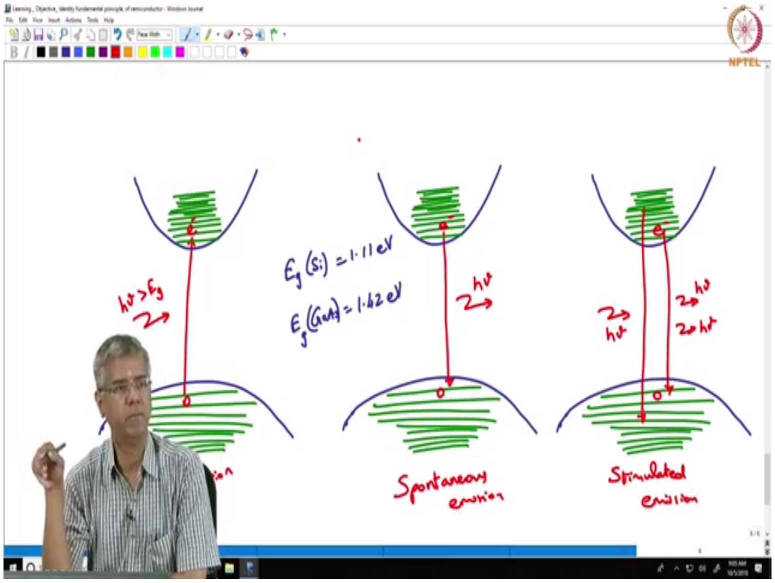

But for today we will focus on light emission and light emission essentially happens when you have an electron recombining with a hole so electron in the conduction band recombining with a hole in the valence band could lead to light emission especially if the band gap is much greater than the thermal energy. So typically we are looking at band gap energy is, for example I did not mention this yesterday for when we talk about Eg with the band gap energy for silicon it is about 1.11 Ev whereas Eg the band gap energy for Gallium Arsenide is about 1.42 Ev right.

So you have essentially you know light emission when this recombination event happens and you could possibly you know look at light emission also being stimulated so if you combine with photon with energy greater than the band gap energy and at those corresponding energy levels you have an electron and a hole then you can actually have stimulated emission ok, for example so I should emphasize the fact that there should be an electron and a hole present at those energy levels for example if you combine with H mu like this and that energy corresponds to let us say something like this and if you do not have an electron and hole present an electron present in the conduction band and a hole present in the valence band then this corresponding energy levels you will not have stimulated emission you will not have gain, you understand that.

So the presence of an electron in the conduction band and a presence of a hole in the valence band with and the energy level difference if it corresponds to this H mu then only you have stimulated emission ok. So let us now move forward and start looking at semiconductor light sources in a little more detail and we will start with talking about so what we will attempt to do today is to understand light emission in a semiconductor light emitting diode ok. So what do we need for that?

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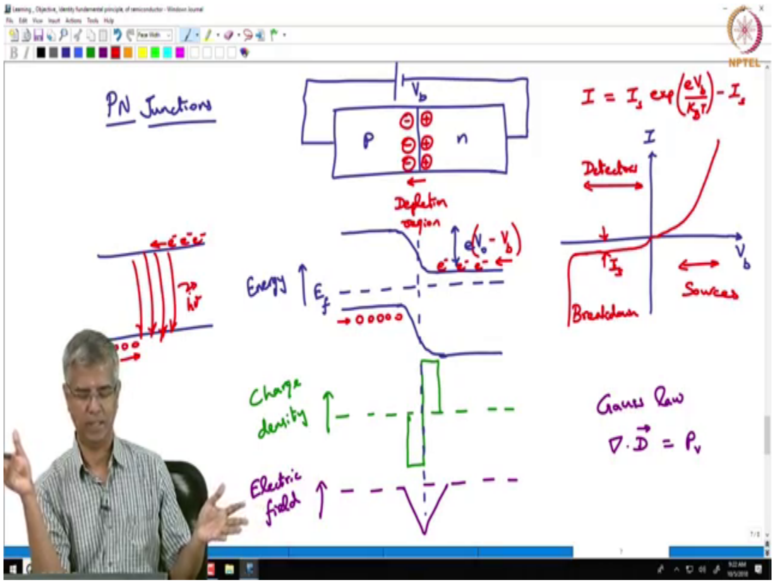

Well so far we have been looking only at P type semiconductors and N type semiconductors so now it is time to look at P-N junctions. Ok what if you bring a P type semiconductor and a N type semiconductor together ok so let us say you have a P type on this side and the N type on this side ok. Now we know that the P type the majority carriers are holes and the N type the majority carriers are electrons so the moment you bring them together you going to have electrons leaving from the N type semiconductor and that leaves behind some fixed charges ok with positively charged ions and similarly when the holes leave from the P side to the N side that is going to leave behind this fixed negative charges ok and since this are fixed charges and ofcourse you can say this are positive and this is negative then there is a small electric field that gets developed over there and since this are fixed charges that depleted off any mobile charges this region is called the depletion region ok.

So you have a depletion region where you do not have any mobile carriers ok and ofcourse you can also say that there is a electric field across that and correspondingly there is a potential difference that is developed across the junction ok so let us look at this a little more detail let us look at it from a perspective of the energy level diagram one of the things that happens is this way this charges will move across until two things happen one is that the Fermi energy on either side is going to become equal ok so that the Fermi energy is going to be uniform across a structure and the other is ofcourse you have a potential barrier there and which discourages further diffusion of carriers across the junction ok.

So those are the two things that happen so let us look at this a little more detail. First of all if we say on the N side if the Fermi energy is over here we know that the conduction band cannot be very far from that point so the conduction band and the N side is going to be like this and then you can say the valence band is somewhere over here right and similarly you will say that if a Fermi energy is like this on the P side the valence band has to be closed to that a Fermi energy and the conduction band is somewhere over there. So what you have here is a barrier that tis created this barrier here can be represented as the electronic charge multiplied by certain voltage V knot ok.

So ofcourse you can also look at the distribution of the electric field across this junction and to do that you let us say you are tracking the charged density ok so the charged density is negative charged density on this side and then it is growing upto positive charged density on the other side right so this is in terms of charged density right and just to make sure this is in terms of energy over here right and we know from Gauss's law so Gauss law tells us that whenever you have is fixed charges you have divergence of the electric field or basically you can just say del dot d equals to row b right the electric field divergence of the electric field displacement is given by the volume charged density and ofcourse the integral form of that will say that integral of d dot D L is going to give you is going to be equal to the charges present.

So correspondingly if you look at the electric field across this region so you have an electric field that goes like this so this is in terms of the electric field and this electric field this which corresponds to this built in potential acts like a gate so it basically says ok I cannot allow anymore diffusion of charges nether side you know beyond a certain point and the equilibrium condition is to quickly achieve when the Fermi energy on both sides are equal or uniform right so any question about this so far? Ok so that is a regular P-N junction now interesting things happen when you connect a voltage source external to this structure right when you apply a bias let us say first we consider a positive bias let us call this V b right.

So when you apply that positive bias it essentially means that it you are injecting carriers so you are injecting carriers you are injecting electrons from this side and you are injecting holes from this side ok. So what that ends up doing is it ends up actually also reducing the potential barrier so it will start moving the Fermi energy on either side apart such that the that barrier is reduced ok and ofcourse when the barrier height becomes zero that means there is a free flow of electrons from left to right and holes from sorry right to left electrons from right to left and the holes from left to right ok.

So essentially we will say that and ofcourse you can look at the converse also you can say that if my bias is negative which means that you have reverse bias then the barrier height becomes so much more that you do not have any possibility of the charges coming across going across the junction the electric field potential at that junction is further enhanced so it does not allow movement of charges so you would say that under reverse bias condition your diode does not conduct and the forward bias condition especially when you have a bias that nullifies the built in potential then you have a free flow of charges across this.

So that actually brings us to you know what do we expect when you know what is the current we get to see as a function of this bias voltage right and what we will see in this case is under forward bias conditions beyond certain built in potential you have a exponential increase in the current and the reverse bias you should not see much current flow but nevertheless there will be a very small current which maybe called as Is ok (this is capital I s) right and ofcourse you know you keep increasing that reverse potential then this two layers keep moving further and further apart I mean this you know the conduction band on either side is going further and further apart that you may start seeing tunneling phenomena happen.

So beyond a certain point you will have breakdown of your junction and so beyond that it is not usable right so breakdown happens but when you consider this normal operating range you can actually say that when you are tracking that current as a function of voltage you can say that this is going to be given by I s exponential of E times Vb over KBT minus I s and ofcourse that should be such that the expression should be such that at Vb equal to 0, I equal to 0 right so that is what we have here and when we have a very large reverse bias very large negative voltage Vb then the first term essentially goes to zero and then all you have is the reverse current I s ok.

So what we will see is for all our emission you need to have this carriers come across the junction and so that they can have a possibility of the recombining so the electrons are recombining with the holes right so in this region we will have all your sources operating and we will see that all our detectors are operating in typical in this region. So forward bias of a P-N junction if your band gap energy is much greater than the thermal energy then the forward bias can potentially give you light emission and the reverse bias maybe useful for light detection ok. Somehow those specifics we will look into that shortly any questions so far?

Ok so let us look at light emission, so it so happens that when you talk about light emission so when you are talking about recombination of electrons and holes effectively under certain forward bias conditions your conduction band and valence band are aligned and so you have all this electrons that are going from here and all this holes that are injected from here and then you could have recombination and you could have recombination events happening over here which results in light emission ok. But in this picture the problem is that, that recombination can happen anywhere there is no confinement of this carriers and once the recombination happens the light can be essentially emitted anywhere.

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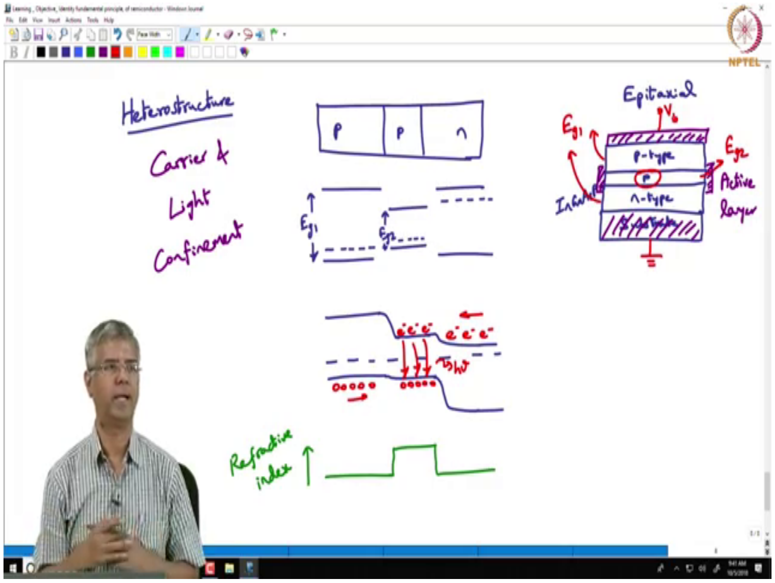

So there is no confinement of the light also, so to improve this to essentially have some sort of confinement of the carriers as well as the light you actually go through what is called hetero-structure so most of the practical light sources that you see actually involve one more layer ok which is typically known as the active layer so what do I mean by this? Now when a hetero-structure is when you have the P and N but you also introduce one more layer in between ok so what is different about this layer? Now this layer is going to have a different band gap energy right so we say with the band gap energy of the P in of this region and this region is equal right they have equal so we can call is Eg1 right.

So on either side there is Eg1 and ofcourse with the P type you say that the Fermi energy is going to be somewhere over here and with the N type the Fermi energy is somewhere over here but in this other material suppose you have a band gap Eg2 right suppose you have a lower band gap and ofcourse it is a P type so the Fermi energy is probably somewhere over here right. If you have that then what happens? Now ofcourse you say how am I able to practically realize this, is it like you take material it is a silicon you doped it with phosphorus to get an N type you take silicon another block of silicon you dope it with aluminum you get a P type and you take those two blocks and get them together.

No, that is not how it works right, so usually what they do is there is something called an epitaxial deposition that happens ok in this epitaxial deposition what you happen what you do is you take a substrate right you take one substrate which is typically a highly conducting material and then you deposit silicon on that ok and even as you are depositing silicon on that you also allow phosphorus to come in to get deposited also so you making the N type ok and then above that you are depositing so upto achieve a certain thickness which is typically in the order of few 100 nanometers or maybe even a micron and once you achieve that thickness then you stop that deposition now you continue depositing silicon but now instead of phosphorus you bring in aluminum.

So you deposit that P type layer on top of this that is what we call as epitaxial deposition. Now to do this hetero-structure what you are doing is let us say you started with (())(25:37) arsenide phosphide ok that is a quaternary semiconductor you deposit you know the gallium and arsenic the proportion of that if you change the proportion of tat the band gap energy changes ok. So you initially start depositing (())(26:06) gallium arsenide phosphide to make that N type layer and then you change that gallium and arsenic concentrations then you are actually and ofcourse the corresponding dope also and then you get a P type layer but with at different band gap energy ok the proportions were not going into the details but that just the idea right so you get different band gap energy and then on top of that you have another P type layer with the original composition itself right.

So the band gap energy is the same so this is what you do so you have N type you have thin P type and then on top of that you have another P type right. So what we are saying is this two layers here have one composition which gives you Eg1 whereas this layer has another composition which gives you a lower band gap energy ok. So that were your overall structure is going to be like this, this is just basically all this layers are sandwiched between two metallic contacts so you then you put a you deposit a contact over here and the substrate itself you may have a contact over here and then you have a possibility of connecting that to an external bias source and you have your light emitting structure or your detector also depending on what sort of bias you put.

Now what is the consequence of having a double hetero-structure like this, one thing you can say is once you put them together like this the Fermi energy once again is going to be equal across this and then what you see over here is there is going to be a step corresponding to the lower band gap energy and then there maybe a step over here corresponding to the N type and similarly on this side you are going to have this is the P type may have a small (())(28:55) here and then you going to have a large step over here so you have something like this ok we were to be perfect about this or more regress about this I would actually see how much of step I have taken here there will be a corresponding step over here right and then there will be some bump over here and similarly here also there will be a bump but for all practical purposes that does not serve much you know too much function so we might just take it like this.

Now what we are doing here is once again we are injecting electrons from this side holes from this side right so they travel upto this point and then what they see is this barrier so they cannot travel any further so that is like a wall over there. So they get injected they go upto a certain point and beyond which they cannot go anywhere else and the only possibility in that region where there is a huge density of this electrons and holes there is a huge probability of recombination happening in that region you understand that? So it gets everything gets accumulated essentially this P type region right and at that P type region does nothing else to do but to recombine between themselves the probability of recombination increases quite a bit in this sort of structure.

So then in this region you have all this recombination happening and because of that you have light emission ok and the added advantage of this structure is that when you look at the refractive index across this structure what you find is that when you have typically when you have lower band gap the refractive index of that region is actually higher compare to the other material ok so this is in terms of refractive index ok and what does tat tell you? If you have higher refractive index, it starts behaving like wave guide right it starts confining light in that structure ok. So this hetero-structure provides both carrier confinement as well as light confinement ok so this we will see so this is happening in this region which we are calling as the active layer.

So you have light emitted between that layer and also guided within that layer. Now that brings up another point of light is guided over that layer there is also a possibility of some other event happening, what is that? Your carrier confinement as well as light confinement so you have the possibility of stimulated emission happening because you have this carrier density the electrons in the conduction band and holes in the valence band and you have photons that are also guided in that region so you have a possibility of stimulated emission happens and that is exactly the principle that we will use in lasers where in either ends of the structure so on this ends if you put a mirror (())(33:44) if you put a mirror then you could have stimulated emission happening and you could actually build towards a laser.

So in some ways it is easier to get laser out of a semiconductor structure like this hetero-structure like this than get LED's so this is quite counter-intuitive you say for a laser you need to do this extra thing and all that putting the mirrors and aligning and all other no alignment is necessary you are basically just cleaning the material right you do this on a large wafer this days you can do it on a 8 inch wafer or maybe even a 12 inch wafer, you do it in a large wafer you build it epitaxially which actually takes a lot of time because we are talking about you know laying one atomic layer on top of another right it is a very-very slow growth but then you have done all of this you look at this each of this devices that you need is only like 100 microns in size ok.

So you can dice it up into that many pieces so with one of this you can get thousands of devices literally right one processing like this you can get thousands of devices and that is the beauty of doing t this semiconductor processing you do not have to do one cavity after another cavity you get thousands of this together and when you dice it right you are essentially making a flat cleave on both sides both ends of this material and the refractive index of the material if you talk about gallium arsenide it is about 3.4 so it is 3.4 in the material and one outside air outside.

So what do you think the reflectivity is going to be? It is fairly high because the huge contrast between the material thing so, naturally has about 30 % reflectivity on either ends so 30% reflectivity can essentially bounce off more photons within that active region and you can easily make a laser out of this. So if you are trying to make an LED your biggest problem is as you increase the current it starts raising ok and there is a big difference I mean when you are making an LED you want light to be spread out if you make a laser light is going just in very specific direction so it cannot use that lightening purposes.

So what you have to do is to take care of that reflection as an extra step ok so you may have to put some anti-reflection coating at the ends or you may have to frustrate that reflection by making that surface rough ok that seems counter intuitive you are talking about an optical surface and you want to make it rough because rough is essentially saying that light will scatter everywhere from that surface but that is absolutely ok because most of the LED application require light to be scattered over a wide region, more the better right. So if you if normally even when the light comes out it comes out only over some 30 degree angle or something now if you put some if you roughen the surface it scatters light over a larger you know range of angles and that is actually better for lighting purposes because it means it covers a larger region.

Even in that case people complain about light LED light being very focused and it is covering only this region (())(38:03) used to have your florescent lamp which is covering a much larger region and so on so you are having to put some extra defuses beyond that. I think there was a question somewhere back yeah.

Student: (())(38:17)

Professor: yes, that is true that is absolutely true that is a very good point the question is that the middle region which we are calling as the active region is actually having a different band gap which means that the emission is going one step beyond where we are right now but we will talk about this in a minute in a few minutes so the emission is going to happen at a different wavelength compared to what happens if you recombination happens on either sides and that is absolutely true and so this is the you start with that requirement you say I want to emit around

1.5 microns you find a band gap which that is your central active region which corresponds to 1.5 microns and you alter the doping that on either side the band gap energy is larger.

So that is the way you go about designing this structures, your target is your active layer right but you want on either side material with larger band gaps so that we can achieve this a carrier confinement as well as light confinement ok understand that ok so enough about structures and all that so let us go ahead and try to now you know put some current through this and see what happens. So what we are essentially talking about is let us say you can ground this and you can apply some bias to the structure what happens in that case?

What happens is clearly you know you have carriers injected into the structure and when carriers are injected into the structures they going to go accumulate in that active layer and then they going to start you know recombining and then you have light emission. So let us actually track this light emission as a function of the injected current ok.

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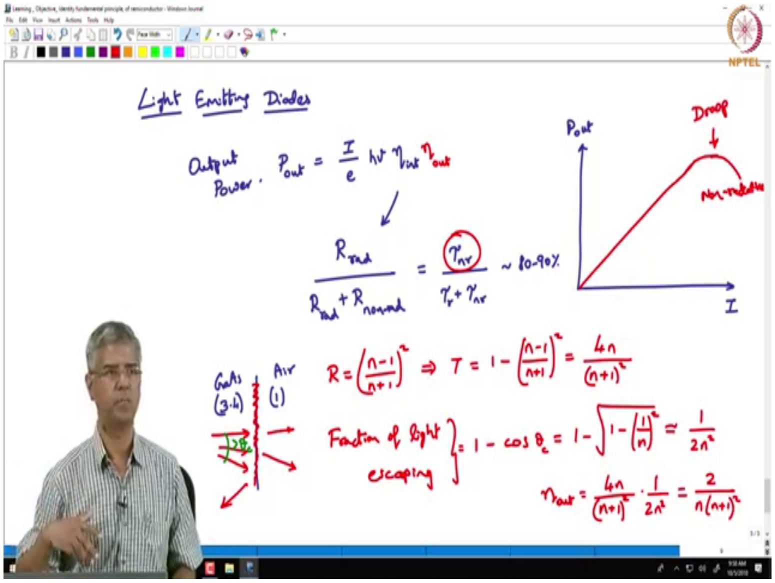

Light Emitting Diodes

Output Power. $P_{out} = \frac{I}{e} h\nu \, \eta_{int} \, \eta_{out}$

$$\frac{R_{rad}}{R_{rad} + R_{nonrad}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} \sim 80\text{-}90\%$$

GaAs (3.6) Air (1)

$$R = \left(\frac{n-1}{n+1}\right)^2 \Rightarrow T = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4n}{(n+1)^2}$$

$$\left.\begin{matrix}\text{Fraction of light} \\ \text{escaping}\end{matrix}\right\} = 1 - \cos\theta_c = 1 - \sqrt{1 - \left(\frac{1}{n}\right)^2} \approx \frac{1}{2n^2}$$

$$\eta_{out} = \frac{4n}{(n+1)^2} \cdot \frac{1}{2n^2} = \frac{2}{n(n+1)^2}$$

So what are the so we are now talking about light emitting diodes so what are the characteristics of light emitting diodes. So the first thing that we want to track is output power let us call this P out, how that output power changes how P out changes as a function of current that is injected into the structure. Now the rate at which you are injecting current will be I over the charge Q you could have put E also does not matter I mean so yeah we have been putting E as the electronic charge so that you can (())(41:52) consistent with respect to that. So I over E represents the rate at which current is injected into this region. Now this so that talks about rate at which carriers are injected into the structure and this carriers would have to recombine and give you light, light with energy H mu right multiplied by eta int so what is this eta int signify? Not every electron hole pair is going to give you a photon right somebody was asking yesterday what are the chances of non-radiative recombination.

Chances are low from the perspective of you know recombination of electron with a hole and not emitting a photon you know that thing is low but nevertheless you could have this electrons colliding with each other right because the carrier density is very high in this region so the electrons could collide with each other and they might (generally) generate heat and then through since they are losing energy as heat you know the you may actually lose that corresponding you know electron energy in the conduction band and so that would be a non-radiative mechanism because now you are not extracting a photon out of that those electrons.

So eta int can be defined as the total radiative emission rate over the, the overall rate at which the carriers are lost so that could be non-radiative mechanism also ok so R rad over the total rate at which carriers are lost you know represents this eta int and since the rate is inversely proportional to the time right so you can write it R rad as 1 over tau rad tau R let us call it and similarly the denominator is 1 over tau R and this is 1 over tau and R. so if you put that together you get this expression that this is going to be equal to tau and R over tau R plus tau n r right. Will just substituting R by 1 over tau so if you do that then you get this expression.

So it basically says that if tau R is far-far less than tau n r right then eta int is going to be equal to 1 right so that is the that is one of the advantages of this hetero-structure because what it essentially means is that you have this carrier accumulation which immediately says ok once the carriers are accumulated it can immediately recombine so the tau R can be much less than tau n r in this case. So for this hetero-structures you typically see that the values are relatively high and so this could be 80 to 90% or 0.8 to 0.9 as far as this in gallium arsenide is concern in silicon the story is different in silicon we understand that it is actually indirect band gap semiconductor, so there is no like direct recombination that is happening.

So that recombination would have to be associated with typically a (())(46:50) or a vibrational mode that take out that extra change in K the momentum and that means your eta int is much-

much lower ok the probability of radiative emission is much lower compare to the non-radiative emission in that case and because of that you know silicon material by itself silicon diodes P-N junctions diodes do not give you very good light emission ok so silicon what is your band gap energy correspond to?

You know we said about 1.1 Ev on 0.1 Ev would say that the cut off is around roughly around 1.1 electron or 1.1 micron so the emission would be you know lower wavelengths than that ok and so you could potentially get visible emission from silicon but the efficiency of that is very-very low because it is an indirect band gap semiconductor which results in this eta int being very small. So if you use gallium arsenide or if you want to get you do have this LED's right this visible LED's that is how we are getting this visible light so you ask what about this things because gallium arsenide is typically used for you know longer wavelength emission ok.

But for this things you use a material called gallium nitride infact a few years ago the Noble prize was given to the person that invented this gallium nitrate material called light emission ok so this are typically gallium nitrate based LED's which is actually once again a direct band gap semiconductor and because of which the radiative efficiency so much higher ok. So that is one part and this constitutes the total power that is generated within that structured within that hetero-structure ok but not all the power escapes the that structure, why? Because if you look at what happens at this interface right this is the interface between let us say this is gallium arsenide this is air ok.

Gallium arsenide as 3.4 refractive index, air has 1 refractive index so when light is incident on this there is going to be refection right not all of that is going to go through there is going to be reflection at that point that reflection that reflectivity is going to be given by n minus 1 divided by n plus 1 the whole square right that is going to be the reflectivity. Like I said if you n equal to 3.4 and you compute this tat will probably come out to be about 30%. So this implies that the amount of the fraction of light that transmitted is given by 1 minus n minus 1 over n plus 1 the whole square which approximately be equal to, no it is approximately it is equal to 4n over n plus 1 the whole square ok.

So that is the fraction of light that is transmitted not only that we say ok if you have some off axis sort of emission that will also refract and go out like this but you keep looking at larger and larger off axis angles and especially at off axis angles greater than the critical angle then what happens? If you have such a ray that is greater than the critical angle it be totally internally reflected right it won't escape that material so it will be totally internal reflected within that material itself and you won't see the light come out of that. Now if you look at the fraction of light escaping that would correspond to 1 minus cos of theta c ok.

So that would be the fraction of light that is escaping and this is cos theta c can be written as route of 1 minus sin square theta c and sin theta c is nothing but 1 over n right so this is root of 1 minus root of 1 minus 1 over and the whole square ok which if you do the math you will find that it is approximately equal to 1 over 2 times n square ok. So you have a certain reflectivity and the other part is the total internal condition allows you to only you know send out fraction of the light that is emitted so if you put both of the together you get this other factor eta out where eta out is given by 4 n over n plus 1 the whole square multiplied by 1 over 2 n square and that is equal to 2 over n and n cancels so n multiplied by n plus 1 the whole square ok.

So only a fraction of the light that is emitted is actually coming out of that structure ok and that fraction if you substitute n equal to 3.4 that is 2 over 3.4 multiplied by 4.4 square so that could be a very small percentage just a few percent right, so it is only a few percent of light that comes out of the sting normally so that is where we are saying that we will have to you know put some do something at the interface to frustrate the reflection you can frustrate the reflection you cannot do a whole lot about this total internal reflection condition ofcourse you can say that I am going to make this (())(55:19) so the total internal reflection condition also may be you can frustrate that right and then you can have more light emission.

So those are some of the things that are done for this practical light sources but overall when you look at this entire thing you will say that your output power is going to be increasing linearly as a function of as you increase your current and that is what you doing in the lab session this week and upto a certain point beyond certain point you will see some saturation and maybe even you know the power going down this is a process that is called droop ok and that is the process that limits eventually the amount of light that you can get from LED(())(56:21) people talk about going upto 8 watts, 10 watts LED's are available but this are typically multiple LED elements each LED element you know maybe only you know less than a watt and that is because as you go to very high carrier densities in the recombination region the active region they end up colliding with each other and so they generate lot of heat rather than light ok.

So your non-radiative this thing is more possible than the radiative even beyond that points so because of that non-radiative process is dominating there you will start seeing actually the power is dropping beyond the point and it might end up melting the junction also at that particular point of the heat is not taken out properly ok. So let me stop at this point what where we are going with this is beyond this we will look at the modulation characteristics of this light emitting diodes and also the spectral characteristics of this light emitting diodes so will do that before we jump on to laser diodes next week ok, thank you.