Semiconductor Optoelectronics
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Lecture - 32
Light Emitting Diode-V
Materials and Applications

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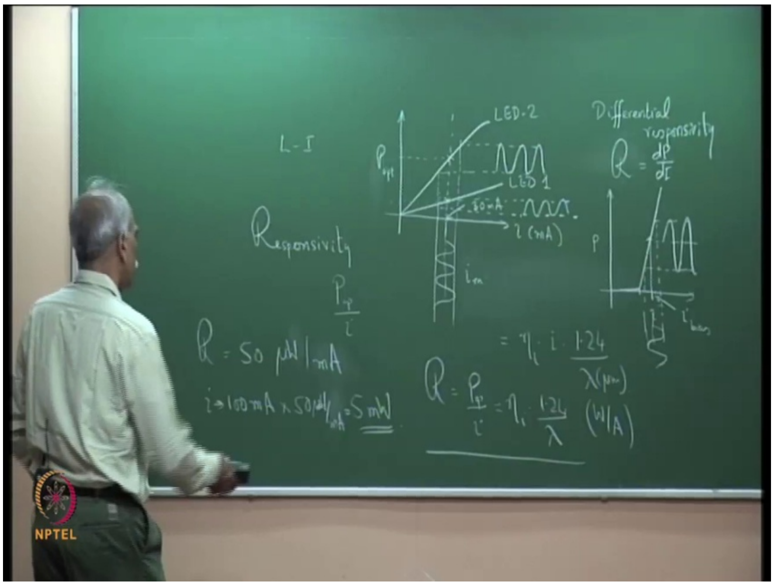

Today we will discuss materials and applications, last of the lectures in light emitting diodes, but before I proceed just a couple of points from our last lecture's, we had a L-I characteristic light current characteristic, we have discussed this in detail. There is a parameter, which is usually used to characterize an LED and that is called the responsivity. Responsivity is simply defined as P optical is divided by current i. We have an expression we have derived an expression P optical is equal to eta i into i by E into H nu which turned out to be eta i into i into 1.24 divided by lambda in micrometers.

So, the quantity P by i, responsivity equal to P by i, say optical power by i equal to eta i into 1.24 divided by lambda. The units are optical power by current, so watt per ampere. We will later on see a similar responsivity for detectors, which will be amperes per watt. So, it is responsivity, because if you pass a current i what is the optical power generated? So, typical numbers like responsivity is let say 50 micro ampere per watts per milli ampere per sorry 50 micro watt per milli ampere, typical numbers micro watt per milli ampere. What it means is, if you pass, let say you pass 100 milli ampere, if you pass 100 m A, if i is equal to 100 m A, because this is nothing but P opt optically divided by current. Therefore, responsivity equal to 100MA into 50 micro watt per milli ampere. So, you have 5 milli watt of power.

So, the optical power output is 5 milli watts if you pass one hundred milli amperes. One hundred milli amperes of current multiplied by the responsivity 50 micro watt per MA which is 5000 micro watt, which are 5 milli watts. Usually it is linear we operate in the linear region. This responsivity is an important parameter in modulation applications for example; you may have a LED which as i, P curve like this. So, this is P optical power P optical and this is current i in milli ampere.

A particular LED1 may have responsivity like this so, this is LED1and this is LED2. This important for a design engineer because to get a certain amount of optical power what is the current that he needs to pass. Accordingly, he has to design rest of the circuit and therefore, you will see if you take data sheets of LED's there will be a parameter called responsivity, it is simply nothing, but this we have already derived this.

So, P optical divided by current. So, if you have a 2 LED's with different responsivity, here it refers to slope, because i by P everywhere, because it starts from 0 it is the slope and therefore, if you choose an operating current here let us say some operating current here let me say this is equal to some for example, 30 milli ampere or 40 milli ampere whatever, some current then the Q point for this LED's is this one and Q point for this LED, that is the operating point is here.

So, the output powers are here, but more importantly from a modulation point of view, if you non-modulate this LED, with whatever signal if you want sinusoidal, you can modulate with a sinusoidal signal, which means you are superposing on the bias current 30MA is the bias current, a signal a current variation im so, modulating current this is i bias biasing the LED at in the linear region, a Q point and if you modulate this you can see the corresponding optical variation is here. So, the optical power varies here, because this axis is optical power. So, when the current is varying this much that is, the variation in the current is so, much you can see the optical power is varying.

Whereas, the same current on the second LED, because the slope is higher, the depth of modulation in this case is larger. So, if the responsivity is higher, the depth of modulation is larger. We will see a similar parameter later on when we deal with the laser diodes, a laser diode has characteristic, that usually up to a threshold the power output is very little and then you have a linear characteristic, P optical divided by I for a laser diode LD. In this case here its starts from 0 therefore, responsivity is sufficient to identify what kind of modulation that you get, in this case usually one defines a differential responsivity, because it does not the optical power is not linear from here and therefore, you bias it somewhere here this value of current is i bias and then you apply a modulating signal.

So, you can see now that the modulating signal is here, and what is the variation in amplitude? Variation in amplitude is very large. in the case of a laser diode because this slope is very large. So, this is in a laser diode it is characterized by differential responsivity, which is defined as R differential responsivity is equal to dp by di that is the slope of this curve. Whereas, in the case of a LED simply responsivity is sufficient to identify the modulation depth, in other words, if you want a higher depth of modulation you have to choose an LED which has a larger slope.

Which is true, in this case also, but here we have to talk in terms of differential responsivity, because the current does not the optical power is not linear from here, but it is linear from here. we will discuss about that a little later. So, this is one parameter and one other parameter which I had briefly mentioned, but not discussed is the total light conversion efficiency, or the wall plug efficiency, that is given some amount of electrical power applied to the LED.

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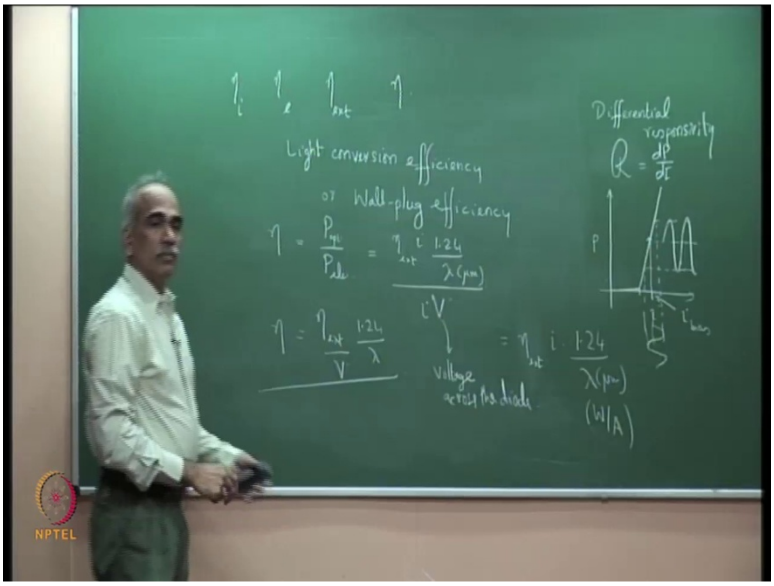

Light Conversion Efficiency or Wall Plug Efficiency: eta without any suffix is the total conversion efficiency, till now we had eta i, eta external, and eta e extraction, and so on, but this is just eta, wall plug efficiency, which is equal to P optical divided by P electrical. So, P optical is eta i into i 1.24 divided by lambda. Correct the expression eta i as an eta external, which contained extraction efficiency. So, this is external quantum efficiency, recall that the product of eta i into eta extraction efficiency we called as eta external. So, this is divided by i into V, where V is the voltage across the diode. iV, current is the same So, this i cancels off, and you have this equal to eta external 1.24 or you could keep the HC by E 1.24. Typical numbers we had several etas recall eta i, eta e eta external and finally, eta. Internal quantum efficiency, extraction efficiency, external quantum efficiency, and the wall plug efficiency.

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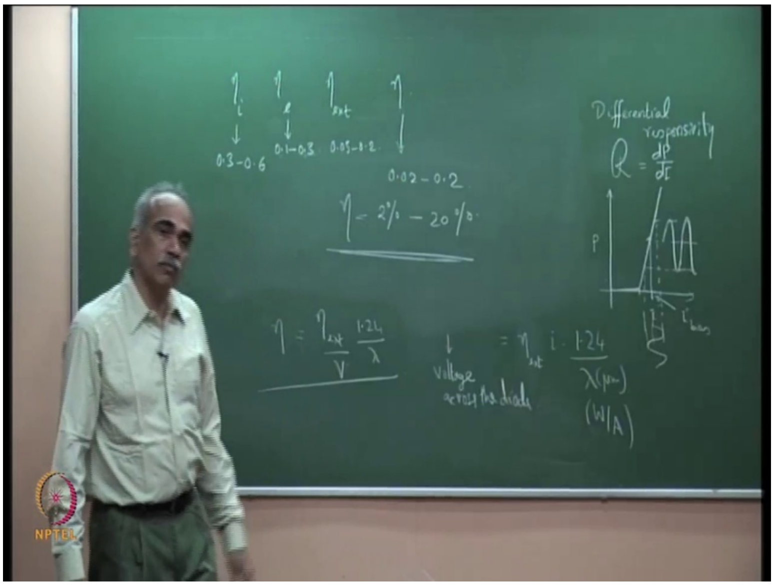

Typical numbers for eta i is 0.3 to 0.6. Typical numbers internal quantum efficiency about 50 percent for gallium arsenide, and depending on the material typically, extraction efficiency is typically 0.1 to 0.3 by texturizing you could go up to point three. So, this depends on the device structure, this depends on the material, this depends on the device structure, this is simply the product of these two, and you if you take product you can see this will be 0.03 if you take the lowest, and if you take these it is about 0.2,0.18 or 0.2. So, typical numbers are 0.03 to 0.2.this eta is very close to eta external almost equal to this and therefore, that means, in general that this eta is approximately 0.02 to 0.2, or the overall conversion efficiency is generally from 2 percent to 20 percent this is a very good efficiency.

Over all conversion efficiency is generally 2 percent to 20 percent for LED’s. laser diodes as we will see later have much can have much higher efficiency 50 percent, 60 percent electrical to optical conversion very efficient devices. We just quickly go back go to applications and material. It is the applications which will determine what material of led that you need to use there are large number of applications.

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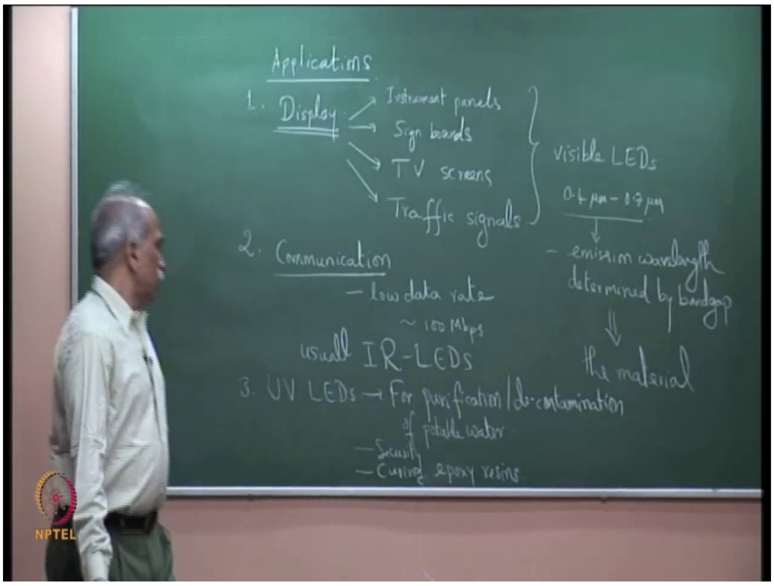

Let me first list the applications and then we will see what the most important application of led? So, applications are,

Display: Display on instrument panels. For example, display of sign boards, sign boards we will see, although sign boards running sign boards in air ports, even in our institute sign boards, TV, these days LED TV’s which have TV screens and traffic signal. Most of these are all visible LED’s, in other words we need visible LED’s, why this part was required? Because now the wavelength of emission should be visible to the eye, which means we are interested in 0.4micrometer to 0.7micrometer. The emission wavelength is determined by the band gap of the material, and so, the emission wavelength determined by band gap hence, the material that is why I had linked this topic applications and materials or materials and applications.

Communication applications: Usually low data rate, including fiber communication using multimode fibers, light emitting diodes with multimode fibers form low data rate communication systems. The advantage is it becomes very cheap because, LEDS are not that sensitive, that laser diodes are very sensitive to temperature variations therefore, when you make instrumentation, it is much easier, and much cheaper cost effective, if you use a L ED. So, low data rate low data rate means up to about 100Mbps. you can go up to this. It is not low, does not mean very low, you can go up to this 100Mbps, but usually 1Mbps, 10Mbps, local area networks, within the building, it is very easy to use

LED’s with optical fibers, multimode optical fibers, the connectors are very cheap they are much tolerant to temperature variations.

So, there is a no point in if your application does not require 10 GBPS or hundred GBPS systems. There is no point is going for such expensive systems to kill a fly you do not need a machine gun. So, it is just like that as simple as that. So, communication low data rate applications usually, IR-LED’S infrared LED’S and therefore, the materials as we will see will be different communication and in opto electronic systems.

UV-LEDS: UV-LEDS is an application for purification, or decontamination of potable water, potable systems for decontamination or purification. UV-LEDS are widely used for this. And also in security to detect counter fee currency notes, people use UV lights there are certain signatures, which are visible, only when you see UV and also, for curing epoxy. For curing epoxy resins there are many epoxy resins which are used which cure only if you expose it to UV light, very fast curing takes place if you expose it to UV light including those of you have studied optical fiber manufacturing the fiber which is drawn from the tower passes through a U V cure curing coating. So, that is he passes through a coating and then immediately expose to U V light. So, that the coating hardens immediately.

So, UV curing epoxies are widely used in optics for bonding optical components, and these days earlier I want use to use big UV lamps, but today small UV-LEDS serve the purpose. there are more applications what else can we think of.

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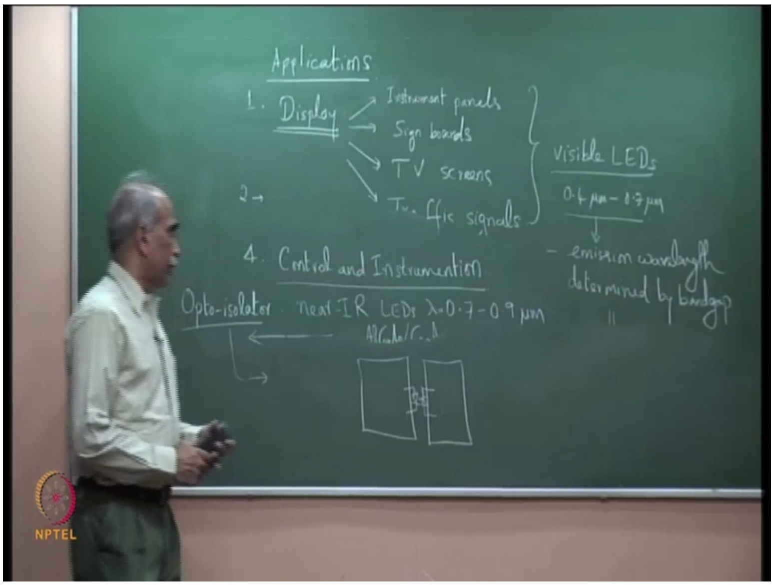

Control and instrumentation: control and instrumentation usually one uses near IR-LEDS in the range of 0.7 to 0.9micro meter, lambda emission usually in this range. these are usually gallium arsenide base LEDS very reliable aluminum gallium arsenide, very dependable LEDS for control and instrumentation one example is, all the consumer products which have remote control, those remotes are all these LEDS very reliable and one small battery runs for two years long life reliable control units for remote controls, but also there are many instruments where you need to trigger relays or switching where people use these IR-LEDS. In fact, one of the earliest applications here was opto-isolator.

Opto-isolator is a LED and photo detector combines electrically which is used to electrically isolate two different circuits. So, two chips electrical isolation to bring in electrical isolation may be in the first class I just mentioned about it. So, this is one of the earliest application that is you have two chips electrical circuits, and you want to isolate them electrically you do not want them to be connected then what is done is the last component here is an LED. The two chips are talking to each other, but you do not want any electrical connection between them and therefore, there is a LED and a photo detector combination which is used. So, that whatever signal is coming from here it is passing through the LED corresponding current generates light which is detected here and the current signal flows here electrically they are completely isolate, but the same signal comes here. So, this is one of the earliest applications in the 1970s people use to use this component called opto-isolator. It is also a part of instrumentation control and instrumentation.

There may be more applications we can discuss them a little later. So, the point to recognize is, we need LEDS right from UV up to IR. LEDS are widely used from UV to IR. So, let us see without going into specific applications our interest is to see, the materials used for these range.

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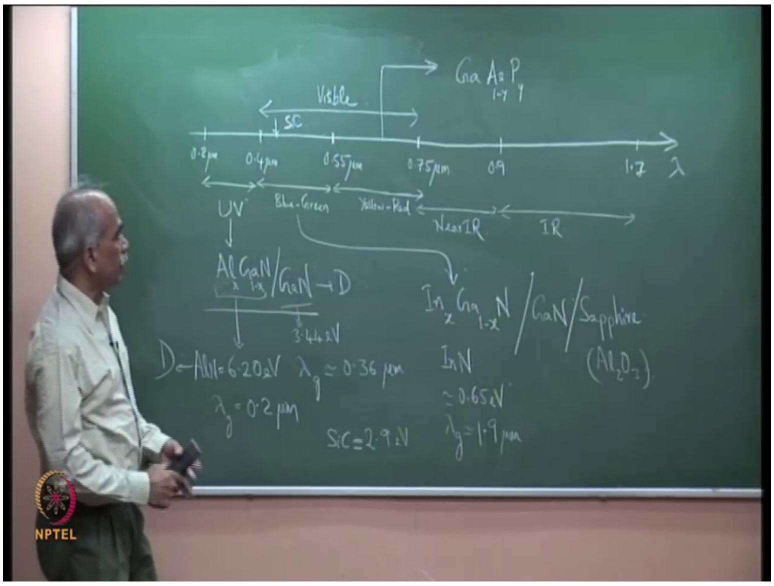

So, let me draw the range this is lambda, increasing lambda starting from 0.2 micrometer here 0.2 to 0.4, 0.4 to 0.55, 0.55 to 0.75, 0.75 to 0.9, this is not a linear scale 0.9, and from 0.9 to 1.7. What are the materials used in this range? you can see this is our visible region. Visible contains a blue green region, where the materials used are different and yellow to red. This is the near IR and in fact this is also near IR, but a little bit away. So, let me write this as IR, IR goes much beyond.

So, let me recollect again IR communication applications 1.3 to 1.55 micro meter optical fiber communication applications, control and instrumentation here the near IR-LEDS visible yellow red region, and blue green region. We need for example; in traffic signal we need green, yellow, and red. all the three colors are required there are many applications where you need blue also for example, the TV screen which contains RGB red, green, and blue. So, it is a triplet which contains R G B red, green, and blue. So, by an appropriate combination of this you can generate various shades, and various combinations, various colors appropriate levels of power you can generate. So, we need blue, we also need green, we also need red, and this is the UV. These are our display LED'S that familiar yellow red display LEDS are here. these let me start from this side UV these UV LEDS are aluminum gallium nitrite, ALxGa 1 minus x and gallium nitrite, gallium nitrite has a band gap of 3.44 Ev Eg of gallium nitrite 3.44 E v corresponding lambda G you can calculate lambda g, very quickly you can calculate 1.24 by 3.44. So, this is I think approximately 0.36 micrometer or 366 nanometers. This is aluminum gallium nitrite so, if x equal to 1 we have aluminum nitrite, aluminum nitrite has a very wide band gap semi conductor 6.20eV. Aluminum nitrite an insulator literally very wide band gap semiconductor 6.20eV which means what is the wavelength lambda g 1.24 divided by 0.62. So, this is lambda g is equal to 0.2 micro meter that is 1.24 divided by 0.61 0.24 divided by 6.2 that is 0.2 micrometer. So, this end is point two micro meter in principle it is possible, but, usually it is little bit difficult to have only although this is also a direct band gap material this is also direct band gap gallium arsenide is a direct band gap material this is also a direct band gap material. So, this range is covered by the ternary compound aluminum gallium nitrite on gallium nitrite wide band gap semiconductors both are wide band gap semiconductors, UV-LEDS originally let me go to the next one blue, green. Blue, green is indium gallium nitrite Inx gallium 1 minus x oblique. Indium gallium nitrite what has this mean what is the substrate gallium nitrite indium gallium nitrite gallium nitrite indium nitrite has a band gap of I think approximately 0.65eV, 0.65eV gallium nitrite is 3.4. So, it is about 0.34 which means this can go to lambda g approximately 1.6 micro meters approximately. So, in principle this can go up to 1.9 micro meter, but in practice it is very difficult because has x becomes larger and larger these are material aspects of fabrication there are clusters formed and therefore, usually this material can be used for relatively small values of x.

So, indium gallium nitrite gallium nitrite forms this blue green region. The blue green LEDS entire are currently made and you know the blue lasers are made by the same substrate. In fact, the materials that I will discussed will also be the materials for laser diodes and therefore, when we go to laser diodes again we will not discuss materials because it is the same materials indium gallium nitrite on gallium nitrite and usually gallium nitrite is grown on sapphire, these are fabrication details sapphire substrate on which gallium nitrite is first grown.

And then indium gallium nitrite is grown on this sapphire is crystal iron AL2O3. It is a dielectric AL2O3. So, blue green region is by this material earlier initially much before indium gallium nitrite came people had made LEDS here in silicon carbide, sic silicon carbide, silicon carbide had a band gap of 2.9eV approximately and you could have a LED's emitting here about 0.42 or 0.43. the early blue LEDS, In fact, in the 1980s the blue LEDS which were available where from silicon carbide, but it is very in efficient and therefore, now a day's all the blue LEDS are indium gallium nitrite based we go to the yellow red region here the display LEDS, what is the material used for display LEDS? Gallium Arsenide Phosphate so, y 1 minus y Gallium Arsenide Phosphate in this range, it is gallium Arsenide Phosphate which is used,

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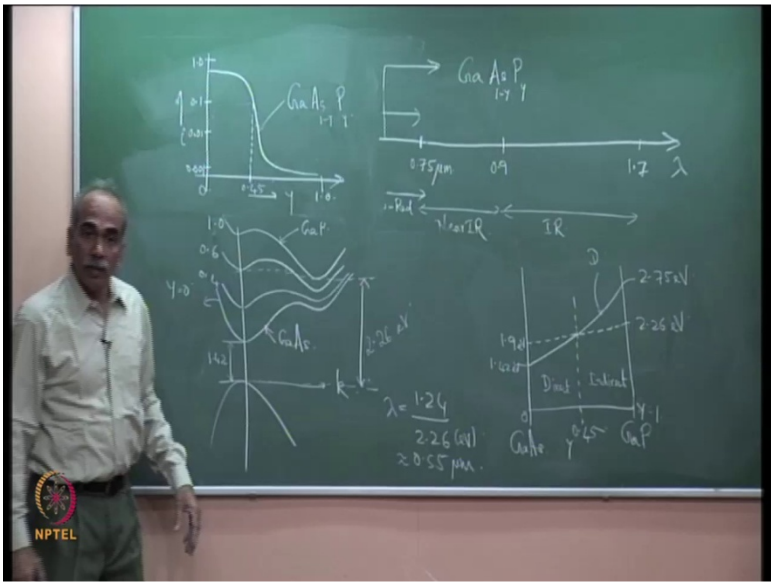

But if you recall if you recall this diagram which we had I think I had discussed this gallium arsenide, gallium phosphate, gallium phosphate with x composition x equal to 0, x equal to one, if you put y; then y equal to 1; if you put y is equal to 1; we have Gallium Phosphate at this end. This is y equal to 1; y equal to 0 is gallium arsenide, the band gap of Gallium Arsenide varies 1.42 to 2.75eV. The direct band gap of this material D and the indirect band gap varies I had discussed this with respect to Aluminum gallium Arsenide I think this is 2.26 and this is 1.9eV approximate numbers. You can check from the literature exact numbers. So, what you see is up to this x value the ternary compound Gallium Arsenide Phosphate up to this value of y has a direct band gap, this is direct band gap beyond that the indirect band gap is lower than direct band gap therefore, the material becomes indirect band gap. So, this is this region it is direct and this region it is indirect. If you are forgotten just recall the picture.

The E k diagram if you see, Gallium Arsenide has a band gap, this is 1.42 this difference here this is E c of Gallium Arsenide this is y is equal to 0, y is equal to 0 implies we have gallium arsenide. This is the E k diagram this is for y equal to 0 as you increase, y this is for y is equal to 0.4; y is equal to 0.6; and y is equal to 1.0; different compositions I have approximately plotted. So, this gap is the direct gap, direct gap means the top of the valence band and the bottom of the conduction band here or at the same value minima of the conduction band, but as you go to higher values minima in the conduction band is here and this is indirect band gap and at y is equal to 1 we have Gallium Phosphate, which is an indirect band gap material. This means what is this band gap here if I were to draw this gap the energy difference here this energy difference is 1.42 this energy difference corresponding to gallium phosphate. So, this is pure Gallium Phosphate this is pure Gallium Arsenide. The E k diagram I have plotted as a function of x y the composition.

This is pure gallium phosphate which is an indirect band gap material. So, the indirect gap is here 2.26eV. So, this is a direct gap 0.4 it is a direct gap because this is lower than this. So, in this graph up to 0.45; y is equal to 0.45 gallium arsenide phosphate is a ternary compound gallium is a direct band gap material up to that value and beyond that, it is an indirect band gap material. So, in this whole range if you substitute for example, gallium phosphate, if you substitute lambda is equal to 1.24 divided by this end 2.26; approximately 0.55. This is micro meter lambda in micro meter to this is eV approximately this. So, if you make a Gallium Phosphate LED, it should give about 0.55 which is the yellow green region, but remember that gallium phosphate material is indirect band gap.

And we know that in an indirect band gap, the eta i is very small internal quantum efficiency is very small if I plot the internal quantum efficiency graph if you plot eta i. So, here is a plot of eta I, eta i versus x ,the eta i drops the numbers here are typically you can see the literature which says about 0.1, 0.01, and 0.001 this is eta i you see eta i is about 0.5, when it is Gallium Arsenide this is point for log scale. So, here it is 0.699 is 0.5 log of. So, here eta i is this much, but as you come to. So, this drops down to about below 0.1 at 0.45 this is an indirect band gap, eta i of the indirect band gap. So, I have plotted eta i for Gallium Arsenide Phosphate with respect to x, y. At y is equal to 0 Gallium Arsenide eta is about half 50 percent as y increases I cross over from direct band gap material to indirect band gap material eta i drops down rapidly, exponentially and you see this is the kind of values.

So, how will I make my 1 is here? This is 1.0, this is 0 y. How can we make that blue green or yellow green LED’s at 0.55 with gallium phosphide? How to make with gallium phosphide?

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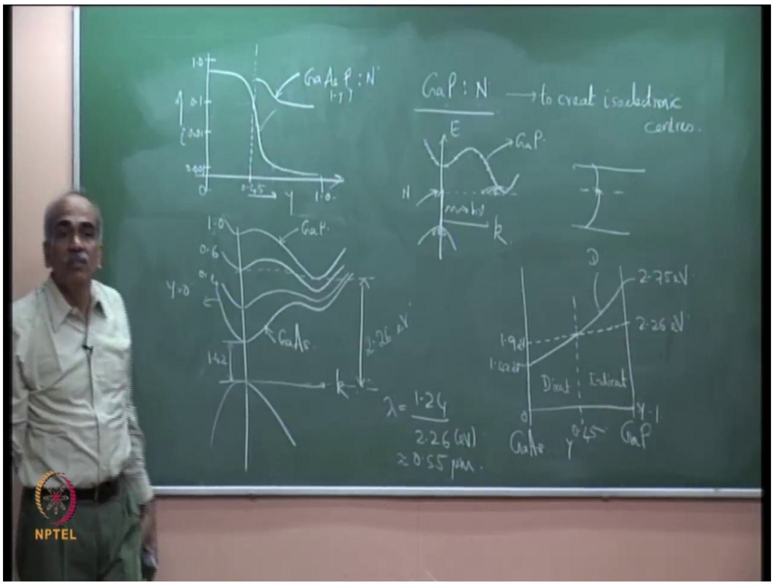

So, what is done is, there are what are called doping by nitrogen, to create isoelectronic centers. Nitrogen doping gallium phosphide doped with nitrogen to create isoelectronic centers, isoelectronic centers quite a bit of solid state physics here and there, but as a engineers we have an explanation why that the eta i is so, small is there any way of lifting the eta i, otherwise the output power will be very small. if eta i is very small to create isoelectronic centers, nitrogen doped gallium, doping nitrogen creates isoelectronic centers which means nitrogen forms an atom which has similar energy as Gallium Phosphide. Which means let me now repeat this is Gallium Phosphide it gives out it generates energy levels which are of similar order these energy levels.

This is E axis, k axis there are energy levels or states there are states which are due to nitrogen which correspond to the lowest energy value permitted for Gallium Phosphide now electrons which are accumulated here can make a transition to this because, there energy is the same and then once it is here it is free to move and the holes which are here can directly recombine with the electrons here. please see this levels these states are because of nitrogen doping now it is not what are these are nothing, but what is this graph this graph represents allowed states or conduction band of gallium phosphide allowed state of nitrogen is here which has the same or similar value as that of the minima here therefore, because energy values are same the electrons can always move to these states. once it is in this state it is free to move and therefore, it can come to low momentum values and recombine with the hole here, giving out photons the process is slow therefore, the rates of emission and absorption is slow, and you cannot make lasers by doing this doping by isoelectronic centers the rates of emission and absorption will be affected because of this additional process it is like traps centers were which act as recombination centers. You know that if there are trap centers in the band gap this can act as recombination centers the hole and electron can combine here it is almost like that, but, the isoelectronic centers are close to the band edge here.

Conduction band edge therefore, these levels are actually acting like trap centers they facilitate recombination and photon emission; however, the process is now slow down and therefore, you cannot use the same technique to realize laser diodes, but LED's with relatively low radians are made by this technique. So, the visible LED's that we see. So, if you dope this with nitrogen the value here eta i the graph changes to. So, this is Gallium Arsenide Phosphide with nitrogen doping. Gallium Arsenide Phosphide one minus y; Py with nitrogen doping. this is pure gallium Phosphide where eta i has gone down because it is a indirect band gap material with nitrogen co-doping the eta i is listed to similar numbers 0.1, 0.2 and therefore, you have been able to rise the internal quantum efficiency. So, the visible LEDS display LEDS that you see are usually made of this material these days there are several other materials which are available, but let me not go into the further details of material for that range because we still have some more ranges left. For example, for this you can read some Zee, S M Zee physics of semiconductor devices one of our references.

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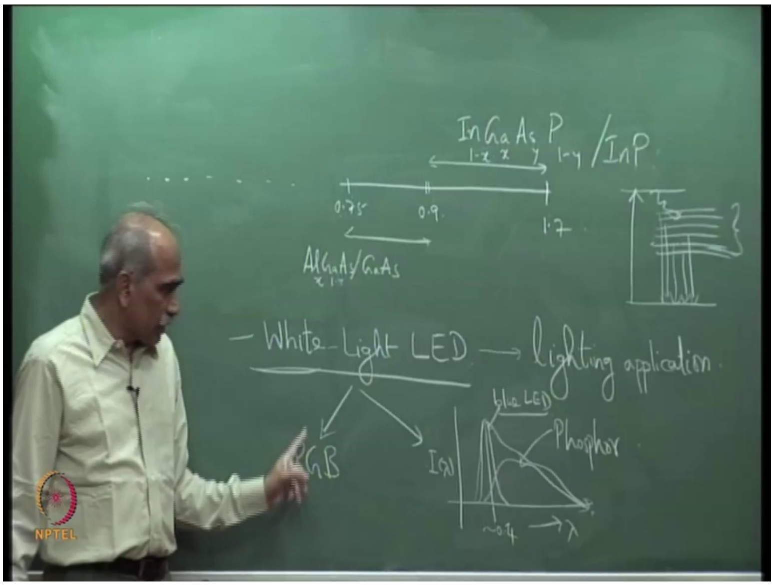

We come to the last two ranges these we have discussed and we are here now 0.75 to 0.9, the material is gallium arsenide/aluminum gallium arsenide. Wonderful material all the remote controls and LEDS used are this for control and instrumentation, and from 0.9 to 1.7 the communication grade LEDS are made by that quaternary compound indium gallium arsenide phosphide. 1 minus y, y, x, 1 minus x this is lattice match to indium arsenide, lattice match to indium phosphide substrate for certain compositions you recall we had drawn those lattice matching curves and we have found out a particular line over which indium phosphide was lattice matched to this for a range of value. So, I choosing an appropriate composition you can realize LEDS in this range the edge emitting LEDS for communication low data rate communication at 1.3 and 1.55 are made by this material, and as we will see later that it is this material itself which is used to realize today’s modern optical laser diodes for modern optical communication in the 1.55 micrometer window the DWDM systems use laser diodes which are made by this material indium gallium arsenide phosphide/indium phosphide. So, a range of materials there are certain new materials there are strained layer structures which are used I will not go into more details of this and we will stop here for the LED. One can see one last point one last application white light LEDS for lighting applications. So, many commercial products lighting applications what is the material used for this white light LED it has be emit over a wide region. So, naturally one material cannot emit that. Course the RGB that is three LEDS it is a matrix. So, if you make a torch light with plenty of these LEDS then each led that you see has three LEDS within that one emitting

So, there are two options which are followed both are used one is of at red, another emitting at green, and blue, and then you control the current depending on the current controlling the current, you can get the light white required radians of each of these component LEDS you can get white light. So, it is a mixing of RGB is 1 approach; there is a second approach where you use a phosphor that is you have LED which is emitting here close to the blue region. So, around 0.4 and the LED is pumping the light output from the LED pumps a phosphor which has a response like this. So, this is a phosphor the response this is the blue LED or near UV-LED, blue LED which pumps that is which is exciting a phosphor the light output coming from the LED is that LED is coated with a phosphor, phosphor is one when you pump which emits over a wide band.

So, if you phosphors are generally having a wide band excited state. So, you pump here and then it comes down to this bunch of levels from where emission takes place over all energy ranges. So, what I have plotted here is I of lambda this is the like the photo luminescent spectrum that this is the response of the phosphor wavelength. So, this axis is wavelength intensity. So, if you pump the phosphor, the phosphor has a response like this is the LEDS spectrum which we discussed wavelength spectrum of LED this is a blue LED or near UV-LED which is pumping the phosphor.

And therefore, overall response will be which means the entire range 0.4 to 0.7 which means it is a white light. So, it looks white because it is emitting all wavelengths. So, this is the second approach, one approach is here which requires more controls here you do not require any control because only one led is lighted the phosphor is a material a suitable phosphor is coated on the LED. So, that the light blue light coming out of the LED pumps the phosphor and leading to emission from the phosphor which is a wide band emission. So, both approaches are followed currently. So, I will stop here and in the next class we will start with semiconductor lasers.