**Semiconductor Optoelectronics**
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**Lecture – 31**
**Light Emitting Diode-V Material and Application**

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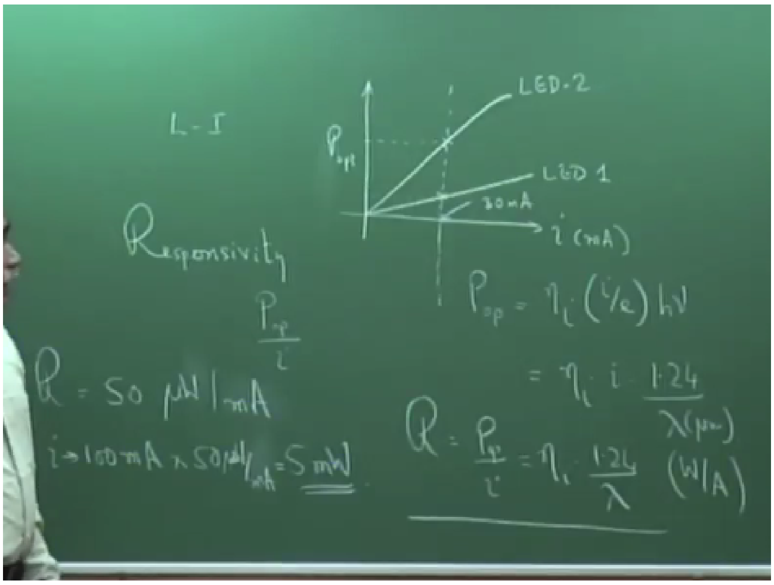


Okay, today we will discuss materials and applications, last of the lectures in light emitting diodes but before I proceed just a couple of points from our last lectures. We had a LI characteristic; light current characteristic, we have discussed this in detail. This is a parameter, which is usually used to characterize an LED and that is called the Responsivity. Responsivity is simply defined as P optical/ the current i.

We have an expression, we had derived an expression P optical = ETA i * i/ E * h Nu, which turned out to be ETA i * i * 1.24/lambda in micrometres. So, the quantity P/i took; responsivity = P/I, so same optical power/ i = ETA i * 1.24/ 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 us say 50 micro ampere watt; per milli watt for; sorry, 50 micro watt per milli ampere; typical numbers, microwatt per milli ampere. What it means is;

if you pass let us say, you pass 100 milliampere, so if you pass 100 mA, if i = 100 mA because this is nothing but P optical / current.

Therefore, responsivity = 100 mA * 50 microwatts per milliampere, so you have 5 milli watt of power, so the optical power output is 5 milli watt, if you pass 100 milli amperes; 100 milli amperes of current multiplied by the responsivity 50 micro watt per mA, so you can see here 50 micro watt per mA, which is 5000, microwatt which is 5 milli watt. Usually, it is linear; we operate in the linear region.

This responsivity is an important parameter in modulation applications for example, you may have an LED which has IP curve like this, so this is P; optical power, P optical and this is current i in milliampere. A particular LED one may have a responsivity like this, so this is LED 1, this is LED 2, 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 a data sheets of LEDs, there will be a parameter called responsivity, which is simply nothing but this, we have already derived this, so P optical divided by current. So, if you have a 2 LEDs, with the different responsivity, here it refers to slope because i/ P everywhere because it starts from 0, it is the slope and therefore, if you choose an operating current here.

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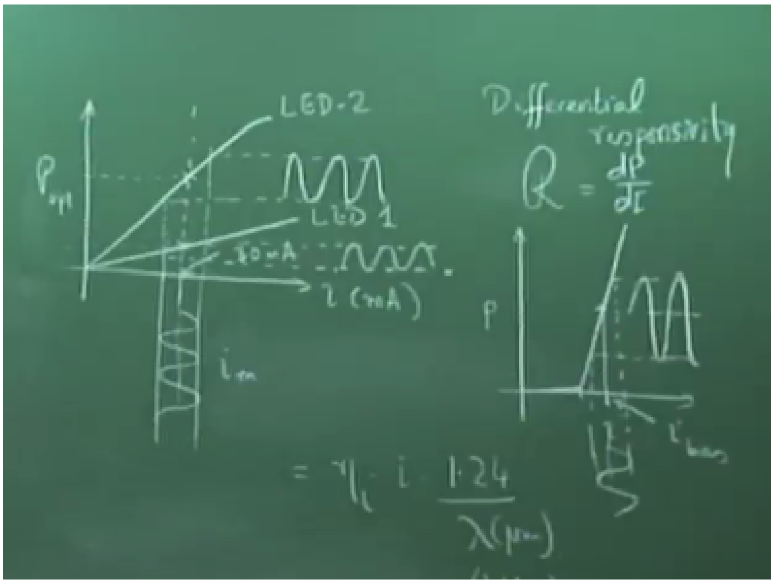


Let us say some operating current here, let me say this is equal to some for example, 30 milli ampere or 40 milli ampere whatever, some current, then the Q point for this LED is this one and

Q point for this LED that is the operating point is here. So, the power, which is the output powers are here but more importantly from a modulation point of view, if you now 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, 30 mA is the bias current; a signal; a current variation im, so modulating current. This is i bias; biasing the LED in the linear region at Q point and if you modulate this, you can see the corresponding optical variation is here. So, let me take it a little further off, so the optical power varies here because this axis is optical power.

So, when you; 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 here. Whereas, the same current on the second LED because the slope is higher, you can see that the modulation is larger, 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 just for interest, let me mention here, it usually up to a threshold, the power output is very little and then you have a linear characteristic P optical / i for a laser diode, for an LD. In this case, here it 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? The 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; differential responsivity, which is defined as R differential responsivity is = dP/ dI, so that is really 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; the light conversion efficiency or the wall plug efficiency that is given an optical; an electrical power, some amount of electrical power applied to the LED.

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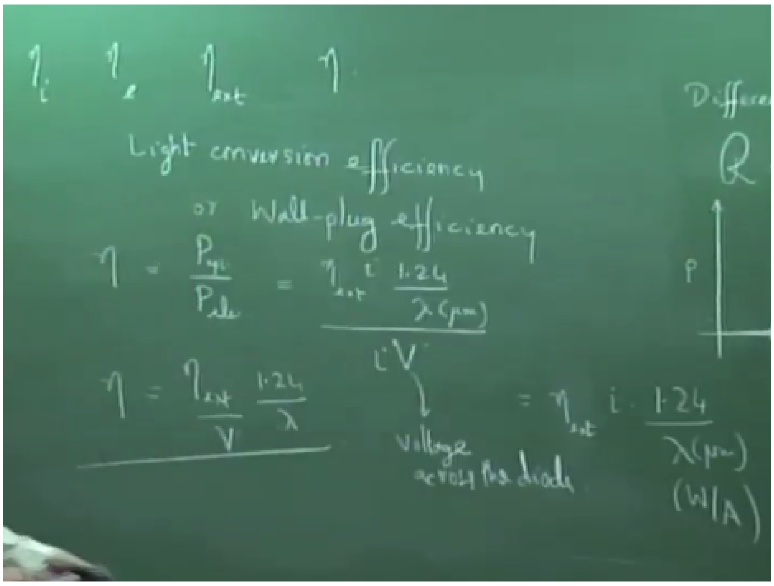


What is the optical power generated? So, light conversion efficiency, wall plug efficiency; eta; this is ETA without any suffix is the total conversion efficiency, till now we had ETA I, ETA external and ETA e extraction and so on but this is just ETA, wall plug efficiency, which is = P optical/ P electrical. So, P optical is ETA i * i 1.24/ lambda, oh! This is not ETA i, I am sorry please correct the expression, what was this? ETA external.

I am sorry, please correct that expression; ETA external it was, which contained extraction efficiency; ETA external, so this is external quantum efficiency, recall that the product of ETA i * ETA extraction efficiency, we called as ETA external, so this is divided by i * 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/e 1.24.

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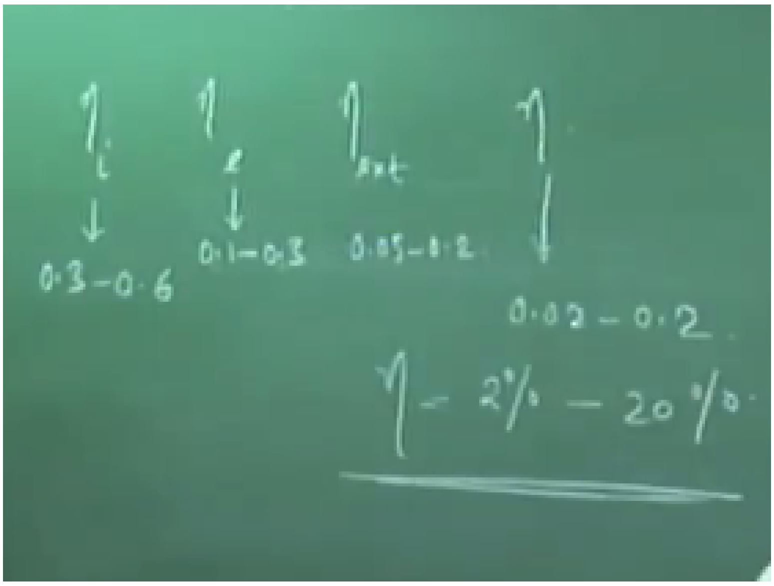


Typical numbers; we had several ETAs, recall ETA i, ETA e, ETA external and finally ETA internal quantum efficiency, extraction efficiency and external quantum efficiency and the wall plug efficiency. Typical numbers for ETA i is 0.3 to 0.6, typical numbers; internal quantum efficiency about 50% for gallium arsenide and depending on the material typically, extraction efficiency is typically 0.1 to 0.3. By texturizing, you could go up to 0.3.

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 2 and if you take product, you can see this will be 0.03, if you take the lowest and if you take this, it is about 0.2, 0.18 or 0.2, so typical numbers are 0.0, let me write here the same product 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% to 20%, this is a very good efficiency; overall conversion efficiency is generally 2% to 20% for LEDs, laser diodes as we will see later have much can have much higher efficiency 50%, 60%, electrical to optical conversion, very very efficient devices, alright.

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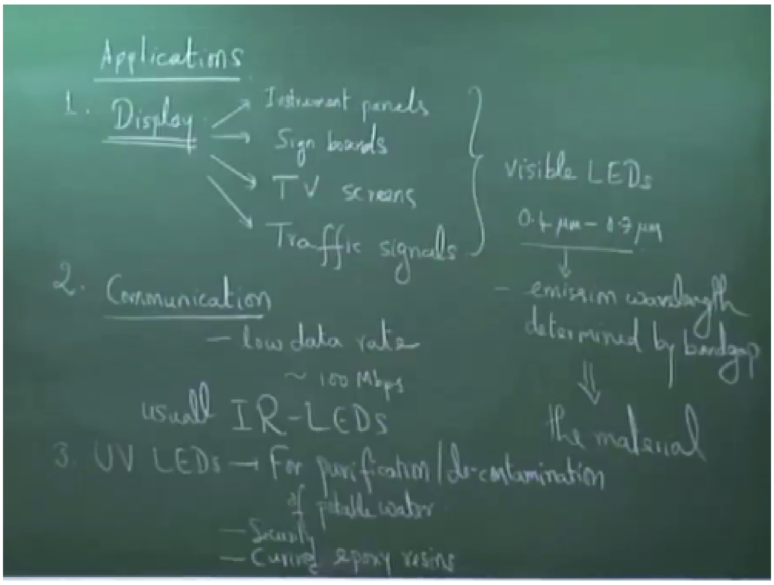


We just quickly go back to; go to applications and materials. Materials and applications or applications and materials, it is the application, which will determine what material of LED that you need to use. There are large number of applications, let me first list the applications and then we will see what; the most important application of LEDs, so applications is display. On instrument panels, so display on instrument panels.

For example, display of signboards; signboards, you will see although, sign boards; running sign boards in airports, even in our institute sign boards, TV. These days LED TVs, which have TV screens and what else, traffic signal, most of these are all visible LEDs. In other words, so you need visible LEDs; visible LEDs. Why this part was required? Because now the wavelength of emission should be visible to the eye, which means we are interested in 0.4 micrometre to 0.7 micrometre.

The emission wavelength is determined by the band gap of the material and therefore it is determined by the material, so emission wavelength; 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; 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, we will see later on that laser diodes are very sensitive to temperature variations therefore, when you make instrumentation, it is much easier and much cheaper cost effective, if we use LEDs. So, low data rate; low data rate means up to about 100 megabit Mbps, you can go up to, it is not a low, does not mean very low, you can go up to this 100 Mbps.

But usually, 1 Mbps, 10 Mbps local area networks within the building, it is very easy to use LEDs with the optical fibers; multimode optical fibers, the connectors are very cheap, they are much tolerant to temperature variations, so there is no point in; if your application does not require 10 Gbps or 100 Gbps systems, there is no point in 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 LEDs; infrared LEDs and therefore the materials as we will see will be different communication and in optoelectronic systems. What do you think are the applications of UV LEDs? Is an application but I have written UV LEDs, for example; for purification or decontamination; decontamination of potable water potable systems for decontamination or purification, UV LEDs are widely used for this.

And also in security to detect counterfeit currency notes, people use UV light there are certain signatures, which are visible only when you see UV and also for curing; 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 UV curing coating, so there it passes through a coating and then immediately exposed to UV light, so that the coating hardens immediately. So, UV curing epoxy are widely used in optics for bonding optical components and these days earlier, one used to use a 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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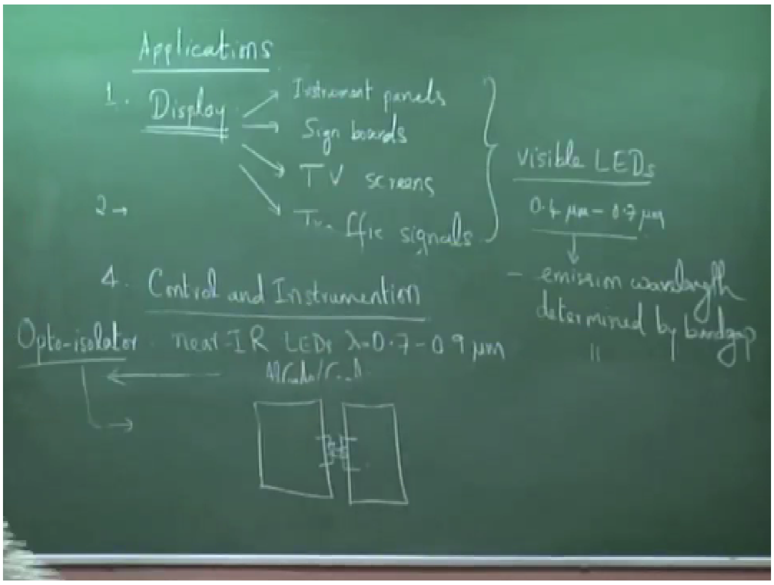


So, let me erase the lower part, control and instrumentation 4; so, visible LEDs; visible LEDs here, communication next where IR LEDs; IR LEDs, for the second application you require IR LEDs, for the third application UV LEDs emitting in the UV and control and instrumentation usually, one uses near IR LEDs; near IR LEDs in the range 0.7 to 0.9 micrometre lambda emission usually in this range.

These are usually gallium arsenide base LEDs, very reliable aluminium gallium arsenide very dependable LEDs for control and instrumentation. One example is all the consumer products which have a remote control, those remotes are all these LEDs, very reliable and one small battery runs for 2 years, long life reliable control units for remote controls but also there are many instruments where you need to trigger relays or switching, which were people use these IR LEDs.

In fact, one of the earliest application here was opto isolator; opto isolator, what is this opto isolator? It is and an LED and photo detector combined, which is used to isolate electrical; electrically which is used to electrically isolate 2 different circuits or two chips, electrical isolation to bring in electrical isolation maybe in the first class, I just mentioned about it, so this is one of the earliest application.

That is you have 2 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 2 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 is generate; current generates light, which is detected here.

And the current signal flows here, electrically they are completely isolated but the same signal comes here, so this is one of the earliest applications in the 1970s, people used 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.

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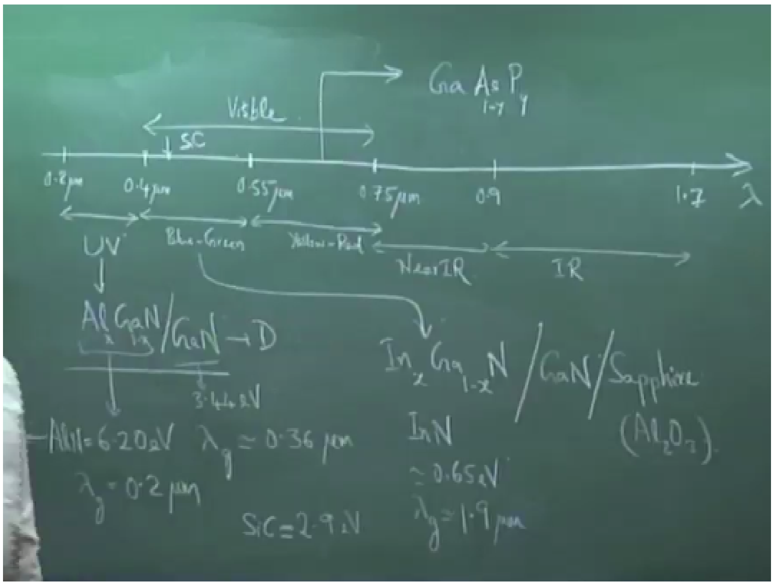


LEDs are widely used from UV to IR, so let us see without going into specific applications, our interest is to see the materials used for these range. So, let me draw the range, this is lambda; increasing lambda starting from 0.2; 0.2 micrometre here, 0.2 to 0.4, 0.4 to 0.55, 055 to 0.75, 0.75 to 0.9, 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; blue green region, where the materials used are different and yellow to red, this is the near IR and this is in fact, this is also near IR but a little bit away. So, let me write this as IR, the IR goes much beyond. So, let me recollect again, IR communication applications 1.3 to 1.55 micrometre, optical fiber communication applications.

Control and instrumentation here, the near IR LEDs visible a low red region and blue green region, we need for example, in traffic signal, we need green, yellow and red, all the 3 colours are required. There are many applications where you need blue also for example, the TV screen which contains RBG; red, green and blue, so it is a triplet which contains RBG; RGB, red green and blue.

So, by an appropriate combination of this, you can generate various shades and various combinations, various colours, appropriate levels of power, you can generate; so we need a blue we also need green, you also need red and this is the UV. These are our display LEDs, the familiar yellow red display LEDs are here. This okay; let me start from this end; UV, these UV LEDs are aluminium gallium nitride, gallium nitride.

Al x Ga 1 - x and gallium nitride; gallium nitride has a band gap of 3.44 eV; eg of gallium nitride, 3.44 eV corresponding lambda g, you can calculate lambda g, very quickly you can calculate 1.24/ 3.44, so this is; I think approximately 0.36; 366, so approximately 0.36 micrometre or 366 nanometers, this is aluminium gallium nitride, so if x = 1, we have aluminium nitride.

Aluminium nitride is a very wide band gap semiconductor 6.20 UV aluminium nitride, an insulator literally very wide band gap semiconductor 6.20, UV which means what is the wavelength lambda g? 1.24/0.62, so this is lambda g is = 0. 2 micrometre that is 1.24/ 6.2 that is 0.2 micrometre. So, this end is 0.2 micrometre, in principle it is possible but usually, it is a little bit difficult to have only; although, this is also a direct band gap material, this is also a 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 aluminium gallium nitride on gallium nitride, 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 nitride Inx, Gallium 1 – x, oblique indium gallium nitride.

What does this mean, what is the substrate? Gallium nitride Indium gallium nitride, gallium nitride; indium nitride has a band gap of; I think approximately 0.65eV, gallium nitride is 3.4, so it is about 0.36, which means this can go to lambda g approximately, 1.6 micrometre approximately, 1.6; 1.9, is not it? 1.24/ this, so 1.9 in principle, this can go up to 1.9 micrometre but in practice, it is very difficult.

Because as 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 nitride, gallium nitride forms this blue green region, all the blue green LEDs are currently made and you know the blue lasers are made by the same substrate. In fact, the materials that I will discuss 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 material indium gallium nitride on gallium nitride and usually, gallium nitride is grown on sapphire, these are fabrication details; sapphire substrate on which gallium nitride is first grown and then indium gallium nitride is grown on this; sapphire is crystalline Al2O3, it is a dielectric Al2O3.

So, blue green region is by this material. Earlier, initially much before indium gallium nitride came, people had made LEDs here in silicon carbide; silicon carbide; SiC, silicon carbide. Silicon carbide used to emit; I think silicon carbide had a band gap of 2.9, let me see if I have the number. I do not have the number but silicon carbide had a band gap, I think approximately, 2.9 eV, approximately.

And you could have a LEDs emitting here about 0.42 0r 0.43, blue LEDs; the early blue LEDs in fact, in the 1980s, the blue LEDs which were available were from silicon carbide but it is very inefficient and therefore, nowadays all the blue LEDs are indium gallium nitride based. We go to the yellow red region, here the display LEDs, what is the material used for display LEDs?

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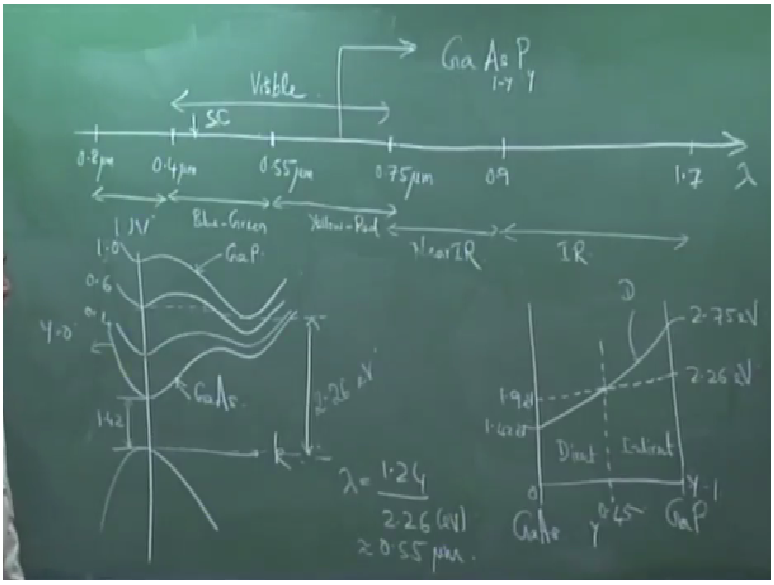


Gallium arsenide phosphide, so y, 1 – y, gallium arsenide phosphide, in this range it is gallium arsenide phosphide, which is used but if you recall; if you recall this diagram, which we had. I think I had discussed this; gallium arsenide, gallium phosphide, gallium phosphide with x composition, x = 0, x = 1, if you put a y okay y, we will written y; y = 1. If you put y is = 1, we have gallium phosphide at this end, this is y = 1, y is = 0 is gallium arsenide.

The band gap of gallium arsenide varies 1.4 to something like this, so this is 2.75 eV, this is 1.42 eV, the direct band gap of this material, this is a direct band gap and the indirect band gap varies, I had discussed this with respect to gallium arsenide; aluminium gallium arsenide I think. This is 2.26 and this is 1.9 eV 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 phosphide 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 here. So, this is this region it is direct and this region is indirect. If you are forgotten, just recall the picture, the EK diagram if you see, gallium arsenide has a band gap.

This is 1.42, this difference here, so this is EC of gallium arsenide, this is y is = 0, y is = 0 implies we have gallium arsenide this is the, EK diagram, this is for y = 0. As you increase y, this is for y is = 0.4, y is = 0.6 and y is = 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 are 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 = 1; at y is =1, we have gallium phosphide which is an indirect band gap material, which 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 phosphide, so this is pure gallium phosphide, this is pure gallium arsenide.

The EK diagram I have plotted as a function of xy, the composition, this is pure gallium phosphide which is an indirect band gap material, so the indirect gap is here, 2.26 eV, so this is 2.26 eV, is this clear. So, this is a direct gap, so 0.4 is a direct gap because this is lower than this, so in this graph up to 0.45 y is = 0.45, gallium arsenide phosphide 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 phosphide; if you substitute lambda is = 1.24/ this end, 2.26, how much will this be? Approximately, 0.55, this is micrometre; lambda in micrometre, this is eV approximately this. So, if you make a gallium phosphide LED, it should give about 0.55, which is the yellow green region.

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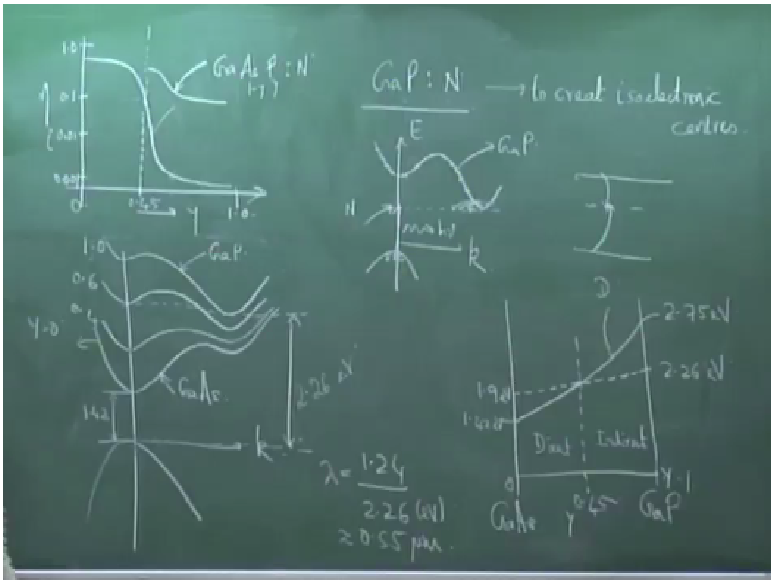


But remember that gallium phosphide material is indirect band gap and we know that in an indirect band gap, the ETA i is very small, internal quantum efficiency is very small. If I plot the internal quantum efficiency graph, my board is full now, okay let me erase here, the internal quantum efficiency if you plot ETA i, so here is a plot of ETA i versus x, the ETA i drops the numbers here are typically, you can see the literature this is 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 0.5 log scale, so here it is 0.699 is 0.5, okay log off; 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 what is; whatever I plotted; I have plotted ETA i for gallium arsenide phosphide, okay, we usually plot with respect to x, y.

At y is = 0 gallium arsenide, ETA i is about 1/2, 50 %, 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 one easier, this is 1.0, this is 0 y. How can we make readily that blue green or yellow green LEDs at 0.55 with gallium phosphide, how to make with gallium phosphide?

So, what is done is there are what are called doping by nitrogen to create isoelectronic centres, nitrogen doping; gallium phosphide doped with the nitrogen to create isoelectronic centres; isoelectronic centres, quite a bit of solid state physics here and there but as engineers, we have to have an explanation why, whether 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 is very small.

To create isoelectronic centres, nitrogen doped gallium doping nitrogen creates isoelectronic centres, 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 these because their 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; nitrogen doping.

Now, it is not; what are these; these are nothing but; what is this graph, this graph represents allowed states for 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 rate of emission and absorption is slow and you cannot make lasers by doing this doping by isoelectronic centres. The rates of emission and absorption will be affected because of this additional process, it is like trap centres, which act as recombination centres, you have; you know that if there are trap centres in the band gap, this can act as recombination centres; the hole and electron can combine here.

It is almost like that but the isoelectronic centres are close to the band edge here; conduction band edge therefore, these levels are actually acting like trap centres, they facilitate recombination and photon emission. However, the process is now slowed down and therefore you cannot use the same technique to realize laser diodes but LEDs with relatively low radiance are made by this technique.

So, the visible LEDs that we see, so if you dope this with nitrogen; the value here ETA i the graph changes, so this is gallium phosphide; gallium arsenide phosphide with nitrogen doping; gallium arsenide phosphide 1 - y Py with nitrogen doping. This is pure gallium phosphide where ETA i has gone down because it is an indirect band gap material with nitrogen doping, the ETA i is lifted to similar numbers; 0.1, 0.2.

And therefore, you have been able to raise 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, let me go over quickly to more details you can read for example, for this you can read from Sze; SM Sze, physics of semiconductor devices, one of our references.

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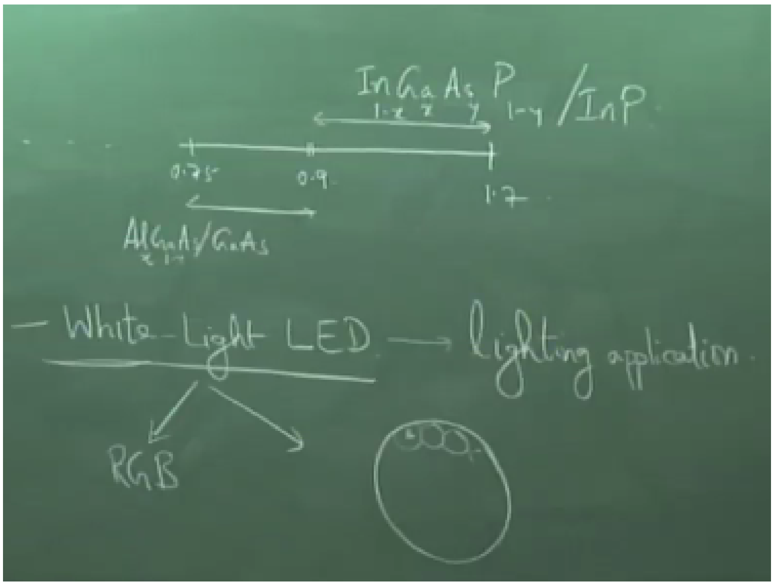


We come to the last 2 ranges; these we have discussed and we are here now, 0.75 to 0.9, the material is gallium arsenide; aluminium gallium arsenide, wonderful material, all the remote controls and LEDs you start this for control and instrumentation and from 0.9 to 1.7, the communication grade LEDs are made by the quaternary compound indium gallium arsenide phosphide 1 – y, y, x, 1 – x, this is lattice match to indium phosphide; 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 or which indium phosphide was lattice matched to this, for a range of values. So, by 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 micrometre 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 LEDs if I do not mention about white LEDs; white light LED, it is not white LED, I am sorry white light LEDs. For lighting application, if you see so many commercial products; lighting application, what is the material used for this white light LED? It has to emit over a wide region, so naturally one material cannot emit that.

So, there are 2 options, which are followed both are used; one is of course, the RGB that is 3 LEDs, it is a matrix, so if you make a torch light with the 20 of these LEDs, then each LED that you see has 3 LEDs within that. One emitting at red, other 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.

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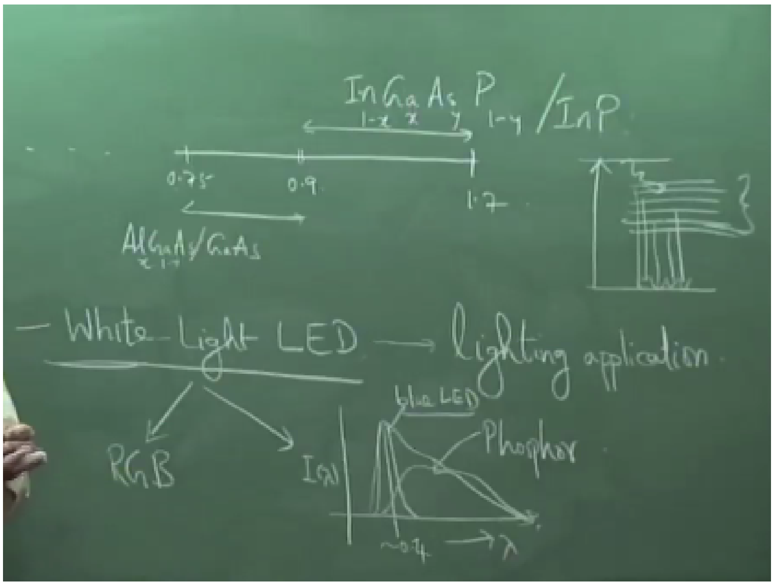


So, it is a mixing of RBG is one approach; there is a second approach where you use a phosphor that is you have an LED, which is emitting here close to the blue region, so around 0.4 and the LED is pumping the light output from the LED, pumps a phosphor which has a response like this. So, this is a phosphor, this is the LED 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, it emits over a wide band, so it is like this. So your phosphorus are generally having a wideband 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 photon emission 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, this is the LEDs spectrum which we discussed; wavelength spectrum of LED, this is the 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 wideband emission. So, both approaches are followed currently. So, I will stop here and in the next class, we will start with semiconductor lasers.