Fundamentals of Semiconductor Devices
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Lecture - 53
Visible LED: photometry and colorimetry

Welcome back, so if you recall in the last lecture we have been discussing about LED's a lot of things have been discussed in terms of efficiency, extraction a loss escape cone total internal reflection loss and other things right, so all these things are building up or you know understanding of LED.

Also the electrical properties the series and shunt resistance that can affect your LED's adversely and how you know different LED's of different colours which corresponding different band gaps have they have different turn on voltages, non radiative recombination radiative recombination efficiencies all these things we have covered.

So, we are pretty much done with LED accept that today I told you that today's lecture will be a brief discussion on the visible LED you know the aspect of visibility. Because all the LED's that we have been talking about are of any colour including UV and IR that are not sensitive to human eye.

But if we talk about visible LED's or white light LED's or bright LED's that you know we use for illumination and other purposes which are sensitive to human eye, then we have a you know a more subjective kind of a discussion on the LED with respect to human vision. It is not a part of any course exam or syllabus, but it should be you should be aware of in general because this is a very useful information when you try to understand Opto electronic devices and LED's with respect to human eye ok.

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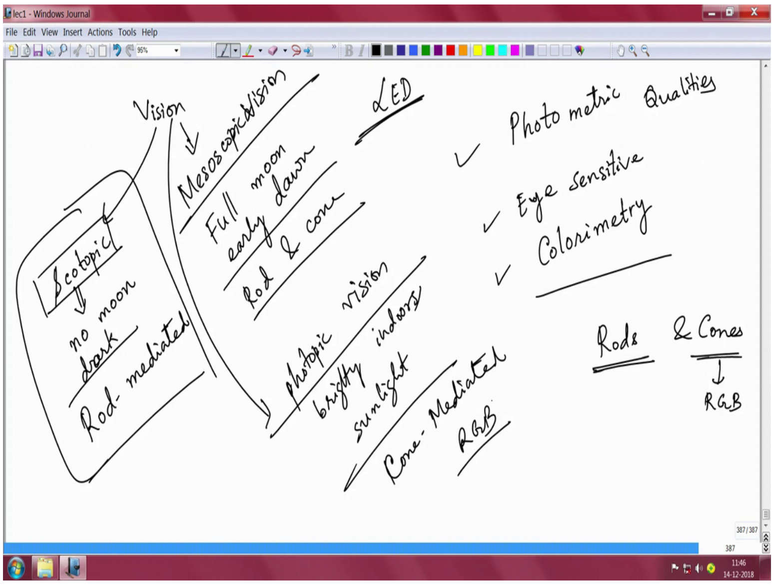

So, we will come to whiteboard here so today we will conclude LED and you know we will discuss some of the fundamentals that are related to human eye and LED for example ok. So, these are called Photometric qualities these are called photometric qualities I will come to what photometric qualities are and then Eye Sensitivity there is something called Eye Sensitivity ok.

Your eye is not sensitive to all wavelengths equally even indivisible and there is something called colorimetry. Colorimetry is the science of colour there are some very interesting and intriguing questions that will come along this so I will come to that.

So, human eye has many regimes ok, human eye has many the vision of human eye can be broadly defined into 3 categories one is called Scotopic vision, this scotopic vision is the vision that gets activated during the night time or especially like very dark like no moon. For example, no moon very night deep nights sort of thing know dark very dark environment you have for example, then human eye vision is called scotopic vision that are just the darkness.

It is mostly region which is mediated by rod human eye cells are basically made of 2 kinds of cells one is Rods and Cones this rods cells are more abundant and they are sensitive to visible, cone cells and pretty much sensitive to only RGB RED Green and Blue.

In the scotopic vision in this dark you know very dark environment like there is no moon light outside it is dark no electricity that kind of vision is dominated by rod and your sense of colour is lost in the scotopic vision, because in the night time you cannot distinguish between colour in the darkness right.

So, that is that vision when you lose the colour these are important parts of LED actually visible LED and that is why I am taking about. Then in case of say then there is something called Mesoscopic vision mesoscopic vision and mesoscopic vision kicks in your eye in terms of something like say full moon light it is not very dark, but is not super bright also like full moon night or you know early twilight like early dawn like before sunrise.

So, this kind of when it is like between bright and darkness then you have mesoscopic vision which has both rod and con cone contribution vision and the third category is called Photopic vision, photopic vision of human eye which kicks in that vision kicks in when you have you know like bright like brightly lit office you know, bright indoors office indoors or proper you know sunlight outdoor sunlight and here you primarily have a cone mediated vision. So, you have a strong sense of colour and that colour is mediated primarily by RGB the human eye senses that.

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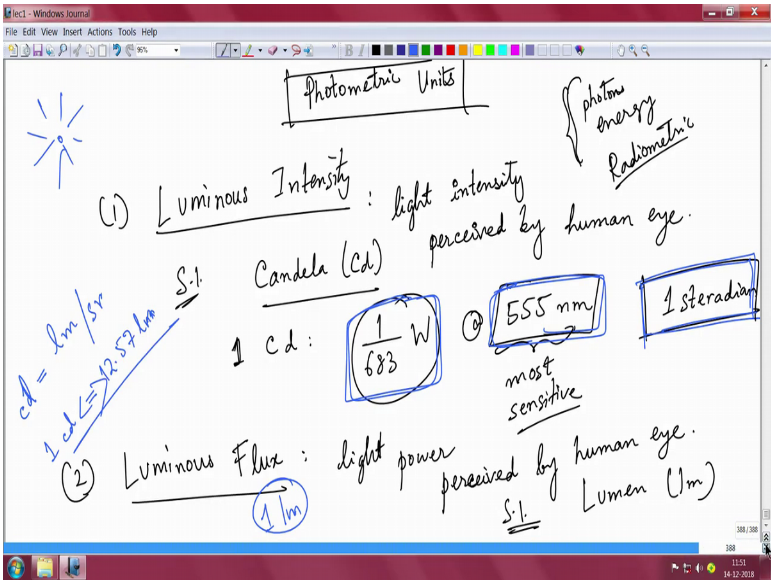

So, that is that is about the human vision, the now those vision that the reason I talked about vision is because the photo metric units of LED or any light source are related to the reason of human. So, what are photometric units this photometric units are units of you know the quantity like photons energy power all this thing as perceived by the human eye this is also called Photometric.

So, when you talk about units in general something like say photons or photon energy or photon wavelength and all these things there are for generic electromagnetic waves that may or may not be many may not be sensitivity to human eye and we call them radiometric parameters ok. The moment we talk about photometric parameters we only talk about those parameters which are as perceived by the human eye as perceived by the human eye.

So, the first important photometric unit is called luminous intensity you might have heard this word luminous intensity. What is luminous intensity of a source? Suppose I have an LED or I have incandescent lamp I have a tube light I have a CFL bulb their luminous intensities might be different. Luminous intensity actually is the light intensity luminous intensity is the light intensity as perceived by the human eye as perceived by the human eye that is called luminous intensity. And the SI unit of luminous intensity is called Candela Cd candela is the SI unit of the luminous intensity and 1 Candela this comes from candle by the olden times this is the light intensity as perceived by human eye and luminous intensity unit is Candela 1 Candela is actually the luminous intensity of a monochromatic light ok.

Single wavelength light which is emitting an optical power of 1 by 683 of a watt at 555 nanometre which is pure Green ok, that is because human eye is the most sensitive at this wavelength you will see that human eye is most sensitive to Green 555 nanometre.

So, at 555 nanometre if there is single wavelength light monochromatic light that is emitting a power total optical power of 1 by 683 watt, over a solid angle of 1 steradian in what direction in all direction. But in the solid angle 1 steradian angle solid angle because, it is 3 you know then that amount of luminous intensity is called Candela that is called candela and a related important quantity is luminous flux.

These are terms that are used to quantify and compare light sources like tube lights CFL bulb even your earthen lamp that DR that you know light in Diwali. For example, an LED bulb everything you can compare with this quantities luminous intensity Luminous flux. Luminous flux is actually the light power perceived by the human eye light power as perceived by the human eye, light power as perceived by the human eye and the SI unit of luminous flux is something that you know more you know used frequently it is called lumen l m lumen ok.

Lumen Candela is luminous intensity lumen is luminous flux and I told you luminous flux essentially is the light power perceived by the human eye, the definition is very similar to that of luminous intensity accept that here we will say that 1 lumen of luminous flux is actually corresponds to a monochromatic light that emits a power 1 by 63 1 by 683 watt at 555 nanometre in all direction there is no like this no concept of it should emit only in one steradian 1 is basically a 1 solid angle in a way. In a particular like when you talk about 2 D you can say that this is the light emitted at an angle of 90 degree so on and so on. So, within an cone of 90 degree and so once the radian is in 3D that conditions comes in candela intensity.

But in power is the total power so no condition of steradian, so essentially one lumen corresponds to the power of a source that is emitting 1 by 683 watt at 555 nanometre that is it. And that is why you can say that Candela the unit Candela is actually lumen by steradian lumen by steradian and of course 4 pie steradian is the total solid angle.

So, in a case isotropic source which means it is emitting in all direction ok, if it is emitting in all direction in 3 D then 1 Candela is actually 12.57 lumen that is the conversion rate corresponds to 12.57 lumen it is not equal to it is the corresponds thing ok. When you normalize the steradian, these are the parameters that you compare LED’s for example that is why I am talking about this quantity.

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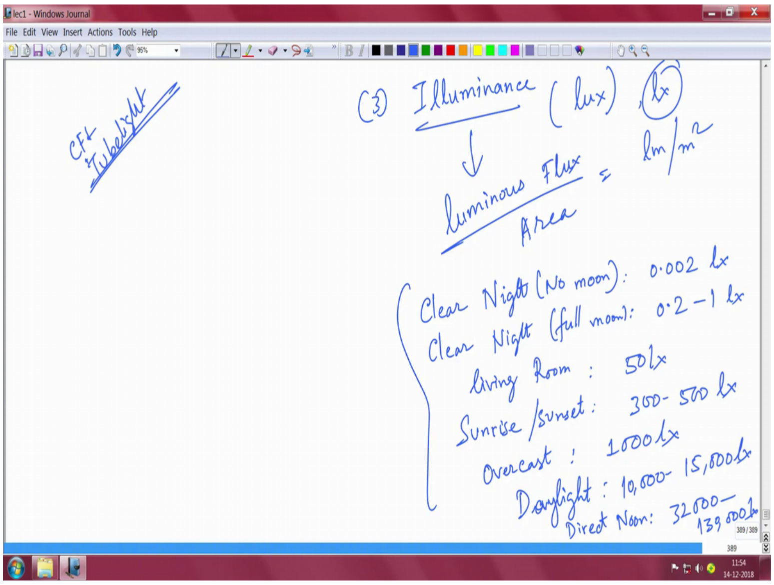

So, and the third parameter is Illuminance ilu illuminance I l u m i n a n c e illuminance and the unit is actually called lux or we can say lx, illuminance actually is illuminance flux illuminance flux per unit area divided by area ok.

So, this is lumen per metre square or centimetre square you are normalizing the area. So for example, on a clear night on a clear night this luminous flux or illuminance or lux gives you an idea also of the power and the brightness only.

So for example, on a clear night if no moon if there is no moon on a clear night no cloud no moon no electricity nearby, then the amount the illuminance is around 0.002 lux very low the surrounding ambient brightness, on a clear night which is full moon which is full moon you have around 0.221lux right. Inside a living room inside a living room when you have a light glowing and inside a family living room you will have 50 lux ok, illuminance sunrise or sunset when you are getting sunset it will be between 300 to 500 lux that is the illuminance of the environment ok, on an over cast day which means there is a cloudy day in the afternoon it is 1000 lux ok.

In a typical daylight in a typical daylight say morning 10 o clock or afternoon 3 o clock and so on that would be around 10000 to 15000 lux and direct sunlight at noon if you have direct known sunlight overhead that is around 32000 to 113000 lux 1.3 lux. So, this is just the idea of the illuminance around the surrounding things.

So, when you discuss about LED we have to compare with respect to this you know like how much is the LED you will see that you know CFL bulb or you know tube lights and other things those cannot match the illuminance of LED is specially respect to power. You know at very low power you can give you must higher brightness that is the beauty of LED I am talking about visible LED as perceived by human (Refer Time: 11:48).

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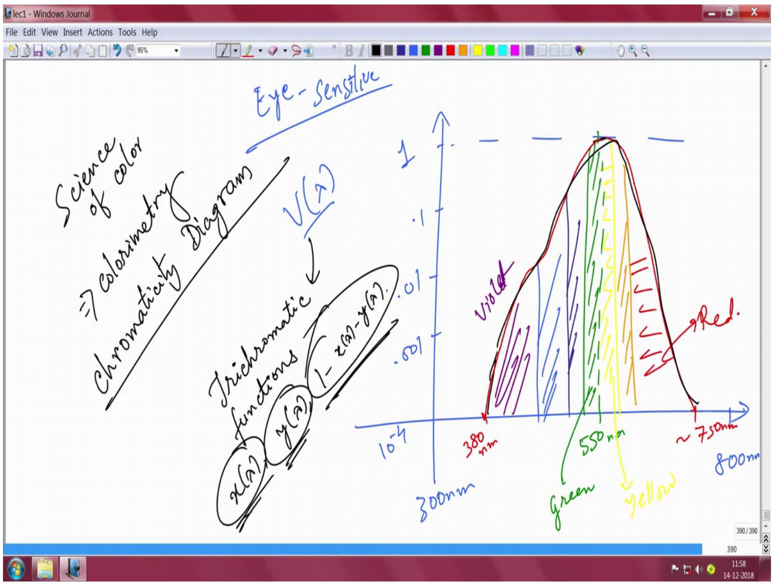

So, that is why there is something called Eye Sensitivity Function, the eye sensitivity function like how is the eye sensitive what wave length is the eye sensitive. So, eye sensitivity is function is called something like v lambda because it is a function of lambda and lambda suppose I go from 300 nanometre to suppose you know it 800 nanometre, so this an eye sensory function this is an arbitrary unit if I can normalise it actually. So, this is 1 [FL] is the eye is most sensitive there and it goes as logarithmic 0.1 0.01 point 0.001 and this is suppose 10 to the power minus 4, so it is a logarithmic scale on the y axis is a distance scale.

So, the I sensitivity function will go something like [FL] second let me draw it again, eye sensitivity function will go something like sorry will go it will not go slightly it will go it will not go slightly it will go steeply it will go like that and it will fall back it will fall back around 750 nanometre and here it will be around 370 maybe 380 nanometre and your peak comes at around 550 nanometre 555 nanometre ok.

So, this is Green this part is Green this is Green when it is more sensitive, just to the right of Green you have you cannot see probably this is yellow you cannot see it probably and then you have orange right then you have red, RED is large this is RED. And then you have of course you know (Refer Time: 13:44) like here then you have Blue of course, then of course you have violet that is how your eye sensitivity function looks like, it is a it is a very quantitative sort of thing and this is how human eye response ok.

So, this is the peak is around 550 nanometre is Green and this eye sensitivity function can be approximated by 3 polynomial, 3 polynomial can be used to approximate that is why it is called a Tri chromatic [FL] because RGB RED Green Blue right it is Trichromatic functions colour matching functions can be used to mimic the human eye vision. You can use 3 functions x of length of the y of lambda and z of lambda and the addition has to be 1, the total summation has to be 1 it is a tri sensitivity functions, so z of lambda is also 1 minus x of lambda minus y of lambda.

So, these are 3 polynomial functions which are used to mimic this particular eye sensitivity function can be mimic by them it can be mimic by that, the science of colour the science of colour is called Colorimetry science of colour is called colorimetry colour colorimetry science of colour is called colorimetry. It is a bit subjective there are many organisations that will have their own principles, but typically we follow international commission for elimination and so using this 3 polynomial functions x of lambda y of lambda and you know 1 minus x minus y we should be able people try to match the human eye sensitivity function.

So, you know there is to get any colour or any perception of any colour you can use different fractions of this x and y and z lambda and so that diagram that will portray any colour with a function of x and y and lambda this is called chromaticity diagram chromaticity diagram chromaticity diagram we will show that chromaticity diagram. So, you know how did this x and y and z look like actually so essentially I will show you here.

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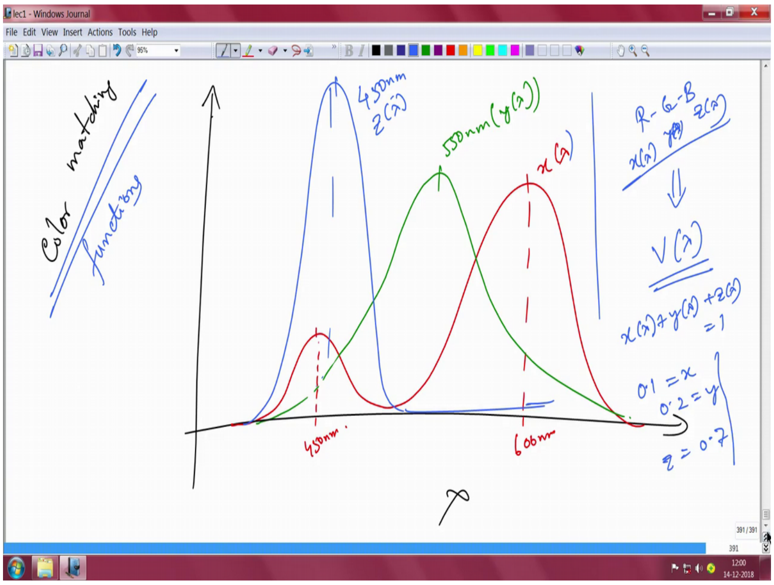

So, essentially you have this colour matching functions this x y and z are called colour matching function. So, if plot that colour matching functions x y and z and this is lambda of course so you will see that you know x for example x, x will have a function like this is your x of lambda this you will keep it around 600 nanometre. And this will you will keep it around say you know 450 nanometre then you have y, y will probably be around something like this and the peak of y will be around 550 nanometre RED Green and Blue of course and then you have z this is this is sorry this is y of lambda ok.

And then you have finally z of lambda which is basically one minus x minus y, z of lambda be something like that and this peak will be on say you know 450 nanometre maybe it is the peak is almost the same is this one. So, these are 3 function these are z lambda and the summation the of this all these 3 which has to be 1 in terms of the normalised value. So, these 3 functions RGB function in a way you can call x lambda y lambda and z lambda ok.

This 3 functions are called colour matching functions colour matching function and by taking any value on this by bringing mix and match of these 3 functions you should be able to replicate the human eye sensitivity diagram is v of lambda, the human eye sensitivity diagram can be replicated by this. So, how much fraction of this is needed for example the addition of x lambda y lambda and z lambda has to be equal to 1.

So, maybe I can mix up say for example, if I mix up 0 0.1 of x and then I mixed up for example 0.2 of y which means z will be equal to 0.7 then what colour will you get if you mix this up what colour will you get. So, there is called chromaticity diagram you can Google up for the chromaticity diagram.

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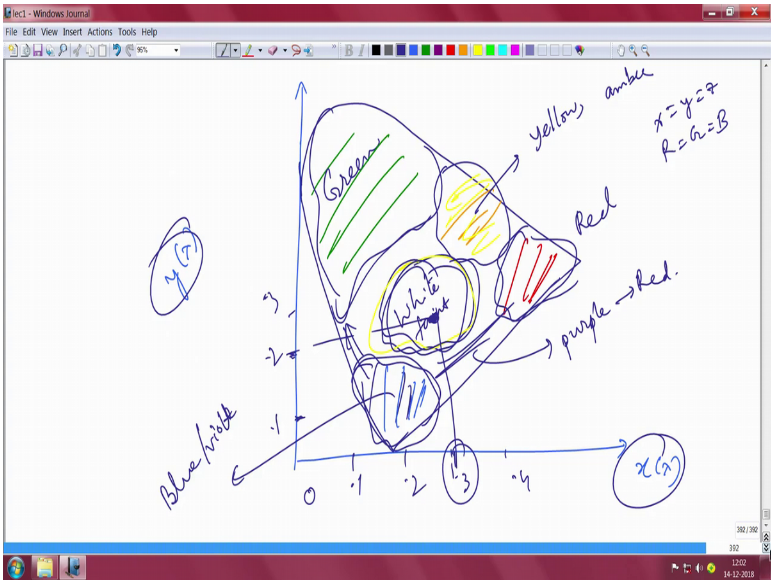

You will see that chromaticity diagram I know on the this side will be y coordinate, so it will be y lambda what is the value of y lambda you are taking this will be x lambda and z lambda will be 1 minus x minus y, so that is not portrayed here the chromaticity diagram will look something like this I will draw it look something like it will looks something like this ok. It will look something like this part this part loosely is like a Blue violet Blue violet and it gradually becomes slightly bluish this part this said this part is Green.

Of course, the intensity varies dark Green light Green and all this thing this part is Green this part is sort of whitish and faint like almost colourless ok, this part is orange and you know like a yellow and amber colour like orange colour sort of thing this colour is like to RED, of course this part is like you can say it is like purple you know RED that goes towards RED and so on.

So, this part is around Green this part is around Blue this part is around RED this part is around orange and yellow right in this part is around this part is around you know white in between, so these values are you know starts from 0 here. So, this will be point one this might be 0.2 0.3 0.4 and so on and this might be also like 0.1 0.2 0.3 these are values of x and y that you are taking.

So for example, if you take a values of you know 0.4 in maybe 0.3 x in x and then may be 0.3 0.2 in may be y and you come here then you get 0. I mean you will get a whitish colour which means if you have almost equal quantity of x and y and z which means if RED and Green and Blue are almost equal quantity 0.3 then you will probably get around white colour, if your RED if your x component is more than you will get more RED if your white component is more you will get Green.

Of course, because z component is more which means x and y both component are low x is point one y is a 0.1, that means z is higher know then you will get Blue because z is more corresponding to Blue. So, this is called chromaticity diagram and any LED and other things have to be compared with respect to the chromaticity diagram so that is that thing [FL].

There are many things associated with this diagram let us not go into so much there, but you know so when you have LED's. So, I will talk in respect to LED is not because LED is what we are interested in right

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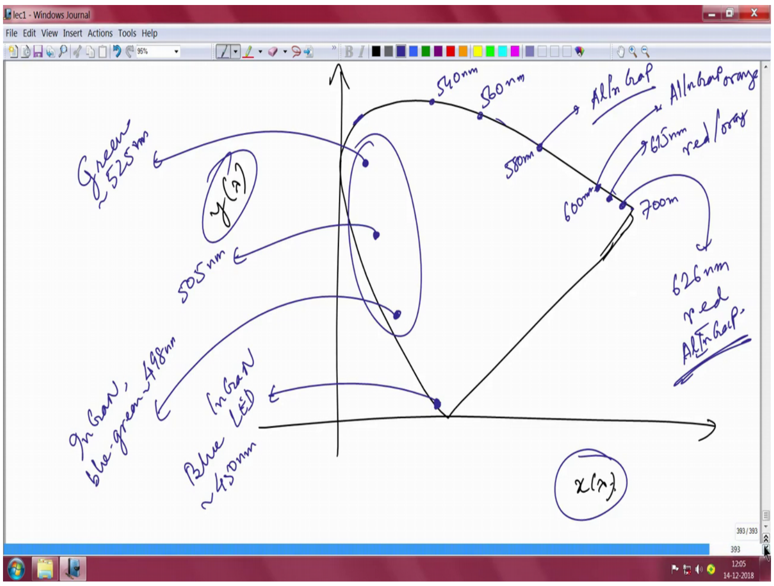

So, this chromaticity diagram you know on this is chromaticity diagram this is y lambda this is x lambda of course, on this chromaticity diagram I will use the black colour only on this chromaticity diagram which looks like this right. Now you know please recall to the previous figure ok, so now you know here so in the chromaticity diagram where are the different LED is positioned ok.

So, I will tell you something, so this at this around this point at this point you have the InGaN Blue LED, the classic Blue LED of InGaN which emits at around 450 nanometre will be at this point in the chromaticity diagram ok. At this point for example will corresponds to InGaN like Blue Green LED Blue Green LED that emits at around 498 nanometre 500 nanometre this point, this point of over here will be again 505 nanometre Blue Green LED of InGaN ok.

This over here at this point will be a Green LED of InGaN that will emit at around 525 nanometre, 525 nanometre this point is 520 nanometre. For example, this is 540 nanometre the wavelength of the light this is around 560 nanometre this is 580 nanometre that is corresponding to AlIn Gap LED AlIn Gap aluminium indium gallium phosphide LED that emits 580 nanometre is there, this will be here 600 nanometre emission of a LED when I say 600 that is the peak wave length LED is not strictly mono chromatic this you have you know 620 650 and this will be like 700 nanometre.

So this will be for example 600 nanometre will be for example, again AlIn Gap LED which is orange AlIn Gap LED which is orange LED then you might have 615 LED nanometre LED which is a RED orange RED orange LED again AlIn Gap and then this could be around say 626 nanometre which could be RED LED based on aluminium indium gallium phosphide. Aluminium indium gallium phosphide AlIn gap LED on the red, so this is how different LED's will correspond to the different points in the chromaticity diagram.

This is the diagram with you basically this diagram is used is drawn by x and y lambda which are used to mimic the human eye sensitivity. So, you see that RED and orange LED's are pretty much on the periphery but Green LED's are not so much on the periphery, But Green LED's are more towards the centre it is an important food for thought and this is about this thing. But you know you know how do you get white LED's from this actually.

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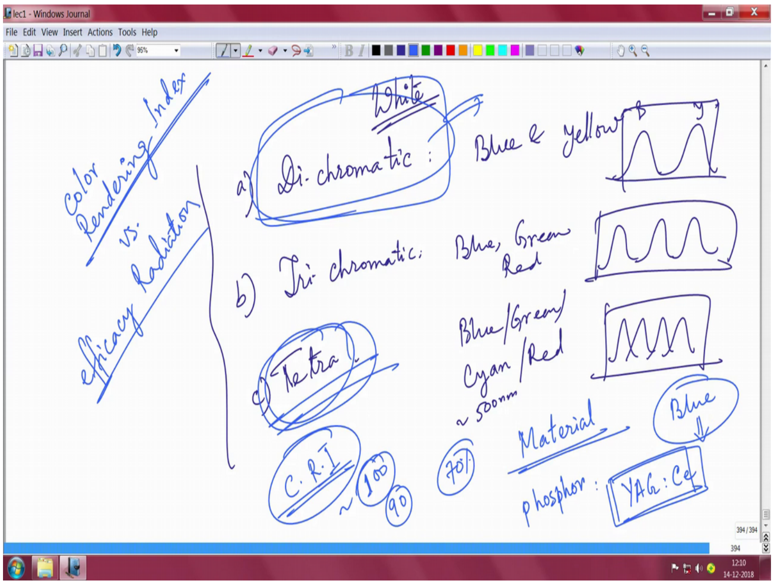

So, white how do you get white light from all this how can we make a white LED, you can have white LED of three categories one is called dichromatic which means you are going to use two sources to make your I will sensitive sense it like a white, you can use Blue and yellow LED.

So, if we use a Blue and yellow LED and mix it an appropriate quantity with some encapsulation you are going to see like a white. So, you have to 1 Blue 1 yellow and the human eye will perceived it as a white kind of thing this is called dichromatic. Of course, it will be the cheapest one, but also not the highest quality one then you have tri chromatic excuse me Tri chromatic where you will mix 3 you will mix Blue you will mix Green an you will mix RED.

So, you have Blue Green RED and then I will perceive it as y it is a little higher quality (Refer Time: 24:23) same in the quality there is something called colour rendering index I will come to that. Then there is also tetra chromatic tetra chromatic will include 4 colours Blue Green Cyan, Cyan is like Blue Green around you know 500 nanometre 0 is cyan Green and cyan and red.

So, you will have 4 1 2 3 4 this will have 4 and then you can make a wide LED their quality will of course be high in tetra also the cost will be there. So, essentially this three LED’s they have a trade off they have a trade off between something called colour rendering ok, that means how good quality a colour you can give I will come that something called colour rendering index ok. They will have to trade of between colour rendering index and efficacy of radiation ok, how efficient they are essentially in terms of saving power and giving light ok. If you get if you want a higher colour rendering index you go for tetra you know chromatic LED you will get very high quality light, but your efficiency will low in the sense that you will have to burn more electricity to get that same colour ok.

So, high so there is called colour rendering index, a high colour rendering index light source means that you can see the colour of the objects much clearly in a high quality, this is important in shops in some offices in homes and all in grocery stores. When you for examples and fruits and vegetables or you have expensive jewellery or clothes in the store you know branded clothes. And all this very nice fruits and vegetables, if that colour the white light colour that is shining on top of the clothes or vegetables is has a low colour rendering index then those things will appear very shaggy you know very bad people will not buy.

So, you need very high colour and living index bulb very high colour rendering index bulb which are used in shops to display things because, they give a very brightness and very colourful appearance. Typically a good you know it should be in a scale of 100, so if you have a colour rendering index of the 100 it means it is the best quality 90 or above is very good, but 70 or low is pretty bad even 80 is not so good ok.

If you have a lower so this will give you have higher colour rendering index this will give you low colour rendering index, but this will give you higher efficiency this will give you lower efficacy of radiation so that is important. See quantity of light will not matter as long as it is bright in terms of places like parking garage or street lights you know parking places staircases there we just need to light up you do not have to display something very gorgeous, then you have to use low colour rendering index because you get higher efficacy of radiation right a higher efficacy of radiation.

So, the material that is used to when you just cannot make some material and expect you know to always give you white light, for example the classic white light made of gallium nitride indium gallium nitride you know you have a Blue LED and that is actually converted to white light, but there you do not have a yellow LED separately, but that will increase the cost.

What do you do is that you the Blue LED and you can you can you have a coating of phosphor around it, so that it will phosphor will absorb and emit in yellow and that yellow and Blue will mix to give your light. So, what is Phosphor? Phosphor is not actually phosphorus by the way phosphorus actually is a complex it is call YAG it is a YAG is a very yttrium aluminium garnet it is a very complex like a oxide you can say and you dope it or you mix it with something very rarer like caesium for example, or (Refer Time: 27:50) iridium or some.

You know some very complex you know nebular material then this is complex is called a aluminium yttrium aluminium garnet you know (Refer Time: 28:00) kind of thing and this is called a phosphor. If you have a Blue LED covered with phosphor then it will convert to yellow and that yellow and Blue will mix 2 give you White ok.

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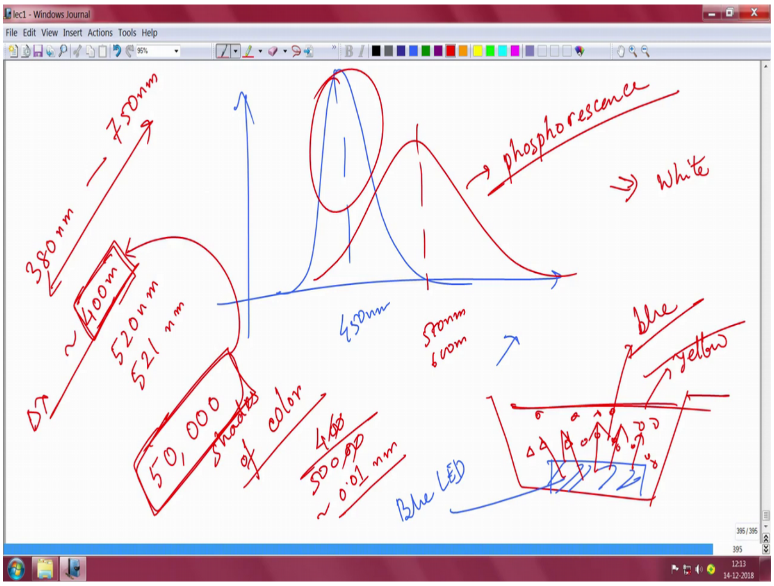

So, essentially what happens is that you know if you have this is the optical power intensity for example and this is your wavelength, then the Blue LED actually is emitting like this it is emitting at around 450 nanometre. But there is also here is also yellow that will come like this that yellow will around come around 570 nanometre for example or 600 nanometre that comes because of phosphorescence phosphor phoresence. This phosphorescence comes around because the phosphor coating convert that by stokes shift and this 2 will mix up and give you white LED light and that white light is actually that comes out in your white LED.

Essentially what happens is that a fraction of this Blue light is absorbed by the phosphor and is reemitted in a longer wavelength yellow and both of them will actually give the white light feeling. So, the way you give this phosphor is there suppose you have this LED encapsulation and this is your Blue LED suppose this is your Blue LED this is your Blue LED chip this is a Blue LED, then you will have phosphor here ok. Let me draw it here you would have phosphor particles this yttrium aluminium gallium things I told you this will have phosphor particles here and that is your Encapsulation.

So, when the light comes for no Blue light comes out this will absorb and phosphor will convert to yellow some of them and some of them will still come out as blue. So, those Blue and yellow mix up and give the colour of the white. The way you can distribute this phosphor also has a lot of thing like (Refer Time: 29:37) distribution conformal distribution and so on. Let us not going to that so much, but that is how white light LED's actually emit you know are emitted from a Blue light, I keep telling that if you stare into a white LED you will see actual this blue.

So, that is however white LED and colour sensitivity functions and so on and so forth. One last question that I will you know leave it with you and then you think about it may be I will not tell the answer is that human eye is roughly sensitive to 380 nanometre to around 750 nanometre that range of wavelength to which human eye can is sensitive is typically around 400 nanometre right, this is the range the delta lambda which human eye can sense be not exactly 400 slightly less than 400 but it is.

So, which means human eye can differentiate colour in this in this range. Now human eye definitely cannot distinguish colour at 1 nanometre, for example 520 nanometre is Green if you show me 520 nanometre and if you show me 521 nanometre monochromatic light human eye will not cannot differential that because, this is too shorter difference right. But eye can differentiate 50000 shades of colour human eye can differentiate 50000 shades of colour that human eye can only be sensitive to around 400 nanometre of wavelength. But there are 50000 colour that human eye can differentiate does it mean that human eye can differentiate every you know 400 by 50000 what is that.

That is like almost 0.01 nanometre does it mean that human eye can differentiate every 0.01 nanometre wavelength no it cannot. So, how is there 50000 shades of colour that we can differentiate, how is it accommodated in only 400 nanometre of wavelength do you know how can? So, that is a question that I leave it with you if you please feel free to talk to me and you know email me your discuss with me about the answer, but that is an important question if you think about.

So, we shall rap the class today here and we are in you know done with LED's. So, we have finished all the discussions that we need to do for LED, today's lecture was mostly on human eye sensitivity function colorimetric chromaticity diagram and how a white light is emitted what is colour rendering index and how we perceive the light of different quality how white light LED's are made with Blue light LED using phosphor coatings and so on and those are the things and you know these are the quantities that are only specifically mentioned or you know discovered or used for human eye sensitivity.

We do not use those terminology for all the other wavelength like UV and IR, but anyways this after (Refer Time: 32:05) portion of this syllabus is done we are now familiar with solar cell photo detector and LED.

So, the remaining fuel excess that are there in the course, we will go with the different types of transistors the required for different cancer applications and also if time permits we can go through some of the steps of practical fabrication to you know get these devices this fabrication and clean room processes that enable this devices whether it is Opto electronic device or electrical device ok. So, thank you for your time we will meet in the next class with starting with application of transistors in different areas ok.

Thank you.