

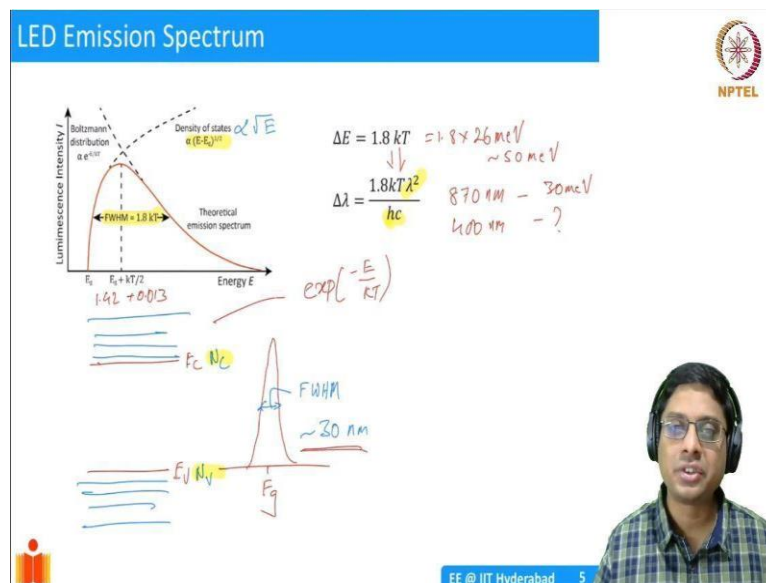
Introduction to Semiconductor Devices
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Lecture - 77
LED Emission Spectrum

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Alright, let us get started. So, in the previous video, we have seen some basic properties of LEDs. We have looked at how light emission happens and then how it can be improved and how it can be tuned, rather. So, in this video, I would like to talk about the theoretical limit of the width of emission of an LED. And then I will introduce hetero structures, which are some fundamental, which are very, very important. They have very significant impact on technology. Alright, to get started, let us see.

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We talked about emission from semiconductor. So, you have these 2 levels, let us say, E_V , and E_C , this is towards two energy levels, you could say conduction band and valence band. And I mentioned to you that the emission looks something like this, you know, you might have a peak around E_g . That is the bandgap. I said, well, that is an approximation. In reality, it is a little bit different.

And I just wanted to briefly tell you that it is more of a you know, additional bit of knowledge. And it is important the line width right, for example, this is the peak, we call this width as full width at half maximum, FWHM. So, this is significant, because it determines the spectral purity of emission and we want it to be as small as possible for various reasons. So, what are the theoretical limits?

If I told you I think already that this will be about 30 nanometres, for a blue LED. So, what are the theoretical limits? So, well, that is depended on the fundamental parameters. So, when I discuss semiconductors in the beginning, I said that, you know, there are this density of states, you know, there are a lot of states about E_C . And then there are a number of states below E_V and we did not really take into account how the distribution of the states is with energy.

We said all of that is simply encapsulated into what we call this effective density of states, which I called as N_C , and for the valence band, it is N_V , these are effective density of states, we talked about in the discussion of semiconductors. But if you want to understand, you know, if you want to go into greater detail, we will have to look at how the states are distributed, you know, in the conduction and valence band.

And I might even have mentioned that has a dependence of \sqrt{E} . So, density of states is proportional to \sqrt{E} . So, from the bandage, you know, they continue to increase \sqrt{E} and below the E_V also they continue to increase as \sqrt{E} that is the way the states are increasing. And as you go to higher at higher energy levels, what is a probability of electron occupying that particular level?

Well, that is that probability is given by what is called as Maxwell's distribution, which is exponential $\exp\left(\frac{-E}{KT}\right)$. If you have 2 energy levels; separated by an energy E , the higher state will have the probability of occupation of the highest is going to be $\exp\left(\frac{-E}{KT}\right)$. And let us say the ground state is 0. That is how Maxwell's distribution was. So, we have these 2 basic curves that you know, the first one is the density of states, which increases as \sqrt{E} .

And Boltzmann distribution which decreases as $\exp\left(\frac{-E}{KT}\right)$. So, because of that, the theoretical limit of emission theoretical curve of emission looks something like this, which is shown in the

red here. So, it turns out that it has a peak, the peak is not exactly E_g , but it is slightly higher than E_g . For example, if you take gallium arsenide, this was 1.42 eV.

And let us say KT is room temperature, so 26 milli electron volts, so I will add 30 milli electron volt 0.13. So, you see that the back of the shift, there is a slight shift. I mean, for practical purposes, you can take it to an E_g that is a reasonable approximation. But if you want to be exact, there is a slight shift. And that increases with temperature. And the other feature is the FWHM, theoretically turns out to be $1.8 KT$.

So, $1.8 \times KT$ was let us say 26 meV. So, 26×2 will bring in 52. So, this will be roughly about 50 milli electron volt slightly less you can calculate exactly. So, that can also be calculated, you know, you can translate that into wavelength units. I mean, if you are interested, you could try this in terms of wavelength and delta lambda it gets this form. So, it is essentially dependent on $\frac{\lambda^2}{hc}$

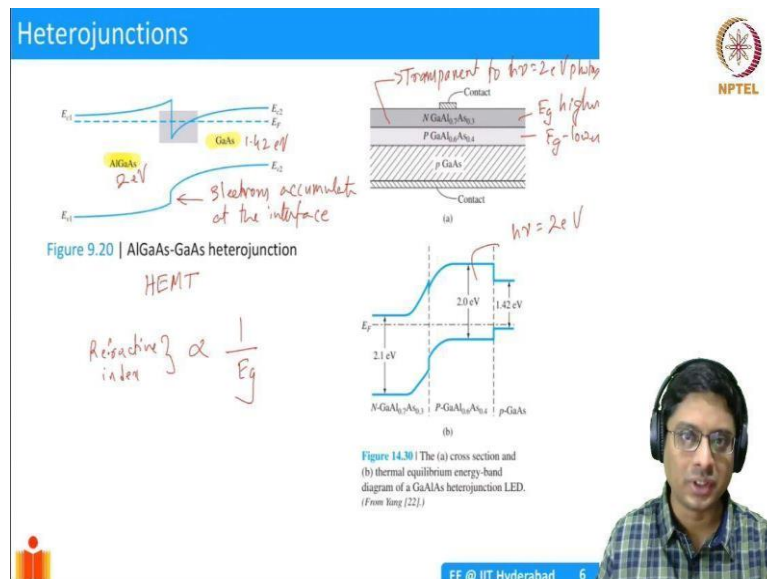
So, because of this you can compute let us say to take typical you know, 870 nanometre wavelengths, you know this is a gallium arsenide wavelength. I think this turns out to be about 30 meV or something like that. But if you take 400 nanometres, blue emission, what will be the FWHM, you can check it out. I told you that for blue LED, typically it is about 30 meV experimental it looks like this.

So, you do not see this sort of a, you know, falling tail experimentally we see the sort of more or less symmetric, it depends on the quality of the LED that we manufacture. Alright, so, but this is useful for us to know how, good our LED devices. So, if it is as close as possible to theoretical limit, then it is better. So, this field, you know, if you notice, there is been a significant improvement in LEDs.

I showed you one chart where in in the lumens per watt was very small initially, but then over the years, it improved. And that improvement happened because a number of technological advancements were done to improve the efficiency. So, when you have a narrower emission, you are essentially reducing emission at undesired wavelengths, and then at the main wavelength visual design, you are trying to improve the efficiency.

That is how we improve efficiency. So, one of the major advances in the development of or improvement of efficiencies has been the innovation, the invention of heterostructures.

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So, we have already seen you know, whatever pn junction we have seen, we have taken let us say silicon p type and n type, same material. But in principle, you could also have two types of materials for example, I can have a junction between gallium arsenide and aluminium gallium arsenide. So, let us say here I have gallium arsenide, and aluminium gallium arsenide. What happens when I make a junction?

Well, gallium arsenide has a 1.42, eV bandgap. And this guy has definitely greater than, you know, 1.4 to let us say, you know, for discussion purposes, let us say this is 2 eV, when you make a junction between these two things, what happens? Well, I mean, there us a lot of things we could discuss, I do not want to get into all that. I just wanted to mention that, you know, the band diagram looks slightly more complicated.

Now, the principles that we applied, we have to add to that, we have to consider the offsets band offsets, while trying to band diagrams, that becomes a little tedious for us. Anyway, so, the final band diagram looks something like this. So, you have the equilibrium fermi level, which is constant. And you notice that the electrons if you have a hetero structure, you know, electrons accumulate at the interface.

This is a very interesting thing that, you know, scientists have discovered and then this has a lot of implications. So, if you know, if you look at the MOSFETs, we want the electrons to be

at the interface. And it turns out that it is not that easy, I mean, we have to dope a semiconductor and then we have to bring the way it causes to achieve inversion then we can get the electrons at the interface.

But in the process of doping, we are actually reducing the mobility of the semiconductor. It turns out that by building such hetero structures, you can actually do not need to dope and still get a very thin layer of electrons at the interface. And so, this sort of devices, you know, are very popular. And they are called as the HEMT devices, high electron mobility transistors. I am digressing so, I just wanted to introduce heterojunctions.

So, let me get back to the discussion. So, you can have pn junctions with hetero junction, we know pn junctions consisting of different materials. For example, here on the right, you are seeing you know gallium arsenide, on top of it, we type gallium arsenide, gallium aluminium arsenide, and then the increased concentration of aluminium. So, basically, you have 2 materials. So, we saw that as you increase the aluminium E_g increases, E_g higher right.

This is E_g relatively lower. So, as you increase E_g , what happens? Well, it has an advantage, because let us say if you emit photons in this region, $h\nu = 2\text{eV}$ it will emit photons. The idea is that we want to extract as much as possible outside as many photons as possible outside. So, when you have a higher E_g material on top here, especially it is transparent to the photons.

So, this particular material is transparent to $h\nu = 2\text{eV}$ according to eV photons. So, that is an advantage, you can improve the collection efficiencies by building heterostructures, we still maintain the same, you know, the pn junction, but then we have a better collection efficiency. There is an added advantage that is, if you look at the refractive index of materials, it turns out that this is proportional to $\frac{1}{E_g}$, is inversely related to the E_g .

So, if you have a higher bandgap material, it has a lower refractive index. And that also improves the external quantum efficiency of LED. So, this is one use of heterostructures. I mean, I am trying to only give you a snapshot. So, of course, there is a lot more that we can go into, but it is not required for this course. I just wanted to mention one more aspect of heterojunctions that is useful that is formation of double hetero structures.

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Double Heterostructure

Figure 14.38 (a) Basic double heterostructure. (b) Energy-band diagram under forward bias. (c) Refractive index change through the structure. (d) Confinement of light in the dielectric waveguide. (From Yang [22].)

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So, what we can do is? We can sandwich a smaller bandgap material between two higher bandgap materials. For example, I can put a gallium arsenide let us say here, my gallium arsenide, I can send it sandwiched between 2 higher E g materials like this, this could be aluminium gallium arsenide. Why would I do that? Well, I can create different doping. For example, here trying to be consistent with the figure on the left.

So, I will take this to n type. And then I will take this to p type. So, now we know from our basic semiconductors, that electrons will come to the lower energy states, because there is a lot of states available gallium arsenide, so they are nicely come into the gallium arsenide. Similarly, holes will come into this part. So, what you are having is, you know, you can control this by your growth techniques.

You can control let us say, this is 100 nanometres, I just put the thickness, some nanometres sickness. Then, I am actually you know, in a regular pn junction, the photons are emitted everywhere, I mean, there is a diffusion of carriers, and they can recombine at any location within the diffusion length. But instead, if you form a hetero structure, you can force it to happen from a certain physical location.

And that will improve the efficiency of like an issue. So, in principle, what we are doing is qualitatively the band diagram looks like this. So, you are actually injecting electrons into this region, the sandwich region. Similarly, you are injecting holes into the sandwich region and you are having light emission from there. This is a very, very crucial phenomena for construction of lasers.

We will discuss that in the next lecture. But I just wanted to introduce a concept since we are talking about heterostructures. And there is an additional benefit, I talked about refractive index be inversely proportional to the bandgap. So, if you have a hetero structure like this, the smaller bandgap region has a higher refractive index. Because of that, if you look at the refractive index profile, it is lower effective, high refractive and low refractive.

So, the difference is not really that much. No, it is just in this case, it is about 5% or so, very small change, but it still is enough to confine the light in that region. So, if you look at the light emitted from the photons that are emitted there going to be confined mainly to the region in between the sandwich region and because of that, we can make improve light efficiency or you know, devices better quantum efficiency.

So, this is called double hetero structures because we are having confinement, confinement off both photons and electrons, that is why we call it a double heterostructure. So, this is very, very useful technology. And because of this importance, it was given Nobel Prize in the year 2000. So it is, I mean, it has really changed electronic industry.

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The slide, titled "White light LEDs", compares two types of white LEDs. On the left, "Phosphor based LEDs" are shown with a graph of Intensity (a.u.) vs. Wavelength (nm) from 400 to 800 nm. It features a sharp blue peak at approximately 450 nm labeled "Blue light from LED chip", and two broader peaks labeled "Green phosphor" (around 520 nm) and "Red phosphor" (around 620 nm). On the right, "Multi-color LEDs" are shown with a photograph of a chip emitting blue, green, and red light, and a color wheel diagram with R (Red), G (Green), and B (Blue) segments. Below the color wheel is a graph of Intensity vs. Wavelength (nm) showing three distinct peaks for Red, Green, and Blue light. The slide includes the NPTEL logo in the top right, a small book icon in the bottom left, and a video inset of a speaker in the bottom right. A URL is provided at the bottom: https://en.wikipedia.org/wiki/Light-emitting_diode and the text "EE @ IIT Hyderabad" is visible.

So, before I close, I just wanted to introduce white LEDs, you know, these are very useful for practical applications because you know, they can be used in lighting and displays. There are two broad classes of white LEDs. One is Phosphor based LEDs, other ones multicolour LEDs. So, I mentioned photoluminescence before. So, if you have a material, you can pump it with a high energy photon.

And those photons, the electrons, you get excited, you generate electron hole pairs, and those can relax the edge of the band and then emit a different wavelength. The materials which can exhibit that are called as phosphors, then it is not phosphorus, it is phosphor. Phosphor is type of material, it can be very complicated, you know, it can have a lot of different materials. So, you see that here in the picture, on the left, there is blue light emitted by LED.

And that I can use to excite a phosphor and phosphor can have relatively broad wavelength emission. In the case of displays, we want it to be broad, we do not really like it to be very narrow, not sorry, display. In the case of lighting, we wanted to simulate white light. So, we can excite a green colour phosphor or a red colour phosphor or both. When you do that, you get emission or a broad range, and you get white light.

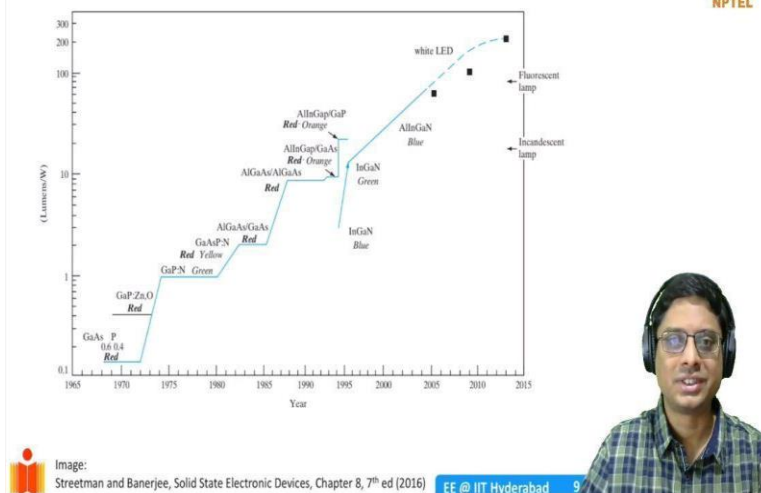
So, this is quite now well researched because of which we see that you know, you have white LEDs in our homes. So, this is a lighting application. In the Display applications, we use multicolour LEDs. So, what we can do is? We can take different LEDs, for example, red, green, and blue, you make them on a chip, you connect them, you inject carriers, and then you generate light.

And you see that if you have a combination of red, blue and green, you can get white light. If you have only red and green, you can get yellow, if you have red and blue, you can get pink and so on. So, by controlling the combination of these 2, these 3 colours, you can generate various colours. So, you can use this for display monitors, TVs and so on. So, I just wanted to give you a snapshot of it again, the three colour emission is what is it from Wikipedia, I can go back and read.

So, this is about applications of LEDs. And I just want to close by going back to the graph that I have shown you already.

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Recent improvements in luminous efficiency



So, this was basically over time, how did the lumen intensity, or an emission efficiency rate of LEDs changed. So, this is lumens per watt, I think I have shown you only up to 2000 or so in the last lecture. So, I just found some of the graph which actually compares it with the most recent development. So, you see that in this decade, we have already reached about 300 lumens per watt sort of efficiency, which is very, very good.

And that is why we see semiconductor LEDs standard is so prominent, they become quite cheap as well. So, with that, I would like to stop the discussion of LEDs and in the next lecture I will talk about laser diodes. And with that, that the course will be complete. So, thank you very much for your attention. I will see you in the next lecture. Bye.