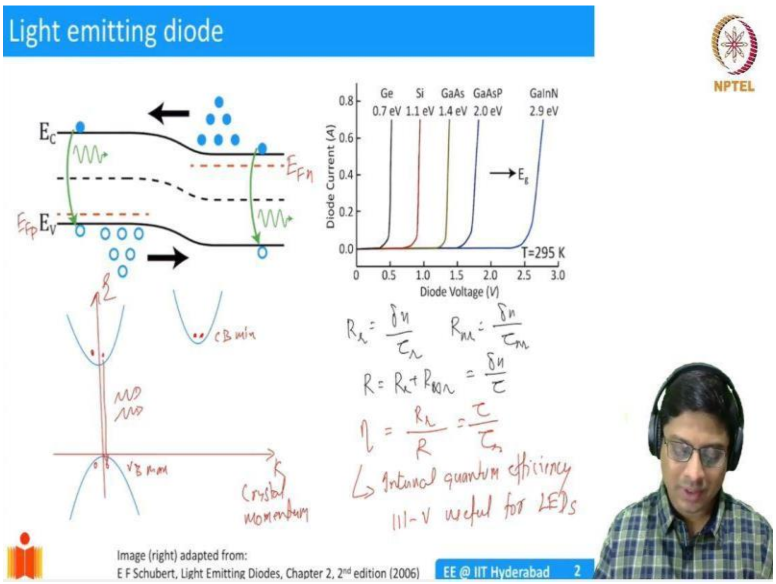
Introduction to Semiconductor Devices
Prof. Dr. Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology, Hyderabad

Lecture - 76
Operating of a Light Emitting Diode (LED)

Alright, welcome back. So, this is the last week of introduction to semiconductor devices. In the last lecture, we have seen how optical emission is possible and what are the various materials for optical emission. So, in this lecture, I would like to give you a quick overview of light emitting diodes. So, the light emitting diodes and also lasers, they are actually a full, you know, there are a significant subject by themselves.

And you could go into a lot of depth, but today my goal would be to give you a basic overview. So, I will show you what are the key developments, there might seem a little disconnected, but I would ask you to you know, be patient and then if you want more information, you could always refer to the sources in every slide, I would put some references, you can always go back to the references and read up a little bit more.

(Refer Slide Time: 01:10)



So, what is the light emitting diode? Well, a light emitting diode is very similar to a pn junction. So, this is a band diagram of a pn junction in forward bias you have seen it many times so, far in this course. So, essentially here we are applying a forward bias so, there is a difference in the quasi Fermi levels. So, this will be your E_{Fn} and this will be E_{Fp}. So, the splitting of Fermi level happens because we are applying voltage.

And because of this the barrier is reduced and your electrons are injected into the p side holes are injected into the n side. So, the minority carriers are injected. So, what happens after that? So, in principle, what could happen is a hole can recombine with electron like in the p side. So, the holes are majority carriers and the electron can recombine with the hole and give out a photon.

And similarly, in the n side an electron can recombine with a hole and get a photon. So, the main distinction between a simple pn junction that we use in electronics and LED is that we use direct bandgap semiconductors. The reason this is important is, we have already seen it a couple of times that you know your bandgap if you look at the E k diagram. So, this is k versus E so you have the peak in the valence band.

And in a indirect bandgap semiconductor this peak in the valence band does not coincide with the dip in the conduction band. So, this is an indirect bandgap semiconductor. So, this is CB minimum, this is VB maximum they occur at different k s, and this k is crystal momentum we talked about it in the beginning. So, essentially how the electron moves in a lattice? So, now, we have a lot of these electrons.

If you take a simple pn junction with , and inject electrons and holes with forward biasing what happens is you will have lot of electrons here. And we will have a lot of holes here, but they cannot recombine because when they emit a photon, you saw that the photons energy , you know it could be on the same order of magnitude here, but then the momentum of photon is very very small.

So, it has to be accompanied by an emission of a phonon. And because of the second order nature of the process, indirect bandgap semiconductors are not really efficient optical materials because especially for optical emission they are not good. You can still use them for detection, but emission they are not really good. So, instead if you have a direct bandgap semiconductor, the conduction band minimum will basically coincide with the maximum of the valence band.

So, now you can have your electrons easily recombining with holes and giving a photon, this is a very easy process very simple process. So, how do we quantify this emission of photons are real or not. So, we talk of various we talk of mainly two types of recombination processes. The first step of recombination process , So, the first step of recombination process is what we call as radiative recombination.

And we have seen that the recombination is basically dependent on density of the excess minority carriers divided by the lifetime of R n call it.

$$R_r = \frac{\delta_n}{\tau_r}$$

. This is one of the processes radiative recombination that means it is emitting a photon. The other process you know, the it can be a whole bunch of processes. It can be you know, trap assisted recombination or surface recombination or you know, what are the many different processes.

So, all of that will bunch into what we call us non radiative recombination and the rate again will be dependent on delta n. So, tau n r, these are the 2 channels.

$$R_{nr} = \frac{\delta_n}{\tau_{nr}}$$

And of course, you know, you can the total recombination rate is going to be r you know, can we like total recombination is simply a sum of these two recombination rates. And I could just define it by delta n by tau I can just give it delta.

$$R = R_r + R_{nr} = \frac{\delta_n}{\tau}$$

So, this is going to be the effective recombination time, the total recombination time rather. So, now, in a light emitting device, for example, LED we would like the radiative process to be dominated, we do not like the non-radiative process. So, the way we quantify that is by a term which is known as internal quantum efficiency. And defined internal quantum efficiency by the symbol era and that is essentially going to be radiative rate divided by the total rate.

$$\eta = \frac{R_r}{R}$$

So, this I will call us internal quantum efficiency is an important characteristic. And if you want to talk in terms of lifetimes, so R is inversely proportional to τ . So, you could always write this as τ. And radiative rate is inversely proportional to τ_r, so I will write it as τ_r, here. So, if you have a very short recombination time, radiative recombination that we like, I mean, it will with a lot of photons.

$$\eta = \frac{R_r}{R} = \frac{\tau}{\tau_n}$$

And direct bandgap semiconductors have a very short radiative recombination time that is really recombination rate is higher. So, this is the main difference between you know, direct and indirect bandgap semiconductors and because of which, direct bandgap semiconductors are useful for III-V for LED's, III-V materials, or sorry, III-V useful for LEDs. If, you just look at the I-V characteristics, you make a diode out of silicon and III-V.

I-V characteristics will look similar to that. So, this is just a schematic illustration of that. So, here I am showing you various materials and the bandgaps here on the top here. So, if you made diodes out of this, just simply drop the material has p and n and then you make diodes, then you see that IV characteristics essentially look similar. You know, the threshold like behaviour.

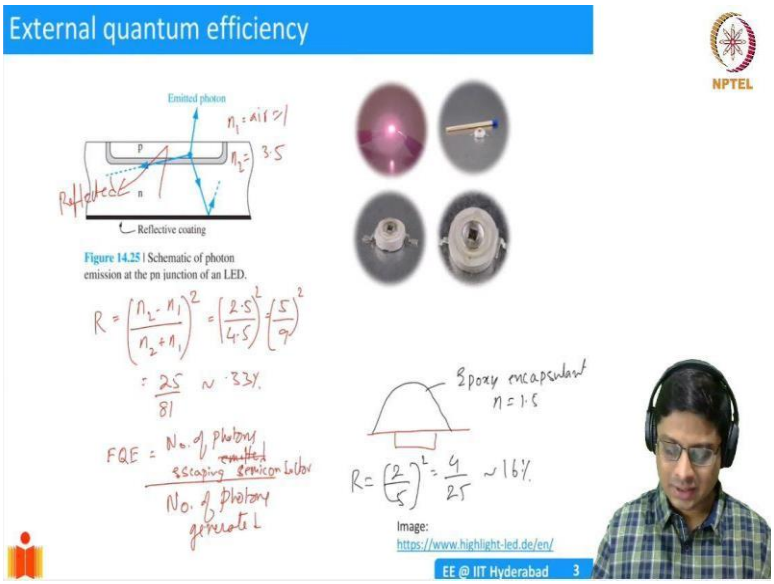
The threshold shifts, the reason is, we saw that in a pn junction, the maximum threshold that you can achieve is essentially when your formula was you know, the n-type goes to Ec and the p-type goes to Ev. So, the maximum VT that you can achieve is about the bandgap. It is usually slightly smaller than the bandgap. So, unless you dope it very, very high? So, that is not a very ideal thing to do.

So, roughly the VT will be of the order of the bandgap. So, if we choose let us say gallium nitride devices, the bandgap is 3.3 eV. So, the voltage threshold voltage will be large, but then I can combine with Indium to bring down the bandgap a little bit we know there is this gallium indium nitride which has about 2.9. Just this is a schematic illustration just to tell you qualitatively what is happening? So, electrically there is not much of difference.

In fact, you know, we use some of these III-V nitrites for high power applications. For example, let us say you know, your power electronics and you know, switching the supply of voltage supply of current to the home and all that, we have this high tension wires and stuff like that. So, where you want to have high power electronics which can withstand large voltages or pn junctions will break the regular silicon based pn junctions will break down within you know a few tens of volts.

But you want them to withstand large voltages. So, we have power electronic devices that can be built that is an entirely different branch of electronics. That is also interesting. So, we are not really touched about any of the power electronic devices, but this is the only difference. But they also have the same operating principle. So, you could easily learn that all. So, this is you know, this is how the pn junctions are different from light emitting diodes. So, internal quantum efficiency is one of the factors.

(Refer Slide Time: 09:41)



The other important factor is what we call an external quantum efficiency. That is, you know, it is well and good for a photon to be emitted. But will the photon be transferred outside the semiconductor? That is an important thing. And that is a concern because if we just you know, take a schematic cross section of LED, it could be something like this, you can have a p region, you can have an n region, there is a depletion region.

You forward bias we are just doing the bare minimum parts and then photons emitting. Will the photons emitted come out? How many of the photons will come out? So, internal quantum efficiency tells you, for every electron how many photons are coming out, but you know, out of the photons emitted how many will actually reach outside, because some of the photons can easily be absorbed in the semiconductor.

So, that is a concern because, you know, they can also be some reflections. The reason is, if you of the semiconductor having, let us say refractive index of n2. And also, this outside air, right is called air basically 1. Inside this is n2, I will say roughly 3.5, this is just a typical number. Of course, this is going to wavelength dependent will have to be exact about it, but I will assume that at a particular wavelength is 3.5.

So, how many of the photons will come out? Some of the photons will simply hit the interface and come back, they will get reflected. So, this is basically going to be reflected. So, reflected photons are going to be absorbed in the semiconductor, let us say no, or they can just go multiple cycles and then they get eventually absorbed. So, what is the reflection coefficient? When you have this difference in refractive index.

So, the difference in refractive index will lead to what is known as condensed reflection coefficient. So, R that is simply given by

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

So, how much would that be? Well, if you take n2 of 3.5 and n1 of 1, so this is going to be 2.5 divided by this is 4.5. So, this is 5 by 9 oh sorry, this is a square. So, how much is this? 25 by 81, roughly now, I will just say 1 by 3 I will approximate it with a 33%.

1 by 3 will be 25 by 75 slightly less than 1 by 3. So, 33% of reflection. So, if you have 100 photons 33% are actually getting reflected only 66% are coming out and this is known as external quantum efficiency. Now, there can be other things you know, some of them can be

absorbed also. So, effectively external quantum efficiency quantifies EQE quantifies the number of photons emitted divided by number of photons generated.

Maybe you know, I should not call it emitted because you know that might be confusing. Number of photons reaching outside escaping semiconductor. So, what is a way I mean this seems like a large number 33 1 by 3 of the photos are getting reflected that is not a good thing. So, in the semiconductor LEDs if you noticed, now, you would see that you will have LED chip which is let us say some p n junction and all that.

There is some chip here which is something on top of it you will see a dome like material or something like this, some curved shape it looks like a glass. So, these we call as epoxy encapsulate. Basically, you are using epoxy. Epoxy is type of a glass you can think of it and then that will surround the material because of which, this can have a refractive index of let us say 1.5. If you have a refractive index of 1.5 now, what will be the reflection coefficient?

R is going to be into is you know what is 3.5. Now, no one is 1.5. So, $\left(\frac{2}{5}\right)^2$. So, 4/25, so, now it is much smaller 1 by 6. So, this is about 16% roughly 16.5%, something like that. So, we are managing to like have less reflection, and this is kind of shaped in a way it is shaped in a curved way so that most of the photons will finally come out.

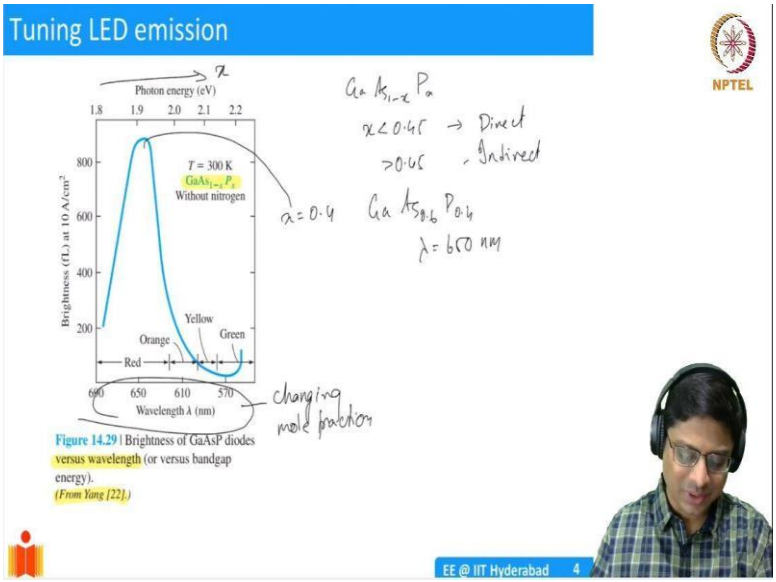
And there is a lot of research ongoing; about you know, using high index epoxies or you know, graded index epoxies and things like that. So, to basically to enhance the collection, improve the collection efficiency of the light emitted in LED. So, I just picked up a few images from the web. So basically, these are how LEDs look like, if you break up one of the lands in your home, you will find something like this there will be a chip.

Sometimes you might find something small encapsulants surrounding it, the size of the chip is quite small. But I mean, you could try it as an experiment, you know, for some projects, you know, break open a tube light and see what kind of chips are there and, you know, you try to apply a voltage to that with the battery, and you will see it glowing, it is fantastic, we should try it out. You can explore or you know, take a broken LED.

LED tube light which is damaged and you can experiment with that, you can actually open it and you will see an area of LED chips on it. You can experiment there are even you know, YouTube videos explaining how to check them and all that. So, if you are interested you can always take a look. So, these are the 2 parameters. Of course, there are a few more things we can always get into greater and greater amount of detail.

But I think for this course, internal quantum efficient external quantum efficiency are the main things that I wanted to touch upon. And we also mentioned that you know, you can tune the wavelength.

(Refer Slide Time: 16:15)



We can of course, you know, have semiconductors at every particular Eg, you can only have you can change the composition of the semiconductor by changing the mole fraction is what we discussed. Now, in the last lecture, we talked about gallium arsenide phosphide, wherein, if you change the x, which is a mole fraction, if x was, I think we change x = 0 to 1. So, if x is less than 0.45, it was direct bandgap.

And if it was greater than 0.45, it was indirect bandgap I remember it correctly. So, now what happens is, as you change x, you can try to look at how Eg changes. You know, on a curve, we showed you that there is a line that we are showing, but how do you determine that? Well, it turns out that you do experiments to figure out those things. So, this is one such experiment, which shows you the LED emission as a function of its wavelength.

But in fact, you know, if you look closer actually, this is based on changing mole fraction. mole fraction, so, if you change the mole fraction, you are changing bandgap and because of that, the emission is change. So, you see increasing x this is basically. So, and you will see that the brightness of the LED you fix the amount of current that you are supplying into the LED. So, larger amount of current you get larger photons, number of photons.

So, and you see that at a certain wavelength there is a peak, I think this peak turns out to be for this particular case, x is = 0.4 or so. So, gallium, arsenic, phosphorus, like $GaAs_{0.6}P_{0.4}$. These devices will give you a light emission at λ = 650 nanometres. In fact, this is experimentally shown that this is taken from this, you know, the textbook refers to this particular book, which has a lot of information.

But that is really a lot of information for you guys. I just wanted to point out this thing for you. And if you continue further increasing x, it becomes indirect bandgap semiconductor and because of the efficiency of light emission reduces. So, you might ask me, why is this peak here? It turns out that there is a lot more physics behind it. And I do not want to get into it right now. I just want you to accept that this is an (()) (18:45).

Take it like an experiment. For the purposes of this course, it is we do not need to get into why the peaks are appearing and so on.