Fundamentals of Semiconductor Devices
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Lecture - 50
Basics of recombination

Welcome back. So, today we shall start with LED; Light Emitting Diodes ok; till now we have studied about photodetectors and solar cells where light that falls is converted to electricity.

We will start the reverse topic where you are injecting electron holes by applying a voltage and you are getting light as output. In solar cell and photo detector detectors light was the input and electricity was the output because, photons getting absorbed in the semiconductor creates an electron hole pair right. An electron from the valance band absorbs the photon, gets excited to the conduction band that is available for carrier transport now it creates a hole behind right.

The reverse process is that your injecting electrons and holes and you expect them to recombine in the depletion region and recombine radiatively. So, that it can that energy that is lost in recombining is emitted is a photon that is the basic principle of LED. LED is also very vast topic, there can be many courses on LEDs. We shall keep things fairly simple and we will try to understand the basic working operational principle of LED and many other kinds of LEDs ok. So, let us come to white board here.

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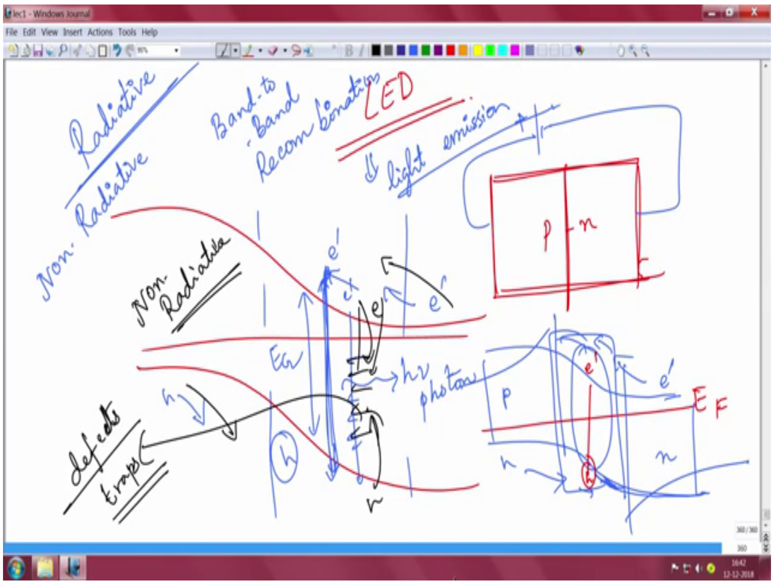

So, we will talk about LED; LED is the opposite of your photodetectors. So, what happens if that LED has to be a p-n junction ok. If you look at the white board here so, you have a p-n junction; this is p and this is n for example ok. The idea is that LED is also a p-n junction, a solar cell a photo detector can also be a p-n junction.

We talk about this Fermi level here and then this is your band diagram ok, this is your p, this is your n. And now remember that your just like photodetector you can emit light at different wavelengths by using band gap, different band gap material which are direct band gap ok. So, LEDs are always biased in the forward direction which means you have positive and you have negative.

So, you bias that then what will happen is that electrons will be injected this way, holes will be injected this way, it is a majority carrier device not a minority carrier device like photo detector. And this electrons that go you expect that they will recombine in the depletion region because, once they come this edge they will diffuse away. Once they come this edge they will diffuse away, you want them to recombine in the depletion region.

Once the recombine in the depletion region the idea is there if they recombine radiatively band to band electron and hole you see. This is your conduction band, this is your valance band; if the electron and the hole combines from conduction into valence band that is called band to band conduction band to band recombination, band to band right band to band recombination.

Band to band recombination electron in the conduction band and hole in the valence band; you are injecting hole from this side, you are injecting electron from this side; the idea is that they will recombine in the depletion region. If they recombine radiatively this is very important term. What do I mean by radiative recombination? I mean that the energy that is lost when an electron and hole recombines and electron will fall back from here to there recombine at a hole. That energy that is lost band to band ok, if it is radiative which means that energy lost is given away as a photon that photons energy will correspond to the energy of the band edge or the band gap here right.

Then you get light emission; then you get light emission or LED light emission or LED you get ok. Please remember that recombination has to be rediative and band to band. The reason I am stressing this so, much is that there could be non-radiative recombination also which means an electron and hole might recombine from the conduction and valance band, but the energy is not released as a photon.

It is released in the form of heat to the phonon the lattice vibration or any other kind of other things that is a non-radiative recombination, it can also happen in direct bandgap material if the middle quality is not good ok. You do not want that there could be many defect states, there could be many defects in the material in the band gap.

These defects will manifest as trap states in the band gap and these traps can also recombined, the electrons can recombined at the traps also. The holes can recombined at the traps also most of them are non-radiative recombination which means the electrons and holes that you are injecting that you are injecting those electrons and holes are recombining with some traps defect states.

And then there because its traps and defect states will eat away the electrons holes you can say. So, then those will lead to non-radiative recombination and not contribute to light emission, it will kill your efficiency right. The whole idea of an LED working is that you are injecting excess carriers by applying a voltage.

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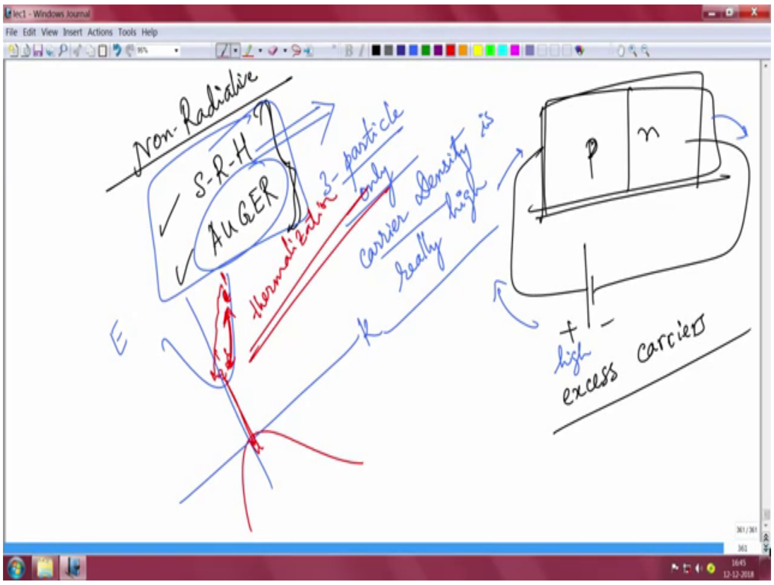

You are having a p-n junction and you are essentially forward biasing it to inject excess carriers. And this excess carriers have to recombine radiatively from band to band in order for the LED to work because, defects states can take away the electrons and holes know that is not good. And so, radiative recombination efficiency is what matters in LED. I told you non radiative recombinations are there two primary non-radiative recombinations are one is the Shockley-Read-Hall recombination; the trap related and one is called the Auger its looks like Auger, but it is called Auger recombination. Probably I have discussed Auger recommendation also in the one of the earlier classes, but I will tell you anyways.

So, this kind of recombinations will not lead to radiative recombination, not lead to write and light emission. They are useless, wasted recombinations of electrons and holes that you are so, you know much injecting in the device and that injected electron holes are basically recombing through this then your device is waste; because you will get very low efficiency.

Shockley-Hall-Read efficiency the recombination is with trap recombinations and so on. Auger recombination is a three particle non-radiative recombination that happens only when the density carrier density is very high, only when your carrier density is really high. What I mean by really high is that your biasing the LED at very high voltage.

So, that you are getting very high injected current and this very high injected current means that you are injecting a lot of excess carriers. If that is the case then only Auger recombination comes into picture. If you recall E K diagram, this is your E and this is your K and what does Auger recombination mean is that this is your valance band, this is your conduction band. If you are injecting carrier you know you have an electron at very high energy electron, you if the electron falls down and recombines with a hole the extra the energy that is lost is not emitted as a phonon or I mean as light.

It will use that energy that is lost to excite another electron up in the conduction band from where it was to another higher position. You see my point the energy that is gained or the energy that is I mean the energy that is dissipated when an electron and hole recombines does not come out as photon, but it is used to excite a third electron and a third particle to go to high energy. And that high you know electron in a high energy state will eventually come down to lower energy state by thermalization [FL]; it is losing energy by thermal process.

So, this is your non-radiative process and this Auger recombination becomes dominant non-radiative recombination process when your injection density is high, when you have very large number of carriers. So, you have n plus p plus dope layer sort of things. So, that is the thing; now you remember the essentially LED is the opposite of photo detector right.

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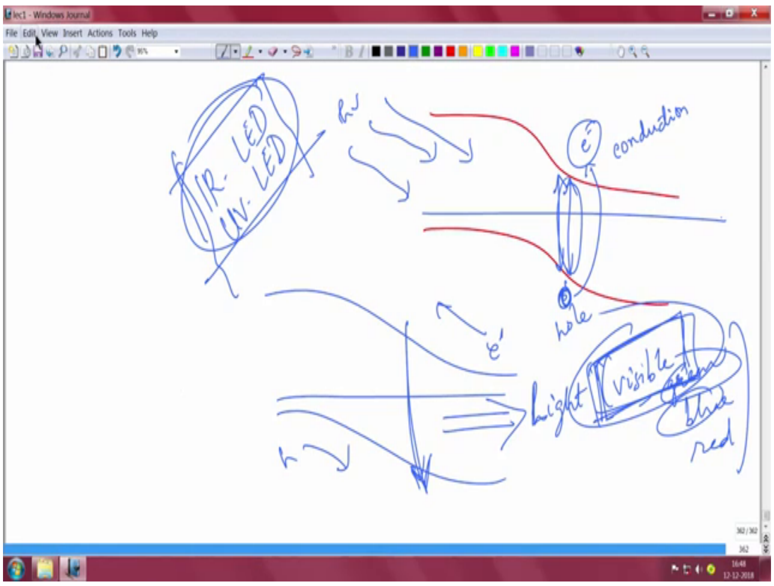

In a photo detector if this is your the band diagram again you are shining light. The photon that is coming and absorbing here, the photon that is absorbed here that is absorbed by electron from the valence band and electron can take that photon energy and get excited to the conduction band here, conduction band. And when the electron jumps go to the conduction band it leaves behind a hole here, that is how a hole electron pair is created by absorbing energy of the photon.

Of course, the photon energy has to be equal to or more than the energy of the band gap. A LED is a reverse process, I keep telling you where electrons and holes that you are injecting electrons and holes that you are injecting will recombined band to band and idea is that they will recombine radiatively, so, that they can emit light. They can emit light now, the light can be again it can be visible. So, as to you can say you mean to say it can be green, it can be blue, it can be red, orange, yellow whatever. They can be used for display applications many of the laser diodes and other things visible LED of course, wide LEDs is used for lighting purpose.

It is a very big industry based on gallium nitride LEDs I keep telling you, but when you talk about visible LED that is a LED is that are a green blue whatever the visible LEDs; you are talking about the LEDs that are sensitive to eye that is a different ball game. You might also talk about infrared LEDs and you might also talk about UV LEDs, but those emit light that are not visible or sense the eye is not sensitive to those wavelength. Then in that case you cannot compare the human eye perception, you know there is a science of human eye perception.

The vision of human eye and chromaticity diagram like how do you perceive colour and colour depends on the ambient light. All these things how bright an LED is, what is the colour your perceiving based on the light that you are shining. For example, depending on tube light or an LED bulb you might perceive the colour of a you know material little differently.

All those things are important only for visible LEDs not for IR and UV LED ok. We also talk about visible LEDs slightly more details because, that is what is more widely used you know. But, now you know that whatever be the case an LED can be only made from a direct band gap material.

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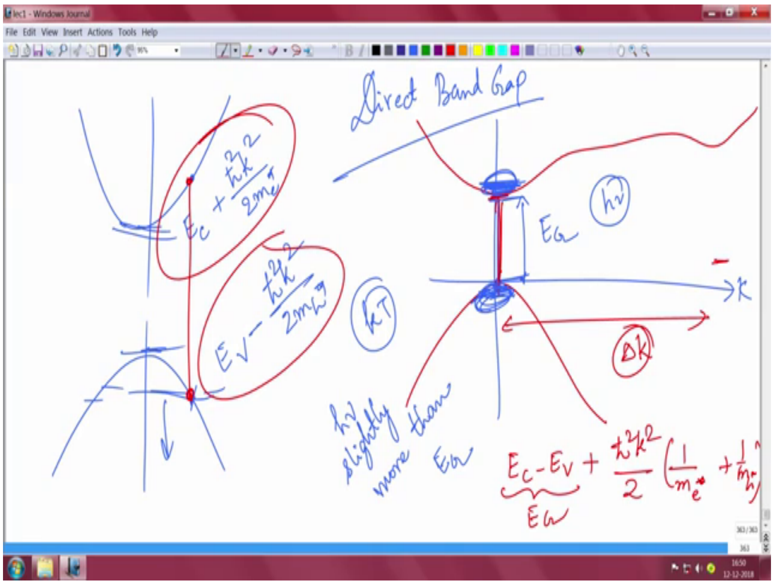

An LED can be made only from a direct band gap material that you know now right. So, it what it means is that in an E K diagram, if you have your conduction if you have your valence band like that a conduction band minima also should be on the same K.

So, that electron hole can recombined without any change in momentum because, if your conduction will minimize somewhere here than electron hole recombination will have to change the lot of momentum; that momentum change makes a very inefficient you cannot emit light ok. So, that is why you need to have direct band gap materials, silicon cannot emit light that remember. Now, suppose I talk about a diode band gap material only like that ok, you see there is always a distribution of carriers here.

Electrons will occupy the lowest part, holes will occupy the lowest part, the centre of the distribution is not exactly at the band edge. So, although the band edge or the band gap is E G the light emission wavelength the energy the photon will be slightly more than the band gap because, the electrons are distributed like this and holes are distributed like this ok. So, slightly you know because that room temperature any temperature T there will be distribution and there is a room temperature energy associated with it. So, that is why the energy of the photon emitted is slightly more than E G, very slightly more than E G; you get my point right is slightly more than E G ok.

Now, if I talk about the E K diagram again this is your conduction band, this is your valence band ok, this is the bottom of the minima, this is the maxima that is minima. At any point here I can write it as this is the reference for example, this is reference. I can write the energy as E C plus h square excuse me k square by 2 m electron. Similarly, at any point here I can write the energy as E V minus this is going the other direction, you know h square k square by 2 m whole.

So, actually the difference of the energy is this of emission for example so, that is actually E C minus E V plus which is the band gap you have to subtract this from this. So, that is equal to h square k square by 2 1 by m electron plus 1 by m whole that is like the harmonic mean ok.

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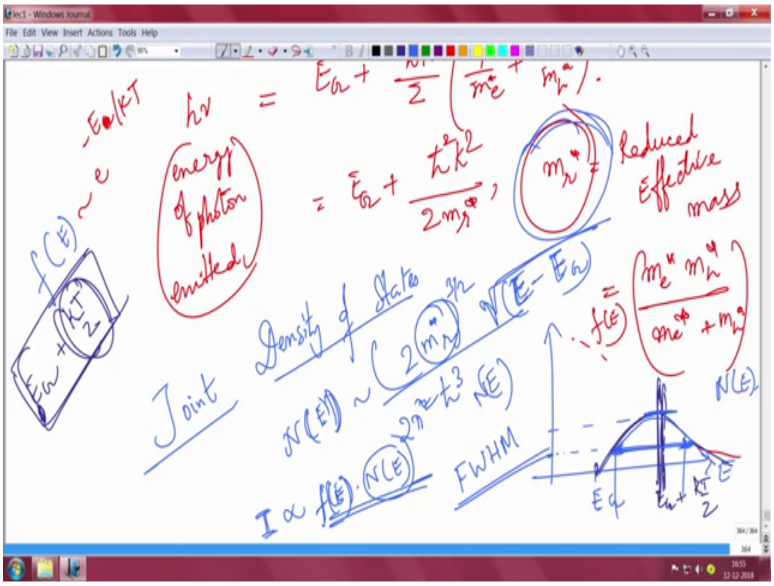

So, what I mean is that you can define that h nu, the photon that energy of the photon this is the energy of the photon that is emitted ok. Energy of the photon that is emitted could be equal to band gap plus h square k square by 2 1 by m e plus 1 by m whole right. And the whole thing can be written as E G by E G plus h square k square by 2 m r star where, m r star is called the reduced effective mass of the electron hole pair, reduced effective mass. Because, the electron hole pair recombining you know this reduce effective mass can be written as m electron times m hole divided by m electron plus m hole.

This is called reduced effective mass and because you talk about reduce effective mass because you have essentially you have essentially the electrons and holes recombining from the conduction to valence bond which are slightly more energetic than the band edge. Now, you use this effective this effective reduce massed, reduce effective mass is used for all calculations of LEDs and other things ok.

So, you remember density of states density of states from your earlier classes ok. In LED because it involves an electron and hole that are recombining between the conduction valence band, you contact take them together with reduce effective mass and the corresponding density of states is called joint density of states.

What it means is that it takes into account both the electron and hole pair together, this is this joint density of states is called N E joint density of states is called N E. And this is equal to something like 2 times effective reduce effective mass 3 by 2. And then 2 pi square pi square h bar cube into square root of E minus E G; that means, the emission will start only from energy equal to a mod n the band gap, it cannot go mod n band gap ok.

So, this quantity actually if you plot this energy only from E G; only from E G this quantity will go like parabolically, this is the density of states that is the available number of states per unit energy per unit volume. When I talk about both the electron in the hole together using a reduced effective mass representation it goes like that right.

Now, there is a Fermi function also, if you remember Fermi function and the Fermi function is the probability and the Fermi function goes as e to the power minus E G by kT ok. So, that E by kT you can say so that Fermi function actually comes something like this, this is your Fermi function and this is your density of states it.

So, happens that the emission the light emission because, of electron hole recombination that emission is proportional to the Fermi function times the density of states function. Like this also gives you the number free carriers, if you remember along back of talk about electrons and holes, but here the joint density of states basically captures both the electron and hole.

The probability that the recombining and the density of states available with them. So, the intensity of light that is emitted depends on the probability of the occupancy and the product of that into the density of states how many states are available. So, if you multiply this together you are going to get this plot like this, you are going to get a plot like this which means your emission is peak that has energy that has energy which is slightly more than E G. And it turns out the this is E G plus kT by 2 which means if you have a band gap of E G the emission peak actually does not come at E G, but it comes at E G plus kT by 2 of course, kT is very low at low temperature room temperature.

So, unless you go to slightly higher temperature or unless your using a low band gap material you will not see an appreciable change. But, if you use a low band gap material or go to high temperature you will see that kT by 2 becomes important. So, the peak actually emission is not an E G the band gap is slightly more than E G ok. And please remember that there is a thing called full with a half maximum. You take this value whatever is value is, you take the half of that values.

This is the value suppose some value we take half the value here and you go what is the spacing here, what is the width here that is called FWHM; Full Width at Half Maximum. It can be an any other like pl x rd any other data you can use pl fully half maximum concept. Here I am using full width at half maximum to emission. If you take that full width at half maximum emission you will see that the value of that quantity this you know this is a spacing right.

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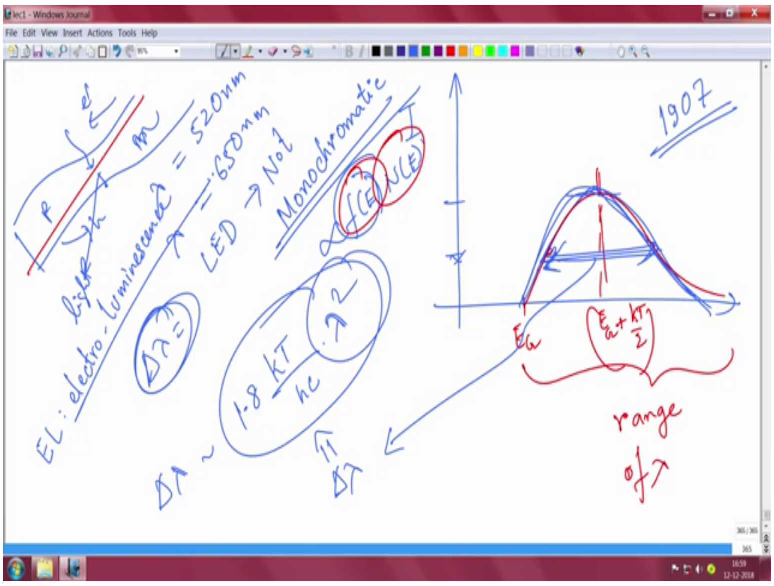

Let me use a difference picture here may be, that intensity thus intensity to emission which is proportional to the product of Fermi function times the density of states it goes like this right. This is your E G, there will be no emission below band gap. There will be slight you know at higher E G plus kT by 2 is where your peak emission happens and your emission does not happen at one wavelength. It happens over a range of wavelength, it happens over a range of wavelength range of wavelength and the full width a half maximum is this.

So, this is some value you take half the value and you take the width here this is called the full width a half maximum, this is delta lambda. Delta lambda is basically the range of wavelengths over which the spectra is happening, that range the full half maxima is given by this delta lambda is given by 1.8 times kT that is the thermal energy kT by hc into lambda square. So, if you are talking about green lambda is equal to 520 nanometre, you plug in this and you will see some value.

If you are talking about IR you know red is 650 nanometre, you plug it in you will see here some value. Red will be larger wavelength so, your delta lambda also will be large by the way ok. In other words delta lambda this spread in blue will be lower than the spread in red and so on. So, this spread has to be there which means LED does not emit exactly in one wave length.

But, the light emission rather light emission does not happen at one wave length which means this light emission is not mono chromatic. Mono chromatic means emission only at one wavelength, your light emission from this kind of device a p-n junction an LED is not monochromatic, it has a spread of wavelength. And that spread of wavelength is given by delta lambda which is very small in few may be few 10's of nanometre maybe 20, 30 nanometre, 40 nanometre.

Your human eye is not so sensitive; so, the human eye perceives the LED to be nearly mono chromatic. It looks like it is only emitting red or green or blue or whatever, but practically speaking if you use a very advanced tool you will see that your actually using emitting an range of wavelength.

Not so wide spread, but it is using it is a red it is a spread of wavelength anyways. So, this is not laser, this is not a monochromatic light, this is a spreader wavelength is there [FL]. So, please keep that in mind and this is because the density of states and the Fermi function, their product gives the probability of emission. Like this is what is the distribution of electron holes, what is the probability that they are occupy, how many states are there? All this things are important you know, that is why they are giving this non-monochromatic sort of a light. And this emission that happens in a p-n junction, I keep talking about right.

If I talk about this p-n junction this is p suppose this is n and I talk about that you know on the p side you will inject holes, from the n side you will inject electrons. And they will recombine in here and emit light that process of injecting carriers and emitting light is called EL which is also called Electro Lumi ne scence. We call it electroluminescence ok, please remember that electroluminescence is the process we are we are injecting electrons and holes; essentially you are injecting current.

Injecting electrons and holes in forward bias means injecting current, you are basically applying voltage and in you basically having a current that leads to an light emission that is called electroluminescence ok. And do you know when this process of electroluminescence was discovered? It was first discovered in 1907 more than 110 years back ok, I will talk about that.

So, we shall wrap up the class here today, we shall end the lecture on LED today here. We have a lot of things to cover in LED in the next one or two classes. I will give you just very briefly the history of how LEDs are developed, where they are now and I we will talk about little bit on the physics of you know radiative, non-radiative recombination.

And how you define efficiencies of LEDs, wall plug efficiency is a different time of type of efficiency. What is the; you know use of applications of different LEDs of different wavelengths, I will talk about the losses the loss mechanisms and LEDs are even more interesting than a photo detectors and solar cell; we will talk about those.

And then we will see that for visible LED which human eye perceives you can have different kind of definitions with respect to the human eye. The scotophil vision, the chromaticity, the coloured diagram we will try to see you know just to understand the context of LED with respect to human vision and the white LEDs.

But, UV LEDs and higher LEDs are not with respect to that; you cannot define brightness of a UV LED ok, you can only define brightness of a visible white LED sort of thing ok. So, that is why those things we will study, we will also study about a human eye sensitivity diagram and so on. So, those we will take up in the next lecture or next lectures ok.

Thank you for your time.