Lecture - 74
Radiative Absorption and Emission Processes
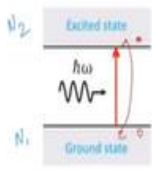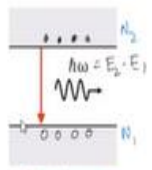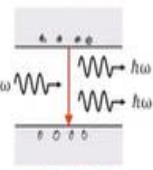
Let us get started. Hello everyone, welcome back to introduction to semiconductor devices. So, in this week we will understand light emitting devices. So, far now we have understood the fundamentals now we want to focus on light emitting devices. So, what are the fundamental mechanisms of light absorption and emission?

(Refer Slide Time: 00:34)

So, I think we have covered light absorption in some depth. So, we now understand for example, if you take any material maybe a semiconductor you have the conduction band and the valence band. So, we could think of it as two levels so, that is what I am representing here, so I will represent lower level, maybe the number of electrons in the lower level, I will call it as N_1 and then the higher level I will represent it number of electrons in higher level N_2 .

So, I can model the absorption process in the form of a two-level system, for the case of semiconductors, the ground state is a valence band and the excited state is the conduction band.

You could also have atomic absorption in gases. Like in that case those lower and higher levels or ground state and excited state are not continuous bands but they are discrete levels in the gaseous species because they are isolated atoms.

The energy levels will be discrete or it can have various other solids you can have multiple levels like this. So, the two-level system model now, this way of representing is the simplest model of representing optical system or optical material. So, on a two-level system if you have a photon incident, what happens? Well, it turns out there are three different processes that can happen and we will study them in some detail right now.

The first process is what we call us absorption. So, this is already familiar to us when a photon is incident on a material it can take let us say an electron from the lower state to the higher state it can take it to an excited state. So, what happens? In the case of a semiconductor, you will have an electron in the conduction band and the hole in the valence band this is what is happening in a semiconductor.

Or you could simply just excite an electron in the gas, you take it to higher energy level. This is the absorption process. And the way we can understand absorption process and we try to model it by writing a rate equation for it. So, for example now I said the population of the ground state is N 1 and the population of the excited state is N 2. So, now if I want to understand what is the rate of let us say increase in the or rather, I am taking the electrons from the lowest state to the highest state.

So, what is the rate of decrease of electrons in the lower state? So, that I can write it as let us say derivative of N 1 with respect to time

$$\frac{dN1}{dt}$$

Let us say I am finding some photons. So, how will the population of the lower state change? Of course, it is going to be proportional to the number of electrons in the lower limit. So, that will be proportional to N 1 because if there are no electrons present in the ground state then there is no absorption that is possible.

$$\frac{dN1}{dt} = -B_{12}N_1 u(v)$$

So, this will definitely be proportional to N 1, it is going to be proportional to the intensity of light that you are shining. And that I will represent by a term which call as u(ν) which is essentially capturing the spectrum spectral density let us say energy density. So, basically saying that at each wavelength or at each frequency how much is the intensity of light that is present.

You can have a monochromatic light that is a one single wavelength present or you can have a broad band range of sources. For example, Sun is a broad source you have various three wavelengths that are present in the sun solar radiation. So, the spectral density is basically u(ν). So, if you have that energy source incident on this material the rate of change of this is going to be proportional to that.

And definitely the number of electrons in the ground state will reduce, so we will actually put a minus sign and finally there is one last term which is called as an Einstein coefficient because Einstein developed the theory of radiation in 1905. So, he gave this coefficient so we call them Einstein coefficients and this particular coefficient is going to be called Einstein B coefficient and B 12.

$$\frac{dN_1}{dt} = -B_{12}N_1 u(\nu)$$

So, I am going from lower level to the higher level, so I will call it as Einstein coefficient. So, this is the coefficient that will capture and we will understand that later on a little bit more about it, Einstein's let us say B coefficient, there is one more A coefficient that will come shortly. So, this is the absorption process. You can also have the opposite process happening which is emission.

So, for example, if you take a semiconductor, I will take the same N_2 and N_1 to represent the populations in the higher and the lower states. So, let us say if you take example of a semiconductor you can think of a scenario wherein there are number of electrons in the higher state and there are corresponding holes let us say in the lower state, what will happen?

Well, the electron in the higher state can give up that energy and come down to a lower state. How much is the energy of the photon that is emitted? Well, it turns out to be equal to E_2- E_1. So, the difference in the energies between the highest state and the lowest state, let us the highest state energy E_2 the lowest state energy is E_1. The photon that is emitted is actually turning out to be $E_2 - E_1$.

So, this process is known as spontaneous emission process, this is one of the emission processes. Wherein without doing anything just the material if it has electrons in the higher state, there will simply de excite and then give you a photon. This is one this is a spontaneous emission process and we can also write rate equation for this. In this case, let us say we are talking about the higher level.

So, let us say how what is the rate of change of population in the higher level with respect to time. In the case of spontaneous emission process, for example this is going to be dependent N_1 or N_2, well we need electrons to be present in the higher excited state. So, definitely it is going to be proportional to N_2 but there is one catch here I mean what is the rate of emission. The proportionality constant is actually given by a coefficient which is called as Einstein coefficient again Einstein's A coefficient.

$$\frac{dN_2}{dt} = -A_{22}N_2$$

This is basically to capture the spontaneous emission process. So, that means spontaneous emission means the photon can be emitted at any random point in time so, photon are emitted at some instant at random instant. There is no way of predicting that so it is a spontaneous admission process. By the way, it is not going to be on single photon, I mean you can put in let us say 10 power 16 electrons in the higher state.

And similarly, 10 power 16 holes in the lower state. Then any of these electrons can de excite and there is no way of predicting when a particular electron will de excite. But when you consider them as a combination of all the electrons, there is a certain probability that at a particular time they will de excite and all that, then we will talk about that in a short while. So,

this is the spontaneous emission process which is again the second fundamental process in any material.

I mean it does not have to be only semiconductors it could be even gases and so on. Anywhere you can model a system a two-level system lower state in a higher state this loss will hold. So, now the last process of emission is known as stimulated emission. What happens here is, instead of just leaving the material to de-excite you shine a photon. For example, here I am showing that we are shining a photon of ℏω, this energy incident on the material.

So, now what will happen? Suppose it has the same scenario of many electrons in the highest state and there are corresponding holes in the lower state, you have this scenario available. Then when this photon is incident is actually the photon is incident, it will cause us emission of a second photon which is coherent. What I mean by that is the, the second photon that is emitted has the same phase and the frequency as the incident photon.

And that is why we call it a stimulated emission process essentially the photon is stimulating the emission of another photon. So, this particular mechanism can also be written in terms of a rate equation and we can say that dN2 by dt is equal to well, this is going to the de-excitation in this process is going to depend on of course, the population and the higher level which is N 2 and it is also going to depend on the intensity of the incident radiation.

So, we will again write this spectral energy density u of v and the coefficient that determines this process is called as B 21, this is Einstein's again B coefficient but going from 2 to 1. So, this is again another type of B coefficient essentially 3 coefficients.

$$\frac{dN_2}{dt} = -B_{21}N_2u(v)$$

Now the important thing is here emissions is coherent implies the second photon has same phase and frequency as incident photon.

This is a very, very essential phenomena for lasing you might have heard about lasers. So, there is even the pointers are also having lasers nowadays. So, all of them are based on this process of stimulated emission and spontaneous emission is any tube light or any LED all of them are

spontaneous emission processes and absorption of course you know what is absorption. So, these are the three fundamental mechanisms of interaction of radiation with matter.

(Refer Slide Time: 12:14)

So, I just quickly summarize that once again for you. So, the rate equations are here and it turns out that these Einstein coefficients are not really independent. They are related to each other. If you know one of them you can find out the other two and the relations are given in this box here. Essentially telling you that A coefficient is related to the B coefficient. Now this is stimulated emission this is going to control stimulated emission.

$$A_{21} = \frac{8\pi h v^3}{c^3} B_{21} \qquad g_1 B_{12} = g_2 B_{21}$$

And this is spontaneous emission and of course the stimulated emission and absorption are in some sense related. Because both of them require an incident photon it is just a reverse process. So, this B_{12} and B_{21} are related by this relation well this g 1 and g 2 I mentioned these are degeneracies of the level 1 and level 2 sometimes you can have multiple levels at the same energy.

So, I mean we can assume to be g 1 = g 2 = 1 actually, you can even say it is equal to 1for simple systems. So, essentially $B_{12} = B_{21}$ this is going to hold for most of the system unless it is specified you know that it is not. So, if you know let us say B_{12} you can determine both B_{21}

and A_{21} or any one coefficient is what you need. I just wanted to point out one more small thing which is if you look at this expression A_{21} and B_{21} there is a term of frequency here.

Everything else is a fundamental constant but the spontaneous emission seems to increase as a function of frequency Q. This is very important because you might have seen red lasers, green lasers but it is not very easy to build a blue laser. Because if you know that frequency of red is having a lower frequency, green is having a slightly higher frequency and when you come to blue it is still higher frequency.

So, it turns out that as you go to higher and higher frequencies, the spontaneous emission process becomes very strong. So, this A_{21} spontaneous emission is strong at higher frequencies and because of which it is difficult build lasers because lasers we want stimulated emission to take place, we want emission to be coherent, we want the photon that is emitted to have the same frequency and phase as the incident photon.

We will actually talk about the construction of a laser in the next couple of lectures but right now we want we just want to say that stimulated emission is essential for laser and that becomes hard or that becomes less compared to A_{21} which is a spontaneous emission. You take the ratio is going to scale as frequency Q. So, that is why spontaneous emission is much more stronger in blue frequencies. So, these are the fundamental processes of emission and radiation.

(Refer Slide Time: 15:51)

So, let me introduce, let me take one more step forward and essentially this this process of emitting emission of photons is called as luminescence. So, we talked about emission but we

just want to understand it in a greater detail. For example, now let us consider a scenario wherein you have this 4 electrons which are at the edge of the conduction band and then there are these 4 holes which are at the edge of the valence band.

So, what will be the frequency that is emitted? So, if I ask you, let us say to draw the spectral intensity or other spectrum of the emission process. For example, I want you to draw, so this is I want let us say energy or wavelength or you could even call it wavelength it does not matter, you can interchangeable you can calculate that and I want to calculate the intensity here.

For our purposes since we are talking of semiconductors, let us just talk off right now energies, let us talk in terms of energies. So, I want you to draw energy versus intensity this is a spectrum. So, which energy will you have strong emission of photons? Well, will you have let us say this is E_g, this bandgap I will take it to be E_g. Will you have emission at the E_g or rather if you have emission let us say I will put E g here for reference.

Now, will you have emission at energy is much lower than E_g? Well, there are no states available. For example, if you had electrons at this state and this some states in between then you could have emission between that. But since we do not have any state the smallest energy that you could end it is at E_g. So, there should not be any emission, it turns out that it will not be exactly easy but it will be growing in this fashion as you grow higher the intensity of the emission increases.

Now the other question is let us say you have a scenario you somehow are injecting electrons from the into the conduction band or in upper state and then you are injecting holes into the lower state. So, let us say you managed to inject electron at higher energy. Now we said that as you go deeper into the conduction band, we can represent we know that this is having a higher energy and this is again higher energy hole.

So, can this electron recombine with this hole and give you a higher energy photon? So, the question is, can you get $h\nu$ greater than E_g. Is this possible? If so, how much energy is possible, because we know that there are a lot of energy levels in the bottom here. So, will it emit all frequencies or all energies are at a particular energy? The answer to that is, it turns out that you will have emission only centred on E_g. So, I will just put it in blue.

So, this will be our emission process. The reason is, if even if you have an electron which is in a higher energy level. For example, here even if it is here, what happens is this electron loses its energy by we call it thermalization or we also call it is relaxation, so it relaxes here. So, this is called as relaxation. What essentially is happening is? It loses energy to the lattice and comes down to the edge of the band.

Because that is where that is the lowest energy state possible and it will try to come down to the lowest energy state. Similarly, a hole will relax to the lowest energy state for the holes. Remember always this is increasing energy for electrons in this direction, energy increases for electrons whereas for holes this is the direction of increase of energy. So, if you if the hole loses its energy, it will come closer to the valence band.

So, this way it relaxes it is again a relaxation process. It turns out that the excited carriers are high energy carriers will relax and come down to the edge of the band. So, this is a simplistic picture but finally what happens is, there is the emission process has a certain energy, bandwidth, you know full width half maximum. So, there is a centre wavelength and then there is a spread around that.

So, it turns out that this spread is very important. If you have any LED emission, the spread is going to be about 20 to 30 nanometres that is a typical number. So, if you have a blue light LED, you will see that it predominantly blue or a green LED. So, predominantly it is going to be maybe 10s of nanometres width whereas if you come to lasers, red laser or a green laser they are very coherent.

That means that monochromatic in a sense, they will just have a couple of nanometres or one nanometre or if you have gas lasers actually have even lesser width. So, you want it to be as pure laser as possible, you could relate it maybe in a way to if you take signals and systems courses you will talk of sine waves, a pure sine wave is a perfectly monochromatic wave when it has a single frequency.

But then if you introduce some distortions in that, then the width of the line with the sine wave becomes broader, the frequency becomes broader rather. Let us say if you apply a window to that sine wave, when you apply a window essentially a broadening the sign because there is a

more, it is fundamentally related to the uncertainty actually. So, just wanted to point out that this is the emission, this is a way that emission happens.

So, let us just try to do some, just introduce some numbers. So, we said that already the population in the highest state, the $\frac{dN_2}{dt}$

is going to be dependent on Einstein coefficient, A_{21} spontaneous emission and N_2 that is it. So, if you want to add stimulated emission, we have to create some necessary conditions for that and we will talk about it later right now simple spontaneous emission because we want to talk about LEDs.

So, $- A_{21} N_2$. So, if you solve this equation the solution turns out $N_2(t)$ is going to be

$$N_2(t) = N_2(0)exp(-A_{21}t)$$

So, if you look at it, I mean you will immediately recognize that this is something similar to the rate equations we have seen right before. So, rather the exponential decay that we have seen, we could write it as

$$= N_2(0)exp\left(-\frac{t}{\tau}\right)$$

I will call it τ radiation. So, τ_r which is the lifetime radiative lifetime.

$$\tau_r = \frac{1}{A_{21}}$$

So, this is going to be equal to 1 over A 21, this I will call as my radiative lifetime. Essentially, how much time it takes on an average for an electron to be excited emitter photon. So, this is how the radiative decay happens but as the name indicates when there is something called as a radiative decay, there is also going to be something called as non-radiative decay. What is non radiative decay?

Well, your electron instead of emitting a photon it could simply just lose its energy to the lattice. Lattice essentially it means it is just a lattice atom are there they are vibrating at whenever temperature is not 0, they are vibrating. So, in a sense your electron can lose its energy to the

lattice vibration and just come to the lower state and get captured. So, that is called as a non-radiative decay process.

So, non-radiative decay electron loses energy to the lattice. So, this is also going to be present of course, you know, it is never going to be that only ready to be case present. We would like to have radiative decay to be more because we want photons to come out. If when you say non radiative it is losing to the lattice that means you know, we save phonons no phonons, it is essentially heat. It is heating up the semiconductor which we do not like.

So, we can write a rate equation as well, we can add a term into this. So, the upper state like rate of change of population is going to be

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_R} = -\frac{N_2}{\tau_{NR}}$$

And then there is another channel, which you call us, τ_{NR} , non-radiation channel, these two channels are going to be there always. You know, we will see when we actually make, we will talk of LEDs, we would like to have radiative channel to be more efficient or more.

So, if your τ radiation is much, much smaller, let us say if your τ_R is smaller than τ_{NR} what happens? Well, when τ_R is small then this is going to be large. Basically, this is going to be large that means light emission is efficient. So, in this case, what happens is light emission is efficient, in a way, we are saying that A_{21} is large, indirectly. So, you want it to quickly emit light, you want to quickly emit photons.

If you consider other scenario, where τ_R is much, much greater than τ_{NR} what happens, essentially, it means that it is taking more time for electron to emit a photon, but instead before that, it will actually non radiative decay into phonons. So, this here, actually light emission is inefficient. So, heat is generated as a by-product. which is undesirable for us. Unless you are heat, you are trying to heat something.

We do not like non radiated decay processes. So, these are essentially the fundamental, this is a fundamental description of how the radiation happens. Before I stop, I just quickly wanted to show you two types of emission, or luminescence.

(Refer Slide Time: 27:38)
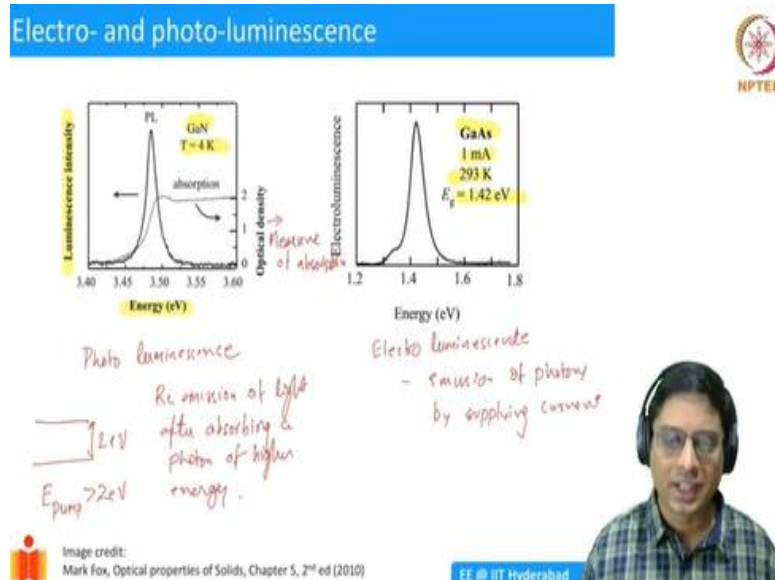
Luminescence is basically emission of a photon. We can have photo luminescence photo luminescence, which is essential you know shine a photon. Like for example, I take a semiconductor, which has a bandgap of 2 eV, I shine light, which has an energy of 2.5. eV, and then I will make it emitted 2 eV. If I have a bandgap, for example, the bandgap, in this case, 2 eV I can shine any photon of higher energy.

For example, E pump, which is pump is a semiconductor with high intensity of energy or greater than 2 eV, E pump is greater than 2 eV. When I do that, I will basically create lots of electrons and holes. When I do that, they will relax to the band edge and then emit a photon it 2 eV, so basically, this process is known as photo luminescence process. So, basically, it is re emission of light after absorbing a photon of higher energy.

So, this is known as photo luminescence just indicating that, you are using light to cause luminescence higher energy, so the luminescence is going to be at the band edge. And an example of that is shown in the graph here. So, in this graph, what you are seeing is energy versus luminescence, how much strong light is and you see, two things. One is the peak which is characteristic of the luminescence PL, we call it the photo luminescence.

And you see that it is a low temperature, by the way, and it is gallium nitride sample. So, the bandgap is about 3.3 eV, 3.6, 3.5, 3.4 7eV. So, anyway, there is a small difference because of the temperature. So, you have the PL which is I talked about this sort of a peak which will occur, emission is occurring around the band edge. And then what happens to absorption we have already discussed absorption.

So, this optical density is a measure of absorption, this is basically a measure of absorption. So, what you see is any photon which is higher than the bandgap it will absorb, this is a logarithmic scale by the way, you should not wonder why it is not steeply increasing since it is a logarithmic scale. We can quickly see an increase in absorption and then it saturating at some time it does not you know; it does not have any more it saturates.

So, this is absorption process, whereas, the photoluminescence happening around the peak this is one of the ways to characterize a semiconductor bandgap. You can do this experiment at various temperatures, this is at four Kelvin, and you could do it at room temperature and see the shift in the PL that tells you how the bandgap is changing with temperature. This is one of the practical ways of measuring bandgaps.

So, this is one of the processes, there is another process which we call us electro luminescence which essentially means, you are having emission of photons by supplying current. So, I supply my electrons and holes into the semiconductor and then I will make it emit light. That is known as electro luminescence process for example, your lasers LEDs all of these are electro luminescent devices.

So, again the same characteristic peak, this time this is a different material gallium arsenide current supplied is one milliamp and temperature is this the bandgap is 1.42 eV. So, you get an emission around that around 1.42 eV there is some emission, So, these are quite clean spectra, there are some, there are many, many more things by looking at the shape of it, and we can infer a lot of information about the material.

So, if you do research in some of these things, you will clearly analyse these spectra in more detail and you will study why all of that is happening. So, this is the fundamental process of luminescence. So, with this I hope I have explained the basic phenomena of how radiation

happens in a semiconductor, it is much more general, but semiconductor is what we are talking about in this course.

So, radiation in semiconductors, so with that, I would like to stop this video. In the next video I talk about various materials for optical you know, optoelectronics rather. I will see in the next video. Thank you very much for your attention. Take care. Bye