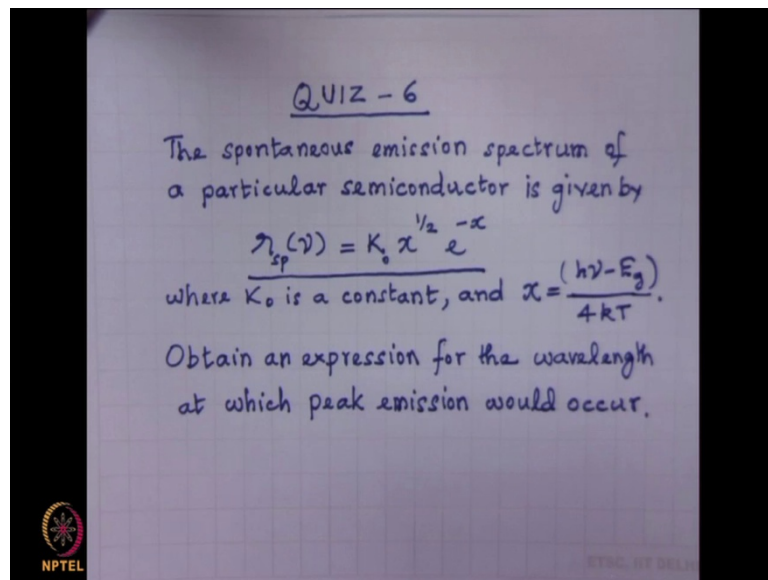


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**Lecture - 22**  
**Absorption Spectrum of Semiconductor**

Ok. Today we start with the absorption spectrum of semiconductors. Before I begin with the, with the lecture let me recall the quiz that I had given in an earlier class.

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Have already most of you have done it rightly, but just to show the correct answer; the spontaneous emission spectrum of a particular semiconductor is given by so, an expression is given  $I_{sp}(\nu) = K_0 \nu^{1/2} e^{-x}$ , where  $K_0$  is a constant and  $x$  is given. Obtain an expression for the wavelength at which peak emission would occur.

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QUIZ-6: ANSWER

Given:  $\mathcal{R}_{sp}(\nu) = D x^{1/2} e^{-x}$ ;  $x = \frac{h\nu - E_g}{4kT}$

$$\frac{d\mathcal{R}_{sp}}{d\nu} = \frac{d\mathcal{R}_{sp}}{dx} \cdot \frac{dx}{d\nu}$$
$$= D \left[ x^{1/2} \cdot (-e^{-x}) + e^{-x} \cdot \frac{1}{2} x^{-1/2} \right] \frac{h}{4kT}$$

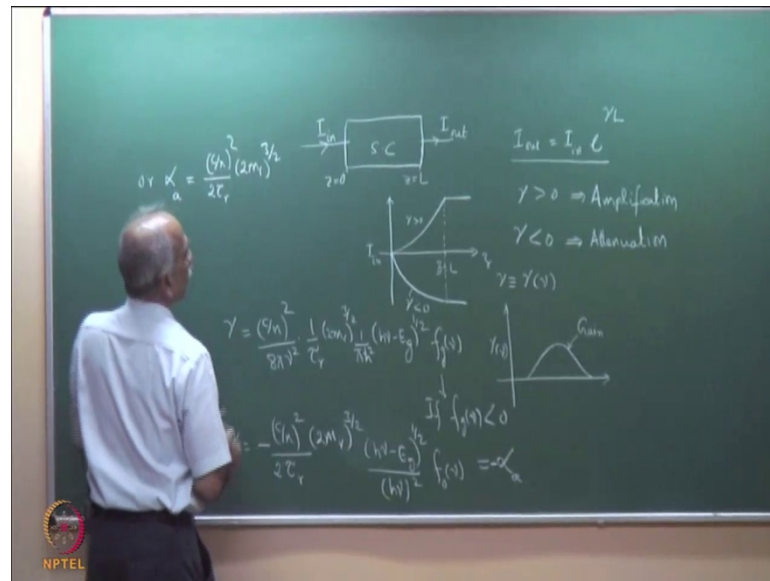
= 0 gives value of  $x_p$  for  $\mathcal{R}_{sp}^{max}$ .

$$\therefore x_p = \frac{1}{2} = \frac{(h\nu_p - E_g)}{4kT}$$
$$\therefore h\nu_p = E_g + 2kT$$
$$\lambda_p = \frac{c}{\nu_p} = \frac{hc}{(E_g + 2kT)}$$

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So, the answer is, while writing the answer I by mistake I wrote K 0 as D, but that is the K 0 which I had given in the question. So, this was by mistake I wrote it as D, but it is a constant. So, d r s p by d nu, you can split like this instead of a trying to have a complex derivation there. If you split the advantage is you first differentiate with respect to x and then you differentiate x with respect to nu put that equal to 0 and you get x p is equal to and then since x p is given by this expression here. We have h nu p is equal to E g plus 2 k T and lambda p is equal to c by nu p equal to h c by E g plus 2 k T. As I have seen most of you have done it correctly. In the last class we saw about the gain and amplification by stimulated emission and the condition for amplification by stimulated emission and the laser amplifier.

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If we recall the same expression had our objective as I said was to find out if a beam of light is entering a semiconductor of  $I$  in intensity, then what is the output  $I$  out? So, this the semiconductor and we have got an expression that  $I$  out is equal to  $I$  in into  $E$  to the power  $\gamma$  into  $L$ . If  $L$  is the length of the semiconductor then so, this is  $z$  equal to 0 and  $z$  equal to  $L$   $E$  to the power  $\gamma$   $L$  and we had said, that  $\gamma$  if it is greater than 0, it implies amplification and  $\gamma$  less than 0 implies attenuation.

So, if you were to plot the intensity here versus length so in the  $z$  direction then, if  $I_0$  is the intensity here that is  $I$  in is the intensity at  $z$  equal to 0. Then for  $\gamma$  equal to  $\gamma$  greater than 0 the intensity will build up exponentially so up to  $z$  so,  $z$  equal to  $L$  and after that of course outside it is. So, if  $I$  were to plot the intensity versus  $z$ , we would get an expression get a curve like this; this is for  $\gamma$  greater than 0. For  $\gamma$  less than 0, it will exponentially drop down here and then so, this is for  $\gamma$  less than 0 that is attenuation. We know also that  $\gamma$  is a function of frequency,  $\gamma$  is identically is a function of frequency.

Therefore, the absorption spectrum or gain spectrum refers to dependence of  $\gamma$  on  $\nu$  and we have seen that the gain spectrum so, if you plot gain versus  $\nu$ , it approximately behaves something like this. So, this is  $\gamma$  of  $\nu$  gain so, this is a gain plot. So, today we will see how would the absorption spectrum be and there are many

more processes because, this gain that we have calculated is gain due to stimulated emission. So, stimulated emission takes in place in the presence of an incoming photon.

And therefore, we have worked out that this is the expression, this is the spectrum gain spectrum of a semiconductor amplifier, semiconductor laser amplifier. So, we will see how would the last spectrum look like. So, recall that we have expression for  $\gamma$  which is  $c \cdot n^2 \cdot 8 \pi \nu^2 \cdot \frac{1}{\tau} \cdot \frac{m_r}{m} \cdot \nu^3$ . There was  $\frac{1}{\pi \hbar^2}$  also, so let me write it here because, this is part of the density of states and then  $h \nu - E_g$  to the power half.

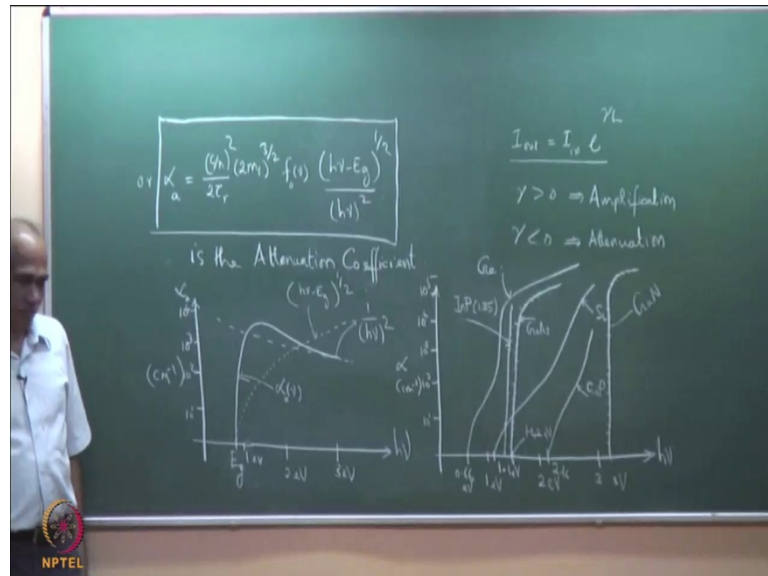
This was the expression that we have for gain coefficient into  $(\ )$  into  $f_g$  of the Fermi inversion factor  $f_g$  of  $\nu$ . So, if  $f_g$  of  $\nu$ , we first started with the  $a_0$  k experiment, thought experiment where  $f_g$  of  $\nu$  was either plus 1 or minus 1 and we obtained the gain profile and then we took a finite value and saw that the gain profile looks like this. If  $f_g$  of  $\nu$  where negative. So, if  $f_g$  of  $\nu$  is less than 0  $\gamma$  is negative;  $\gamma$  is negative means, we have an expression where it is  $E$  into minus  $\gamma$  into  $L$ . So, if  $f_g$  of  $\nu$  equal to 0, then  $\gamma$  is equal to minus  $c \cdot n^2$  I will write the same expression again maybe, I can club some of these here so,  $c \cdot n^2$  and there is a  $\pi$  here and there is a  $\pi$  here. So,  $\pi^2$  and  $\hbar^2$  has  $\hbar^2$  divided by  $2 \pi$  the whole square so  $4 \pi^2$  so,  $\hbar^2$  is equal to  $\hbar^2$  by  $4 \pi^2$ ,  $4 \pi^2$  square. So, this  $\pi^2$  cancels with these 2 and 4 cancels with 2 here  $(\ )$  8 to give you 2 and  $h \nu$  I am taking together.

So, I have  $2 \tau_r$ ,  $2 \tau_r$  into if I make a mistake please point out.  $2$  twice  $m_r$  to the power  $3/2$  into  $h \nu - E_g$ ,  $E_g$  divided by to the power half and  $h \nu$  whole square into this quantity is negative now; so, I want, I have taken the negative sign here and I write this as  $f_0$  of  $\nu$ . Where  $f_0$  of  $\nu$  is mod of  $f_g$  of  $\nu$  sign have kept here and then I want to call this as equal to  $\alpha_a$  minus, this quantity equal to minus  $\alpha_a$  or  $\alpha_a$  is equal to  $c \cdot n^2$  whole square.

Let me write again into twice  $\tau_r \cdot \frac{m_r}{m} \cdot \nu^3$  into  $f_0$  of  $\nu$  I am writing  $f_0$  of  $\nu$  into to indicate, that this is the positive number  $f_0$  of  $\nu$  is basically, mod  $f_g$  of  $\nu$  into  $h \nu - E_g$  to the power half divided by  $h \nu$  whole square. So, is, is the attenuation coefficient, if I plot the frequency dependence of this attenuation coefficient,

I will see the attenuation spectrum. So, how would this look like so, alpha a is basically minus gamma so, alpha is a positive number is the attenuation coefficient.

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If you see again that of course, there is a small frequency dependence here  $f_0$  of  $\nu$ , what I have been missed? We have not missed. There is a frequency dependence here  $f_0$  of  $\nu$ ; otherwise it primarily depends on  $h\nu - E_g$  to the power half and  $h\nu$  whole square. So, if I plot this earlier also we had a similar expression here and I had said that  $h\nu$  square variation is very small in the range of interest. In the range, the range of interest was the bandwidth of the amplifier, which was only  $10$  to the power of  $13$  hertz and therefore, that is a small fraction of light frequency.

But when we measure the absorption spectrum, the absorption takes place over a wide range and therefore, now I would like to consider this also. If you remember I had showed this as a variation, because it is  $1/x$  square variation. So, this is  $h\nu^{-1}$  over  $h\nu$  whole square variation. Now we want to plot it over a wide range for example, from  $E_g$  here to a wide range, wide range what do I mean by wide range is, let us say this is one electron volt this is  $2$  eV. So,  $1$  eV,  $2$  eV,  $3$  eV earlier where did we plot it? From  $E_g$  to  $E_g + 0.1$  eV or  $0.2$  eV that solve, because that was the amplification band and therefore, it was only a small fraction of this and that is why I had assumed it to be constant.

Now I am not assuming it to be constant because I want to see for example, as you will see later, the absorption coefficient is important when you want to use the material for photo detection. So, a photo detector can detect over a wide range of wavelength and therefore, we have to consider the absorption spectrum over a wide range of energies. The plot which I had made earlier, this amplification band corresponds to  $E_g$  to approximately  $E_g + 0.1 \text{ eV}$  or  $0.2 \text{ eV}$ ,  $0.2 \text{ eV}$  is a very small range of this spectrum that I am going to plot now and therefore, I had assumed this, this dependence as constant. But now we want to plot it over a wide range and therefore, I have to consider that.

The other part is, as you know it starts from  $E_g$   $h\nu$  minus  $E_g$  to the power half goes the same way  $x$  to the power half dependence. So, this is  $h\nu$  minus  $E_g$  to the power half. So, the net result is, so the absorption coefficient so, this is variation of  $\alpha$ . So, what I have plotted here is  $\alpha$ , any question? Is it All Right? (( )) I am sorry I would showed that as 1 and this is  $E_g$  it should thank you. Actually, it should start from  $E_g$  because, this is valid for  $E_g$  greater than,  $h\nu$  greater than  $E_g$  and the density it starts from  $E_g$ . I am sorry I wrote there 1 and ok so let the 1 be here; does not matter because, there are materials with  $E_g$  less than 1 if you take germanium it is  $0.66 \text{ eV}$ .

So, from  $E_g$  this starts from  $E_g$ , so this is  $1 \text{ eV}$  here, please correct it. That is start from  $E_g$  goes up and then as a variation like this. This is what we expect to get in a semiconductor the absorption spectrum of a semiconductor, but in practice if you see the absorption spectrum I will draw typical absorption spectrum just by the side here. So, let me again put  $1 \text{ eV}$ ,  $2 \text{ eV}$  so this is  $h\nu$  photon energy versus gallium arsenide let us start with gallium arsenide one alright let us start with a lowest one. So, germanium is  $0.66 \text{ eV}$ ,  $0.66 \text{ eV}$  this is germanium let me plot typical numbers here. So, this is  $10$  to the power 1,  $10$  to the power 2,  $10$  to the power 3,  $10$  to the power 4,  $10$  to the power 5  $\alpha$  in centimetre inverse, centimetre inverse  $\alpha$  centimetre inverse. You can see a gamma or  $\alpha$  as to have inverse length dependence to centimetre inverse.

This number is typical of gallium arsenide that I have plotted. So, typical numbers are  $10$  to the power of 2,  $10$  power 3,  $10$  power 4,  $10$  power 5 and so on. So, if I start with germanium this has a behaviour, this is for germanium, let us starts with  $E_g$  and it goes like this. We will see, we will discuss why it is behaving like this, if you take silicon the

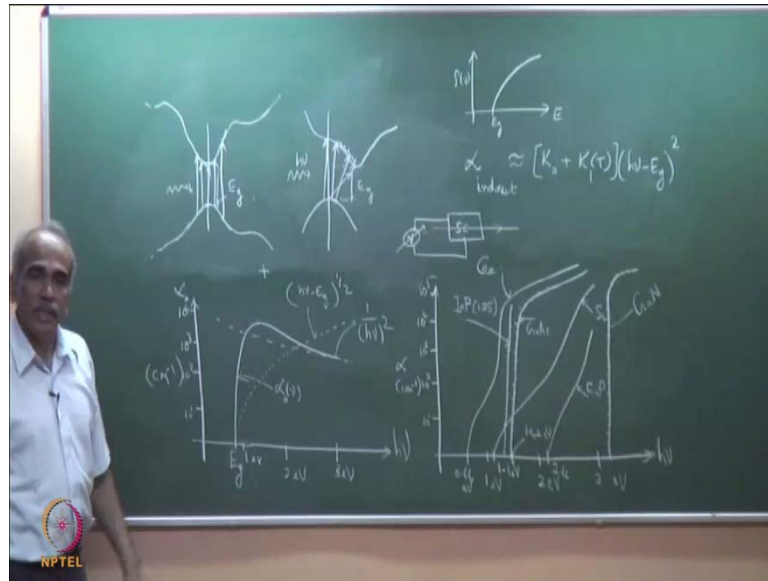
next one that is 1.1 e v. So, you know that silicon has a band gap of 1.1 e v and this does this.

This is for silicon the numbers and these are typical is alright little bit variation. So, next comes gallium arsenide so I have to gallium arsenide. So, gallium arsenide is here 1.42, so 1.42. So, gallium arsenide does this you see the difference and just for differentiation this is what I have plotted for gallium arsenide. The numbers are very typical if you see in a literature you will see that the numbers are typical gallium arsenide, 2.16 gallium phosphide again gallium phosphide does this. So, this is gallium phosphide let me plot this and then we have something to discuss gallium phosphide. If we take gallium nitrate wide band gap semiconductor 3.3 e v here it is also a direct band gap material and this goes like this.

That I am showing by a mark here this is gallium nitrate, these are direct band gap let me draw one more this is this one here is indium phosphide whose band gap is 1.35 e v. we have something to discuss 1.35 e v, but if you just look at the graph you can all the once which are dash mark here or direct band gap materials and the other once are indirect band gap materials. So, just looking at the absorption spectrum you can see something that for direct and, band gap materials, the absorption curves shoots up as soon as you cross the  $E_g$ , as soon as you cross the  $E_g$  it simply shoots up almost vertically whereas, for indirect band gap materials it goes like this.

But for none of these it appears that none of them seem to be coming down. Here we have expected it to come down, but it does not seem to come down. There are several explanations that are due this graph that we obtained by considering a direct band gap semiconductor.

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We have considered a direct band gap semiconductor and we have concentrated only on the parabolic approximation closed to the band edge. This is close to the band edge, but these bands do have behaviours which are very different.

Closed to the band edge if you are seeing, let us say  $E_g + 0.2 \text{ eV}$ ,  $0.1 \text{ eV}$ ,  $0.2 \text{ eV}$  parabolic approximation is a very good approximation and based on that we have derived these expressions for a direct band gap semiconductor, but beyond that this is not true. So, these curves are only valid close to the band edge point number 1. Second there is always almost all materials also have an indirect band gap and therefore, if you consider the theory of an indirect band gap semiconductor and find out the absorption phonon assisted absorption, phonon assisted absorption.

Then you have a variation which looks like this  $\alpha$  indirect. So, this  $\alpha$  that we have is  $\alpha$  direct band gap,  $\alpha$  indirect we are not going to this derivation is approximately, empirically this is given that approximately you can show that this variation is of the form  $K_0 + K_1(T) \frac{1}{(h\nu - E_g)^2}$ . We are not going to derive this there is a, these are constants  $K_0$  and  $K_1$ ,  $K_1$  is a temperature dependent constant  $\frac{1}{(h\nu - E_g)^2}$ . So, this variation looks like this typically, what I am plotting is the variation at different temperatures  $T_1$ ,  $T_2$  which is greater than  $T_1$  and  $T_3$  which is greater than  $T_2$ . That is because of this term  $K_1(T)$  the second constant  $K_1$  is a function of temperature.



The numbers here are slightly smaller so  $10^1$ ,  $10^2$ ,  $10^3$ ,  $10^4$ . So, they are little smaller you can see these have already reached  $10^4$ ,  $10^4$  the direct gap has come to  $10^4$ . This particular graph is approximately calculated for gallium arsenide. So, it should have been 1.42 eV because, if you use the parameters of gallium arsenide then approximately  $10^4$  is the peak.

Therefore the net absorption is this plus this absorption due to direct and absorption due to indirect plus there are other components, but this plus this will give you reasonably it explains the why gallium arsenide beyond this continues like this, because if you add this and this you will get a variation which is approximately like this. So, that is why this portion is going up both for germanium, gallium arsenide almost all of them.

This is the first reason why this is not coming down second why in indirect band gap it goes like this whereas, in direct band gap it shoots up like this. Let us see the  $E-k$  diagram as soon as  $h\nu$  reaches  $E_g$  so this gap is  $E_g$ . It gets density of states for interaction  $\rho_{\nu}$  if you recall the density of state  $\rho_{\nu}$ , let me plot it here. So,  $\rho_{\nu}$  versus  $E$  we have already plotted this, then you we have seen that it start from  $E_g$  and goes up. So, as soon as photons reach this energy there are plenty of states which are available and absorption starts immediately before this there is no absorption and therefore, absorption is literally 0.

There are other components will come to that, but write now absorption shoots up like this. That is why absorption shoots up in direct band gap semiconductors what about indirect band gap semiconductors. So, if I want to plot the  $E-k$  diagram of a indirect band gap semiconductor an indirect band gap semiconductor we see that this is  $E_g$  so gap is  $E_g$ . There are as soon as you cross there are states it is the available states  $E_g$ , but they do not any absorption going at an angle like this in  $E-k$  diagram, in the energy space is an oblique transition violates the law of conservation of momentum. And therefore, although the states in this case the moment the energy exceeds  $E_g$  all absorptions can take place, because all are vertical transitions which are highly allowed transitions. So, the probability of this transition is very high in the case of a direct band gap semiconductor.

Where as in the case of a indirect band gap semiconductor the probability is low, because of this photon assistant transition, because of violation of conservation of momentum.

And therefore, the, the graph slowly starts increasing absorption can take place, but increases relatively less rapidly as compare to direct band gap semiconductors. However, as the energy increases please see if I have a slightly higher energy then this may make a less oblique transition. If I have more higher energy this will make almost vertical transitions. If I as  $h\nu$  increases as the frequency, at the energy of photon increases it can make vertical transitions and that probability is very high. That is why you see, germanium after words again it does this rapid increase, because now vertical transitions can also take place you have higher energy band gap is the minimum energy.

So, if you have photons incident with higher energy, they can cause vertical transitions which are highly probable. And therefore, the absorption coefficient shoots up same here with silicon you see it going like this; then again it started increasing same here with gallium phosphide. So, it is as the energy increases the probability of vertical transitions increase and once of course, the carrier comes here then it will thermalize and it will come down here like this. This is thermalization which we have discussed due to phonon transitions and therefore, the graph again shoots up.

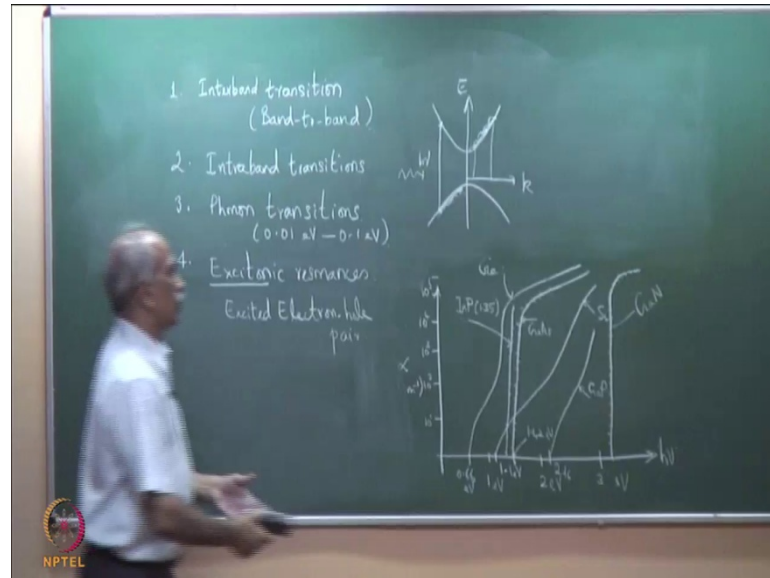
So, two things just by looking at the absorption spectrum almost you can make out whether the material is direct band gap or indirect band gap. You just measure the absorption spectrum and you can make out whether it is direct band gap or indirect band gap. Write at the beginning when we started with direct and indirect how would one know which is direct band gap and which is indirect band gap, if you are given a piece of semiconductor how would you know.

From here is the simple test so you have a energy source. So, here is the semiconductor, let say you have a tuneable source here that is  $\nu$ . Tuneable source which is frequency variable and you pass light through this, this is light I am talking of light it is not electrical current. Tuneable source and you measure the absorption output as a function of the frequency and simply plot this. You can identify which is a direct band gap material and which is a indirect band gap material.

So, this the, this term here explains for the transition which is going up, there are many more effects. These are not the only effects what we have discussed is, inter band transition, conduction band to valance band or valance band to conduction band. This is intra band transition there are also intra band transitions which are possible. What is intra

band transition and there are phonon transitions which are possible, and there are excitonic resonances which are possible. So, the absorption comprises of several effects not just direct band gap or vertical transitions.

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So, what we have discussed is 1 inter band transition. That is band to band, valance band to conduction band; inter band or band to band transition. There is intra band transition within the band, these are generally low frequency or low energy transitions if you look at the eke diagram. Every time you see this is the eke diagram which tells about all the physics, which I mentioned in one of the first classes. An electron which is sitting here can make an upward transition to a position here. An electron which is here makes an upward transition to a higher vehicle state within the band by absorption of photon of course, this will require phonon assistance. Because there is a change in momentum, but an electron can make an upward transition here by absorption of photon and this is called intra band transition within the band, but the carrier which is here sub sequentially will thermalize and come down through phonon transitions.

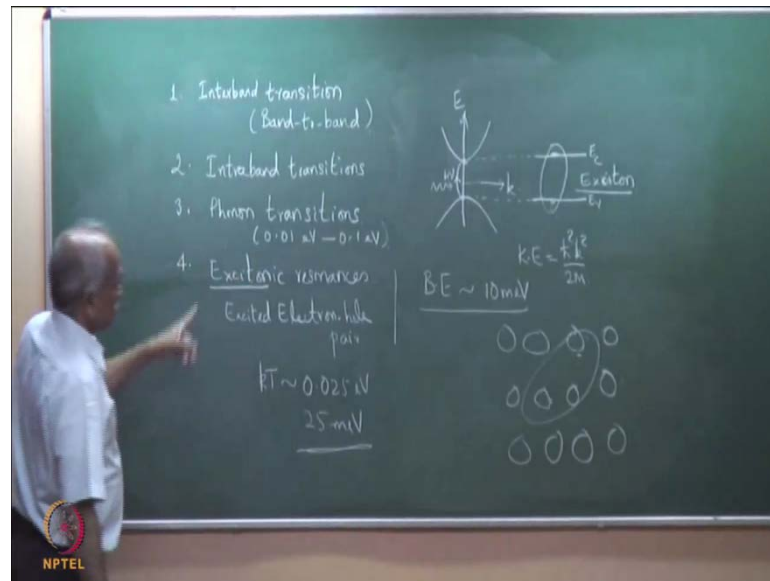
This is intra band transition. So, when photon of a broad spectrum of energy is incident. So, if you are finding the energy spectrum, if you assumed that the sources as all these wavelength. Then some of the wavelengths particularly here at the lower energy will result in an electron gaining energy and going to a vacant position and this becomes a hot electron. The higher kinetic energy electron is called an hot electron, but sub sequentially

it will come down by thermalization this is intra band transition. Same thing can happen with a hole a hole for example; a high energy photon lifts an electron from here to here. Then it leads a hole here a high energy photon incident here can make a vertical transition so this electron goes here.

There is a hole here, but hole here is a high energy state and electrons which are sitting here will immediately come down to this. An electron from low energy can immediately come down there. So, what happens then the hole moves here and electron comes to that vacant state leads the hole moves up this is also within the band. So, intra band transitions or vice versa a hole which is sitting here can absorb energy and go to this place. So these are intra band transitions generally, the energy of intra band transitions are less than band gap transitions. A third type of transitions are phonon transitions, but we know that phonon energies are typically in the range 0.01 eV to 0.1 eV.

Phonons can also absorb energy low energy photons can be directly absorbed by phonons or low energy photons can directly generate phonons within the semiconductor. And therefore, the absorption of photon a low energy photon to give rise to phonons will also have absorption somewhere in this range particularly low energy range. And a fourth type of absorption, which is also possible are excitonic absorptions, excitonic resonances, excitonic resonances. So, some of you may not be knowing what is an exciton, exciton here refers to an excited electron hole pair here, hole pair what it means is excited electron hole pair.

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Let us see this is only an introductory I write the eke diagram erase it explain something and erase it again you need eke diagram. So, so many times you need to draw the eke diagram. This is our traditional band diagram an electron which is sitting at the bottom here or a hole which is sitting at the top of this band or low energy states, very low energy state. Therefore, the K is almost 0 which means the kinetic energy is very closed to 0 very small kinetic energy, because kinetic energy is  $\hbar^2 k^2 / 2m$ . So,  $\hbar^2 k^2 / 2m$  is very small because K is almost 0. That means, they are low kinetic energy carriers closed to the edge of the band; an electron sitting at this place can absorb a photon of energy which is just near to  $E_g$  and make an upward transition if there is a vacant state, if there is a vacant state.

So, there is a whole which is positively charged and there is an electron which is negatively charged. So, there is a hole which is closed to the edge of the band and there is an electron which is just gone up to this  $E_g$ . So, the positively charged whole and negatively charged build up Coulomb attraction. If they are close in space this is energy axis, but if they are close in space physically, then they form a hydrogen atom like bond. Like a hydrogen atom they behave like a hydrogen atom, which is held by Coulomb interaction between a positively charged nucleus and negatively charged electrons.

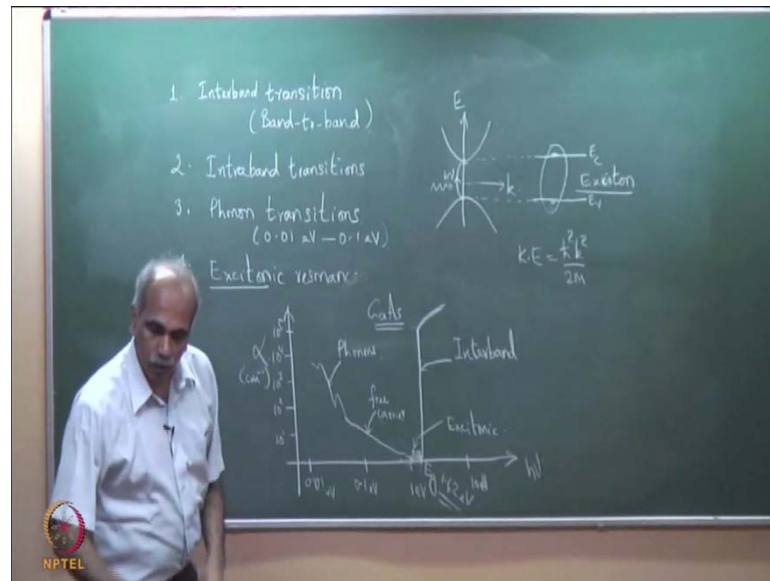
So, if you see the semiconductor lattice there may be large number of atoms which are sitting. Maybe, in one of the atoms there is a whole here low energy whole there may be a electron somewhere here and they form a there is a column be get attraction. In addition to all the bonds which you have, coherent bonds there is a column make attraction between them. So, the electron and hole are localized. So, this localized particle, if not a particle it is localized entity is called an exciton. Sorry.

The localized entity is called exciton the binding energy though between these is extremely small. Typically, the binding energy of this binding energy is of the order of  $10\text{ m e V}$  10 mille electron volt of the order typically 8 10 12 15. Binding energy of this exciton is very small in a hydrogen atom, what is the binding energy of hydrogen atom more than  $10\text{ e v}$ ,  $10\text{ e v}$  more than  $10\text{ e v}$  is the binding energy of the hydrogen, but this is not exactly like a hydrogen atom, but it behave they are weakly coupled. There is some positive charge there or positive field and there is a negative field, which tries to hold together with a very small binding energy and this is called exciton. Normally, at room temperature you do not see bind excitons in semiconductors, because the room temperature kinetic energy, average kinetic energy is  $0.025\text{ e v}$ , which is  $25\text{ e v}$ ,  $\text{m E v}$ .

So, binding energy that is kinetic energy that is  $K T$  is of the order of  $0.025\text{ E v}$  or  $25\text{ m E v}$ . So, this much average thermal energy is present in the material and therefore, the exciton get dissociated, because the binding energy is only  $10\text{ m E v}$ . So, if already so much energy is present the exciton is dissociated, dissociated means they are no more holding together. So, they are free carriers. So, they behave like free carriers. So, at room temperature you would not see this, but due to this binding due to this positive potential the energy of this is slightly lower, energy of this pair is slightly lower than  $E_g$  this was at  $E_g$ , but the net the net state here exciton as a slightly lower energy. And therefore, this leads to states which are here closed to the band edge, but little less than band edge.

So, photons of energy slightly less than  $E_g$  can also be absorbed and these are excitons states. So, there is a density of states due to excitons. So, photons closed to the band edge even a little less than actual  $E_g$  can also get absorbed by in the formation of excitons. This is excitonic transition and therefore, now we have if I take the total spectrum let us look at a total spectrum. We will discuss a little bit more about a excitons a little later because, we are going to discuss the quantum confined torque effect and I will discuss about the probable in a later class.

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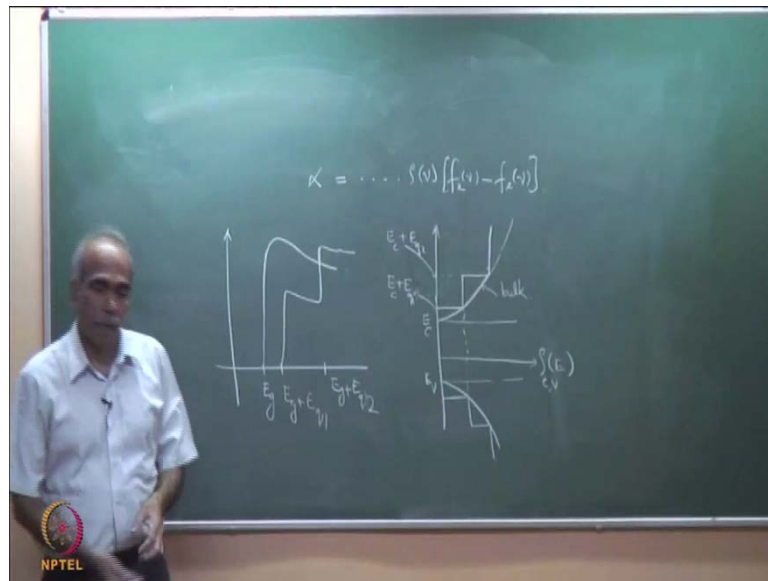
But, if you now see the total spectrum  $h\nu$ . We are starting now from 0.01 not 0.1 not so 0.01 eV, I let say 0.1 eV, 1 eV and then 10 eV anyhow 10 eV is too much then we do not need it. So, the whole absorption spectrum earlier I had plotted 1, 2, 3, 4 but now we are looking at the entire absorption spectrum  $\alpha$  of a semiconductor typical. I will plot for this typical gallium arsenide numbers. So, you have 10 to the power of 2, 10 power 4 so, this is 10 to the power 1, 10 power 2, 10 power 3, 10 power 4, 10 power 5 centimetre inverse. All the inter band transitions which we discussed where from here 1.42 let say, this was  $E_g$  for gallium arsenide  $E_g$  1.42 is here. Now I want to plot how it would look qualitatively, that there are there is absorption taking place at lower photon energy said. So, this goes of course, shooting up like this, have over short around 10 power 4 it will start turning.

Below band gap there are some excitonic resonances, these are normally peaks like this; here not below 1 eV here so, excitonic resonances and then there are free carrier absorption which looks something like this; just you showing the overall this is free carrier absorption and then there are phonon absorptions. So, this part here is primarily due to free carrier, free carrier you remember within the band intra band transition. So, this was free carrier portion, this is excitonic resonances just below the band gap excitonic and then this is due to phonons because, the energy range here corresponds to that of phonons that is creating vibrations in the lattice. So, energy is spend in creating lattice vibrations directly. So, this shows the come and this is due to inter band. So, in

this complete spectrum we see all the four points which I have been taken. So, inter band excitonic, free carrier and phonon transitions.

This is the spectrum of absorption spectrum of a typical semiconductor, what I have plotted is for a gallium arsenide of course, I hope we understand why the behaviour of spectrum come. Before we stop I want to just talk one step here and that is, how would the absorption look like in a quantum (( )).

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We have an expression for lose coefficient alpha, which had alpha is equal to so many constants, there was rho of nu; the density of states. It is the density of states which gave and then f g of nu or f 0 here, that is f a probability of absorption f 0 which is f a minus f e and we write it fully. So, this is f a of nu minus f e of nu, some constants here rho of nu and this and this rho of nu is one which gave as the term h nu minus E g the power half, the density of states and recall that the density of states the first time when we plotted E and this was E v. So, this is E v E c and then we saw that the density of states goes like this density of states variation.

This is from this we derived all the absorption coefficients and then we got this absorption coefficient which doing this, band to band transition we are in a photonics we are interested in band to band transition because, we are looking at photon energies which are normally in the visible or higher. So, we do not. So, most of the times we will focused on band to band transition. So, the absorption coefficient was like this; rho nu



was varying like this. In a quantum well structure, we know that  $\rho_{\nu}$  is a step function. So, it starts from somewhere here, more than  $E_g$  and then it is constant up to certain energy and then it remains constant here.

So, this was  $E_c + E_{q1}$ . So,  $E_c + E_{q1}$ ; that is  $q$  equal to 1 state. The density of state was constant, we have some values for this here, then when the energy reached  $E_c + E_{q2}$ . So,  $E_c + E_{q2}$  there was a second step varying like this and then continuing like this. So, this for the bulk and this is for the quantum line, this is for the bulk and it is a state function same thing here. So, if I assumed that  $m_c = m_v$ , then I will have a similar variation, what does this mean? This means, that is all for photon energies from this gap here  $E_g$  up to this the density of states is constant therefore, the absorption should remain constant.

Density of states will constant it is no more varying this is variation, but here density of states is remaining constant. This is I have also plotted here; this is not k why did I plot k here? This is  $\rho_c$  and  $\rho_v$  so,  $\rho(E)$  let me write  $\rho(E_c, v)$ , this is for c and this is for v  $\rho_c, v$ . For all energy from  $E_g$  up to this, the density of states number of available states is constant and therefore, the absorption coefficient must also remain constant because, absorption remains this almost constant here and then suddenly the density of states increases.

And therefore, absorption coefficient should suddenly increases and need quantum well structures show an absorption coefficient variation which is like this. So, if I want to plot in the same graph, then this is  $E_g$  there is no absorption at  $E_g$ , first absorption starts at  $E_g + E_q$ . So in the same graph if I want to plot, it shows absorption and then the absorption remains constant almost constant except for the  $1/h\nu^2$  dependence almost constant till  $E_g + E_{q2}$ ,  $E_g + E_{q2}$  and then the absorption again jumps vertically, almost vertically and then it remains constant.

A step like variation of absorption coefficient and if you connect this to the last class, a step like variation in the gain coefficient as well and therefore, it is the density of states which determines what is the absorption spectrum or gain spectrum of a semiconductor, that is why we spend so much time on density of states. So, you get a step like variation and this as very important applications. So, we will discuss about this in one of them

later classes, but remember that, a quantum well structure will show step like absorption spectrum. We will stop here and continue in the next class.