Semiconductor Optoelectronics

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Lecture - 24
Electro-absorption Modulator

So, we start with the, this is the first device electro-absorption modulators or Quantum Well modulators. So, before I start, I will briefly discuss the answer for the quiz, yesterday's quiz.

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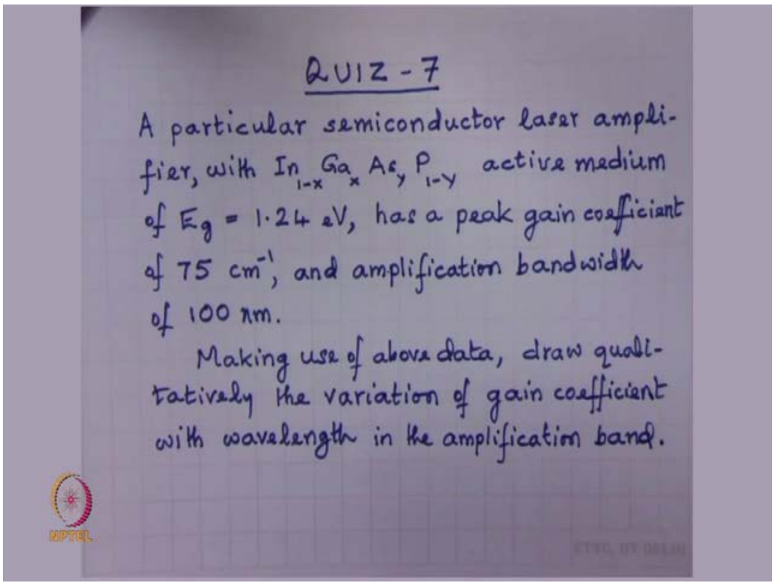

QUIZ - 7

A particular semiconductor laser amplifier, with $In_{1-x}Ga_xAs_yP_{1-y}$ active medium of $E_g = 1.24$ eV, has a peak gain coefficient of 75 cm^{-1}, and amplification bandwidth of 100 nm.

Making use of above data, draw qualitatively the variation of gain coefficient with wavelength in the amplification band.

So, this was the quiz. A particular semiconductor laser amplifier with indium gallium arsenide phosphide active medium of E g equal to 1.24 eV has a peak gain coefficient of 75 centimeter inverse and amplification bandwidth of 100 nanometer. Making use of the above data, draw qualitatively the variation of gain coefficient with wave length in the amplification band. As I have keep on repeating quiz is a simple question, you should think simple and a little quick. The answer is very simple; most of you have right to see complicated answer in that.

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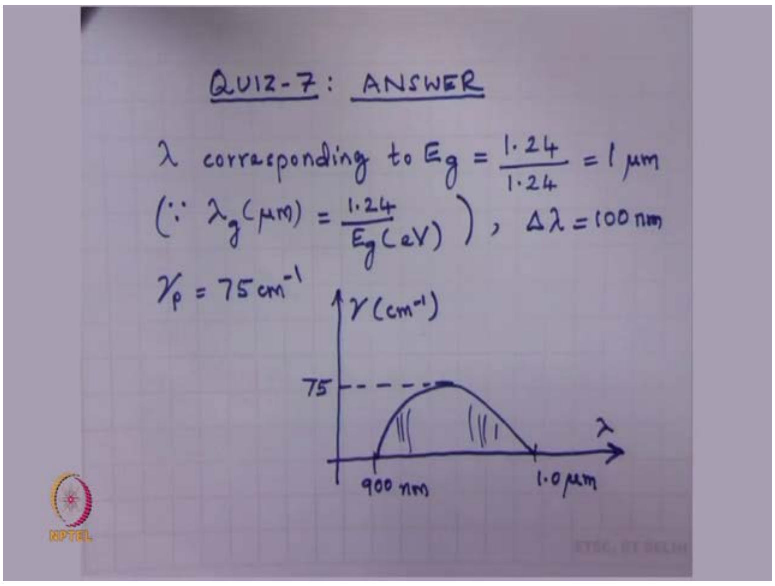

QUIZ-7: ANSWER

λ corresponding to $E_g = \frac{1.24}{1.24} = 1\ \mu m$

$\left(\because \lambda_g(\mu m) = \frac{1.24}{E_g(eV)}\right)$, $\Delta\lambda = 100\ nm$

$\gamma_p = 75\ cm^{-1}$

So, the answer is here. The fact that E g was given 1.24 e V should have been a hint to you that it will give lambda equal to 1 micron, because lambda equal to 1.24 by E g in electron volts. So, lambda is 1 micron, delta lambda is given 100 nanometer, gamma p is given and an important point is that we or know is if frequency is increasing in this direction then wave length will be decreasing in this direction. Energy is increasing means wave length is decreasing. So, that is all the points to be used and you have a similar variation in frequency h nu starting from E g here, but this time it starts from opposite end because high energy is to this end and that is all. No need to remember any formulae, apply any formulae, apply any variations because it is a quiz. I have already corrected, but I forgot to bring it. Electro absorption modulators, these are also called Quantum Well Modulators.

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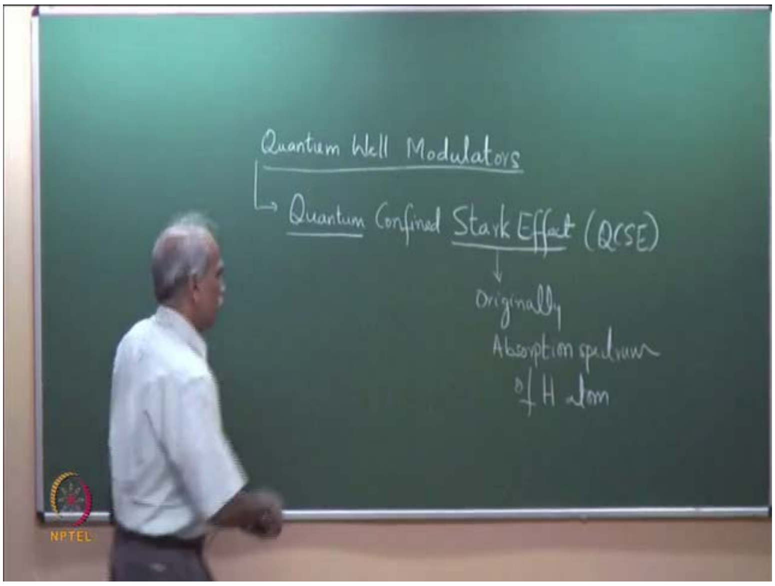

Quantum Well Modulators, these works on the principle of Quantum-confined Stark effect Quantum-confined Stark effect Quantum-confined Stark effect. We know, what is Stark effect? Stark effect refers to shift in the absorption spectrum. Originally, this was originally observed in the spectrum of hydrogen atom, absorption spectrum of hydrogen atom by Stark absorption spectrum of hydrogen atom absorption spectrum of hydrogen atom, shift in the absorption lines of the hydrogen atom in the presence of an applied electric field that was Stark effect. We are looking at Quantum-confined Stark effect; Quantum here referring to the Quantum Well.

So, we are looking at Stark effect in a Quantum Well structure. Stark effect in a semiconductor Quantum Well structure that is Quantum-confined Stark effect Q C S C and this is QCSC - Quantum-confined Stark effect is made use of to realize Quantum Well modulators or electro absorption modulators. So, let us see first absorption in semiconductors. We know the absorption spectrum in the semi conductors as well as in Quantum Well structure, we have seen this in the last classes.

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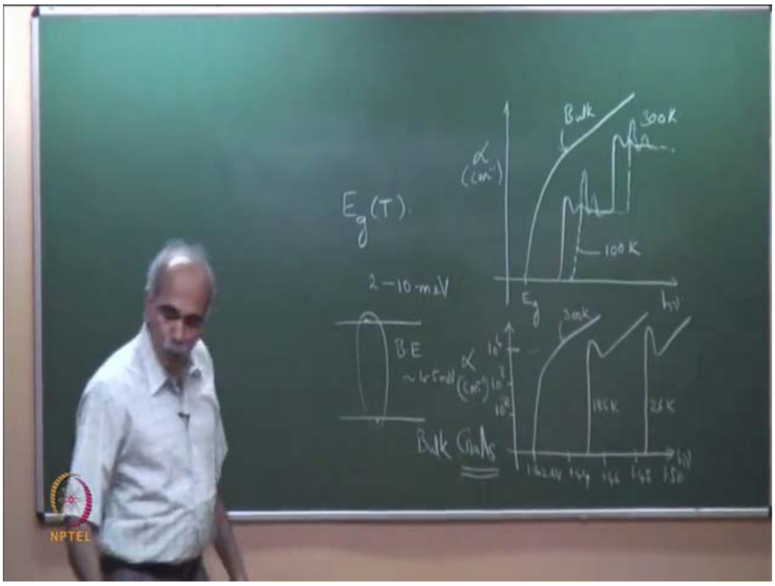

So, let me quickly recall what we have seen, the absorption spectrum in Quantum Well structure; h nu and alpha attenuation coefficient centimeter inverse alpha, in a bulk semiconductor the attenuation varies something like this. So, this starts from E g for bulk, by quick recap bulk semiconductor and if you use a Quantum Well structure it starts a little later. We have already seen and then I had drawn, this is at room temperature and we mention that this peaks are corresponding to exitonic peaks. So, this is at room temperature say 300 Kelvin at room temperature. If you measure this at lower temperature, if you measure the absorption spectrum at lower temperature, what you would see is, so, let me draw with the dotted lines.

Say, let us say this is at 100 K. So, two things that we observe, one is the absorption edge is shifted, this is called absorption edge. Absorption edge is the energy or wavelength at which the absorption suddenly changes rapidly, that is the absorption edge, absorption edge. So, absorption edge is shifted to higher energies and the second thing that we observed is these peaks are more pronounced, this is in a Quantum Well structure. In a bulk semiconductor at room temperature we do not see any exitonic peaks.

However, if a measurement is made at low temperature, in fact in the early 1960s there were low temperature absorption measurements in semiconductors and for example if you take gallium arsenide h nu here. So, this is 1.42 e V at room temperature. Let say 300 K then if you measure at a lower temperature. So, let me write this as 1.44, 1.46, 1.48 and 1.50 and so on. Then if you measure at a lower temperature, then you would see the absorption and if you lower the temperature further. So, this is at 300 K, this let us say 186 K and this is at 26 K. The numbers here 10 to the power of 4, 10 power 3, 10 power 2 centimeter inverse alpha in centimeter inverse; so this for gallium arsenide.

Several people measured these set in the early 60s. So, what you observe is at room temperature the absorption coefficient does not see, show any peaks, but if you lower the temperature there are exitonic resonance peaks here and the peak become sharper if you go to lower temperature. This is because excitons which we call, which correspond to a electro statically bound electron hole pair closed to band edge where kinetic energy is minimum. The binding energy of these excitons binding energy at room temperature is of the order of 4 to 5 M E V, binding energy is of the order of 4 to 5 M E V that is 0.004 electron volts, millielectron volts M E V. So, the binding energy in in most semiconductors, the binding energy is 2 to 10 M E V excitons at room temperature, some wide band gap semiconductors like gallium nitride has a much higher exitonic binding energy about 25 M E V also.

But most of the semiconductors which are in this range, we have 2 to 10 M E V, gallium arsenide has about 4 to 5 M E V that is the binding energy and as I discussed earlier that at room temperature the average kinetic energy, thermal energy is of the order of 25 M E V. So, the thermal energy due to the large thermal energy in the (( )) is these are immediately disassociated, ionized they no more hold together and they are ionized.

So, excitons do not exist at room temperature or they form and immediately dissociate. So, you do not see any resonance peaks but if you lower the temperature if you lower the temperature then the thermal energy k T reduces and therefore the binding energy becomes comparable and then you start seeing resonance peaks in the absorption. And if you lower further you can clearly see resonance peaks. So, these are bulk, these not Quantum Well this is bulk gallium arsenide, bulk gallium arsenide.

In fact this is, these are very important tools for the existence of excitons, very clearly experimentally you can see the excitons, existence of excitons in the semiconductors. In the case of one other thing what we observe is these and what about the shift, the band energy also shifting with temperature. This is because of temperature dependent band gap E g is temperature dependent, for semiconductors E g is the function of temperature.

Generally, E g is higher at lower temperature for example, gallium arsenide if you go to 26 K or 27 k it is about 1.5 is the band gap in e V. So, E g is temperature this shift in bulk is because of change in band gap energy. So, the same thing we observed here that it is shifting to higher energies because band gap is increasing as you lower the temperature. So, it shifts to higher energies. The second thing that you see is the peak sharpens. In the case of Quantum Well structure you already have a small peak even at room temperature.

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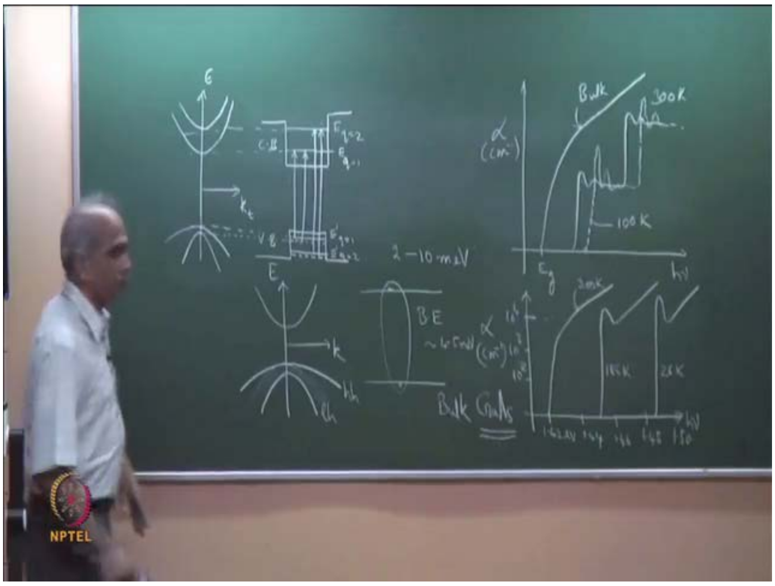

This is because of quantum confinement which leads to higher banding energy of excitons. The excitons have a higher banding energy generally about 3 to 4 times that are bulk because of quantum confinement. So, recall. So, what is this quantum confinement? Let me take two states here. So, this is E 2. So, this is E E 2 or E q equal to 1 q equal to 1 and E q equal to 2 in the conduction band. So, this is the conduction band and this is valance band. This is E dash so E dash q equal to 1 and E dash q is equal to 2 in the valance band.

The question is, is band gap energy increasing? That is what I said, band gap energy is increasing as you lower the temperature for semiconductors. So, please see this we have, I have considered a Quantum Well with two levels. In the case of valance band if you recall I had mentioned that there are light holes and heavy holes. So, there are heavy holes and light holes. So, this is the band corresponding to light hole and this is band corresponding to heavy hole in the case of valance band. They can be degenerate or they need not be degenerate. So, if they are not degenerate at k equal to 0 which means if this light hole band which is the case in normally in Quantum Well structures. If it remains likes this, this is the light hole band then you can see although k is 0 they are degenerate here, this is E k diagram so k verses E then the energy corresponding to light hole here is different.

Therefore, actually I have to show, I am showing this by dash line the light hole bands. So, that these are, these correspond to energy sub bands; we have done in the last class, energy sub bands like this. So for every level correspondingly there is energy sub bands in Quantum Wells; so here also corresponding to this there is an energy sub band. So, we have a light hole band and corresponding to this we have, this is what I have drawn. So, forget about this, this is for bulk. In a Quantum Well structure we have energy sub bands, this is what we discussed in the last class.

Corresponding to each q value that is 1 q equal to 1 determines the k z value, but k x and k y are continuously varying almost continuously varying and therefore, we have energy sub bands, formation of energy sub bands. So, corresponding to each energy level here there is a sub band formed because this is the transverse k t that is square root of k x square plus k y square. Corresponding to heavy hole and light hole there are two sub bands here and this is although k equal to 0 here, there are two sub bands and that is why have shown like this. The allowed transitions are this one is an allowed transition and this is also an allowed transition. Similarly, the allowed transition here that is delta q equal to 0 is an allowed transition. This is a allowed transition and this is also an allowed transition. This is the same energy value q equal to 1, but there are light hole and heavy hole bands. So, that dash line here corresponds to light hole band. What I have shown here and

(( ))

q equal to 2 to q equal to 1. No, the question is whether q equal to 2 to q equal to 1 is valid allowed or not, this is not allowed. Quantum mechanically you can find out what are the allowed transitions and delta q equal to 0 which means q equal to 1 here must have q equal to 1 here. So, that is why this, what I have shown are allowed transition please remember allowed transition does not mean a transition from here to here will not take place. The probability is very low, allowed transition means probability is high, but forbidden transitions can take place, but with low probability. So, corresponding to this excitons had formed the heavy hole to this, we have the first peak.

Please see here the energy difference from this to this is the first peak here in the Quantum Well. The second small peak that you have see is from the light hole to this band. So, q equal to 1, but 1 is light hole and there is heavy hole. That is why you see two peaks here, exitonic peaks, two peaks and corresponding to this the second step here, the second step is, so, this step is because of absorption here and the second step that we have is because of absorption here, from here to here and there also you see two peaks. This is because of light hole and heavy hole.

So, in the further discussions I will not bring in light hole and heavy hole because it is also possible to have only one it is also possible to have only one peak by using strained layer Quantum Wells, it is possible to merge these. So, that these are degenerate and you will be left with just one peak here. So, it is possible and therefore, in future discussions I will not bring these two peaks but the important point to note is where is the peak because of exciton, exitonic resonances that is absorptions taken, energy taken by the excitons, formation of excitons. That is why there is an Exitonic peak. So, you have an exitonic peak and you can see excitons at room temperature in Quantum Well structures. This is because of quantum confinement. What is this quantum confinement?

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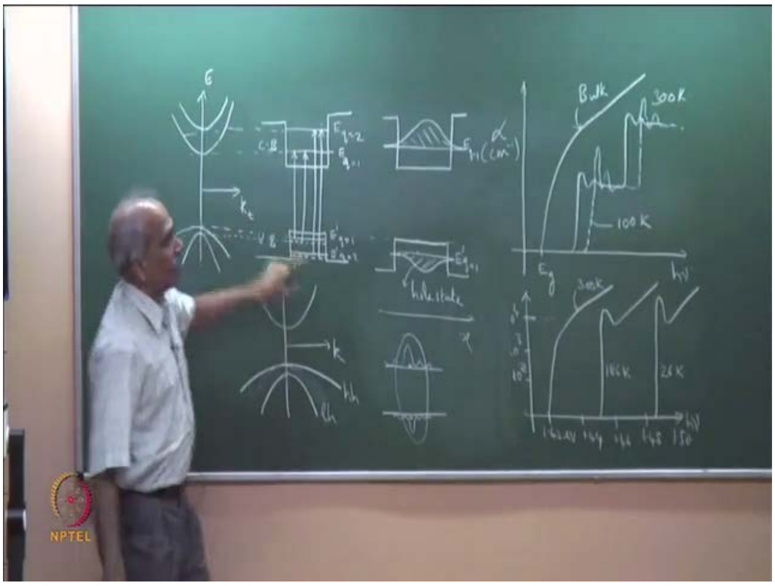

Let me draw again the same structure, because now I want to show wave functions. In the case of a Quantum Well structure if I consider one level, just let me consider one energy level that is E q equal to 1 and E dash equal to 1, this is for the holes and that is for, there is a, this is the lowest energy. Therefore, what I am plotting is the wave function associated with the electron here and the wave function associated with the hole, I can draw it upward or downward, it does not matter, it simply indicates that there is a phase change of pie. Otherwise you can also plot this same way upward. So, what I have plotted is the wave function, correspond, this is whole wave function, whole state and this is the electrons state in the wave function. Even in the case of bulk if you have an electron here and a hole here there is an associated wave function, it is like a packet and therefore, there is an associated wave function. But this wave function is not confined by any potential barrier.

Therefore, slight energy, supply of slight energy will simply dissociate this. But in a Quantum Well structure the wave function is confined by this potential energy barrier and this is for quantum confinement, there is no confinement here. It is just because of the (( )) attractive potentials that they are holding on together with a weak binding energy, but in this case there is a potential barrier which is confining the electron state here and the hole state here. Which means, please remember this axis is x. At a given spatial position they are made to hold together. Therefore, this is called quantum confinement. Quantum confinement refers to this and this confinement leads to additional binding energy. And therefore the binding energy of these is higher, binding energy of excitons is higher than binding energy in bulk semiconductors. This is typically the binding energy is typically 4 times 3 to 4 time that of bulk, which means if I take gallium arsenide which has a binding energy of about 4 M E V, then in Quantum Well structure it will have binding energy of 15 to 20 M E V, typically 15 to 20 M E V.

Now, the direct binding energy is higher although it is comparable it is higher. Therefore, the, they do not dissociate so quickly and therefore, you see this at room temperature. The second peak as I already said, it is due to light hole band. So, please focus of one of, one of the peaks and this peak appearing at room temperature is because of the increased binding energy due to quantum confinement. Now, we will see what is Quantum confined Stark effect refers to shift in absorption peaks or absorption lines and red shift of the absorption in Quantum Well structures is called the quantum confinement, Quantum-confined Stark effect. So, let me illustrate it and then it will become clear. At a given temperature this shift is because of change in temperature. Now, we will see a similar shift will be there because of an applied electric field and that is called Quantum confined Stark effect. Let me erase and rub this and draw a fresh figure for the absorption spectrum of Quantum Well construction.

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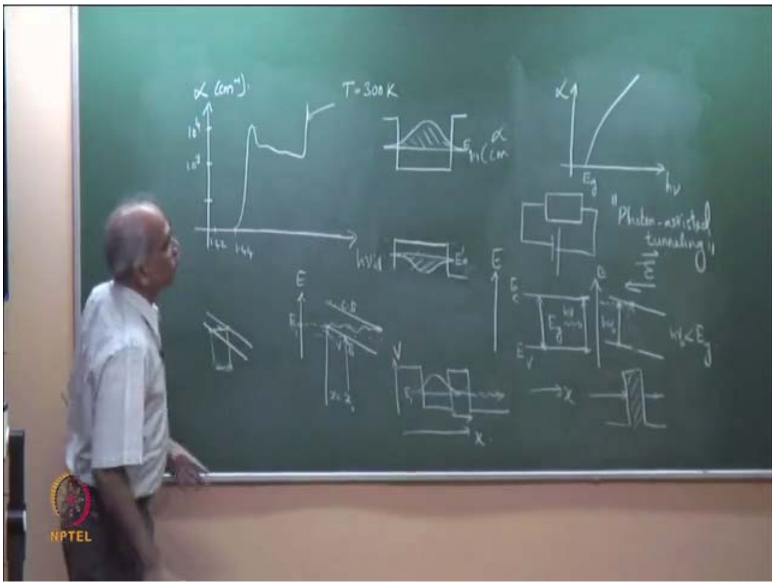

So, this time I will focus only on the first step. Similar step is the second step, but I will focus on the first step; h nu here and in a Quantum Well structure therefore, absorption peak I am focusing only on a single peak. The second step is there, I am not concerned about that. If this is gallium arsenide 1.42 is here and the step starts a little later 1.44 e V this is h nu e V. I am taking gallium arsenide that is the one widely studied and also we can put some number. So, numbers will give you a better feel how much it is shifting. That is why I am taking gallium arsenide. So, this is alpha and the numbers here are typically 10 power 3, 10 power 4. So, 10 power 3, 10 power 4 alpha in centimeter inverse, this is at a particular temperature. So, T equal to all T is equal to 300 K room temperature and no electric field applied. What happens, if we apply an electric field.

First, if you take a semiconductor, a piece of semiconductor and apply an electric field, a piece of semiconductor has an energy band diagram like E v E c and E g. If we are putting x equal to 0 at this end and x equal to l at this end then this is x. We applied an electric field, it is not p n junction, it is just a p subs (( )) so what will happen to the band diagram, if we apply an electric field what will happen to the band diagram? This end is at a positive potential which means electron potential energy is lower. Please remember this is E and therefore, the band bends. So, the energy band diagram bends like this. The gap is the same E g there is no change in energy gap. This is E g. In the presence of an electric field which is like positive, so this is positive end, this is the E field, electric field, applied electric field and the band bends, this fashion. In this case if you have an energy, a photon of energy E g equal to h nu, h nu equal to E g or more.

An electron getting close to the band edge can make an upward transition and comes here. E g equal to h nu or E g is slightly greater then h nu. This can come here and that is why we know that absorption for this semiconductor if I plot the absorption. Let me plot it here, it start from E g and goes like this. So, h nu E g alpha for a bulk semiconductor absorption starts at E g because of this region. What will happen to this? Please, let me illustrate a little bit if I increase the electric field, this will tilt more.

If I increase the electric field let me draw here it will tilt more and let say I have a semiconductor with band gap E g but this is now tilted. What is this? These are all, this is the valance band and this is the conduction band, bands which have allowed states and electron at a particular value of x. Let us say x equal to x 0, x equal to x 0. This end is x equal to 0, this end is equal to l, at x equal to x 0 there is an electron which is sitting here. This cannot go to this band, because there are no allowed state, but an electron which is sitting here.

Please see an electron in the valance band here has energy E is equal to E 1. An electron allowed state in the conduction band also has an energy E equal to E 1 therefore, in principle the electron exist here or here or the electron which is sitting here can tunnel from here to this state because it is at the same energy state, this quantum mechanical tunneling. Okay, recall what we know in quantum mechanical tunneling. If you have an electron state here which has wave function here, this the basic quantum mechanics. This is reach the potential and this is x, v of x those who are not familiar, this is elementary quantum mechanics. This is an allowed state inside the well, bound state inside the well, but here also you can have energy vessel, this is the first state E 1. You can also have energy here, the same energy is possible in this region because the potential is lower, if you want you can make another well here.

This is the identical well which we have talked about and then there is an allowed value here also and therefore, the two wave functions can interact the directional coupler in fiber optic, the two wave functions can interact which means if I have the wave function here it can interact with this and energy can get transport to that or if I did not have this then what it mean is if at this value of E E 1 states are permitted in this region and therefore, this electron the (( )) come here because this is the allowed state, it starts oscillating an electron can tunnel from here to this.

The tunneling coefficient or the probability that the electron can go from here to here depends on the width, this width of the barrier. This is the barrier, it is seeing this potential barrier. I did not have a well, I can also have simply a barrier step and I can have an electron which is incident like this. This is a barrier, potential energy barrier. What is the probability for this electron go to the other side? Classically it cannot go, but quantum mechanically it can go to the other side. It can tunnel through the barrier. The tunneling probability depends on the width of the barrier and height of the barrier. The probability of tunneling depends on the width of the barrier and height of the barrier. I will come back, this much elementary concept is sufficient, we cannot go into too much of quantum mechanics here.

The point is the same, the electron allowed state is here and allowed state is here, there is a barrier in between. There is nothing, no allowed states there like here inside the barrier there are no allowed state. So, there is a barrier and a separation delta x separation. So, this electron can in principle tunnel here, but the tunneling probability will depend on the separation between there. If I make it more steeper or for example if I have a semiconductors which has a small band gap and more steeper. More steeper means I have applied a stronger electric field then this electron will have a probability to go to here which is much better because the difference is small. The barrier width is small. So, this is the barrier width, this is quantum mechanically tunneling.

In the case of a semiconductor we can also have photon assisted tunneling photon assistant tunneling photon assistant tunneling. What is this photon assisted tunneling? An electron which is sitting here let me remove this E g. So, that the picture is clear, there is a photon which is incident, which has energy E g less at nu less than E g. It is able to lift only up to this. It is not possible that you can, it can absorb, normally it is not possible, but if it is able to lift up to this height, please see at this energy if I go here, there is an allowed state here and therefore, this electron which is sitting at the band edge here can make a transition to this state through photon assistant tunneling.

The photon in the energy space, please see this is energy axis, this is not physical height, this is energy axis. In energy the electron gains energy from photons and lifts it up to this energy from where it can tunnel to the state and this difference, it is very small, the tunneling probability is very high. This is called photon assisted tunneling, photon assisted tunneling. This gap here is made up by tunneling because photon to lift it up to this, at the same energy we have a vacant state, so, this electron essentially goes like this, but with the help of photon assisted tunneling.

In an earlier classes we have discussed about phonon energy transitions. It is like photon assisted transition and this is, this means this energy h nu here h nu 0 h nu 0 is less than E g, this means there is a probability of absorption of photons with energy less than the band gap. And what would happen to the absorption spectrum of my this bulk? This will now shift here, the absorption spectrum this is with E equal to 0 the electric field E equal to 0 and this is width electric field, finite electric field and this famous experiment was done by Franz and Keldysh and is known as Franz-Keldysh effect.

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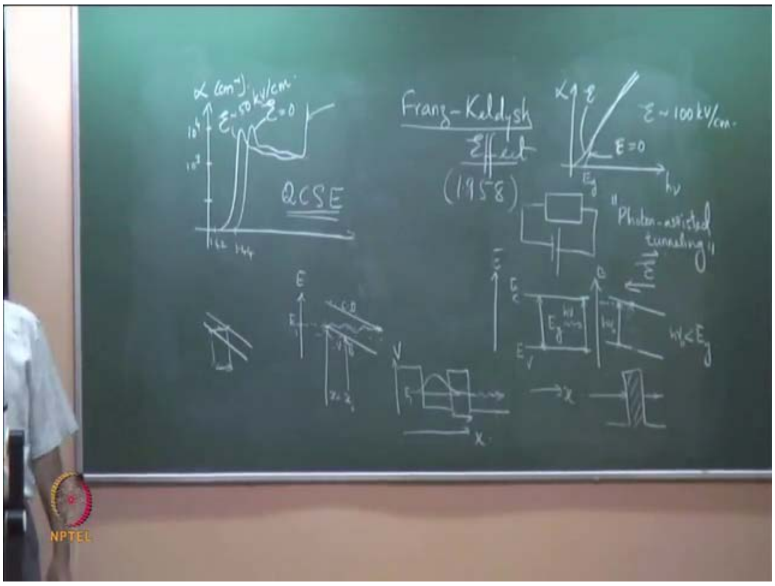

Franz-Keldysh effect, this was discovered in 1958. Franz-Keldysh a German scientist Franz and a Russian scientist Keldysh discovered this effect that in the presence of an applied electric field the absorption edge shifts to lower energy or higher wavelength, lower energy or higher wavelength. So, it is called red shift of the absorption edge Franz-Keldysh effect. Red shift of the absorption edge in semiconductor, it is explained by the phenomena of photon assisted tunneling photon assistant tunneling. Why did I discuss this? Shifting of, red shifting of the absorption edge in bulk semiconductors is called Franz-Keldysh effect.

If you apply an electric field to Quantum Well structure you will see a similar shift effect to this side. So, red shifting of the absorption edge, red shifting of, red shifting means shifting to lower energy shifting to higher wavelength. So, red shifting of the absorption edge in a Quantum Well structure is called Q C S E quantum confinement structure. This is E equal to 0 and this is E of the order of, typical numbers are 50 kilo volt per centimeter. The electric field applied is. This happens where the typical electric field of the order of 100 kilo volt per centimeter. You need a little higher electric field 100 kilo volt per centimeter. This happens 20 kilo volt per centimeter, 30 kilo volt per centimeter is not a very big electric field, we will see because it is per centimeter.

Dimension will be very small. So, first the definition of Quantum-confined Stark effect is the red shift of the absorption edge of a Quantum Well structure is called Quantum-confined Stark effect. It is quantum confined because this step like variation with an exitonic peak is because of quantum confinement and it is Stark effect because the shift is because of an applied electric field. So, Quantum-confined Stark effect, this is Franz-Keldysh effect. Basically it is Franz-Keldysh effect, but in a Quantum Well structure. We will come to the modulator, we would wonder where is the modulator. The modulator will come shortly. So, what is happening? I draw this again the Quantum Well structure.

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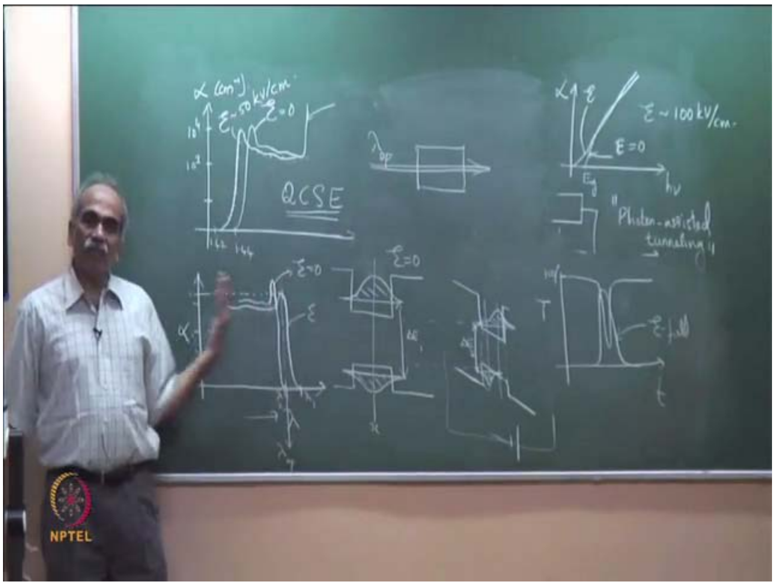

Quantum-confined Stark effect, we have the electric, the wave function of the electron, wave function of the hole here. This is without the electric field, what will happen to this if I apply the electric field? The band will start bending and what you get here is. So, this is E equal to 0 and e equal to let us say 50 kilo volt per centimeter. The energy here, this energy goes down because of the band bending and this energy comes up, the area under the curves are the same, but just that what has happened is if I call this as some energy delta E 1 then this difference now is smaller. Delta E 2, then delta E 2 is less than delta E 1 because of the applied electric field, there is a small displacement also. I should have shown that also. The electron wave function becomes asymmetric, why do you think electron wave function becomes asymmetric?

Because remember I have applied a positive voltage here. So, the electron is getting attracted towards the positive voltage. So, it is trying to go that side, if I had taken a simple bulk semiconductor the electron will immediately rush towards that end, that is why the, it will dissociate immediately. Here it is trying to go, but the barrier is stopping it from going. Thus wave functions have separated out, here in space at any given value of x you see the peak of this is at the same position as peak of this. But here the peak of this is here and the peak of this is here.

The wave function is trying to separate out because this is getting attracted toward this end this is, but what is important is as I said change in energy, difference in the effective band gap, this is the effective band gap E g q 1 and this is E g q 1 bar. Now, q 1 is smaller which means photons of lower energy can be absorbed, which means the band edge is shifting to lower energies. So, this is the (( )) after applying electric field red shift of red shift of the band h because of quantum confinement, the electron fields are still held together and therefore, if there is a, if there is a exciton formed the exciton is still there.

Exciton has not gone, exciton is still holding together because of quantum confinement. If there was no quantum confinement the exciton will be immediately torn apart, dissociated because of their applied electric field the electron will travel this end, hole will travel this end. So, there will be no more exciton in bulk semiconductor, even at lower temperature, but in the case of Quantum Well structure, the electron wants to go, but the barrier is stopping it. Hence, Quantum-Confined Stark effect, it is because of quantum confinement the exitonic peaks still remain. Where is the modulator? We will discuss more details of the modulator later, but you imagine that, this is in terms of energy if I were to plot this in terms of wavelength, how would it look? It would, this is shifting.

Which one is with E equal to 0 and which one is with E greater than 0? So, what is on the right side is E greater than 0 because this is red shift. Please see now, this is I am plotting the wavelength lambda, lambda versus alpha. So, this is with E and this one E equal to 0. I should actually show this as a higher peaks because the peak goes down a little bit. Now, very quickly where is the Quantum Well modulated? Suppose, there are two wavelengths here; let us say this edge was at lambda 1 and this at lambda 2. If I put a wavelength which corresponds to this, I am showing here lambda operating. If I launch a wavelength through this structure, Quantum Well structure. We will discuss about the device in a next class.

This is the Quantum Well structure and I am putting wavelength beam of wavelength lambda o p. How to apply the field, what is the device configuration? We will discuss, but very quickly and I am applying this wavelength is passing through the device, lambda o p is a here. When there is no electric field, what is the attenuation coefficient? Almost nil. This axis is attenuation coefficient, so, 10 to the power of 1, 10 to the power of 2, 10 power 3, 10 power 4. So, at this wavelength this is the last curve. So, lambda o p which is just greater than lambda 2 there is no loss, this medium is transparent. When I apply the electric field, this curve has shifted here.

So, what has happened at this wavelength you see, the loss is 10 to the power of 4 attenuation coefficient here for this curve when electric field was not there, we will discuss again, but the electric field was not there, lambda operating this medium was transparent. So, complete transmission when I applied the electric field the last curve shifted here which means alpha has increased by orders of magnitude because now the second curve is applicable, not the first curve because I applied electric field. So, this is the curve which is applicable and this wavelength correspond to the peak here. So, the attenuation coefficient is very high which means this will absorbed it, nothing will come out.

So, what is the point? If I see the transmission T versus time, if I apply an electric field pulse like this, this is E field an electric pulse in time, then the transmission which was full 100 percent here originally, when the electric fields comes the transmission will go down like this. This is optical transmission, this is applied electric field, an electric pulse applied to the device, the transmission has gone down like this. This is modulation. Modulation of intensity, the intensity which has been modulated and this response in electro optic modulator, electro absorption modulator is very small time of the order of 10 to 20 pico seconds. You can really have electro absorption modulators at 40 gigahertz 50 giga hertz and so on. We will discuss the device configuration in a next class. I will stop here and discuss the device configuration later. This is the principle how the Quantum-confined Stark effect can be used to realize electro absorption modulator.