Semiconductor Optoelectronics
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Lecture - 24
Electro-absorption Modulator - I Principle of Operation

So we start with this is the first device electro-absorption modulators or quantum well modulators. So before I start I will briefly discuss the answer for the yesterday’s quiz.

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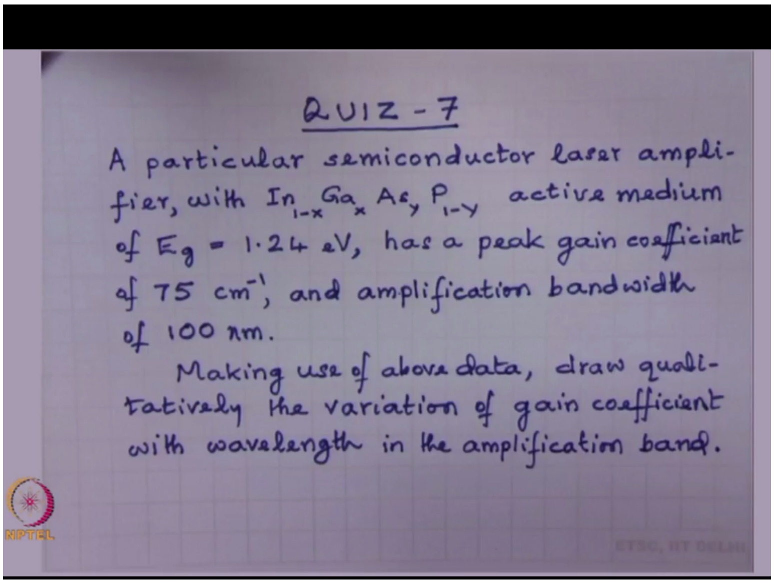

QUIZ - 7

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 Eg=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 wavelength in the amplification band. As I keep on repeating quiz is simple question.

You should think simple and a little quick. The answer is very simple. Most of you have tried to see complicated answer in that so the answer is here.

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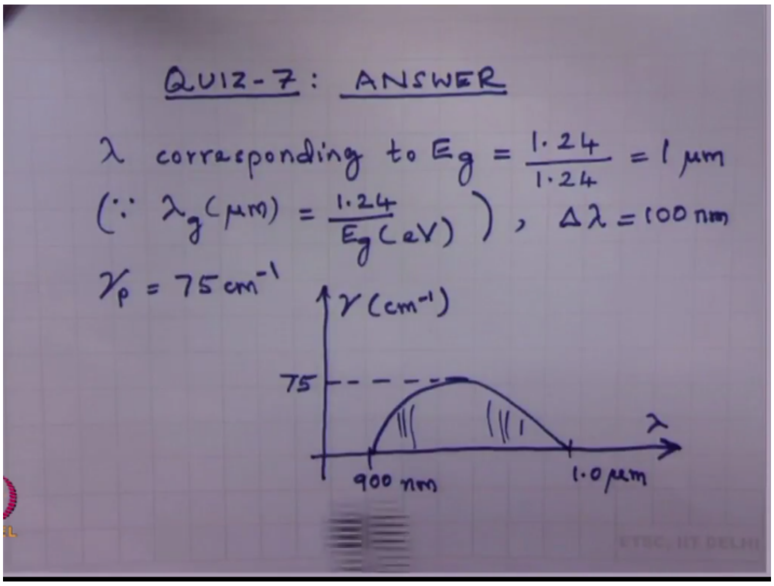

QUIZ-7: ANSWER

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

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

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

The fact that Eg was given 1.24 eV should have been a hint to you that it will give lambda=1 micron because lambda=1.24/Eg in electron volts. So lambda is 1 micron. Delta lambda is given 100 nanometer, gamma p is given and an important point that we all know is if frequency is increasing in this direction then wavelength will be decreasing in this direction. Energy is increasing means wavelength is decreasing.

So that is all the points to be used and you have a similar variation in frequency h nu starting from Eg here, but this time it starts from the opposite end because high energy is to this end and that is all. No need to remember any formula, apply any formula, apply any variations because it is a quiz okay. I have already corrected, but I forget to bring. Electro-absorption modulators, these are also called quantum well modulators.

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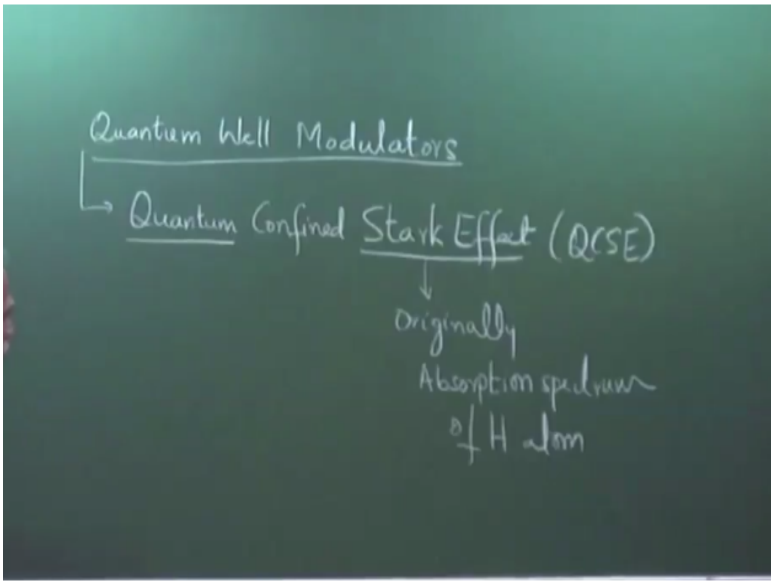

Quantum Well Modulators

↳ Quantum Confined Stark Effect (QCSE)

↓

Originally

Absorption spectrum

of H atom

These work on the principle of quantum confined stark effect. We know what is stark effect. Stark effect refers to shift in the absorption spectrum. This was originally observed in the absorption spectrum of hydrogen atom, shift in the absorption lines of hydrogen atom in the presence of an applied electric field that was stark effect. We are looking at quantum confined stark effect.

So 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 and that is quantum confined stark effect QCSE and this QCSE 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 semiconductors as well as in quantum well structures. We have seen this in the last classes. So let me quickly recall what we have seen the absorption spectrum in quantum well structures.

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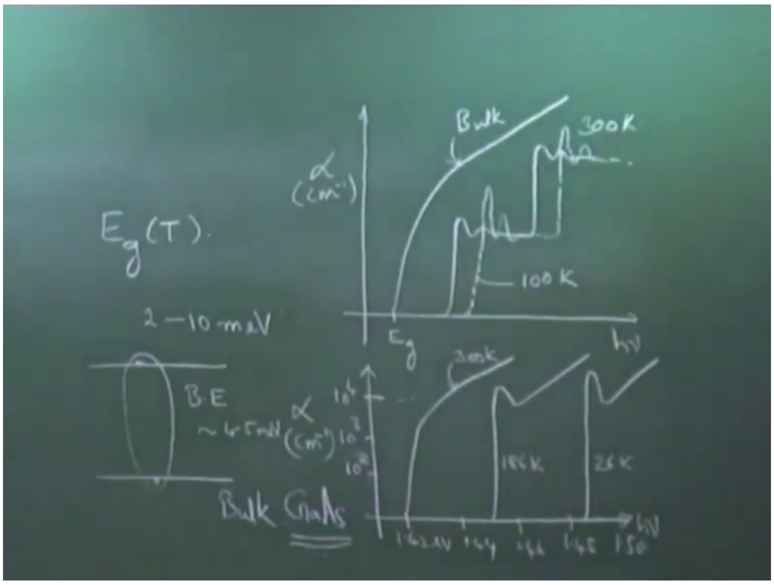

H nu and alpha attenuation coefficient centimeter inverse alpha, in a bulk semiconductor, the attenuation varies something like this, so this starts from Eg for bulk a quick recap, bulk semiconductor and if you use a quantum well structure it starts a little later. We have already seen and then I had drawn. This is at room temperature and we mention that these peaks are corresponding to excitonic peak.

So this is at room temperature say 300 K at room temperature. If you measure the absorption spectrum at a lower temperature what you would see is so let me draw this with the dotted lines. Let us say this is at 100 K so 2 things that we observe, 1 is the absorption edge is shifted, this is called the absorption edge. Absorption edge is the energy or wavelength at which the absorption suddenly changes rapidly that is the absorption edge.

So absorption edge is shifted to higher energies and the second thing that you observe 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 excitonic 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 eV at room temperature let us 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 is for gallium arsenide. Several people measure this in the early 60s so what you observe is at room temperature, the absorption coefficient does not show any peaks, but if you lower the temperature there are excitonic resonance peaks here and the peak become sharper if you go to lower temperature.

This is because excitons which recall which correspond to an electrostatically bound electron hole pair close to the bandage where kinetic energy is minimum. The binding energy of these excitons at room temperature is of the order of 4 to 5 meV. Binding energy is of the order of 4 to 5 meV that is 0.004 milli electron volts. So in most semiconductors the binding energy is 2 to 10 meV excitons at room temperature.

Some white band gap semiconductors like gallium nitride has a much higher excitonic binding energy about 25 meV also but most of the semiconductors which are in this range we have 2 to 10 meV. Gallium arsenide has about 4 to 5 meV as the binding energy and as I discussed earlier that at room temperature, the average thermal energy is of the order of 25 meV.

So due to the large thermal energy in the lattice these are immediately dissociated, ionized. They no more hold together and they are ionized. So excitons do not exist at room temperature or they form an immediately dissociate. So you do not see any resonance peaks but if you lower the temperature then the thermal energy KT 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. This is not quantum well; this is bulk gallium arsenide. In fact, these are very important proofs for the existence of excitons very clearly experimentally you can see existence of excitons in semiconductors. In the case of one other thing, what we observe is these and what about the shift?

The bandage is also shifting with temperature. This is because of temperature dependent band gap, Eg is temperature dependent for semiconductors EG is a function of temperature. Generally, Eg is higher at lower temperature for example in gallium arsenide if you go to 26 K or 27 K it is about 1.5 is the band gap in eV. So this shift in bulk is because of change in band gap energy.

So the same thing you observe 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 structures, you already have a small peak even at room temperature. 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 of bulk because of quantum confinement.

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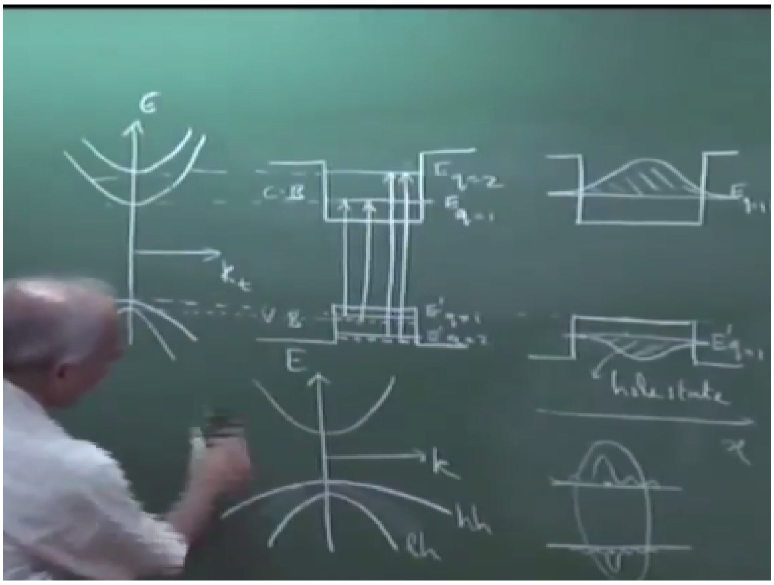

So recall so what is this quantum confinement? Let me take 2 states here so this is Eq=1 and Eq=2. In the conduction band, so this is the conduction band and this is the valence band. This is E dash so E dash q=1 and E dash q=2 in the valence band. **"Professor - student conversation starts."** The question is, is band gap energy increasing. That is what I said. Band gap energy is increasing as you lower the temperature for semiconductors. **"Professor - student conversation ends."**

So please see this. I have considered a quantum well with 2 levels. In the case of valence 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 the band corresponding to heavy hole in the case of valence band. They can be degenerate or they need not be degenerate.

So if they are not degenerate at K=0, which means if this light hole band which is the case normally in quantum well structures. If it remains like this, this is the light hole band then you can see although K is 0 they are degenerated here so this is E-k diagram. So K versus 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 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 band 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 1q=1 determines the kz value but kx and ky are continuously varying almost continuously varying and therefore we have formation of energy sub bands. So corresponding to each energy level here there is a sub band formed because this is the transverse kt that is square root of kx square+ky square.

Corresponding to heavy hole and light hole, there are 2 sub bands here and this is although k=0 here there are 2 sub bands and that is why I have shown like this. The allowed transitions are this one is an allowed transition and this is also an allowed transition. Similarly, the allowed transitions here that is delta q=0 is an allowed transition. This is an allowed transition and this is also an allowed transition.

This is the same energy value q=1, but there are light hole and heavy hole bands so the dash line here corresponds to light hole band what I have shown here and "Professor - student conversation starts." q=2 to q=1 no, the question is whether q=2 to q=1 is valid, allowed or not? This is not allowed. Quantum mechanically you can find out what are the allowed transitions and delta q=0, which means q=1 here must have q=1 here.

So that is why these what I have shown are allowed transitions. "Professor - student conversation ends." 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 formed from 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 see is from the light hole to this band so q=1 but 1 is light hole, another is heavy hole that is why you see 2 peaks here excitonic peaks, 2 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 2 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 1, it is also possible to have only 1 peak by using strained layer quantum wells it is possible to merge these.

So that these are degenerated and you will be left with just 1 peak here so it is possible and therefore in future discussions I will not bring these 2 peaks but the important point to notice where is a peak because of exciton, excitonic resonances that is energy taken by the formation of excitons formation of excitons that is why there is an excitonic peak.

So you have an excitonic peak and you can see excitons at room temperature in quantum well structures. This is because of quantum confinement. What is this quantum confinement? So 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 1 level just let me consider 1 energy level that is Eq=1 and E dash q=1.

This is for the holes and that is for, there is a 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 pi. Otherwise, you can also plot this in the same way upward. So what I have plotted is the wave function.

This is the hole wave function hole state and this is the electrons 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, supply of slight energy will simply disassociate this.

But in a quantum well structure the wave function is confined by this potential energy barrier and this is called quantum confinement. There is no confinement here. It is just because of the Coulomb 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 and therefore this is called quantum confinement.

So quantum confinement refers to this and this confinement leads to an additional binding energy and therefore the binding energy of these is higher, binding energy of excitons is higher than the binding energy in bulk semiconductors so this is typically the binding energy is typically 3 to 4 times that of bulk which means if I take gallium arsenide, which has a binding energy of about 4 meV then in quantum well structure, it will have a binding energy of typically 15 to 20 meV.

Now that binding energy is higher although it is comparable it is higher therefore they do not dissociate quickly and therefore you see these at room temperature. The second peak as I already said it is due to light hole band so finish focus 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? So stark effect refers to the shift in absorption peaks or absorption line 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. So let me erase and rub this and draw a fresh figure for the absorption spectrum of a quantum well structure. So this time, I will focus only on the first step. Similar step is there the second step but I will focus on the first step.

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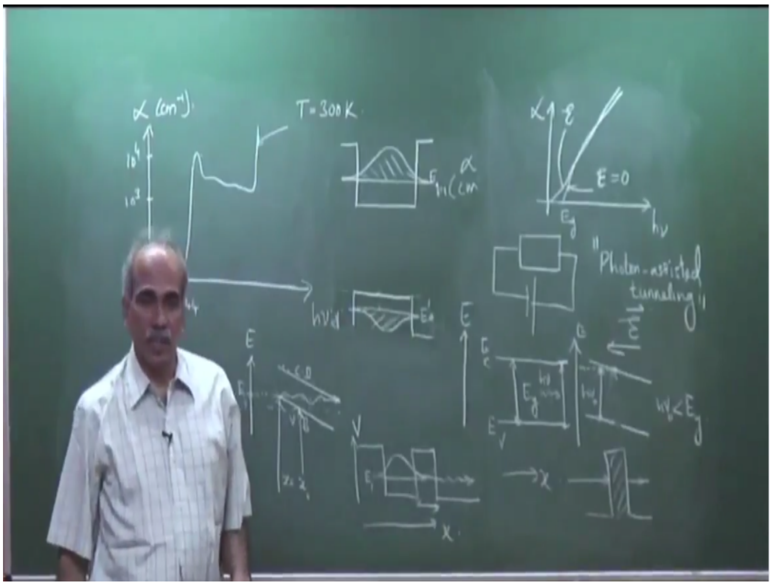

H nu here and in a quantum well structure therefore absorption peak and I am focusing only on a single peak. The second step is there I am not concerned about that. So if this is gallium arsenide 1.42 is here and the step starts a little later say 1.44 eV. This is h nu in pV. I am taking gallium arsenide because that is the one which is widely studied and also we can put some numbers.

So numbers will give you a better feel how much it is shifting. So 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=300 at room temperature and no electric field applied. What happens if you 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 Ev, Ec and Eg. If you are putting x=0 at this end and x=l at this end, then this is x. We apply an electric field, it is not a p-n junction, it is just a piece of semiconductor. So what will happen to the band diagram? If we apply an electric field what will happen to this 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 Eg. There is no change in energy gap. This is Eg. In the presence of an electric field which is like positive, this is positive so this is the E field the applied electric field.

And the band bends in this fashion. In this case, if you have a photon of energy Eg=h nu, h nu=Eg or more an electron sitting close to the band edge can make an upward transition and come here Eg=h nu or Eg is slightly>h nu this can come here and that is why we know that the absorption for this semiconductor if I plot the absorption let me plot it here it starts from Eg and goes like this.

So h nu Eg alpha, for a bulk semiconductor absorption starts at Eg 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 Eg but this is now tilted. What is this? This is the valence band and this is the conduction band.

Bands which have allowed states an electron at a particular value of x let us say x=x0, this end is x=0, this end is x=l at x=x0 there is an electron which is sitting here. This cannot go to this band because there are no allowed states but an electron which is sitting here please see here if I put this axis as energy E if I draw a horizontal line there is a state here which has the same energy here.

Please see an electron in the valence band here has energy E=E1, an electron allowed state in the conduction band also has an energy E=E1. Therefore, in principle the electron can 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 is quantum mechanical tunneling okay recall what we know quantum mechanical tunneling.

If you have an electron state here, which has a wave function here. This is the basic quantum mechanics. This is V the potential and this is x V of x those of you 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 so this is the first state E1 you can also 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 2 wave functions can interact the directional coupler in fiber optics. The 2 wave functions can interact which means if I have a wave function here it can interact with this and energy can get transferred to that or if I did not have this then what it means is if at this value of E1 states are permitted in this region.

And therefore this electron the evanescent wave tail comes here but because here it is an allowed state it starts oscillating and electron can tunnel from here to this. The tunneling coefficient or the probability that the electron can go from here to here depends on this width of the barrier, this is the barrier, it is seeing this potential barrier. I need not have a well I can also have a simply a barrier step.

And I can have an electron which is incident like this. This is a potential energy barrier. What is the probability for this electron to 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 the height of the barrier. The probability of tunneling depends on the width of the barrier and height of the barrier.

I come back this much elementary concept is sufficient. We cannot go into too much of quantum mechanics here. The point is the same. A 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 states. So there is a barrier and a separation delta x a separation.

So this electron can in principle tunnel here but the tunneling probability will depend on the separation between them. So if I make it more steeper or for example if I have a semiconductor 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 mechanical tunneling. In the case of a semiconductor, we can also have photon assisted tunneling. What is this photon assisted tunneling? An electron which is sitting here, let me remove this Eg so that the picture is clear. There is a photon which is incident which has energy h nu<Eg, it is able to lift only up to this.

It is not possible that 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 assisted 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 photon and lifts it up to this energy from where it can tunnel to this state and this difference if it is very small the tunneling probability is very high. This is called photon assisted tunneling. This gap here is made up by tunneling because photon could 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 assisted transition so it is like photon assisted transition and this means this energy h nu here h nu 0 is<Eg. This means there is a probability of absorption of photons with energy<the band gap and what would happen to the absorption spectrum of this bulk? This will now shift here. The absorption spectrum this is with E=0, the electric field E=0 and this is with finite electric field.

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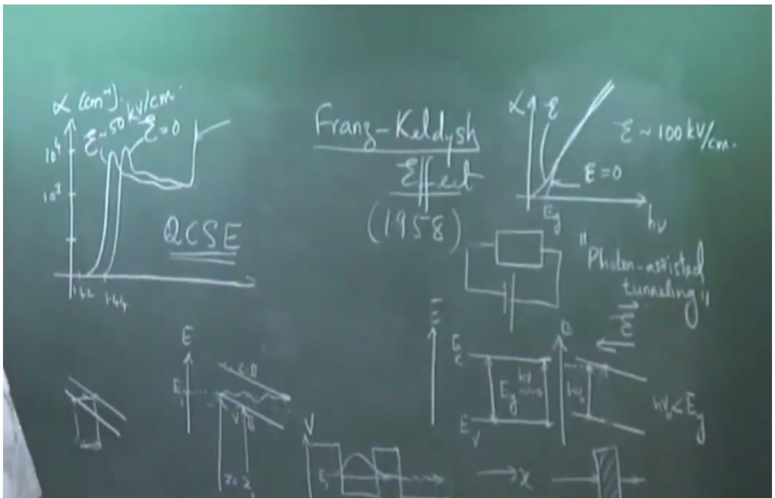

And this famous experiment was done by Franz and Keldysh and is known as the Franz-Keldysh effect. This was discovered in 1958, a German scientist Franz and a Russian scientist Keldysh discovered this effect that in the presence of an applied electric field the absorption edge shifts to lower energy or higher wave length. So it is called red shift of the absorption edge Franz-Keldysh effect, red shift of the absorption edge in semiconductors.

It is explained by the phenomena of photon assisted tunneling. Why did I discuss this? 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 to this side so red shifting of the absorption edge, red shifting means shifting to lower energy shifting to higher wave length.

So red shifting of the absorption edge in a quantum well structure is called QCSE. This is with E=0 and this is E of the order of typical numbers are 50 kilo volt per centimeter. This happens with typical electric field up to order of 100 kilo volt per centimeter. You need a little higher electric field 100 kilo volt per centimeter. This happens with 20 kilo volt per centimeter, 30 kilo volt per centimeter.

It 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 excitonic 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. So 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.

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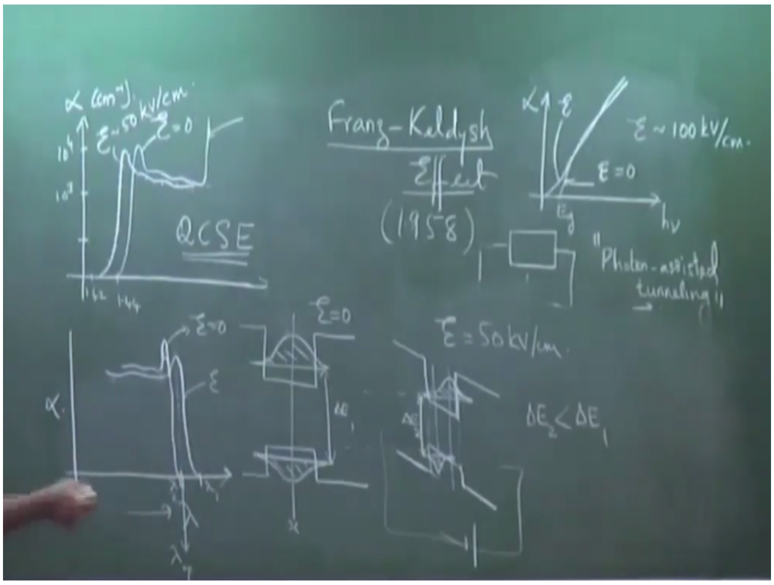

The modulator will come shortly. So what is happening? I draw this again the quantum well structure, quantum confined stark effect. We have the wave function of the electron, wave function of the hole here. This is without the electric field. What will happen to this if I apply the electric field? The band will start bending and what you get here is so this is E=0 and E=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 E1 then this difference now is smaller. Delta E2 then delta E2 is<delta E1. 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 to that end that is why it will disassociate immediately. Here it is trying to go but the barrier is stopping it from going.

The 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 towards this end but what is important is as I said change in energy difference in the effective band gap.

This is the effective band gap Egq1 and this is Egq1 bar but now Egq1 is smaller which means photons of lower energy can be absorbed which means the band edge is shifting to lower energy. So this is after applying electric field, red shift of the band edge because of quantum confinement, the electron fields are still held together and therefore 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, disassociated because of the applied electric field the electron will travel this end, hole will travel this end. So there will be no more exciton in a 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 excitonic peaks still remain. Where is the modulator? We will discuss more details of the modulator later but you imagine that okay this is in terms of energy.

If I have to plot this in terms of wavelength how would it look? So this is shifting, which one is with E=0 and which one is with E>0? So what is on the right side is E>0 because it is red shift please see now this is I am plotting with wave length lambda, lambda verses alpha. So this is with E and this one is with E=0. I should actually show this as a higher peak because the peak goes down a little bit. Now very quickly where is the quantum well modulator?

Suppose so there are 2 wavelengths here. Let us say this edge was at lambda 1 and this edge is 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 next class.

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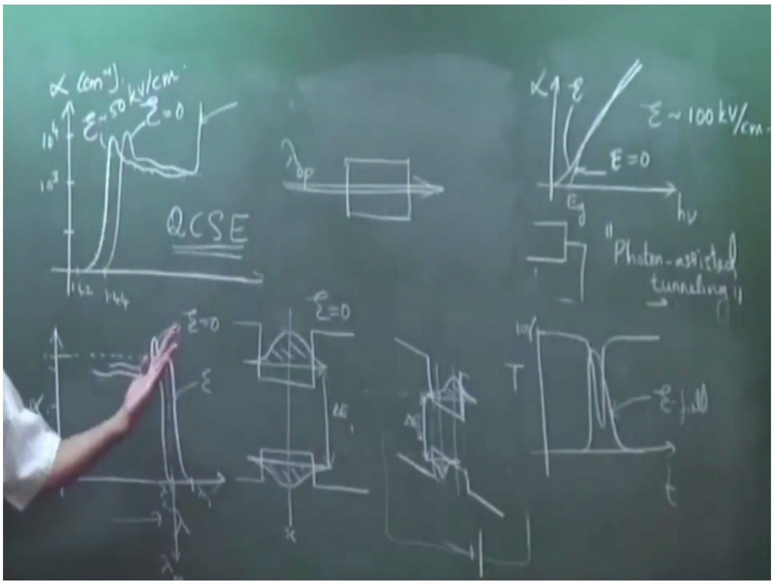

This is the quantum well structure and I am putting beam of wave length lambda op. How to apply the field? What is the device configuration? We will discuss but very quickly I am applying this wavelength is passing through the device. Lambda op is here, when there is no electric field, what is the attenuation 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 wave length this is the last curve so lambda op which is just>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 wave length? 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 when the electric field was not there, lambda operating this medium was transparent. So complete transmission, when I applied the electric field the loss 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 have applied electric field, so this is the curve which is applicable.

And this wave length corresponds to the peak here. So the attenuation coefficient is very high which means this will absorb it, nothing will come out. So what is the point? If I see the transition 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% here originally when the electric field 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 which modulation of intensity. The intensity which has been modulated and this response in an electro-absorption modulator is very, very small time of the order of 10 to 20 picoseconds. So you can really have electro-absorption modulators at 40 gigahertz, 50 gigahertz and so on.

We will discuss the device configuration in the next class. We will stop here and discuss the device configurations later. So this is the principle how the quantum confined stark effect can be used to realize electro-absorption modulator.