Semiconductor Optoelectronics
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Lecture - 25
Electro-absorption Modulator - II Device Configuration

In the last class, we discussed about electro-absorption modulators.

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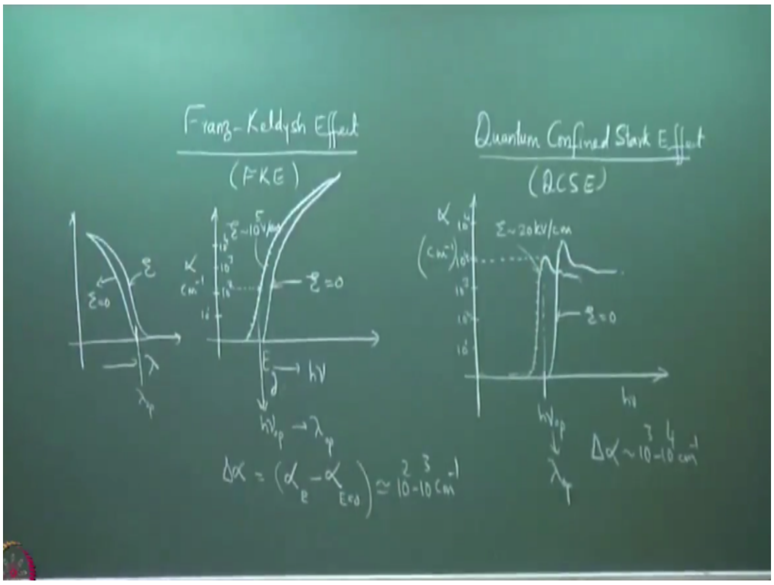

Basically, we discussed the principle of operation of an electro-absorption modulator, which is Franz–Keldysh effect and quantum confined stark effect. Both these can be used to realize electro-absorption modulators. So if you recall the characteristic of Franz–Keldysh effect is shifting of the red shift of the absorption edge of a semiconductor. If you have alpha the loss coefficient in centimeter inverse versus the photon energy h nu.

Then normally the semiconductor may have a loss which goes like this starting from Eg. Then in the presence of an applied electric field, this shifts so the later one is in the presence of an electric field. Just to distinguish let me mark that graph so this is with E=0 applied electric field=0 and this is with applied electric field E of the order of 10 to the power of 5 volt per centimeter, 10 to the power of 5 volt per centimeter.

That is 100 kV per centimeter so if you use the operating wavelength somewhere here that is if you use a lambda op or h nu op, op standing for operating and corresponding to this there is a lambda op. If you choose the wavelength such that you are here then in the absence of the electric field, the absorption is very little.

This is absorption so 10 to the power of 1 typical numbers, 10 to the power of 2, 10 to the power of 3, 10 to the power of 4 and so on centimeter inverse. So before application of the electric field, the absorption coefficient is very small negligible here but in the presence of an electric field so you have an absorption coefficient which is here, which is significantly larger now.

This is Franz–Keldysh effect. In the case of quantum confined stark effect, because of the step response of the absorption coefficient and because of the presence of excitonic peaks, the change is very large. So in the absence of the electric field, you have a response which is like this which shifts in the presence of the electric field. So this is with E=0 and this is typically you need lesser electric field here.

So E of the order of 10 to 20 kilo volt per centimeter, here you need of the order of 100 kilo volt per centimeter, here 10 to 20 kilo volt per centimeter. So if you again choose lambda op here so this is h nu versus alpha, similar numbers 10 to the power so 10 power 1, 10 power 2, 10 power 3, 10 power 4 centimeter inverse and if you choose h nu operating or a new operating or a corresponding to that a lambda operating such that you are located here in energy.

Then in the absence of the electric field the attenuation coefficient here is negligibly small and when you apply the electric field, attenuation coefficient jumps to a large value. So the primary difference here is because of the quantum confined stark effect, the primary difference is a large change in attenuation coefficient and the peak here excitonic peak adds to it.

Because here there is no peak, so typical delta alpha that you can get delta alpha, which means delta alpha=alpha when E=0 so in the presence of E-alpha in the presence of E=0 delta alpha the change in attenuation coefficient is of the order of 10 to power of 2 to 10 to the power of 3 centimeter inverse whereas in this case delta alpha here is typically of the order of 10 to the power of 3 to 10 to the power of 4 centimeter inverse about 10 times more.

Otherwise both of them refer to red shift of the absorption edge of a semiconductor, absorption edge refers to the wavelength or the energy where the absorption coefficient suddenly starts shooting down, that is the absorption edge so red shift shifting to lower energies or shifting to higher wavelengths. So if you want to plot the same graph in terms of wavelength, it would have been the other way.

So this is lambda and then in the presence of an electric field, it would shift like this so this is with E and this is with E=0. So red shift shifting towards longer wavelengths so this is with E in the presence of E and the lambda op that I was talking is somewhere in between here somewhere at the edge so lambda op because normally we talk in terms of operating wavelengths in optics and optoelectronics.

So this is Franz–Keldysh effect and quantum confined stark effect “Professor - student conversation starts.” The question is why does the excitonic peak reduce due to an application of the electric field? When you apply an electric field as I had discussed in the last class, the wave functions associated with the electron and hole which forms the exciton tend to dissociate that is they tend to ionize. “Professor - student conversation ends.”

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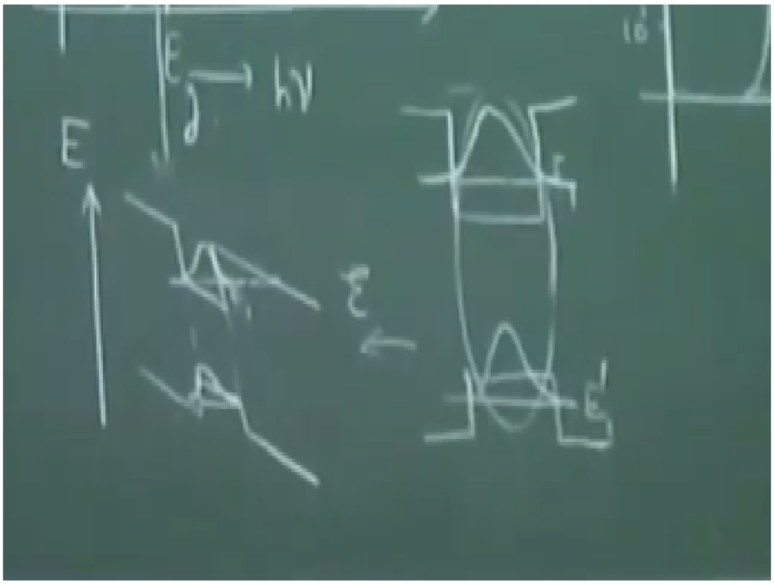

So if you recall the quantum well structure here a single quantum well showing you a single quantum well and there is the wave function here correspond this is the lowest state and you have a wave function corresponding to this, this state and similarly you have a hole here corresponding to that there is a wave function like this. You can show it inverted or this way it does not matter.

So we have E1 and E1 dash so these are overlapping and they are holding together due to columbic attraction and therefore it forms an exciton. In the presence of an applied electric field, the well bends so in the presence of an applied electric field the well takes this form. So this after application of an electric field, there is a change in the energy E1 but more importantly because of the applied electric field, the wave function becomes asymmetric.

And it tends to be located more to the other side because there is a positive potential here and therefore the electron has an attractive potential to this end, which means in simple terms the electron wants to move towards the positive end, which means the probability of locating the electron is more to this end which means the wave function is more shifted to this end and that is why the wave function becomes asymmetric.

Here it is perfectly symmetric but here it becomes asymmetric. Similarly, this wave function associated with the hole tends to move to the other end. Now this tends to move, they are not separated because a quantum confinement still blocks them, but the moment you have this one coming down please see here corresponding to this axis is energy everywhere this vertical axis is energy.

Corresponding to this value of E there is a state and this electron of this energy can tunnel and go out, which means this electron has a probability to tunnel which means there is a probability of dissociation increased probability of dissociation and therefore the excitonic peak goes down. It is just like increasing the temperature, the excitonic peak goes down.

So exactly like that because the electron now has a probability to tunnel, the dissociation probability increases and therefore the resonance peak goes down. This is why when you apply in fact if you apply stronger electric field which completely gets dissociated and you will not see any peak. If you apply more stronger field, it will shift to this side so typically I would show this.

So you will have something like this and if you apply further, there will be nothing for the higher electric fields. We do not want to go up to that because we want if the peak is present then the step change delta alpha is larger. If the peak is not there, you see immediately now delta alpha is a little less so we would like to use the excitonic resonance peak.

Today we will see how to apply we talked of 20 kilo volt per centimeter, 10 kilo volt per centimeter. How to apply this electric field and what is the device configuration? So we will discuss this today. First let me discuss device based on quantum confined stark effect. Early devices were based on this but now there is another way of using a new configuration where you can use Franz–Keldysh effect as well as QCSE, both can be used independently.

There was an early article in physics today. I would recommend you to read this article.

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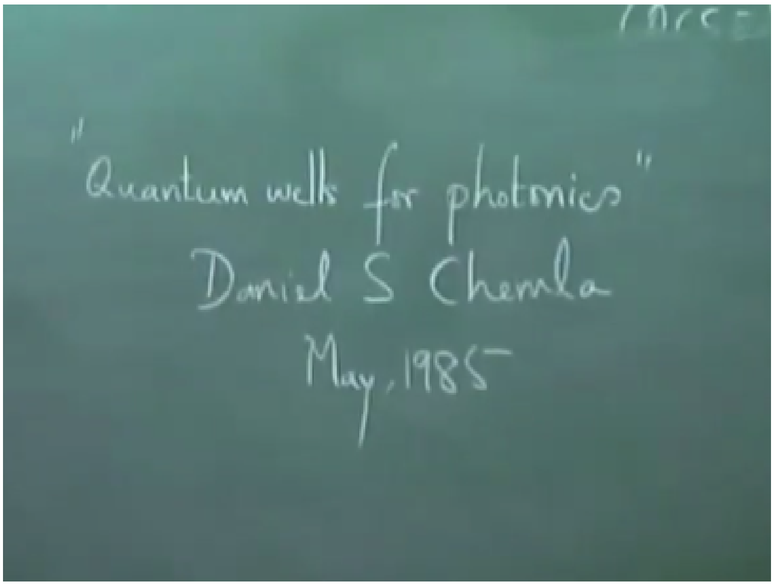

"Quantum wells for photonics"
Daniel S Chemla
May, 1985

This came in Physics Today in article titled quantum wells for photonics by Daniel S. Chemla then Bell Labs. He was Daniel S. Chemla. This is say popular level article May 1985, easy to understand, very old article, 25 years back but still very nice and relevant. The concepts are given very nicely quantum wells for photonics, May 1985. Please see this article. It is quite nice.

So the question is how to apply a large electric field like 10 to the power of 5 volt per centimeter or 20 kilo volt per centimeter?

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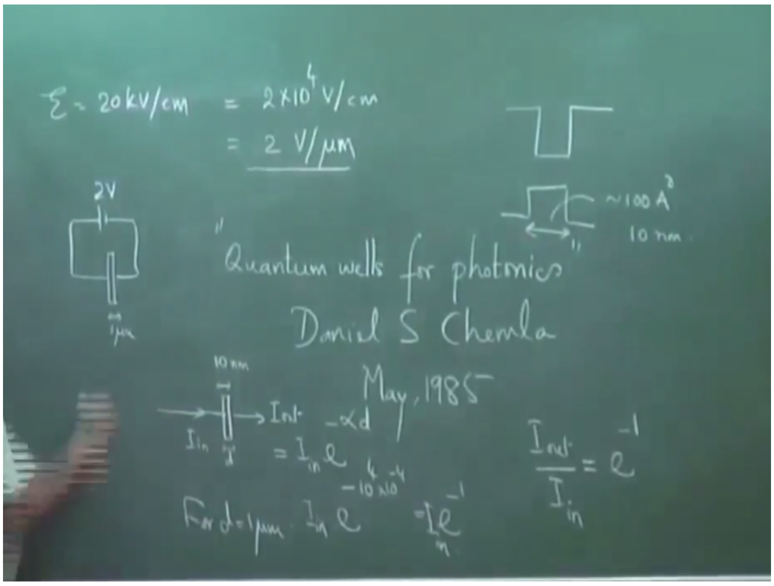

So E=20 kilo volt per centimeter, so this is=2*10 to the power of 4 volt per centimeter and 1 centimeter is 10 to the power of 4 microns so that is=2 volt per micrometer, 20 kilo volt per centimeter is 2 volt per micrometer means if you can apply 2 volt across 1 micrometer so if this is 1 micrometer if you can apply 2 volt across this you are getting the field so it is not a big idea.

So it is not a very big number provided you apply it across a small thickness so 2 volt per micrometer. This is the kind of electric field that is required. Now if you take a quantum well, 1 quantum well typically, please see the logic here. The width of the quantum well here is typically of the order of 100 angstroms which means 10 nanometer okay typical width.

Now if I take this quantum well, which is 10 nanometer thick so 10 nanometer, there is light incident here I in then I out will be=I in*E to the power –alpha*d where d is the thickness. Alpha is absorption coefficient even if alpha is 10 to the power of 4 centimeter inverse, so this is I in*E to the power–alpha so 10 to the power of 4 centimeter inverse and therefore if I substitute d=1 micron.

For example, if I substitute d=1 micron then this will be=10 to the power of -4, for d=1 micron this is =10 to the power of -4 which is=E to the power of -1. I input*E power-1 is that alright and therefore I out/I in=E to the power-1 that is 1/E.

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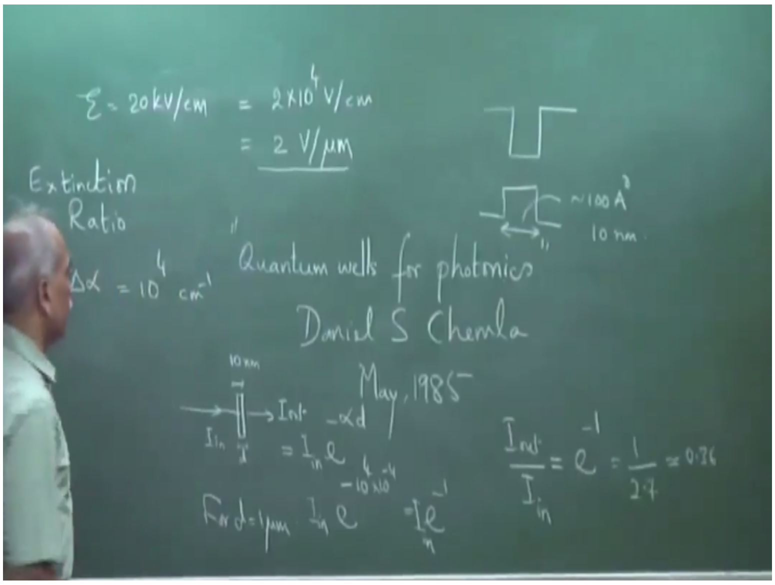

Normally, there is a parameter called extinction ratio okay I will discuss about this with the filed and without field. I will discuss about this a little later. So this is nothing but E is approximately 2.7 so approximately of this order which means you see that I out has dropped down by a factor of about 3 or so that is considering d=1 micron, 1 micron is 1000 nanometers.

If you take 1 quantum well, it is only 10 nanometer. So we need at least 100 quantum wells to have 1 micron thickness. So that this ratio is significant please see this is of the order of 0.33 or something like that so 0.35, 0.36 or something like that. So to have the output drop by this much more than half you need 1 micron which means you need 100 quantum wells indeed if you want to have significant attenuation.

We had delta alpha=10 to the power of 4 centimeter inverse so even if the absorption changes by 10 to the power of 4 that multiplied by length of the device will give you total attenuation and that total attenuation to be significant you have to have at least 1 micron, which means you need 100 quantum wells indeed the early devices the first device early in the 1980s, 1984, 1985 used quantum wells.

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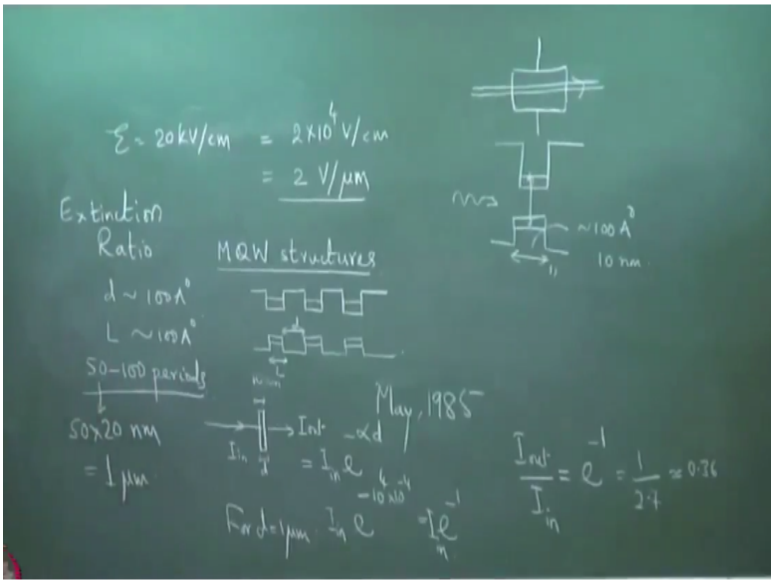

One of the early experiments at Bell Labs used multiple quantum well structures MQW structures, which means you have wells, barriers, wells, barriers. So this is the well and if they are non-interacting then the energy remains the same and all the properties remain the same so typically well width d of the order of 100 angstrom and l the separation so this is l and this is d.

We have taken a problem of the order of 100 angstroms and about 50 to 100 periods, 1 period means 1 well and 1 barrier, 1 well and 1 barrier is 1 period. So if I say it is 100 angstroms width 100 angstroms this so total is 200 angstroms that is 20 nanometer. If I have 50 wells if this is 50 periods which means 50*20 nanometer which is 1 micron. If you use 100 periods then you will have 2 micron.

So the well width, the total well width where attenuation please remember attenuation is only here, outside there is no attenuation. Why there is no attenuation? Because the photon energy corresponds to this band edge outside if I take a single quantum well please see we had E1 here E1 dash here. The band edge corresponds to this energy gap. The band edge where the attenuation suddenly starts shooting up corresponds to this.

And we have biased it just at the band edge, the input photon which is coming here you recall in the principle that we discussed in the last class, light beam is passing through this and electric field is applied to the structure and the output will be full or no output depending on whether you have applied electric field or not. This is the principle but now we want to see with numbers. What is the real device?

If I have an h nu corresponding to this, outside it will not be absorbed because band gap is larger, absorption takes place only in the well region. Therefore, if I have 100 periods, I have 100 wells of 10 nanometer, which means total thickness of the semiconductor where absorption takes place is only 1 micron and therefore this calculation that I have done 1 micron 10 to the power of 4 is alpha alpha*d applies for 100 wells.

In other words, to have significant measurable attenuation you need large number of quantum wells. Single quantum well will not do, but we are using property of a single quantum well but to enhance the effect we have to use large number of wells. So the structure that we have to use is MQW, multi-quantum well structures or multiple quantum well structures. So typically 50 to 100 periods are used.

I have still not told how to apply the electric field. First I have said that we need if you are going to use quantum confined stark effect, we need at least a 100 periods, 100 quantum wells to have significant effect. How to apply the electric field? We have to apply this much which means 2 volt per micrometer.

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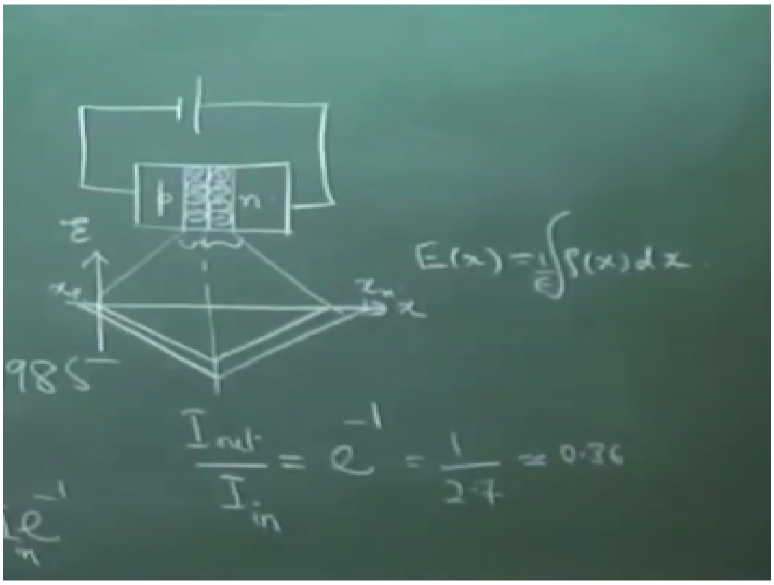

In electronics, we know a simpler idea that is if you take a p-n junction we have already discussed this p-n then you know that there is a depletion region here and from p side holes move to the other side so leaving behind negatively charged immobile ions and positively charged so there is field here p-n junction. If you apply a reverse bias, so we apply a reverse bias then this depletion region spreads further.

And the built-in potential here becomes larger. Now if you see the electric field, I just zoom this a little bit we have already discussed this how to calculate the electric field because E of x=integral rho x dx 1/epsilon. Recall de/dx=rho/epsilon from Gauss law, del dot divergence of E=rho/epsilon from there if you take one dimensional and if they are in the same direction it is de/dx.

Therefore, E=this which means if you are finding the electric field, the electric fields starts from here so it is negative so electric field increases linearly and then as you add positive charges to the negative, electric field decreases and then it comes down here. So what I have plotted electric field. Electric field versus distance, this is the electric field. Beyond this there is no electric field which means the entire electric field is appearing across the depletion region.

And what is the thickness that we have here? Typically, the thickness of the depletion region is of the order of 1 micron or 2 micron. So if you apply a reverse bias then this field may spread a little bit more so this will spread and you will have the electric field varying like this. What I have shown here is this is x versus electric field. This is width of the p region many times we denote it as xp and width of the n region xn in the depletion region.

And this entire width is of the order of 1 micron so the point is the applied voltage 1 volt, 2 volt, 3 volt whatever reverse bias that you are applying is appearing across the junction. The entire electric field is across the junction and therefore what is the electric field that we have here? This is of the order of 10 kilo volt per centimeter. It is 2 volt per micrometer but it is 20 kilo volt per centimeter.

So using this concept if you use a pin structure so what is the device configuration? Almost all devices use reverse biased pin structure.

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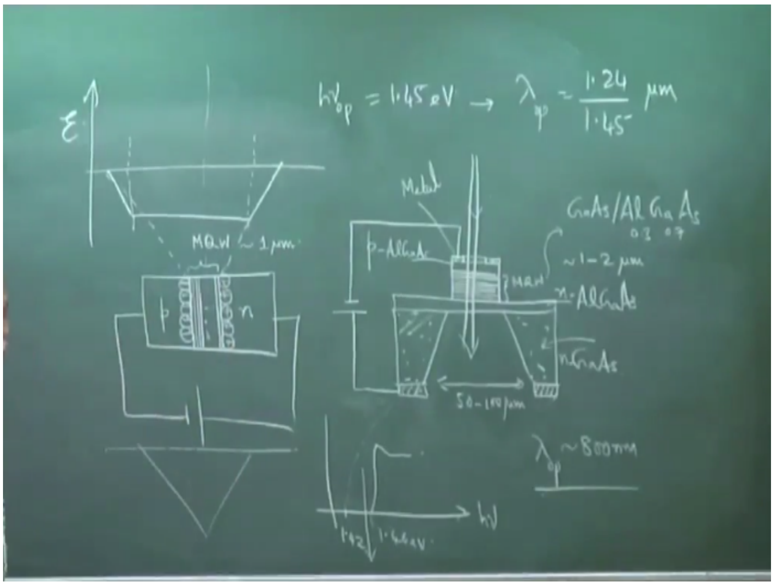

So the structure looks like this. I will show you a better, this is schematic representation. This is p side, n side and this is the intrinsic region, which comprises of quantum well structures. So the i here is MQW, the intrinsic region and then you apply a reverse bias. So pin, the intrinsic region comprises of multiple quantum well structures, typically 50 to 100 periods so if you plot the electric field across this, how does it look?

So if you plot the electric field, the charges here will be negative and the charges here will be positive and in the intrinsic region there is very little charges and therefore if you plot this you have electric field varying rapidly like this and then in the entire intrinsic region approximately constant and then dropping down like this. This is at the junction p and intrinsic junction.

This is at the n and intrinsic junction and in the intrinsic junction, the electric field remains almost constant. Electric field=charge*dx integrated so you integrate it, all the negative charges here so the field increased up to that and hardly any charges here in the intrinsic region. So the field is remaining constant when you reach this end the negative charge is compensated by positive charges, so the sum is decreasing so the electric field is decreasing.

In the case of a p-n junction, we had the electric field variation like this. In the case of a pin, the electric field almost remains constant. There could be little bit slope depending on which p side is more doped or n side is more doped, but almost constant. Remember that this axis is electric field. So we have a uniform electric field of the order of 10 to the power of 5 volt per centimeter applied to the intrinsic region.

And what is the thickness of this intrinsic region is just about 1 micron or 1 to 2 micron, 100 quantum wells 2 micron is the total thickness of this. So we are able to apply a large electric field at the junction region. So this is the device configuration which is used. A practical device looks like, this is a schematic illustration, a practical device looks like, let me show you a practical device how it looks like.

So you start with the gallium arsenide substrate, you see the procedure is also illustrated here gallium arsenide, on this you deposit aluminium gallium arsenide. On this by deposition and etching, you grow multi-quantum well structures. First start with n gallium arsenide, so n gallium arsenide substrate, on this you deposit n aluminium gallium arsenide and then you deposit the multi-quantum well structure MQW here.

This MQW comprises of gallium arsenide, aluminium gallium arsenide Al 0.3, Ga 0.7 arsenic MQW structure. Over that you have p type aluminium gallium arsenide and over that the metal electrons. Now the substrate is etched from the backside till you reach, so this portion is etched away and then etched away means the material here is etched. It will become clear why that is done.

So this is the substrate and then you deposit annular electrode. I could have shown you the structure directly but I just wanted to illustrate the procedure also. So a substrate on which epitaxially these layers are deposited and then this is etched away and an annular electrode, why annular electrode is required because light enters from here. This is the path of the light, please see the structure.

Here you apply this is the negative electrode so n and therefore you have to apply positive. This slot is vacant slot is for light to pass through. This is gallium arsenide aluminium gallium arsenide quantum well. This is for operation around 800 nanometer, lambda operation around 800 nanometer because the material is gallium arsenide aluminium gallium arsenide.

The band gap is about 1.42 for gallium arsenide, so 1.44, 1.45 will give you approximately 800 nanometer as the lambda operating wavelength. I hope it is clear you recall that if you had h nu here for gallium arsenide bulk, it was here. This is 1.42 and then for the quantum well it was here. So this maybe about 1.46 eV so your operating voltage has to be somewhere here say h nu op is 1.45 eV which means lambda operating=1.24/1.45 micrometers.

That is about 800 nanometers, 0.8 micrometers approximately around that region because I have used gallium arsenide. If you want to use the electro-absorption modulator for optical communication, it will be based on indium phosphide substrate and indium gallium arsenide quantum wells. Indium gallium arsenide phosphide the quaternary compound is used. Is this picture clear?

That this is n on which intrinsic GaAs AlGaAs layers which are quantum wells. This is p aluminium gallium arsenide. Please note that we have etched this so that the gallium arsenide does not reabsorb this. When this peak is shifted here, gallium arsenide could absorb the light. Light is coming at 800 nanometer so gallium arsenide would absorb it, 800 nanometer is somewhere here so absorption coefficient is large.

So to avoid absorption by these gallium arsenide regions, it has been etched off whereas the region here is aluminium gallium arsenide, the region here is aluminium gallium arsenide they do not absorb because they have a larger band gap. Aluminium gallium arsenide has a larger band gap compared to gallium arsenide. So this is the early structure of electro-absorption modulator based on quantum confined stark effect typical dimension here.

So this is substrate so typically about 100 micron, 60 to 100 micron and this slot which is kept open is also typically this slot and the slot here is 50 to 100 micrometer and this thickness of the MQW is of the order of 1 to 2 micrometer as discussed in the principle and it is a reverse biased ppin structure so pin this is p AlGaAs n AlGaAs and pin structure and reverse biased, this is the device configuration.

But today there are better device configurations because one of the important restriction that we have is 1 micron, 2 micron, you have to write 100 periods, the periods have to be identical. If the periods are not identical the energy is different and then the effect will be different, it is not enhanced it will start broadening and therefore an easier and more better.

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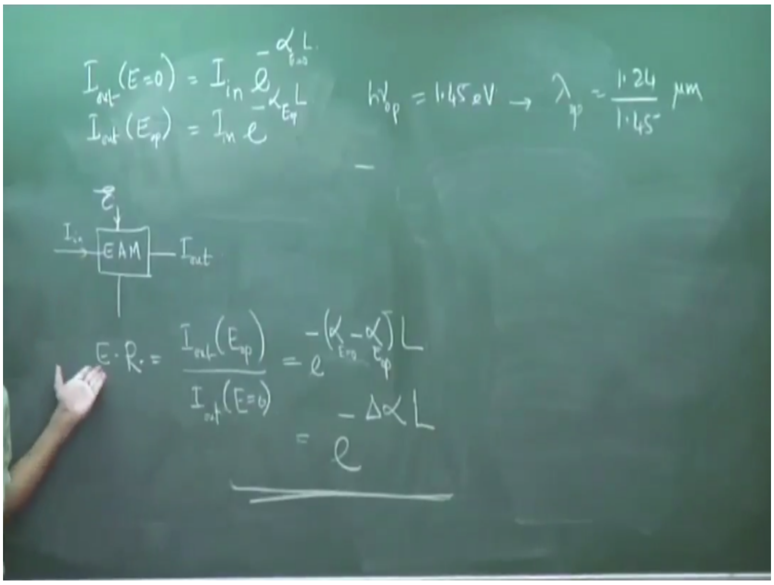

Please see the extinction the difference is given by –delta alpha*l. What is this delta alpha? Please see I output with E=0=I in*e to the power–alpha with E=0*L when there is no applied electric field, I have this device I do not know what is this device. This is electro-absorption modulator. There is an input which is I in, there is an output I out. I out with E=0 is I in*e to the power of alpha is the attenuation coefficient without any electric field.

You are applying an electric field from here let us say this is E field. In the presence of electric field I out with E=I in*e to the power-alpha*E E!=0*L, E is maybe 10 kilo volt per centimeter 20 kilovolt per centimeter whatever E is the operating so let me put EOP okay operating electric field EOP. This is the output when there is no applied electric field and this is the output when there is electric field.

So what is modulation? Modulation is the ratio between these 2 in the presence of electric field and in the absence of the electric field. Modulation is you are modulating the output intensity based on the applied electric field. Modulation means what? So you are applying an digital pattern electric field to this and you are saying how light is modulated. So modulation ratio, the modulation index is given by which is also called the extinction ratio in this case.

So the extinction ratio ER=I out with electric field/I in without electric field. I out without electric field in is constant so this is the extinction ratio and that is=I in I in cancels so we have e to the power–alpha with E=0-alpha with E operating*L so let me erase this structure. I want to discuss a new structure. This is what I had written as delta alpha. So this is=e to the power –delta alpha, delta alpha is the change in attenuation coefficient because of the applied electric field.

This was without the field, this is with the applied field so change in attenuation coefficient*L and this change what is the point to see? Extinction ratio are equivalent to modulation index, the modulation the difference between in the presence of electric field and in the absence of electric field depends on the product delta alpha*L. One is if I have a large delta alpha that would be wonderful.

That is why we said quantum confined stark effect is better than Franz-Keldysh effect because the change in alpha is much larger in the case of QCSE. However, I have a second parameter L. Suppose I make L large, then I can use Franz-Keldysh effect. It is not necessary that I should go to because it is the product which will determine the extinction ratio and hence the new design currently it is the waveguide modulator design, which is used.

So this is the extinction ratio, which clearly tells that it depends on the product of delta alpha, delta alpha is the change in attenuation coefficient due to the applied field*the length of the device.

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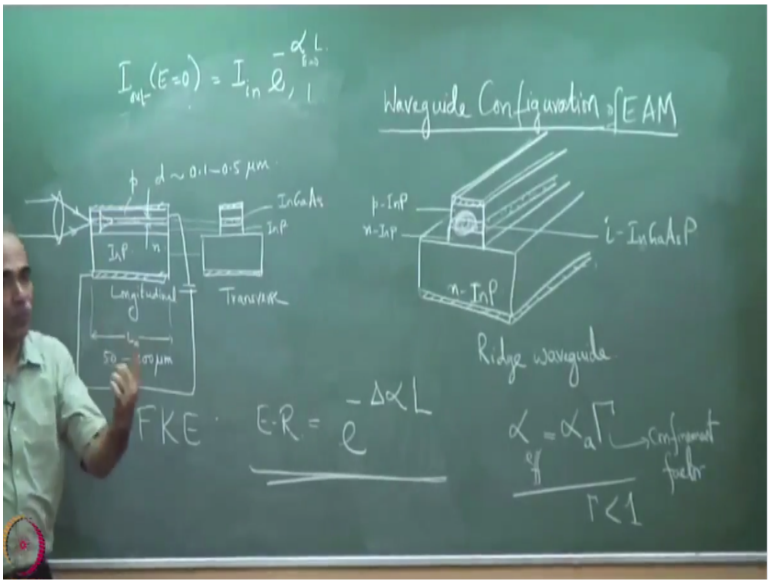

So the current devices are let me show you first the 3D picture is much easier to fabricate and much easier to realize. I will first show you the structure and then I will explain what the structure is okay. Let me make it 3D, so this is actually ridge waveguide structure. So you have the substrate. Let us say n indium phosphide let me draw say now indium phosphide. All the while I am writing gallium arsenide gallium arsenide let me write indium phosphide okay.

And this is the substrate and this is i indium gallium phosphide for communication wavelength. Just to distinguish this internal layer, I will mark it with the dotted lines. So this is n type so n indium phosphide. It could be some other material also and this is p indium phosphide and on top is the metal. This is the contact and at the bottom, there is a contact. Let me draw the structure and then we will discuss.

So what I have drawn is so extinction ratio=this. What I have drawn is a ridge waveguide if I show you only the front end it will be like this. This is the contact, this is the bottom contact and here this is indium phosphide and this is indium gallium arsenide. This is a ridge waveguide. It is called ridge waveguide structure. I will explain what I mean by that. If I show the longitudinal cross-section, it will look like this.

This is the transverse cross-section the end that you are seeing and if I show the longitudinal cross section, it will look like this, one to one correspondence. See this is the same as this, this is the same as this, this is the substrate. So this is longitudinal cross-section. I hope you follow longitudinal cross-section like this and other one is this. So this slice is like this and this slice is like this, longitudinal cross-section so one to one.

So this is indium phosphide, light is launched into this structure. So let me show a lens and light launched into this here this structure. This indium gallium arsenide phosphide forms an optical waveguide. What is an optical waveguide? A high index layer sandwiched between 2 low index material. The guiding film and cladding, outside is the cladding. Indium phosphide has a lower refractive index.

It has higher band gap therefore a lower refractive index compared to indium gallium arsenide phosphide. This has a higher refractive index therefore this structure is an optical waveguide. So here it is so it is propagating in this direction and the thickness of this layer here guiding layer this is D typically 0.1 to 0.5 micrometer and the length here so this is longitudinal.

This is transverse cross-section so L the length here of the waveguide, L is typically 50 micron to 200 micrometer. I have a 0.2 or 0.3 micron thick optical waveguide the thickness and then this is as you can see there this is n, this is p upper one is p. The similar structure we will see for laser diode, but laser diode which is a double hetero structure. Laser diode is operated in forward bias.

Here our objective is to apply a reverse bias across the intrinsic region. So if we apply a reverse bias here, so this one is negative, so I apply a negative bias and this one is positive okay. So reverse bias then across the intrinsic region here, you have the same field. What did I gain by the structure is L earlier my L was just 100 quantum wells I had and the thickness was only 1 micron or 2 micron was L.

Now L is 50 to 200 micrometer therefore I do not even need any quantum well structure. This is not quantum confined stark effect. This is based on Franz-Keldysh effect. I apply an electric field, the absorption of this region shifts, the change is small, delta alpha now will be 10 to the power of 3 not 10 power 4, delta alpha is small but my L is not 1 micron, 100 micron.

So we can realize the same extinction ratio even by Franz-Keldysh effect under this configuration. This is called waveguide configuration of electro-absorption modulator EAM. So the structure looks like this. It is an elevated ridge, we make a ridge because we want a beam to be confined, otherwise if you do only this it will become planar waveguide and that is why we have made a ridge so that if you see the optical mode, optical energy will be confined here like this.

So it is a ridge which is carrying light. So this is the optical mode. One last point is the alpha that you have the attenuation coefficient alpha effective will be=alpha a*gamma. Alpha a is the actual absorption coefficient of the material, which we shift. Alpha effective=alpha a*gamma where gamma is in laser physics this is called confinement factor or overlap factor.

When you launch light of some intensity i note that because of the optical mode a fraction of the energy is outside this layer, not the entire energy is seeing alpha a. Alpha a is the attenuation coefficient actual absorption coefficient of the material, but the entire energy is not seeing this alpha a. A fraction is outside, the outside fraction does not see any absorption coefficient.

Because the material outside is a higher band gap material that is not absorbing and therefore the actual effective alpha you have to substitute here effective alpha to calculate the real extinction ratio, typically this gamma is anywhere from 0.5 to 0.9. So it is not very small but the correction factor need to be applied to take care that now you have an optical mode. In the earlier structure, I showed you a beam passing through that quantum well.

It was not a mode, but now it is an optical mode and therefore a correction factor gamma is required. This gamma is<1, so gamma is<1 typically 0.6, 0.7, 0.8, 0.6 to 0.9 is the gamma. Please see the thickness is very small 0.2 micrometer and therefore even if you apply 1 volt, 2 volt you get 20 kilo volt per centimeter electric field. So all switching voltages required are only few volt 1 to 2 volt is the typical.

Today commercial devices are available and just 1 to 2 volt of switching volt for electro-absorption modulators. We will discuss the actual structure a little later when I discuss about laser packages. These come in butterfly packages what are called 14 pin butterfly packages. We will discuss and how the device actually looks like. It will look like a small IC, a very small IC. We will stop here.