Semiconductor Optoelectronics
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Lecture - 38
Quantum Well Laser

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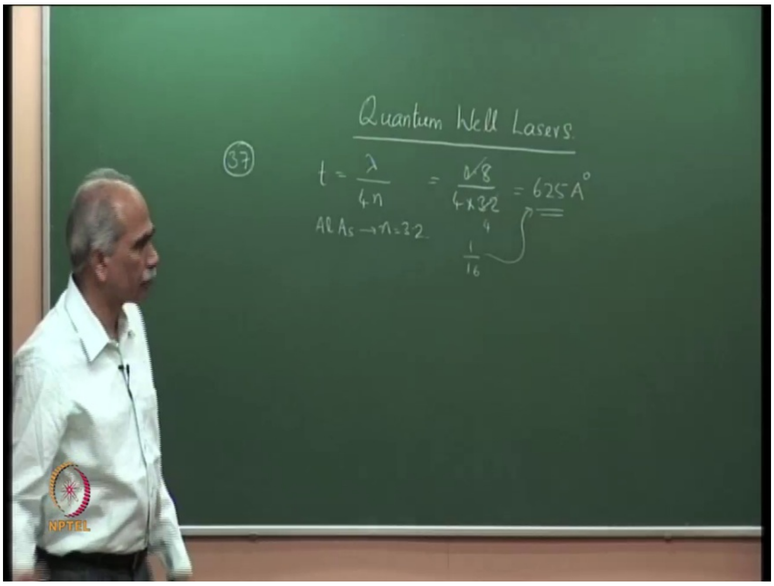

So, today we will discuss quantum well lasers. A very important class of lasers, quantum well lasers. I mentioned that most of the lasers today have quantum well structures in there active region because of certain advantages. Just before I proceed in the last class that is in lecture 37 we may, I made a small calculation error. I was calculating the quarter wave thickness t is equal to lambda divided by 4 n, for aluminum arsenate, aluminum arsenate n I have taken as 3.2 and therefore, this was 0.8 divided by 4 into 3.2, up to this it was right, but this is exactly equal to 625 angstroms. I had written 500 angstroms because what I did was I did this and therefore, 1 by 16 it was, 1 by 16 is this much, but what I did was 0.8 divided by 16. So, I wrote 500. So, please make this correction, everything else is fine. Therefore, the thickness will be slightly different. I just saw that I had made a mistake so I thought I will correct it.

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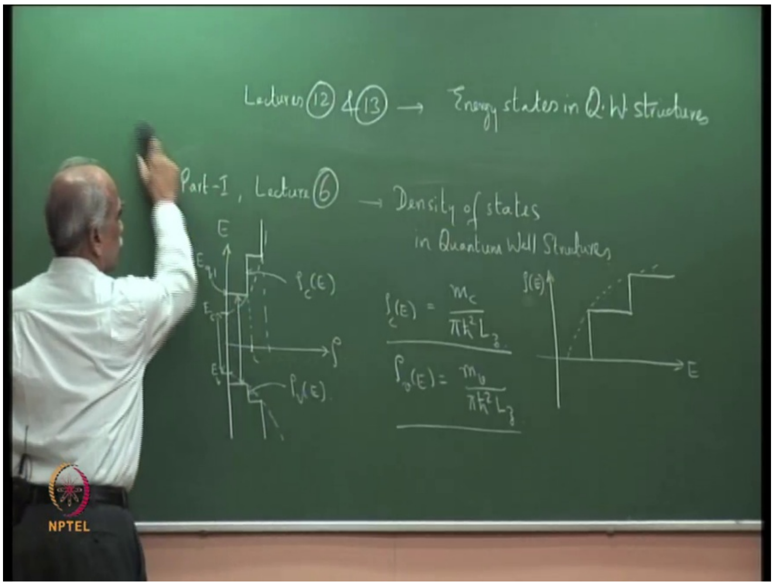

So, quantum well lasers. We have studied most of the essential basics of quantum well lasers. Let me very quickly recall quantum well lasers, what we have already studied. So, quantum well lasers. First in part 1 lecture 6 if you see, part 1 lecture 6, lecture 6 we had discussed in detail the density of states, density of states in quantum well structure, in quantum well structure. Density of states in quantum well structures. What we had seen I may recall that this was the energy axis and this is rho the density of state.

Then for bulk we have square root of E independence which was like this and for quantum well structures we had density of states which was like step function. So, this is in the valence band and in the conduction band. Two points to see here and that is this is E c this is E v. The density of states start up to this, this axis is density of states. So, what I have plotted here is rho c. So, this is rho c of E and this is rho v of E that is density of states in the valence band. So, up to this first sub band energy that is E c plus E q 1, I am just recalling what we had studied.

There was no density of states and therefore, effectively although this is the band gap of the material E g is equal to E c minus E v. The effective band gap is from here to here because before this energy there are no density of states. So, the effective band gap was different in the case of a quantum well structure and we have seen this value here, the density of the states. So, here the value it is rho c of E for the first sub band was equal to m c divided by pi h star square into L z, we had considered L z as the thickness of the quantum well in the z direction and this is two times and so on.

So, this is the density of state and for the valence band rho v of E is equal to m v where m v is the effective mass of holes into, in the valence band into L z. So, this is the, what we have seen. The important point, so if I may rotate this in terms of energy axis. So, because here gain, bandwidth everything we had plotted h nu along this axis. So, if I rotate this then the density of states would look like this step function. So, this is the density of states. Now, here it is rho of E energy versus rho of E, rho nu of E. In fact this is rho nu of E, rho nu of E that is rho of sorry rho of nu or rho of E is a step function like this. In lecture subsequently you may recall that in lectures 12 and 13.

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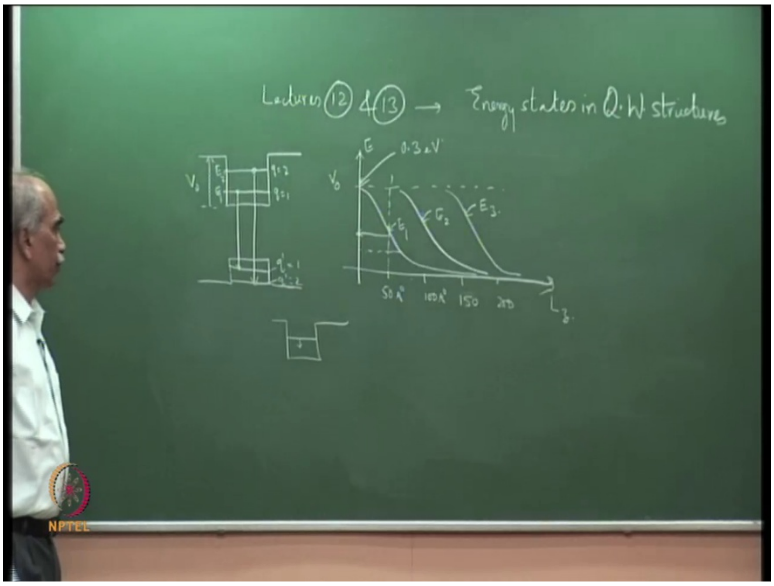

This is just to indicate to you that we have already discussed almost all the essential physics of quantum well lasers. So, we will directly go to device characteristics. So, lecture 12 and we have discussed about energy, energy states in quantum well structures, energy states in quantum well structures. What we have seen a very quick recap is that the allowed energy values are discretized being a potential well, being a quantum well the allowed energy values for electrons in a quantum well are discretized.

And therefore, we have, if you take a quantum well. So, this is the quantum well, if this is height is v naught in terms of potential, then there are discrete energy values here, allowed values are discrete. Similarly, allowed values for holes are also discrete. So, this is for q is equal to 1, q is equal to 2, q q dash is equal to 1 q dash equal to 2 and so on. So, this is for the holes and this is for and allowed transitions are from here to here or from here to here.

The allowed transition selections rule, selection rules require that allowed transitions are these. These are the allowed transition further we had seen that the energy, if I take the upper potential well here the electrons then if this is v 0 v 0 this is the energy allowed energy values versus thickness L z, thickness of the quantum well structure. Then we have energy varying like this. So, what are these? These are the allowed energy values for E 1. E 1 is this one, E 1.

The variation of E 1 and E 2, E 1, E 2, E 3 and so on with L z. The thickness of the potential well, thickness of the well. These are some very important implications in practical devices. So, the numbers could be typically this is 50 angstrom, this is 100, this is 150, 150, 200 angstrom, typical numbers. And what could be v 0? v 0 could be 300 Me V or I will take an example and show you, this may be about 300 Me V or 0.3 e V for example, or 0.4 e V, 0.5 e V that kind of numbers we will get. And what we see is the allowed value which means if you take the well width as 50 angstrom then this is the value of E 1, here is the value of E 1.

And you see that at 50 angstrom the second state is not there or the potential well supports only one state. So, it is a single mode state. So, this potential well here has only one allowed energy value and if you change this width the energy comes down, if you increase the energy, energy comes down which means this level moves down. So, from an engineer’s point of view what is important is if you change this dimension the effective band gap changes, because this level starts coming down as I increase the width this level goes up.

So, effective band gap is this, that changes. If the effective band gap changes then the emission wave length changes. Although, the same material systems are used by simply changing the width of the quantum well we can change the emission wavelength. This is a very important result and very important consequences, it’s consequences or it’s applications are very important because from a material systems point of view that in a fabrication process changing the material composition is not easy because it takes some time for the whole process to reach some steady state and there where as changing the thickness is very easy.

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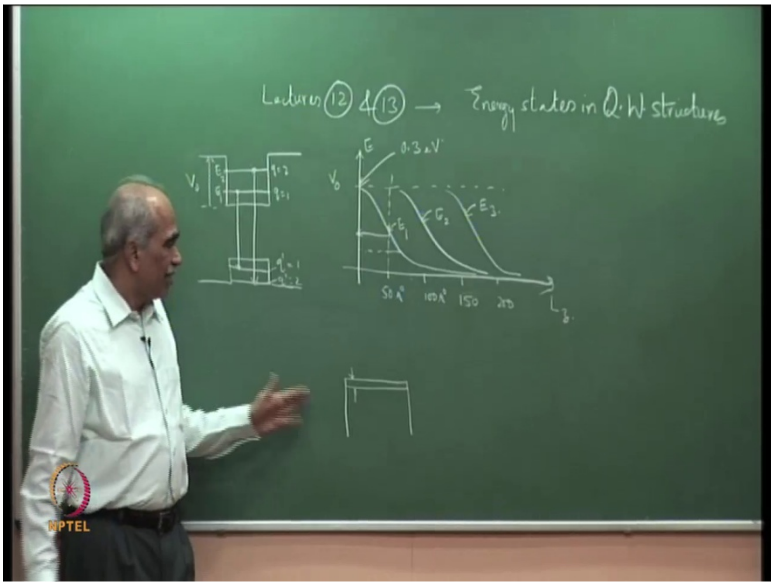

Because thickness of the layer… what I am referring to is if you are or on the substrate if you are depositing a layer by epitaxy, then changing this thickness is very easy. Simply, we have to control the time of deposition and this can be precisely controlled in techniques like MBE we can control the thickness very precisely correct to 1 monolayer, 1 atomic monolayer, but changing the composition it is not, it is possible, but it is not convenient. Therefore, if you want to change the emission wavelength slightly the same material system can be used, but little bit variation in the thickness of the quantum well.

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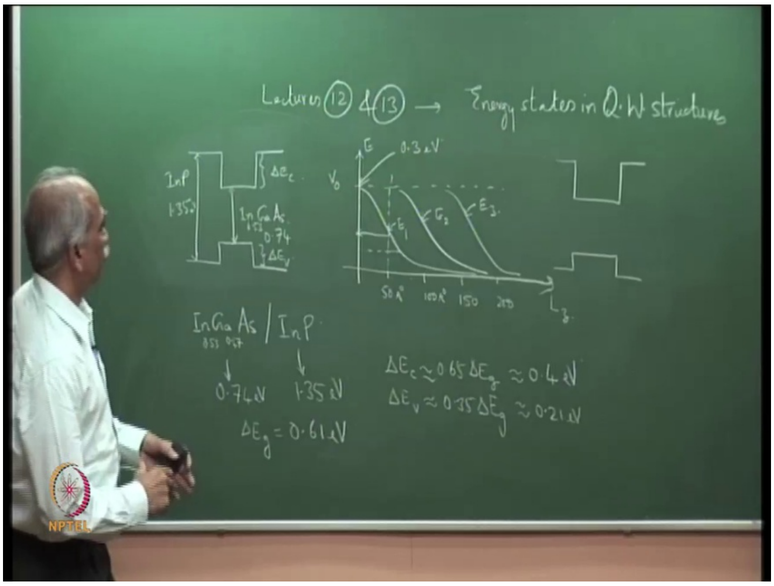

So, this point I would like to illustrate with the help of example. A very important laser material combination used is indium gallium arsenate versus indium phosphate substrate. So, this is I n 0.53 gallium 0.47 and arsenic. Why, we choose this combination is this material is lattice mash to indium phosphate. So, it is a lattice mashed combination. The band gap E g of this is approximately 0.74 e V. I have to illustrate this point and indium phosphate is 1.35 e V which means in this diagram here, so let me erase and draw the diagram corresponding to this.

So, this indium phosphate, 1 point this is indium gallium arsenate and this is indium phosphate. So, this is indium phosphate, this is 0.74. So, what is the E g difference? The difference in E g here is, so delta E g is equal to 0.61 e V, 0.26 and 35. So, it is 0.61 e V and we know that delta E c and delta E v are approximately 35 percent here of delta E g and 65 percent of delta E g which means if you substitute 0.61 and 65 this will be approximately, please verify this 0.4 e V and this will be approximately 0.21 e V. What is delta E c and delta E v? Please see this, this is delta E c and this is delta E v that is the energy gap difference at the valence band change in E c E v value for the two materials. I had written here 0.3 you can see, this is this is what I written as 0.3, but you get, in my calculation here it is 0.4; so that is 0.4.

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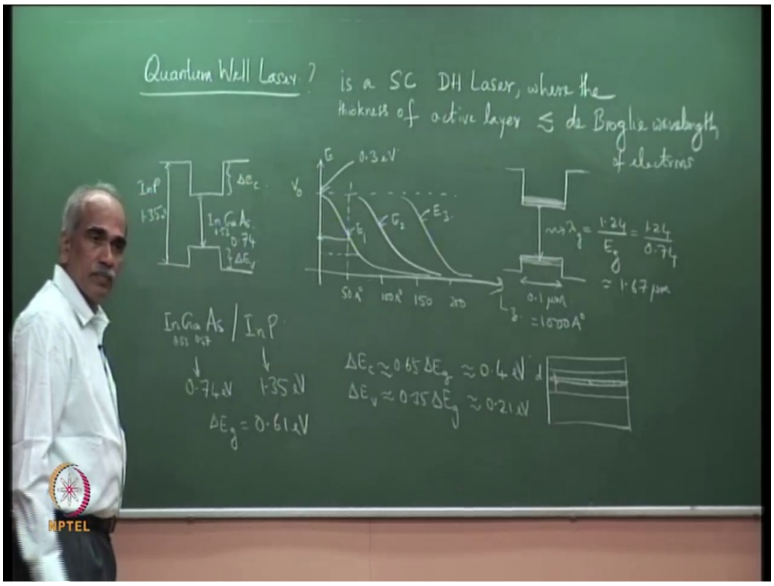

If I take a bulk indium gallium arsenate that is a double hetero structure… before I discuss I just want to, I had written the title quantum well laser. What is a quantum well laser? I had written the title quantum well laser, what is quantum well laser? Quantum well laser is a semiconductor laser, is a semiconductor double hetero structure laser DH laser where the thickness of the active layer, where the thickness of the active layer it is less than or of the order of the De Broglie wave length of electrons.

So, it is a double hetero structure laser. Quantum well laser is a normal semiconductor double hetero structure laser except that the thickness of the layer is very small. Small, very small is quantified in terms of this relation. So, typically 10 nanometers, 5 nanometers, 50 angstroms to 200 angstroms is the typical thicknesses used. So, that there are quantum size effects. Quantum size effects which lead to discretization of energy levels in this potential well, this forms a potential well which is the quantum well.

Now, when the thickness is of the order of let us this is 0.1 micrometer 0.1 micrometer that is a normal double hetero structure, 0.1 or this is the width, this is the width of the active region. If you see the layer structures like this then the double hetero structure is here, this is the active region followed by a cladding region and we have discussed this, but just I am recalling this several classes before. So, this is the active region. The width that I am referring to is this which we had called now as d.

Earlier when we started the physics it was L z. So, L z is nothing but this d here and these are the cladding layers. So, the example that I am taking is this is indium gallium arsenate and these are indium phosphate, indium phosphate. So, the band gaps correspond to these. If the thickness is of the order of 0.1 micron which means this is equal to 1000 angstroms. This is a double hetero structure laser; it is not a quantum well laser. It is a double hetero structure laser, because this is very large, recall that the De Broglie wavelength

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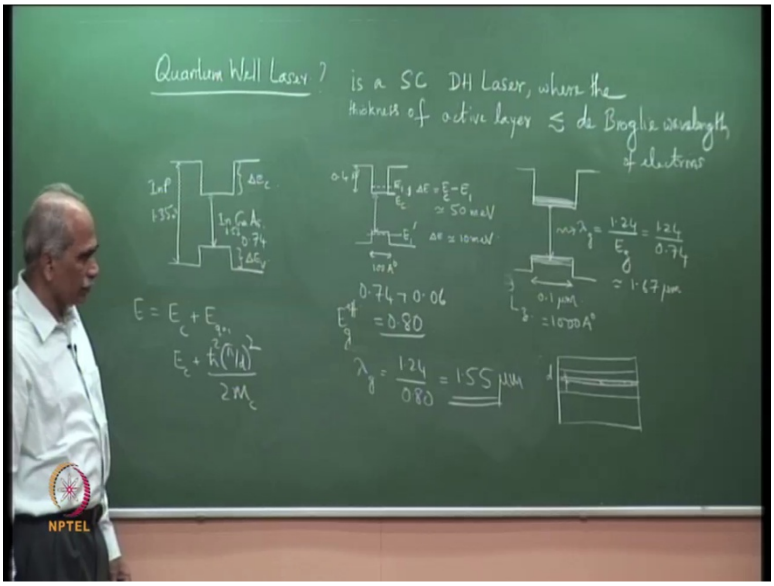
Quantum Well Laser ? is a SC DH Laser, where the thickness of active layer ≤ de Broglie wavelength of electrons

Is of the order of 100, 200 angstroms and we are more than that and therefore, it is a double hetero structure laser which means allowed levels are continue, almost continuum of allowed levels here. They are discrete and they are so close that it is essentially continuum and therefore, the effective band gap is this. So, this is E g. The emission wavelength lambda, lambda g here is equal to 1.24 divided by E g which is equal to 1.24 divided by 0.74.

For this example 0.74 here and that is equal to you can check, I think it is 1.67 micrometer, approximately 167 micrometer. If you now reduce this from 1000 angstrom to 100 angstrom alright, let me erase this. Now, I am reducing it to 100 angstroms. This is not exact to scale, but just… So, this width now is 100 angstrom. It is a quantum well now and therefore, energy levels are discretized. So, if I look at E 1, E 1 is here. So, this is E 1 and E 1 dash is also here which means the lowest allowed energy is here, lowest energy is here. Typical numbers we had used some typical numbers.

You can calculate some typical numbers that this delta E here that is from E c the difference between E c and E 1 which is delta E is equal to E c minus E 1 or E 1 minus E c; the difference is typically equal to 50 m e V that is 0.05 e V. Please see that this height is 0.4 e V, this is 0.4 e V. So, that shift that you got E 1 is 0.05 e V. Typical numbers, so that we have a (( )) and here the shift is relatively less and this delta E is typically about 10 m e V. Why do you think the difference is less?

The difference is less because of the effective mass. If you recall the energy E is equal to E c. So, E q equal to 1 if I put E c plus E q, so here E q equal to 1 the energy corresponding to q equal to 1. This is equal to E c plus h cross square K. K is pi by d whole square by 2 M , 2 M C for conduction band and 2 M v for valence band and M v is mass of holes is much higher usually compared to mass of electrons. Electrons are, the electrons have a much lighter, have a lower effective mass compared to this.

So, this number is small means this number is large. That is why normally you will see that the energy here are different. So, what is the effective band gap now? Please see here, from here to here it was 0.74. Now, 0.5, 0.01 added is 0.74 plus 0.06 equal to 0.80. This is the effective E g. E g effective, when it was bulk the E g was 0.74. Now, the effective E g is 0.80 and therefore, what is the corresponding wavelength lambda, lambda here is equal to 1.24 divided by 0.80 equal to this. These are indeed typical numbers used for optical communication quantum well lasers which are generally about 100 angstroms in thick. You see the wavelength of (( )) has come as 1.55 micrometer, low loss, lowest loss window of optical fiber communication. If you reduce this further to 0.8, let us say I reduced this to 80 angstrom.

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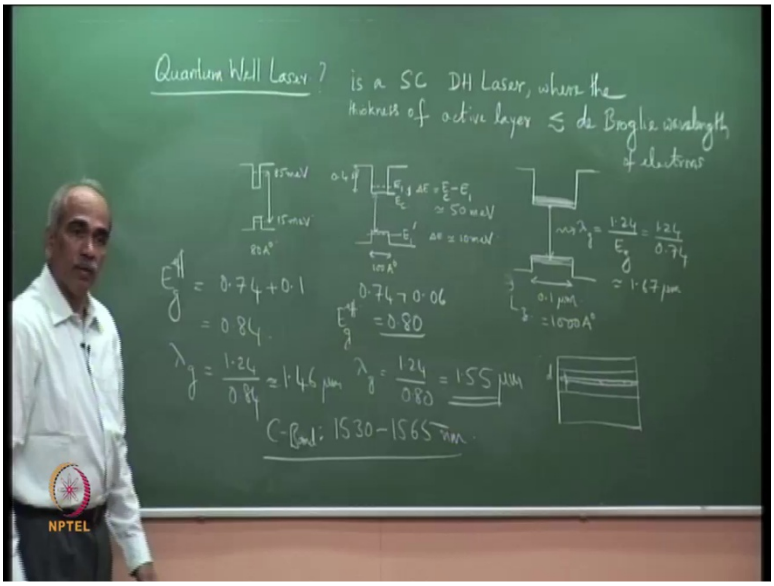

So, if you reduce it further the level further goes up. Here the level further comes down here. So, the effective E g is now this. From 100 angstrom to 80 angstrom if you go it may change from whatever number. So, I am just taking some typical numbers. This may become 80 m e V or 85 m e V and this may become 15 m e V. I am just taking number so that they add nicely. So, this becomes 100 m e V, 100 m e V and therefore, we had 0.74 plus 100 m e V that is 0.1 so E g effective, E g effective is equal to 0.84 and therefore, lambda g is equal to 1.24 divided by 0.84.

I think it is 1.4 something, you can check may be about 1.46 I think, please check approximately. So, through this example what I have illustrated is you can change the wavelength from 1.67 to 1.46 or 1.55 to 1.46 by changing from 80 angstroms to 100 angstrom. A very small change can change a lot. This means a lot for optical communication because in optical communication the c band is 15 30 nanometer to 15 65 nanometer. That is 1530 to 1565 nanometer, this is the c band.

The conventional band for WDM is here and this change is only 30 nanometers, but we have got almost 100 nanometer change by changing from 80 to 100. So, the point is I can make all lasers required for WDM by simply changing the well width little bit quantum well each one of them is the same material. So, the material scientist has nothing to do. He does not have to change any process parameters. Everything is there only deposition time is controlled from 80 angstroms to 85, 90, 95 and you can change the waveform. This is a very important advantage in technology.

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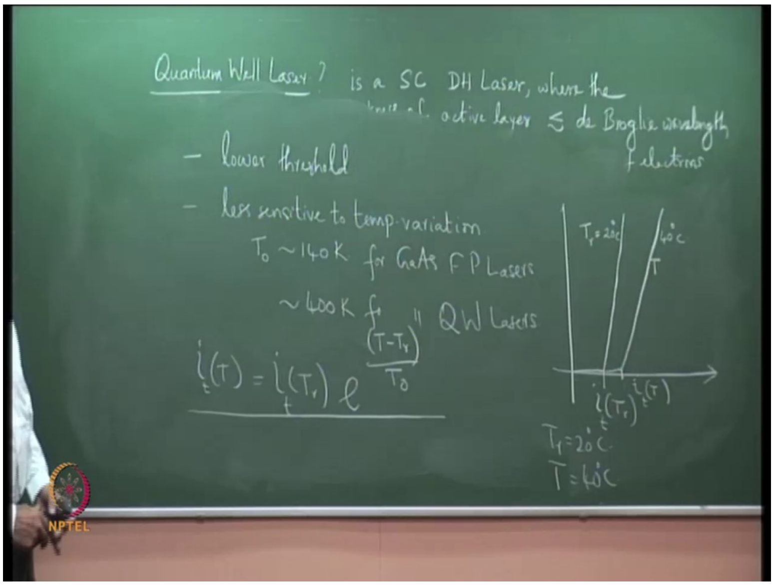

Quantum Well Laser ? is a SC DH Laser, where the width of active layer ≤ de Broglie wavelength of electrons

- lower threshold
- less sensitive to temp. variation

$T_0 \sim 140\text{ K}$ for GaAs F P Lasers

$\sim 400\text{ K}$ for " QW Lasers

$$i_t(T) = i_t(T_r)\, e^{\frac{(T-T_r)}{T_0}}$$

$T_r = 20°C$

$T = 40°C$

So, this we have briefly discussed earlier that modification of band gap by quantum well structures. So, we come to the typical advantages of quantum well lasers. So, why quantum well lasers? They have relatively low threshold, relatively low threshold. So, quantum well lasers lower thresholds, less sensitive to temperature, less sensitive to temperature variation, lower threshold currents. This can be quantified by if you recall that the character I had introduced characteristic temperature T 0 which is approximately 140 K, 140 K for gallium arsenate, for gallium arsenate Fabri Perot lasers F P lasers, we have discussed this earlier.

This is of the order of 400 K for same gallium arsenate quantum well structure, quantum well lasers. What is this T 0? Recall, that i of T, i threshold, this was i threshold, I used i small i t, this t is temperature was equal to some i 0 of i t of 0 or i t of some reference temperature T r into e to the power minus T minus T r by T 0 not plus minus plus. This is the kind of relation we can write for the threshold current i T at a given temperature t is equal to i T at a reference temperature into e to the power of T minus T r by T 0. T r is the reference temperature. What do I mean by this if you see this?

So, let us say this is at 20 degree centigrade and this is at 40 degree centigrade. So, T here, this is T, this is T r. If you know at a reference temperature the threshold, so this is i

T r, i t threshold current is this at the reference temperature. I am just illustrating what does this mean. So, this is the threshold current now here for i of i t at T. So, T is equal to 40. In our case T r is equal to 20 degree centigrade and T is equal to 40 degree centigrade. I am taking an example to illustrate what it means.

And T 0 is the characteristic temperature. A large T 0 means e to the power of a smaller number and therefore, i t will be very close to i t, smaller number e to the power of 0 is 1. So, i t at T would be equal to i t at reference means there is no tend, change in temperature if T 0 was infinity. Larger the value of T smaller will be the shift to this side. Do you follow this? So, this is the, for quantum well structures this is very large. Why is so? There are several reasons; one of the most important reason is that because of the discrete, because of discrete energy levels the electron distribution the carrier distribution within the quantum well structure is not so sensitive to temperature.

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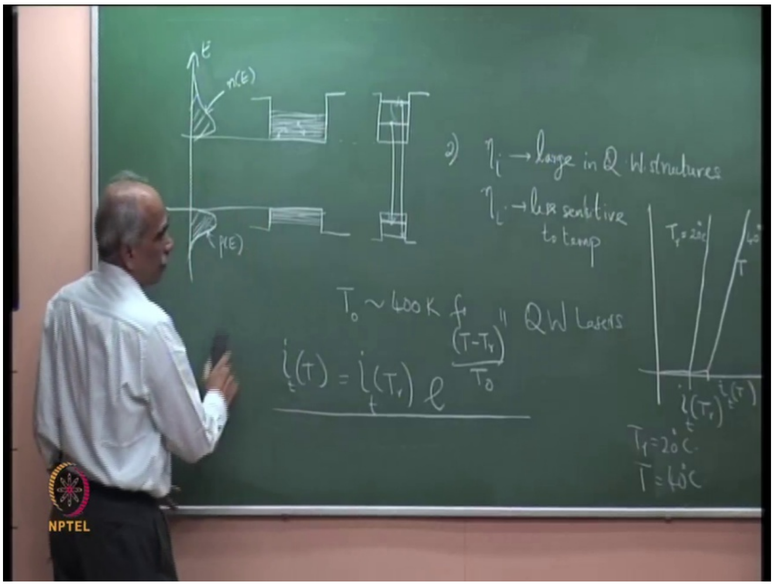

If you take a bulk double hetero structure, I am illustrating this so plenty of allowed states, continuously plenty of allowed states. At any finite temperature there are phonons which cause electrons to go up, down and so on. An electron comes down by a emission of a phonon and an electron can go up by absorbing a phonon. Phonon transitions, the intra band transitions phonon transitions. If you draw by this side the quantum well structure this is not to scale, let us say there are only two levels or one level.

For transition, here transitions are continuous; a small change in a small change in temperature changes the carrier distribution. You recall the carrier distribution we had drawn sometime back that n and p distribution like this. Distribution of carriers, what we had plotted, if you recall (( )) axis is energy, this was n of E and this is p of E. The carrier distribution is very sensitive to temperature because temperature the phonons can induce transitions and distribution changes rapidly.

If the distribution changes the peaks will change and therefore, the maximum gain positions will change in energy, whereas in this case there the phonons have to make this transition because there are discrete levels. It is not continuum and therefore, it is much less sensitive; unless phonons have sufficient energy to get this transition they cannot cause that transition. In other words the carrier distribution in quantum wells is much less sensitive to temperature and consequently the threshold is also much less sensitive to temperature.

The second point, so this is in terms of transitions. The second point is in bulk if the temperature increases non radiative transitions increase. In the case of a quantum well structure the transitions are allowed transitions here. There are very little non radiative transitions. So, eta i is 1 eta i is relatively large in quantum well structures, relatively large in quantum well structures and the eta i is less effected by temperature. Again because these are quantum mechanically allowed transitions, discrete allowed transitions.

Non radiative transition has to be a phonon transition whereas these are quantum mechanically allowed transitions which means they are radiative transitions. And therefore, eta i is also less sensitive, less sensitive temperature. The combined effect of these two points lead to a larger characteristic temperature T 0. Yet another feature of quantum well structures is… So, I had written load low threshold and second one is less temperature sensitive. I have described the first the less temperature sensitive aspect.

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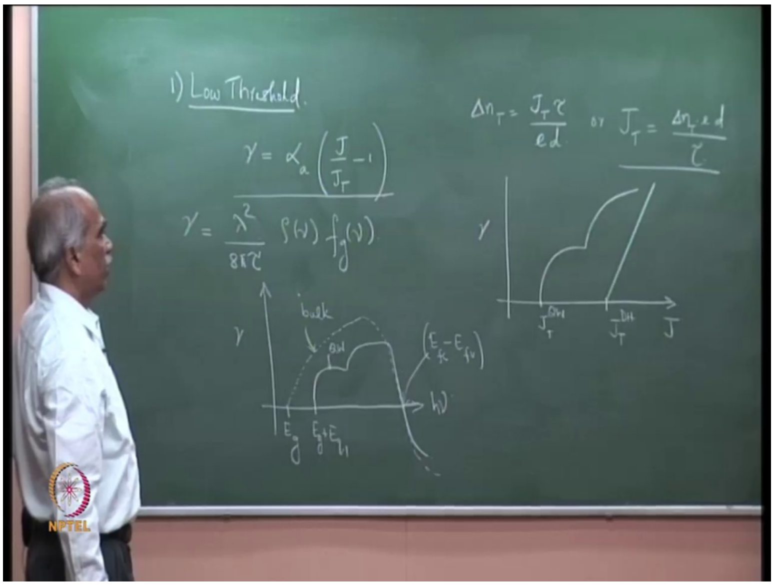

Low threshold, why do we have low threshold? Low threshold, the first point. Let me now discuss the first point. Why do we have low threshold. If you recall we had an expression for delta n T is equal to J T into tau divided by e into d or J T is equal to transparency current density is equal to delta n T into e into d divided by tau. d is the thickness of the quantum well structure. And then if you plot the gain coefficient J T and if you see the gain coefficient gamma is equal to alpha a into I by I T or J by J T minus 1; J by J T minus 1. In the case of quantum well structures J T, d is very small compared to double hetero structures and therefore, J T is a small number.

So, this axis if I show J then J T for a double hetero structure is here J T for D H, then for a quantum well structure it is somewhere here J T for a quantum well structure. The corresponding gamma is here. So, J T is very small and therefore, as a function of J this is the material loss coefficient and if you see gamma, this is gamma and gamma is equal to lambda square divided by 8 pi tau, 8 pi tau nu into rho of nu into f g of nu the fermi inversion factor.

This is the expression for gain coefficient, rho of nu into f g of nu. Rho of nu here is the density of states which is a stair case like function. This is a stair case function and therefore, if you recall the class 23, the lecture 23 we have discussed the gain in a quantum well structure. So, gamma versus energy h nu we had plotted, for the bulk it was, if you recall for the bulk it was varying like this. Then for the quantum well structure it was, it was step like because it was a product of, gamma was a product of rho nu and f g of nu.

Rho nu for that, for the bulk case is varying like this that is e to the power of half whereas for quantum well structures it was a step function and this if you recall this is E g, this is E g plus E q 1. And what is this energy? This energy was E f c minus E f v. Gain coefficient for bulk, this is bulk and the other one is for quantum. The gamma here, the gain coefficient if you change J T, let me just one second. How will I bring that? With the gain coefficient here increases linearly that is with current the gain increases linearly.

I wanted to show this just a minute. So, this is J. So, as J increases J T is fixed, as J increases gamma increases linearly. Please see this, this is for for the case of a, at any particular frequency, at any particular frequency as J increases gamma increases linearly. In the case of a quantum well structure J T is very small, but as J increases gamma will also increase like a step function, gamma increases like a step function that happens because of the density of states because the density of states varies like this. You will see that gamma varies like this, but the important point is at a low value of current we have sufficiently large gain. We see the gain is much larger at low currents.

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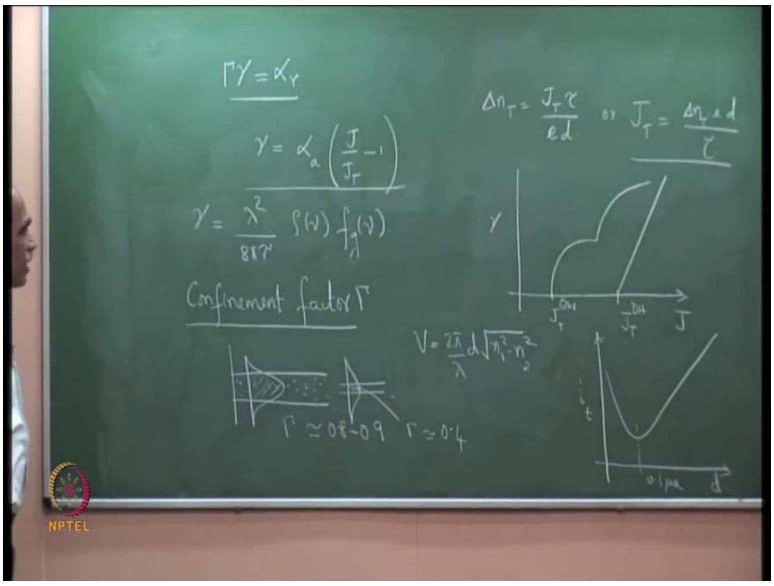

And therefore, and therefore, although I wanted to bring in here two concepts, that is one confinement factor. We have discussed the confinement factor. Let me, it will become clear just in a minute. Confinement factor gamma, with this we had an expression for threshold i t is equal to i T or J you can write for J into 1 plus alpha r we have derived this gamma into alpha a and we had seen that, we have discussed this that the threshold current comes out to be a minimum at a value which is approximately 0.1 or 0.2 micron and that is why double hetero structure lasers at a thickness d is equal to 0.2 micron.

We have discussed this in detail. So, what I have plotted is thickness d clear and i t threshold current or J T any one of them. In the case of a quantum well structure the d is on this side because this is about 0.2 micron meter or 0.1 micro meter. The minima comes out around here, whereas in a quantum well structure it is 0.01 micro meter that is 100 nanometer, 100 angstrom, 10 nanometer, this is 0.1 micrometer which means 100 nanometer, whereas for a quantum well structure it is further down here.

Therefore, we would expect the threshold to go up, but why does this threshold go up because of the factor gamma, confinement factor. We have discussed this in detail that the confinement factor decreases which means in the double hetero structure here, this is the double hetero structure. The optical mode is like this, this is the active region. This is the active region; the optical mode is in this fashion. It varies like this which means the fractional energy in the core, gamma is the fractional energy in the core and typically gamma is 0.8 to 0.9.

The fractional energy inside the core this one, that is confinement factor gamma. If we reduce this thickness, this will spread further. So, if I reduce this here to a smaller value, this mode will spread like this which means gamma now reduces. This is gamma now. Gamma typically in a quantum well laser gamma is of the order of 0.4. Here it was 0.8 to 0.9. This has now reduced because the thickness has reduced which means those of you who are familiar with the optical wave guides V decreases; V is equal to 2 pi by lambda into d into square root of n 1 square minus n 2 square. d decreases means V decreases, the normalized frequency V decreases.

If V decreases the mode spreads out and therefore, the confinement factor decreases. If the confinement factor decreases threshold will go up because in the expression gamma is in the denominator which is the discussion that we had for double hetero structure lasers, but in the case of quantum wells although the confinement factor decreases the gain is very large and therefore, the threshold current is still low. Although gamma decreases the gain is very large at low currents and therefore, the gain is able to compensate for loss.

What is the laser equation? Gain is equal to loss here. Although, and cavity gain gamma times gamma equal to alpha r, this is what we need. Although, gain at the confinement factor is small for a quantum well, gain at the same current is much larger for a quantum well because eta i is very high and there is one more factor that is f g varies rapidly, f g increases rapidly to 1. This has to be, this has to be appreciated how this wave is. I cannot easily show you and that is why the gain becomes very high at small currents and consequently the net effect is although we are here. So, this is for a double hetero structured D H. For a quantum well this is not true, quantum well even at lower values we have a low threshold, though gain at a low current is relatively large and therefore, the threshold is low. One last point in quantum well lasers is multiple quantum well structures, MQW structures.

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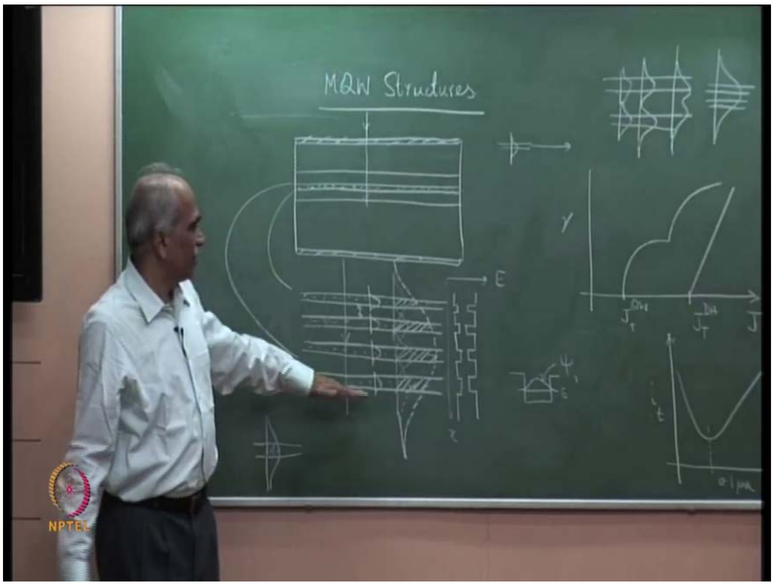

This is the last point I want to discuss for quantum well laser. The active region of a general laser today comprises of MQW. This is the active region and this is the cladding region of any laser. I have drawn this diagram many, many times. This active region if I zoom, today it comprises of MQW structure that means multiple quantum well structure. MQW structure comprises of wells and barriers, potential wells and barriers. So, these are the active region.

So, if I draw the band diagram it will be wells barriers, well identical, all of them identical. So, this is for the valence band and exactly similarly, for the conduction band and this is for the valance band. I hope you appreciate that I have just rotated that band diagram, energy band diagram. So, this is E g this is E versus depth x or d whatever. Current flows like this. As you know there is a contact here, this is a longitudinal cross section of a typical laser diode, current flows like this.

These are the current strips. So, current is flowing in this direction which means current is flowing across this, these are the quantum well and these are the barriers. In an MQW structure the barrier thickness is sufficiently large, so that the electron wave function does not interact. They are isolated. What I have now plotted is not optical mode, please remember. This is electron wave function, this is electron wave function. Whenever you have doubt you just rotate this. In a potential well, so if I rotate this, this is the allowed energy level and where is the electron wave function?

So, this is the electron wave function, fundamental electron wave function, E 1 energy. So, this is E 1 and this is psi 1, the wave function. So, that is what I have plotted. If the barriers are sufficiently apart, sufficiently wide then there is no interaction between the wells and this is called a quantum well structure, a multiple quantum well structure. An MQW structure comprises of several quantum wells which are identical, but non interacting. Non interacting identical wells, why do we use this?

If I had drawn just one well here one well the optical mode I had shown you is this and I said that it is 0.4, confinement factor is very poor because the optical mode is wide. If I draw on the same diagram, please appreciate this. The optical mode here would look like this; this is optical mode of the first one. Optical mode of the second one would look like this. Optical mode of the third would look like this and optical mode. So, what is the point?

The point is the optical field, optical mode EM wave, this is electron function. This is the EM wave field; they are over lapping so strongly that this leads to the formation of a single optical wave like this, single optical field. The wells are interacting so strongly as far as optical field is concerned, as far as the electron field is concerned they are isolated, but the… it is like due to directional couplers, if you take a directly coupler, there is a mode here and there is a mode here.

The tails interact and you have a symmetric mode which is like this, one field symmetric mode, but if you bring this closer, if you bring this further closer the mode will do this, little bit and then like this. And if you bring further closer the two, it will simply become one. You have two wave guides, but they are so close that it will see it as one structure. That is what I am showing here. You have multiple quantum well structure where as far as the electron is concerned they are isolated, but whereas, for the optical field it treats it as one. What is the advantage?

You make use of all properties of a quantum well structure and enhance the gamma. Now, what is gamma? You see here also it is in the gain region. Here also it is in the gain region. So, gamma will increase for this effective field and two you can get more power from this multiple quantum well structure. If you take one quantum well the dimension is so small that the power that you would get is limited, but in an MQW structure there are several active regions which are contributing to the optical power generated and consequently higher output power can be obtained.

So, two advantages of an MQW structure one enhancement of effective gamma by having one single optical field and two to achieve higher optical power outputs because overall active area is now much more. If you had only one well this is the only active volume of the semiconductor is very, very small, but now you have, you can increase the volume by taking 4 5 6, typically 3 to 6 wells are used in the active layer of a standard double hetero structure.

Less temperature sensitive is a good property of quantum well you are making use, lower threshold you are making use of that property and yet you are enhancing gamma and a higher output power. I will stop here for quantum well structures and there are several books on quantum well structures, lot of study on quantum well structures, this just to motivate that you go through these literature if you are interested. We come to a very quick quiz, has to be answered in 1 minute. Very, very simple, one sentence answer 1 minute. Please focus only on your answer. Please write your name and keep it ready.

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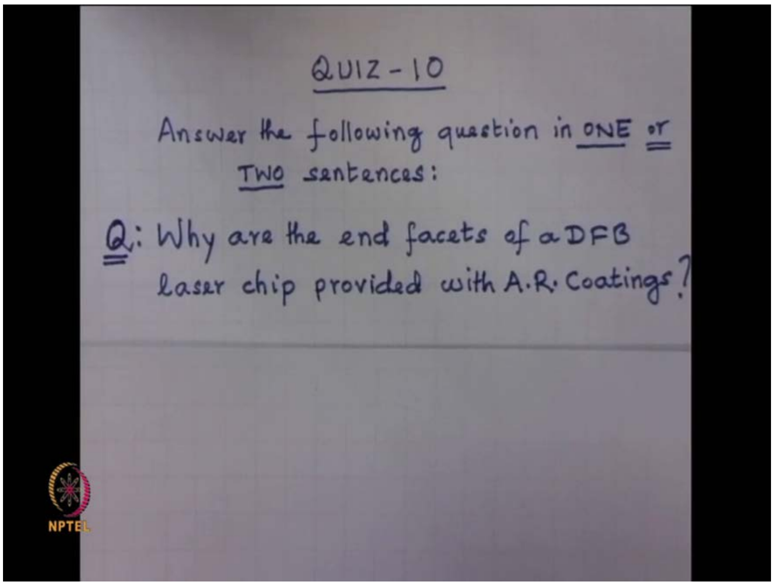

QUIZ - 10

Answer the following question in ONE or TWO sentences:

Q: Why are the end facets of a DFB laser chip provided with A.R. Coatings?

There is the question I have covered because I have written the answer also there. So, answer the following question in one or two sentence. Why are the end facets of a DFB laser chip provided with anti reflection coating? Why are the end facets of a, end facets means end face of a DFB laser chip are provided with, the end face are quoted with anti reflection coatings. So, why are the end facets coated? Answer in one sentence, maximum two.

The end facets of a DFB laser are always coated with anti reflection coatings, A R coatings, why? Do not write a big paragraph, that is why I have said answer in one sentence. It should not take more than 1 minute to write one sentence. So, those of you who have finished please give me. You have to give now, 10 seconds. You have to give now. So, the question is I repeat, why are the end facets of a DFB laser chip provided with A R coatings, anti reflection coatings?

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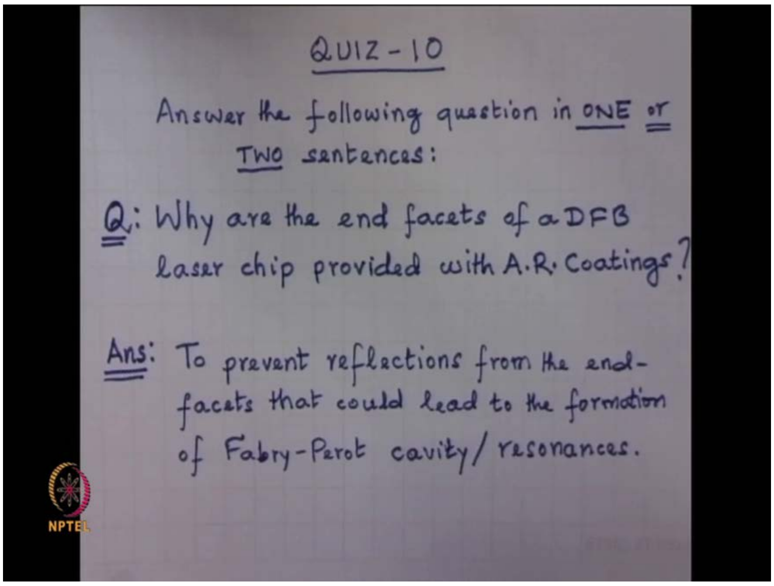

QUIZ-10

Answer the following question in ONE or TWO sentences:

Q: Why are the end facets of a DFB laser chip provided with A.R. Coatings?

Ans: To prevent reflections from the end-facets that could lead to the formation of Fabry-Perot cavity/resonances.

The answer is, here is the answer to prevent reflections from the end facets that could lead to the formation of Fabry Perot cavity or resonances. It is very clear that A R coating as the name indicates it is an anti reflection coating to block reflections coming from the ends. If the reflections come from the end there will be feedback from the ends and the cavity will also form a Fabry Perot cavity and therefore, there will be allowed resonances at those frequencies. To avoid this and to select only one frequency that is selected by the grating we need anti reflection coatings at the ends. That is the answer. I hope it is clear.