Processing of Semiconducting Materials
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Lecture - 22
Molecular Beam Epitaxy I

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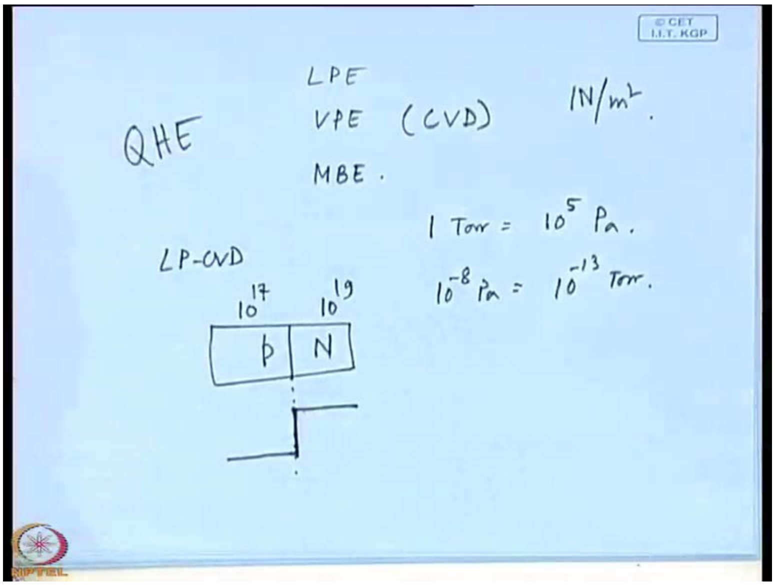

This is the last lecture in series of epitaxial growth of single crystal. We have discussed about the liquid phase epitaxy, then vapour phase epitaxy, which is popularly known as CVD. And today, we shall come across the molecular beam epitaxy MBE.

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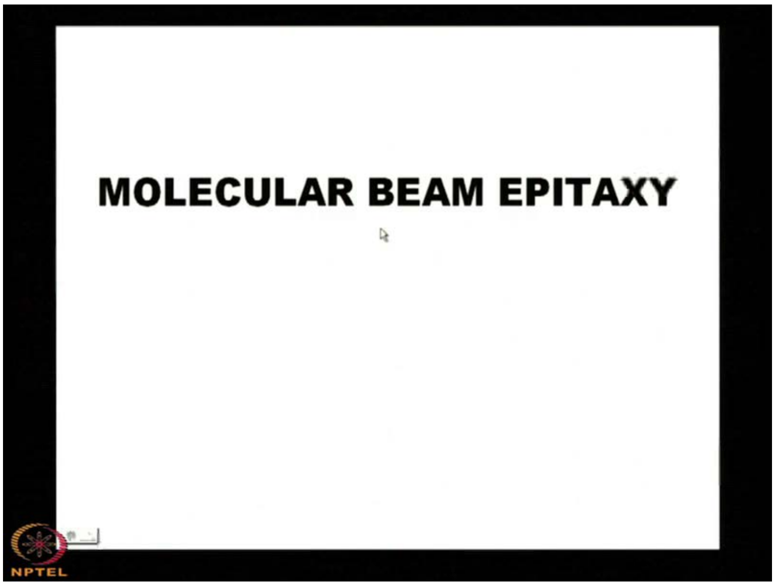

You know that this molecular beam epitaxy, it is a physical vapour deposition, this is not chemical vapour deposition and you need not use any vapour phase reaction; that is not required here. And molecular beam epitaxy is very much useful, and it has many advantages were other kinds of epitaxial techniques in the sense that extreme precise control of doping and hetero structure can be done using this molecular beam epitaxial.

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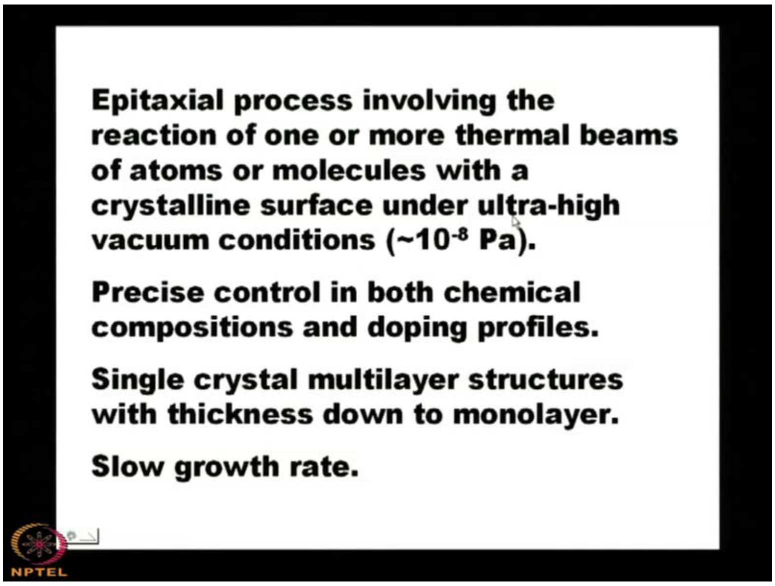

So, now so far as this epitaxial process in MBE concerned you see that it involves the reaction of one or more thermal beams of atoms or molecules with a crystalline surface under ultra high vacuum condition, that is the main theme in MBE that you need ultra high vacuum condition it is of the order of 10 to the power minus 8 Pascal, so how high it is? what do you mean by Pascal?

Student: 10 to the power minus 8.

Newton per meter square meter square, so when one Newton of 4 is exhorted in one meter square area then it is known as the Pascal. So it is very ultra high vacuum condition and if you converted into torr how much torr it is? it comes out to be...

Student: (( ))

1 torr what is the relation between Pascal and torr.

Student: (( ))

Yes, so it is a how much a torr it is?

Student: Ten minus three (( )).

One torr equals to 10 to the power 5 Pascal, so 10 to the power minus 8 Pascal means how much torr?

Student: 10 to the power minus 13.

Minus?

Student: 10 to the power minus 13.

13, so it is very very high vacuum. That is the problem with MBE that means it is very ultra high vacuum system. So, now if you compare with this MBE system with the CVD system what we find? we find that in CVD or BPE, you need not to use any ultra high vacuum condition that is not required for CVD or BPE, there is LP CVD. In LP CVD we find that low pressure that means some very small amount of pressure where vacuum condition is required it is not 10 to the power 13 torr it can be 1 torr 2 torr that much not more than that.

And another thing is that, because of this ultra high vacuum condition the growth rate is very slow. In MBE the growth rate is very slow, sometimes if you want to make one micron thickness epitaxial layer using MBE you have to wait for several hours, you have to wait for several hours. In CVD we find that the growth rate is comparatively faster in some cases you find that one micron per hour or even 10 micron per hour in CVD, but in MBE is very very slow process because of the ultra high vacuum condition.

But you can precisely control the chemical compositions and doping profiles chemical compositions and doping profiles.I mentioned several times that when you talk about your doping profiles, suppose it is a P N junction, that means if I draw the doping profile you see that left side I have doped with p type on the right side it is doped with n type so if I draw the doping profile then it is like this, that means this junction between p and n it is very steep and abrupt it is very steep and abrupt, say it is 10 to the power 17 it is 10 to the power 19. The transition between 10 to the power 17 and 10 to the power 19 is very very sharp extremely sharp you see it’s like delta function.

So, that is possible in MBE, when you come across different types of devices, that those are there in your physics of semi conductor device curriculum say MODFET modulation doped field effect transistor, or quantum casket laser, or quantum well infrared photodetector QWIP. You'll find that extreme control of the doping at different layers is important because then only that effects will be prominent. And you know that probably in 1985 von Klitzing was awarded noble prize for the discovery of quantum hall effect. So, this quantum hall effect was discovered due to the availability of two dimensional electron gas due to the availability of two dimensional electron gas. And that is possible due to the formation of quantum OL because two dimensional electron gas is possible only devices like quantum well not in bulk.

I shall mention these in this lecture that in this age of nano technology, precise control of your special coordinates, or the size, that is possible only using this type of growth that is the MBE type of growth. Quantum dot you want to form a quantum dot of say diameter 1angstrom, 2 angstrom, 5 angstrom, then only that quantum effects will be visible otherwise the quantum effects will not be visible, So those types of dot you can make using this type of epitaxial layers, epitaxial techniques.

Also you see that this single crystal multi layer structures with thickness down to monolayer.

What is monolayer?

Student: (( ))

What is single layer?

Student: (( )) single crystal.

No.

Student: Single (( ))

Yes, monolayer means suppose the diameter of 1 atom is say x angstrom example 3 angstrom, 4 angstrom, so that means it is 1 atoms 4 angstrom, it is second atom 4 angstrom, it is 3rd atom 4 angstrom, it is 4th atom 4 angstrom, so you can form 1 layer of single atoms, you can control you can make 2 atoms may clear, it can be 2.5 what is meant by 2.5? That means 2 fully grown layers and 1 layer is half grown half grown not fully grown, So, that is very important that using such kind of epitaxial techniques growth down to monolayer is possible in some cases say.

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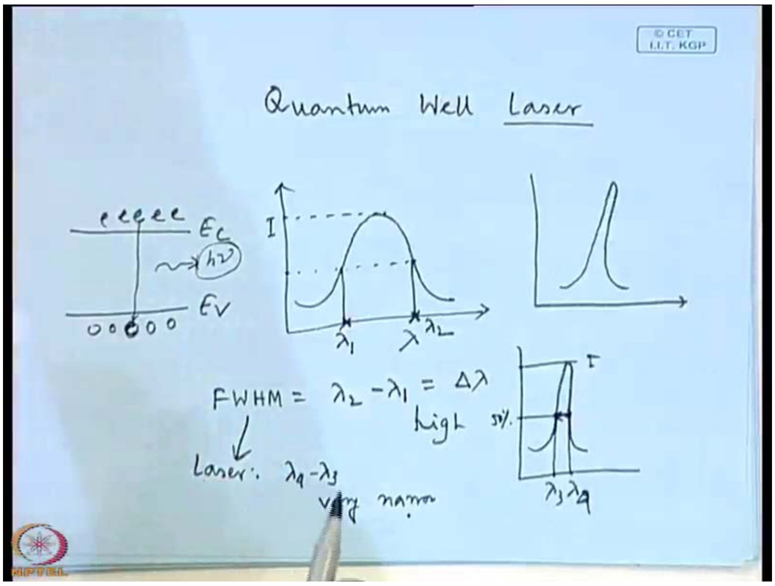

If you want to fabricates quantum well laser quantum well laser, you know what is a laser, highly directional beam of light due to the stimulated emission of radiation, and in LED light emitting diode it is the spontaneous type of radiation, so difference between an LED and laser is the stimulation emission in laser and spontaneous emission in... LED.

Now, spontaneous emission is very easy to obtain say this is your conduction band, it is your valance band, and if you excite the electrons form the valance band to the conduction band it is exited say, so the large number of electrons can be exited to the conduction band leaving holes in the valance band, when electrons will come down to the valance band they will recombine with the holes and this process electromagnetic f will be... generated.

Generated because of the dissipation of the access energy which it has... So, now this electron hole recombines with the emission of h nu or the electromagnet radiation this is the process of spontaneous emission. You don’t have any control over the de-excitation of the electrons from the conduction band to the valance band, you do not have any control they come down of their own they recombine of their own, so that is the spontaneous emission that is why it is not a spontaneous. But for laser what kind of emission is required it is the stimulated emission why is stimulated emission it is required?

Here you see that this h nu it is the energy of the emitted light, nu is the frequency, h is the Planck’s constants. Now, depending on the frequency that means the nu which is given by lambda by c, so different light of colours are emitted. But here you see that nu can be different types of frequencies, that means this nu consists of nu 1, nu 2, nu 3, nu 4, nu 5. So that is the reason that if you plot the emission spectrum form and LED this is intensity versus wave length wave length intensity.

So, this is the typical spectrum of the emission from a light emitting diode and if you measure the FWHM 4 width at half maximum what is that? four with of half maximum is, first you take the maximum intensity then half then make it an half, say maximum intensity is 100 percent so 50 percent is your I by 2, and this difference is known as the full width at half maximum, this is maximum this is half maximum so full with a half maximum, and if I consider that this point is lambda 2, and this point is lambda 1, so what is the FWHM? FWHM is lambda 2 minus lambda 1what is the meaning of this FWHM?

Only change not changes many wave lengths are there in the light. The light is not a monochromatic light, here the light is not a monochromatic light it is a mixture of many wave lengths that means many colours, when you talk about the frequency or wave lengths means.

Student: Colours.

Colours basically, for layman it is the colour. So, here many colours are involved because if it is a monochromatic light then the FWHM should not be lambda 2 minus lambda 1, because lambda 2 minus lambda 1 means say delta lambda and this delta lambda has some finite value it can be 100 nanometre, it can be 50 nanometre, if I plot in the nanometre it can be several angstrom, if the x axis in the angstrom, so this FWHM is high in case of light emitting diode that means it is not a monochromatic light, for laser it is the monochromatic light so when you need any monochromatic light with highly directional beam coherent output it is not coherent also it is not coherent also.

Why? Because the nu's are different the frequencies are different. In laser, if I plot this diagram, this diagram is basically the intensity what is wave length diagram, you will find that for laser it is like this or precisely it is, that means the FWHM is very, very narrow small here this is FWHM is I, this is 50 percent of I, and you take the value of say here lambda 3, lambda 4, so here FWHM is basically for laser it is lambda 4 minus lambda 3very in narrow. So, since it is very, very narrow, so you can consider that the light consist of only 1 wave lengths or very near to that wave length that means the if it is a blue light then peak will be at 4, 2, 0 lambda 4 will be 4, 2, 2 lambda 3 will be 4, 1, polyhedral . So that means the variation is from 4, 1, 8 to 4, 2, 2 that means just four nanometre.

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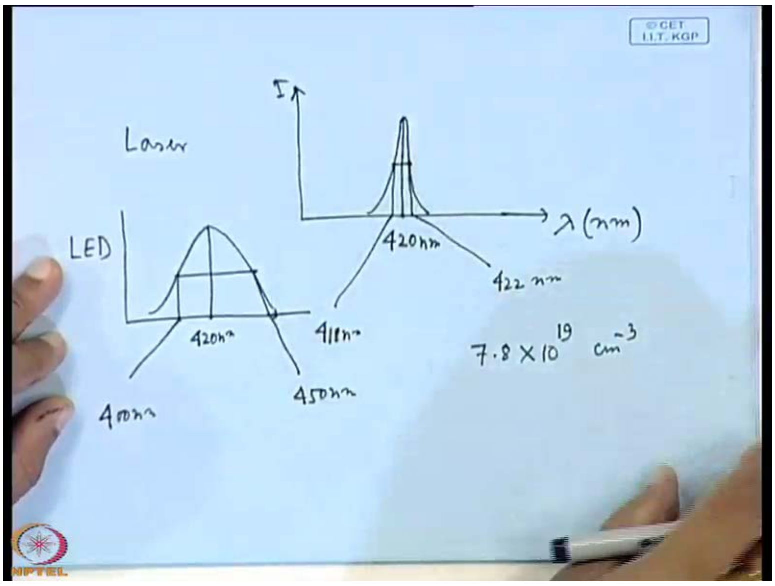

So, that is the implication of that FWHM for laser, say this is ideally it should have been a deltas function then only 1 wave length precisely 1 say it is 4, 2, 0 nanometre, if you plot intensity versus wave length, wave length say in nanometre. Ideally it should have been but this is not possible because the emission or transition of the electrons and holes are basically the statistical process. So form the statistical process you cannot expect the output will be a delta function, so there will be some variation like this, and this variation if I take the FWHM say on the left side this is say 4, 1, 8 nanometre, and the right side it is say 4, 2, 2 nanometre, then what is the FWHM? only 4 nanometre so it is blue you consider it as a monochromic coherent beam of light you can consider because the FWHM is very very small. But in case of LED this is say 4, 2, 0 nanometre and it is say 400 nanometre it is say 450 nanometre so what we find?

Student: 50 nanometre.

That 50 nanometre if the FWHM 450 minus 400, 40, 50 nanometre, So it is not precisely the monochromatic beam of light. Now, this monochromic highly coherent beam of light comes from a special structure which is known as the quantum well laser, quantum well structure. During our discussion on the optoelectronic devices in the next semester we shall come across that kind of a structure an optoelectronics.

So, this quantum well laser, this quantum well structure is formed only by the application of the molecular beam epitaxial system by bulk crystal growth or by LPE, even in using some kinds of CVD you cannot precisely control the structure. Because stimulated emission highly dependent on the doping concentration of the different layers doping concentration of the different layer, you know that for stimulated emission in a structure say for a light laser what to do that the doping must be degenerate type of doping that means, what is degenerate type of doping? That means whether carrier concentration is very, very high carrier concentration is very very high; that is known as the degenerate type of doping, that means already there are some electrons in the conduction band or the Fermi level in that case lie inside the...

Student: Conduction.

Conduction band, then it is known as the degenerate semi conductor. So when it is possible? It is possible only when the doping is very precise, 10 to the power 19 per centimetre cube 7 into 8, 7.8 into 10 to the power 19 centimetre cube inverse doping only will give you the degenerate type of conductivity.

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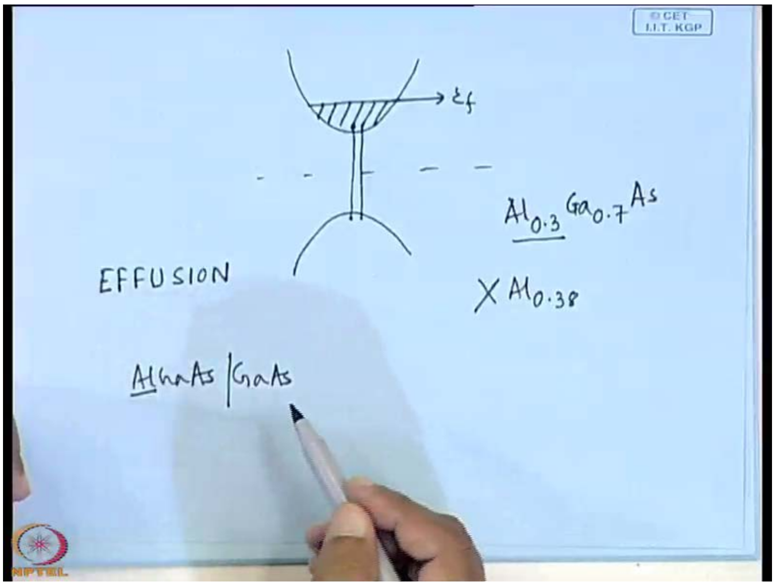

Then this is possible only for by the MBE growth, because you see that for degenerate semi conductor in degenerate semi conductor you see that there will be some the Fermi level will be in the conduction band that means some portion of the conduction band is filled with electrons. The Fermi level in the is in the conduction band what is the physical meaning? the physical meaning is that some portion of conduction band is filled with electrons. So that means there are some electrons in the conduction band then you apply some stimulation to send the conduction band electrons to the valance band some stimulation you then apply, with some stimulation say this electron comes down to here, then second electron comes down here, that is why stimulating the electrons in the conduction band, so that means some stimulation will be there so that the electrons come down to the valance band that is why it is known as the stimulated emission. You are dictating the electrons to come down from the conduction to the valance band you are dictating.

And that dictation is by means of some stimulated you are using say light or any kind of excitation to ask the electrons to come down to the, they are at the roof top and you are throwing from the roof top to the ground. Is it excitation or just heating

Not heating, basically it is done by a various means but the application of light is the one of the important factor. In semi conductor laser the principle is different but normally the stimulated is done by some application of some stimulating force, it may be heat but heat is not generally used.

Student: Sir its excitation.

Heating no, in laser you cannot hit it, hit means HIT you cannot hit it. If someone is say some of your friends are at the roof top you can hit them to fall to the ground, but electronically you cannot hit some application of some force. Excitation means get energy and go to the high energy states, but in this case (( )) electrons fallen from high energy state to low energy state. Yes some metal stable states also excited state.

Student: If (( )) to the upper side...

No.

Student: Where?

Where it will go? I already discuss the thing that the electrons are highly choosy elements particles you cannot send the electrons anywhere. Anywhere. So that is not possible, so when we shall discuss about the laser or the LED at that time we shall concentrate those things. But some stimulating agent must be there to throw them away from the conduction band to the valance band, how is it as if? I shall show you, that is not preview of this class.

Student: Sir that means the power estimated emission.

Yes.

Student: You must have a can degeneration control.

Yes sure yes, for laser that is why I am devoting so much time then what is the use of discussing all those thing, what you have taught it is it is the correct thing, for that reason only MBE used. That high degenerate semi conductors with very, very pure layer free from any kind of contamination any kind of defect must be there to obtained a quantum well laser which will give you highly deductional monochromatic beam of light, so it must be degenerate.

And because of it is very high vacuum system is used, so the so the growth rate is very slow so you see that some of the terms we have introduced in this class, 1 is that it is the ultra high vacuum condition second is that monolayer’s that is also very important thing. That in some applications say 1.5 monolayer 1.8 monolayer 3 monolayers of growth is required and that you can using MBE. Even it is not possible using MOCVD or CVDBP not possible monolayer type of growth.

So, that is the reason that we can tell we can say that MB is the ultimate it is the ultimate in film deposition control, cleanliness and in-stiu chemical characterization capability it has. That is the ultimate it is the end of the epitaxy, it is very, very useful technique apart from the control cleanliness why we’re using the term cleanliness because it is high vacuum system, in high vacuum system there must not be any foreign atoms or foreign impurities, because you are continuously sucking at that high vacuum basically nothing will be there in the chamber. If you take a volume and if you start sucking the air from it and if you can achieve 10 to the power 8 minus 8 Pascal then what should be there in the volume? nothing everything has gone, so there will not be any impurity, no even stress amount of any chemical or foreign impurity or atoms will not be there at that high vacuum system.

And one advantage of this MBE is that it is in-stiu characterization. What is in-stiu characterization? In-stiu characterization is that during growth at the growth chamber itself during growth you can characterise the grown layer, its chemical composition and its surface morphology. So suppose you want to grow aluminium, gallium, arsenide for some application you need 0.3 aluminium 0.7 gallium. So you start MBE growth from the in-stiu characterization you can find whether aluminium is 0.3 or 0.4 or 0.27 that can be determine, that means the chemical composition can be precisely determine.

So if you find that aluminium is now 0.38 so what will you do? You will stop growth. Immediately you can stop growth, because you need a aluminium 0.3. If find that any stage the aluminium concentration is high higher than what you want then you stop growth. Why you will stop growth? so the more chemicals are not wasted out your time, your cost should not be much high so you stop it. Because that kind of a layer will not be of any use if you need aluminium 0.3 then you get aluminium 0.38 that meant you discard this growth.

So that type of characterization during growth, another another thing is that the surface morphology can be view you can observed the surface morphology whether it is rough, whether it is smooth, whether any patches are there, whether any scratches are there, patches, scratches, dislocations. you can see by the application of some electron deflection spectroscopy that shall I discuss, RHEED is there RHEED.

Student: (( ))

That is a electron deflection spectroscopy, reflection high energy electron deflection RHEED. So using that spectroscopy technique you can see the structure or the surface morphology of grown layer. If you see that the surface is rough, when the surface will be rough? when there will be problem with composition. Whether when there is a problem with a lattice matching then only the surface morphology will not shining. Otherwise in epitaxy the most of the cases the surface morphology will very shiny very bright. And if you see it is not so then you can think that something happened during the growth you stop growth. So those in-stiu to characterization facilities are there in a MBE which are not available in other epitaxial systems.

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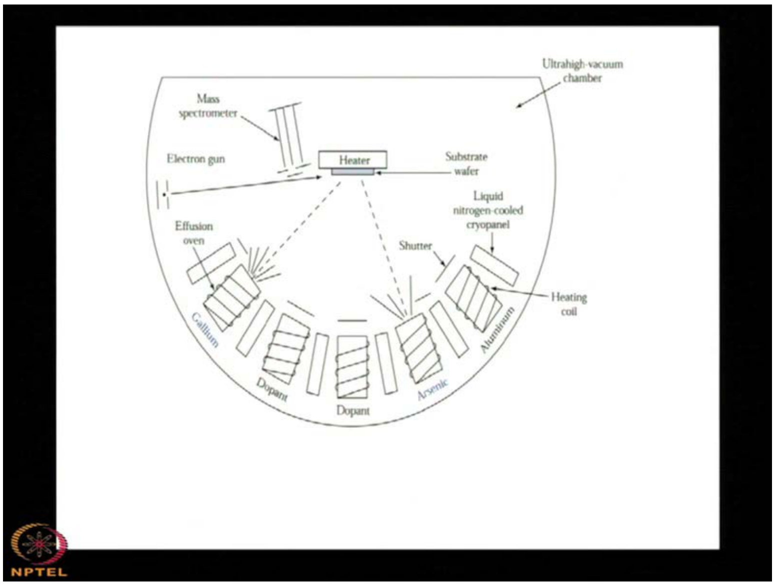

So, this is the typical MBE system what is this? This you see that these are the effusion cell this is known as the effusion cell EFFUSION effusion cell. Now, what is effusion?

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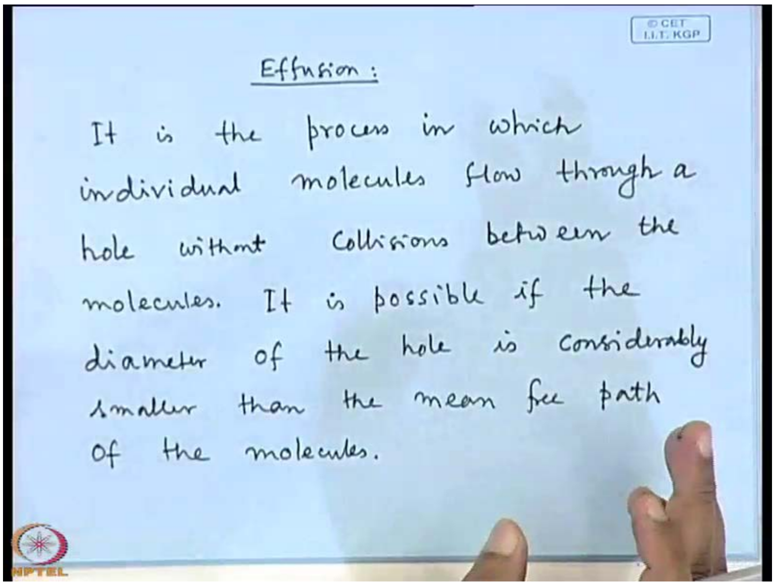

You see that effusion, it is the process in which individual molecules flow through a hole s without collisions between the molecule. without collision between the molecules It is the process in which individual molecules flow through a hole s without collisions between the molecules. And it is possible it is possible or it occurs if the diameter of the hole is considerably smaller then the main free path of the molecules. This is very important that if the diameter of hole is considerably smaller then the main free path of the molecules.

So, one another additional term we are now introducing it is the main free path of the molecules. And the whole MBE system is based on this concept that the main free path of the molecules will be high main free path of the molecules will be high. And that is the reason ultra high vacuum system is required i shall show you by the application of mathematics that how this high vacuum is related to the main free path, so the from the source to the substrate sides the molecules of the materials or the consisting chemicals are freely they can freely move to the substrate side without any collusion. So, first thing is that you heat suppose you want to make gallium arsenide, so you take gallium say this is gallium this is gallium and it is arsenic. So this is an open that is another open it is known as the effusion cell in some books you will find that these are known as KNUDSEN.

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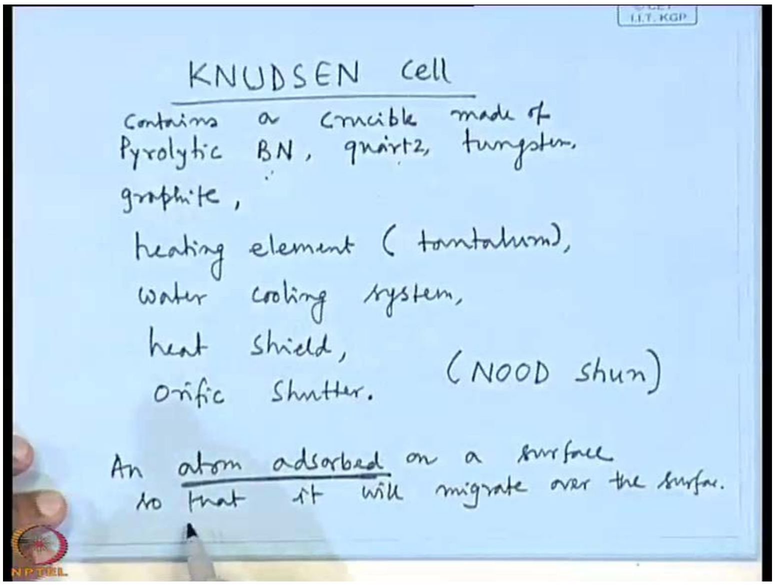

That it that is Knudsen cell, almost same thing almost it is the effusion oven or effusion cell type of concept. It is now this effusion oven or this Knudsen cell whatever be the case it contains the elemental materials which are used for the growth of the semi conductor. Say gallium is used and arsenic is used. So you heat gallium and arsenic they are placed in a ultra high vacuum chamber, all the ovens can be heated separately they have certain.

So that when the shutter is closed no molecules from that particular oven comes out, and when it is heated the molecular beam without any collision it will not separated collision, because of the ultra high vacuum condition of the system, this beam of the molecule directly impeach or directly heat the substrate or the vapour which is heated by some mains of heat, some hated substrates are there, heating elements are there. So the substrate is heated and atomic beam of the materials or molecular beam of the material directly fall on the falls on the substrates without any collision so that means a beam of molecules travels from the oven to the substrates side that is why it is known as the molecular beam epitaxy.

The concept of beam is comes in these manner, the concept of beam that means you heat gallium, so gallium molecules will be form then continuously if you heat continue if you continual heat continuously heat it then the molecular beam of gallium will come out from the effusion oven to the substrate side. Since the it is very high vacuum it is the vacuum is very very high is ultra high vacuum system there will be no collision so the directly the beam will fall on the substrates, that is the reason it is termed as the molecular beam epitaxy.

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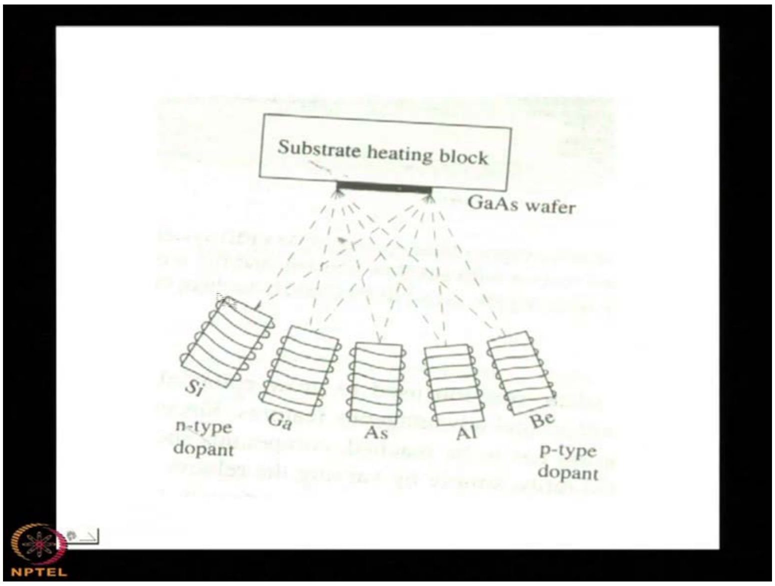

Then this is the effusion oven, see this is silicon, this is gallium, this is arsenic, this is aluminium, this is beryllium, because this silicon is used for n type, and beryllium is used for p type dopant, then gallium, arsenic, aluminium are there, because you can grow gallium, aluminium, arsenide. Because most of this development of the epitaxial technique came out during the gas algas system, gas algas system means gallium arsenide, aluminium gallium arsenide system. Why is this aluminium is used? Why aluminium is used?

To control the band gap.

Yes to control the band gap basically the band gap increases the band gap increases, if you add aluminium the band gap increases, and why this type of material came out? Why the people are discovered this type of a system?

Student: (( ))

Why there are many material, even then why they are concentrated on gas algas system?

Student: To prove (( )).

No. It is because of two reason; one reason is that, this wave length that means if you add aluminium with gallium arsenide, what is the band gap of gallium arsenide it is 1.43 electron volt. If add some aluminium then it will around 1.8 electron volt. From 1.43 to 1.8 electron volt. That band gap was required for using first window of the fiber optic communication. Can you remember the window of the fiber optic communication. On the very first day or in the some past lectures in some lectures I cannot remember probably in 1 or 2 lectures first I show you I showed you that there was a there was 3 windows in fiber optic communication. If I draw that window, it is like that.

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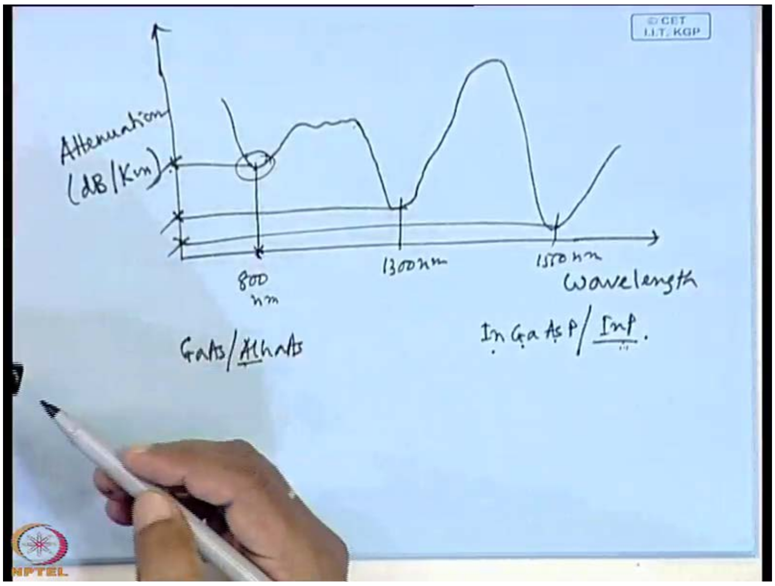

Free hand drawing, this type of a thing, window means, what is this plot? The plot is wave length versus...

Student: Attenuation.

Yes, very good attenuation.

Student: (( ))

Yes attenuation, and it is decibel per kilometre. It is for a typical silica fiber, I am talking about the fiber optic communication, where the silica fiber is used to connect a transmitter with the receiver, and light passes through that silica fiber by the process of total internal reflection. Because no other type of information carrying is possible except light in fiber optics and that to by the method of total internal reflection. So if you plot the wave length versus attenuation, attenuation means loss. Basically attenuation is loss, it is opposite to amplification. So if you plot attenuation versus wave length you see that it is around 800 nanometre, it is around 1300, 1300 nanometre, it is around 1550 nanometre.

Broadly we can consider that there are three window for fiber optic condition. That means where the losses are minimum, you see here the loss is, here the loss is this, and here the loss is this, this is known as the first generation window first generation, just when fiber optic communication has just started and you that this year the Nobel prize in physics went to fiber discovery of fiber optics, optical cable. It was discover some 40 years back but the Nobel was awarded only this time that means after 35 40 years after the discovery KUO.

So, this is the first window. This first window is 800 nanometre and this is achieved by gas algas system ok it is achieved by gas algas system. So the so the 1st thing was that gas algas was used for the... Fiber optic

First window first generation fiber optic communication for making light emitting diode, because if you can use this wave length light than the loss will be? Less. Less compare to the other lights, it will be further less if you use 1550 or 1300 that also discovered and present fiber optic communication supports 1550 or 1300 nanometre. Say another thing is that lattice matching problem. You know that in epitaxy the problem is with the lattice matching proper substrate is required. And for proper substrates the lattice constants of the substrate will be equal to the lattice constant of the grown epitaxial layer. If you can remember I have showed you earlier also the lattice constant versus band gap type of plot, you see that you will see that for all values of aluminium aluminium, gallium, arsenide is lattice match to gallium, arsenide substrate so that is also advantage. Because getting a good substrate having lattice constants same with that of the epitaxial layer is very difficult, here if you can even vary aluminium for a wide range, it is lattice match to Gallium

Gallium arsenide substrate because algas is fabricated on gallium arsenide. So that is the reason that gas algas system was very popular, and in elemental semi conductor we take the example of silicon in compound semi conductor epitaxial growth we take the example of gas algas, that is the most elemental materials in epitaxy. There are other materials for 1300 nanometre or 1500 nanometre we use indium, gallium, arsenide, phosphate on indium phosphate that mean the substrate is the indium phosphate and the material is indium gallium arsenide phosphate and this is for 1300 nanometre and 1550 nanometre.

But we always take the example of gas algas system. So this is the you can see that is the Knudsen cell. and it is made of pyrolytic boron nitride, and it can be heated you can control the temperature and there are heating filaments, the filaments are mostly tantalum the filaments are mostly tantalum, and water cooling system is there heat shield is there and there is a orifice shutter that means you can control the emission.

Student: Emission.

That is the shutter you can stop, it you can open it, when you need arsenic when you open the shutter when you need aluminium you open the shutter if you don't need close the shutter aluminium so that there will no aluminium. So this says are made of pyrolytic boron nitride there is heat shielding there is heating element, and that heating element is mostly tantalum metal, then there is orifice shutter, and water cooling system is also there and you see that the beams are make to fall on the substrate surface and they follow the cosine law, they follow the cosine law.

That means the emission from this oven is basically something cos theta say if you consider the intensity or the flux it is cos theta. Theta means, making an angle from the point of emission to the substrate the angle between the substrate and the oven orifice basically, that is the theta and it always follow the cos theta law. And this Knudsen cell if you consider then I can either it is made of pyrolytic boron nitride, it can be quartz also tungsten can be or even it can be graphite. That means a Knudsen cell contains a crucible made of heating element tantalum, water cooling system, heat shield, and orifice shutter.

So, these are the description of the Knudsen cell, the actual whet is the pronunciation of this Knudsen it is the pronunciation NOOD shun not Knudsen it is NOOD shun cell, like our Czochralski, it is not Czochralski it is Czochralski.

So, this the description of the Knudsen cell, you see that it containers a crucible made of pyrolytic boron nitride or quartz or tungsten or graphite, it has the heating element made of generally tantalum metal, with water cooling system, heat shield, and orifice shutter. So this are the Knudsen cells or the effusion cell, the same thing effusion or Knudsen the same thing. Only thing is that the orifice that means the aperture diameter is smaller than the

Student: Main free path...

Main free path of the...

Student: Molecules.

Molecules. That is the that is the only condition, that aperture or the hole or the orifice the same thing the diameter must be considerably smaller than the main free path.

Student: (( )) this one also Knudsen.

No yes. In this is the total diagram of the molecule epitaxial system. In here you see that it is the Knudsen cells only.

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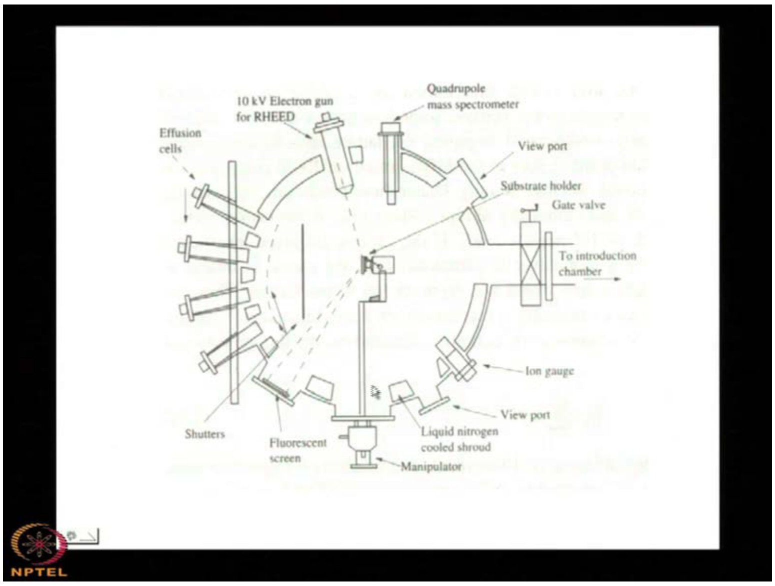

And here the other types of accessories also there here you see here this portion the left portions are effusion cell, then this perpendicular vertical line is the is the certain. Then you see that there is a RHEED 100 k v electron gun for RHEED, then mass spectrometer for the analysis of the residual gasses, then view port you can see what is happing inside there is a substrate holder.

Then a liquid nitrogen cooled shroud for cooling, fluorescent screen is there why there is a fluorescent screen? To see the spectrum or the street from the RHEED. How will you see what is there in surface? So that is the monitor basically this monitor is basically for the RHEED, RHEED system. And you see that there is a another chamber you can take the substrate from this chamber to the another chamber for further processing etcetera. So these are the total set of and it is very complex it is very complex, one of MBE system is there in our physics department with professor s k ray, So when you will go to physics department you can visit the instrument it is very complex instrument and if you see the equipment in real face you find that how it looks like.

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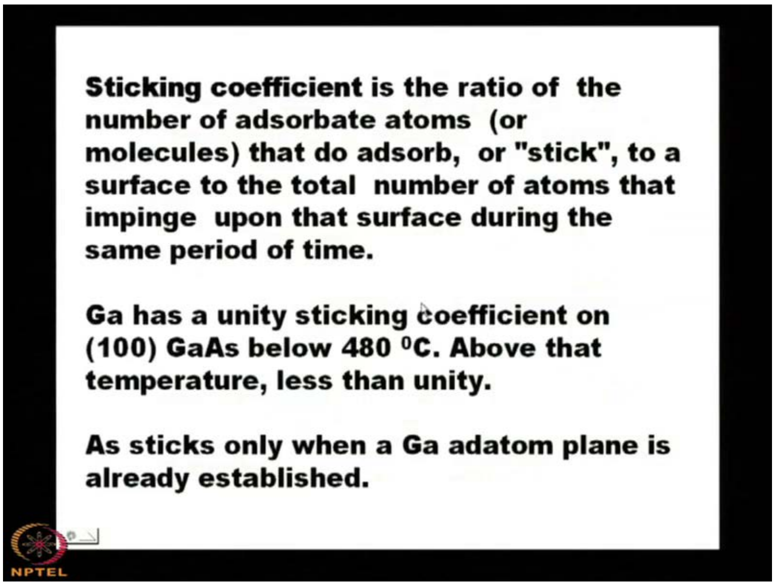

So, another important consideration for the MBE growth is the sticking coefficient. Sticking coefficient means basically the molecules which are coming out from the Knudsen cell must stick to the substrate otherwise how the growth will takes place? so sticking coefficient is the ratio of the number of absorbate atoms that do absorb, or stick, to a surface to the total number of atoms that impinge that surface during the same period of time. So this is the sticking coefficient, actual number of atoms that are being adsorb, to the total number of atoms that are coming from the effusion cell to the substrate, not that all the atoms are going to adsorb only a few percent will be adsorb, some will be evaporate some will be move away.

The sticking coefficient if you see that it is very important because unless it sticks to your substrate you will not get the epitaxial layer. Gallium has a unity sticking coefficient on gallium arsenide below 480 degree centigrade. Unity in sticking coefficient means? all the atoms of gallium stick to the substrate. If you make the growth at 480 degree centigrade or below, above hat temperature it is it is less than unity, that means it may be 0.8, 0.7, 0.5 depending on the temperature. If you increase the temperature it will be 0.2, 0.3 type of thing. Arsenic sticks only when a gallium adatom plane is already established. Arsenic sticks only when a gallium adatom plane is already established.

What is adatom? Adatom is an atom adsorbed on a surface so that it will migrate over the surface. Adatom means absorbed atom basically adatom means absorbed atom on a surface, so that it will migrate over the surface. Because first it will adsorb and then it will migrate then only there will be uniform growth, so that is why it is known as the adatom. So, now arsenic sticks only when a gallium adatom plane is already established otherwise arsenic will not stick. So these are the consideration so in my next lecture we shall conclude our discussion on MBE.

Thank you.