High Speed Devices and Circuits

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Lecture – 10

MBE and LPE for GaAs Epitaxy

We have been discussing the technology of gallium arsenide very briefly, just an overview. We saw that in this connection it requires semi-insulating substrate and on the top of that, we need to have an epitaxial layer. If you have not seen earlier, you can see the growth is done layer by layer gradually. There are different techniques.

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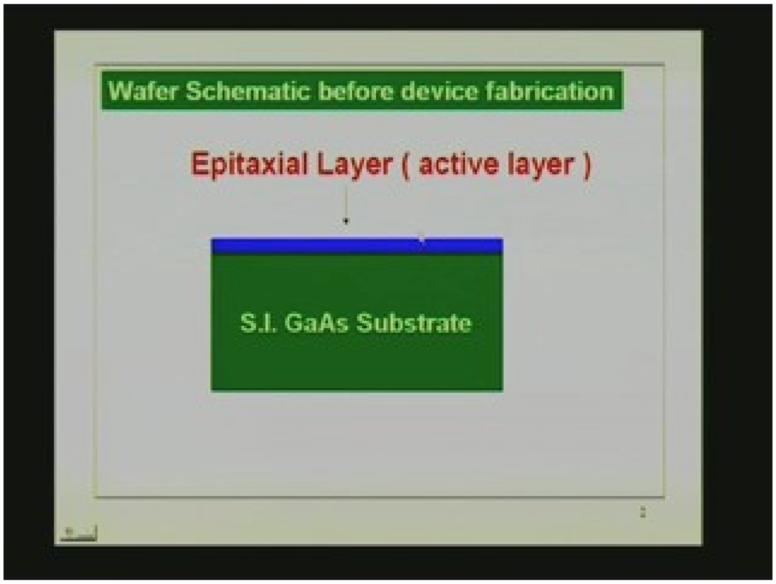

Wafer Schematic before device fabrication

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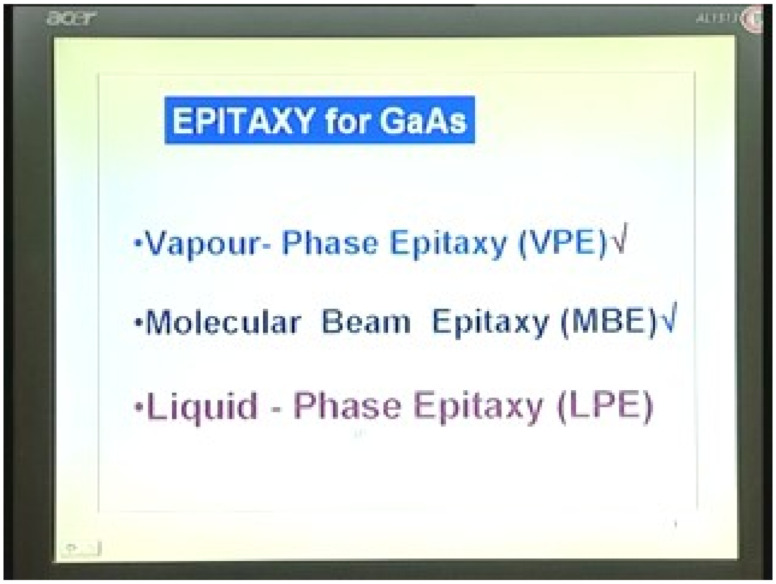

EPITAXY for GaAs

- Vapour- Phase Epitaxy (VPE)√
- Molecular Beam Epitaxy (MBE)√
- Liquid - Phase Epitaxy (LPE)

From the last lecture, we saw one is the vapor phase epitaxy in which there are at least 3 systems: halide, hydride and **MOCVD (1.47)**. Though it is termed as chemical vapor deposition, the real thing is metal organic vapor phase epitaxy. Then, we took a look at molecular beam epitaxy to some extent. There are few aspects that we still want to touch upon in this lecture. Then we will go on to the liquid phase epitaxy which is not really very popular for microelectronics but very useful when you want to have very pure layers for light emitting diode applications. We will see the reason for that. First, we will just go through quickly what we have been discussing.

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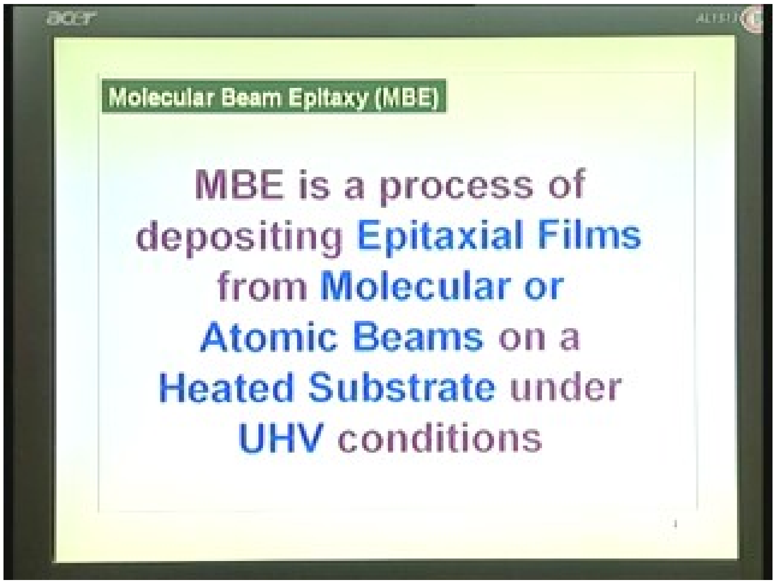

Molecular Beam Epitaxy (MBE)

MBE is a process of depositing Epitaxial Films from Molecular or Atomic Beams on a Heated Substrate under UHV conditions

MBE is a process of depositing epitaxial films from molecular or atomic beams on a heated substrate under ultra high vacuum conditions. All that you need is a source which will actually supply those elements. These are the evaporation crucibles which are known as the Knudsen cells, the shutters and heated substrate. Red color is the heated substrate mounted on a molybdenum substrate which is chosen because of its high thermal conductivity. The entire thing is enclosed in a stainless steel chamber that we would get vacuum levels of the order of 10 to the power of minus 10 to 10 to the power minus 11.

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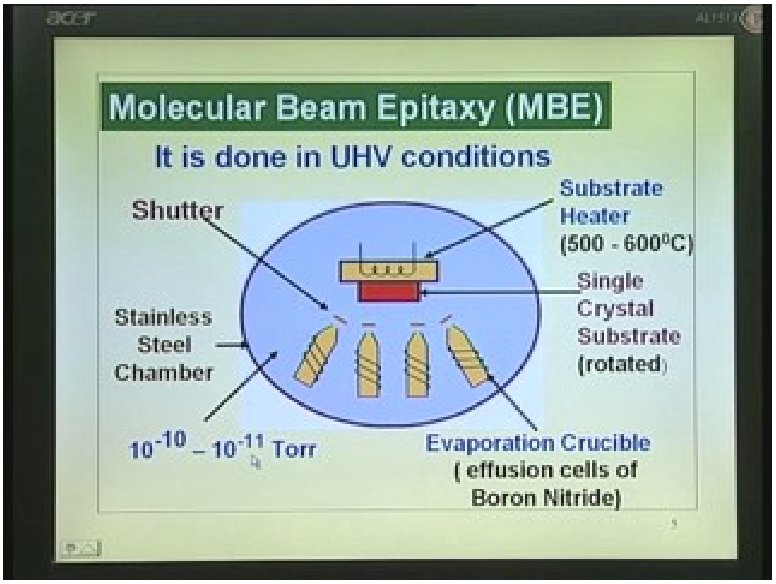

Molecular Beam Epitaxy (MBE)

It is done in UHV conditions

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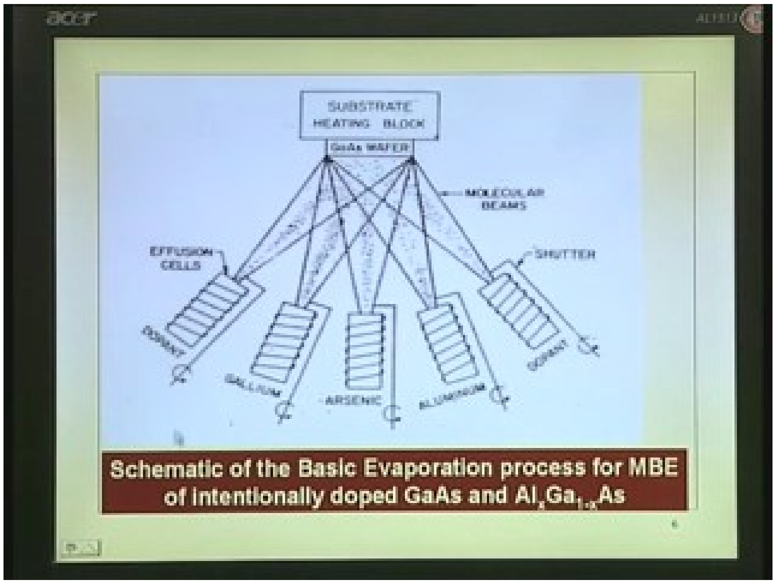

Schematic of the Basic Evaporation process for MBE of intentionally doped GaAs and $Al_xGa_{1-x}As$

This is what is inside. What we are showing is only the source, the crucibles, K-cells, one for dopant, one for gallium, one for arsenic, one for aluminum and for another dopant. These are shutters. You can see the beams are going like that and the beam formation is possible because of very high vacuum of the order 10 to the power of minus 5 Torr. If you have this, you will have mean free path of about 10 meters. If this distance is of the order 30 centimeters, then it is quite good enough.

However, to keep the contamination level by a factor of 10 to the power of minus 5, you must have vacuum further down by 10 to the power minus 5 Torr. To give an idea, 760 Torr is 1 atmosphere. It is way down below the atmospheric pressure is virtually 0. We will talk of that doing MBE in the outer space where there is vacuum. We will talk of that build laboratories there and do the MBE systems. We do not need all these things and that is what we will talk in the space labs. You automatically have high vacuum layers.

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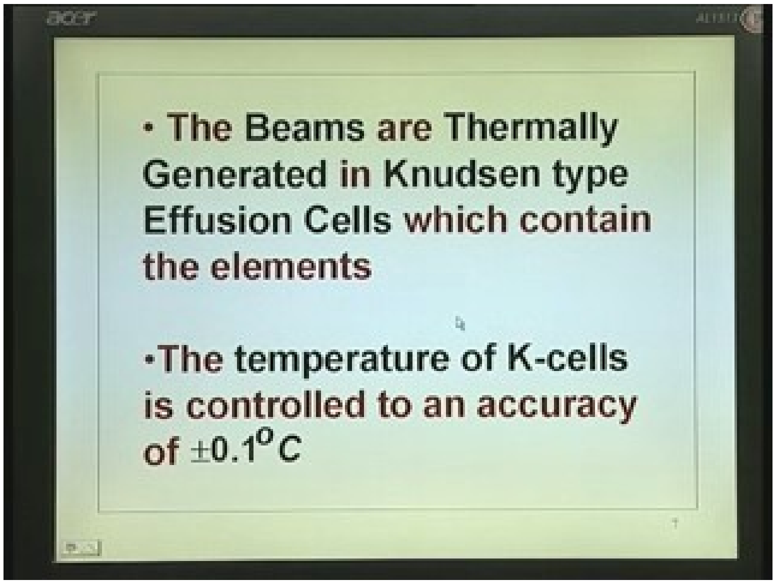

- The Beams are Thermally Generated in Knudsen type Effusion Cells which contain the elements
- The temperature of K-cells is controlled to an accuracy of $\pm 0.1^oC$

The beams are thermally generated in the Knudsen type effusion cells which contain the elements. These are those cells which contain elements: gallium, arsenic, aluminum and all sorts of things which you want plus dopants. The temperature of the K-cells is controlled to an accuracy of plus or minus 0.1 degrees centigrade because that controls the flux of the molecules or atoms.

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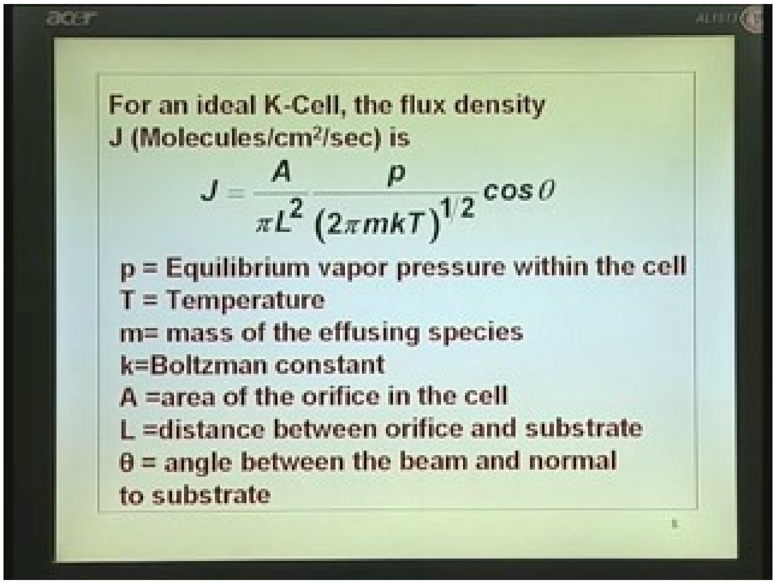

For an ideal K-Cell, the flux density
J (Molecules/cm^2/sec) is

$$J = \frac{A}{\pi L^2}\frac{p}{(2\pi mkT)^{1/2}}\cos\theta$$

p = Equilibrium vapor pressure within the cell
T = Temperature
m= mass of the effusing species
k=Boltzman constant
A =area of the orifice in the cell
L =distance between orifice and substrate
θ = angle between the beam and normal to substrate

You do not have to worry about these equations, just to show that. For example, the flux density of these molecules is related to the equilibrium pressure within the cell and its temperature in this fashion. Theta is the angle between the beam and normal to substrate; if it is 90 degrees, nothing is deposited – flux is 0. If it is 0, flux is maximum. These are just some general ideas you do not have to worry too much about these equations. It is just projected. The flux would depend upon the distance between the orifice and the substrate. More the distance, there is a ______(6.06), flux is low.

So, p is the pressure, T is the temperature, m is the mass of the effusing species, k is the Boltzmann constant and A is the area of the orifice. The area also controls the flux; more the area, naturally flux is more. L is the distance between orifice and substrate, theta is the angle between the beam and normal to substrate. It just gives some idea for those who want to design the system and they will worry about that. The users may not worry about this so much because these are all fixed. The only thing you have to control is the temperature and the partial pressure.

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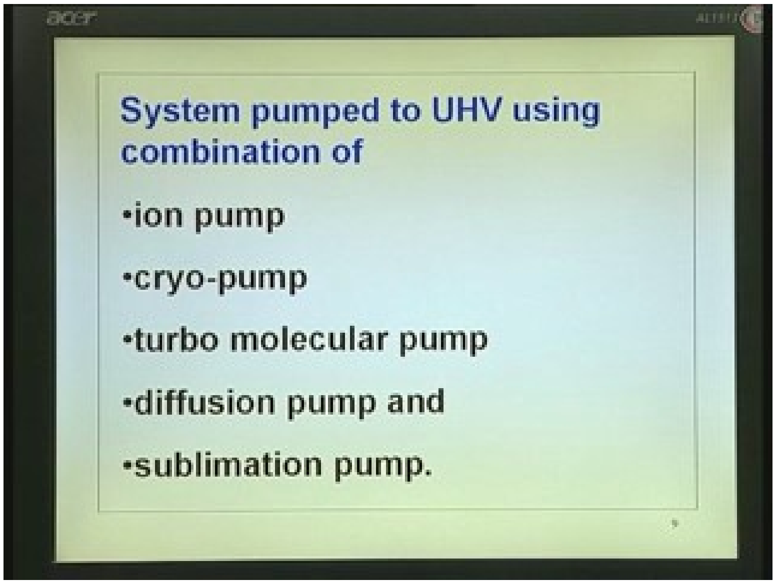

System pumped to UHV using combination of

- ion pump
- cryo-pump
- turbo molecular pump
- diffusion pump and
- sublimation pump.

This high vacuum in the chamber is obtained by using pumps which are oil free. If it is a pump which depends upon some oil system, then there is a fear that oil may get into the chamber. In fact, in the conventional vacuum coating systems also, you have to be concerned about it. The best thing of course is to use some turbo molecular pump, if you do not use oil. In conventional deposition systems where you go for 10 to the power of minus 5 Torr or 10 to the power of minus 6 Torr pressure, there are two pumping systems even is such a simple system.

One is the rotary pump which is pumped down to a milli torr pressure also. Then the rotary pump is not able to pump down because for pumping down; if you have lot of water and if we put our hand like this, then the water goes down. If there is vacuum you put like this, nothing will move. That is why; they use what are known as the diffusion pumps. You connect it to a system which is pumped down and as you create lower pressure here, the molecules will diffuse from the chamber down to this pumping system. That is why; those pumps are called diffusion pumps. Let us not get into more details of that. In fact, you will have a heater which will actually pump oil to the top and that will collect the molecule to bring down.

Therefore, to prevent the oil from entering into the chamber, we have a liquid nitrogen trap so that the oil vapor does not go back into the system. That is why that blocks it. These are some of the things that you do in a conventional system; but here, you may have more than one pumping system to enable pumping of main chamber and auxiliary chambers. These are some of the names which are used in the system.

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- Growth rate ~ 1 μm/hr (one atomic layer / sec)
- Thickness variation ~ (1% within a radius of 5 cm)
- High purity material can be grown
- Any EPI layer composition, thickness and doping can be grown with high accuracy and uniformity

Growth rate in the system is about 1 micron per hour. You can see that it is very slow. We can control one atomic layer in 1 second and layer by layer in 1 second. In fact, you can get because of very high quality layers with the MBE (Molecular Beam Epitazy). You can get thickness variation or you can control the thickness within 1 percent over a 10 centimeter diameter or 5 centimeter radius for the entire wafer. High purity materials can be grown. Composition thickness doping can be controlled with high accuracy and uniformity. These are some of the advertisements for MBE system. In the sense, they are looked forward because of these merits.

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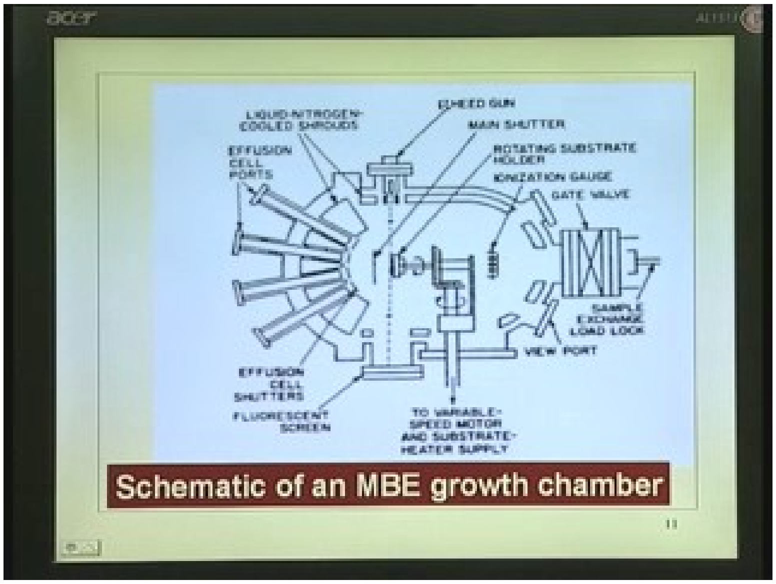

Schematic of an MBE growth chamber

We just projected this to show you the difference between the simple circle that we drew for using a chamber and the real thing is like this. If you want to have a look at this MBE system, then you can walk into our semi conductor device research laboratory. There is one very old system kept their which is not really functional but there are some vacuum problems. What we can see here is the whole thing is a stainless steel chamber into which you have all these effusion cells. 1, 2, 3 and 4 are shown here which are actually used as source of gallium, arsenic, dopants…etc. You can see these shutters are also present here. The shutter is kept closed even though this is heated up and nothing comes out. When the shutter is open, it will let the flux come out only then.

Depending upon what layer you want, you keep the shutter open. You want undoped gallium arsenide; put gallium and arsenic shutter open. If you want aluminum or indium, you open the shutter which contains aluminum or indium. The relative composition is controlled by the temperature – the flux. It becomes more involved here. Now, you can see this is the side which is giving those impurities – dopants or constituents. This is the substrate holder.

That substrate holder can be rotated. This entire assembly is for rotating a substrate. Why do you rotate it? You rotate it to get a uniform layer or thickness everywhere. There are some ionization gauges…etc for identifying what residual gases. More importantly notice here, there is 1 RHEED gun. We will see soon what it is.

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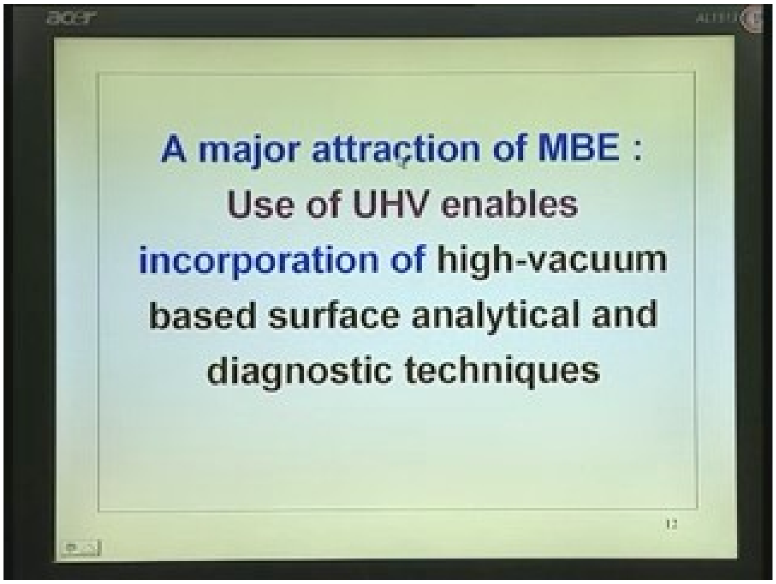

A major attraction of MBE :
Use of UHV enables
incorporation of high-vacuum
based surface analytical and
diagnostic techniques

This is actually high-energy electrons which are gunned towards the surface at an angle of 2 degrees. It is slightly at an angle and when it is reflected, impinges on the fluorescent screen and you will see the pattern from which you can recognize the substrate quality – quality of the layer. The RHEED pattern tells you about the thing. This is just an idea to what all we can put there to characterize the growing layer. This is a very important component of the MBE system. You can also see, there is a port made of glass from where you can view. After all, you must be able to see what is happening inside.

When you see some of the things which are being inserted into the chamber, there is a chance for a leak in this portion. Even the minutest leak will bring your vacuum down from 10 to the power of minus 10 to 10 to the power of minus 4 minus or minus 3 which becomes useless. This whole chamber is not only made up of steel; so that it does not degas and you have the gaskets between these two. After all, you cannot bring two surfaces like this to be vacuum tight; a slightly soft material like gasket is used. They are actually made up of gold metal which we mentioned in the previous lecture.

These are the key things for getting these high vacuums. Also, before turning on the system, the entire assembly will be put in a huge oven which is heated to degas the system. Preparation of the chamber itself is a big job and you must spend a week before you start growing the layer. Once you start pumping down, you have to wait until the vacuum comes down to that level. Once the vacuum comes down, you do not want to open the vacuum to atmosphere. If you open the vacuum to the atmosphere, you are back to square 0, you have to wait again. That is why, this small thing which is called as load lock is there.

What is done is, that is the main chamber. There is a small mini chamber here, very small chamber. This gate is closed and the run is made. You open this gate and insert the wafer into this portion through a wafer holder…etc and keep it there; chamber is closed, pump this down. This is small chamber; otherwise, the whole thing is a big chamber. You have small chamber here which can be pumped down rather easily and may be to an ______(14:43). When this vacuum comes down to an acceptable level, if it is 10 to the power of minus 10; you may have to go close to that here. Then open this gate and push the sample inside. We do not push the sample straight away into the process chamber. In the most modern systems, there will be another chamber in between where it is a preparation chamber.

So, one is for loading it which you do not open the chamber into atmosphere and other one is the preparation chamber. The sample before it goes for epitaxy, you know that you should etch that substrate. So just within that, you will have ion milling system. You can see what all we can insert there for preparing the sample or seeing the crystal growth quality of layer. Everything will be done within the system itself. It is a huge one. We would urge that; sometimes, you walk into our laboratory and ask one of us to show the MBE system that we have got. It is not running right now because of problem in vacuum. This is what we wanted to show you with the actual thing like this. The real thing, you can see physically there.

A major attraction for MBE is the use of ultra-high vacuum enables incorporation of high-vacuum based surface analytical and diagnostic techniques like the RHEED etc.

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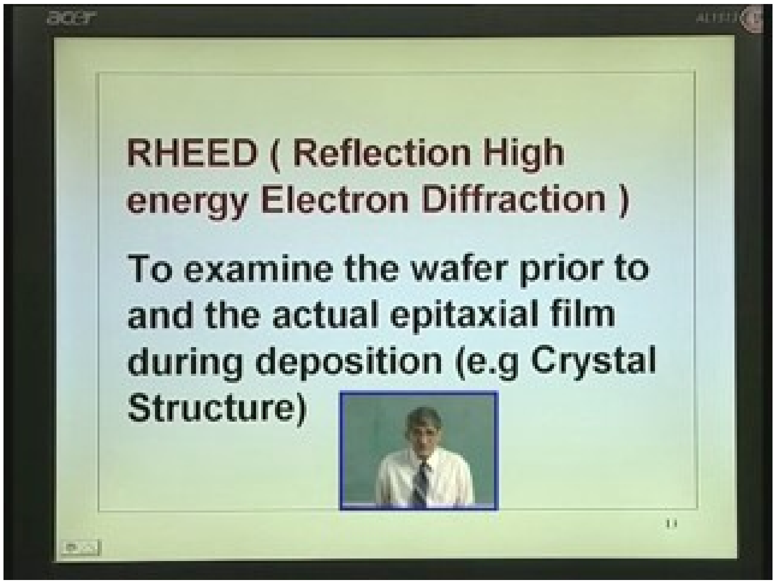

RHEED (Reflection High energy Electron Diffraction)

To examine the wafer prior to and the actual epitaxial film during deposition (e.g Crystal Structure)

The expansion for RHEED is reflection high-energy electron diffraction. After all these lattice atoms look like the gratings. When it falls on to that at 2 degrees and 50 kilo-electron volt energy; high-energy electron beam is reflected and they reflect the property of the atomic layer structure because of the grating nature of the atoms. So, this is to examine the wafer just prior to and actually when the epitaxial growth is taking place. You can put number of things what you want for analytical examination.

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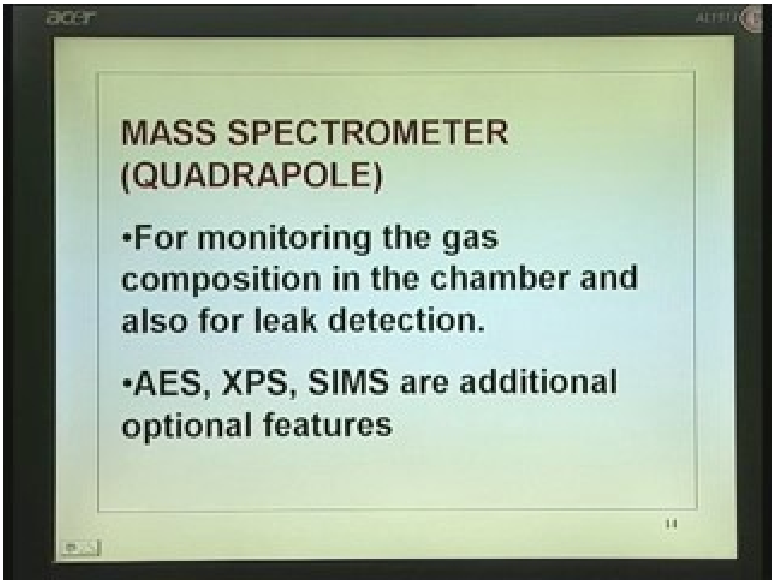

MASS SPECTROMETER (QUADRAPOLE)

- For monitoring the gas composition in the chamber and also for leak detection.
- AES, XPS, SIMS are additional optional features

Mass spectrometer you want to monitor, what are the gases and which are present there? Are there any contaminants? All that is done in the chamber using the mass spectrometer; you can also have surface analysis of the sample – Auger Electron Spectroscope. This is electron and the particle, one more emitted particle, three particle phenomena. These are just some of the names that you will hear, Auger Electron Spectroscopy**,** X-ray Photoelectron Spectroscopy, and Secondary Ion Mass Spectroscopy. All spectroscopes to see what sort of surface you have got as it grows. You get these benefits when you use the MBE system. You can get high quality layers and you can ensure that the contaminants are not there and growing layer is perfect. In situ(18:00) you can examine. You do not have to take it out and see what we got. You can see right there.

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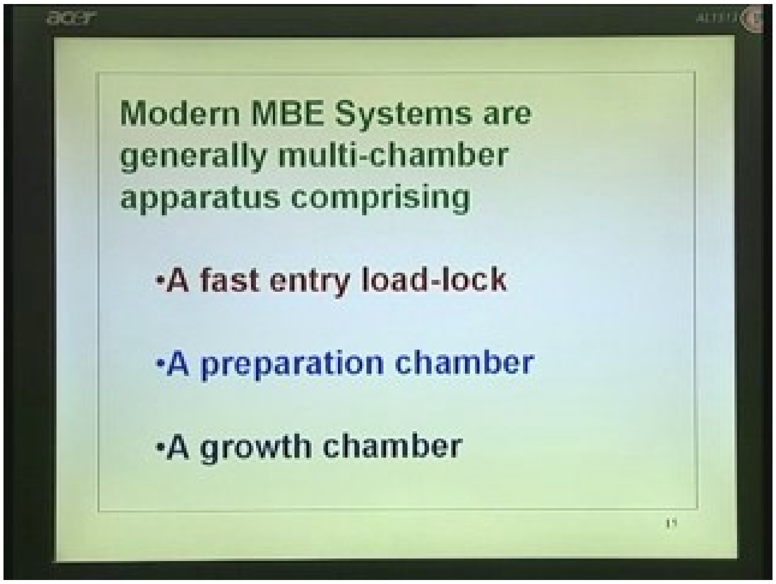

Modern MBE Systems are generally multi-chamber apparatus comprising

- A fast entry load-lock
- A preparation chamber
- A growth chamber

The modern MBE systems are generally multi chamber apparatus comprising the fast entry chamber – load-lock system. Load lock means, you load it and then lock it. A Preparation chamber is the chamber where you prepare the sample to get it ready for deposition by cleaning the surface either by plasma etching or by ion milling. The growth chamber is the real one where you can expose it to the constituent elements.

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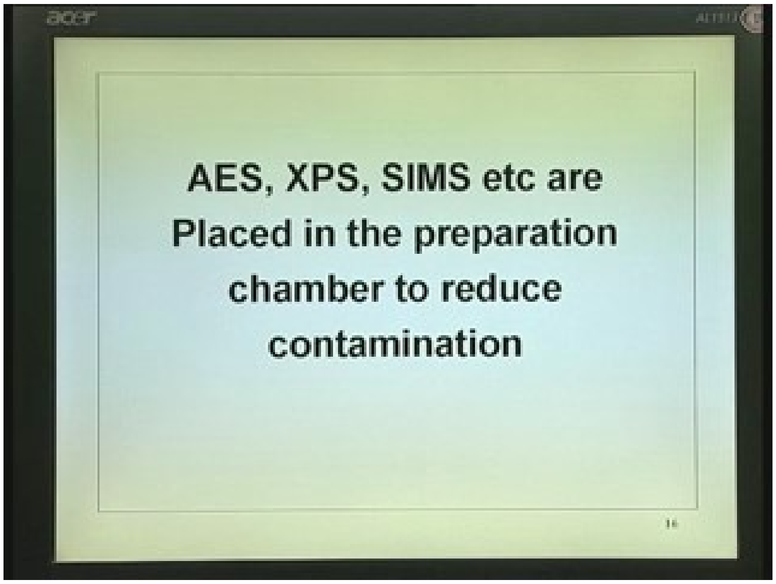

AES, XPS, SIMS etc are Placed in the preparation chamber to reduce contamination

These systems: AES, XPS, SIMS… etc are placed in the preparation chamber, so that contamination can be reduced. You can pull it out there and we can test there it after the growth is done. One thing is, during the growth using RHEED and other one is after the growth and before the growth in the preparation chamber.

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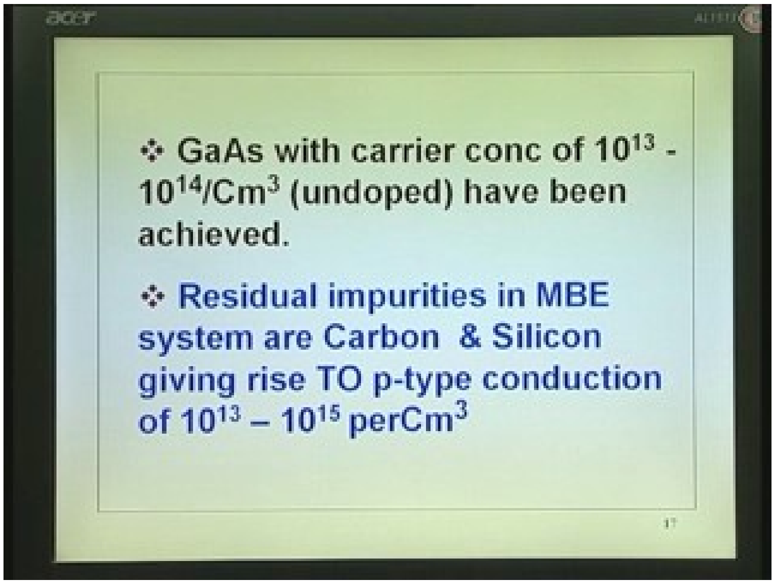

- GaAs with carrier conc of 10^{13} - 10^{14}/Cm^{3} (undoped) have been achieved.
- Residual impurities in MBE system are Carbon & Silicon giving rise TO p-type conduction of $10^{13} – 10^{15}$ perCm^{3}

Gallium arsenide with carrier concentration of 10 to the power of 13 to 10 to the power of 14 (undoped) has been achieved. With all this care, you do not get 10 to the power of 6. You have 10 to the power of 13. Now, you have to go below 10 to the power of 13 because you are able to have the sources which are purer. Gallium shows 79 purity (19:29). Along with that, the mobility of the carrier in those samples has improved and we will come to that when we discuss high electron mobility transistors. Residual impurity; what are these impurities? Which are present in this MBE system? One of them is of course silicon, omnipresent everywhere. Carbon – giving rise to p-type conduction of the dopant.

Carbon gives rise to p-type. Silicon also in cooperation depends upon the temperature; it can be p-type or n-type. Mostly you get p-type when you do MBE at 600 degrees centigrade. That is 10 to the power 13 doping. So, you will say it is undoped layer but at the order of 10 to the power of 13 carrier concentration undoped p-type.

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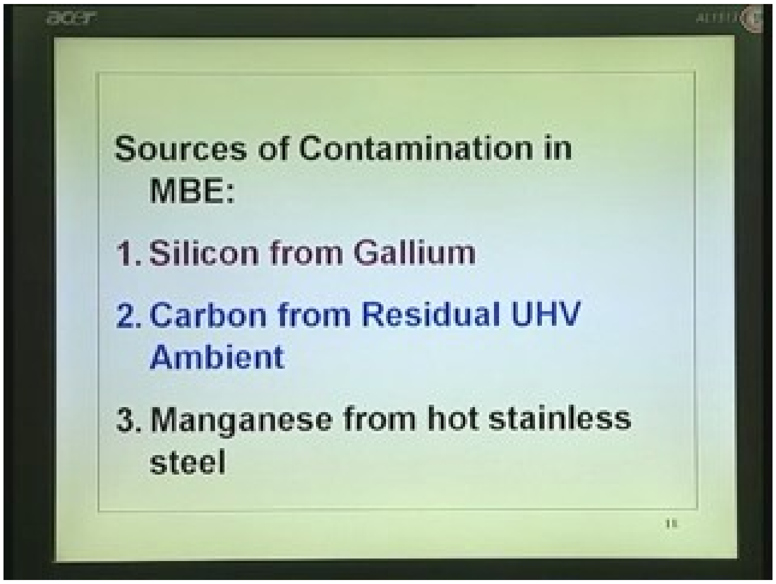

Sources of Contamination in MBE:

1. Silicon from Gallium
2. Carbon from Residual UHV Ambient
3. Manganese from hot stainless steel

Where do these impurities come from? Silicon comes from gallium. When you are using the gallium source, silicon impurities are present to some extent. Whatever residual ambient is present in the UHV (Ultra High Vacuum) contains carbon. Any atmosphere in which there will be little bit of carbon. We have manganese from the hot stainless steel chamber. These are the contaminants which come up. Next topic is disadvantages of MBE.

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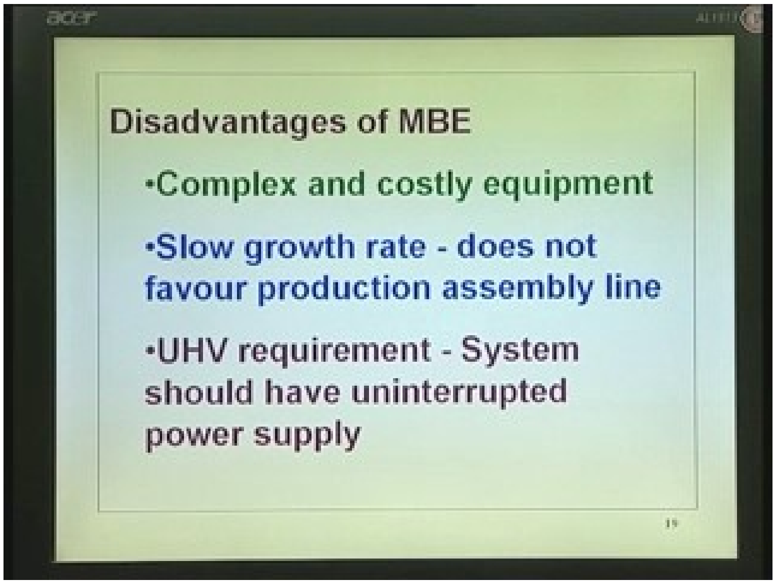

Disadvantages of MBE

- •Complex and costly equipment
- •Slow growth rate - does not favour production assembly line
- •UHV requirement - System should have uninterrupted power supply

Disadvantages, of course are very clear. It is complex and costly. How costly it is, depends upon how many gadgets you added on to that. If you have just a vacuum chamber which can go to 10 to the power of minus 11, that may not cost you much. You may end up spending something like 50000000 or may be 10000000 at the most. If you add all those gadgets, then it goes to 20000000 to 30000000.

Way back, when we bought MBE system in 1980 which is just a simple system, only the RHEED system was there without RHEED and there is no use. You do not know what is happening, whether you are getting good layer or not. At that time, it was about 2500000. The equivalent rupee of 2500000 rupees is now 20000000 because value has come down that much.

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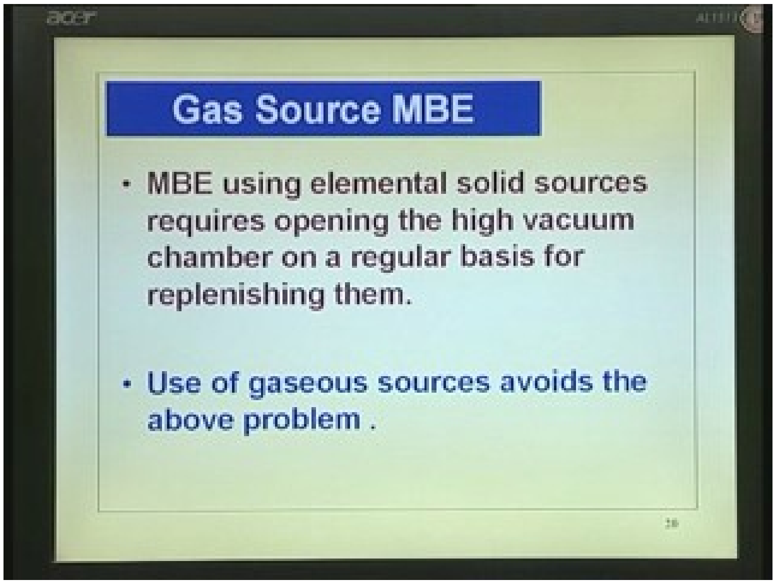

Gas Source MBE

- MBE using elemental solid sources requires opening the high vacuum chamber on a regular basis for replenishing them.
- Use of gaseous sources avoids the above problem .

Whatever we have been discussing is the MBE system with source from these K-cells. Now, there is a problem with the system. We avoid the problem of exposing it to the ambient during loading by having the rule out system. Those K-cells which are sources of gallium arsenic… etc somebody has to fill them up. You need to have say 10 grams, 20 grams, 50 grams and if it is a huge one then that amount of element you must put there. How do you put that? Open surgery, you have to open it totally and then put that. Once you do that, so many contaminants go into the chamber and you have to pump it down. It is a lot of work. That is one of the problems.

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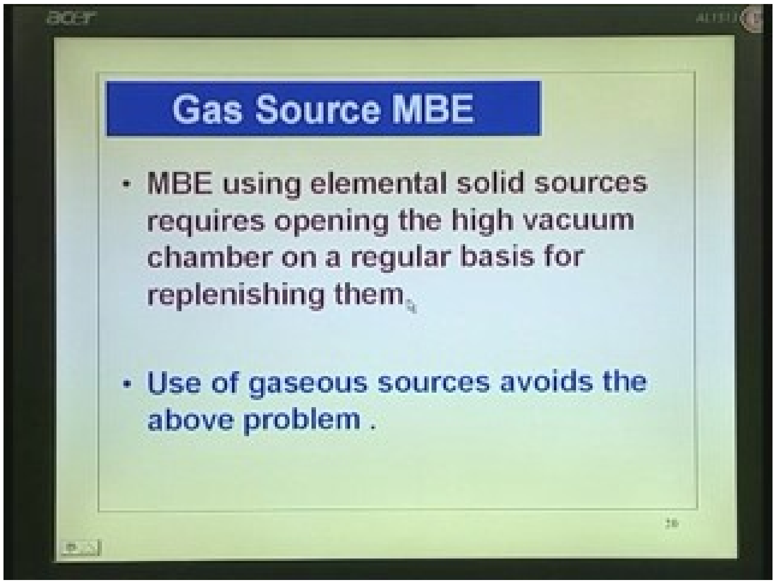

Gas Source MBE

- MBE using elemental solid sources requires opening the high vacuum chamber on a regular basis for replenishing them.
- Use of gaseous sources avoids the above problem .

MBE using elemental solid sources requires opening the high vacuum chamber on a regular basis for replenishing them. You have to fill them up. If you use gaseous sources, you overcome that problem.

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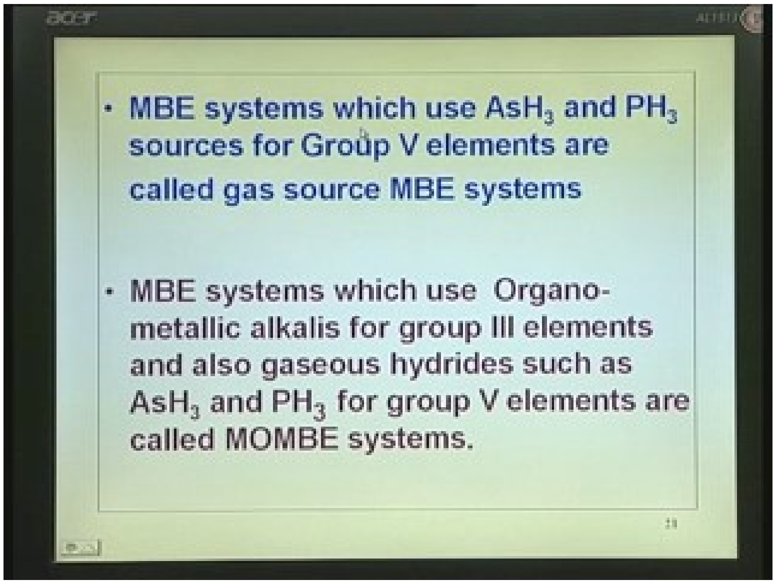

- MBE systems which use AsH_3 and PH_3 sources for Group V elements are called gas source MBE systems
- MBE systems which use Organo-metallic alkalis for group III elements and also gaseous hydrides such as AsH_3 and PH_3 for group V elements are called MOMBE systems.

There are two types of gaseous sources. When you say gas source, we can use only arsine and phosphine – arsenic and phosphorus. Do not use elemental phosphorus and arsenic;

use arsine and phosphine gas. The gas source is outside the chamber. You have a ______24:18 meter… etc mass flow controller. The gas will enter into the chamber instead of the K-cell and there you can crack it by heating it up. When you use for group V elements alone for arsine phosphine, they tried it first that they call it as gas source MBE – GSMBE, but later you have got MBE systems which are called as MOMBE Metal Organic MBE.

It is a MBE system, if the elements are obtained for group III and group V using gases or vapors. For example, organo-metallic alkalis for group III elements and also gaseous hydrides such as: Arsine, phosphine… etc. for group V elements. For example, when you use trimethyl gallium, bubble gas through that, let into the chamber for trimethyl indium, trimethyl aluminium. So, all sources are liquids. Bubble gas through that, let into the chamber for the group V arsine and phosphine. Such a system is called MOMBE. Some people think that you put the MOCVD inside the MBE system. We hear some people say that it is not like that; you use metallic sources outside.

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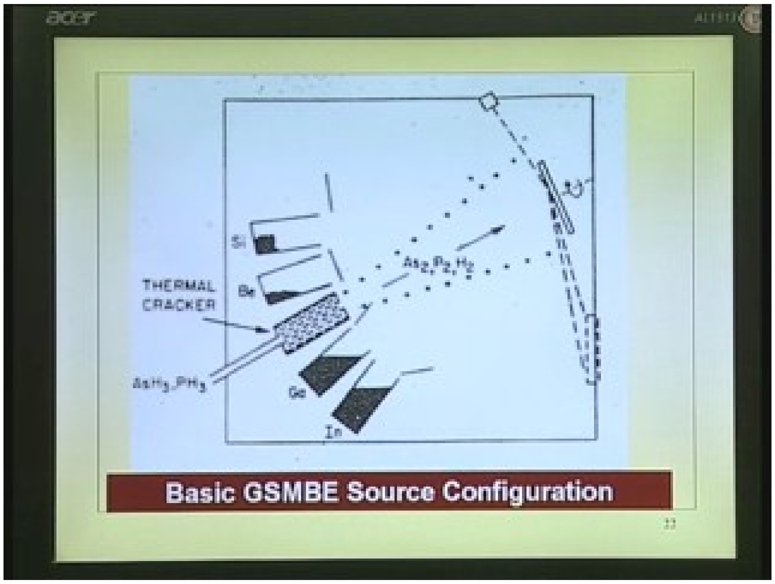

Basic GSMBE Source Configuration

You can see the 2 systems, whatever we have just said is seen here. This is the gas source MBE. Here, you can see this is gallium, this is indium, elemental group III and then the dopants like beryllium silicon…etc are also put here. They are within the chamber. This is the chamber and this will be given afterwards. You can see only for arsine and phosphine; we are using it from outside the chamber. Therefore, only for group V, you use the gas. That is called gas source. Term that is more general is MOMBE. This is closer to the system. You can see chamber in the image. You can let trimethyl aluminum, trimethyl gallium, and trimethyl indium through one port. These are the valves.

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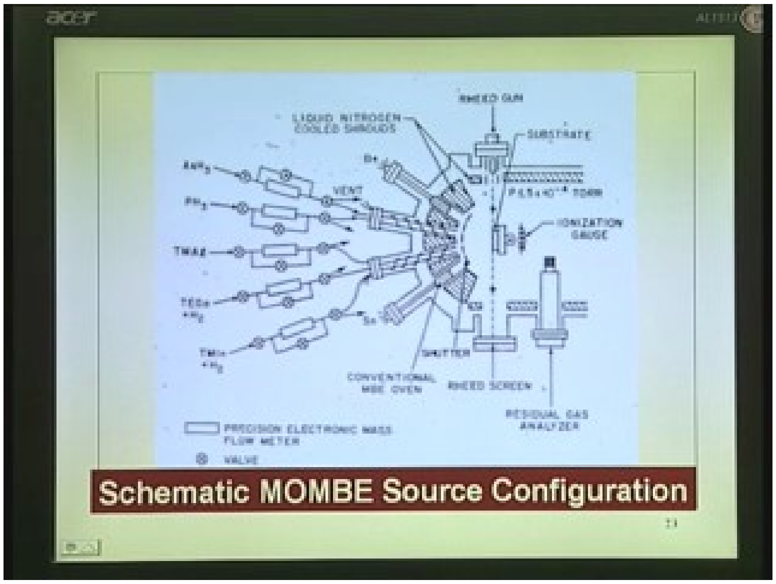

Schematic MOMBE Source Configuration

You can close the valves, if you do not want those vapors coming in that has to be cracked inside the chamber. All the shutters are there and this is the heating part of it. So, organo-metallic compounds of the group III are all mixed together through one port. Then phosphine arsine all mixed together for one port. If you do not want arsine, close this. If you do not want phosphine, close this here. Therefore, you have complete control from outside world. When this is empty, you will replace this bubbler here. You replace the gas cylinder and you do not have to open the chamber. Everything is coming from outside.

You pump down and start running it. These systems should be ON all the time. That is why we need uninterrupted power supply for these systems. When the power fails, the pressure comes back to the atmospheric pressure. So, this is the MOMBE source. Here also you can see that RHEED system is there. It is for monitoring the residual gas and that is mass spectrometer. The substrate is shown here and this is the most modern version of MBE system called MOMBE. We can imagine the cost really going up. It is much more complex and you have the complete benefit of MOCVD and MBE.

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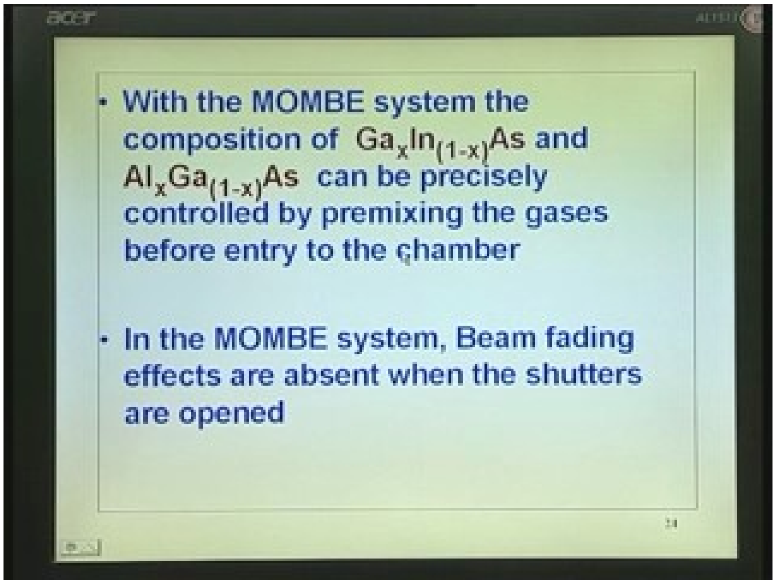

- With the MOMBE system the composition of $Ga_xIn_{(1-x)}As$ and $Al_xGa_{(1-x)}As$ can be precisely controlled by premixing the gases before entry to the chamber
- In the MOMBE system, Beam fading effects are absent when the shutters are opened

Merit of MOMBE is the composition of gallium indium arsenide. For example, you can control; you have to vary x composition of aluminum gallium arsenide. This can be precisely controlled by premixing the gases before entry into the chamber. You can precisely control the flow of aluminum, flow of gallium; gallium actually means the vapor – trimethyl gallium, CH3 thrice Ga. That is what we mean by that.

One more advantage of MOMBE system is as beam-fading effects are absent when the shutters are open. What is implied by this is in the conventional system? Let us just go back and we will come back to this afterwards. In the conventional system when you start, you normally have the shutter is closed and the temperature is set to 1000 degrees. In fact, the temperature here could be 1000 or even more than that within a K-cell. That is definitely hot.

The vapor pressure everything is decided by the temperature. The moment you open it there is a cooling effect. The chamber is not hot but there is a cooling effect. Because of the cooling effect the beam intensity goes down and enters into the K-cell. Therefore, beam intensity goes down. That is called the fading effect. In the gas source system, the source is outside; you have the control and no fading effect. Even if that cools down, the flow is there. That is what we were trying to say. In the MOMBE system, this is outside the thing. We can control the flow of these constituent elements externally and the fading effect of the beam is not present.

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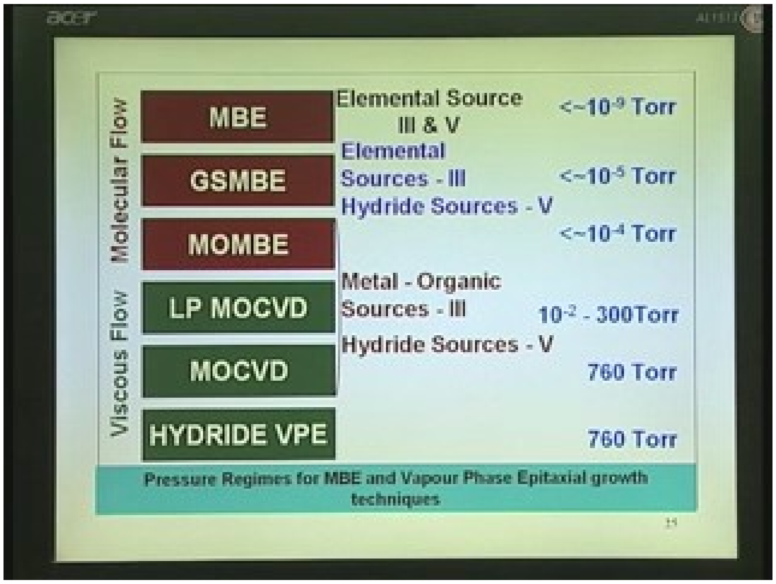

Molecular Flow

MBE — Elemental Source III & V — $<\sim10^{-9}$ Torr

GSMBE — Elemental Sources - III, Hydride Sources - V — $<\sim10^{-5}$ Torr

MOMBE — $<\sim10^{-4}$ Torr

Viscous Flow

LP MOCVD — Metal - Organic Sources - III, Hydride Sources - V — 10^{-2} - 300Torr

MOCVD — 760 Torr

HYDRIDE VPE — 760 Torr

Pressure Regimes for MBE and Vapour Phase Epitaxial growth techniques

This is a general guideline to show you what the vacuum levels which are used generally are. We can see the MOCVD, hydride vapor phase epitaxy… etc are done at atmospheric pressure 760 Torr. You can also have low pressure CVD where you get certain benefits. When you go to low pressures, you get the benefit of longer mean free path. When you put a wafer like this, you can put one wafer behind the other one. If the gas is flowing and if it is atmospheric pressure, you should put the wafer vertically in the furnace like that it will deposit on this it will block.

If you go to lower pressure, the mean free path is long so gas is flowing here. It can flow like that all through. Therefore, the hindrance effect is not there. When you mount a wafer vertically, you have the benefit of any particle that is present may not stay on the wafer; it will fall down. That is the benefit of that. That is why people advocate for low-pressure CVD system.

It is not very high; very low pressure minus 3, minus 2 Torr. Then you have MOMBE etc, where the gases are coming in. There the pressures are not low during the deposition. Please remember, these are the pressures during the deposition. Before you start, you have pump down to 10 to the power minus 5, minus 11 to avoid any contamination. In MBE of course, there are elements that are getting heated up in very small quantities that is 10 to the power of minus 4 Torr during deposition growth. Chamber pressure initially will be minus 10 to minus 11. When you let in the molecules, the pressure automatically will go up. The last one but not the least, in the epitaxy is the liquid phase epitaxy.

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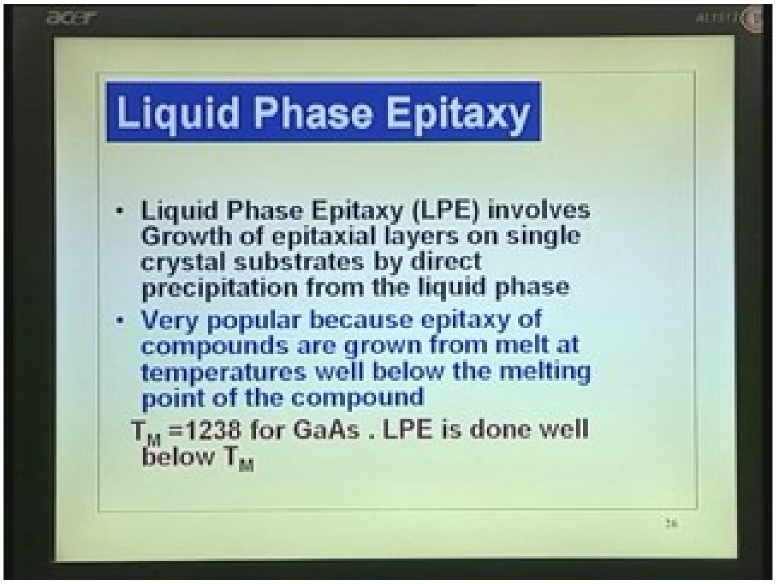

Liquid Phase Epitaxy

- Liquid Phase Epitaxy (LPE) involves Growth of epitaxial layers on single crystal substrates by direct precipitation from the liquid phase
- Very popular because epitaxy of compounds are grown from melt at temperatures well below the melting point of the compound

T_M =1238 for GaAs . LPE is done well below T_M

As we mentioned earlier, liquid phase epitaxy involves growth of epitaxial layers on a single crystal substrate and all the epitaxy involves in that. This is by direct precipitation from the liquid phase, it means, you keep the wafer or a substrate in contact with the liquid and from the liquid; you allow the freezing to take place. Very popular for gallium arsenide light emitting diodes etc., because epitaxy of compounds are grown from melt at temperatures well below the melting point of the compound. This statement will be clear from the diagram.

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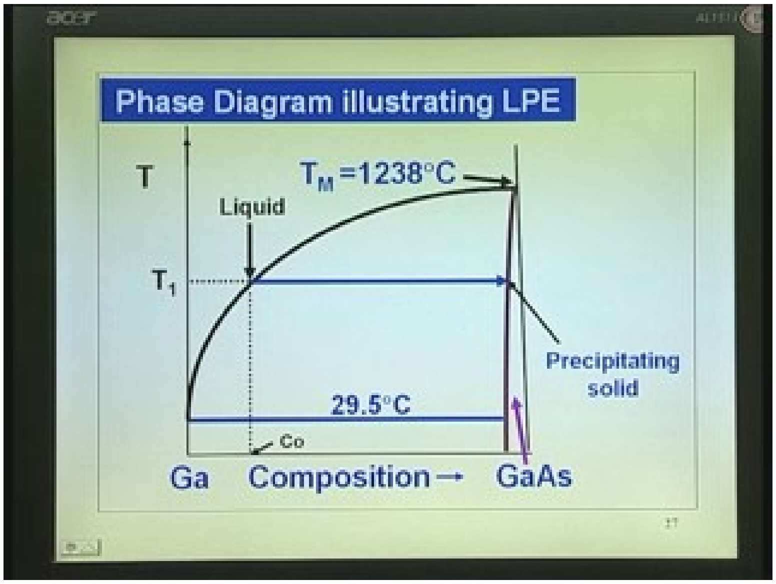

Phase Diagram illustrating LPE

Look at this diagram and try to recognize that we have put one-half of the phase diagrams. Here is gallium, the center 50% gallium and 50% arsenic, you get gallium arsenide. On the other side, it will go like this where arsenic is 100%. We have not shown because this is sufficient to illustrate the principle of liquid phase epitaxy. Usually in the Czochralski technique, you are going from the melt. It is a melt-grown system. You are going from there. That is the melting point of stoichiometric gallium arsenide – 1238 degree centigrade – T_M melting point.

From the melt when you pull the crystal, it is as good as you are coming down in temperature. As you pull it out, liquid solidifies and we get gallium arsenide. We have just expanded this curve. Actually, this whole red thing is one line. This is stoichiometric gallium arsenide or slightly off stoichiometric. This straight transformation to the solid without a liquid phase from liquid to solid state is called congruent transformation. You get directly gallium arsenide. In the Czochralski process, you use that from the melting point 1238 of the stoichiometric compound. This is necessary because that is quite fast. You can grow at least in a day reasonable length of crystal whereas in the liquid phase epitaxy they have mentioned it earlier; we can see this is gallium melting point 29.5 degrees – gallium arsenide melting point. You go down somewhere here. You have a liquid above this line it is liquid. If you move this side, it is gallium rich. If it is here it is totally gallium and melting point is 29.5 degrees. So, somewhere 600 or 700 degrees centigrade, if you grow, you have the liquid of this composition which is gallium saturated with arsenic. When you come down to this particular temperature, it will have that composition. Even if you have liquid lot of arsenic when you come down the temperature to this particular point, particular gallium that is the composition of C_0.

Let us say, you start with the substrate in contact with the liquid which has the composition C_0. C_0 amount of gallium or the ratio, gallium arsenide to gallium or arsenide to gallium, some composition is there; now you start freezing from that liquid. When you freeze here, this pours from here completely below this liquid line and up to this is the solid line. This portion has liquid and solid both. Here the difference is you get straight away solid and that is the congruent transformation property of this phase diagram. Whereas here, when you start freezing you get precipitation of solid and at precipitating solid has a composition given by that.

That is the property of the phase diagram and you must understand from here you freeze. You see where the solid is the composition, that means, when you freeze from a temperature like 600 or 700 degrees centigrade the freezing compound or freezing solid is nothing but gallium arsenide with composition that one that is close to stoichiometry. Whether it is gallium rich or arsenic rich depends upon actually from which point you are freezing but what we get is gallium arsenide is close to stoichiometric composition; growing from a very low temperature.

Of course, we should caution those in the physics for low temperature. It is not lower temperature compared to melting point, you get gallium arsenide. This is the major benefit of growing gallium arsenide from a melt; this is called a solution growth. From a solution, you get gallium arsenide much lower temperature than the melting point. When you slightly come down, you get that composition. It loses the gallium so the gallium concentration comes down. When you slightly come down along this curve, what happens is when you freeze, we are showing this slightly below but for clarity. We will show it bit below. Freezing compound will have that composition and the liquid's composition will be on this side. So you see where is the solid? Where is the liquid? You project on to the liquid's curve which will give liquid composition. Naturally, when you freeze, you lose gallium. Therefore, the gallium richness comes down. If you lose the composition changes what we are worried is not what happens to that, what happens here – that is the freezing solid.

Now, let us see what is the merit of freezing and getting gallium arsenide at lower temperature? Contaminants are less. Why do you say contaminants are less? What contaminants do you worry? You worry more and more about the deep levels. You do not want in the system. If you are going n-type gallium arsenide, you want to make a p-n junction for light emitting diode. When you want to make a p-n junction for a light emitting diode, what do you want? Let us see, if you take E_C and E_V, you want light emitting diode for the particular material and the electron from here make a transition down here. During that time, it will give you the light corresponding to that band gap 1.24 divided by the band gap, so many microns that are what you get.

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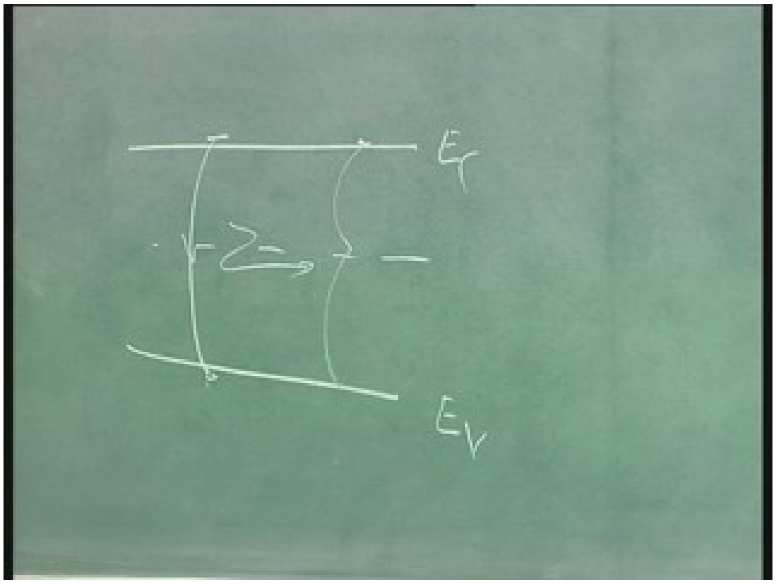

Now, if there are deep levels, deep impurities like heavy metals; copper and things like that can be present in the liquid. If they are present, the transition is from here to here and here. Many other electrons may go through the transition. What is the light emitted by this corresponding to that wavelength so it is entirely different wavelength. If you are looking for red light, you will not get red. You will not get anything because the energy is very small. So energy is very small which will be a very long wavelength you will not even see. If you have light emitting diode, it will be dark.

You will not have any light but there will be some electrons which will be making transition like this. So some of them will make transition like this and many of them will make transition like this. What is the impact of that? The impact is the quantum efficiency. The efficiency in which light is emitted goes down. So, you want very pure material. Now, with the liquid phase epitaxy what happens is, this is a very important thing. Just note down these levels are (42:32). Not all those deep impurities go into the solid when the temperature is low. Here, a metallurgical term is used segregation coefficient. It is you add into a melt some of the deep impurities like chrome, gold, copper… etc, if they are present and if you solidify that the segregation coefficient means. If there are 100 copper atoms, how many go into solid? It may be 0.1, 0.01. How many go into the solid depend upon the temperature.

If you are able to freeze at lower temperature like this here, the number of those impurities getting into solid is less. Segregation coefficient is low at lower temperatures. Therefore, when you solidify at a lower temperature, you get this gallium arsenide. That gallium arsenide has very few impurities. If that is not present, you get excellent light emitting diodes. This is the key for the success of light emitting diodes. This is the one that is used. In fact, a very simple system you do not have to spend crores for this. We shown this diagram for principle where you freeze it and actual system is like this.

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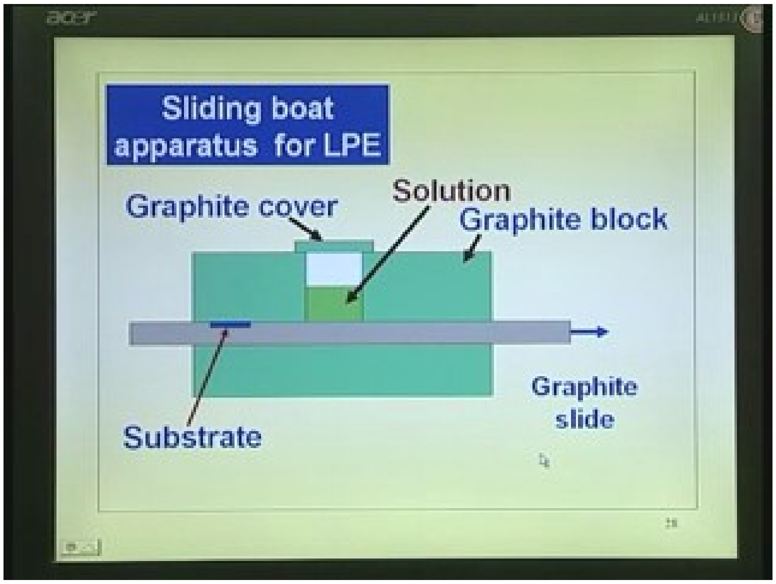

Sliding boat apparatus for LPE

Very simple, all that you need is get in touch with a company which makes some graphite blocks. We are not getting money for advertising the Poco Graphite that is a very famous graphite making company. They make very high purity graphite. So, the whole thing is graphite block. You have a big graphite block in which another graphite can slide. This is the sliding graphite, the middle one. This entire block has hole which can slide. There is a bin, a hole from the top and this is the cross section. In the top, you have a hole and here up to certain depth that hole is there.

So, when this slide goes inside there, that hole is covered. What you do is, you fill in the solution, in fact, gallium with very arsenic rich, gallium arsenide. If you want to go gallium arsenide, you put the solution there in this. This is a graphite cover. The whole thing is graphite because it does not affect the gallium arsenide solution. This is actually a substrate that could be the semi insulating substrate that we have put. So on that slider, we have a depression where you can put the wafer. So, you get the idea, this is the depression in which you put the wafer. We are showing small one which may be 1 inch, 2 inch or 3 inch. Put it there, heat this up to the required temperature and just let us see whether we have that there. The entire system is in hydrogen gas ambient and the temperature is raised to T_1.

How to do that? This is the graphite block with the facility to push and pull the slide, a facility to keep the wafer and a facility to fill this bin with the liquid. Now, you keep this whole thing ready and put it in a furnace. Furnace does not cost much, may be 5 to 10 lakhs. The cost is 0.1 crore, 10 lakhs of rupees. So, you have got the epitaxial systems at your disposal. So, that system is kept in a furnace and raising the temperature to the point where you want says 700 degrees centigrade.

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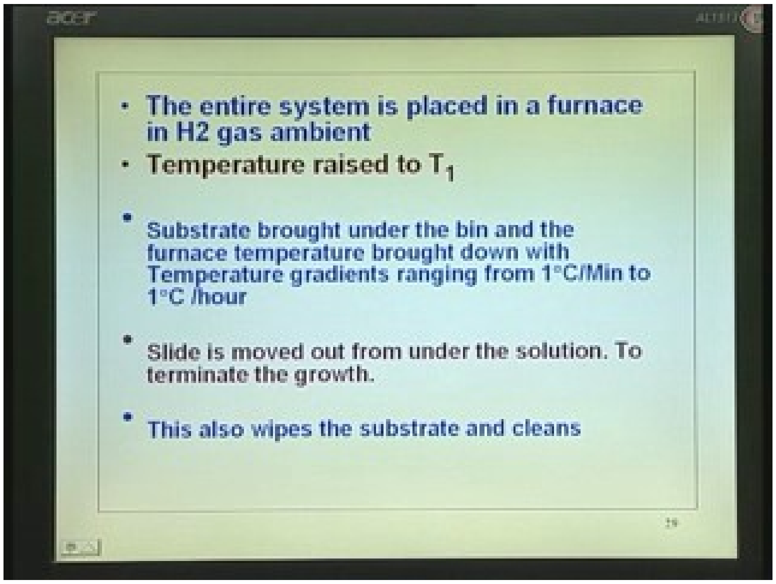

- The entire system is placed in a furnace in H2 gas ambient
- Temperature raised to T_1
- Substrate brought under the bin and the furnace temperature brought down with Temperature gradients ranging from 1°C/Min to 1°C /hour
- Slide is moved out from under the solution. To terminate the growth.
- This also wipes the substrate and cleans

Temperature raised to T_1. T_1 is that temperature where you want to grow. Now, substrate is brought under the bin and the furnace temperature brought down with temperature gradients ranging from 1 degree centigrade per minute to 1 degree centigrade per 1 hour. Can you imagine that? We want to stop the temperature to gram (47:28) such that the temperature falls from 700 degrees centigrade to 699 degrees centigrade in 1 hour. So, it is very small change. Why? That is why because you want to remain at that level and at the same time you want the gallium arsenide to freeze on to the surface.

What you do is a statement that we have made here, substrate is brought under the bin means this substrate is that is this graphite slide is pulled, so that this is coming in contact with the liquid. Now, all that you are doing is ultimately what you achieve is you have where that liquid solution gallium arsenide is there and it is as good as placing this substrate below that. So, slightly reduce the temperature then you have the solid particles which actually ultimately come and you get the epitaxy.

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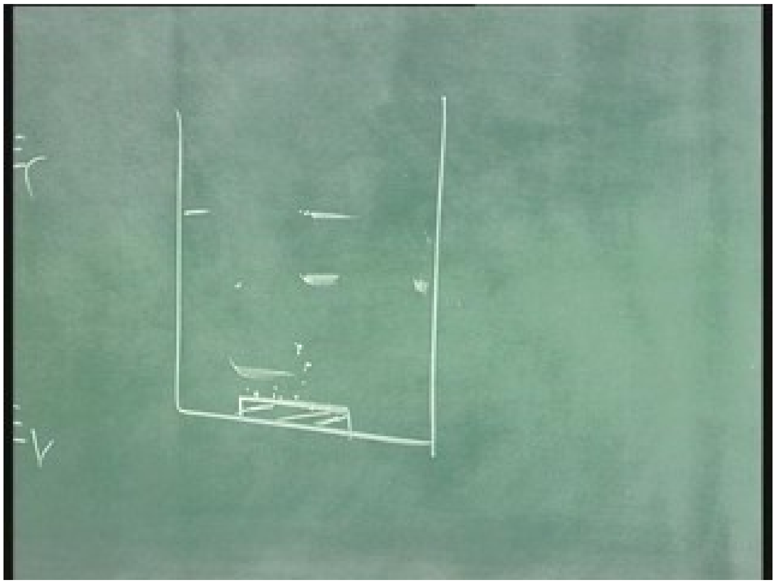

So, it is a very slow process. That is why; you cannot use it for making the gallium arsenide wafers. You can use it for making very thin layer of n-type or p-type because we can add impurities into this if you like or you can change the temperature and into p-type or n-type that we have mentioned earlier. So, that is why the entire control here is ability to grow liquid phase epitaxy is controlled on the programming of the temperature. Then after 49:00, you have grown, let us say half a micron or 1 micron after an hour or two what you do is you pull that slide out. It was sitting here; you pull that out.

Now, this terminates the entire growth process, one. Number two: when this was in this position here the liquid is on top when you are pulling it out like this. You are wiping out whatever fluid is left out double purpose. Terminate the reaction and wipe out the surface so that whatever liquid is there is gone. So, you do not need further cleaning on that. You get the epitaxial layer on whatever substrate you have and you can have compositions varied by varying the composition of this fluid. That is what is done in liquid phase epitaxy.

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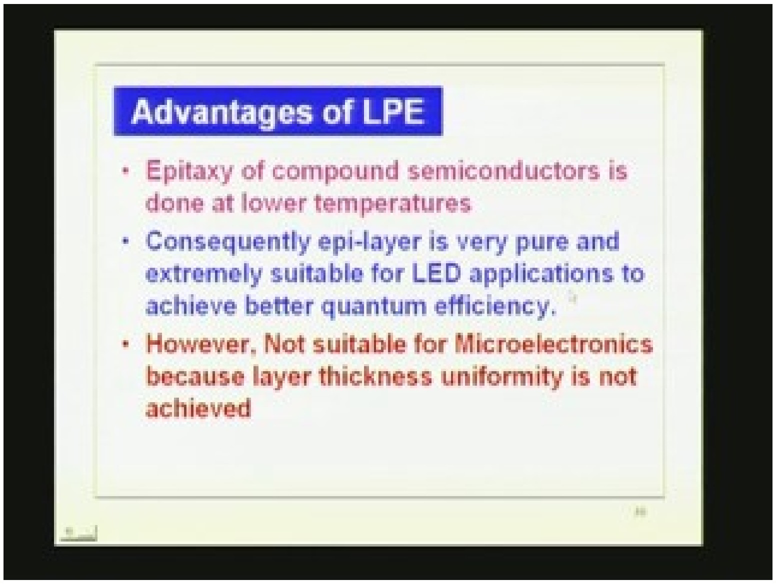

Advantages of LPE

- Epitaxy of compound semiconductors is done at lower temperatures
- Consequently epi-layer is very pure and extremely suitable for LED applications to achieve better quantum efficiency.
- However, Not suitable for Microelectronics because layer thickness uniformity is not achieved

The advantages of the LPE are epitaxy of compound semiconductor is done at lower temperatures as we mentioned. Segregation coefficient is low, so deep level contamination is low. Excellent for LED (Light Emitting Diode) applications is to achieve better quantum efficiency.

Now, if you fancy, you can make layers. Gallium arsenide layers are suitable for microelectronic applications with 1000000 of money. There is one problem; the layer that you grow uniformity is not very good. The thickness uniformity is not very good. Therefore, after all, you know it is just freezing from the liquid. So you do not get control or thickness uniformity of this wafer.

So, if we have a big wafer of 4 inch diameter. We are still talking of inch because people are used to that. If we are growing, it will be varying all over the place. It is all right for making your LED – Light Emitting Diode. Slight variation does not matter because after all what you need is a junction. Whatever happens is happening at the p-n junction. If you have a layer like this, if you have a semi insulating substrate – gallium arsenide on the top of that you want to grow the layer and this is the epitaxial layer or epi layer.

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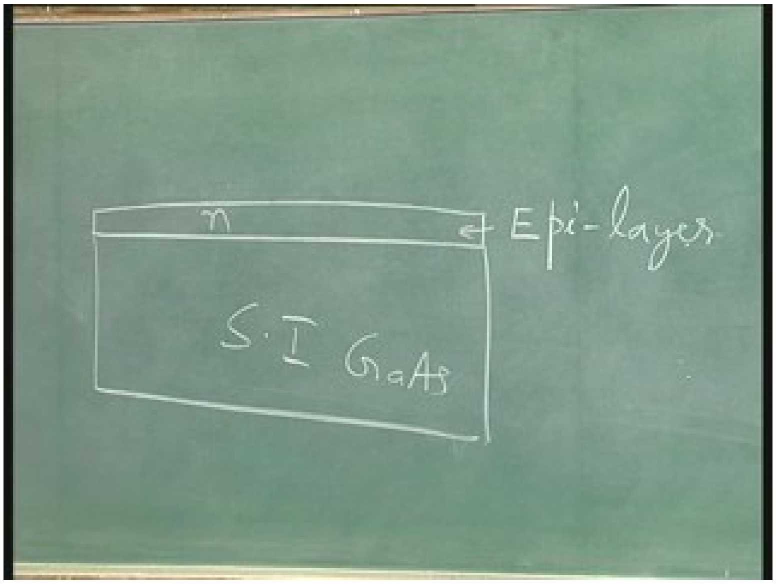

The epi layer must be uniform for microelectronic applications. In fact, you will see if you want to make Field Effect Transistor in this layer. If it is n-type and is not uniform thickness, your entire logic circuit functioning will not be good. If you want to make digital or analog circuits, threshold voltage of those FETs would depend upon the thickness.

You may not agree with us right now because if you look at the MOSFET, the MOSFET threshold voltage would depend upon doping. If you have a JFET or MESFET**,** the threshold voltage would depend upon enhancement mode particular type and on the thickness. If the thickness is varying over the entire surface, what will happen? Threshold voltage will vary. You do not know what is happening in the malfunctioning of circuit.

So, that is why they are not suitable for that. Few things we want to mention before we wind up this particular discussion. What we have said so far for gallium arsenide microelectronics or even for Light Emitting Diodes? You would need epitaxial layers or you need an active layer. An epitaxy can be done to get the active layer either by MOCVD or by MBE or MOMBE. Choice is yours depending upon how good quality you want and how much money you have; both are taken care of.

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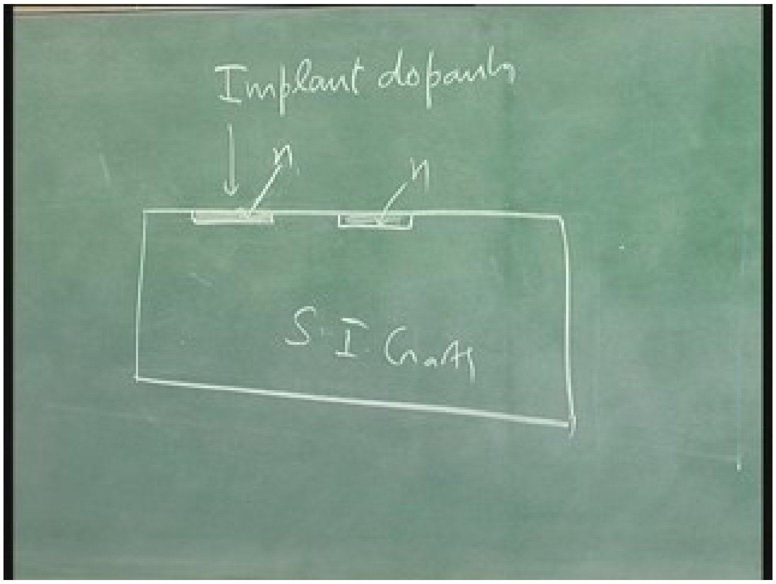

There is another approach which is followed very popularly. All that you need is an n-type layer. In fact, an excellent approach is, do not go to that epitaxy layer use one equipment. The one equipment that you can use for realizing n-type, p-type all sorts of things is ion implantation. We have no intention of going into details of ion implantation but just to show that you can actually take a semi insulating substrate. This is a cross section of semi insulating gallium arsenide. We do not need to put the implantation everywhere – the dopants. We put somewhere here. We can implant dopants so that we can make the layer n-type. Once it is n-type, we can use that for realizing FETs and this is a semi insulating. Here also, we can put n-type.

You can see the interesting part of this is we have got n-type here and n-type there isolated from each other. We cannot ask for more than that because when you want to make devices, you want them isolated. You want them to be connected when you say it must be connected, otherwise they must be isolated. The isolation is provided by means of this particular layer, semi-insulating material. So ion implantation, if you have equipment, you can use that totally for realizing these structures. All that you would need be able to implant and realize this and then make devices on this. What device would you make?

Either you use this device, this implanted portion for making devices or you can use the epitaxial layers for making devices. So, next question is devices using epi layer or implanted layer. This topic, we will discuss next time because that is where we begin our discussion on devices.

You are now ready with the material. When semi insulating substrate epitaxy is implanted, then make devices. What sort of devices you make? Whether it is MOSFET? Is it feasible to make MOSFET? That aspect we will discuss first. If it is possible, you do that. Otherwise, go to MESFET instead of using the native oxide, some other insulator that sort of thing we will discuss in our next lecture.