High Speed Devices and Circuits

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Lecture – 9

Epitaxial Techniques for GaAs High Speed Devices

We begin our discussion on epitaxial techniques for gallium arsenide which will be used for high speed devices. Yesterday, we discussed in detail, how to realize semi-insulating gallium arsenide material because when you want to make a device or integrated circuit what we have discussed yesterday was you need an insulating substrate if not insulating at least semi-insulating. For example, if you take SiO_2 the resistivity is something like 10 to the power of 14 ohm centimeters. Whereas, what you have particularly achieved with gallium arsenide as a semi-insulating substrate is something like 10 to the power of 9 to 10 to the power of 10. 10 to the power 9 is quite good, resistivity that you can get. It is not a perfect insulator that is why it is called as semi-insulating material. We have also seen that you can do it in two ways: one, take poly crystalline gallium arsenide melt it and grow by sucrose technique, at that point of time when you do that what you will get will be an unintentional doped gallium arsenide doped with silicon. Now, then you compensate it by adding chromium which introduces a deep level at the mid gap. Another approach which is now popular with availability of high pressure crystal growth system is, you make the compound in c2 by taking gallium and arsenic. In fact, you can get 7 9's not 6 9's, 7 9 impurity 99. 99999.

So, 7 9 purity gallium arsenide, gallium 7 9 purity arsenic, all those you can get. You can get better purity gallium arsenide substrate. You grow that but when you grow you end up with p type material, if nothing else happens due to the contamination from carbon due to contamination from that liquid encapsulates, which you are using. These are things we saw earlier. But the compensation for that acceptor level, shallow acceptor is done automatically by excess arsenic that is present or the arsenic which is sitting on the gallium sites. In fact, if you have some vacancies present when you grow the crystal, you adjust the composition such that you have deliberately gallium vacancy then some of these excess arsenic atoms will go and occupy the gallium site, that is called anti site defect. Whenever you have got an additional level, this anti site defect is called e l 2 levels. I really do not have information why it is called e l 2. It so happens, that it is called e l 2 level, instead of saying chromium level you say e l 2 level. It is actually due to the anti site defect, instead of adding impurity you have the arsenic sitting there. There is no extra impurity that is added, this itself is acting as an impurity. Whenever you have loss of periodicity or loss of structure, you get additional levels and this gives donor levels at the mid gap and we have gone in detail; if you have acceptor level shallow, you can compensate very easily without worrying too much whether I am having too much of donor level, put the donor level at the mid gap, these are some of things that we discussed. You do not have to worry about that e l 2 name, it is the name given to the defect which is arising out of arsenic sitting on the gallium site that is all. Now having done that, now you see the growth that is the substrate.

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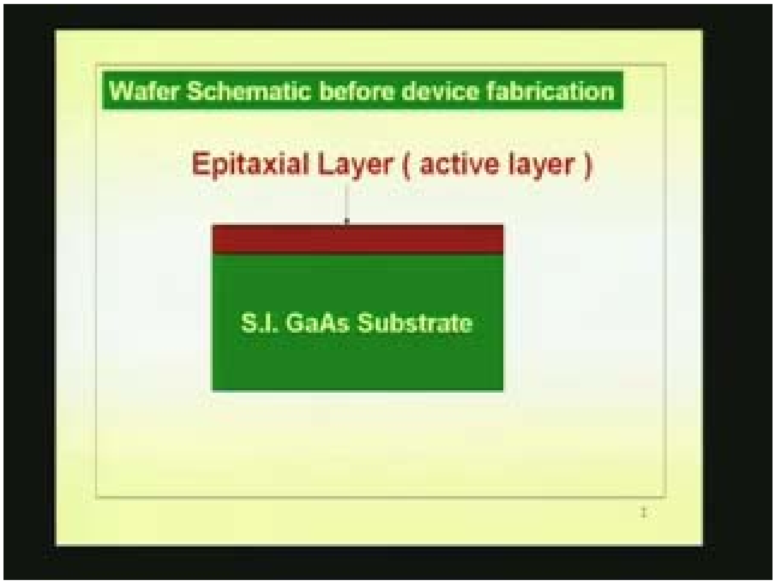

Wafer Schematic before device fabrication

Epitaxial Layer (active layer)

S.I. GaAs Substrate

Having done that red color or brown color is slowly growing here. That is I put it back once again. You can see gallium arsenide substrate then, on the top of that you have that layer slowly growing that is the layer which is the active layer. In fact, I mentioned yesterday, if this is semi-insulating gallium arsenide is chromium doped, before you put this active layer, you introduce a buffer layer. The abuse is taken by the buffer layer. In the sense, when you do high temperature processing all the chromium that is present may go into the buffer layer and actual layer on the top does not get affected.

But today, with the ability to grow high purity gallium arsenide with compensation of e l 2, you do not have to worry. You can straight away grow the epitaxial layer on that active layer on that. Now what we want to discuss today is, about this particular layer. What is that? In fact, you will call this by different names in the sense, if you have leisure gives an epitaxial layer if you are in a hurry it is epitaxy. When you say epitaxy, it is actually growth of epitaxial layer. What is done here is, let us talk of various things. Supposing you are growing silicon on silicon then that is silicon epitaxial layer. Supposing you are growing gallium arsenide on gallium arsenide substrate can have any doping. It can be semi-insulating p type, n type. But here, what we are talking of is semi-insulating gallium arsenide structure. You can grow epitaxial layer of gallium arsenide on the top of that. The layer that you are growing, if you are going by this, whatever technique you are talking of you can adjust the thickness. We can say I want 0.1 micron or 0.2 micron. We can adjust the doping of that level when you grow the crystal when you grow this layer that is the epitaxial layer. When you say grow the epitaxial layer, the meaning is you are arranging the atoms from the gallium arsenide on the semi-insulating gallium arsenide substrate. Arrangement, if you give proper opportunity to these atoms, which are being laid out on the surface, it will take the same crystal structure at the substrate. That is why that is called; in fact, you can call it as auto epitaxy or homo epitaxy.

If the substrate is doped differently but still it is called homo epitaxy n type, p type does not matter but if the substrate is totally different, for example when you grow silicon epitaxial layer on sapphire that is hetero epitaxy. They are totally different substrate. But still you can grow a 1 0 0 oriented silicon on sapphire because there is a good lattice match between silicon with 1 0 0 orientation to that particular layer, one particular orientation of sapphire. So that is hetero epitaxy. Now the process involved in the growth of this epitaxy. What is that? Process is two things should happen. One you must be able to transport these constituents, which form this layer, onto the surface. If it is silicon the constituent is silicon alone. You must transport silicon onto the surface of this silicon substrate. If it is gallium arsenide, you must be able to transport gallium and arsenic, both should be transported onto substrate. How to transport it depends upon the particular process that you are using and you call the particular process by a name depending upon how you transport this impurity, this constituent elements atom.

We will see what the different processes which are involved. Now you transport these constituent elements it is not enough if you transport them. You must give opportunity for these constituent elements. Let us talk of silicon because only one you have to talk of only one element. Silicon atom you have transported onto surface what does it do? If you transport and just do not, if you have just kept this and transport the silicon atom, it will go and rest there. That is not epitaxy; it is just dumping silicon there. You do not want to dump silicon. You want to have silicon arranged with the arrangement same as that of the subject. How can you do that? You must give opportunity for those atoms to move around. It should be able to move around and attach onto some of the sites, which you call it as nucleation sites. Nucleation site is actually a favored site, which will go and sit.

For example if I have a surface a slight kink in some portion. There may be a number of kinks due to the atom itself substrate atom itself, on the atomic scale. There will be small kink, it need not be a kink like that and small kink there this atom that you have put will go and just move around. When it sees the kink it will just stop there, that is stops there that is we can call it as nucleation site. It also involves proper wetting. Simple minded thinking will tell you that, wherever kink sites are there, the atom which is moving around because of the energy given to that. What is the source of energy? Thermal, that is why in epitaxy you must heat the substrate sufficiently, so that the atoms have enough energy to move around. It will go and attach it the kink sites and from that kink site it will move laterally because if I have one atom sitting there, here next atom will come near that, side by side. One layer atom should be arranged once that one layer is complete. Next layer grows; it keeps on growing till you stop the reaction. That is the epitaxy that is the arrangement of atom that is being done.

That is why this diagram, what we saw in this diagram, we can see, we can watch this. You see that is the way it grows unfortunately no color there. It is actually from there onwards, you can see at least the size coming up. You have put like that, you can see that growth so that additional layer that is growing there is gradually growing like this. That is layer by layer. Now if you do not provide additional temperature, additional energy for the atoms to move around, what will happen? Room temperature we cannot have the growth taking place. We will have lumps of silicon or lumps of gallium arsenide coming up. It is no use for making devices. But if the temperature is slightly lower than what is required, the atoms will not have enough energy to arrange themselves. You will end up with not single crystal, poly crystalline material even if the substrate is single crystal. Suppose the substrate is not single crystal, if you have amorphous material like oxide. On the top of it if you grow a layer that will turn out to be poly crystalline. It can be amorphous or poly crystalline depending again upon the temperature. Amorphous is random. Poly crystalline is number of single crystal layer regions, which are joined together.

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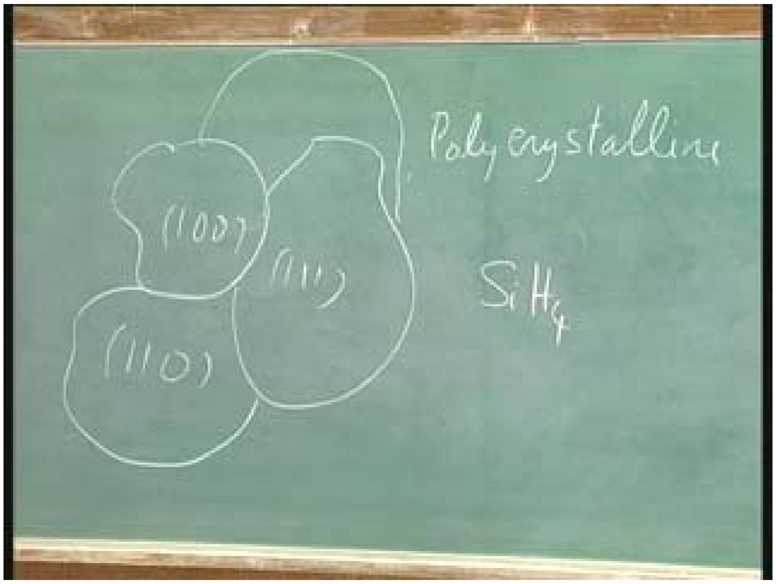

Each region has got you want to see that, at one region it may be 1 0 0 orientation, you will have another region here which is 1 1 1 orientation. You will have another region here 1 1 0 orientation. I am just arbitrarily putting it can be 2 1 1, 2 2 0 whatever. We will have all these things coming up. That is poly crystalline; we are not looking for poly crystalline material here. But in silicon technology you could hear about poly crystalline material very often. Where do you hear that? It is part and parcel of the present day integrated circuit technology because it forms the gate region of the MOS device. That gate region is done not by epitaxy; the temperatures are low for silicon epitaxy. You need about 1000 degree centigrade at least. If you take single crystal silicon and raise the temperature to about 1000 degree centigrade and pass silian gas through that. Silian is nothing but Si H_4. That is silian gas.

If you pass that, at that temperature pyre opens, it will crack into silicon and hydrogen and that silicon atom will be sitting on the surface. If it is single crystal at 1000 centigrade substrate is single crystal 1000 degree centigrade, you will get single crystal silicon.

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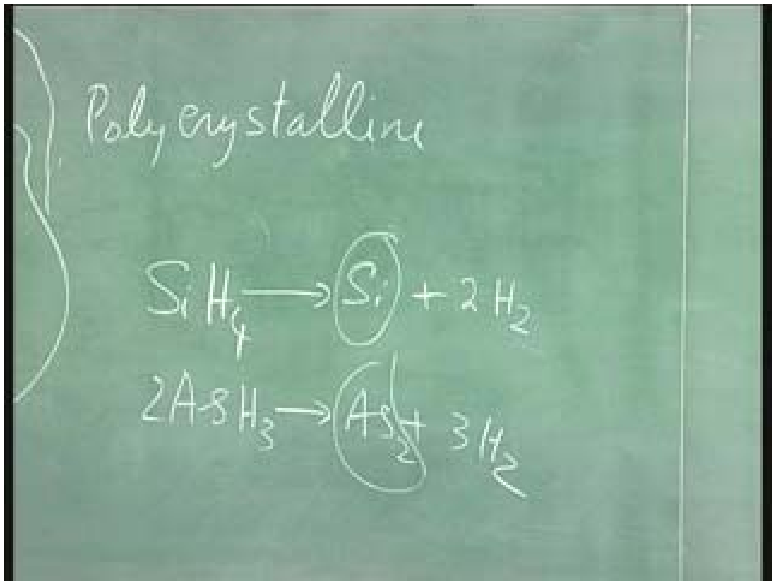

Onto that you add arsine silian is there, this will give you silicon plus 2 H_2. So that is the one which is being deposited. You want to dope to the gas face, you should add arsenic you will get arsenic plus, you will get As 2 plus 3 H_2 or 2 As. That is chemistry. You have arsenic doped silicon, you can add phosphine. You get fifth group phosphorus. You can have silicon doped with arsenic or phosphorus depending upon the dopants added. What I am trying to bring out is I took the example of silicon because it is simple to understand. You can grow an epitaxial layer undoped the epitaxial layer. Undoped means not intentionally dope, you may have contaminants coming in. You can intentionally make it n type, or p type, by adding the suitable constituents to the way you bring in the atoms. Now here this in silicon that poly you obtain there is due to two factors. One is temperature is about 625 degree centigrade in the M O H technology. Two, you grow it on oxide, you deposit on oxide both put together you get poly crystalline 625. You lower the temperature down to 55 centigrade you will get amorphous. You will get amorphous silicon there. It all depends how much energy it has got to move around. At least to some degree of orientation you get the temperature is 625. Now let us not spend our time too much on the silicon epitaxy. This is relevant silicon epitaxy, if you are thinking of silicon on sapphire. That is the same process silian broken into silicon and hydrogen. They get sapphire sufficient that is the temperature 1000 to the deposition. In fact, that is one of the materials which are used for high speed MOS devices. That is why it is relevant to this particular presentation discussion. But if you are talking of compound semi conductor only then, let us see what the things are, that is the basic process that is involved in the epitaxy.

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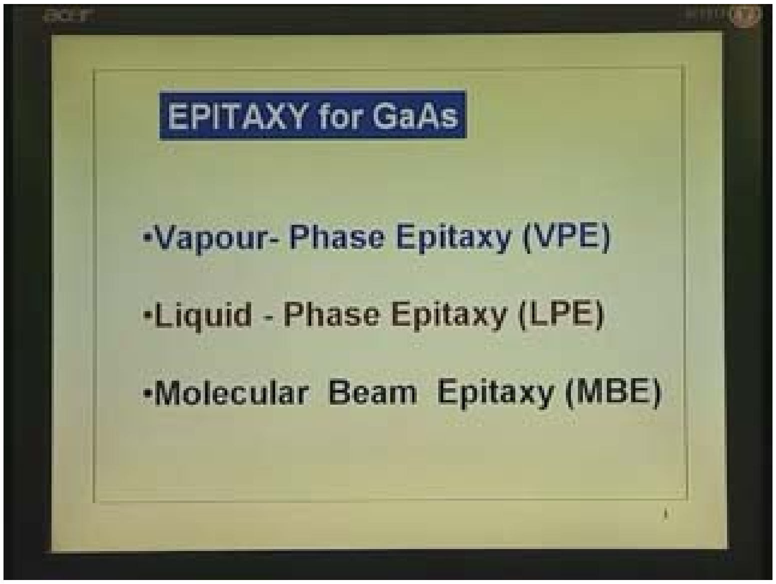

EPITAXY for GaAs

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

Now let us talk of epitaxy of gallium arsenide. As I mentioned one of the requirements is to keep the substrate hot. Other requirement is transport these consequent elements to the vicinity of the substrate. Depending upon the way you transport those consequent elements, you call it vapor phase epitaxy. What it is we will see one by one liquid phase epitaxy I will give a glimpse of liquid phase epitaxy when I discussed about p type, n type dopant by adjusting temperature in the previous lecture, molecular beam epitaxy. That if you talk to the people depending upon what they have at their disposal they will highlight on that. If you talk to MBE person they will say that is the best. Objectively, each has its own merits; each has its own drawbacks also. You have to compromise depending upon what you want.

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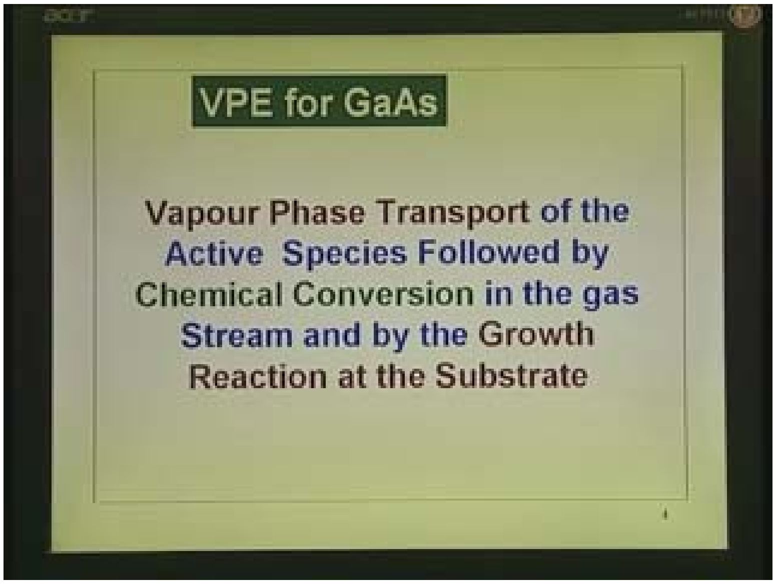

VPE for GaAs

Vapour Phase Transport of the Active Species Followed by Chemical Conversion in the gas Stream and by the Growth Reaction at the Substrate

Let us see vapor phase epitaxy VPE of gallium arsenide. Here this involves the transport of species by some of the volatile compounds of the material. For example, if you talk of silicon, you talk of vapor phase epitaxy. That is vapor phase epitaxy. You talk of the volatile compounds like arsine As H_3 or you talk of arsenic tetra chloride, not arsine it is saline or silicon or silicon tetra chloride. Then release silicon from that, the reaction will be taking from the surface of the substrate, that is the thing. In the case of gallium arsenide, you have to transport a compound containing gallium you have to transport a compound containing arsenic. Then forced reaction in that reaction locker you provide the actual temperature etc, for the reaction to take place forced reaction of the substrate. You do not want; you do not prefer the reaction to take place in the gas space.

Supposing I am having a substrate here like this, if the gas is moving through that you do not prefer the reaction to take place there. You prefer the reaction to take place on substrate because in a gas space it is the reaction which is taking place, you have these gallium arsenide formed there it may be droplets of gallium arsenide coming out there that is not what is required you must have the reaction taking place just near the surface on the surface. So that atoms once they are released they move about and arrange themselves that is called heterogeneous reaction. The reaction will be homogeneous if the reaction is taking place in the gas phase, the reaction will be heterogeneous. If it is taking place on the surface itself, you are the favored or the one that you like is heterogeneous reaction. To put it in simple terms, you want the reaction to take place in some surface that is what happens in a heated substrate right there.

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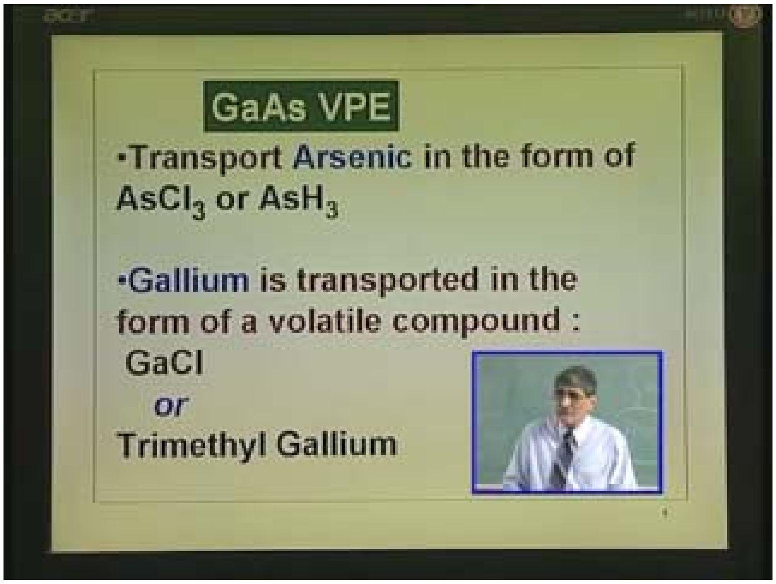

GaAs VPE

- Transport **Arsenic** in the form of $AsCl_3$ or AsH_3
- **Gallium** is transported in the form of a volatile compound :
  GaCl
  or
  Trimethyl Gallium

Now let us see you can transport, see after all you have to transport arsenic and gallium. Today I am giving you the whole gist of epitaxy. If you start talking of this, you can talk for ten hours on this. Just the idea what is involved, what are the compounds involved so that you get a flavor of what is going on around. The transport of arsenic is done in the form of the vapor phase epitaxy is done in the form of arsenic tri chloride or arsine AsH_3. Arsenic tri chloride is liquid. Arsine is gas. Gallium is transported again in the form of a volatile compound either as gallium chloride or tri methyl gallium.

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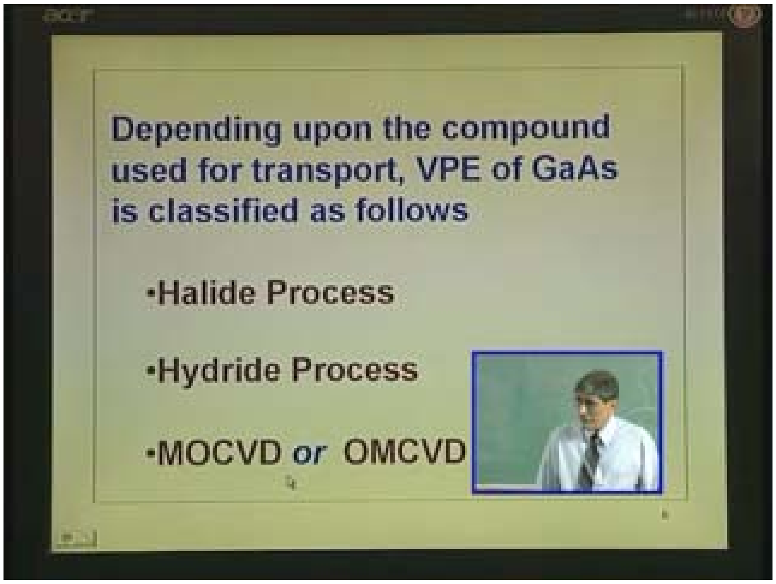

Depending upon the compound used for transport, VPE of GaAs is classified as follows

- Halide Process
- Hydride Process
- MOCVD *or* OMCVD

Now depending upon the compound used for transport, you call it by different names you call it for vapor phase epitaxy. First you have got three classifications. Let me just go back. You have got three classifications depending upon the mode of transport here the transport is through vapor phase compound, the liquid phase it is actually precipitation from the liquid phase. You keep the substrate in contact with the liquid, from the liquid you precipitate those constituent elements that is liquid phase; whereas, molecular beam epitaxy physical transport of gallium physical transport of arsenic in the form of a beam that is why molecular beam. That particular point is that, that is why that forms classification. Now coming to the vapor phase epitaxy, depending upon what sort of compounds you use for transport of the vapors, you call it halide process, hydride process, or MOCVD or OMCVD is one of the most popular epitaxial techniques for gallium arsenide today. Metal organic, chemical vapor deposition, or organo metallic. Both same it is only who is talking somebody will say metal organic CVD or organo metallic CVD. You deal with the same compound trimethyl gallium. That is called depending upon that particular thing, you call it MOCVD. Now let us just take a look at some of the, each one of them in detail.

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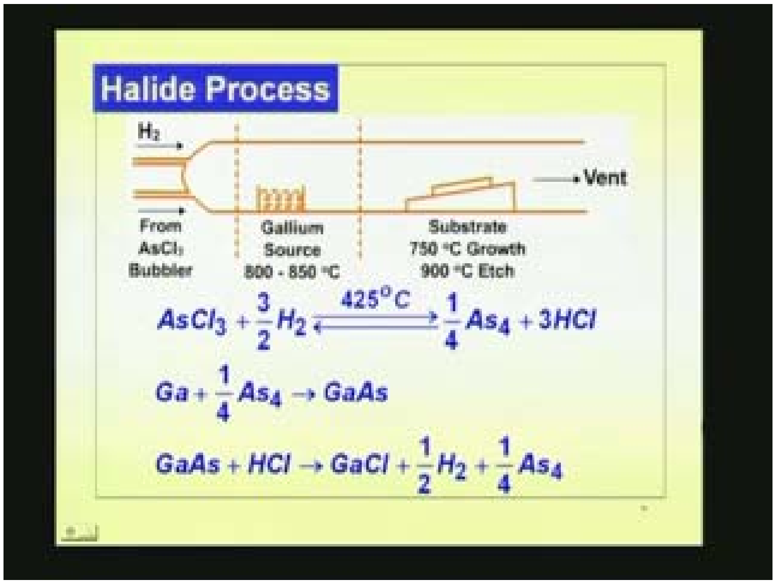

Halide Process

$$AsCl_3 + \frac{3}{2}H_2 \overset{425^{\circ}C}{\rightleftarrows} \frac{1}{4}As_4 + 3HCl$$

$$Ga + \frac{1}{4}As_4 \rightarrow GaAs$$

$$GaAs + HCl \rightarrow GaCl + \frac{1}{2}H_2 + \frac{1}{4}As_4$$

Not in detail just going through the name. Halide process, you can see here, this is a furnace tube, watts tube which is laid out there and it is a 2 zone furnace. Fancy name given to that is the reactor. An epitaxial reactor is nothing but that it frightens you when you say reactor. But if I say it is a furnace that is all that is it. You have a furnace here, for epitaxial reactor, which has got 2 zones. One zone where you can heat it about 800 to 850 degree centigrade simultaneously you must be able to heat other zone to 750 degree centigrade for growth. The philosophy here is this or the approach is we have hydrogen gas and arsenic tri chloride liquid. You have a bubbler, you pass hydrogen through that.

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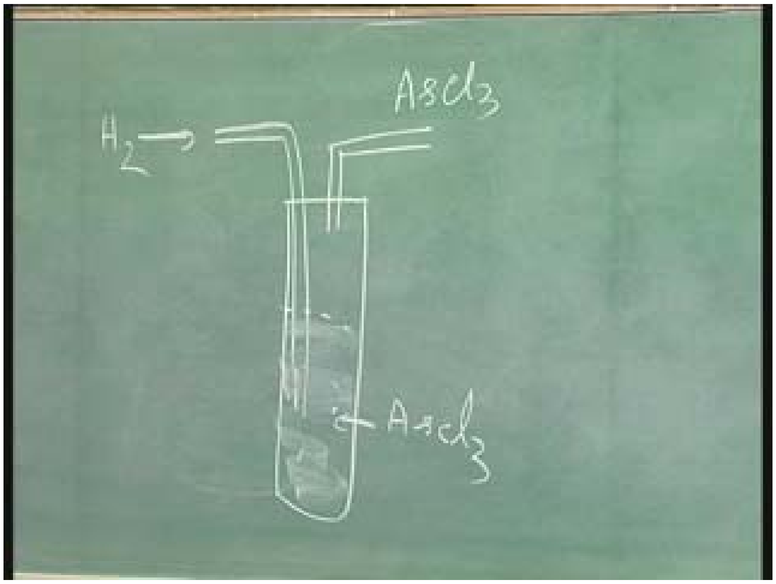

Like this I am just showing a bubbler it can be from flask then you have the arsenic tri chloride. Really a lot of chemistry comes here. We will prove with that with this lecture so, this arsenic tri chloride and a tube coming into that. You pass hydrogen through that, because you can get it in a very pure form. You do not want to use any gas with contaminants from the epitaxial layer. If you pass hydrogen through that if it is very pure, 6th 9 purity and then you notice that is the liquid and this bubbles hydrogen through that. When it comes out it picks up the vapors of arsenic tri chloride. What are transported now are the vapors of arsenic tri chloride that is what is shown here. Arsenic tri chloride vapor is occurring here. What was before that, I have not shown that is a secret. It is what is present there. You control the temperature of the bubbler. We can control the vapor pressure. Once you control the vapor pressure, extent of arsenic tri chloride comes in this control. The controller is there that is the temperature of the bubbler. Now rest is just chemistry. A few equations we will see. Arsenic tri chloride notice here, you have a crucible which contains gallium. Gallium is melt even at 30 degree centigrade. It is the molten gallium. Past this arsenic tri chloride vapor comes in this is our career gas additional to dilution, if you want arsenic tri chloride plus hydrogen will react even at 425 degree centigrade to give you arsenic in that form As_4 and HCL.

Now this arsenic which is coming out here will slowly react with gallium where you have kept the temperature at about 800 to 850 degree centigrade. It will form gallium arsenide on the surface. You may have to keep for that reaction to take place, to form a crust of gallium arsenide on the gallium surface; you may have to keep it for several hours. When I say several hours it is even 24 hours so that a crust is formed. Now, you have a top player of gallium, which is converted into gallium arsenide. Now notice the first reaction that is taking place. You have arsenic which is reacting. You have also hydrochloric acid HCL. This gallium arsenide with HCL will react with the crust, which is formed gallium arsenide and this one here is again an arrow left hand side is the reaction taking place. These are the reaction products. This reaction is either way it will take place. It will proceed from this to that when the temperature is high. You keep the temperature high 800 to 850 back of the temperature is 850, this reaction between gallium arsenide and HCL will take place to release gallium chloride.

What is this whole effort about? Ultimately you want to bring in gallium chloride here and arsenic here and force gallium chloride and arsenic to react, to release gallium arsenide. This weapon that is used is this equation. This equation is a double edged sword. The double edged sword in the sense, we can force the reaction to take place from left to right that is gallium arsenide HCL reaction taking place releasing gallium chloride and hydrogen and arsenic that is taking place here because temperature is about 850 degree centigrade. What is transported across into this, this is this thing what is on the right hand side. Now here you keep the temperature at 750 degree centigrade lower temperature. The reaction proceeds in the upside direction, same species which have been produced at high temperature recombine. This is the thermodynamics of the process that will release gallium arsenide on the surface. This is the graphite substrate you keep it at an angle etc., so that to get uniform deposition all through. To get all through uniform deposition, you keep it in the tilted position so that even if the vapors get depleted, you get higher velocities so that diffusion takes place more on this side. Result is you get uniform layer from this end to that end. This is the graphite substrate which is heated that is the semi-insulating gallium arsenide. On the top of that you will realize this layer that is this reaction taking place releasing gallium arsenide. That is the thing you need, 2 zone furnace with which you can use, gallium as the source to convert it to gallium chloride by the reaction of here.

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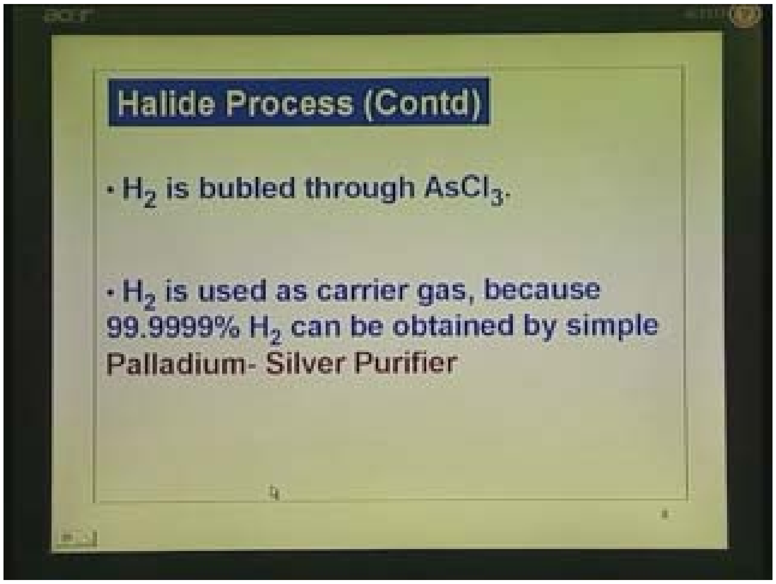

Halide Process (Contd)

- H_2 is bubled through $AsCl_3$.
- H_2 is used as carrier gas, because 99.9999% H_2 can be obtained by simple Palladium- Silver Purifier

This reaction HCL, gallium arsenide and this what you get when you bubble? The process that I discussed here is summarized and that it is available for you to see the hydrogen is of course, you can get 6th 9 purity that is why we use hydrogen as the carrier gas, all that I have mentioned.

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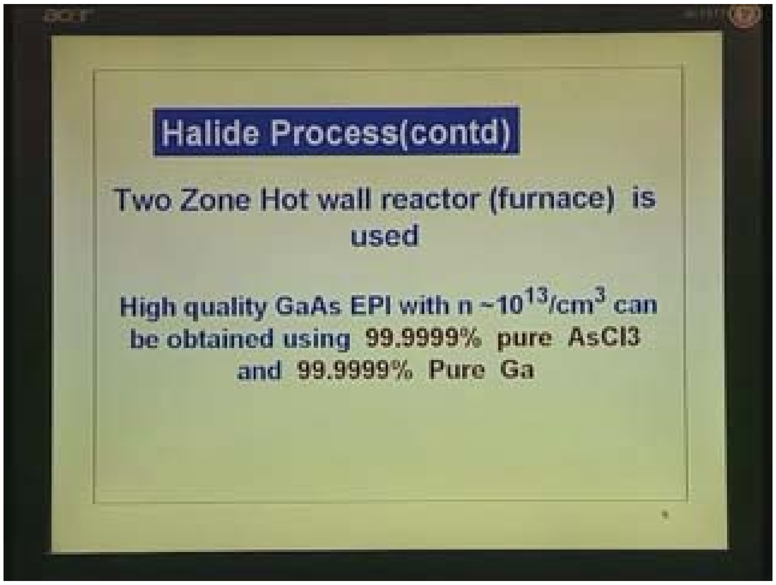

Halide Process(contd)

Two Zone Hot wall reactor (furnace) is used

High quality GaAs EPI with n ~$10^{13}/cm^3$ can be obtained using 99.9999% pure AsCl3 and 99.9999% Pure Ga

Now, the halide process called hot wall reaction process as I mentioned already, high quality gallium arsenide epitaxial layer of career concentration. 10 to the power of 13 per centimeter cube you do not get semi-insulating there because it is just a thing which vary growth vary or transporting. Some of these compounds which will carry some of the impurities. You get 10 to the power of 13 undoped n type. It turns out to be because of some silicon contamination it comes from gallium source that has some silicon contamination. That is enough to give the doping concentration and arsenic tri chloride of course is you can get here. I just want to correct this, because this particular quantity is 1 9 added there and this also 1 9 added there, 7 9 purity because of this purity you can get this. Such load doping level concentrations if you do not have such purity it will be 10 to the power of 15. Now that is the halide process. Quite popular because we get layers which are quite pure.

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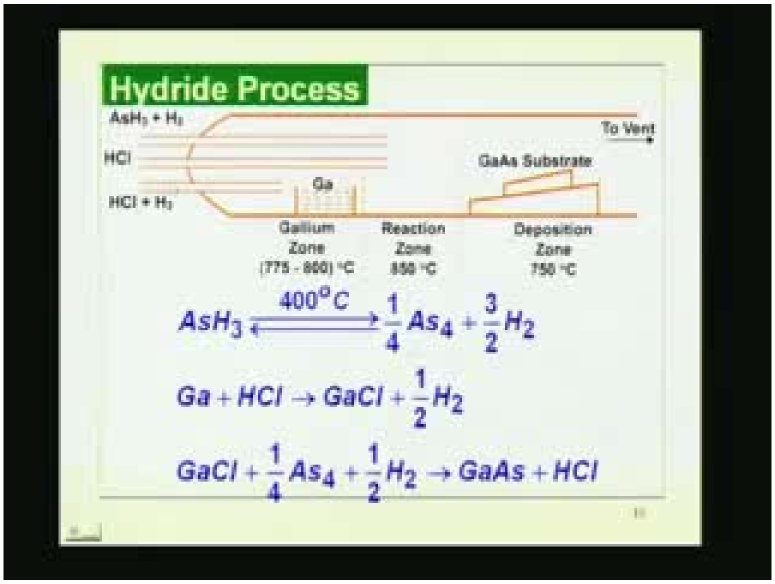

Hydride Process

$$AsH_3 \xrightleftharpoons{400^oC} \frac{1}{4}As_4 + \frac{3}{2}H_2$$

$$Ga + HCl \rightarrow GaCl + \frac{1}{2}H_2$$

$$GaCl + \frac{1}{4}As_4 + \frac{1}{2}H_2 \rightarrow GaAs + HCl$$

Next process is slightly different. The way you transport these ultimately over here, you get gallium chloride and arsenic. So, instead of arsenic tri chloride which you use in a hydride process, have halide process. You use arsenic tri chloride which is used to release arsenic and also gallium. Gallium is released through gallium chloride; arsenic trichloride converts gallium to gallium chloride. I hope chemistry is right. Now here, same gallium is there liquid form, all mechanism same thing and arsine is let inside deep inside. In the previous case arsenic tri chloride was coming right up to this point only so that reaction is forced. Now you straight away transport arsine there and you have HCL also here. That is separately required, if you require you can use it because I just mentioned in the previous thing, before you start growing the layer you must etch the substrate in c 2. Once the temperature everything is reached or even higher temperature, you remove a layer of gallium arsenide. In the case of silicon epitaxy also when you grow silicon just do not go and dump silicon on that. You remove a layer of silicon so that a fresh surface is exposed using HCL etching hydrochloric acid, etching HCL etching is done. That is initially you pass HCL directly to that point which will actually react with gallium arsenide and if the temperature is high initially you keep it at 900 degree centigrade. If you recall in the previous equation HCL plus gallium arsenide will react and remove that h gallium arsenide, if the temperature is high. But the products will be formed gallium arsenide will be formed if the temperature is 750. You can see it here. Just quickly go through that because you can just see it in looking into this arsine breaks up into As_4 and hydrogen then here HCL is passed also on to this previous reaction. You convert gallium into gallium arsenide and allowed arsenic tri chloride to react with that to release gallium chloride transport gallium here HCL is directly supplied to react with gallium to release gallium chloride and gallium chloride with this gallium chloride and this arsenic will react to give gallium arsenide deposit here at 750 degree centigrade. This reaction would have been in opposite direction. The temperature is high. That is actually the hydride process.

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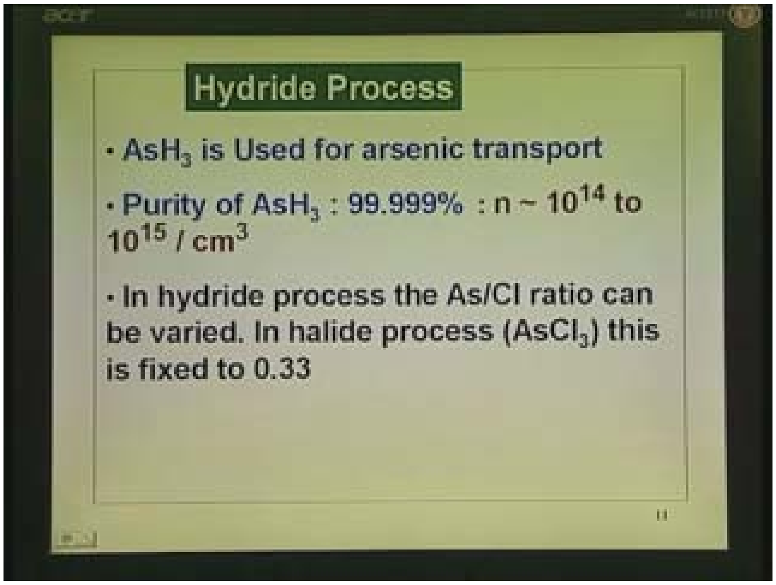

Hydride Process

- AsH_3 is Used for arsenic transport
- Purity of AsH_3 : 99.999% : n ~ 10^{14} to 10^{15} / cm^3
- In hydride process the As/Cl ratio can be varied. In halide process ($AsCl_3$) this is fixed to 0.33

Whatever I have said is written here Arsine is used for arsenic transport purity of arsine is lower than that of arsenic tri chloride arsenic tri chloride purity is about 7 9s today about ten years back it was 6 9s now, 7 9s; whereas, arsenic purity is still about 5 9 purity. Result is the layer that we get you cannot go down to those doping concentrations which are 10 power 13 undoped but you want undoped 10 to the power of 15. No problem you can use this arsine. So the difference here is the ratio of arsenic and chlorine can be varied very easily so they are different sources. If you are using arsenic tri chloride ratio of arsenic to chlorine is 3.33. So you have bit more flexibility for deposition that may not be a big advantage but then that is one of the merits hydride process course is there. If you just go back to the previous thing, you will see in the hydride process or the halide process, first process arsenic trichloride you have to convert gallium to gallium arsenide that takes long time, 24 hours I mentioned; whereas, if you use the hydride process there is no such conversion. Go back and see here (Refer Slide Time: 36:53) straight away, gallium chloride is released by reaction of HCL and gallium in the previous process. Go back further down in the previous process you release gallium chloride required for gallium by reaction of arsenic tri chloride arsenic gallium arsenide formation here. So that process is not there that is what we mentioned here. That is, it does not take it does not wait for the gallium arsenide crust form on gallium straight away pass HCL that will convert gallium to gallium chloride.

Coming to the third process that is M O C V D or metal organic chemical vapor deposition, I just want to give a word of caution. We are talking of vapor phase epitaxy. Sometimes it is also referred to as chemical vapor deposition. It is a generic term, general term that is used when you say chemical vapor deposition; it may be epitaxy or may not be epitaxy. What we are talking of is all these processes were chemical vapor deposition because the transport is through the chemical vapors of the chemical arsenic tri chloride arsine they are all vapors so chemical vapor deposition. Now, same thing that we talked of if you use philine in silicon at lower temperature. It is not single crystal that is not epitaxy but if you take a single crystal substrate, on that use proper temperature then use the chemical C V D that becomes vapor phase epitaxy. The correct term is vapor phase epitaxy. In fact, even here they should have used metal organic vapor phase epitaxy M O V P E. We will use it, but general term is M O C V D. This is epitaxy. What we are telling is if you use M O C V D on a foreign substrate like, molybdenum you get poly crystalline material. If you use M O C V D on the single crystal substrate like gallium arsenide you will get single crystal.

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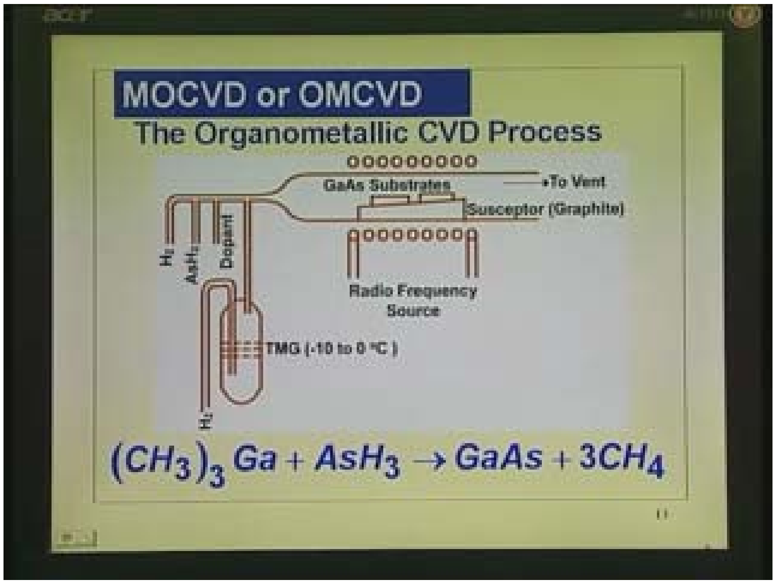

MOCVD or OMCVD

The Organometallic CVD Process

$$(CH_3)_3 Ga + AsH_3 \rightarrow GaAs + 3CH_4$$

Here it is a similar process, much simpler. All that you do is here, it is pyrolitic decomposition. We can use a substrate graphite substrate heated by rf-radio frequency coupled to the substrate alone. When you do that, the deposition will take place only on substrate in a hot wall epitaxy deposition will take place not only on the substrate, it will deposit on the tube also. You have to remove the tube every time and clean it. Here also some deposition will be there. But neither deposition will be here. See here, the organo metallic compound is used for transporting gallium and for transporting arsenic, arsine is used. Not so high purity like arsenic tri chloride but you put up with that. CH_3 thrice gallium is tri methyl gallium that is bubbled hydrogen is bubbled through that bubbler is shown here, which is maintained at room temperature usually 0 degrees easy to maintain. Put ice and maintain and then that is passed through that thing and this tri methyl gallium and in another tube, you have got arsine coming up. Over here, you maintain a substrate temperature at about 650 degree centigrade. That is sufficient for epitaxial gallium arsenide 650 to 750. 650 degree centigrade you maintain and then you will have this reaction taking place on the surface. To release gallium arsenide and methane, you can see the simple chemistry also is simple here one chemical reaction taking place there. But more than that you actually have the merit of using this rf plus you can use this for growing gallium arsenide. Use another bubbler which has tri methyl gallium and tri methyl aluminum, instead of CH_3 Ga CH_3 Al. what will you get? I have one bubbler which takes tri methyl gallium vapors. One more bubbler I attach to take tri methyl aluminum and arsine gas. What will you get? From tri methyl gallium, you get gallium. Tri methyl aluminum, you get aluminum. Arsenic you get arsine. So, you get aluminum gallium arsenide. Such a process is not possible with the other two processes, which we have discussed. You have the aluminum compound, if you realize you have to go to 1100 degree centigrade; whereas, here the aluminum compound is organo metallic compound or metal organic compound. Aluminum tri methyl aluminum this is one of the key merits of M O C V D. Tri methyl gallium tri methyl aluminum. We can tell names tri methyl indium, if you want indium, tri methyl zinc if you want zinc. Dope it in p type put another bubbler. Either you can call tri methyl zinc t m z, or di ethyl zinc d e z ooze out anything names you want. Those are some of the names. The merit of this metallic organic C V D is you can get binary compounds like gallium arsenide. We can get ternary compounds like aluminum gallium arsenide, gallium indium arsenide. You can also dope them with zinc with using diethyl zinc or tri methyl zinc. Of course we can add dopants like sulphur. Use another bubbler that means you will have all bubblers hanging around connected to the system reactor.

Sulphur you can use hydrogen sulphide or you can use sulphur mono chloride that is the sulphur. After all, what you need is a compound of sulphur hydrogen sulphide or sulphur mono chloride. You can add those things; bubbles sulphur mono chloride is liquid. In fact one of the systems which we have been working at, way back was sulphur mono chloride this system. That was used for growing gallium arsenide on molybdenum. Thin layer of molybdenum, gallium arsenide doped with sulphur to make solar cells. There is a huge program on gallium arsenide by solar cells and grow it on molybdenum substrate in terms of poly crystalline. Now this is mo c v d in very nut shell that is the thing. All the advantages I have just told you already. These are put down here.

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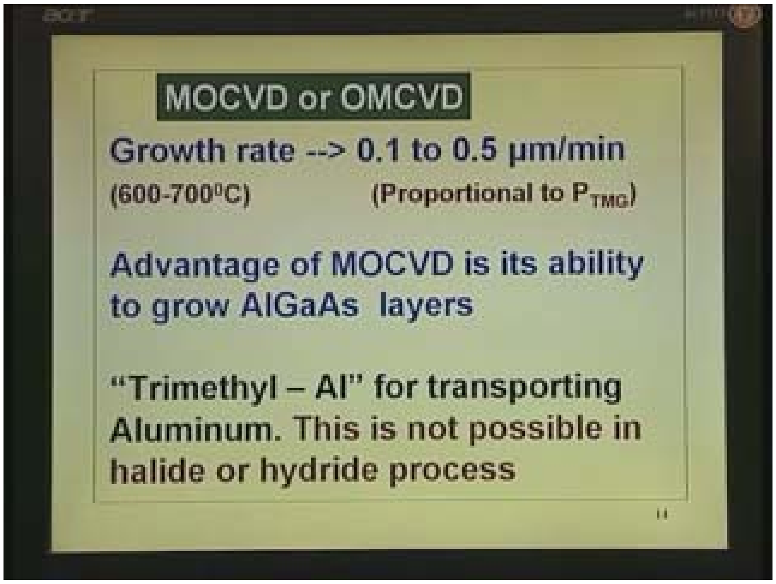

MOCVD or OMCVD

Growth rate --> 0.1 to 0.5 µm/min

(600-700^{0}C) (Proportional to P_{TMG})

Advantage of MOCVD is its ability to grow AlGaAs layers

“Trimethyl – Al” for transporting Aluminum. This is not possible in halide or hydride process

The growth rate is about 0.1 to 0.5 microns per minute. If you want 10 microns there, at least about half an hour or some thing like that you may have to put. 0.3 microns used to grow about half an hour to grow 10 micron layer. That is why I am remembering that number. This growth rate we can control by controlling the partial pressure of tri methyl gallium. You have plenty of arsenic in all these cases. You must have plenty of arsenic. Why? Arsenic over pressure must be maintained. Otherwise, you will lose arsenic from the growing gallium arsenide. For all through you put excess arsenic there to maintain over pressure. That is done here also that arsine is maintained at over pressure, but growth rate is controlled. How much t m z is there for reaction to take place? Excess arsenic is there, through arsine. Now more t m z you add more will be the growth rate. You do not want to have excessive growth rate. The crystal will be better if the growth rate is smaller because it has enough time to organize itself. You prepare further growth rates. Advantage of M O C V D is ability to grow aluminum gallium arsenide etcetera which I have said just now. You can use tri methyl aluminum for transporting aluminum; this is not possible in halide.

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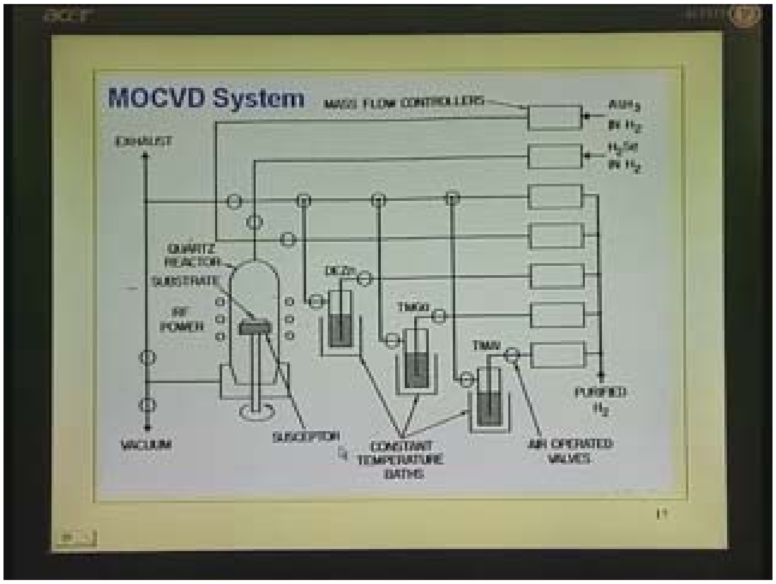

MOCVD System

This is just the system which is shown schematic MOCVD system, which you know that all I have mentioned just now. You can have tri methyl aluminum bubbler, tri methyl gallium bubbler, diethyl zinc bubbler, to dope p type if you want to and all of them we can bubble hydrogen through that. These are all the valves which will be opened and closed by means of hydraulic, that is air pressure. You press a button the valve will open or close to let in that. If you do not want to dope it you close this wall. If you want to dope it open that both of them. Then of course you have got arsine bubbled through that straight away hydrogen sulphide coming in here. Those are for doping if you require tri methyl gallium, this is gallium arsenide.

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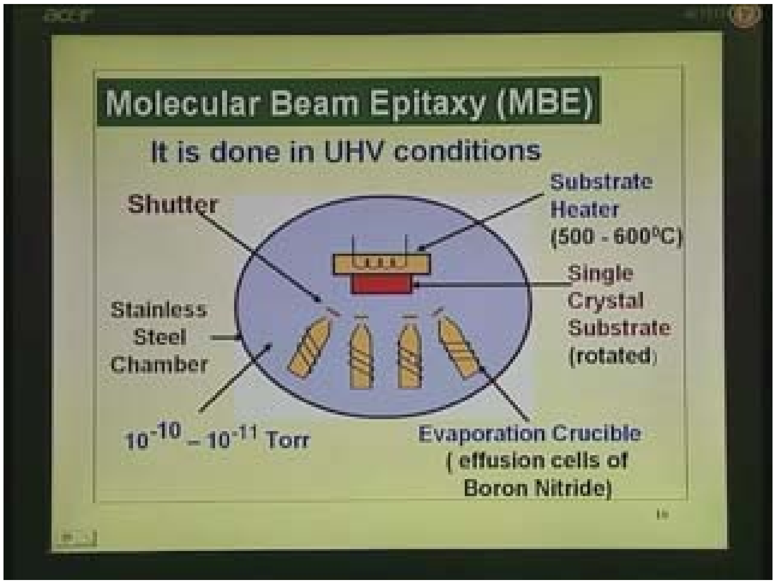

Molecular Beam Epitaxy (MBE)

It is done in UHV conditions

Shutter

Substrate Heater ($500 - 600^{0}C$)

Single Crystal Substrate (rotated)

Stainless Steel Chamber

$10^{-10} - 10^{-11}$ Torr

Evaporation Crucible (effusion cells of Boron Nitride)

The last one that we will have here is the molecular beam epitaxy, the molecular beam epitaxy is different form the vapor phase epitaxy, in the sense the constituent element are directly transporting them physically, a very good example of physical transport. I am sure all of you are familiar, is vacuum deposition. What do you have in the vacuum deposition system, you have chamber in which vacuum is created? You have a filament which can be heated and you keep. For example, if you want to evaporate aluminum, that is you want to transport aluminium on to silicon or gallium arsenide, what you do? That filament is heated. You put aluminum there, heat it. It melts and evaporates and it goes all over and on to substrate. Now same thing is done here. Physical transport, this is nothing but a physical transport. Now you call it molecular beam. Not because just molecules, you will have different effusion cells. These are the different cells crucibles which are heated just like putting some evaporant. You have these crucibles, which you call it as effusion cells. Sometimes they call it as k cells Knudsen cells. These are some of the jargons which the M B E people throw at you. It is just a source, which is heated. Crucible is heated; this heating coil is put around that. Now there are shutters all around here. The entire thing is a stainless steel chamber which is evacuated, by means of complicated pumping system oil free pumping system and each one is the cell which is used for let me use that language evaporation. You may not like it, if I say evaporation. It is actually physical transport. Let us say of gallium, pure gallium 7 9 purity gallium is put inside the cell. You have to fill that in. Arsenic well arsenic is put poisonous deadly poison. There is always a joke, which tells what is poisonous plus, is good for semi conductor. You look at the gases; you look at the substance that you are using. It is only as a lighter sense, do not take it literally. It turns out that arsenic and if you want aluminum, put aluminum here. Indium you put in indium here, whatever if you want to put there the sources. What you do is whatever and dopant you want to put, you can put it there. You can get the required layer of the material gallium arsenide, indium gallium and arsenide etcetera by putting using the proper source. Now, the substrate, the single crystal substrate is put here. And it is attached on to a heated substrate, and the substrate is molybdenum. Molybdenum is used because it is a good thermal conductor. That is chosen because of that and how it is mounted on that. It is mounted on that using indium for mounting and of course indium melts at 150 degree centigrade. Even gallium can be used but it is held there due to surface tension. Even if it melts there, this is held on to the substrate by means of surface tension. Now the key thing here is this actually goes as a beam and it will go as a beam if it is not colliding. It will collide if any of the particles, if there are particles. What are those particles? If it is atmospheric pressure there, what will happen? When you evaporate it, it will not go there. It will just collide and collapse near that. In fact, if you take a vacuum evaporation system and if the vacuum is not proper, aluminium will not go to the substrate. It will just stay there. Spread out. This is one thing which you have seen. You have to create a vacuum of at least 10 to the power of minus 5 so that the mean free path length is much larger than this gap. This will be about 30 centimeters. The distance between the source and the substrate will be about 30 centimeters. It must be much larger than that. A calculation shows if I have about 10 to the power of minus 5 torque; 1 atmosphere is 760 torque this is 10 to the power of minus 5 torque. If you use the mean free path is at least 10 meters, you can be happy with 10 to the power of minus 5 torque.

But if you grow gallium arsenide at that pressure 10 to the power of minus 5 torque and this substrate heated to about 600 degree centigrade, why do you heat the substrate? The atom should be able to move if you heat that. The vacuum here is 10 to the power of minus 5 torque. You will get gallium arsenide. But if you use harsh word that will be junk which in the sense it will have lot of impurities which are coming from this ambience. If you want to reduce the contamination level by another 10 to the power of minus 5 factor you have to go down in vacuum by another factor of 10 to the power of minus 5. The vacuum level that you are talking of here is some thing like 10 to the power of minus 10 to 10 to the power of minus 11 torque. Very high vacuum, ultra high vacuum that is U H V is ultra high vacuum and so the constituents of this m b e system are these, k cells which are the sources of the operand with shutters, which can be opened or closed which ever you want. All of them are heated. You close it, all the things you close, if not only gallium arsenide. Open only these two shutters that is the idea and these shutters can be computer controlled. What we are telling is very high vacuum is created and that is done by using special pumps. I will not read out that.

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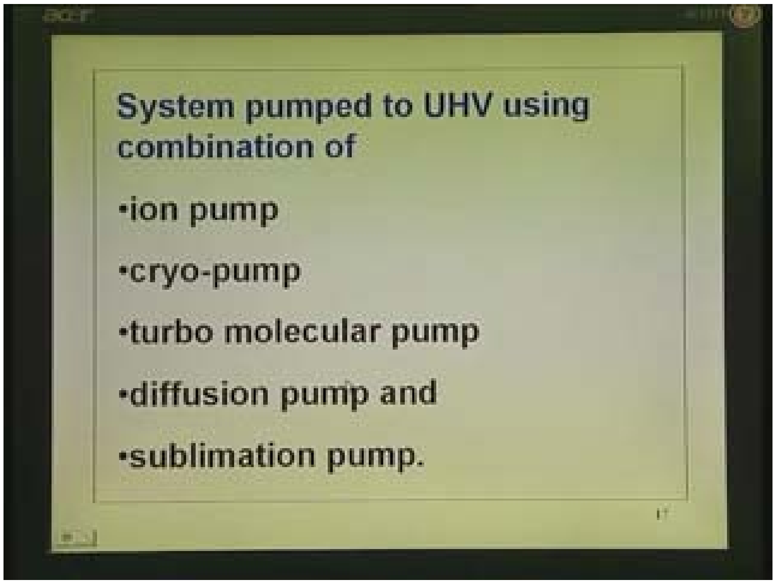

System pumped to UHV using combination of

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

There are all sorts of forms which are available are oil free. Now, what you have here is most important, that I want to point out is I just have drawn a circle there or ellipse there. This chamber is made up of stainless steel, high quality stainless steel if you have to get down to those vacuum and before deposition you feed that chamber to high temperature to degas and pump down all that is done. Not only is the chamber stainless steel, you know when you have this, it looks totally closed. There are ports somewhere in these things. There are ports, stainless steel projecting out with. You know gaskets and valves doors which can be closed, that is not shown here. You get inside to put all these things wafer, chlorine etc, you need those things. When you put close the chamber like that, there will be a gasket. You cannot use any gasket that you like. What you use will be metal gasket. Metal gaskets, what metal? Hold your breath, gold. Gold gaskets are used between those two. Those are some of the things one does to get high vacuum and the entire process of course is simple. Control the flow of gallium and arsenic by adjusting the temperature. The beams which are coming, you get the beams because of the very high vacuum that is why we call molecular beam. It is coming like that from another one like that on to the substrate. You can get gallium arsenide, very high purity gallium arsenide 10 to the power of 13, 14 etc.

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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

Now there is a pumping system and you can get the advantage here is, you can grow 1 micron per hour, very small growth rate you can do when you grow very small rate of growth. Very high purity, excellent crystal power quality and thickness uniformity over a 5 centimeter wafer you can get within 1%. People who want to make quantum wells, very small layers, they resort to this. Today M O C V D is competing with this to grow thin layers. Let me just warn you and leave you on that. This is M B E is very good and M O C V D is competing because mass production if you want MOCVD is better than this. High purity material can be grown and any composition we can get; Indium, gallium, arsenide and also any dopants that you can use. Key thing is control of thickness, control of impurities, precisely done to the extent of a mono layer.

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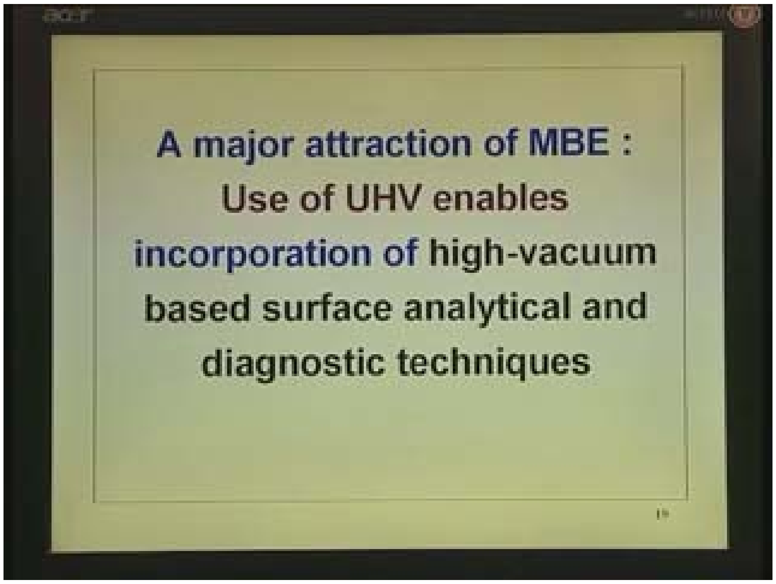

A major attraction of MBE : Use of UHV enables incorporation of high-vacuum based surface analytical and diagnostic techniques

Some of the other advantages are that we can just say. You can actually introduce some of the diagnostic tools along with this thing. Now let me not go into this in detail on to that right now. Let me just sum up at this stage, the M B E system had gained lot of popularity and today people are accepting to use this for some commercial applications because of the high quality that you will get. Particularly those who want very thin layers; for example, aluminum, gallium, arsenide, then gallium arsenide a very thin layer at the Armstrong level then we use those type of approach is highly attractive. This is one of the most popular techniques which are used along with MOCVD. Other two techniques are hydride and halide. It is more of academics. But still a poor man's quality epilayers will be some of those high qualities if you want you can use that halide process. With that I think I will stop the discussion today. Few of the things which are meritorious for gallium arsenide growth with M B E, I will bring out later. Then we will go on to the devices afterwards. We will see in the next lecture.