Nano structured Materials-Synthesis, Properties, Self Assembly and Applications

Prof. Ashok k Ganguli
Department of Chemistry
Indian Institute of Technology, Delhi

Module - 2
Lecture - 8
Synthetic Methodologies (Contd.)

Welcome to the next lecture to the course of nano structured materials, synthesis, properties, self assembly and applications. This is the six lecture of model 2 and we are discussing methodologies of growing nano structures. In the last lecture, we discussed the methodology how we can grow nanostructured films using the chemical vapor deposition technique which is called the CVD technique. Today, we will continue on this topic and we would be discussing today on the physical vapor deposition technique.

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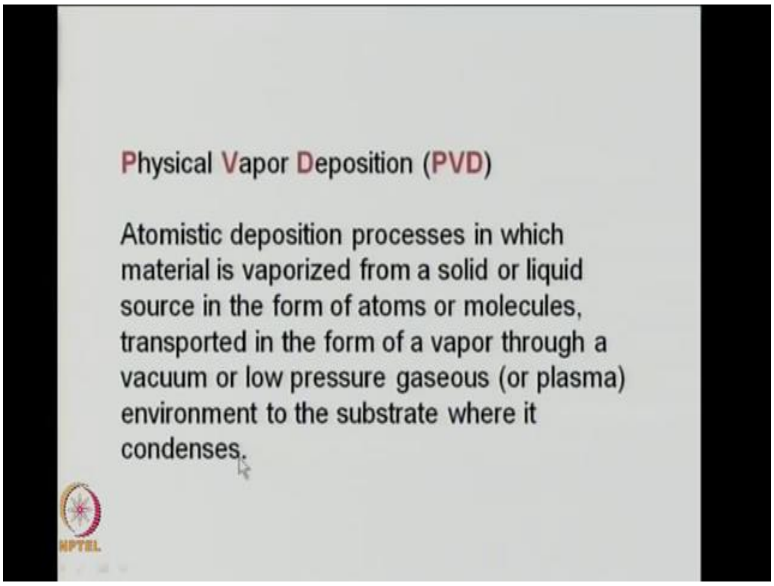

The physical vapour deposition technique basically involves deposition of atomistic processes, that means deposition of atoms in which the material is vaporized from a solid or liquid source in the form of atoms or molecules. These vaporized source of atoms and molecules are then transported in the form of a vapor through a vacuum or low pressure gaseous environment. It can be a plasma and this atom and molecule travelling through this low pressure system a is taken towards the substrate where these atoms and molecules condense and former thin film.

So, this is typically P V D process, that is why in shot it is P V D for physical vapor deposition, which is different from what we studied earlier, which was the chemical vapor deposition technique. So, here atoms and molecules are being transported through a system, it will be a chamber with be at low pressure or we call vacuum with some amount of gas for plasma. It is taken and it is flown towards the substrate, the molecules travel towards the substrate, where it condenses and forms a film.

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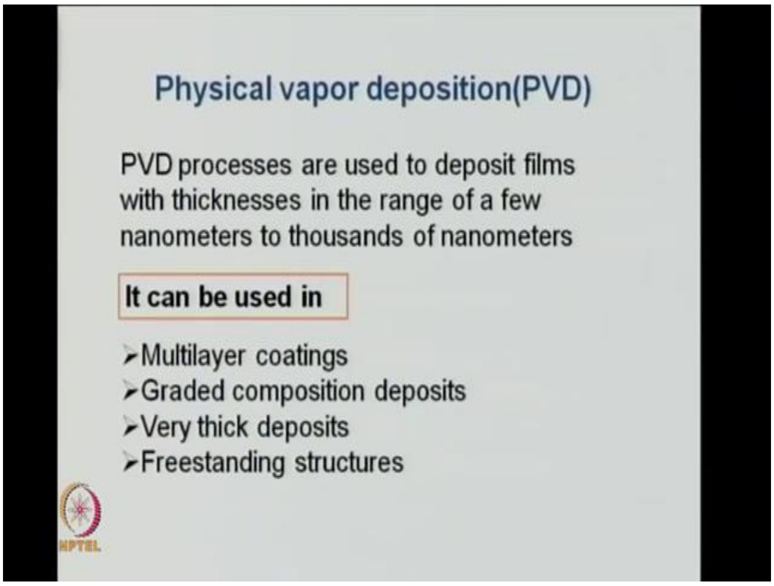

So, P V D processes are used to deposit films with thickness, which are in that range of a few nanometers to thousands of nanometers. So, wide range of thickness are possible to make films which are of the order of few nanometers to thousands of nanometers and it typically is used in multilayer coatings in graded composition deposits.

A very thick deposits and also on freestanding structures, graded composition basically means that till certain thickness, you have one composition. Then, as you have a another layer, as you go deep into the film the composition is varying, so that is why it is called the graded composition deposit are graded composition film. You can have multilayer coatings that mean one layer of material x, which is on top of a material y. So, then a material x, so you got a making different layers of a different materials using P V D processes, so you can make thin films to thick films, a large range of a thickness are possible using the physical vapor deposition technique.

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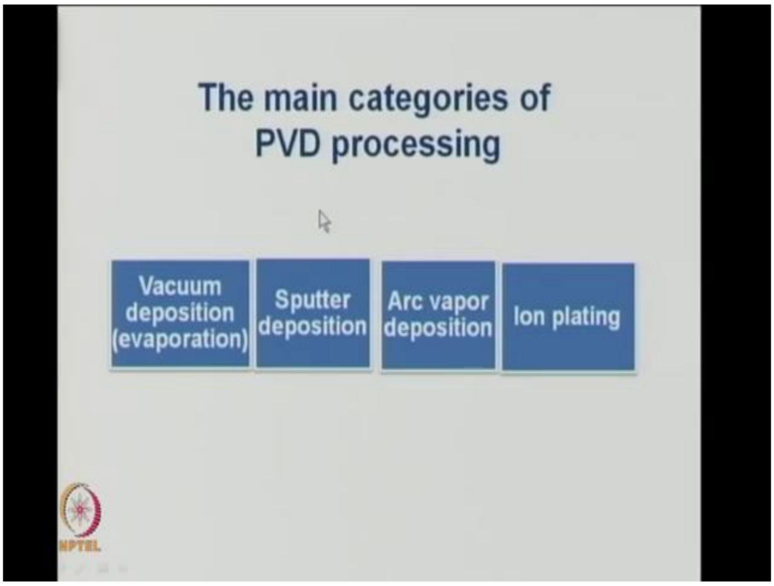

The main categories of this P V D technique can be a divided into four major disciplines on four major methodologies. They are the vacuum deposition technique, which is also called the evaporation technique, the other is this sputter deposition technique, the third one is arc vapour deposition and the four is ion plating. As you can see from the name itself, you can get some idea that what is different among these four techniques belonging to the general P V D process.

Here, as you see it is basically built one vaporation and some material is there and you have to rate in a vacuum and you deposit it on a target or a substrate. Here, use sputter, something sputter means you have a material which has to be quoted on a substrate. You bombard that material with some ions or some other being and atoms are ejected from the target and then they are deposited on a substrate. So, that is sputter deposition arc vapour from the term arc, you can understand that an arc electric discharge has to be generated and during that. There is a plasma, which is created and then you can deposit atoms from that phase ion plating includes methodologies, where you can have the ion assisting in the deposition. We will discuss each of these four methods little bit more in detail and all four belong to the physical vapor deposition process.

So, from the term physical P V D and C V D, the main differences in the chemical vapor deposition process, you can see that you start with some precursors and some chemicals are required. Normally, they involve lesser energy, physical vapor deposition processes are not using that kind of chemicals. Mostly, they started with solids and they maybe metals are compounds, and then use high energy or evaporation techniques or sputter deposition etcetera or electrical discharge to process to form the films.

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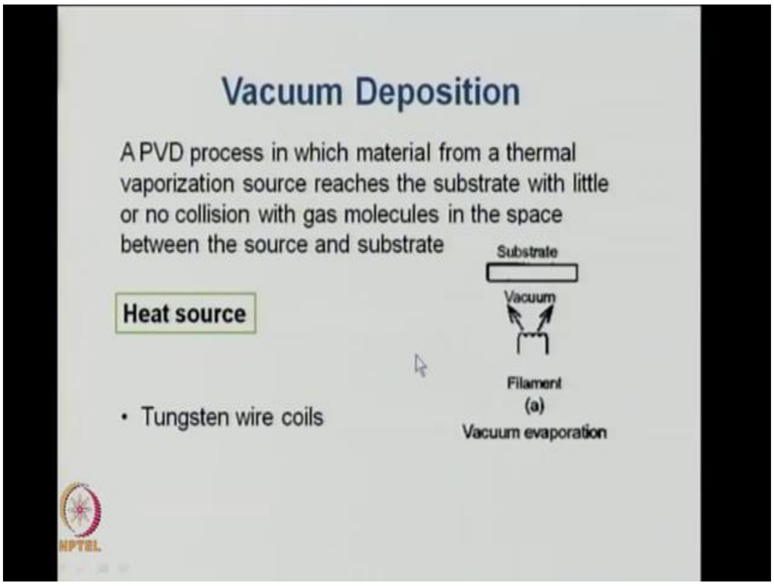

So, coming to the first methodology of the P V D process, it is the a vacuum deposition process in which material from a thermal vaporization source reaches the substrate. There is little or no collision with gas molecules in the space between the source and the substrate. In other words, you have this filament, which on heating, you have a material on this, so on terminal evaporation of the material thermal evaporation, you will have the molecules going through this vacuum or where very little gas molecules are there. So, they will not face any collision and they will be deposited on the substrate here, so this kind of a vacuum evaporation technique is possible to make thin films. Normally, the heat source that we use here for heating the compounds, which would be evaporated is you use tungsten wire coils as the filament during the vacuum evaporation.

So, this is a very simple technique is an evaporation technique you can call it or a vacuum deposition technique, where you are using tungsten wire or similar wires which can give rise to a thermal effect. The material which has to be deposited on the substrate can be coated on this wire and then because upon heating, it will evaporate and pass through a vacuum chamber.

Here, it will meet very little collisions because the density of gaseous molecules is very less and you will expect that those molecules, which are evaporated from the surface of this filament will go onto the substrate and make a uniform film. So, this is a vacuum deposition technique, the next technique we can discuss this little bit more on detail the instrumentation of the vacuum deposition technique.

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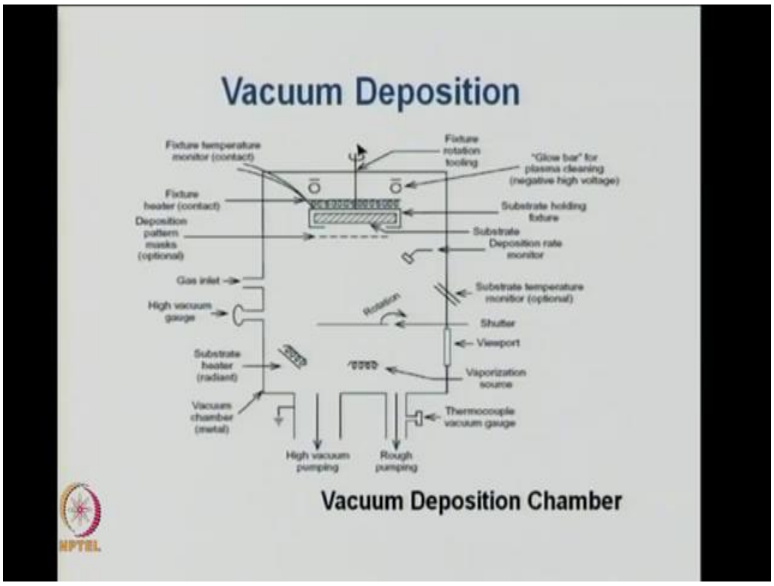

So, here is the filament where you will have your vaporization source, so this will a start generate evaporating from the filament, where the source is there. So, it will the molecules will start evaporating and they have to go on to the target, which is here or it has to go to the substrate here. The substrate is held in a kind of fixture, which is shown here such that the substrate does not fall and the substrate can be heated and that a heating can be done by this substrate heater, which is shown here that is the heater for the fixture.

You can also heat the substrate using a heater which is little away from the substrate and this will heat radiatively and so you can keep the substrate, you can heat up substrate holder or the substrate fixture. Of course, you have to heat this coil, which has the source, which has to be evaporated, now apart from this, there are possibilities of a rotation a here and you can monitor the substrate temperature. You can control or you can monitor the deposition rate here. So, you can have many other fixtures and electronics along this vacuum system, which needs pumps to activate the gas, so you have a roughing pump and you have a high vacuum pumping system here.

So, this is a more or less a schematic with diagram, which shows you about the evaporation source, the substrate, the substrate heaters. This is a fixture heater, the viewport the shutter and then you have this high vacuum gauges, you have the gas inlet and the thermocouples etcetera, which is all connected to this methodology of depositing a film using P V D technique. This is based on evaporation or it is also called vacuum deposition, so one needs to have a good vacuum. You need to have proper pumping systems and monitoring the vacuum the temperature of the substrate because certain growth of films can take place only under certain temperatures.

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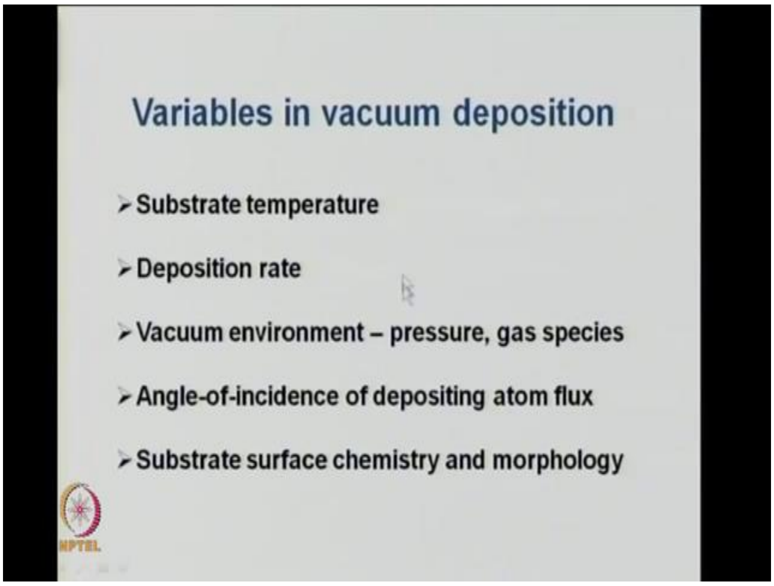

So, the variables in this technique of evaporation or vacuum deposition are the substrate temperature, the deposition rate, the environment inside the chamber that is the pressure and which gas your usual using the angle of incidence of the depositing atom flux. So, you can rotate that source or substrate, one of them you can move the substrate surface chemistry and morphology. If you modify that will also affect the deposition in this condition, so all these things we just discussed substrate temperature deposition rate environment since you can change.

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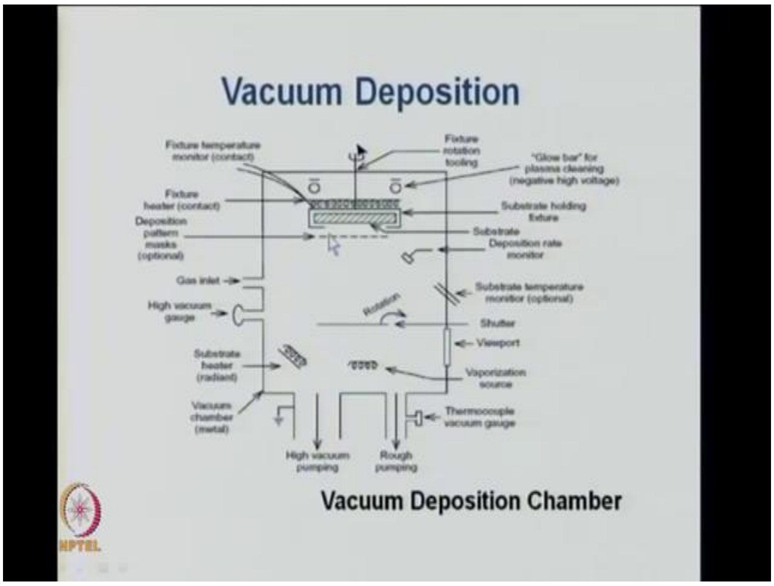

So, with you have to monetary change and that is what is shown in this picture, how you can monitor the substrate temperature, the deposition rate the rotation here and the heater which is heating the substrate radiatively and the pumping systems etcetera. The gas inside can be modified and you can use different types of gases, in addition you can also use masks here to form patterns. If you want to make films not continuous, but according to a certain pattern or design, then you have to have mask here, which is kept in line of the deposition between the evaporating source and the substrate.

Depending on the design of the mask you will have a patterning on the surface of the substrate. So, this sometimes masks are important for making devices, where you have to make certain contacts or certain circuits and you want to coat say a conducting material like copper according to certain design which will be then useful to make contacts.

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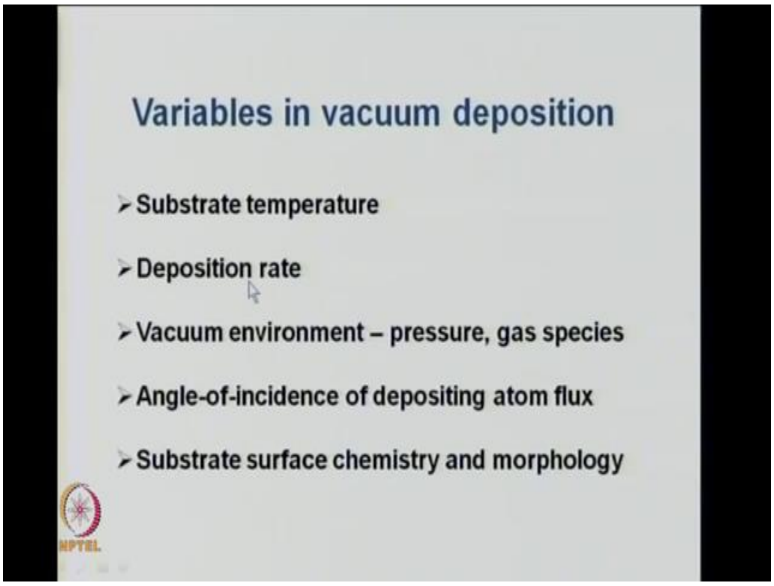

So, these are all the variables we discuss right now and each of them has to be controlled carefully and then the growth rate can be modified, how the films is growing, whether it is farming as a uniform film. There is an island, which is forming and is the rate of growth too fast or too slow, we can control using these parameters.

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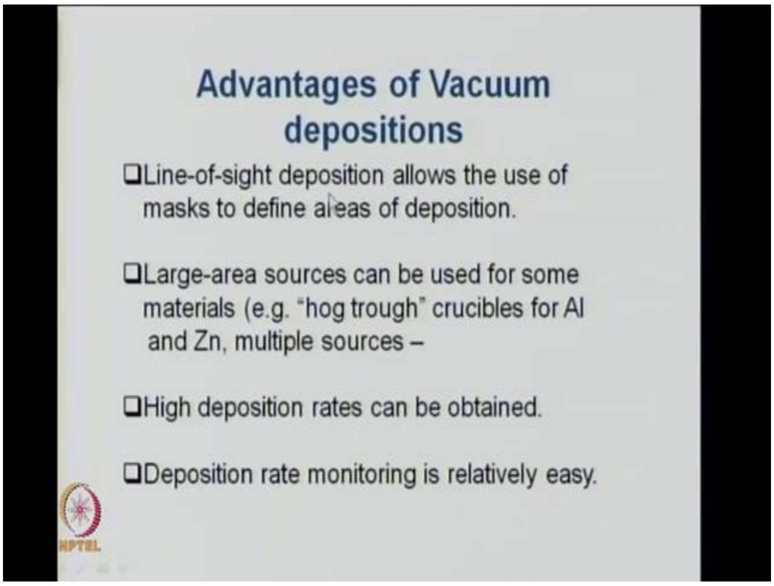

Now, the advantages of vacuum deposition, the vacuum deposition is also called a line of sight deposition.

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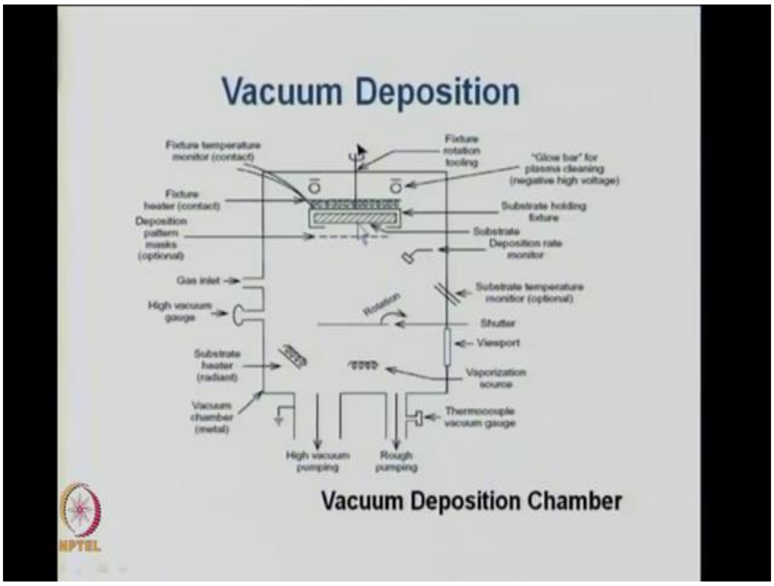

That means that the substrate is directly in the line of or in the in front of the evaporating source and this is call line of sight vision.

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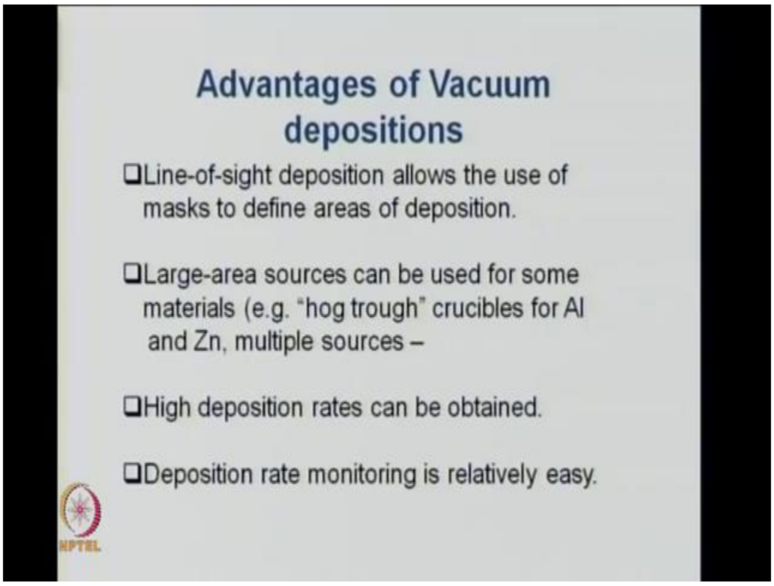

In this kind of technique, it allows you to use masks to define areas of that deposition, which is what I described just before.

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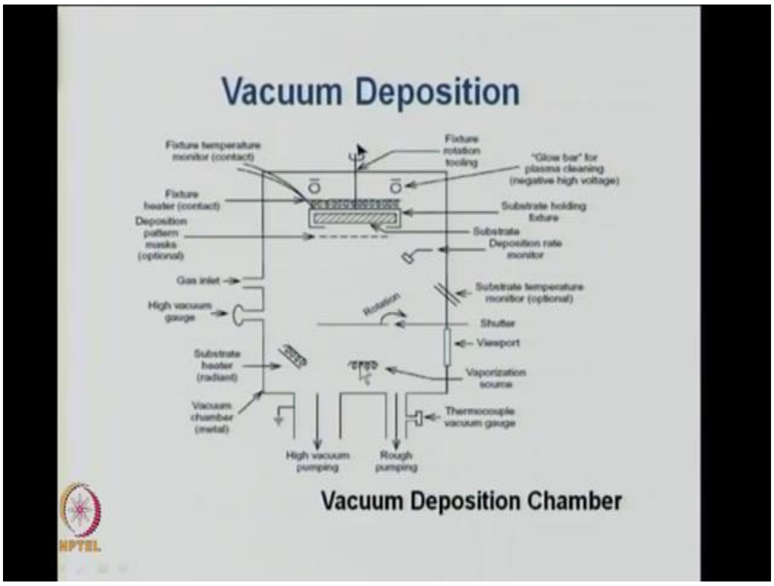

If you design a mask and keep it in front of the substrate, then this mask will allow only certain portions of the substrate to be covered by the atoms which are falling, which are being evaporating from this filament or on top of this filament, so you can create a pattern or a design.

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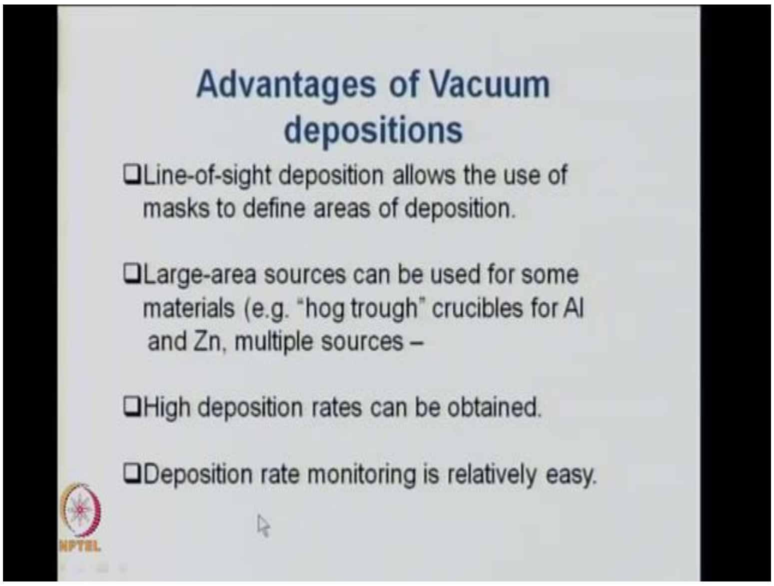

So, line of sight deposition allows the use of masks to define area, where you want to deposit ion and where you do not want to deposit ion. The next thing is you can deposit very large area, using very large sources, so you can you something which is called a hog trough crucible, you can use multiple sources. So, instead of one source here you can use multiple sources and very large sources can be used to deposit materials.

You can achieve a high deposition rates and deposition rates can be monitored relatively easily as compared to other techniques. So, these are some of the advantages of the vacuum deposition method, it is also party evaporation method.

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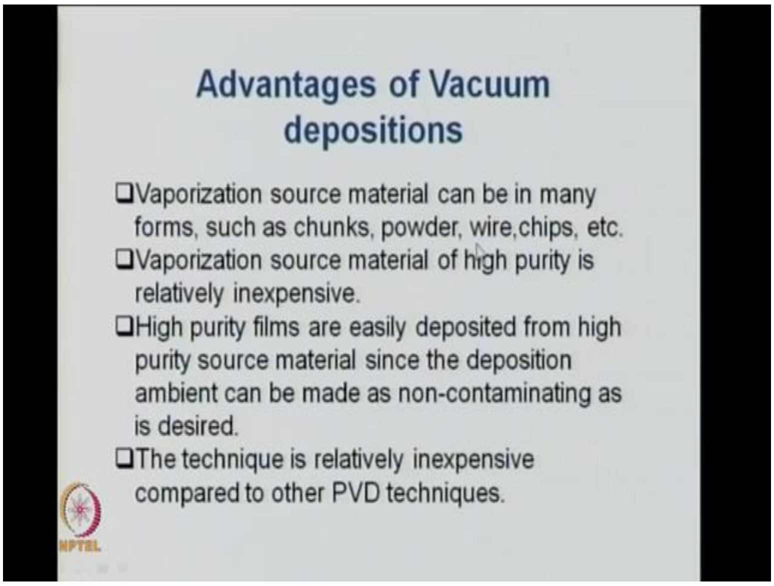

Further, you can use various types of liberalization source materials such as chunks or powders or wires or chips and the vaporization source material which normally is used can be found with a high purity and relatively inexpensively. So, they are not very expensive to use and high purity films are easily deposited from high purity source material since the deposition environment, which is the ambient cannot can be made as non contaminating as desired.

So, overall this technique is relatively inexpensive compared to other P V D techniques and hence this kind of thermal evaporation or vacuum deposition technique is being used routinely in several types of materials. One of the most important thing is you can use different forms of materials, you can use chunks powders wires and chips, etcetera, say it is a reasonably inexpensive method for making large scale thin films.

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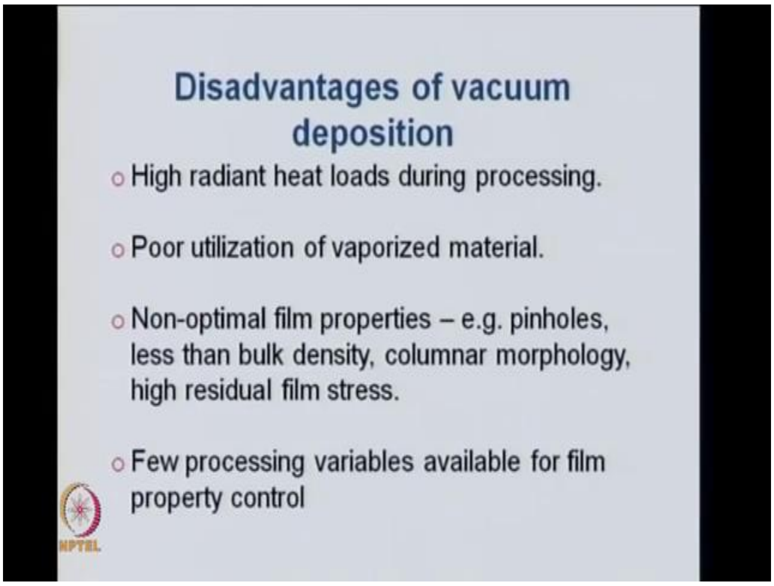

Now, there are of course some disadvantages of vacuum or evaporation technique vacuum deposition or evaporation technique, where one of the thing is the line of sight deposition though it has some advantages where you can use masks. This also gives you a poor surface coverage and you need elaborated tooling and fixtures to have perform this kind of vacuum deposition and surface coverage is little difficult. Similarly, this methodology, which depends on the line of sight deposition provides poor uniformity of the film over a large surface area.

Again, unless you have very complex fixturing and tooling, it is difficult to deposit uniformly the film over a very large area. Then, if you want to deposit many and different alloys and compound, this technique has some drawbacks. It may be good for metals etcetera, but for binary's or turnery's alloys and compounds sometimes, it gives us not a very uniform film. So, these are some of the eight disadvantages of the vacuum deposition technique or thermal technique, which we can remove in going to the other techniques.

We will discuss the other disadvantages of vacuumed deposition is the involvement of high radiant heat during processing. So, that is another disadvantage, the vaporized material is not used very efficiently. So, what you are vaporizing is not only falling on your substrate, but is also falling and several other parts, so non utilization or poor utilization of the vaporized material is one drawback, then you have non optimal film properties. For example, you have pinholes, then you get less than bulk density of the films, many times you get columnar morphology and you sometimes have high residual film stress in the films produced using vacuum deposition.

There are few processing variables available for film property control in the thermal evaporation technique or the vacuum deposition technique. So, with so many disadvantages, of course one of the main advantage of the vacuum deposition is it is inexpensive and it can use a wide variety of materials, but we also saw that there are many disadvantages of the vacuum deposition technique.

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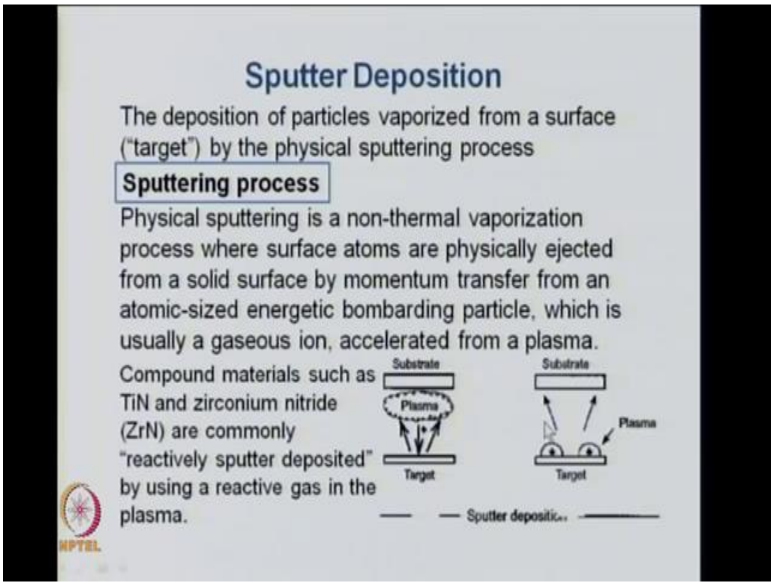

Now, let us look at another deposition technique and this is the sputter deposition, in the sputter deposition basically you deposit particles which are vaporized from a surface which we call a target by the physical sputtering process. So, you deposit particles which are coming out of a target and these atoms, particles which are coming out of the target are basically produced by a physical sputtering process.

So, what is this sputtering process, the physical sputtering is a non thermal vaporization where surface atoms are physically ejected from a solid surface by momentum transfer. So, it is not an evaporation technique, so what you are doing is you are bombarding a target, so this is your target and you are bombarding the target with some sputtering. Either it is a atom atomic being which is highly energetic are a gaseous ion, which is accelerated from a plasma. So, here you see plasma and this a gaseous ion beam which is being accelerated towards the target and the target atoms then come out and then they fall on the substrate and you get up film on the substrate.

So, there are two parts, first is the sputtering using ions generated from this plasma onto the target, which then sputters atoms of the target material which you want to be coated on a substrate. So, the first is getting those ions are a atoms out of this surface using either energized atoms or ions from a plasma and then depositing them on the substrate. So, basically many different compounds can be made because the target can be any compound and then you can attempt to generate atoms of the species.

Then, they are kind of moving towards the substrate and then the deposit on the substrate and you get a film. So, these are examples of titanium nitride and zirconium nitride, which are commonly the actively sputter deposited by using a reactive gas in the plasma, so if you have a reactive gas, then it is called a active sputter deposition. You can have this technique to make films like titanium nitride and zirconium nitride etcetera. So, this is what is being shown here, so this is that target and you generate those kind of ions and then those ions fall on the substrate. Basically this is through momentum transfer that you are creating these ions not through evaporation and you get films on the substrate.

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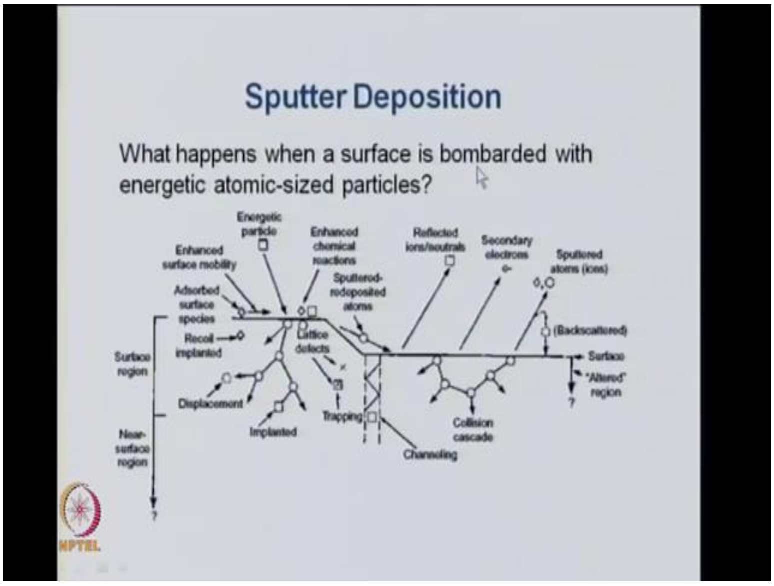

Now, there are many things, which happen when you are bombarding a surface during sputter deposition with energetic economic sized particles. So, here is your energetic particle and it falls on your surface, so this is your surface and on the surface you have say an adsorbed surface species. This adsorbed species gets enhanced mobility when this energetic particle falls on to it what else can happen you can create these energetic particles can go deep inside and get implanted.

You can have then there maybe lattice defects and this energetic particle can get trapped in the lattice defect, it can get channeled like this through some channels and this is known. It can also create a cascade, it can also generate ions which are reflected electrons which are ejected which are called electrons and some of the sputtered atoms from the surface can come out. It can be possible that some of the atoms, which are coming out of the surface interact with the energetic particles.

Then, they are backscattered, so several processes can occur, so depending on what you are looking at you can study some of these event, which are taking place at the at the same time in certain cases. All the events need not possibly take a place at the same time, there maybe one two three events taking place.

It is not necessary all the events listed here a taking place in every sputter deposition that would depend on different parameters of the sputter deposition process. So, we saw mainly that you have energetic particle falling on a surface bombarded onto a surface which normally creates enhanced mobility for any atom or molecule on the surface. Those atoms and molecules can move around and you can get these surface atoms re deposited on to on the sputtered atoms which are coming out re deposited.

You can take some of the atoms can really come out or they are backscattered here and many other things can happen including ion implantation to which is happening here, so near the surface this is the surface region all these activities are happening. As you are going deep interior, there are less activity in the near surface region, so this surface region is a near surface region.

Most of the activities are happening in the surface region when a surface is bombarded with energetic atomic sized particles. So, what are these different effects, and what are the times scales of these different effects during the sputtered deposition of this process by which, we trying to make films on substrates. So, you can classify these events in four different ways depending on the time required for those effects.

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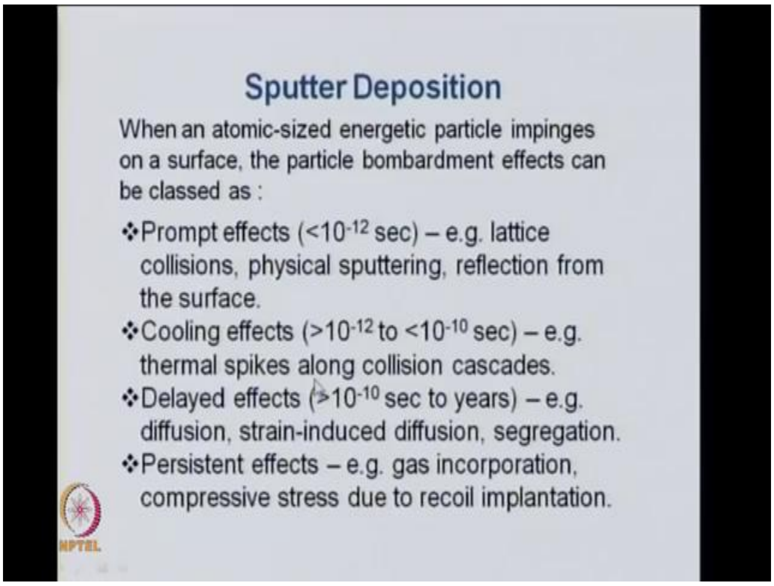

So, if the very small time domain, say less than ten to 10 power minus 12 second, which is less than 1 pico second. You can have effects which are called the prompt effects like lattice collisions, physical sputtering reflection from the surface in the range of some 10 nanoseconds to 1 pico second. So, this the range 10 minus 12 to 10 to the power minus 10 second 10 to the power 10 second is 10 nanosecond. So, between 1 pico second to 10 nanosecond, you can see what are called cooling effects, where you see thermal spikes along with collision cascades.

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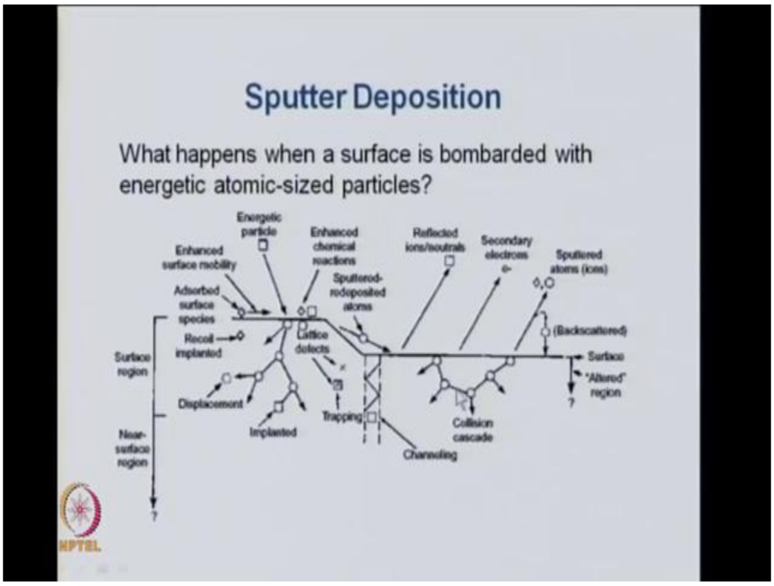

So, in the picture, you can see where is the collision cascade which is happening, so this is happening in the time scale of around 1 pico second to 10 nanosecond.

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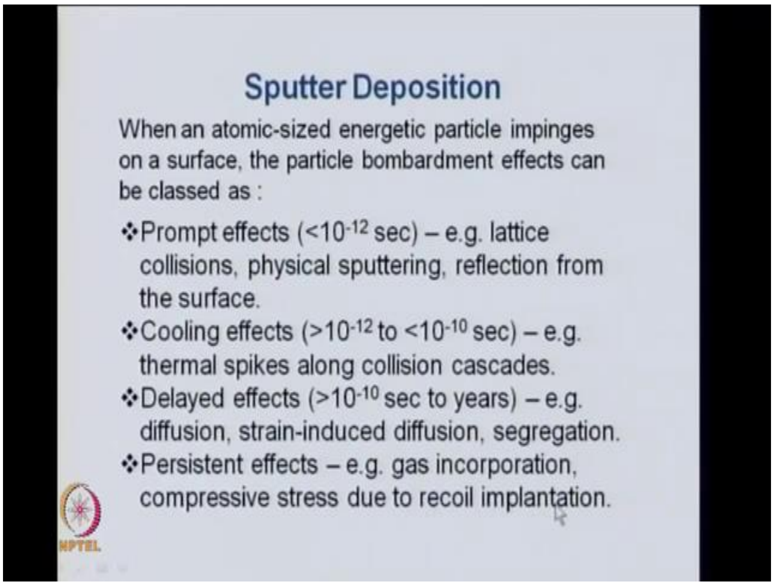

Then, you can have delayed effects, these delayed effects can take long time, they can take few second or microseconds to sometimes years and they involve processes like diffusion, strain induced diffusion, segregation. Then, there are something which are called persistent effects example gas incorporation or compressive stress due to recoil implantation.

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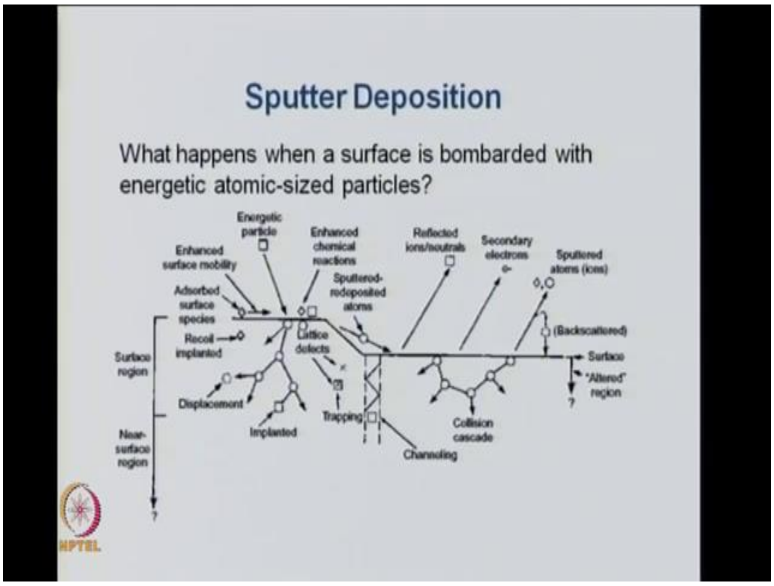

So, when you have something like implantation, recoil implantation, so you can have these kind of delayed effects or persistent effects in these sputter deposited films.

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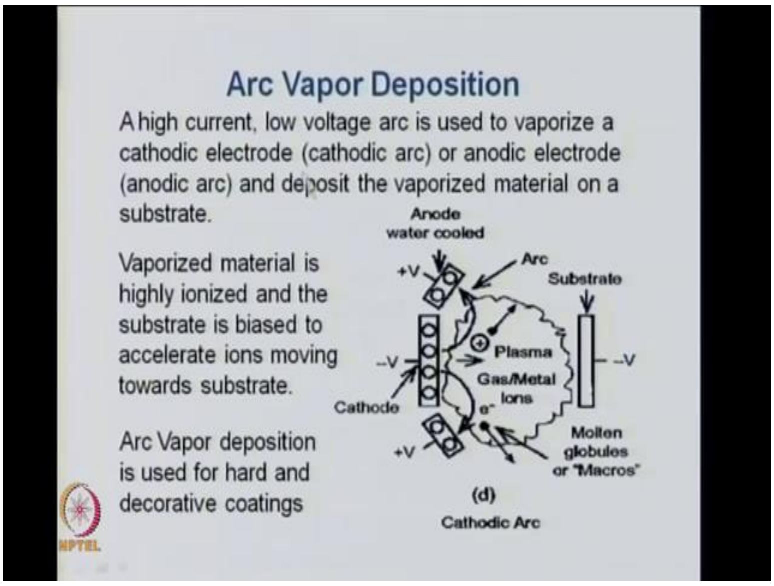

Now, coming to another methodology, so we looked at physical vapor deposition, two methodologies. One was the evaporation method or which is also called the vacuum deposition process and the second one that we looked at was these sputter deposition process. Now, we look at the third method, which is the arc vapor deposition, so as the term arc suggest to you that you have to generate an arc and an arc is normally generated between two electrodes at different potential. One is the cathode, one is the anode, so you can have a cathodic arc like it is shown here, so you have here a cathodic arc and you can also have an anodic arc.

So, once you have a cathodic arc, that means the electrode which is forming the cathode from there you can generate plasma and you can get deposition on the substrate of atoms belonging to this cathodic material. So, if you have a cathodic arc, then you can make a film of the cathode material and if you have an anodic arc, then you can make film from the anode material. So, basically a high current and low voltage arc is used to vaporize a cathodic electrode is called the cathodic arc or anodic electrode, which is called the anodic arc and deposit the vaporized material on a substrates.

So, the substrate is here and when the vaporized material is highly ionized and the substrate is biased. So, the ions moving towards the substrate, then you can get deposition and mostly arc vapour deposition is used for hard coatings and decorative coatings and very commonly it is used. So, you use basically a high current and low voltage arc discharge system.

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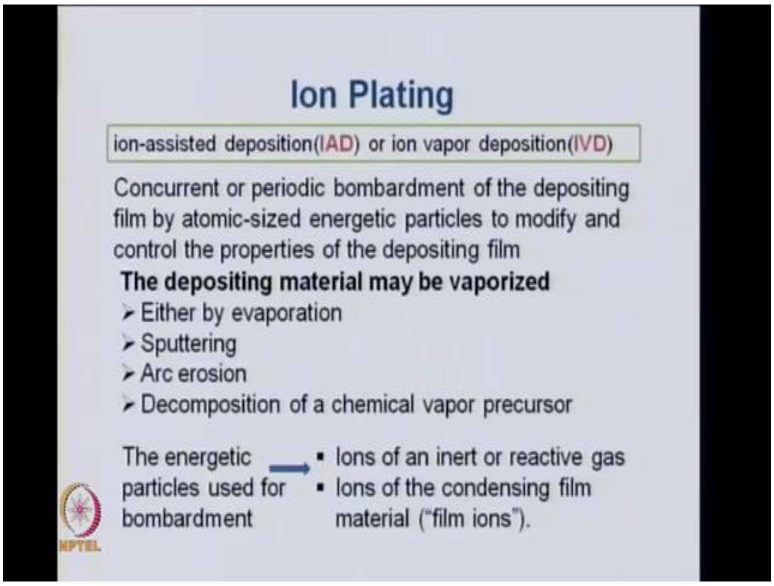

Now, then you can also have a technique, which is called the ion plating technique in the ion plating or ion assisted deposition which is called I A D or ion vapor deposition I V D. Now, in these techniques, there is concurrent or periodic bombardment of the depositing film by atomics sized energetic particles to modify and control the properties of the depositing film. So, you can first vaporize the depositing material by any of the methods which we discussed earlier. So, you can vaporize the material that you want to deposit by evaporation or sputtering or by arc erosion or by C V D by any of these decomposition of a chemical vapor precursor.

So, any of these methods can be used to a first deposit the film and then you a either simultaneously or periodically bombard that depositing film by atomic sized energy particles. So, one of these is used along with either an atomic or ionic beam to assist the deposition, so the energetic particle which are normally used for bombardment are ions of an insert or reactive gas ions of the condensing film material itself. So, you can use different methods, you can use a inert gas and its ions or a reactive gas ions or the ions of the same material, which is condensing onto the substrate.

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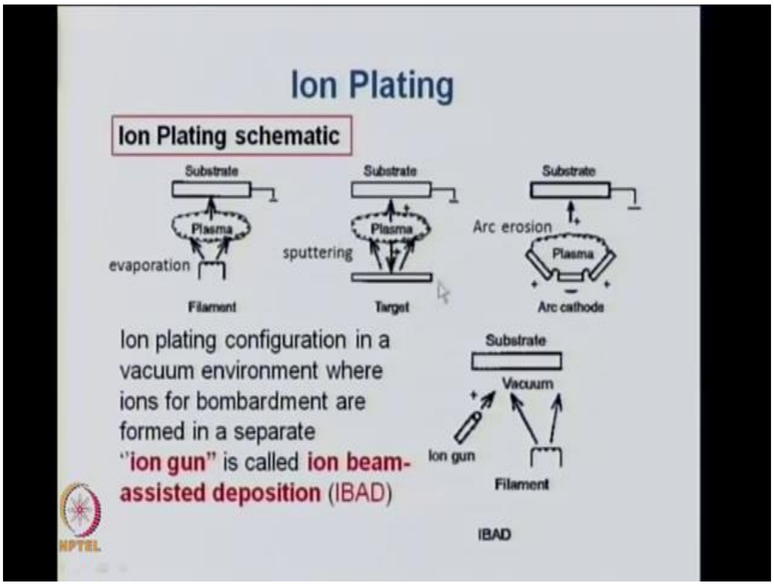

So, depending on them, you can have different schemes, so in this ion plating scheme you can do the evaporation technique which we discussed earlier, the sputtering technique the arc erosion technique along with and ion gun. So, when you have these ion gun along with one of these techniques separately you are using an ion gun and then this is called an ion beam assisted deposition.

So, you are doing in this ion plating, one of these techniques has to be used along with the ion gun which is generating ions assisting the deposition of the film which the ions are being generated by either thermal evaporation or through an arc cathode or anode or a sputtering technique. So, there are various techniques, which we already discussed and along with that use a ion gun and this technique, then becomes an ion beam assisted methodology for deposition of thin films.

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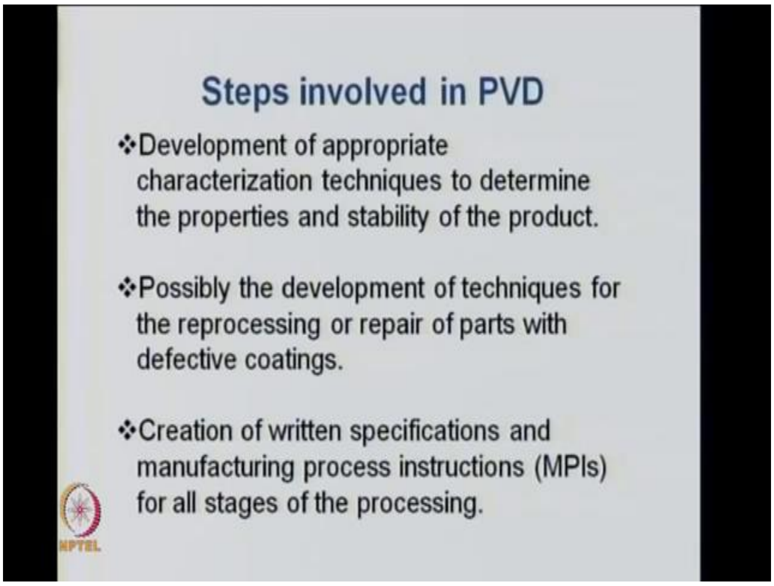

So, what are the steps involved in general in choosing a P V D process, so in all the P V D processes that we discussed using either evaporation sputter deposition. Then, this kind of ion assistant deposition is the arc method of deposition over the first thing that you do is you choose a substrate. This substrate has very important role to play during the growth of the film and the substrate can be a single crystalline, polycrystalline and it depends on what is the type of film that you are trying to grow. So, choosing a substrate is important and then we need to understand define what the critical properties of the substrate surface are, which are important for the film that we need and how these can be determined.

So, then we develop an appropriate surface preparation process the substrate has to be clean in a particular manner. So, this is called the surface preparation process, which includes cleaning and may involve changing the surface morphology or chemistry. So, that is called surface modification of the substrate, and then you have to select the film material and the film structure to produce the correct film addition. You need your film to be strongly bound to the substrate. So, to have that kind of addition you need to select proper film material and the structure of the film which you are trying to grow on the substrate.

So, the film edition and film properties that you require need the a very careful selection of the film with which you are going to start and the film structure. Then, you need to use understanding of the various fabrication or the thin film deposition processes to choose the right process, which would provide reducible coating and long term stability of the properties that you want in your thin film.

So, what material y you are going to use to coat the substrate, it is very important to know because that will enable you to choose the proper fabrication process. Then, you need to develop the equipment that is the chamber in your vacuum has to be generated or the arc has to be generated. If you need to flow of gases and how the substrate can be rotated or the substrate heater has to placed, so all that part of is a is a part of a design to produce an equipment that will give the necessary product through. So, you also need fast product throughput for industry applications and so your choice of production equipment is very necessary the development of the fabrication equipment process parameters, parameter limits and monitoring and the controller techniques.

Ultimately, it will give you the best product and also a high yield, so it is important to choose a proper substrate, the proper methodology and the proper process parameters along with the appropriate equipment The quality and design will ultimately yield a good product with a very high yield, you have to develop appropriate characterizations to determine the product. So, along with choosing the right substrate the right materials for the growth to generate the molecules, which will be deposited on the substrate, you have to choose the characterization techniques to determine the properties of the film which you have made.

So, you have to also develop techniques for the reprocessing or pair of the defective coating. So, if you have a films which have pin holes or which are not farming very uniform films in their needs to be a possibility of developing a method by which you can remove those pinholes. You can do some annealing or other processing by which you can improve the quality of the film, make it more uniform, make the film which is lacking in pinholes with uniform thickness etcetera.

Then, all these processes etcetera need to be written down, all the specifications and manufacturing process instructions need to be written down and as manual for everybody to use at all stages of the processing. So, all the details need to be written down specifically for the manufacturing process, so that proper quality control of these films can be and adhere to…

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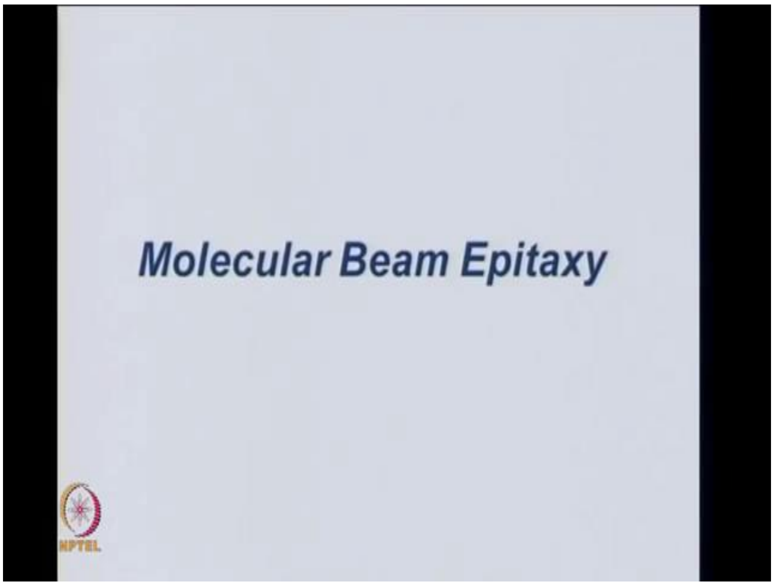

Now, we come to another technique, so far we were doing the P V D technique, so in my previous lecture we did the C V D technique and then today we looked at the physical vapor deposition techniques, what are the different kinds. So, four different kinds of P V D techniques we looked at. We looked at their advantages, their disadvantages and the kind of instrumentation that you need and the kind of parameters you need to control like the substrate the substrate temperature, the gas pressure, the distance between the substrate and the source etcetera. Now, we discussed another technique, which is a highly precise technique though it is a bit expensive technique is the monocular beam epitaxy method.

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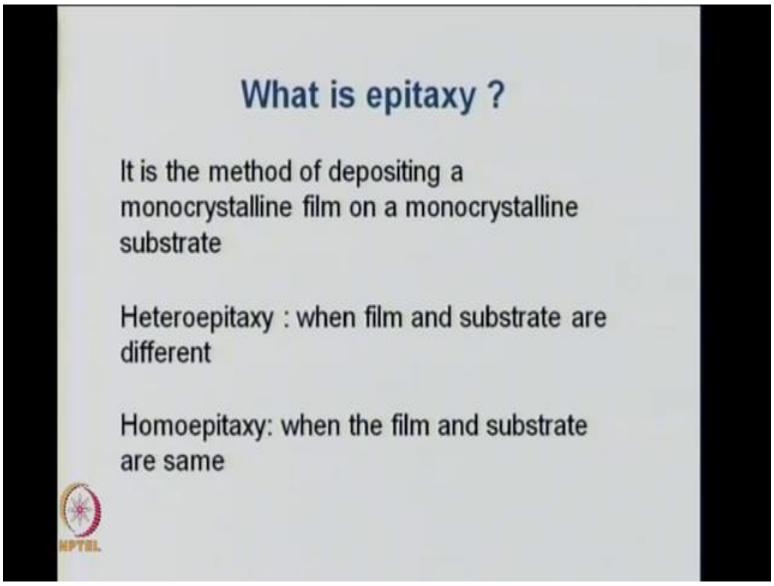

So, what is epitaxy, epitaxy is basically growth deposition of a mono crystalline film on a mono crystalline substrate. Now, if you have the same film, a different film and substrate, so when the film and substrate are different, then it is called hetero epitaxy and when the film and the substrate are the same, then you call it homo epitaxy. So, epitaxy basically means depositing or growing a monocrystalline film on a monocrystalline substrate and it is of two type which can be homo epitaxy and hetero epitaxy.

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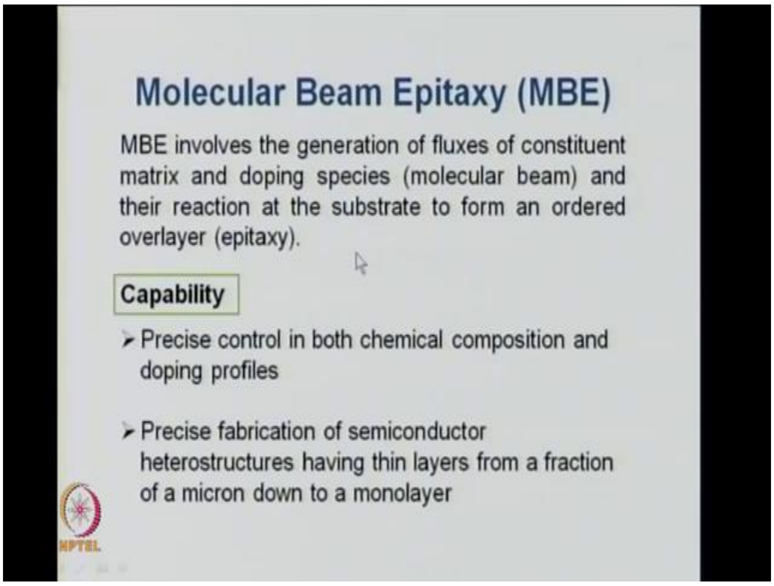

By molecular beam epitaxy MBE, what we mean is that we generate fluxes of constituent metrics and doping species to form a molecular beam. So, these fluxes basically mean you are generating a molecular beam and then their reaction at the substrate. So, the doping species and the matrix species from the molecular beam and they react at the substrate to form an overlayer. So, the substrate and the overlayer are exactly matching and hence it is called a epitaxy. So, the overlayer is guided by the structure of the substrate and hence it takes the structure exactly of the substrate, then only you get epitaxy.

Now, the capability of the MBE technique is to precisely control both chemical composition and the doping profiles. So, it is a very precise technique, you can fabricate precision semiconductors has especially hetero structures having very thin layers from a fraction of a micron down to a monolayer. So, you can have precise fabrication of films on substrates with very precise control of the structure, which is more or less matching with the substrate structure. So, that is why this called epitaxy is called molecular beam epitaxy because we are generating flux or molecular beams of the matrix and doping species.

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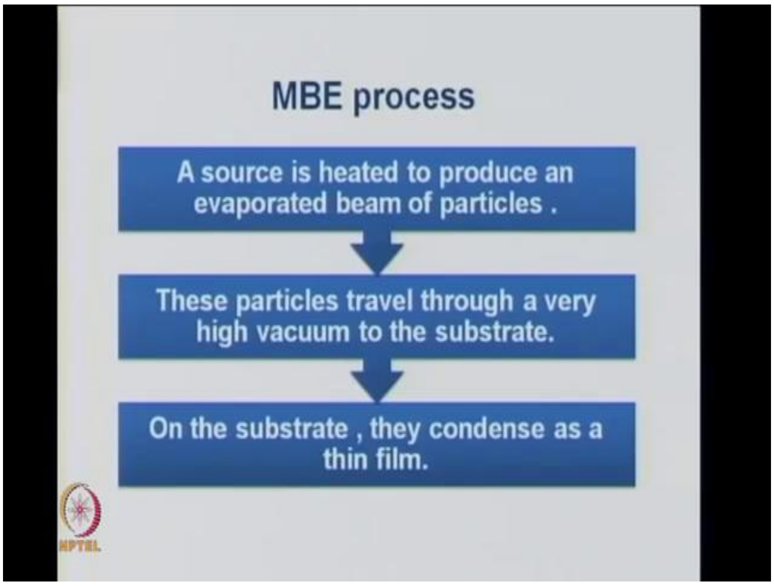

So, in the MBE process, we have a source, which is heated to produce a evaporated beam of articles and these particles then travel through a very high vacuum to the substrate and on the substrate the condense as a thin film. So, this is the typical MBE process, so you have a source again to produce evaporated beam of particles, this particles travel through a chamber in which very few gas molecules are there, that means the chamber is in high vacuum. Then, these particles are directed towards the substrate and on the substrate they condense as thin films.

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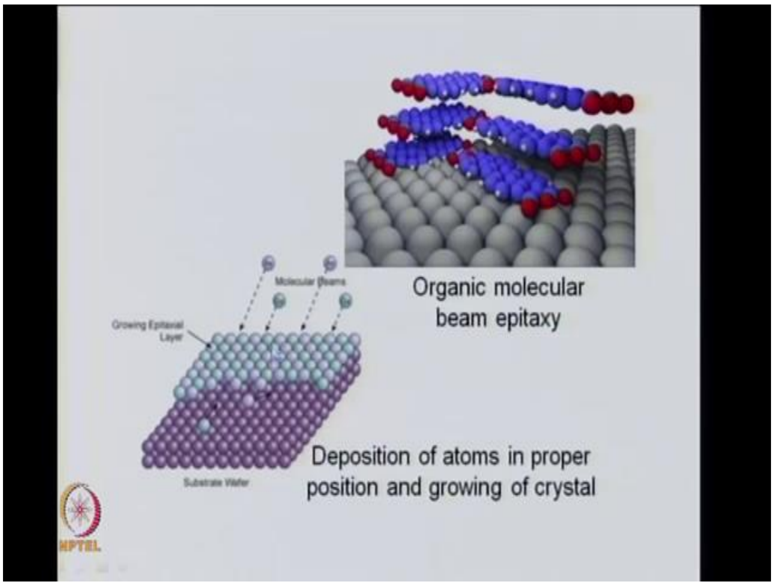

So, here there is a picture of what is happening, so this is the substrate and you can see on that atomic scale and then in an this is a organic molecular beam epitaxy. So, organic molecules are coming and forming layer and this top player is exactly being guided by the substrate structure and you form these kind of layers one on top of the other. This is organic molecular beam epitaxy because organic molecules are part of the dope in flux on the substrate. Now, if you have atoms like you have here gallium atom and arsenic atom and they are falling as molecular beams or fluxes of these gallium and arsenic atoms on top of a substrate.

So, this one is a substrate vapour and on top this gallium and arsenic are falling as a molecular beam. Then, they form this layer on top of this substrate and the structure of the gallium arsenide layer exactly matches the structure of the substrate. So, this is typical molecular beam epitaxy method gallium arsenide as you know is a very important semiconductor and used for many applications. So, this is using an MBE technique, you can manufacture very precise films with controlled morphology and controlled composition of gallium arsenide or as epitaxial layers on proper substrates.

Now, the mechanistic pathway during the MBE process is basically you have an absorption to the surface absorption to the surface, then surface migration and dissociation.

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Then, incorporation into the crystal lattice and thermal desorption, so these are the ways the molecular beam interacts with the surface and the film grows with first absorbing on the surface. Then, it tries to migrate on the surface and so they go the atoms move to the right positions and then incorporate themselves into the crystal lattice and unwanted molecules are thermally desorbed.

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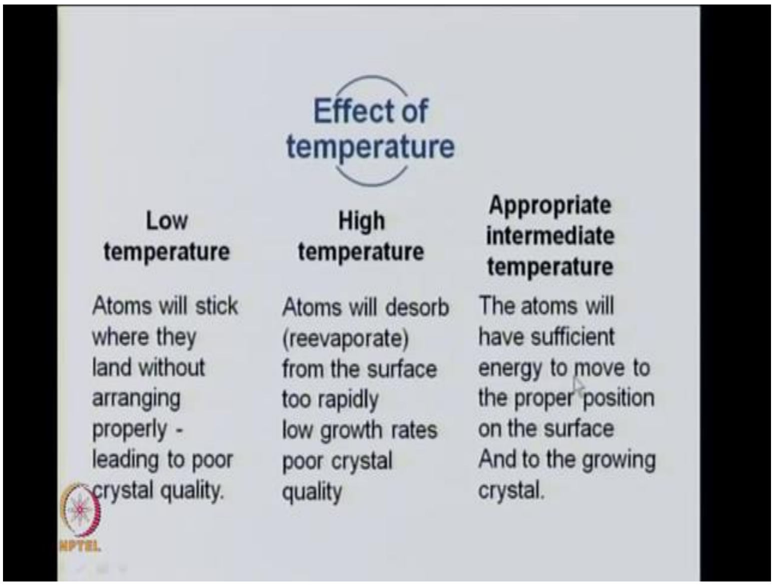

So, this desorption and absorption depends on the temperature, so there is important effect of temperature on absorption and desorption in the MBE process. So, at low temperature, you will have atoms which will stick where they land without rearranging. So, that would lead to poor crystal quality if you have high temperature than atoms will atoms absorbed and desorbed very fast. So, they will re evaporate from the surface too rapidly and the growth rates will be very small again leading to poor crystal quality. So, you have to optimize between low temperature and high temperature, the temperature should be sufficient.

So, you need an appropriate intermediate temperature and at that temperature the atoms will have a sufficient energy to absorb and then move to the proper position on the surface which will give the epitaxy or which will lead to the epitaxial layer. That will be the correct growth of the crystal, which you want, so you need to optimize the temperature such that such that you do not have a very low temperature to have the atoms sticking wherever they are falling or you have very high temperature. When the atoms absorb and desorb immediately or evaporate, you want a temperature where the atom absorbs and then has some energy to move to find the proper position, which has many minimum in energy on the surface.

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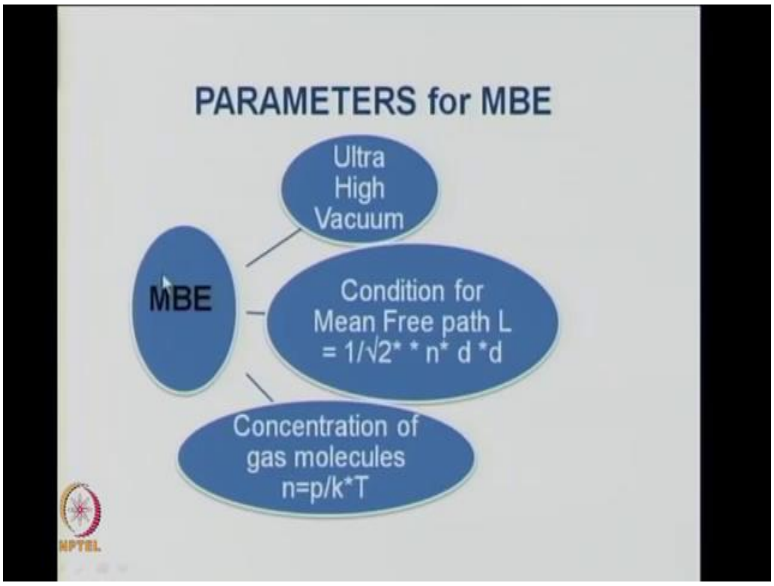

So, the parameters for the molecular beam epitaxial method or the MBE method, you need ultrahigh vacuum and you need some conditions for the mean free path. This is given by the diameter and the concentration of gas molecules and by this equation and the concentration of gas molecules of course depends on the pressure and the temperature, so all these things need to be controlled when you control the MBE process.

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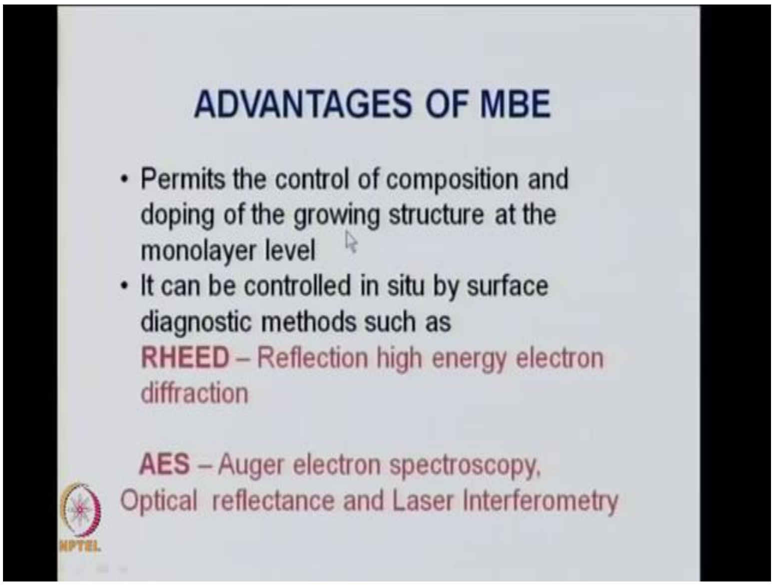

The advantages of the molecular beam epitaxial method are that it permits the control of composition and doping of the structure at the monolayer level. That means you can get single monolayer with the right composition with the right epitaxy using the MBE technique, it can it is also advantageous. It can be controlled in situation by surface techniques you can wild of layer is growing the epitaxial layer is growing.

You can study the layer by very efficient techniques like the reflection high energy electron diffraction, which is called the Reed technique. Also, the Auger electron spectroscopy or optical reflectance or laser interferometry, all these techniques allow you to control the composition and the doping of the growing structure, so these are some advantages of using the molecular beam epitaxy method.

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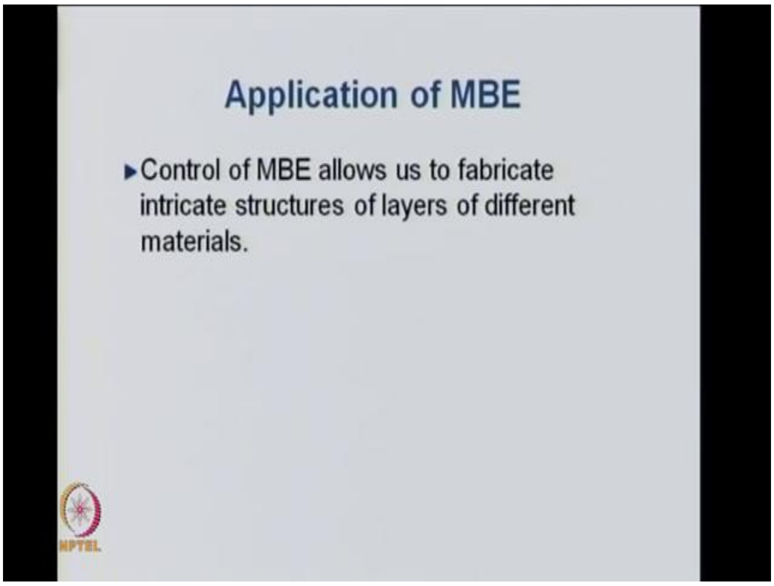

Finally, the application of MBE, the control of the molecular beam epitaxy method allows us to fabricate very intricate structure of layers. So, you can precisely make a very say a ten layer system or a four layer system and each layer having the condition that you want by properly choosing your flux. That means the molecular beams and the temperatures etcetera and the substrate, you can really control the layers and grow highly ordered epitaxial layers of various compositions. So, it is very, very important tool to grow multi layers.

So, thank you for this lecture, and we will continue our course on nanostructure materials, till then good bye.