Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

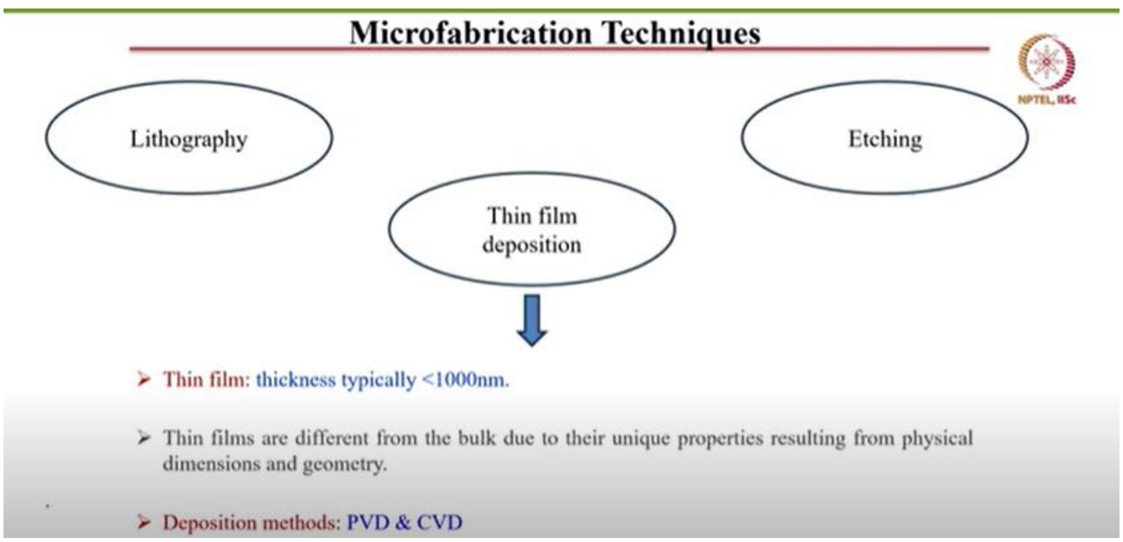
Prof. Karla P. Mercado-Shekhar, Prof. Himanshu Shekhar, Prof. Hardik Jeetendra Pandya

IIT Gandhinagar, IISc Bangalore

Lecture: 25

Chemical Vapor Deposition I

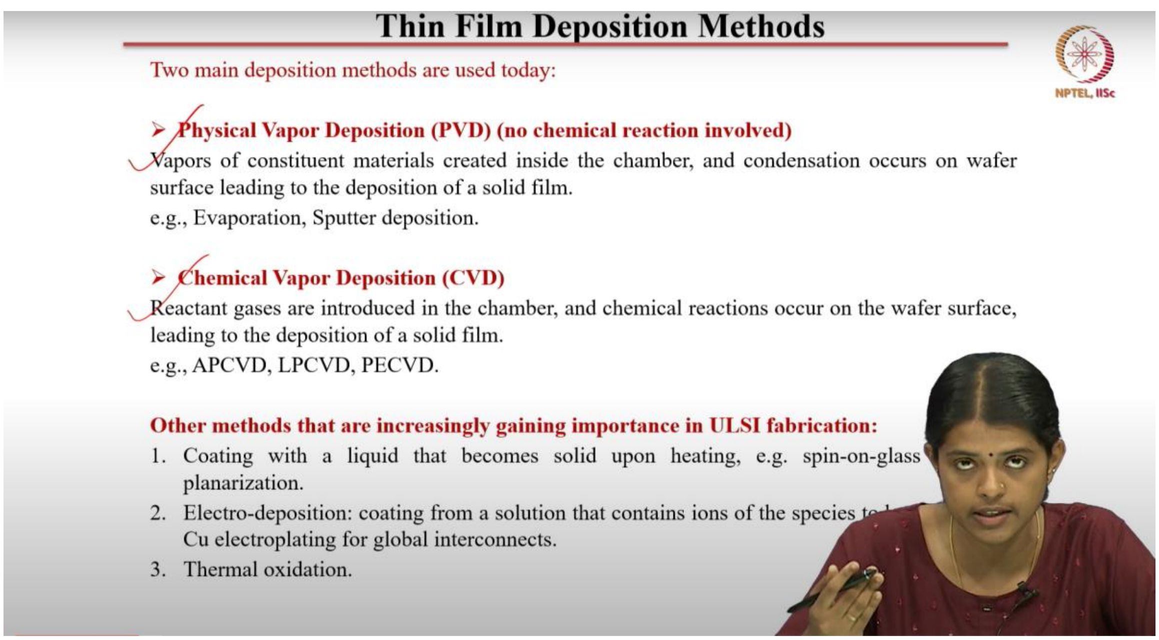
Hi everyone, welcome to this particular session on Chemical Vapor Deposition. So, in your previous lectures you might have seen the different microfabrication techniques that are used for achieving a specific pattern or to produce a specific sensor or a device. So, talking from the microfabrication perspective, there are three main techniques that are used to realize a particular device or a particular sensor that you are trying to fabricate. So, the three main steps that are used in microfabrication techniques are as shown in the slide they are, lithography, various thin film deposition techniques and etching methods.



Lithography is the art of transferring a pattern to a substrate. and the pattern can be based upon the device or the sensor that you are trying to fabricate. So, you might have learned the basics of photolithography where using a UV light, the pattern on a mask is transferred to a resist coated substrate. Then you have various thin film deposition techniques that are used to deposit thin films of various materials like metals or dielectrics. You have learned about physical vapor deposition and also you might have heard about the term CVD which stands for chemical vapor deposition. So, using this thin film deposition, various thin films are deposited on the substrate. Then you also have different etching techniques which includes wet etching, dry etching techniques. The thin films deposited either using physical vapor deposition or chemical vapor deposition are patterned or the unnecessary films that are lying at desired locations on the substrate are removed using various etchants. It can be using a dry etching technique or you can use a solution based etching where you are using some wet etchants to remove the material which are lying at the undesired locations.

So, in this particular lecture, we will talk in detail about the thin film deposition techniques. Mainly, when you talk about a thin film, it refers to films that are having thickness less than 1000 nanometers. And obviously, due to this geometrical construction there are different properties. Thin films have very different properties compared to that of a bulk material due to the unique properties that arises from the dimensions and geometry limitations.

To realize a thin film above your substrate, you can either go for a physical vapor deposition mechanism or a chemical vapor deposition mechanism. So, as we mentioned the major thin film deposition mechanisms are physical vapor deposition and chemical vapor deposition. So, as the term suggests, in physical vapor deposition there are no chemical reactions involved in that particular process. So you have learnt physical vapour deposition is of different types like evaporation and sputtering. And again evaporation techniques are classified into thermal evaporation or e-beam evaporation based upon the method that is used to evaporate the source material. Here the constituent materials are evaporated using either thermal energy or an electron beam and this vapors travel towards a substrate where you have placed your silicon wafer or any other substrate that you are planning to have a thin film deposited on. This substrates are placed inside a chamber and this vapors travel and get condensed on the wafer surface leading to the formation of a thin film. As we mentioned it can be of evaporation method or sputtering technique.

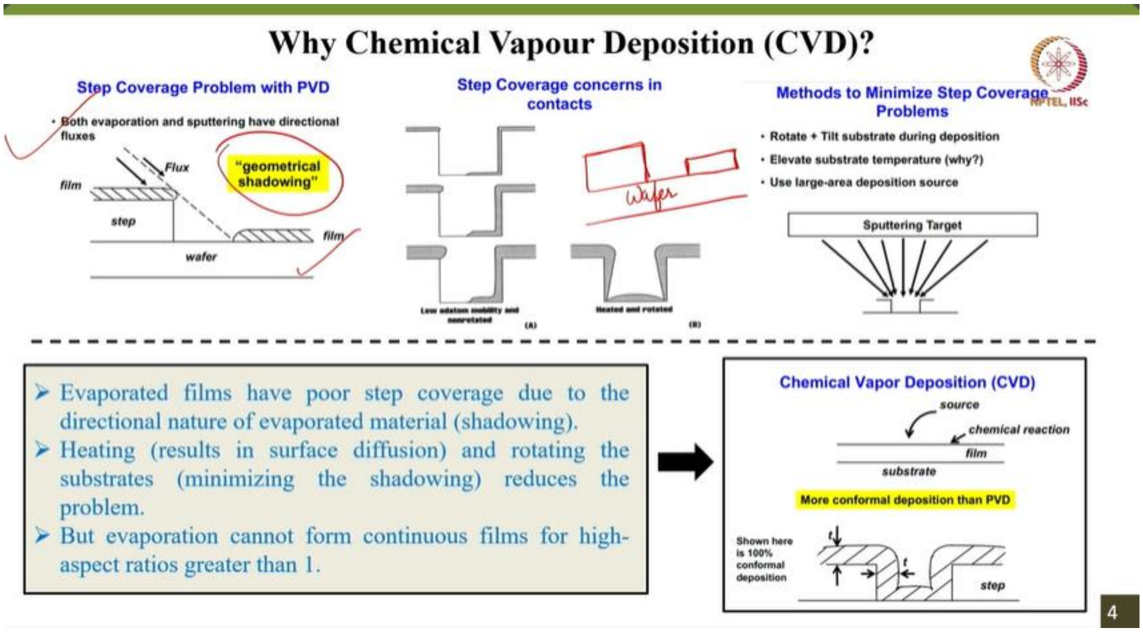


Coming to chemical vapor deposition method, as the name suggests there are some sort of chemical reactions taking place in the chamber. For example, in a chemical vapor deposition technique, the reactant gases which are required to realize a particular thin film on a substrate are introduced into the chamber and then various types of chemical reactions takes place on the surface of your wafer. As a result, a thin film will be formed above your wafer surface.

Chemical vapor deposition technique is classified into different types based upon various conditions maintained inside that chamber where the CVD reactions happen, like APCVD which stands for atmospheric pressure chemical vapor deposition. Then we have low pressure CVD, whose short form is LP-CVD and then we have plasma enhanced chemical vapor deposition, where instead of thermal energy plasma is used to initiate a particular reaction to happen in the chamber.

Other than these physical vapor deposition and chemical vapor deposition techniques, there are various other methods that are gaining importance in ULSI fabrication. First one is a spin on glass technique where a liquid is coated upon a substrate and then later on it is heated so that a solid layer is formed. Then there is electro-deposition. You might be familiar with the electrolysis method, where we will be having a solution which has the particular ions of the species to be deposited. For example, the copper electroplating to form the global interconnects. Electrolysis is the basic principle behind electrodeposition. We have learned about the thermal oxidation as well, where for example, if you are talking about silicon dioxide formation above a silicon wafer, how thermal oxidation reactor chamber looks like, how the process proceeds further consuming a certain amount of the substrate to realize a particular layer of silicon dioxide. So, these are few other techniques that are used for realization of a thin film above a substrate.

Moving on to the need of chemical vapor deposition compared to various physical vapor deposition techniques. The first figure below shows the main problem that is encountered with a physical vapor deposition technique known as geometrical shadowing. For example, if you have your wafer and you are having a step like profile above your wafer, and if you are planning to realize a thin film of material above this particular step like profile. in such a case in both evaporation and sputtering, we have a directional flux of the molecules that travels towards the wafer surface eventually getting deposited on the wafer surface. But due to this directional flux of atoms you would not be having a uniform coverage of film above the horizontal surface as well as along the side walls.

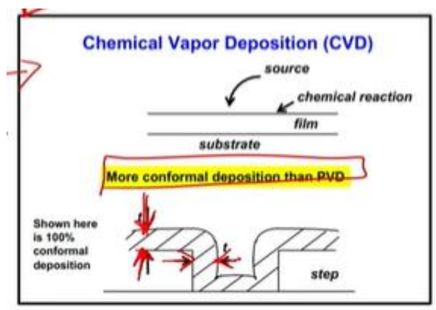


So when you look into a step like profile existing on your wafer surface due to this particular directional flux in evaporation and sputtering, this sidewalls will not be covered uniformly and that process we call it as geometrical shadowing. So when you are concerned about a contact where you want to take electrical contact from your substrate due to this unequal coverage of the thin film in the horizontal direction as well as in the vertical direction the deposited layer will not be conformal or in other words you can say that the layer that is formed above your substrate is non-conformal. That means the thickness of the layer deposited in the horizontal direction as well as the thickness of the layer that is deposited along the sidewalls or in the vertical direction will not be the same and in such a situation we call the deposited layer as a non-conformal layer. So, this is a main issue with the physical vapor deposition technique.

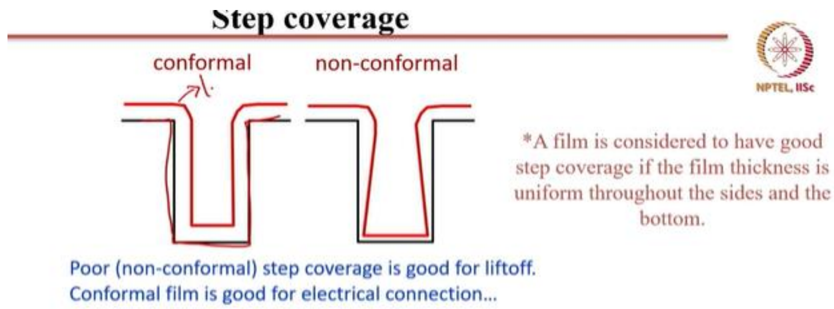
There are a few steps and techniques you can adopt to minimize this step coverage issue. First one is you can rotate as well as you can tilt your substrate during the physical vapor deposition mechanism. So, while the deposition process is happening, if you are continuously rotating the substrate or tilting it at a certain angle, this may help to have a uniform step coverage or it may help to have equal deposition among the sidewall as well. Also you can raise the substrate temperature. What happens when you raise a substrate temperature is that when you after depositing a thin film and when the substrate temperature is raised it will result in enhanced surface diffusion as well as when the substrate is rotated it will minimize this shadowing effect. So, these are a few techniques that can be used to minimize this step coverage concern. Also, you can use a deposition source that covers a larger area.

Even if you adopt these techniques in your chamber you cannot completely solve the step coverage issue or you cannot have a fully uniform step coverage in a physical vapor deposition chamber. This is because if you are talking about a structure where the aspect ratio is greater than 1, for example, if you have a deep trench like this, where the dimension in the vertical direction is more than that of the dimension in the horizontal direction such a structure or geometry you call it as a structure with aspect ratio greater than 1. So in a structure with a high aspect ratio even if you rotate or tilt your substrate or even if you increase the temperature, the coverage of the film deposited in the structure will not be the same. This is a main drawback of a physical vapor deposition mechanism and in such a situation we prefer to go to the technique which I have already mentioned that is a chemical vapor deposition technique.

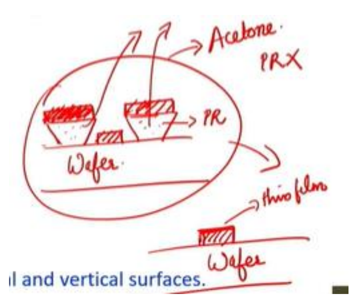
So, the main advantage of a chemical vapor deposition technique compared to a PVD technique is that, the Chemical vapor deposition is more conformal than PVD that means the thickness of the layer deposited in the horizontal and vertical directions will be the same. The below figure shows a 100 percent conformal deposition. That means the layer deposited is uniform throughout the surface of your substrate.



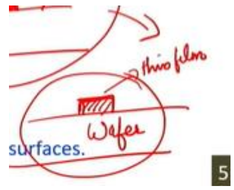
So again the next slide shows the example of a conformal deposition and a non-conformal deposition. The black structure shows the geometry existing in your wafer surface and the red layer shows the layer that is deposited above your substrate. So, you can say the first figure is a conformal deposition, it is because the thickness is the same in the horizontal dimension as well as in the vertical dimension. But looking at the second figure you can say directly that it is a non conformal deposition. That means the thickness of the layer in both the horizontal dimension is the same but coming to the side walls or in the vertical dimension ,the thickness is not the same. So the first figure is a conformal deposition whereas the second figure is a non-conformal deposition.



But can you think of a situation where you wish to have a non-conformal deposition. You might have heard of the term lift off. So what happens in lift off compared to a conventional lithography technique? For example, if you have a wafer and you are depositing or spin coating a photoresist above your wafer. So in lift off you will be having your wafer, you will deposit your photoresist you will spin coat your photoresist and you are getting a pattern photoresist in this particular manner where the photoresist is abbreviated as PR. The photoresist is patterned above your silicon wafer. And now using any of the thin film deposition technique for example, say a physical vapor deposition technique, the thin film layer deposited will be of this particular manner because in PVD as we mentioned the thickness of the thin film that is deposited above your structure in the horizontal direction will not be the same in the vertical direction as well. So now when you dip this entire structure in acetone for removing photoresist above your wafer, it removes the thin film that is deposited above your PR layer. So after the acetone dip technique, a step the pattern that will be existing above your wafer. This is a thin film existing above your wafer and it is because acetone has dissolved your photoresist and therefore the metal layer above the patterned photoresist will also be removed. So this is just the thin film that is existing above your wafer. So, when you think of a situation or when you think of an application when you are using a lift off technique you would always prefer to have a non conformal deposition because if the deposition of the thin film was conformal then the layer will be covering entire side walls as well.



So, the thin film deposited would cover the sidewalls as well as the horizontal dimension. So, when you think of putting this entire structure in acetone for removing the photoresist what happens is the photoresist in the region marked with arrows will be dissolved. But since there is a metal coating along the sidewalls as well, you will not be able to get a perfect thin film structure as shown in the figure below. So if you are intending or if you are planning to have a lift off technique in your entire process flow, it is always desired to have a non-conformal deposition.



But if you are planning to have a normal lithography and patterning technique, you would always prefer to have a conformal deposition. So, the entire catch point from this particular slide is that depending upon your process flow based on whether you are adopting a lift off technique or you are adopting a normal lithography and thin film deposition technique, the choice of the deposition techniques would vary. If there is a lift off process in your process flow, you would prefer to have a non-conformal deposition of the thin film, so that it is more or less easy to remove that particular layer. And if there is a normal lithography and a normal process flow, (normal in the sense it is not a kind of lift off technique) then you would like to have a conformal deposition and in that case you would prefer to have chemical vapor deposition as the thin film deposition mechanism.

So the figure below shows another example for a conformal and non-conformal deposition. So this particular figure a, is a conformal deposition because throughout you have a uniform thickness of the metal film that is deposited above your wafer which is having a particular geometry. And in the figure b, you can see the thin film deposition thickness is different along the vertical dimension. So that is obviously a non-conformal deposition.

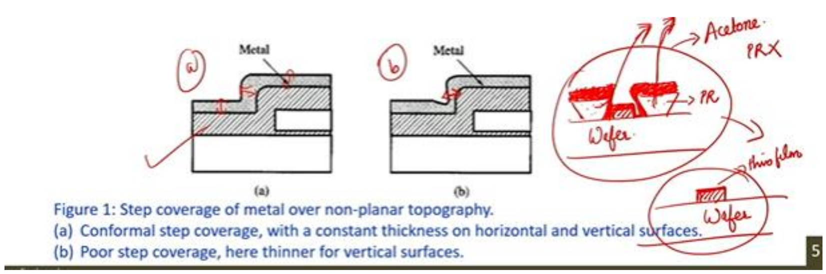


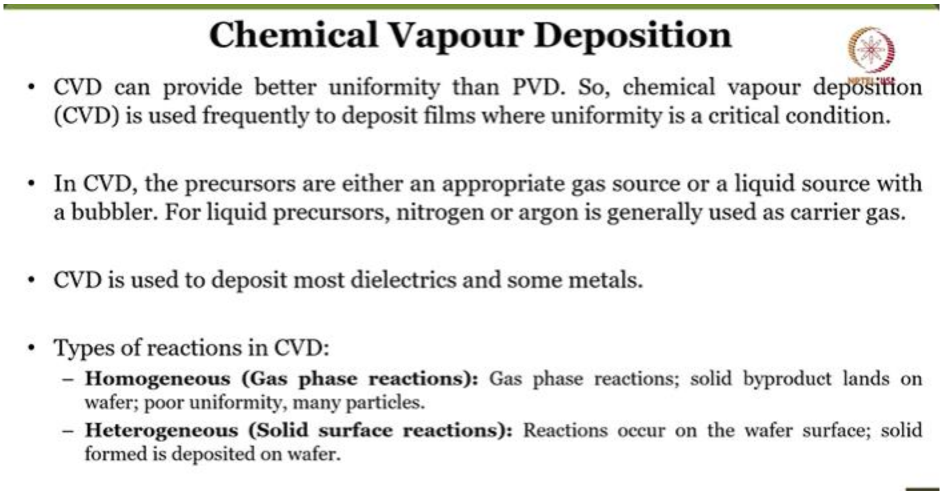
Figure 1: Step coverage of metal over non-planar topography.
(a) Conformal step coverage, with a constant thickness on horizontal and vertical surfaces.
(b) Poor step coverage, here thinner for vertical surfaces.

Okay so moving on to the basics of chemical vapour deposition technique. As we mentioned, CVD can provide better uniformity than a physical vapour deposition technique. So wherever uniformity is a critical condition, we always prefer to choose CVD as a thin film deposition mechanism. So as the name suggest there are some sort of chemical reactions happening within the chamber. So, the precursor molecules are chosen depending upon the thin film that you would like to realize above your wafer surface. So, the precursor molecules can be either in the gaseous form so that it can be directly taken inside your chamber where your substrates are aligned, or the precursors can be in a liquid form. For example, it can be taken in a bubbler and you can evaporate it so that the vapor molecules can be taken to the chamber and reacted with your substrate to form a thin film.

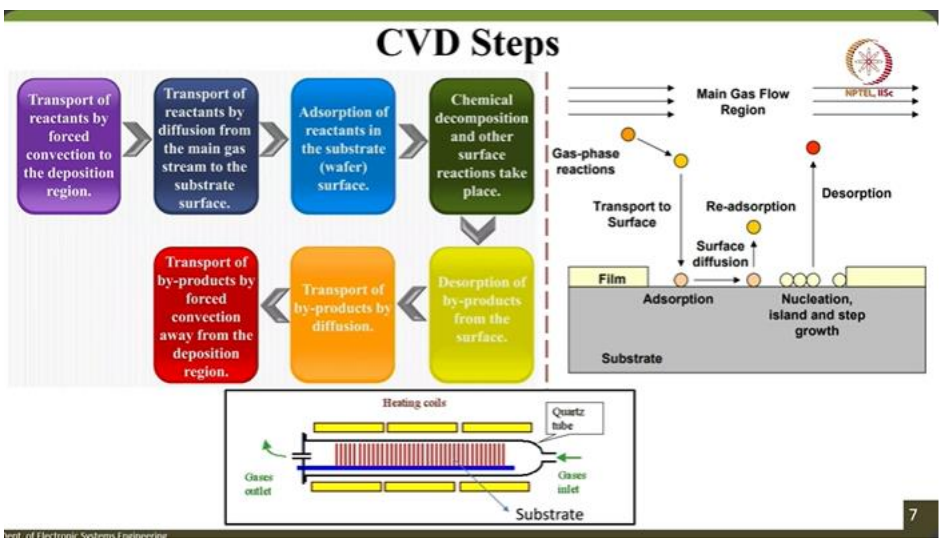
Whenever you are using a liquid source as your precursor molecule, you have to use an inert gas like nitrogen or argon that would act as a carrier gas. Carrier gas is used to take your vapor molecules from the bubbler to the chamber. So, the purpose of using an inert gas is that it should not react with your substrate at any cost, but at the same time the precursor molecules which are evaporated from the liquid source in the bubbler should be taken appropriately to the chamber where you have your substrate placed for the reaction to happen. Then CVD can be used to deposit different metals or different dielectric materials.

There are two types of reactions that is happening in a chemical vapor deposition process that is a homogeneous or gas phase reaction and heterogeneous or a solid surface reaction. Homogeneous reactions means that the reactions happen in the gas phase and as a result the byproducts that are formed will get deposited on your wafer. Here, the reaction is not happening on your wafer surface, but in turn it happens in the gas phase and only the byproducts will get deposited above your wafer surface. So, if homogeneous reactions are happening more in your reaction chamber, you can say that the deposited layer would be of poor uniformity or it will not be of that good quality because only the byproducts are landing on your wafer, which lead to a non-uniformity in the deposited layer.

In the other case you can have a heterogeneous or solid surface reaction and that is a type of reaction that is preferred in a CVD chamber because in this particular type of heterogeneous reaction, the actual chemical reactions are happening on the wafer surface itself and a solid film is deposited on the wafer. So compared to homogeneous reaction, in a CVD chamber where heterogeneous reactions happens more, you can say that the quality of the deposited film will be more better and the layer formed will be more uniform as well. So always in a CVD chamber, the partial pressure of the reactant molecules are adjusted in such a way that always heterogeneous reactions are preferred.



So, the figure shows the basic steps of a chemical vapor deposition process. As I mentioned you will have a chamber, where you will have a substrate holder and you can arrange your substrates in the manner as required and you will have a inlet where the precursor molecules are taken to the inside of the reactor and chemical reactions takes place in your chamber and a layer of film will be deposited or formed on your wafer surface. After the particular chemical reaction, the byproducts generated will be taken outside of the chamber. This is the entire overview of a chemical vapor deposition process.

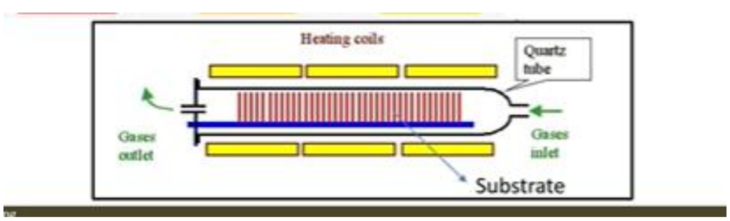


So the first step as I mentioned would be that the reactants will be transported to the chamber where the deposition process takes place by means of a forced convection because you are using some sort of pump or some forceful mechanism to take your precursor molecules to your chamber and that is why you term that process as a forced convection mechanism.

Once this reactant molecules enter your chamber you can say that at the inlet of the chamber, the concentration of the precursor molecules will be high compared to the other areas of your chamber. So due to this difference in concentration, the reactants will be diffused from the main stream to the place where you have kept your wafer. It is due to the diffusion mechanism the reactant molecules enter the chamber and it gets attracted to the place where you have kept your wafer above your substrate holder and some sort of chemical reaction starts to happen and this process is due to the diffusion mechanism due to a concentration gradient. And once this reactant or precursor molecules reaches your wafer surface, adsorption happens, and all the precursor molecules will be adsorbed onto your wafer surface and as a result different types of chemical reactions happens like thermal decomposition or some sort of pyrolysis reaction or a reduction mechanism. So depending upon the temperature in the chamber, the pressure in the chamber, and the type of precursor molecules that you have chosen, certain set of chemical reactions would happen on your wafer surface, and a few byproducts will be produced that will be later on desorbed from the surface of your wafer.

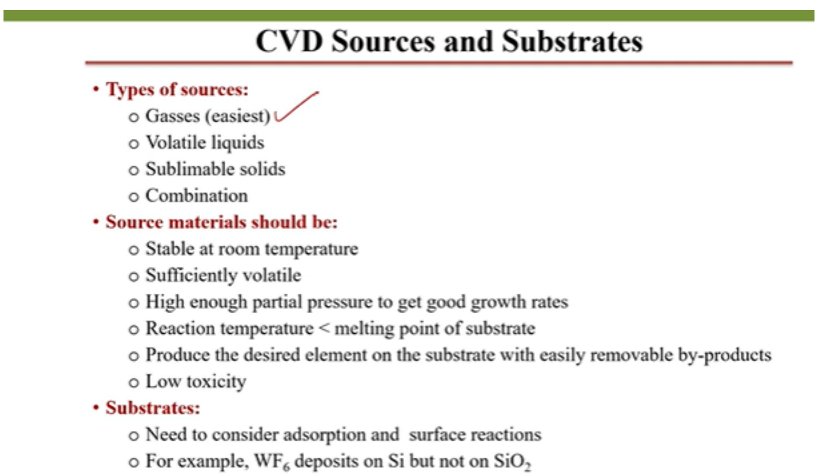
Again due to the concentration difference of the byproduct at places near to your wafer and at regions away from your chamber, this byproducts will be taken or moved away from your substrate surface and finally again by means of a forced convection mechanism, this byproducts will be taken away from the deposition chamber.

The figure below, shows the basic just a schematic of how a CVD reactor would look like. You have a quartz tube. that is shown in the black color where you have a substrate holder and all your substrates are arranged in a vertical direction. So the number of substrates, and how the wafers are stacked inside your chamber, depends upon the type of the CVD mechanism.



Then there are heating coils to heat the chamber to a high temperature at which a particular reaction happens and at this point, the precursor molecules are taken inside the chamber and at the other end you have an outlet so that the byproducts are taken outside the reaction chamber.

What are the basic steps that you should take into consideration when you are designing a particular chamber? That is, what type of source should be used in a CVD chamber. So the type of source chosen can be either gas which is the easiest type of source because you can directly take this precursor gaseous molecules to the chamber where the reaction happens. Also the source can be in the form of a volatile liquid so that the liquid evaporates or it can be taken in a bubbler, it evaporates and using a carrier gas this vapor can be taken to your chamber. Also you can use a solid which are sublimable in nature so that it can be directly converted to the vapor form and the vapors can be taken for the reaction. You can also use a source that is a combination of either a gaseous form or in a liquid form or in a solid form. Whatever be the type of source material that you are using, it should be sufficiently stable at the temperature at which the particular reaction happens and the source should be sufficiently volatile in nature. And as we mentioned in the first slide, the partial pressure in the chamber should be such that heterogeneous reactions are favored. Even though heterogeneous reactions takes place, we should be able to have a good growth rate inside the CVD chamber. So the choice of the source material should be such that it favors good growth rate at the particular partial pressure at which the reaction chamber is maintained. Also the temperature at which the particular reaction happens, should be always less than the melting point of the substrate that you have chosen. The byproducts that is formed after the particular chemical reaction, should be easily removable and the toxicity nature of the source material should also be as less as possible. The type of substrate that is chosen is also important because for example tungsten hexafluoride film can be easily formed on a silicon substrate but it is difficult to form that particular film on a SiO2 substrate. So the type of the substrate that is chosen in a particular CVD process also matters.



We will end this particular session by this particular slide and we will continue with the remaining portions in the next class. Thank you.