Microrobotics

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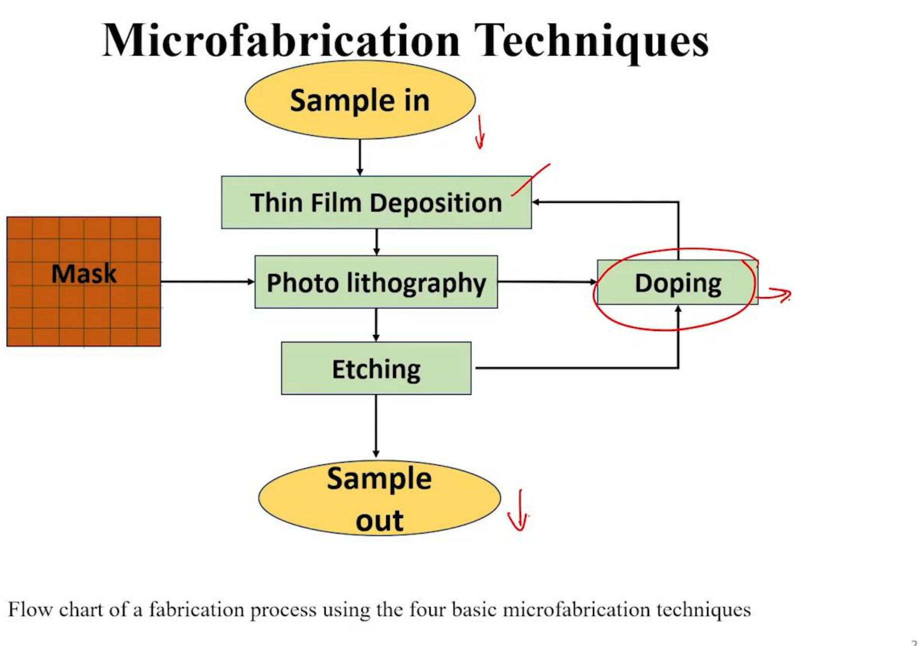
Week- 03

Lecture No- 11

MicroMechanics System Design (Micro-Fabrication of Micro Robots) - Module 01

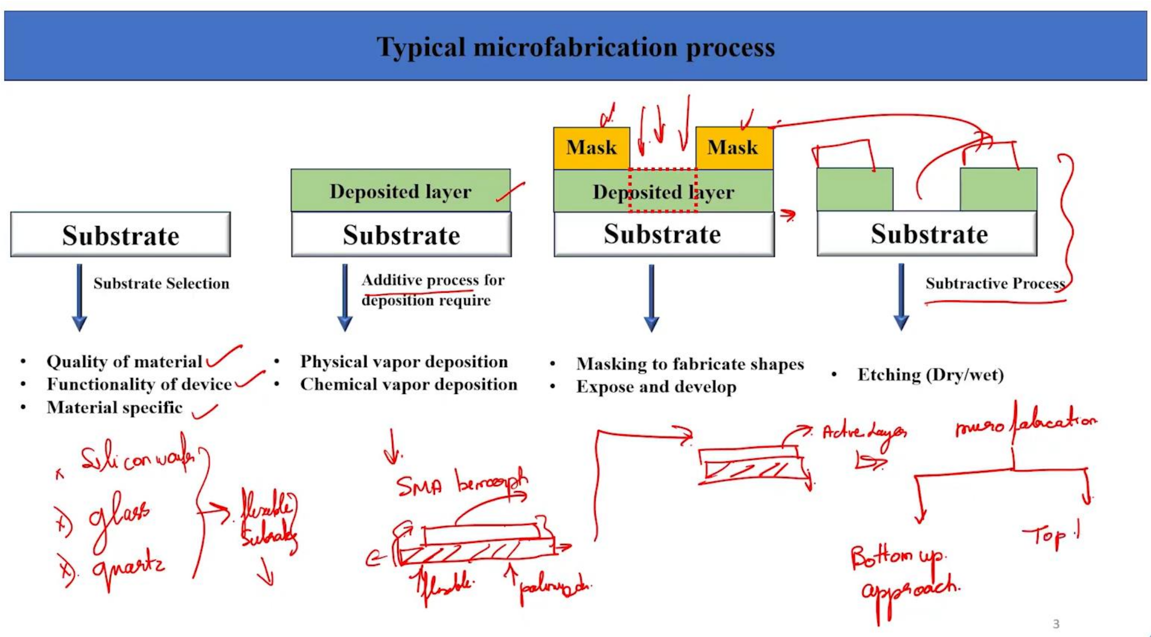
In this module, the discussion will be on the microfabrication techniques that are being used for developing micro robotic systems. Ideally, the main focus of this particular module is to expose the participants to the different microfabrication techniques that are being employed for developing any kind of microsystems or microdevices. In order to develop a certain amount of mechanisms that have a direct relevance to microfabrication-related applications, we should take an overall look at the microfabrication techniques, as this is essentially how a fabrication process is deployed. There are four basic microfabrication techniques that exhibit. So, this is a kind of flow that is being deployed here. So, in this particular flow, let us consider this as a kind of sample that is being used.



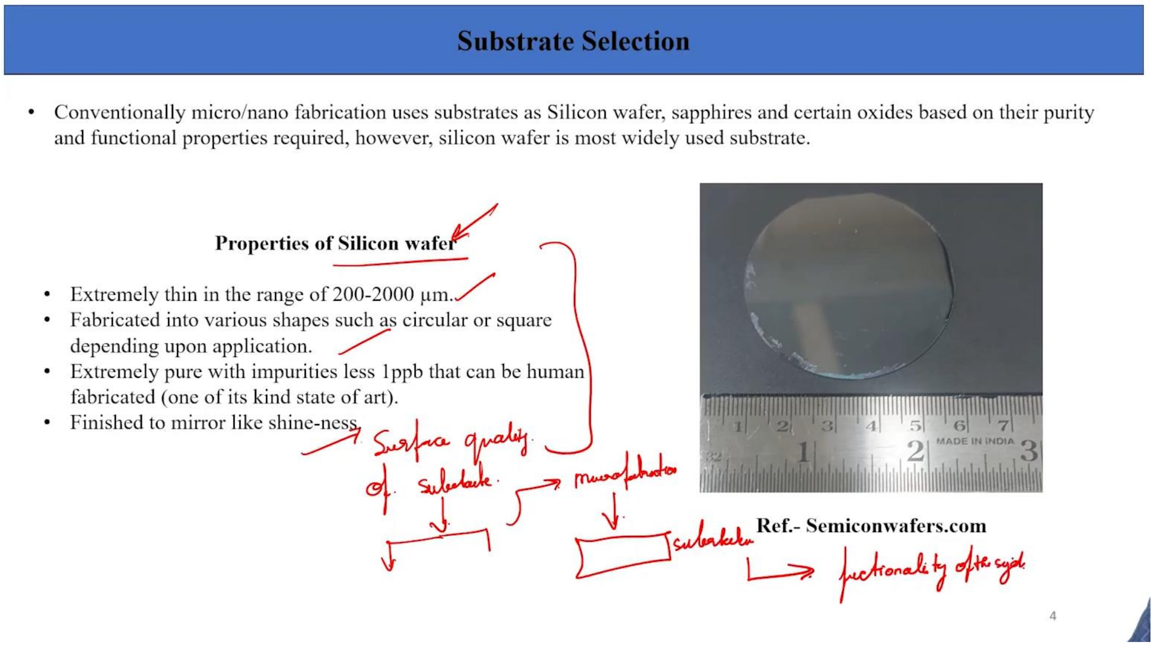
Flow chart of a fabrication process using the four basic microfabrication techniques

So, within this sample, there is a kind of thin film deposition which is followed by either photolithography, in case we are working in a domain that is less than a few microns, or in certain cases we don't use photolithography. We will directly go for a wider spectrum where we are working in the range of one micrometer, etc. Then we have a process called etching. In between, there is also a process called doping, and the main function of this doping is to improve certain functionalities, which include a kind of charging capability or a kind of electrical capability, etc., that are taken care of by this doping process. And then there is a mass process exhibited here, and finally, we get a product coming out of it. This is a kind of generalized process flow chart or process map that is being established for developing different microsystems or microsensors, etc. However, in order to classify the type of microfabrication process or to introduce you to the different components that contribute to microfabrication or to developing a kind of microsystem, the first component that exhibits is the substrate. So, the substrate is a kind of freestanding layer; over this freestanding layer, we try to build the structure we are looking for.

For instance, the substrate can be either glass or a specific quality of material, or it is more towards being material-specific. So, the substrate can be either a silicon wafer or, in certain cases, it can be glass. If we are focusing more on a kind of optical functionality, quartz can also be used. In addition to this, different flexible substrates are also available. So, the main function of these flexible substrates is that we have an active medium, and in order to cater to the active medium or to participate along with the active medium, such kinds of flexible substrates can be deployed, and these flexible substrates are sometimes transparent enough in such a way that we can see the complete functionality of the device we are fabricating.



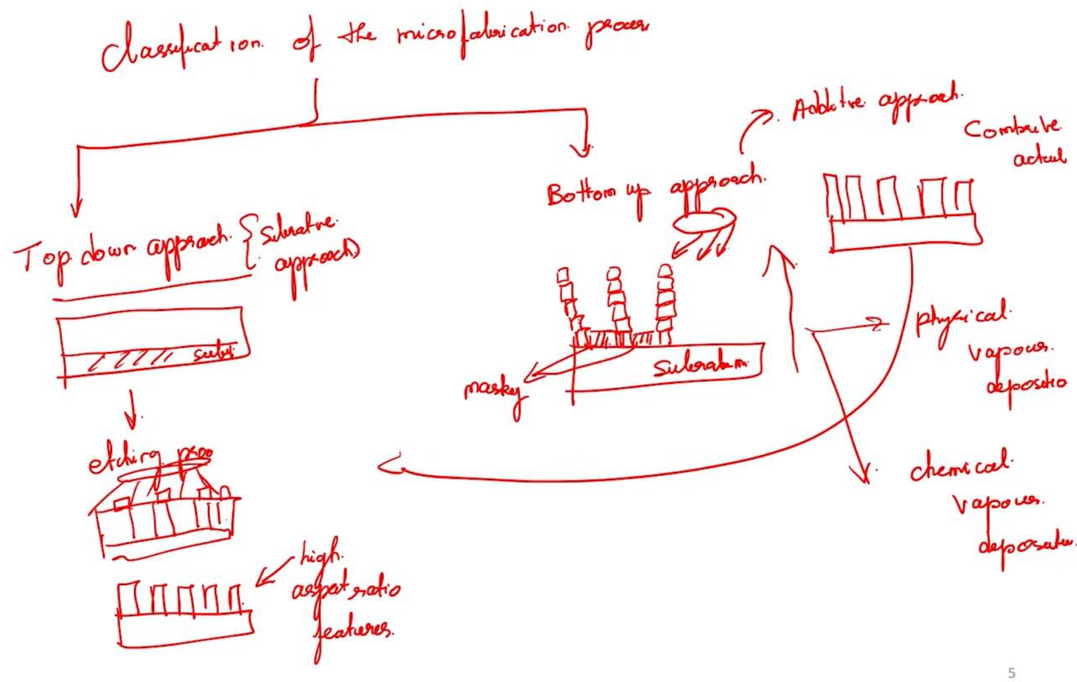
Now, when we try to look into the substrate selection, the substrate is basically selected based on the quality of the material, the functionality of the device, and the material specifics. This substrate acts as a base, over which materials are normally deposited. So, in certain cases, for example, if you are talking about a smart material, these smart materials can be efficiently deposited on a substrate, and by actuating them appropriately, we can have a certain functionality. Let us understand through a simple example, where we are working on this concept called SMA bimorph. So in the case of SMA bimorph, we have a shape memory alloy that is being deposited on a polyimide layer.



These polyimide layers are programmed in such a way that they have a good adaptability with the SMA. When an SMA is actuated in this particular direction or with a particular displacement, this polyimide will also try to take the same shape. That is, when we try to actuate this shape memory alloy, there will be a kind of deflection that occurs here, and when we try to cut off the actuation, it returns to its shape. So here, in this particular case, the substrate is participating with the actuator for our applications. This is a kind of flexible substrate that also exhibits a supporting structure.

So, over the substrate, a layer can be built and then this substrate can be etched so that this active layer can be efficiently used for actuation as well as for different micro-robotic or microsystem applications. So ideally, this deposited layer is considered to be an active layer that participates in the system. Now, if we need to create a certain amount of features on this deposited layer, we may need to have a kind of masking that is exhibited here. These masks are placed, and then we try to expose these layers to a kind of light, which might be a laser, or it might be a kind of mechanical machining where these layers can be efficiently removed. So ideally, what happens is if I want to create a feature like this, a mask that is placed over here will protect the particular deposited layer that is below this mask.

Then I get the final features I am looking for. Now, ideally, if I see this, it is a particular overall flow. There are two important technical parameters being emphasized here: one is called an additive process, and the other is called a subtractive process. As far as the additive process is concerned, it involves adding material, while the subtractive process involves removing material. Generally, the microfabrication process for MEMS or micro robotic applications can be classified into two different approaches.



One is called a bottom-up approach, and the other is called a top-down approach. So what are these bottom-up and top-down approaches? So before going into this, we have to understand the overall functionality of the substrate we are using. One of the key substrates that exhibit this is a kind of silicon wafer, which is used for growing a certain number of layers. The overall functionality of the growth basically depends on the thickness of the silicon wafer, and it also depends on the size and shape of the structure for different applications. It also depends on the purity of the material and the overall surface quality of the substrate.

For instance, suppose we are designing a micro robot for a type of underwater application. It is expected that it should have a kind of hydrophobic capability so that the water doesn't stick to the surface. In certain cases, we may need to have a type of robot, specifically micro robots, that have a hydrophilic capability. Here, surface quality plays a vital role, so wherever necessary, we need to have a structured pattern. So, in those structural patterns, based on functionality or characteristics, generate such kinds of impacts on the surface quality based on the requirements or characteristics.

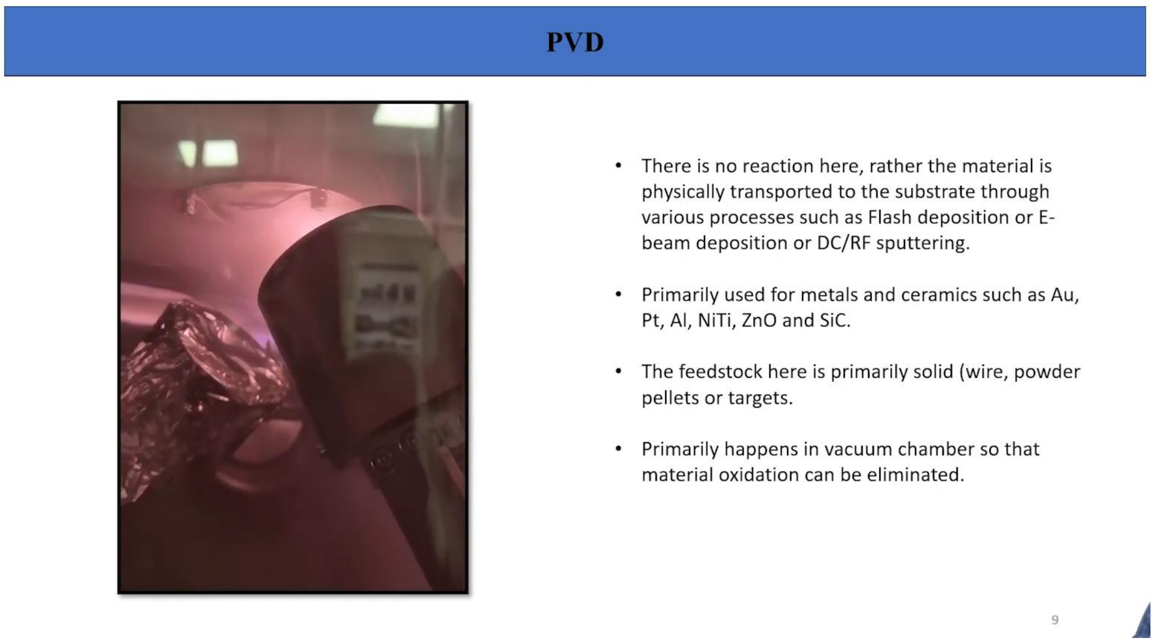
The most important point that may need to be considered here is that microfabrication should go hand in hand with the substrate properties, which have a direct impact on the functionality of the system. Now, let us discuss the overall classification of this microfabrication. Ideally, a microfabrication process is classified into two: one is called a top-down approach and the other is called a bottom-up approach. Let us consider that we have a substrate. Over the substrate, if we need to build a structure like developing a comb drive actuator (part of it).

So, I have two different options: one is with reference to the substrate, which can build layer by layer. In order to build a layer-by-layer formation, I need to create an appropriate mask here. This mask will take care of the feature generation. So, when trying to build these structures, have a specific targeted material and a type of substrate material. Through this targeted material, attempt to deposit the particle onto the substrate.

So, when trying to throw the particle onto the substrate, the particle will try to get aligned or it will try to build, and wherever the particle deposition is required, that particular domain is taken into consideration. Wherever the particle is not required, we have masking in place. By leaving the masking, appropriately try to build the structure. This is called a bottom-up approach, where we are trying to build the structure from the bottom. In a top-down approach, consider a bulk layer over the substrate and perform an etching process. Before that, create a mask over the bulk layer, and by exposure to light, through a laser, or sometimes by exposure to chemical means, etch these layers, finally ending up with such high aspect ratio features. This process is called a top-down approach. So, a top-down approach is also mentioned as a kind of subtractive approach, while a bottom-up approach can also be called an additive approach. There are a wide variety of techniques available for this top-down approach as well as for this bottom-up approach. As far as top-down approaches are concerned, in the case of thin film technology, lasers are being efficiently used for etching applications.

Also consider a kind of electron beam lithography or electron beam-based etching that can be used for efficient etching applications. Apart from this, also go for a certain amount of chemical treatment that is being effectively used for etching such features. So in all these cases, either use a mask or, in certain cases, try to focus the energy that we are using so that these energies can be efficiently used for etching-related applications. However, in the additive approach, features are tried to be built layer by layer. For this layer-by-layer processing, there are different types of techniques available.

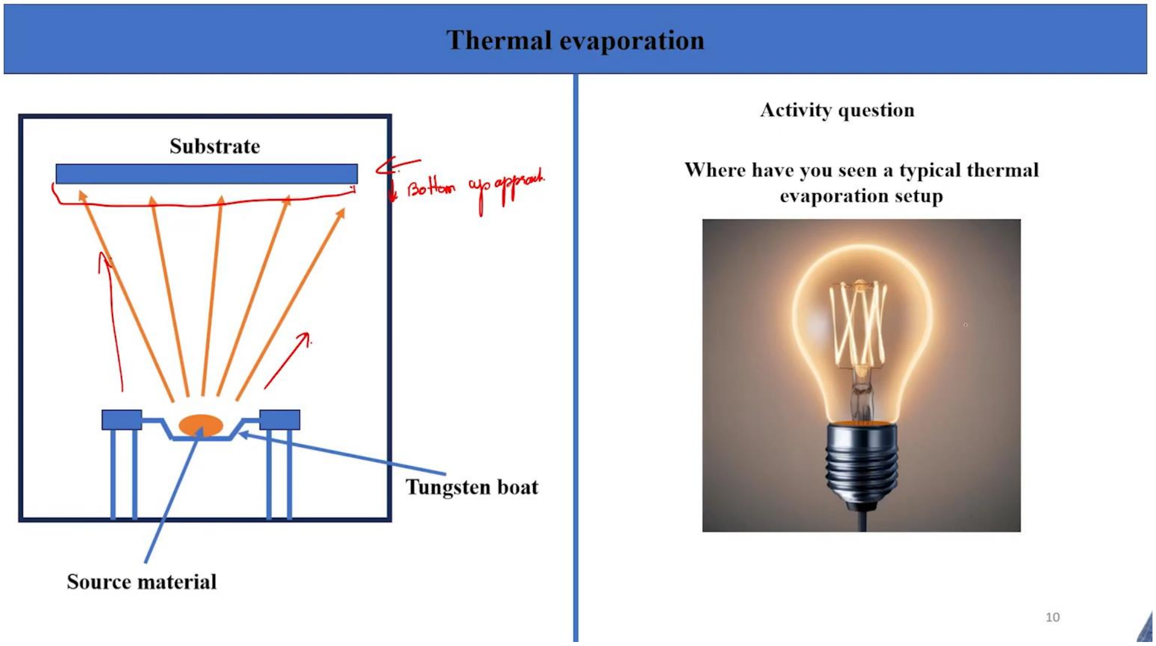
These techniques are classified into two: one is called a physical vapor deposition technique, and the other is called a chemical vapor deposition technique. In this physical vapour deposition technique, a material is converted into a vapour, and these vapours are efficiently deposited on the surface. The sputtering process, which falls under the category of physical vapor deposition, does not involve any reactions. Rather, a material is physically transferred to the substrate through various processes such as flash evaporation, e-beam process, or RF sputtering. So, if you look at the overall materials, we have metals and ceramics that are being efficiently used, and the primary feedstock for such physical vapor deposition might be a wire, a powder, or a pellet.



So primarily, if we try to look into physical vapor deposition, this process happens inside a vacuum chamber. There are different types of physical vapor deposition. One of the preliminary physical vapor deposition methods is a kind of thermal evaporation. In this thermal evaporation process, when I try to introduce you to the different components, we keep the substrate, which is a kind of source material. The source material that can be efficiently deposited using this technique will be a metal, and this metal will be placed inside a tungsten boat, as exhibited here.

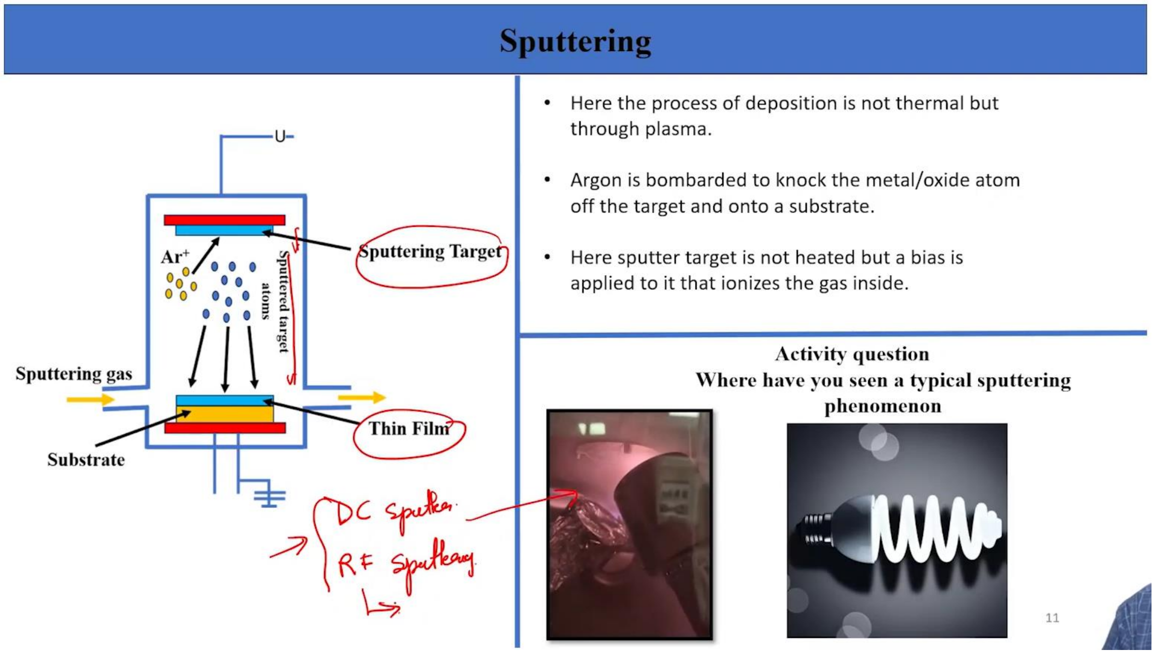
The tungsten boat basically heats the material, and the material enters a vapor phase, which will then deposit on the substrate. When the vapor is deposited on the substrate, there is a kind of bottom-up approach that exhibits, and owing to this bottom-up approach, we try to create a thin film or a thin layer that persists here. Based on this thin layer, you can see a kind of structure being established. So, if you try to look into the overall characteristics of it, almost a working of the bulb, it is a kind of similar phenomenon. Where we have a filament, we try to heat the filament.

The glow discharge from the filament is seen as a kind of glowing discharge that is exhibited over here. Similarly, one of the other examples or one of the other methodologies of a PVD process is the sputtering process. This sputtering process is slightly different from the earlier thermal evaporation techniques. Here, the process of deposition is not thermal, but it is through plasma. In that have a vacuum chamber in place, then there is a sputtering gas which is made to flow into it.



Then have a thin film which is being kept over here and then there is a sputtering target which is available. Through the sputtering gas, so we try to, so this is the material which needs to be deposited on the substrate. So let us consider that I need to sputter a kind of shape memory alloy-based micro robots, where we are trying to develop a nickel-titanium target. This nickel-titanium is being sputtered by applying a potential to it. We get a kind of plasma that is being exerted over here, and this plasma is made to sputter on the surface in the form of a thin film, which will result in a deposition.

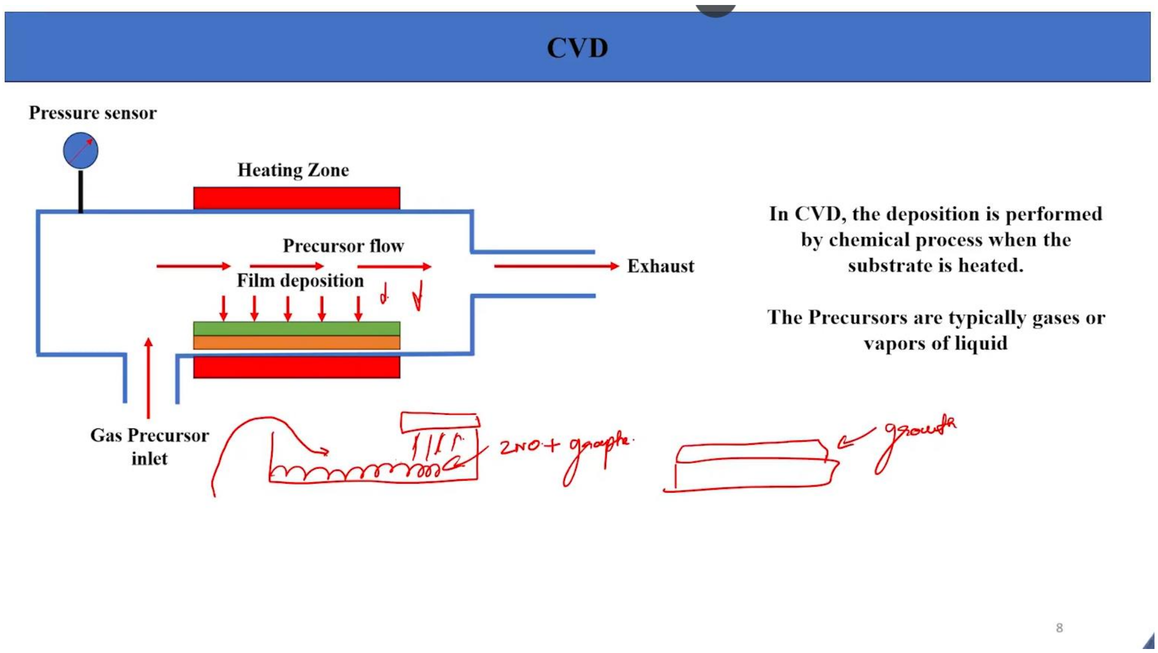
These sputtering processes are classified into two: one is called DC sputtering and the other is called RF sputtering. So, DC sputtering is mainly meant for metals and RF sputtering is mainly meant for oxides. In fact, the typical sputtering phenomenon is almost like a CFL bulb where plasma is used as part of the process. In the CVD process, there is no kind of physical alteration, such as melting the material; it is more related to the type of chemical reaction that occurs here. So, in the case of a CVD process, a substrate is in place, which is being kept over here, and then a gas precursor is made to pass through this particular vacuum region.



When the gas precursor is made to pass through this vacuum region, there is going to be a certain kind of chemical reaction that occurs over here. For example, if we are trying to develop some kind of zinc oxide-based structures, what we try to do is keep a boat. Over the boat, we try to keep zinc oxide plus graphene. This graphene will act as a catalyst along with the zinc oxide. The area where it needs to be coated with zinc oxide will be placed over this board.

The gas precursor inlet will be made to pass through this. So, when the gas inlet is made to pass through it, it reacts with zinc oxide and graphene. Thus, leading to a kind of evaporation that is exhibited here, and this evaporation will result in a grind of the growth of the film. So, wherever we are working on high-temperature materials such as silicon carbide, this kind of CVD process can be efficiently used. However, one of the major limitations of this CVD process is masking because masking in the CVD process is quite difficult.

However, in the case of a PVD process, it is possible to do masking appropriately to create a certain structure or specific parameters based on our requirements or the characteristics we are looking for. So, that is one advantage of using this. So, that is one advantage of going for a PVD process, whereas in a certain amount of high-temperature applications, we normally prefer to go for a CVD process. So, ideally, if you try to look into the overall additive processing, that is a bottom-up approach. These two processes take a major share in building up a certain amount of structures for our applications or for different micro-robotic systems.



Shape memory alloy-based thin film microactuators can be fabricated using physical vapor deposition techniques. In physical vapor deposition techniques, we are basically creating physical vapors of the material that are deposited on a substrate. The techniques that we will be discussing here are thermal evaporation and electron beam evaporation. So, this is our machine for thermal evaporation.

Its basic principle is Joule heating. In joule heating, what we are basically doing is simply heating the material, which will melt and evaporate before being transferred to the substrate material. The substrate material that we are using for the fabrication of the flexible micro actuator is Kapton polyimide because it is flexible and can withstand very high temperatures of 500 degrees Celsius without being degraded, allowing it to cater to our high-temperature actuation needs. We can use this Kapton polyimide in two different forms for substrate material: one is in sheet form, which can be seen here in this substrate holder, and the other is in plate form, depending on the pre-straining we want to do in our material. So this is basically for the training of our material, training of shape memory alloy-based thin film, because in thin film we can do training post-deposition. That is why we are doing pre-staining in the substrate itself.

These substrates can be deposited with nickel titanium (NiTi) or nickel titanium copper (NiTi-Cu) based thin films using tungsten boats that you can see here. These are tungsten boats in which the material is being fed, whether in, let us say, powder form, pellet form, or wire form. So, currently we are using it in wire form in the current deposition. So, this is the basic chamber inside the thermal evaporation unit.

We will be putting our material here on the top. This is our substrate material, which is going on the top, and at the bottom, in the tungsten boat, we will be putting substrate; we will be putting source material, which is nickel titanium, let's say for the current case. This tungsten board is being heated with the help of two copper electrodes that are being supplied with very high power, making them red hot, which melts and evaporates the material. Also, the deposition process is being done in a closed evacuated chamber at a very high vacuum of around 5 x 10 raised to minus 5 millibar, so this high vacuum is maintained by rotary and diffusion pumps. Post-deposition, our film will be deposited on a Kapton polyimide substrate, and it will have a silverish color, similar to NiTi film. This structure is a double-layer structure where nickel titanium is being deposited on the Kapton polyimide substrate, and we term it a bimorph.

Why? Because it has two active materials. One is kept on polyamide and the other is nickel titanium. Both take part in actuation cycles: one in the cooling cycle and the other in the heating cycle. The second process for shape memory alloy-based microactuator fabrication using physical vapor deposition is electron beam deposition. So, this is the unit for electron beam deposition. The basic principle for E-beam deposition, or electron beam deposition, is the generation of a high-energy electron beam that will hit our material and melt and evaporate it.

So how do we generate it? It is basically done using a tungsten coil. So here you can see at the bottom there is a tungsten coil, and when we supply very high power to that tungsten coil, it will generate an electron beam by virtue of thermionic emission. That electron beam will come directly out, so we turn it by 270 degrees using a magnet that is just behind the coil itself. So, as my electron beam goes into that crucible by bending through 270-degree angles, it will hit my material, which is source material that can be nickel titanium, nickel titanium copper, or any other shape memory alloy that I want to pour. As it reaches the melting temperature and evaporation temperature of the source material, my material will evaporate and deposit on the substrate, which can be in sheet form or plate form, as we have discussed previously.

So this is the Kapton polyimide substrate in sheet form, and we will put it here; we will hang it right above the crucible, where my crucible is placed, so the electron beam will hit the material in the crucible, which is made of graphite, and my material will get evaporated and deposited on the sheet itself. Then I will get a bilayer structure, which is a bimorph structure for actuator fabrication. So different kinds of actuators can be fabricated using this flexible structure, and we can also have customized structures by using laser micro-machining, which we will discuss further. This is my tungsten crucible where we will put our source material, which is nickel titanium or any other shape memory alloy you have for the deposition on the substrate, and we will place it just above the tungsten coil where the electron beam will hit, causing the melting and evaporation of the source material for deposition. Since we are using the electron beam for directly heating the material, there is no indirect heating; it is direct heating of the source material.

In this case, the great advantage is that we can melt and deposit very high melting point materials. The flexible micro actuators are fabricated using laser energy with a fiber laser after deposition. So why are we using it? Because we want to make flexible actuators of customized size. Generally, for thin films, laser energy is a very high-energy source for machining, so it either burns the film or creates damage to the film. With fiber lasers, the energy direction of the laser can be easily controlled to achieve customized shapes, and the advantage here is that we have a galvo.

So that galvo controls the position of the laser beam that is coming through, and it is always in focus. The basic thing in a fiber laser is that it has a fiber laser source, an optical fiber, which is a lasing source. It is pumped through a diode laser, which amplifies the diode signal to produce a laser beam that then reaches the galvo head, where we can move it with the help of a moving coil mechanism. So, there is a moving coil inside it, a magnetic coil, which will move according to the input given through the software, so we can directly put whatever structure we want into the software, and that can be directly replicated in the laser motion here on the platform itself, and that way we can get the desired shape and size of any of the actuators that we want. So, there are different kinds of actuators that we have fabricated using this fiber laser, including circular, triangular, and rectangular shapes, as well as one other application for which we have used it: this optical shutter.

In the next part, we will see how directly we are using laser energy for fabricating these different structures, let's say for triangular actuators or optical shader actuators. So, the bimorph beds' flexible actuators are tested for electrical actuation using the customized test bed, which is shown here. In this, we supply electrical power at different frequencies and different power levels so that it actuates for a number of cycles up to the failure of the bimorph structure. So, the basic circuit consists of the following components: first, our power supply, which will directly connect the control circuit to our bimorph structure. The control circuit consists of two components: an Arduino and a relay, which are used to change the frequency of the supply power so that we can have different kinds of motion for the bimorph structure.

As we supply the power, the bimorph will actuate in the forward direction, and that actuation is captured with the help of a laser displacement sensor. The input to the laser displacement sensor is recorded using a data acquisition system or DAC unit, which will convert this laser displacement data into reportable data that can be displayed in a lab with software in graphical form. Then that graphical form can be used for further studies, so this setup is used for the study of bimorph for electrical actuation for a number of cycles; let's say we use it for 1 lakh to 2 lakh cycles up to the failure, where either the thin film we have deposited will get delaminated or we will experience burning of the film. So in that case, the actuation of the film stops, and there we can say we have studied the life cycle of the biomorph structure. The shape memory alloy thin film biomorph that we have fabricated using different physical vapor deposition techniques, such as thermal evaporation or electron beam evaporation, can be used in various applications, such as steward platform assembly, which we are going to show here.

Firstly, what we will do is we will cut different structures such as circle or triangular structure with the help of laser energy with laser micro machining as we have also discussed previously. So, the same structures we use for the fabrication of the steward platform assembly, this steward platform assembly is basically what we have learned in different studies; the base is a fixed base on which we have a moving platform, which in our case is a lightweight mirror located in the central part, as you can see here. This is our central part, which is the movable platform or the mirror, and that mirror is supported using four different actuators. All the parts are NiTi SMA-based and have been machined using the laser energy of the fiber meter, and then this structure. In this structure, the mirror is moved with the help of the motion of these four actuators individually or in combination.

So, when we supply electrical energy to any one of the actuators, it will actuate in the forward direction, as we have seen in the electrical actuation video. Also, when we apply the energy, the actuator will move in the forward direction, and because of that forward motion, our mirror will tilt in the upward direction or downward direction according to the motion of the actuator. And because of that motion, our mirror tilting will be there, and that mirror tilting will be used for further applications of laser beam steering, for, let's say, optical scanning or optical communication applications. So, the first thing here is, you can see there are ARCO markers. These ARCO markers are basically used for the position detection of the mirror. So that we can accurately determine at what position or angle our mirror is currently at, we have placed three different argo markers at different positions on the mirror. Initially, at the horizontal position, there is a camera on top that continuously monitors the position of the argo markers. So initially, our mirror is in a horizontal position, and in that position, the camera takes the position of these three argo markers to generate the equation of a plane that corresponds to the horizontal position of the mirror. And as we supply power to any one of the actuators, this mirror will actuate, and because of that, the position of the ROP markers with respect to our camera will change, and as it changes, the new position will be detected by the camera, which will again generate an equation of the new plane and will give the final angles of the plane or the mirror with respect to the initial position, so like here you can see in this part.

When our mirror is moving, the X and Y positions are changing. These red, blue, and green lines are the X, Y, and Z axes of the argo markers. And as our mirror is moving, these positions and our angles are also changing. Here. So we can get a live feed of what our angles are and what the position of the mirror is. We can also use this as feedback to control the input power to the actuator so that we can control the final position of the mirror. As a result, we can control the final position of our laser beam or optical beam to the point where we want to position it, or let's say, if we want to scan a whole area by cyclically moving the optical beam. Then we can provide power to any one or more of the actuators continuously in cyclic form so that our mirror will move in a to-and-fro motion; it will tilt upwards in one cycle and then come back in another, allowing us to have a raster scanning pattern for the whole area. Additionally, the argo markers can be used in other applications, such as position detection of any moving object.