

# Microrobotics

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Week- 03

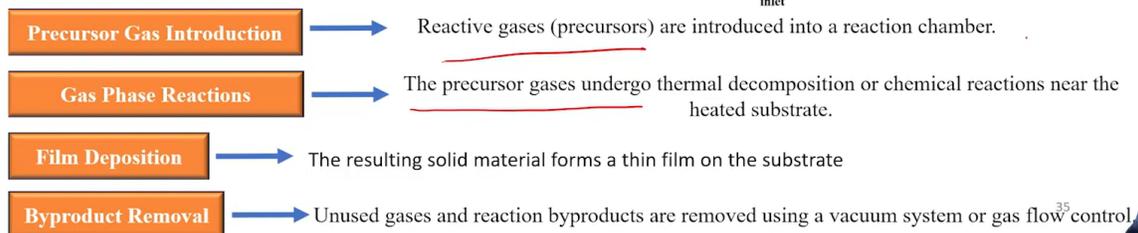
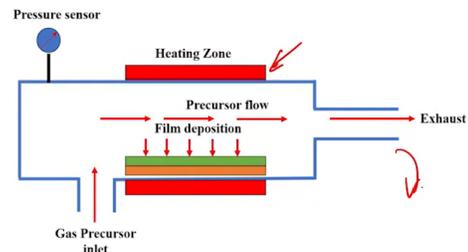
Lecture No- 12

## Micro-Mechanics System Design (Micro-Fabrication of Micro Robots) - Module 02

In the previous module, we discussed the overall details of the CVD process. The CVD process is widely used as a thin-film deposition technique in which gaseous precursors react or decompose on a heated substrate to form solid material. Ideally, as discussed earlier, this heated substrate acts as a catalyst for the growth of these thin films, and CVD is crucial for producing high-quality films in semiconductor manufacturing, especially in the case of nanotechnology and protective coatings. In particular, if you look into the advantages of the CVD process, it will ensure uniformity in the thin film and also result in high-purity deposition. So that is one advantage of this CVD process. In a closer view of the CVD process, there is a vacuum chamber, and we have a heating zone that helps catalyze the growth or film deposition, along with a precursor flow, and there is an exhaust that tries to exit it.

### Chemical Vapor deposition

- Chemical Vapor Deposition (CVD) is a widely used thin-film deposition technique in which gaseous precursors react or decompose on a heated substrate to form a solid material.
- CVD is crucial for producing high-quality films in semiconductor manufacturing, nanotechnology, and protective coatings due to its excellent uniformity, conformality, and high-purity deposition.



As far as the introduction of this precursor gas is concerned, reactive gases that are considered precursors are introduced into the reaction chamber, and in the case of gas-phase reactions, the precursor gas undergoes thermal decomposition or a chemical reaction near the heated substrate. As far as film deposition is concerned, the resulting solid material forms a thin film on the substrate. Byproduct removal, the unused gases and the reaction byproducts are removed using a vacuum system or a gas scrubber. As mentioned earlier, an appropriate catalyst is used for the growth of this CVD process.

These CVD processes are classified based on the type of functionality and the type of application. The first type of CVD is called atmospheric pressure CVD. The main function of this atmospheric pressure CVD is that it is conducted at atmospheric pressure using a controlled gas flow rate over a heated substrate. So the main advantage of this particular process is that it has a high deposition rate, and from a methodological perspective, it is a kind of simple step process. The case of disadvantage is concerning; it has poor step coverage, and sometimes it may lead to non-uniform TBI systems.

Chemical Vapor deposition (Types)	
<p><b>Atmospheric Pressure CVD (APCVD):</b>            Conducted at atmospheric pressure, using a controlled gas flow over a heated substrate.  <b>Advantages:</b>            High deposition rate, simple setup.  <b>Disadvantages:</b>            Poor step coverage and non-uniformity.  <b>Applications:</b>            Oxide coatings, protective layers in microelectronics.</p>	<p><b>Plasma-Enhanced CVD (PECVD):</b>            Uses plasma (ionized gas) to enhance precursor decomposition, allowing deposition at lower temperatures.  <b>Advantages:</b>            Lower deposition temperatures, good film quality, enhanced control over film properties.  <b>Disadvantages:</b>            More complex system, requires plasma generation..  <b>Applications:</b>            Passivation layers, optical coatings, MEMS devices.</p>
<p><b>Low-Pressure CVD (LPCVD):</b>            Performed under reduced pressure (~0.1–1 Torr) to improve film uniformity.  <b>Advantages:</b>            High-quality films, better step coverage, reduced gas-phase reactions.  <b>Disadvantages:</b>            Slower deposition rate than APCVD.  <b>Applications:</b>            Silicon nitride (Si<sub>3</sub>N<sub>4</sub>), polysilicon, and silicon dioxide (SiO<sub>2</sub>) deposition in semiconductor fabrication.</p>	<p><b>Metal-Organic CVD (MOCVD):</b>            Uses metal-organic precursors to deposit complex compounds, often at high temperatures.  <b>Advantages:</b>            can deposit III-V and II-VI semiconductor materials  <b>Disadvantages:</b>            Expensive precursors, sensitive process conditions.  <b>Applications:</b>            Growth of GaN, InP, and other compound semiconductors for LEDs, lasers, and high-frequency electronics.</p>

From an application perspective, any kind of oxide coating or protective layer in microelectronics is well taken care of using this atmospheric pressure CVD. Next, we have a plasma-enhanced chemical vapor deposition process. It uses a plasma, which is nothing but an ionized gas, to enhance the precursor deposition and allow for deposition at a lower temperature. So the main advantages are the lower deposition temperature, good film quality, and enhanced control over the film properties. However, the major disadvantages observed in this particular system are that it is a more complex system and requires a high amount of plasma to be generated.

When referring to the application perspective, it can be used as a passive layer; it has an optical coating and is mainly meant for MEMS-based devices. Now we have the low-pressure CVD process, which, as the name suggests, is performed under reduced pressure, around 0.1 to 1 Torr, to improve the film uniformity. And as far as an advantageous perspective point of view, it has a high-quality film, better step coverage, and a reduced gas phase reaction. Whereas, from a disadvantageous perspective point of view, it has a slower deposition rate compared to atmospheric pressure CBD.

From an application perspective, these kinds of systems can basically be deployed for silicon nitride, polysilicon, and silicon dioxide deposition in the case of semiconductor fabrication. Now, in the case of metal-organic CVDs, which we call MOCVD, these are used for metal-organic precursors to deposit complex compounds, often at a high temperature, and the major advantage is that they can deposit a range of 2 to 6 semiconductor materials and 3 to 5 semiconductor materials. The major disadvantages are that the precursors are highly expensive and highly sensitive to the process conditions. When we try to talk about applications, materials like gallium nitride, indium phosphide, and other compound semiconductors for LED lasers and high frequencies are among the key outcomes of this particular metal-organic system. The most important CVD process is called atomic layer deposition.

## Chemical Vapor deposition (Types)

### Atomic Layer Deposition (ALD) (A Special Case of CVD):

Involves sequential exposure of precursors in a self-limiting manner, allowing precise atomic-scale film thickness control.

#### **Advantages:**

Exceptional uniformity, precise thickness control.

#### **Disadvantages:**

Very slow deposition rate, high cost.

#### **Applications:**

High-k dielectrics, barrier layers in advanced semiconductor devices.

This atomic layer deposition involves the sequential exposure of precursors in a self-limiting manner, allowing precise atomic-scale film thickness control. So, the main advantage is that it has exceptional uniformity and precise thickness control. However, a major disadvantage is that it has a very slow deposit rate at a higher cost. From an application perspective, materials with high dielectric and high barrier layers in advanced

semiconductor devices may be considered part of those that can be easily deposited using this atomic layer deposition. Now, there is an overall comparison concerning a physical vapor deposition process and a chemical vapor deposition process.

Based on the deposition mechanism, in the case of physical vapor deposition (PVD), the physical material is transformed into vapor and is used for deposition. In the case of chemical vapor deposition (CVD), a chemical reaction of a precursor gas is used on the substrate. From a process environment perspective, it is a type of high vacuum and plasma-assisted system in PVD, whereas in the case of CVD, it is an atmospheric low-pressure or plasma-enhanced system. Based on temperature requirements, PVD is capable of working in the range of 100 to 500 degrees Celsius. However, CVD has a higher range of 300 to 1100 degrees Celsius, except in the cases of PECVD and ALD.

PVD vs CVD		
Feature	PVD	CVD
Deposition Mechanism	Physical transfer of material in vapor form	Chemical reaction of precursor gases on substrate
Process Environment	High vacuum or plasma-assisted	Atmospheric, low-pressure, or plasma-enhanced
Temperature Requirement	Lower (~100–500°C)	Higher (~300–1100°C) (except PECVD & ALD)
Film Purity	High purity ✓	May contain impurities from precursor gases
Step Coverage	Limited, non-conformal	Excellent conformal coverage
Deposition Rate	Generally slower	Faster than PVD ✓
Material Range	Metals, oxides, nitrides ✓	Metals, semiconductors, ceramics, polymers
Film Density	High, but may have voids in some methods	High, dense, and uniform
Adhesion to Substrate	Good, but requires ion bombardment for better adhesion	Excellent due to chemical bonding
Equipment Complexity	Requires vacuum and plasma systems ✓	Requires gas handling, reactors, and vacuum systems
Process Control	Physical parameters (temperature, plasma power)	Chemical reaction control (gas flow, reaction kinetics)
Common Techniques	Sputtering, Thermal Evaporation, Electron Beam Deposition, PLD <i>pulver laser deposition</i>	APCVD, LPCVD, PECVD, MOCVD, ALD ✓
Typical Applications	Decorative coatings, hard coatings, optical coatings, semiconductor metallization	Semiconductor fabrication, nanomaterials, protective coatings, optical films

While comparing the film purity, which is nothing but the purity of the active layer, it is highly pure in the case of the PVD process. In the case of the CVD process, it may contain a certain amount of impurities from the precursor gases. While comparing the step coverage, PVD has limited and non-conformal coverage, whereas in the case of a CVD process, it has excellent conformal coverage, which is considered one of the major advantages of this particular system. Now, with reference to the deposition rate perspective, PVD is generally slower; however, the CVD process is much faster compared to the PVD process. Now, with reference to the material range, PVD has metals, oxides, and nitrides that are exhibited here.

However, in the case of CVD, there are metals, semiconductors, ceramics, and polymers that are exhibited. From a film density perspective, it is high but may have

voids in some methods. However, in the case of CVD, it is high, dense, and uniform. Adhesion to the substrate is a concern; it is good but requires a type of ion bombardment for better adhesion. That is, you need to have a type of surface treatment to achieve better adhesion properties.

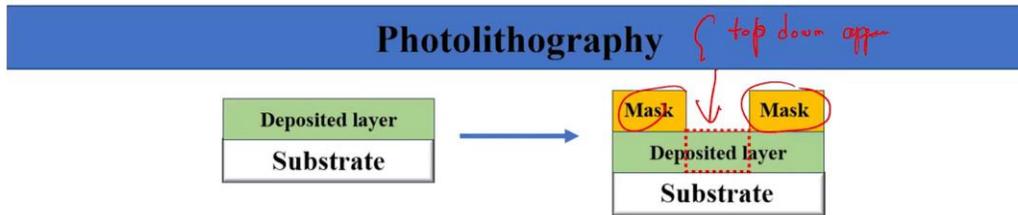
This surface treatment might involve creating a rougher surface for higher adhesion, or we can also heat the substrate to achieve higher adhesion. However, with reference to the CVD perspective, we have a high-density and uniform film that is exhibited in this particular process. In addition to the substrate, it is good, but it requires a kind of ion bombardment. From the perspective of equipment complexity, it requires a vacuum and a plasma system. In the case of the CVD process, it requires a gas handling system, a reactor, and a vacuum system, as exhibited here.

From the process control perspective, we have the physical parameters, and in the case of CVD, there is a type of chemical reaction that occurs. Automatically, for a chemical reaction, we require a certain amount of elements and sub-elements that need to be integrated, which include gas flow and reaction kinetics. Some of the common techniques of this particular process of PVD are the sputtering process, thermal evaporation process, electron beam process, and PLD, which is nothing but the pulsed laser deposition process. However, in the case of CVD, we have APCVD, low-pressure CVD, physically enhanced CVD, metal oxide CVD, and ALD, which we discussed in the earlier applications. Wherever we require a type of hard coating, an optical coating, or a decorative coating, along with semiconductor materialization, such a PVD system is exhibited.

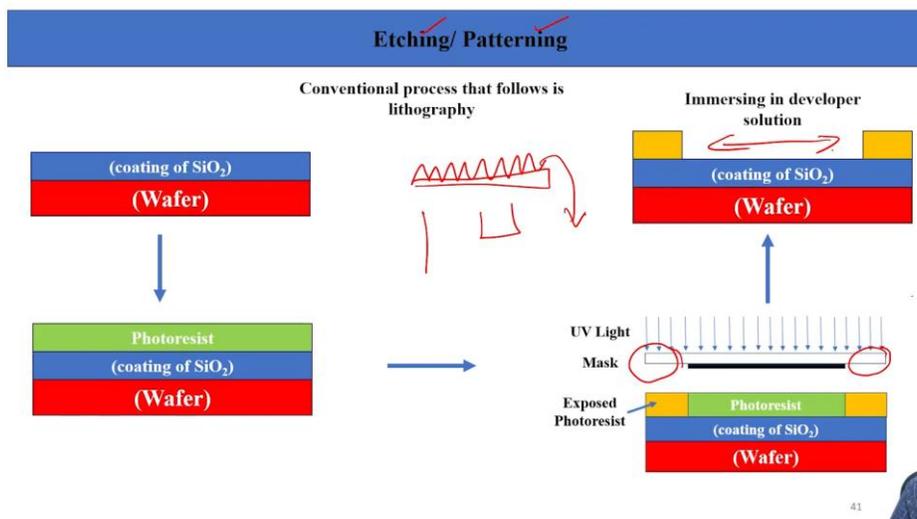
However, in the case of semiconductor fabrication or in layers where we have a surface that exhibits, such CVDs can be used efficiently. So, this will help in identifying coating techniques or microfabrication techniques based on our requirements or based on the material we are using for micro robotic applications. The photolithography process falls under the classification of the top-down approach, where we have a deposited layer, and whenever we want to remove that deposited layer, we try to integrate a mask in this particular region, and then we expose it to a laser or sometimes use chemical etching. This way, we can appropriately remove the material based on our requirements. So just to give you an overview of this photolithography, lithography means it is a combination of two Greek words, which are litho and graphein: litho means stone and graphein means to write.

So this term, the photolithography process involves the use of an optical image and a photosensitive film to produce a pattern on a substrate. It's a technique to create a pattern on a substrate with submicrometer resolution. So, in microelectronics applications or micro-robotics applications, these patterns are necessary to create a certain amount of electronic layer on top of them. This is exactly where photolithography plays a vital role.

So, these photolithographies are used to set a pattern for a mask for cavity etching in bulk micromachining or for thin-film deposition and etching of the sacrificial layer in the case of surface micromachining.

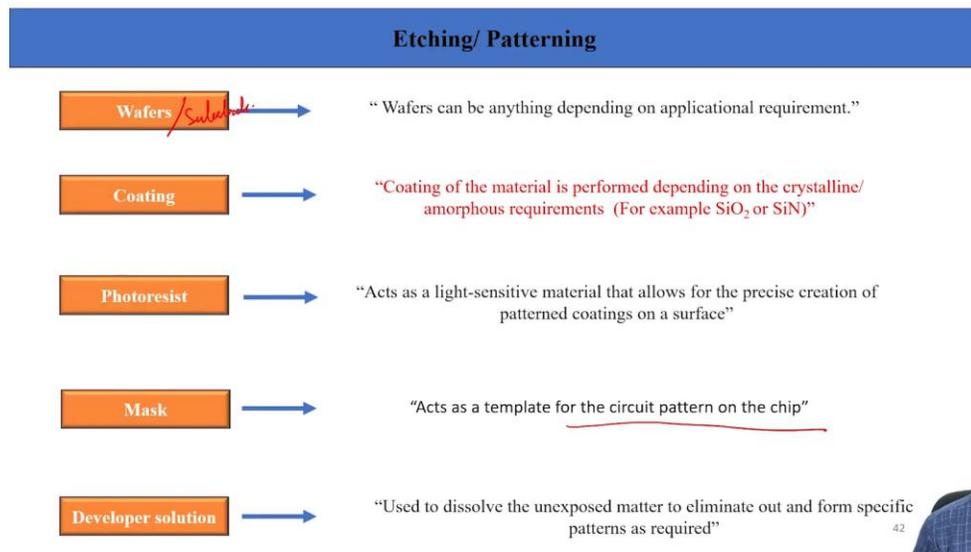


In all these domains, such photolithographic processes are being employed. Now, I will introduce you to two important terms. Both of these terms are well performed using the same process: one term, which we call etching, and the other term, which we call patterning. So what do you mean by an etching? Etching is nothing but the removal of a selective material, whereas patterning is something like creating a kind of structure based on our requirements. In the case of the etching process, wherever I have a material and if I want to remove it, this etching process can be efficiently used. However, in the case of patterning, I have a layer and want to create a kind of patterned structure on the surface so that this will be helpful for me to functionalize my system based on my requirements or characteristics. Let us see the conventional process that flows in the case of a photolithography process. In the case of a photolithography process, in order to introduce you to the photolithography process, let us consider a wafer over which a silicon dioxide coating is applied. So, the main motto of this process is that I need to create a kind of patterned structure on the surface. On this coated structure, we are trying to use a photoresist layer.



And when we try to introduce this photoresist layer, its main function is to indicate the region where we may need to remove the material. Now what we are trying to do is

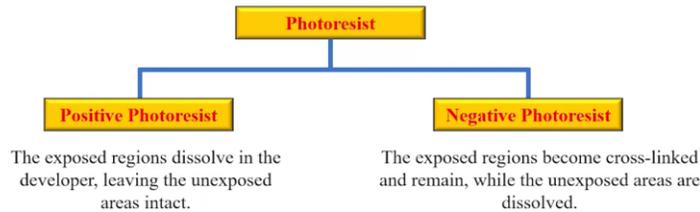
create a kind of masking that exhibits. In this mask, the main objective of this particular process is to create a structure similar to this. In this structure, it's a kind of bond structure where we have two masks, and then we may need to remove the material. So what we can do is use a mask that is available, and a UV light is made to interact with the material, passing through the photoresist, which is then exposed. If you closely observe this mask, one layer of the mask is kept blocked while the other layer has a direct interaction with the photoresist, thus leading to the removal of the material here, and the region that is masked is kept constant. This is the overall conventional process of lithography that is efficiently used for differences. So, overall, if you try to look into the overall nomenclatures or the elements that have been participating in this etching or patterning, The first one is wafers; they can be anything depending on the application. Ideally, wafers are nothing but the substrate that has been discussed a lot.



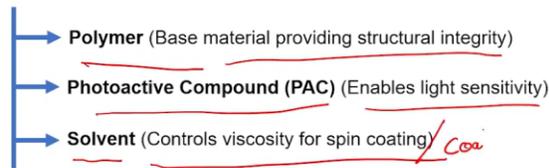
The next one is coating. The coating of the material is performed depending on the crystalline as well as the amorphous requirements. So what we try to do is have a coating layer, and then we try to use a certain amount of treatment to create crystalline structures or a single crystal structure, etc. The next one is photoresist, which is available. The main function of this photoresist is that it acts as a light-sensitive material that allows for the precise creation of the patterned coating on the surface. Then have a mask in place. The main function of this mask is to act as a template for the circuit pattern on the chip. And the last one is the developer solution; this developer solution is used to dissolve the unexposed matter to eliminate it and form a specific pattern as and when required. So these are the different elements that are available. The functionality of a photoresist is that it is a kind of light-sensitive material used in photolithography to transfer the pattern onto a substrate. This photoresist is classified into two categories: one is positive photoresist, and the other is negative photoresist.

## Etching/ Patterning

A photoresist is a light-sensitive material used in photolithography to transfer patterns onto a substrate.



The composition of Photoresist includes

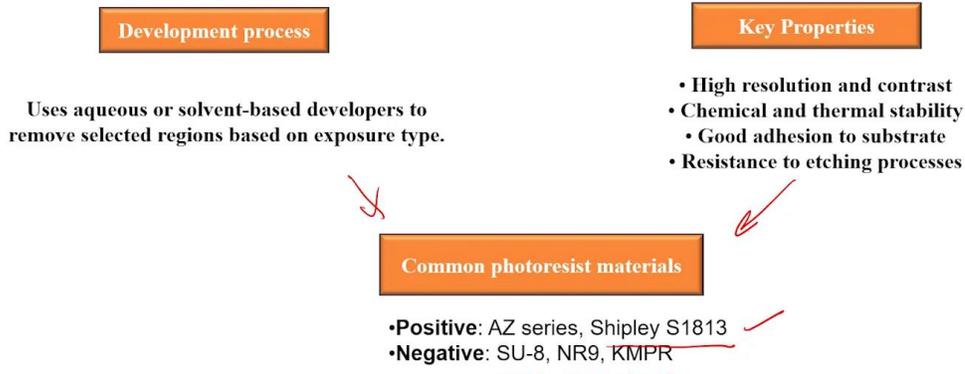


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In the case of a positive photoresist, the exposed region dissolves in the developer, leading to the unexposed area remaining intact. In the case of a negative photoresist, the exposed region becomes crosslinked and remains when the unexposed regions are dissolved. The different composition of the photoresist includes a polymer based on the material that provides structural integrity. The photoactive compound (PAC) enables light sensitivity. There is a solvent available, and its function is to control the viscosity for spin coating or any other kind of coating based on the requirements or characteristics.

In the overall development process, it involves using an aqueous or solvent-based developer to remove the selected region based on the exposure type. However, with reference to the key properties concerned, it has high resolution and contrast. Chemical and thermal stability, it has good chemical and thermal stability. It should have good adhesion to the substrate, and it should provide a kind of resistance to the etching process. Now the common photoresist materials that exhibit positive characteristics are the AZ series materials and the Shipley S1813, both of which are available. In the case of a negative photoresist, we use S8, NR9, and KMPR, which are used as negative photoresist materials. Now, let us discuss masking in photolithography. A mask in photolithography is a transparent plate. Typically, it is made of quartz or glass with an opaque pattern that defines the circuit layout for microfabrication. The common materials included are kinds of quartz; sometimes it might be a type of soda-lime glass, or it might be fused silica with a chrome layer for patterning.

## Etching/ Patterning



There are different types of masks. One is called a binary mask; the function of the binary mask is that its opaque region blocks light, while its transparent region allows light to pass through. So it is something like this. For example, if I need to create a mask and if I want to create a pattern, this is a kind of binary pattern I can exhibit. When I try to expose it, the light falls on it; finally, it ends up in a textured pattern, something like this. Finally, it ends up in a textured part, something like this. So this is an application of a binary mask. There is another kind of mask called a phase-shift mask. This phase-shift mask is used to enhance the resolution by phase-shifting the light to improve its contrast. Then there is a grayscale mask that uses a 3D microstructure by allowing for different exposure intensities. The importance of the resolution role in masking essentially determines the feature size in microfabrication and also affects the final device performance. Now, in this particular patterning or masking, we may need to understand certain terminologies.

## Patterning (Masking)

- A mask in photolithography is a transparent plate (typically quartz or glass) with opaque patterns that define the circuit layout for microfabrication.
- Common materials include quartz, soda-lime glass, or fused silica with a chrome layer for patterning.
- Types:
  - (a) **Binary Mask**: Opaque regions block light, and transparent regions allow light transmission.
  - (b) **Phase Shift Mask (PSM)**: Enhances resolution by phase-shifting light to improve contrast.
  - (c) **Gray Scale Mask**: Used for 3D microstructures by allowing different exposure intensities.
- Resolution Role: Determines feature sizes in microfabrication and affects final device performance.



One term is related to fabrication, which is created using electron beam lithography or laser writing for high precision. The next one is about usages; it is placed between a UV

light source and a photoresist-coated wafer to transfer the pattern. From an alignment perspective, it is critical for a multilayer process to ensure an accurate overlay feature. When we talk about mass defect, any imperfection can lead to a defective circuit pattern or may also reduce yield. As far as cost considerations are concerned, it has a high resolution and is expensive; it acts as an alternative solution that includes a kind of maskless lithography for prototyping.

### **Patterning (Masking)**

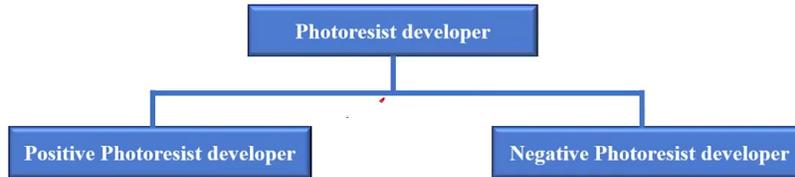
- **Fabrication:** Created using electron beam lithography (EBL) or laser writing for high precision.
- **Usage:** Placed between a UV light source and a photoresist-coated wafer to transfer patterns.
- **Alignment:** Critical for multi-layer processes to ensure accurate feature overlay.
- **Mask Defects:** Any imperfections can lead to defective circuit patterns and reduced yield.
- **Cost Considerations:** High-resolution masks are expensive; alternative solutions include maskless lithography for prototyping.
- **Storage & Maintenance:** Requires cleanroom handling to prevent contamination and damage.

Storage and maintenance require a clean room to handle such a system, so these are some of the things that we may need to consider. Now, when I talk about this photolithography and the photoresist developer, as we mentioned earlier, they are classified into two categories: one is called a positive photoresist developer, and the other is called a negative photoresist developer. So, when the positive photoresist developer is concerned, the exposed region of the photoresist becomes soluble and is removed by the developer. Most common developers include a kind of aqueous alkaline solution, TMAH, which is heavily used. Sometimes sodium hydroxide or potassium hydroxide is also used in a diluted concentration to develop these positive photoresists.

In the case of negative photoresist developers, the exposed region becomes crosslinked and remains while the unexposed areas are dissolved. So the common developers include an organic solvent such as xylene, methylene, or isobutylene ketone, which are heavily used as a kind of negative photoresist developer. Some of the key parameters that affect these developers are concentration, because concentration has an impact on the development rate as well as on the resolution. The time during the development can lead to excessive material removal. The high temperatures may increase the development speed but can also cause unwanted diffusion in the system. Agitation may ensure uniform development and pattern accuracy. Therefore, these are the key parameters that have to be considered from a patterning perspective.

## Patterning (Developer solution)

- A developer in photolithography plays a crucial role in the process of fabricating micro and nanoscale patterns on semiconductor wafers.
- In photolithography, a developer is a chemical solution used to dissolve the exposed or unexposed regions of a photoresist layer after UV, deep-UV, or electron beam exposure.



## Patterning (Developer solution)

### 1. Positive Photoresist Developer

1. The exposed regions of the photoresist become soluble and are removed by the developer.
2. Common developers:
  1. Aqueous alkaline solutions (e.g., Tetramethylammonium hydroxide (TMAH))
  2. Sodium hydroxide (NaOH) or potassium hydroxide (KOH) in diluted concentrations

### 2. Negative Photoresist Developer

1. The exposed regions become cross-linked and remain, while the unexposed areas are dissolved.
2. Common developers:
  1. Organic solvents such as xylene or methyl isobutyl ketone (MIBK)