
Deposition Overview for Microsystems

Primary Knowledge

Instructor Guide

Notes to Instructor

Deposition Overview for Microsystems is the introductory primary knowledge unit for the Deposition Overview for Microsystem Learning Module. It is a general overview of deposition processes used in the fabrication of microsystems.

The *Deposition Overview for Microsystem Learning Module* consists of the following units.

- Knowledge Probe (KP) - pretest
- **Deposition Overview for Microsystems PK**
- Deposition Terminology Activity
- Science of Thin Films Activity (Supporting SCME Kit available @ <http://scme-nm.org>)
- Activity – What Do You Know About Deposition?
- Final Assessment – Multiple choice Participant Guide

Two PowerPoint presentations are available: a narrated presentation that can be downloaded by participants and a non-narrated presentation that can be used by the instructor as a classroom presentation. Both presentations are short summaries of this lesson and can be downloaded from the SCME website.

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the coaching and review questions at the end of the unit.

Description and Estimated Time to Complete

Deposition is the fabrication process in which thin films of materials are deposited on a wafer. During the fabrication of a microsystem, several layers of different materials are deposited. Each layer and each material serves a distinct function. This unit provides an overview of the deposition processes and the various types of deposition used for microsystems fabrication.

This learning module introduces you to the common processes used to deposit thin films in the fabrication of micro-size devices. Activities provide further exploration into these processes as well as the properties of the thin films deposited.

Estimated Time to Complete

Allow at least 20 minutes to complete this unit.

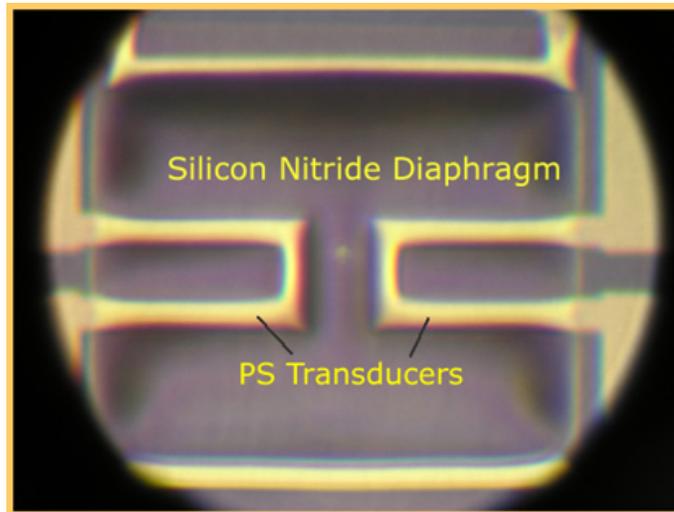
Introduction

Microsystems (or MEMS) are fabricated using many of the same processes found in the manufacture of integrated circuits. Such processes include photolithography, wet and dry etch, oxidation, diffusion, planarization, and deposition. This unit is an overview of the deposition process.

The deposition process is critical for microsystems fabrication. It provides the ability to deposit thin film layers as thick as 100 micrometers and as thin as a few nanometers.¹ Such films are used for

- mechanical components (i.e., cantilevers and diaphragms),
- electrical components (i.e., insulators and conductors), and
- sensor coatings (i.e., gas sensors and biomolecular sensors)

The figure below shows a thin film of silicon nitride being used as the diaphragm for a MEMS pressure sensor.



*MEMS Pressure Sensor close-up
(Electrical transducers (strain gauges) in yellow, Silicon nitride diaphragm in gray)
[Image courtesy of the MTTC at the University of New Mexico]*

Because thin films for microsystems have different thicknesses, purposes, and make-up (metals, insulators, semiconductors), different deposition processes are used. The deposition processes used for microsystems include the following:

- Spin-on film
- Thermal Oxidation (oxide growth)
- Chemical vapor deposition (CVD)
- Physical vapor deposition (PVD)
- Electroplating

This unit provides a brief overview of deposition and each deposition method. More in-depth coverage can be found in additional instructional units.

Objectives

- Briefly describe two (2) deposition processes.
- Create a chart that illustrates the type of thin films deposited which each deposition process.

Key Terms (These terms are defined in the glossary at the end of this unit)

Chemical vapor deposition (CVD)

Deposition

Electroplating

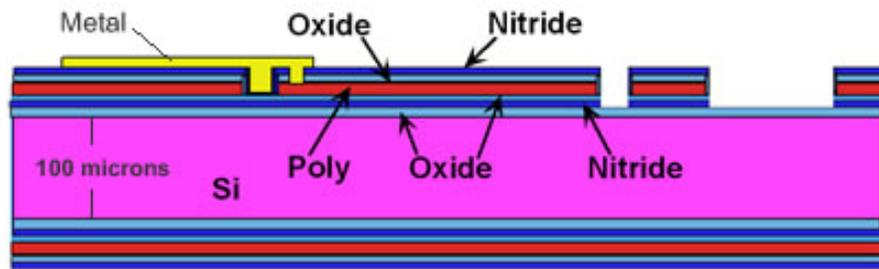
Evaporation

Oxidation

Physical vapor deposition (PVD)

Sputtering

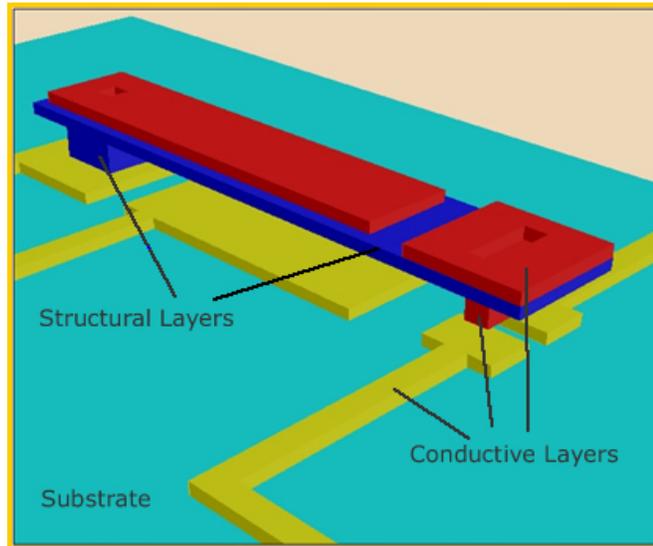
What is Deposition?



*Deposited Thin Films for MEMS Structure
[Image courtesy of Khalil Najafi, University of Michigan]*

Deposition is any process that deposits a thin film of material onto an object. That object could be a fork, a door handle or, in the case of microsystems, a substrate. It is one of the primary processes in the construction of microsystems. Prior to the photolithography and etch processes, a solid, thin film of material is deposited on the wafer. For microsystems, this thin film is a few nanometers to about 100 micrometers thick.¹

What is the Purpose of a Deposited Layer?



*Layering for MEMS Switch
[Khalil Najafi, University of Michigan]*

The actual thickness and composition of the film is dependent on its application within the device. There are several different functions for thin films within microsystems fabrication. Here are some typical layers.

- Structural layer (used to form a microstructure such as a cantilever (above), gear, mirror, or enclosure)
- Sacrificial layer (deposited between structural layers, then removed, leaving a microstructure like the cantilever in the above graphic)
- Conductive layer (usually a metal layer that allows current flow)
- Insulating layer (separates conductive components)
- Protective layer (used to protect a portion of another layer or the entire device)
- Etch stop layer (used to stop the etch of another layer when a cavity depth or a membrane thickness is reached)
- Etch mask layer (A patterned layer that defines the pattern to be etched into another layer)

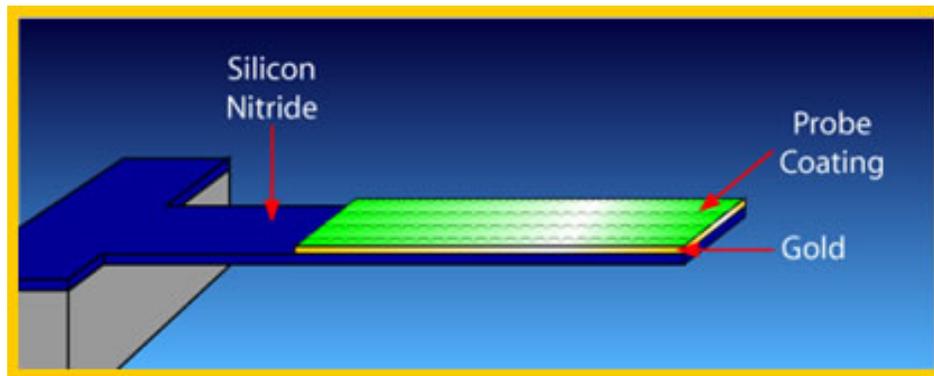
Type of film vs. Application

Different films are used for various applications:

Type of Thin Film	Applications
Silicon Dioxide (oxide)	<ul style="list-style-type: none">• Sacrificial Layer• Masking Material
Polysilicon (poly)	<ul style="list-style-type: none">• Structural material• Piezoresistive material
Silicon Nitride (nitride)	<ul style="list-style-type: none">• Electrical isolation between structures and substrate• Protective layer for silicon substrate• Environmental isolation between conductive layer and atmosphere• Masking material• Structural material
Phosphosilicate Glass (PSG)	<ul style="list-style-type: none">• Structural anchor material to the substrate• Sacrificial Layer
Various metals (Aluminum, gold, platinum)	<ul style="list-style-type: none">• Conductive electrodes• Reflective material
Spin-on Glass (SOG)	<ul style="list-style-type: none">• Final layer for planarized top surface
Zinc Oxide (ZnO)	<ul style="list-style-type: none">• Active piezoelectric film• Sacrificial layer
Photoresist	<ul style="list-style-type: none">• Masking material• Sacrificial material

Table 1: Type of Thin Film vs. Application

MEMS Deposition Processes



Polysilicon structural layer (the cantilever structure), Silicon nitride (isolation), Gold adhesive layer, probe coating (chemically reactive layer to sense specific particles)

The goal of deposition is to achieve a high quality, thin, solid film on the substrate surface. Since microsystems fabrication requires different layers for different purposes, deposition could occur many times during the fabrication of a MEMS. The graphic shows four layers used for a microcantilever sensor: cantilever structure, silicon nitride, gold, and probe coating. Each layer requires a specific deposition process to deposit the specific film of a desired thickness.

The most commonly used deposition processes for microsystems include the following:

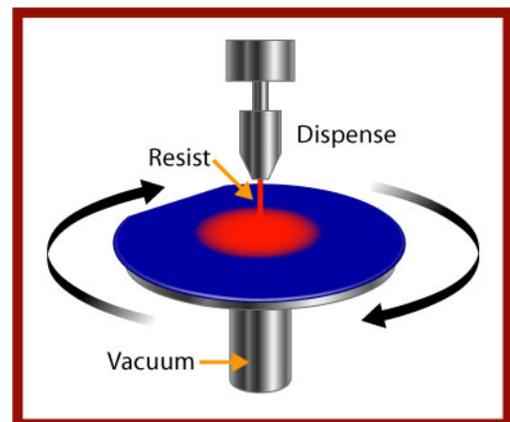
- Spin-on film
- Thermal Oxidation (oxide growth)
- Chemical vapor deposition (CVD)
- Physical vapor deposition (PVD): Evaporation and Sputtering
- Electrodeposition (electroplating/electroforming)

Following are brief discussions of each of these processes.

Spin-On Deposition

Spin-on deposition is the process of literally spinning a liquid onto the wafer surface. The thickness of the film is dependent upon the liquid's viscosity and spin speed. Once the liquid is spun onto the wafer, the solvents within the liquid are thermally evaporated through a curing process. The result is a thin, solid film.

Spin-on deposition is used primarily for photoresist and spin-on glass (SOG). A more detailed discussion of the spin-on process can be found in the SCME *Photolithography Overview*.

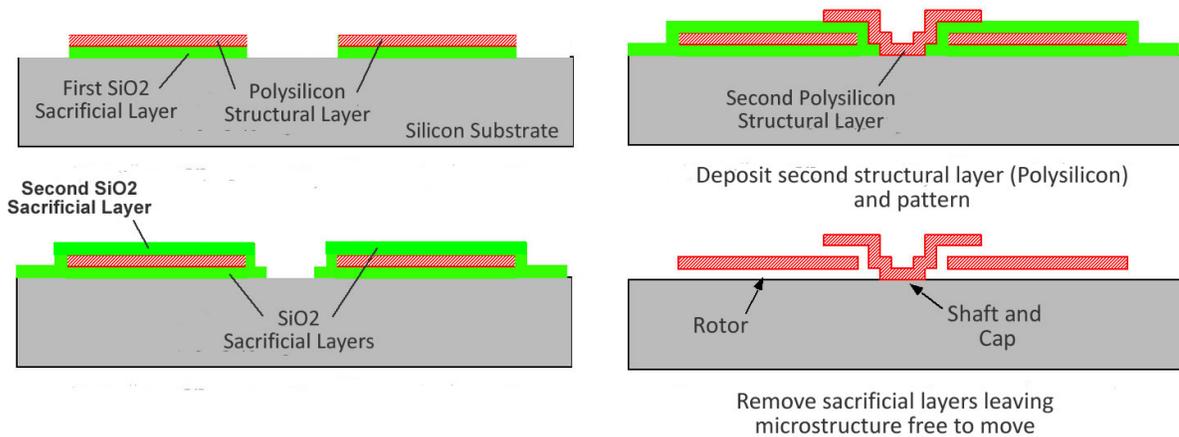


Spin-on Photoresist Layer

Thermal Oxidation

Thermal oxidation is the process used to grow a uniform, high quality layer of silicon dioxide (SiO_2) on the surface of a silicon substrate. Thermal oxidation is different from other types of deposition in that the silicon dioxide layer is literally "grown" into the silicon substrate. Other types of deposition "deposit" the layer on the substrate surface with little to no reaction with the surface molecules.

Silicon Dioxide



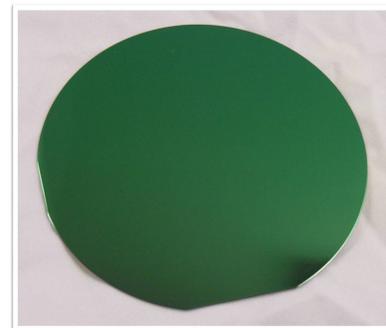
Two silicon dioxide layers used as sacrificial layers for MEMS structure

This graphic depicts the use of silicon dioxide for two different layers. The first layer (or bottom green layer) uses thermal oxidation to grow the silicon dioxide on the silicon substrate (see the discussion on Thermal Oxidation Process). The second oxide layer (the top green layer) is deposited using chemical vapor deposition (CVD). Silane gas and oxygen are provided and combined to form the silicon dioxide (oxide) layer. (More on CVD later in this unit.) Both of these oxide layers are considered sacrificial because they are subsequently removed to create the free, moving components of this structure.

Silicon dioxide is a high-quality electrical insulator. It can be used for a variety of purposes:

- A barrier material or hard mask
- Electrical isolation
- A device component
- An interlayer dielectric in multilevel structures
- A sacrificial layer or scaffold for microsystems devices.

Silicon wafer with a layer of silicon dioxide

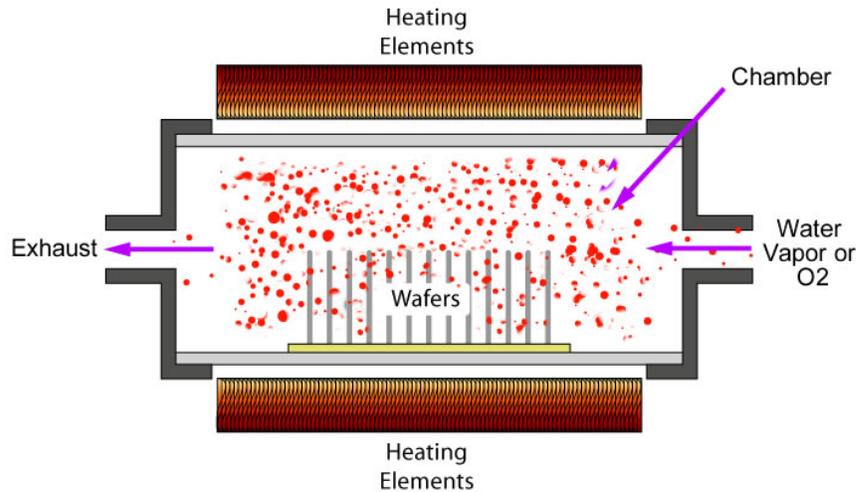


Thermal Oxidation Process

When a silicon substrate is exposed to oxygen, the silicon surface oxidizes to form a layer of silicon dioxide (SiO_2). The amount of oxygen available, the source of the oxygen (gas or vapor), temperature, and time determine the final thickness of the oxide layer. This process is analogous to rust growing on iron. Rust is iron oxide and is formed by a chemical reaction between iron and oxygen. The amount of rust is dependent upon the temperature and humidity of the surroundings. For example, rust grows faster and thicker in hot, humid environments than in cool, dry environments.



Loading silicon wafers into a thermal oxidation furnace [Image courtesy of UNM-MTTC]



Thermal Oxidation Furnace

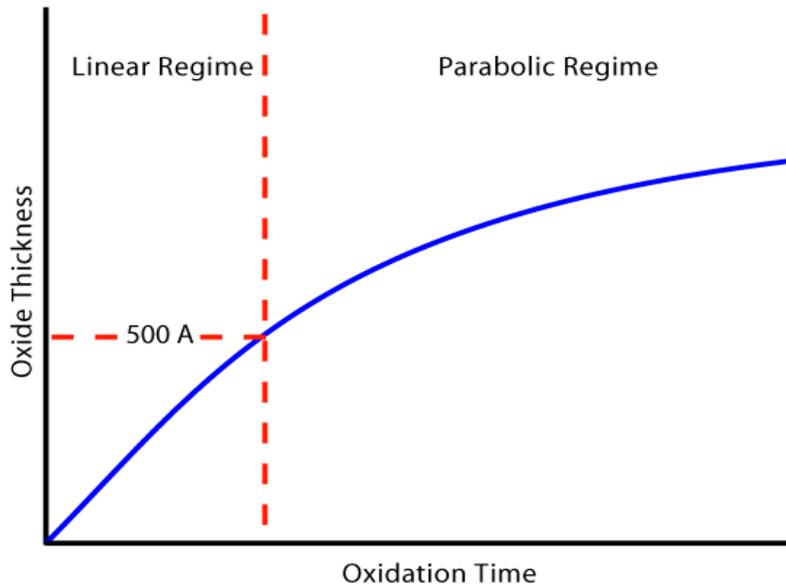
For microsystems fabrication, the thermal oxidation process includes three basic steps:

- The silicon wafers are placed in a heated vacuum chamber (typically 900 – 1200 degrees C).
- A source of oxygen (gas or vapor) is pumped into the chamber.
- The oxygen molecules react with the silicon substrate to form a layer of silicon dioxide (SiO_2).

The longer the wafers or metal are exposed to oxygen (O_2), the thicker the oxide layer becomes. The higher the temperature and “humidity”, the faster the reaction rate. *More on this later.*

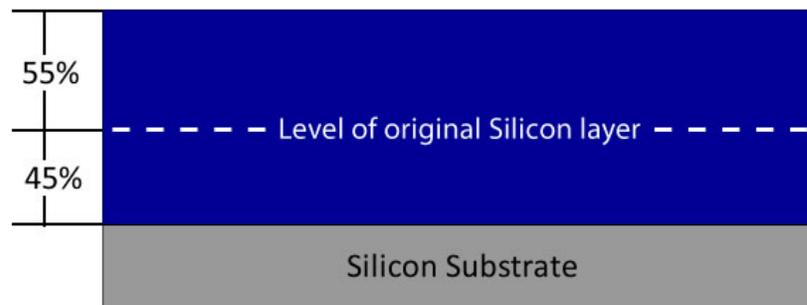
Oxide Growth Kinetics

The oxide layer actually consumes a portion of the silicon just as rust consumes a portion of the metal. Initially, the growth of silicon dioxide is a surface reaction only and has a linear growth rate (*see graph below*). However, after the SiO₂ begins to grow on the silicon surface, new arriving oxygen molecules must diffuse through the newly formed SiO₂ layer to get to silicon atoms below the surface. At this point (approximately 500 Å thickness) the SiO₂ growth is occurring within the substrate. Because the oxygen molecules now have to travel through silicon dioxide to find silicon atoms, the growth rate decreases exponentially. This oxide thickness as a function of time is shown in the diagram below.



As a general principle, the amount of silicon consumed in the oxidation reaction is 45% of the final oxide thickness (*see figure below*). For every 1 micrometer of SiO₂ grown, about 0.46 micrometers of silicon is consumed.

Silicon Dioxide Growth

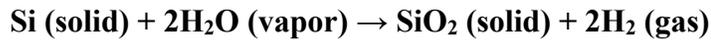


Wet vs. Dry Oxidation

There are two basic thermal oxidation processes: wet and dry. Both processes use heat to assist in the reaction rate. In dry oxidation, dry oxygen is pumped into a heated process chamber. The oxygen reacts with the silicon to form silicon dioxide.



In wet oxidation, oxygen saturated water vapor or steam is used in place of dry oxygen.



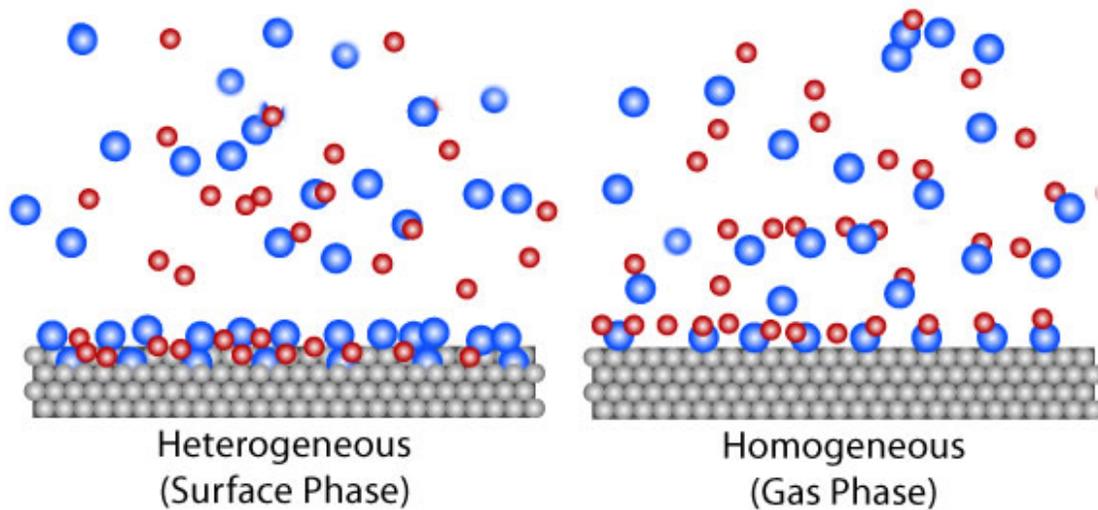
H₂O is much more soluble in SiO₂ than O₂; therefore, this leads to higher oxidation rates (faster oxide growth).

Wet oxidation is used in the manufacturing of microsystems to grow thicker layers (in the micrometer range) at a faster rate than is possible with dry oxidation. For thin layers (in the nanometer range) dry oxidation is used. Dry oxidation allows better control over the growth of thin oxides.

Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is the most widely used deposition method because of the different types of CVD available, allowing for a variety of films to be deposited. In all CVD processes, the films deposited during CVD are a result of the chemical reaction between the reactive gas(es) or reactants, and/or between the reactive gases and the atoms of the substrate surface.

CVD Reactions



CVD Reactions

Two types of reactions can occur during the CVD process:

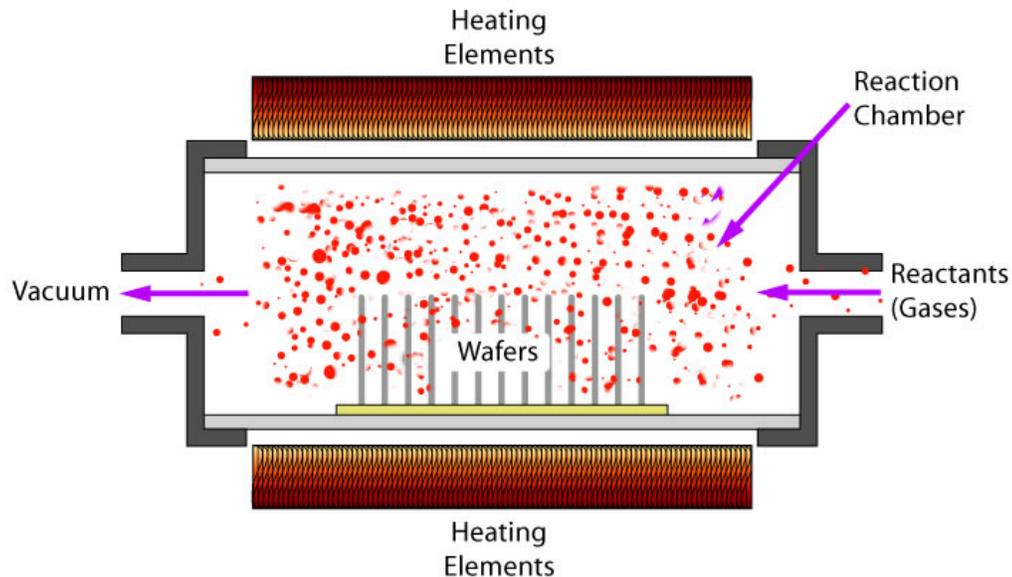
- Homogeneous (gas phase)
- Heterogeneous (surface phase)

Homogeneous reactions occur before the gas molecules reach the wafer surface. Because homogeneous reactions consume the gas reactants before reaching the substrate, the reaction rate at the surface is reduced. The result is a low-density and normally, a poorer quality film.

Heterogeneous reactions occur on or near the substrate surface. These reactions occur as the reactant gases reach the heated substrate. Heterogeneous reactions produce good quality films because of the proximity of the reaction to the wafer's surface. Heterogeneous reactions are preferred over homogeneous reactions.

The rate at which a reaction occurs in either phase affects the deposition rate and quality of the deposited layer. Both phases are greatly affected by temperature. The higher the temperature the greater the reaction rate.

CVD Process



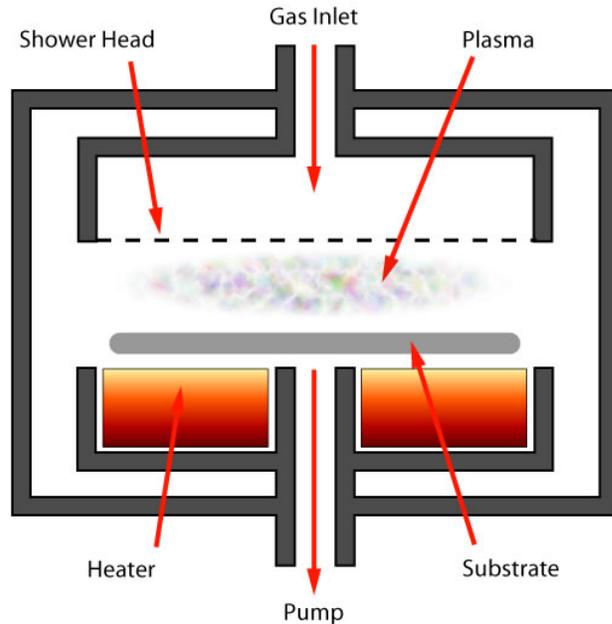
A Low Pressure CVD System

All CVD systems consist of the following three subsystems: gas delivery to the chamber, gas removal from the chamber (vacuum system or exhaust), and a heat source. The steps of the CVD process are as follows:

- The substrate is placed inside a reactor
- The pressure and temperatures are set to the programmed setpoints.
- Select gases (reactants) and inert gases are introduced into the chamber..
- These gases travel to the substrate surface.
- The chamber and substrate temperatures cause the gas molecules react chemically with each other and/or the substrate surface. These reactions form a solid thin film that adheres to the wafer surface. This reaction is referred to as adsorption.
- Gaseous by-products are produced by the chemical reactions at the substrate. These by-products are expelled from the wafer's surface and vented from the reaction chamber.

The resulting film's thickness is dependent on various process parameters such as pressure, temperature and the reactant's concentration. As indicated by the graphic, some CVD systems are similar to oxidation furnaces: a chamber with an input, exhaust and heating elements.

CVD Systems



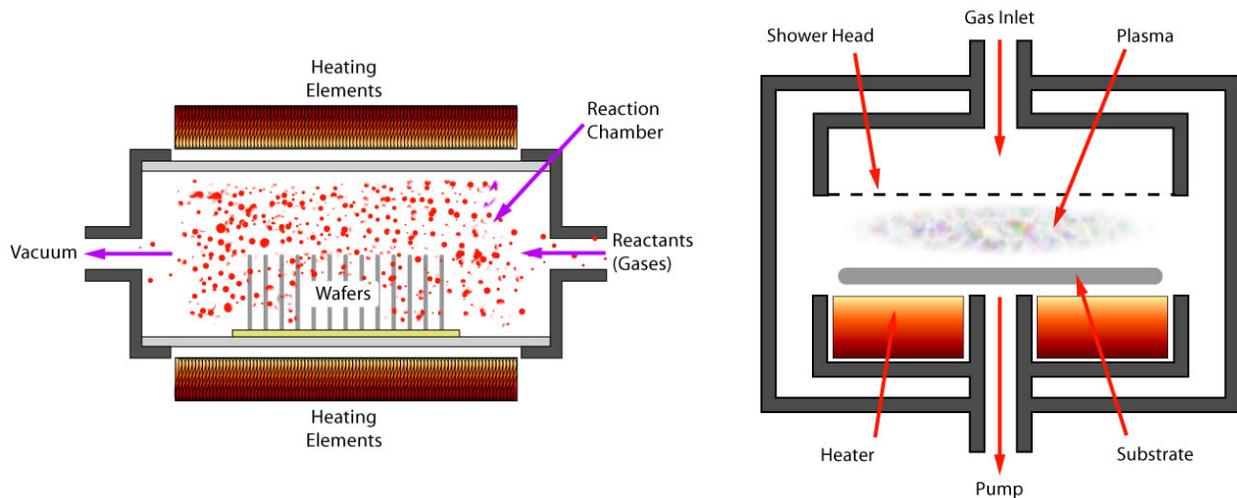
Plasma-enhanced CVD Systems [Image courtesy of UNM-MTTC]

There are many different types of chemical vapor deposition systems, each employing different methods in order to achieve a high quality films. The important distinctions between the different CVD techniques are the amount of pressure required in the reaction chamber and the energy source.

- An atmospheric pressure chemical vapor deposition (APCVD) system uses atmospheric pressure or 1 atm in the reaction chamber.
- A low pressure CVD (LPCVD) system uses a vacuum pump to reduce the pressure inside the reaction chamber to a pressure less than 1 atm.
- Plasma-enhanced CVD (PECVD) also uses a low pressure chamber. However, a plasma is introduced to provide higher deposition rates at lower temperatures than a LPCVD system. (see graphic) More on this in the next section.
- High density PECVD (HDPECVD) uses a magnetic field to increase the density of the plasma, thus further increasing the rate of deposition compared to a LPCVD.

All CVD systems have a heat source to catalyze the desired chemical reactions. The heat source is used to heat the entire chamber or is applied directly to the substrate. PECVDs are further equipped with RF generators to increase the reactivity of the reactants by creating a glow discharge or plasma.

CVD Systems for Microsystems



LPCVD (left) and PECVD (right)

The two most commonly used CVD systems for MEMS fabrication are LPCVD and PECVD¹:

- LPCVD (Low pressure CVD)
- PECVD (Plasma-enhanced CVD)

Both CVD processes require a vacuum to remove the atmospheric gases prior to introducing the reactants and inert process gases. LPCVD systems operate at temperatures higher than 600°C. PECVD systems operate at lower temperatures (down to 300° C). A plasma is used to provide more energy to the reactant gas molecules.

The different operating temperatures can affect the quality of the thin films deposited as well as applications. The higher temperature of LPCVD “produces layers with excellent uniformity of thickness and material characteristics.”¹ However, the higher temperatures result in a slow deposition rate and can be too high for certain films already deposited on the substrate. PECVD operates at a lower temperature (down to 300° C), however, “the quality of the films tend to be inferior to processes running at higher temperatures.”¹

LPCVD can batch process, meaning it can process at least 25 wafers at a time. It is also used exclusively when a film needs to be deposited on both sides of the wafers. PECVD can only deposit a film on one side of the wafer, and on just 1 to 4 wafers at a time.¹ LPCVD is used to deposit phosphosilicate glass (PSG), phosphorus-doped polysilicon, and silicon nitride. PECVD is also used for silicon nitride, but is primarily used for films or wafers that contain layers of film that cannot withstand the high temperatures of the LPCVD systems.

Physical Vapor Deposition (PVD)

Physical Vapor Deposition (PVD) includes deposition processes in which the desired film material is released from a source and deposited onto the substrate. This deposition method is strictly physical. No chemical reaction occurs at the substrate as with CVD. The two types of PVD processes used in microsystem fabrication are sputtering and evaporation.

PVD is normally used for the deposition of thin metals and metal alloy layers (e.g., Al Au, Ag, AlCu, Cr). These thin metal layers are used for conductive layers and components such as electrodes, active piezoresistive layers, and for reflective material for optical devices. PVD is also used in the construction of RF switches and coated cantilevers for devices such as chemical sensor arrays (CSAs). In CSAs a gold layer can be deposited on the cantilevers' surfaces prior to applying a probe coating. For example, since gold is relatively chemical inert it can be used in biosensors to provide a functionalized surface for antibody-antigen reactions.²

PVD Basic Process

There are three basic steps to a PVD process:

- The source material to be deposited is converted into vapor either through evaporation or sputtering.
- The vapor is transported across a low pressure region from the source to the substrate.
- The vapor condenses on the substrate to form the desired thin film.

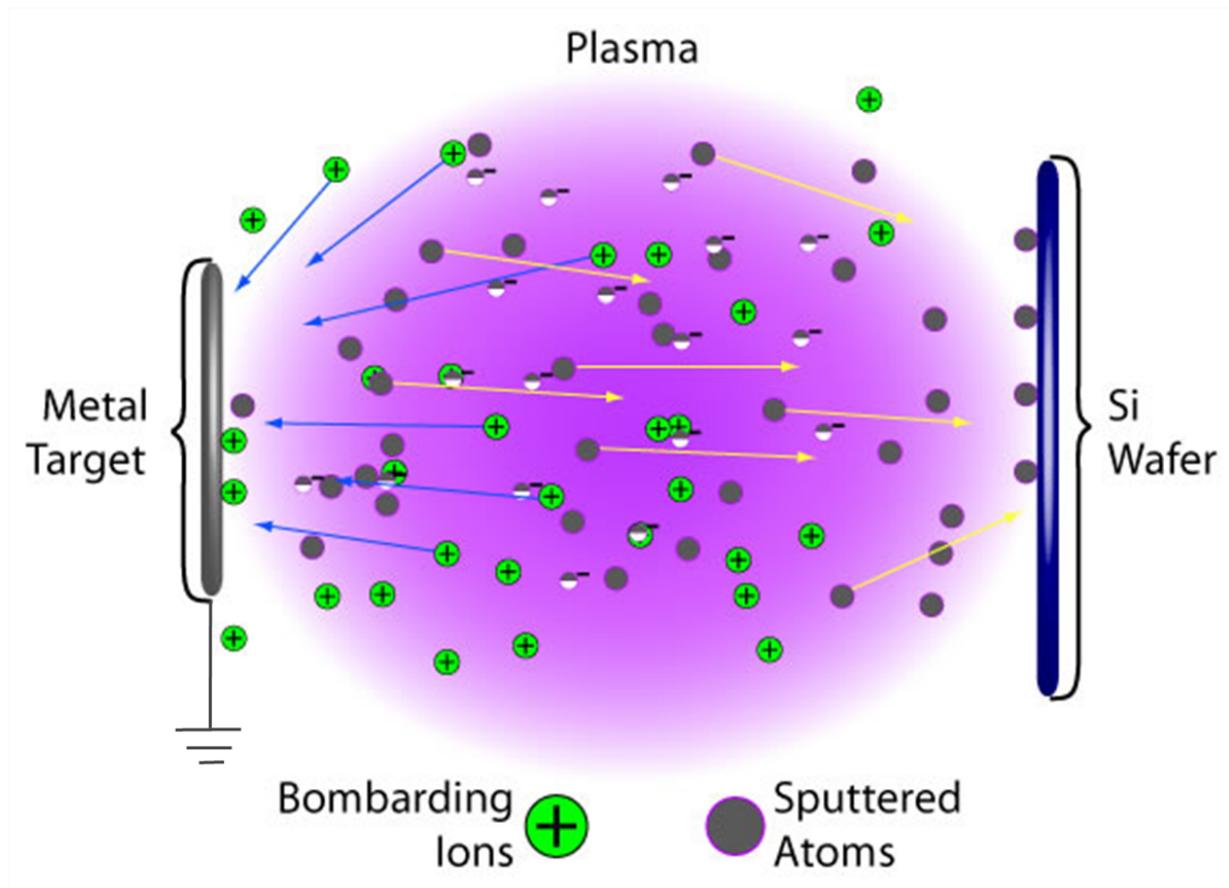
Sputtering

PVD sputtering is a process by which atoms and molecules are dislodged or ejected from a source material by high-energy particle bombardment. The ejected atoms and molecules travel to the substrate where they condense as a thin film.

Sputtering Process

The basic sputtering process includes the following steps:

- The substrate is placed in a chamber with the source material (called the target).
- The chamber is evacuated to the programmed process pressure (usually in the high vacuum range).
- An inert gas (such as argon) is introduced.
- A plasma is generated using a RF power source. This causes some of the gas molecules to lose an electrons, becoming positive ions.
- The ions accelerate toward the target which is at ground or negative potential.
- The high-energy ions bombard the target causing target atoms to break off as a vapor.
- The vapor expands and condenses on all surfaces. The condensation forms a thin film of source material on all surface including the substrate.



Evaporation

PVD evaporation is a process in which a source material (the thin film material) is converted to a vapor by applying high heat to the source. The applied heat is high enough to cause the source to boil and to vaporize. As with sputtering, a high-vacuum environment is required. Such an environment minimizes collisions between atoms or molecules as the vapor expands to fill the volume of the chamber, coating all surfaces, including the substrate. Once on the substrate (or any surface), the vapor condenses forming the desired thin film.

Evaporators use a planetary system (*picture right*) that holds several wafers near the top of the chamber. This planetary system allows for batch processing.

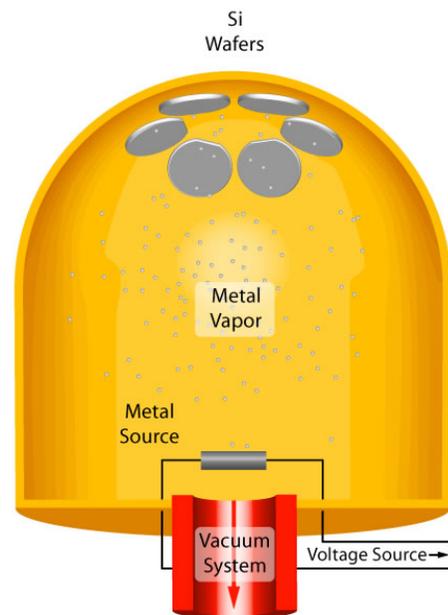


*Planetary System used in evaporators.
[Image courtesy of MJ Willis]*

Evaporation Process

The basic evaporation process includes the following steps:

- The substrate and the solid source material are placed inside a chamber.
- The chamber is evacuated to the desired process pressure (usually a high vacuum).
- The source material is heated to the point where it starts to boil and evaporate.
- The evaporated particles (atoms or molecules) from the source expand to fill the volume of the chamber, condensing on all surfaces, including the substrates. The high vacuum allows the vapor molecules to expand with minimal collision interference.
- The vapor molecules condense on all surfaces including the substrate.



Evaporation Heat Source

The primary difference between evaporation processes is the method used to heat (vaporize) the source material. The two main methods are e-beam evaporation and resistive evaporation. In e-beam evaporation an electron beam is aimed at the source material causing local heating and evaporation. In resistive evaporation, a tungsten boat containing the source material is heated electrically with high current causing the material to boil and evaporate.

Electrodeposition (also known as electroplating¹)

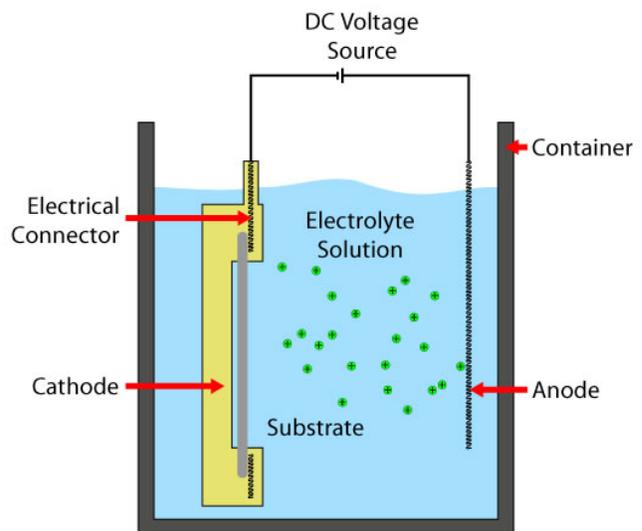
Electrodeposition is a process that uses electrical current to coat an electrically conductive object with a relatively thin layer of metal (electroplating), or to coat and fill a micro-sized cavity with metal (electroforming). Electroplating is a commonly used deposition technique for thousands of everyday objects such as faucets, inexpensive jewelry, keys, silverware and various automobile parts. Electroforming is a process used in LIGA (lithography, electroforming, and molding) micromachining to coat and fill cavities formed in relatively thick Plexiglas type material. Electrodeposition does have environmental disposal issues with the liquids used in the processes.

For microsystems, electrodeposition is used to deposit films of metals such as copper, gold and nickel. The films can be made in any thickness from $\sim 1\mu\text{m}$ to $>100\mu\text{m}$. The LIGA process uses electroforming for the construction of devices with very high aspect ratios, ratios of 100:1 or greater.

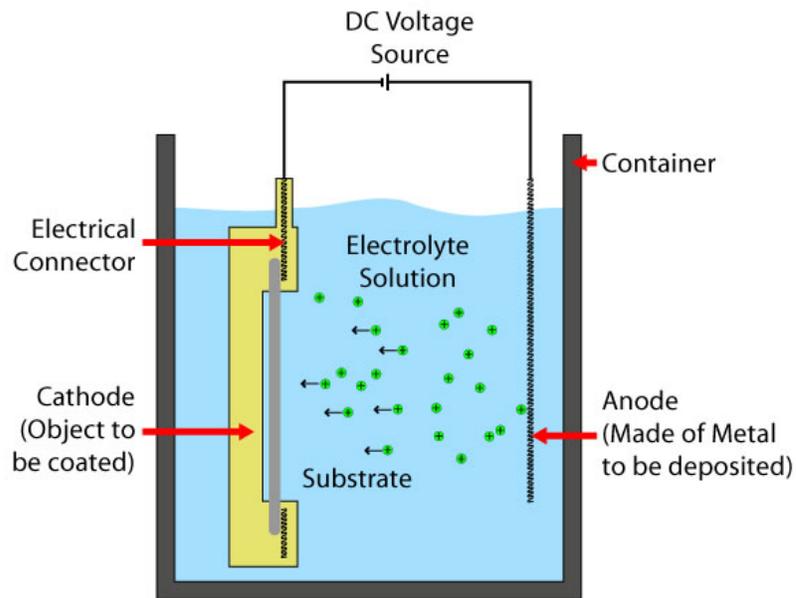
Electroplating Materials

Comparatively, electrodeposition is a simple process using very few materials:

- Container
- Electrolyte Solution
- DC power source
- Anode (Desired metal coating)
- Cathode (Object to be coated)
- Cathode holder with electrical connector



Electroplating Process



Electroplating Process

The electroplating process includes the following steps:

- The object or substrate to be coated is immersed into an electrolyte solution which contains metal salts and ions to permit the flow of electricity.
- The negative side of the DC power supply is connected to the cathode.
- The positive side is connected to the anode.
- The metallic ions of the salt carry a positive charge. They are attracted to the negatively charged substrate.
- When the metal ions reach the substrate, the negatively charged substrate provides the electrons to "reduce" the positively charged particles to metallic form.
- The metal ions are replenished by the release of metal ions from the anode.
- This process continues until the cathode is completely coated with the desired thicknesses.

What's What? (Answers)

Match the following deposition process with its unique characteristic.

		Process		Characteristic
D	1	Spin-on	A	Resistive heating for target
E	2	Oxidation	B	Electrically conductive substrate
F	3	LPCVD	C	Ion bombardment
C	4	Sputtering	D	Photoresist films
A	5	Evaporation	E	Silicon Dioxide films
B	6	Electroplating	F	Two-sided thin films

Table 2: Processes and Unique Characteristics

What's What?

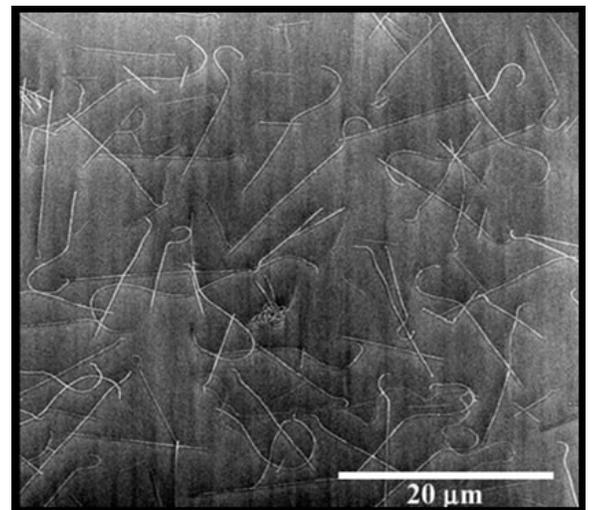
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	2	Oxidation	B	Electrically conductive substrate
	3	LPCVD	C	Ion bombardment
	4	Sputtering	D	Photoresist films
	5	Evaporation	E	Silicon Dioxide films
	6	Electroplating	F	Two-sided thin films

Table 3: Processes and Unique Characteristics

Nanotechnology has led to the development of new applications for deposition. For example, chemical vapor deposition is used for the self-assembly of carbon nanotubes (CNTs) (*see picture*). CNTs are structures that might be used as nanowires in integrated circuits, or as tips for scanning-probe microscopy, or for electron emitters, or in conducting films.

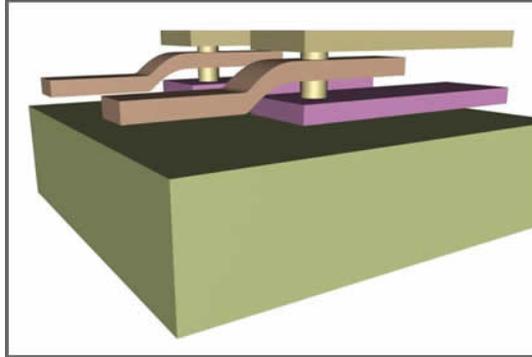
Carbon nanotubes (or hooktubes) grown by the CVD process on a silicon dioxide covered silicon chip. The thin white lines are the nanotubes. [Courtesy of Michael S. Fuhrer, University of Maryland]



Summary

Deposition is any process that deposits a thin film of material onto a substrate. A thin film can range from greater than 100 micrometers to only a few nanometers thick. Some gate oxides are even thinner, on the order of tenths of microns. Microsystems technology uses a variety of deposition processes. The type of process used depends on the thin film material, thickness and desired structure (stoichiometry) being deposited.

Questions



MEMS Linkage Assembly

[Courtesy of the University of Michigan, Khalil Najafi]

Study the graphic of the microsystems linkage assembly.

How many different deposition layers do you think were used to construct this component?

What types of deposition layers were used (insulating, conductive, structural, sacrificial, masking, etc.)

You see deposited films everyday of your life even though you may not realize it.

What are some examples of deposited films outside of microsystems or semiconductor processing?

Questions (Answers)

There is no wrong answer to the above questions. The purpose of these questions is to have the participants use the information from this SCO to make an "educated guess".

In the first question on the number of layers in the Linkage System, participants should recognize at least 3 structural layers and at least 3 sacrificial layers as a minimum. However, they should also discuss the masking layers used to form the structures as well as the layers need to construct the vertical posts for the assemblies. Since no electronics are indicated, conductive and insulating layers do not exist.

In the second question, participants should recognize items such as chrome plated fenders and facets, tints for glass (glasses, car glass),

protective coatings for all types of items (material on chairs and couches, painted objects, wood floors), and many more.

Glossary

Chemical vapor deposition (CVD) - A process used to deposit material onto a wafer using chemical reactions on the wafer surface to modify the material during processing.

Deposition - A process that deposits a thin film of material onto an object.

Electrolyte - A solution through which an electric current may be carried by the motion of ions.

Electroplating - The process of using electrical current to coat an electrically conductive object with a layer of metal.

Evaporation - The process by which molecules in a liquid state become gaseous, such as water to water vapor. In MEMS fabrication, evaporation is used to deposit metal vapor onto the wafers forming a solid metal film.

Homogeneous reaction - A single phase reaction. A reaction in which the reacting molecules are in the same state or phase (gas, liquid or solid)

Heterogeneous reaction - A reaction that takes place at the interface of two or more phases, such as between a solid and a gas, a liquid and a gas, or a solid and a liquid.

Oxidation - The process used to grow a uniform, high quality layer of silicon dioxide (SiO_2) on the surface of a silicon substrate.

Physical vapor deposition (PVD) - Deposition processes in which the desired film material is released from a source and deposited onto the substrate.

Plasma - An ionized gas wherein the electrons of an atom are separated from the nucleus. It is the fourth state of matter.

Sputtering - A physical vapor deposition process by which atoms and molecules are dislodged or ejected from a source material by high-energy particle bombardment. These ejected atoms and molecules travel to the substrate where they condense as a thin film.

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