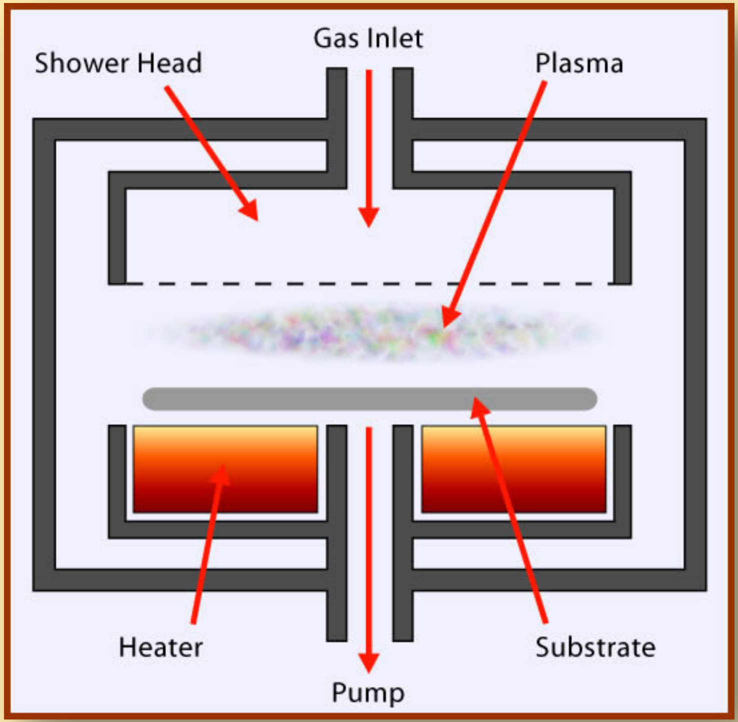
DEPOSITION OVERVIEW FOR MICROSYSTEMS



Plasma Enhanced Chemical Vapor Deposition (PECVD)

Unit Overview

The deposition process is critical for micro and nano systems fabrication. It provides the ability to deposit thin film layers as thick as 100 micrometers and as thin as a few nanometers.

This unit is an overview of the deposition process and the various types of deposition used for microsystems fabrication.

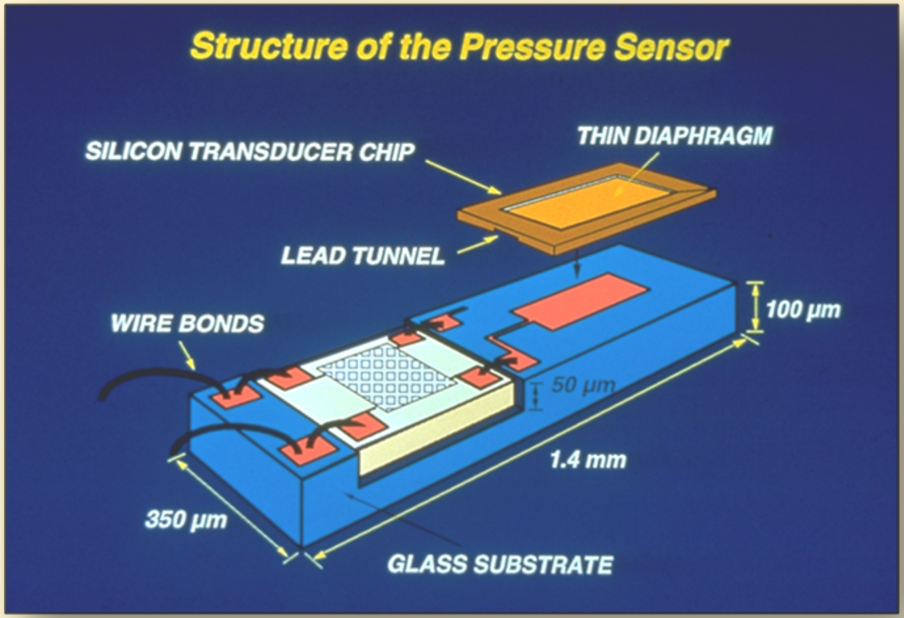
Objectives

- Describe two (2) deposition processes.
- Develop an analogy for a deposition process.

Introduction

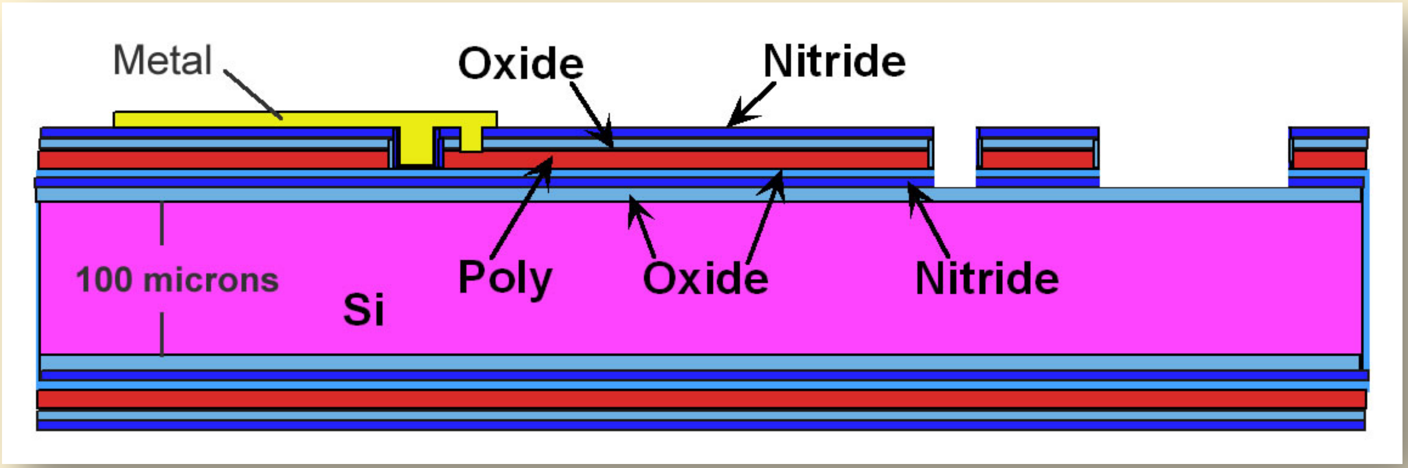
Microsystems are constructed using many of the same processes found in the manufacture of integrated circuits:

- Photolithography
- Wet and dry etch
- Oxidation
- Diffusion
- Planarization
- Deposition



[Graphic courtesy of Khalil Najafi, University of Michigan]

Microsystems Thin Films



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

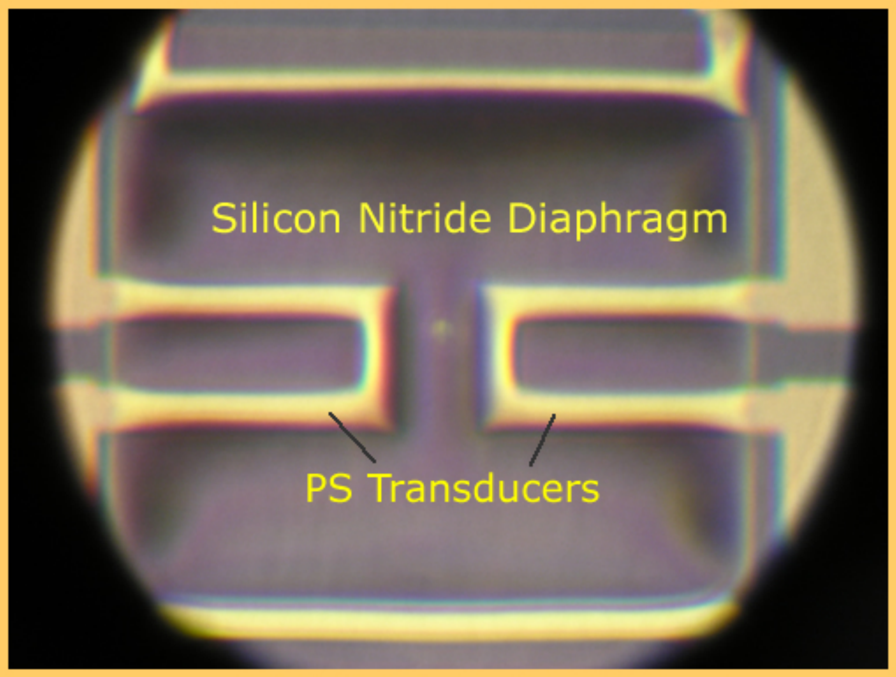
Each deposition step in a process deposits a thin film layer that can be as thick as 100 micrometers or as thin as a few nanometers.

Thin Films in Microsystems

Thin films are used for

- mechanical components
- electrical components
- sensor coatings

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



MEMS Pressure Sensor [University of New Mexico, MTTC]

Types of Deposition

Thin films for microsystems have different thicknesses, purposes, and composition; therefore, different deposition processes are required for different films.

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

This unit provides a brief overview of each of these deposition methods.

What is Deposition?

- Any process that deposits or grows a thin film of material onto an object. Object could be a fork, a door handle, a substrate (e.g., silicon, glass) or another thin film on a substrate.

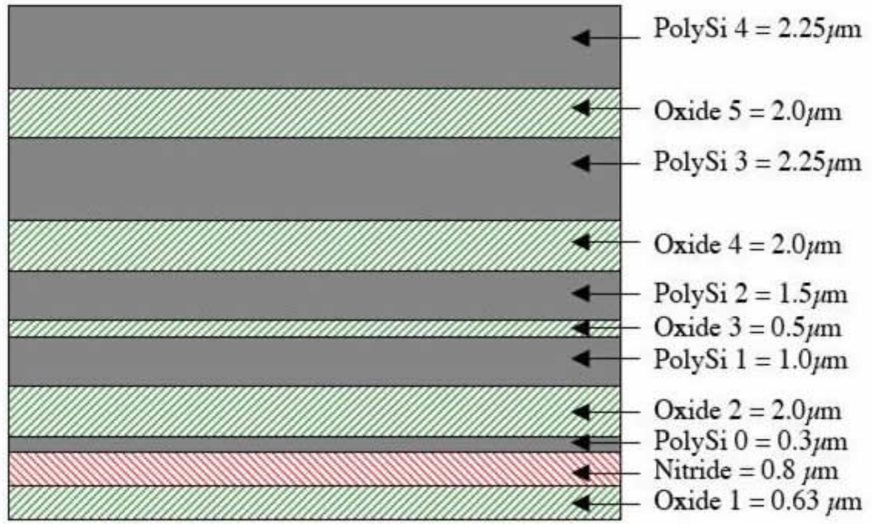
- One of the primary processes in the construction of micro and nano systems.

Where is Deposition?

Deposition usually precedes the photolithography and etch processes.

The thickness of the thin film depends on its function within the fabricated device.

The graphic illustrates the thickness of deposited thin films.

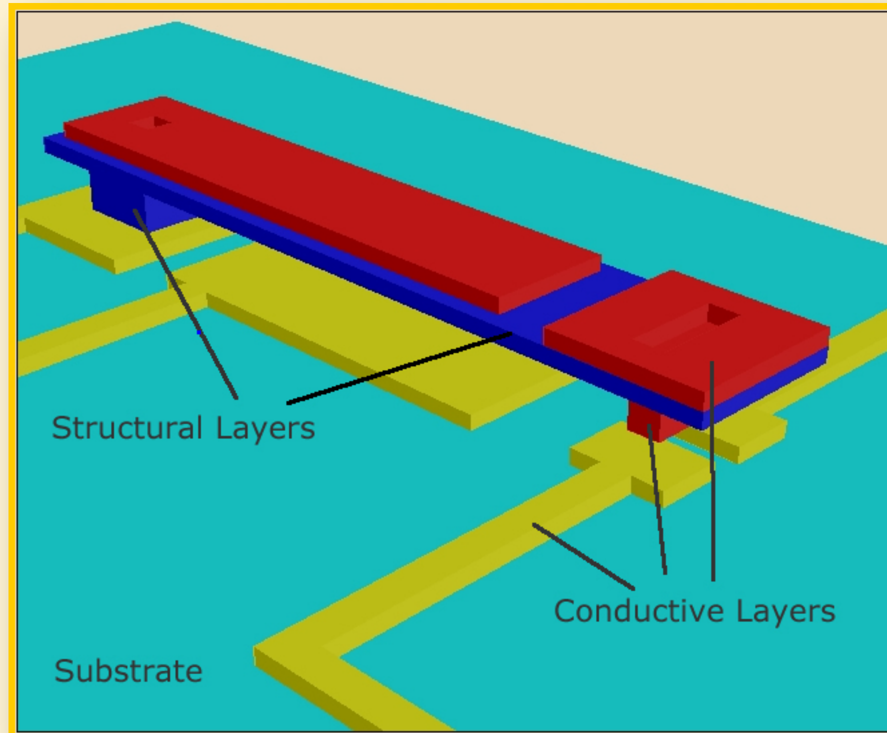


The Sandia Ultra-planar, Multi-level MEMS Technology (SUMMiT™) Fabrication Process is a multi-layer polycrystalline silicon surface micromachining process developed for building complex mechanical systems. It uses 5 layers of polysilicon, with interlayers of silicon dioxide sacrificial layers. (www.mems.sandia.gov)

Thickness of deposited layers used in the SUMMIT™ Fabrication Process developed at Sandia National Laboratories (SNL). [Image courtesy of SNL]

Function of a Deposited Layer

- Insulating layer
- Sacrificial layer
- Conductive layer
- Structural layer
- Protective layer
- Etch stop layer
- Etch mask layer

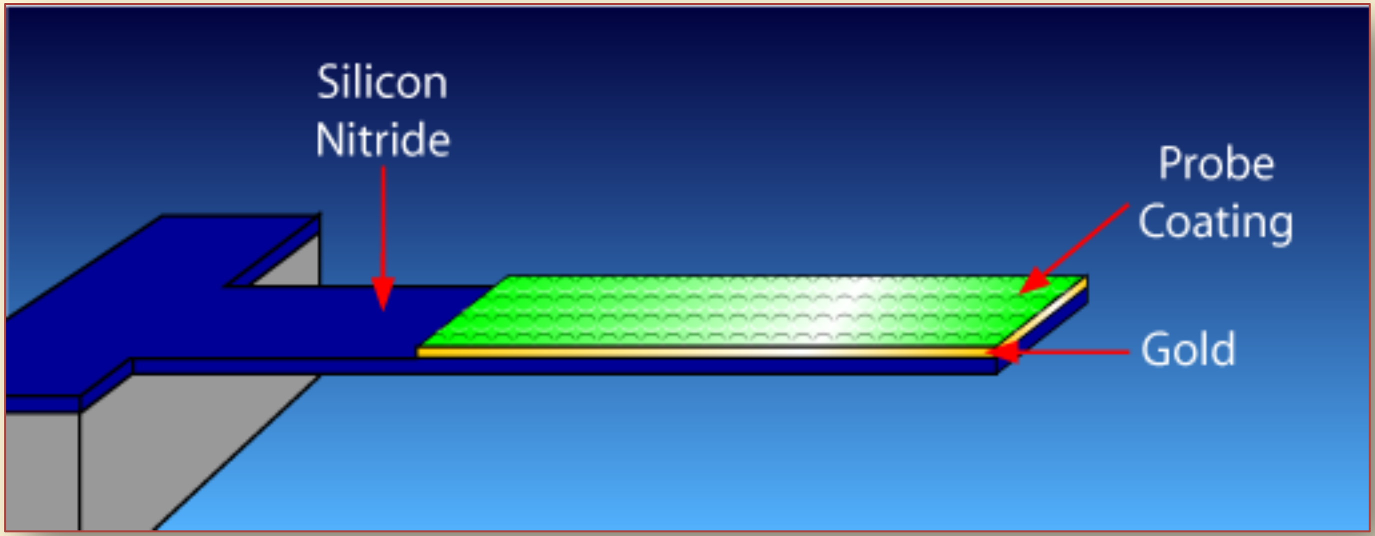


Different Layers for building a MEMS
[Khalil Najafi, University of Michigan]

Type of Film vs. Application

Type of Thin Film	Applications
Silicon Dioxide	Sacrificial
	Masking
Polysilicon	Structural
	Piezoresistive
Silicon Nitride	Electrical Isolation
	Masking
Phosphosilicate Glass (PSG)	Structural anchor to substrate
	Sacrificial
Metals	Conductors
	Reflective
Spin-on Glass (SOG)	Final Layer
Zinc Oxide	Piezoelectric
	Sacrificial
Photoresist	Masking

MEMS Deposition Processes



Layers for a MEMS cantilever transducer. Silicon Nitride is structural layer, Gold is an adhesive layer. Probe Coating is the "sensing" layer that identifies target molecules in a sample.

- The goal is to achieve a high quality, thin, solid film.
- In microtechnology fabrication, deposition can occur many times.
- The graphic shows three layers for a cantilever transducer. Each layer requires a unique deposition process.

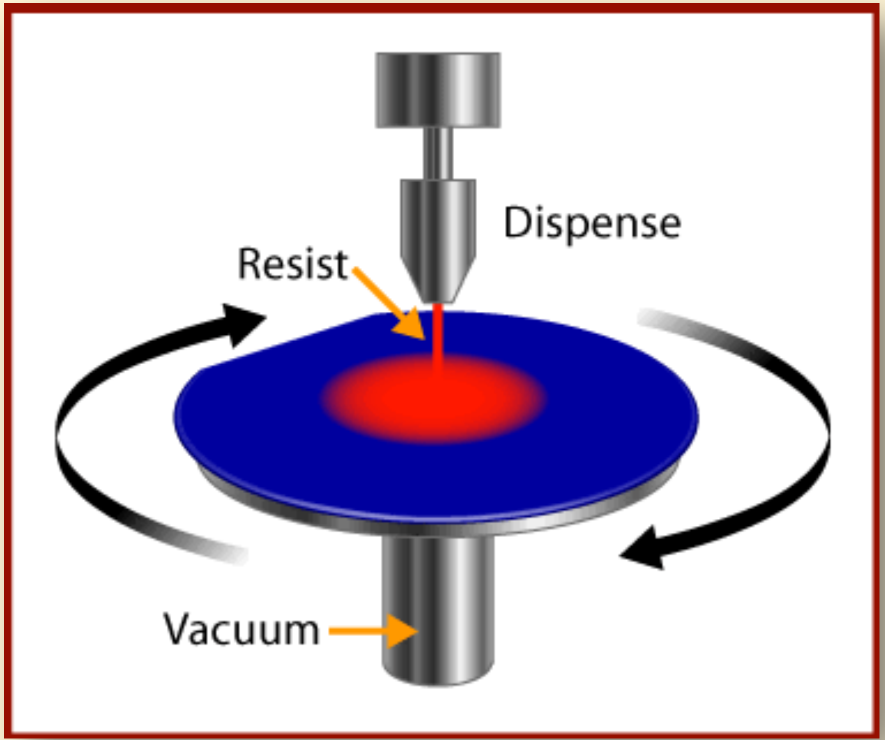
Deposition Processes

The deposition processes used for microsystems include the following:

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

Spin-on Films

- The process of literally spinning a liquid onto the wafer surface.
- Thickness of the film is dependent upon the liquid's viscosity and spin speed.
- Spin-on is primarily used for photoresist and spin-on glass (SOG).



Spin-on Photoresist

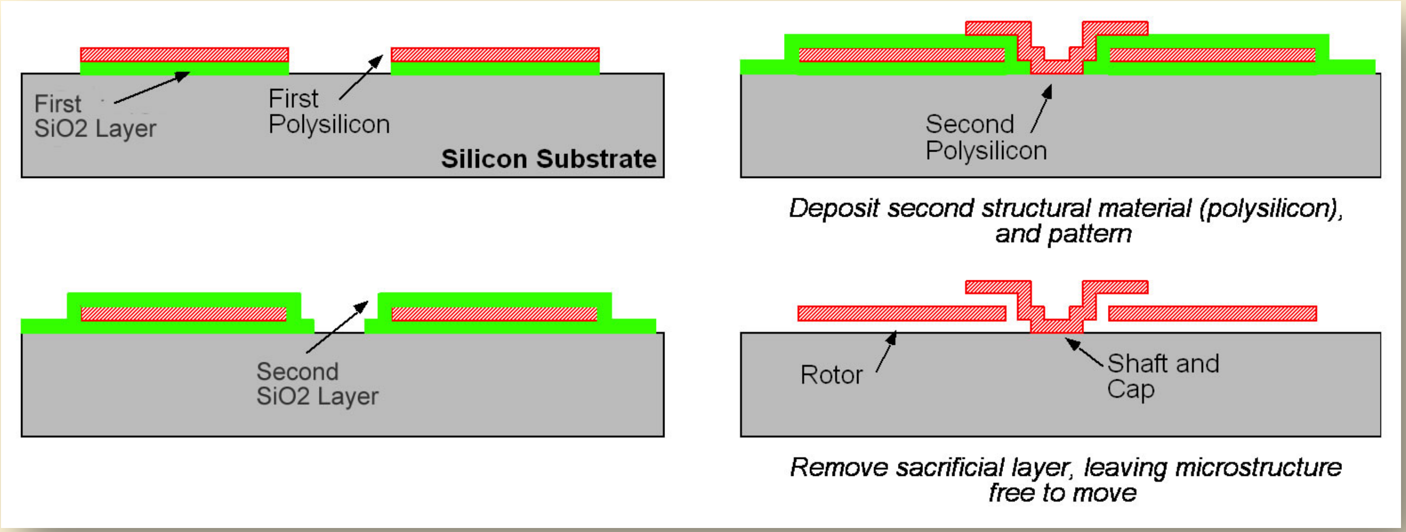
Thermal Oxidation

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

- The SiO_2 layer literally “grows” **into** the silicon substrate consuming silicon.

- Other types of deposition "deposit" the layer on the substrate surface with little if any reaction with the surface molecules.

Silicon Dioxide



Silicon Dioxide as Sacrificial Layers

When exposed to oxygen, silicon oxidizes to form silicon dioxide (SiO_2). SiO_2 is used for …

- Barrier material or hard mask
- Electrical isolation
- Device component
- Sacrificial layer or scaffold for microsystems devices.

Thermal Oxidation Process

Three basic steps:

- Silicon wafers are placed in a heated vacuum chamber (typically 900 – 1200 degrees C).
- An oxygen source (gas or vapor) is pumped into the chamber.
- Oxygen molecules react with the silicon to grow a silicon dioxide (SiO_2) layer within and on the substrate.

Oxide Growth Kinetics

- This oxygen/silicon reaction is analogous to the oxidation or rusting of metal (e.g., oxygen and iron).
- The longer the wafers or metal are exposed to oxygen (O_2), the thicker the oxide (or rust) layer becomes.
- What do you think? The higher the temperature, the (*higher or lower*) the reaction rate.

Oxide Growth Kinetics

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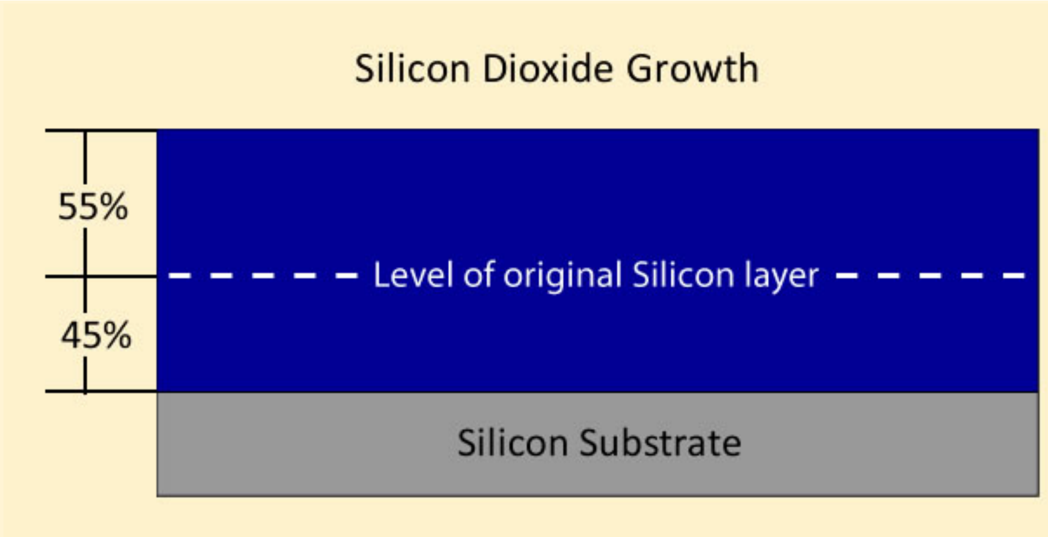
  Answer: higher

Kinetics (continued)



The amount of silicon consumed in the oxidation reaction is 45% of the final oxide thickness

The oxide layer consumes a portion of the silicon just as rust consumes metal.

Initially, silicon dioxide growth is a surface reaction only.

Additional oxygen molecules must diffuse through the surface SiO_2 layer to get to silicon atoms below. At this point the SiO_2 growth occurs **within** the substrate.

Wet vs. Dry Oxidation

There are two basic oxidation processes: wet and dry.

- Both processes use heat to assist in the reaction rate.
- Wet oxidation is used to grow the thicker layers (in the micrometers) at a faster rate than is possible with dry oxidation.
- Dry oxidation is used for thin layers (in the nanometers). Dry oxidation allows better control over the growth of thin oxides.

Dry Oxidation

Dry oxygen is pumped into a heated process chamber.

The oxygen reacts with the silicon to form silicon dioxide.

$$Si\ (solid) + O_2\ (gas) \rightarrow SiO_2\ (solid)$$

Wet Oxidation

- Oxygen saturated with water vapor or steam is used in place of dry oxygen.
- ***Si (solid) + 2H_2O (vapor) → SiO_2 (solid) + 2H_2 (gas)***
- H_2O is much more soluble in SiO_2 than O_2 leading to higher oxidation rates.

Bubbler used to generate steam for wet oxidation process

Wet vs. Dry Thermal Oxidation

- Below are three animations that illustrate
  - Wet Oxidation
    - https://youtu.be/o7gZP55J_bE
  - Dry Oxidation
    - https://youtu.be/Kt_z2mX5DfY
  - Comparison of wet vs. dry
    - https://youtu.be/nzF8f6ocqXo

Chemical Vapor Deposition (CVD)

The most widely used deposition method.

Films deposited during CVD are a result of the chemical reaction

- between the reactive gas(es) and
- between the reactive gases and the atoms of the substrate surface.

CVD Reactions

Two types of reactions:

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

The rate at which a reaction occurs in either phase affects the deposition rate and quality of the deposited layer.

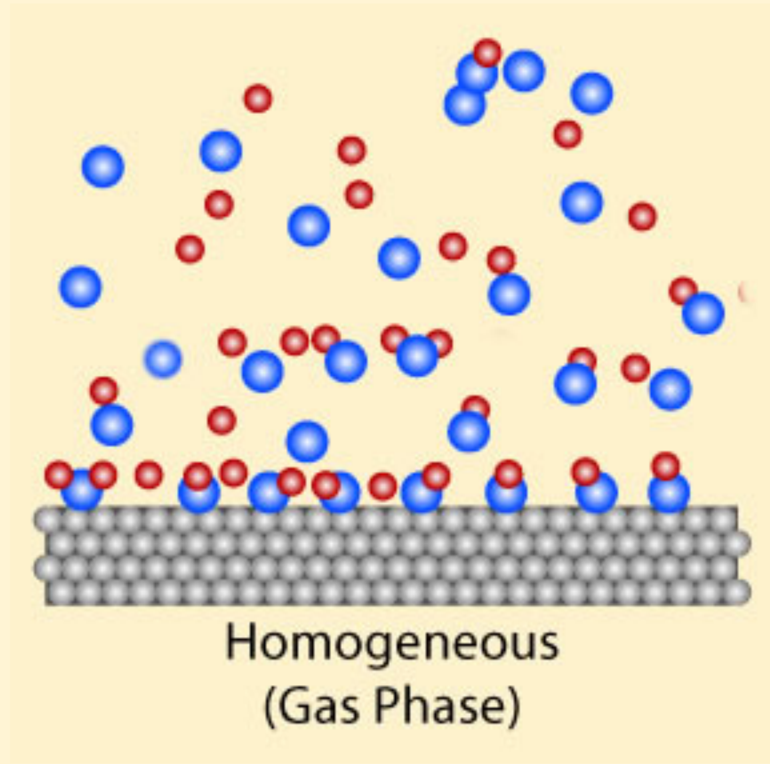
Both phases are greatly affected by temperature. The higher the temperature the greater the reaction rate.

Homogeneous Reactions

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.



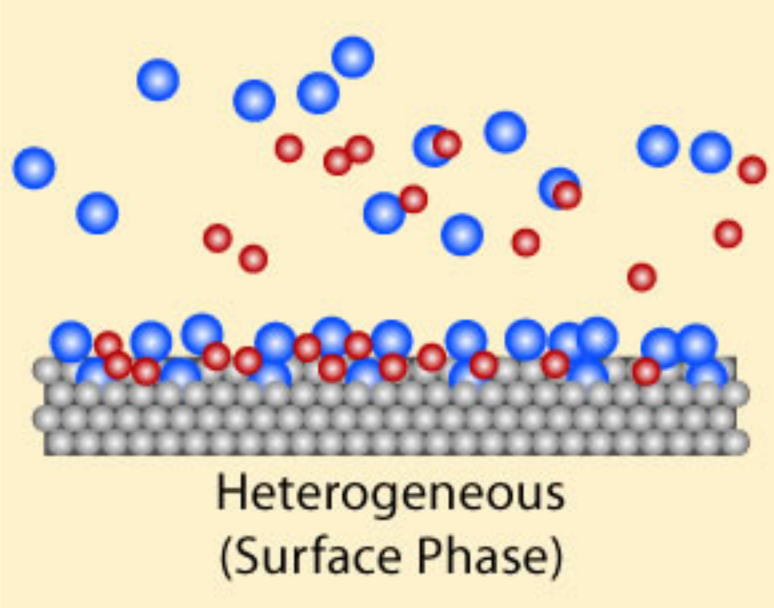
Homogeneous Reaction

Heterogeneous Reactions

Heterogeneous reactions occur on or near the substrate surface.

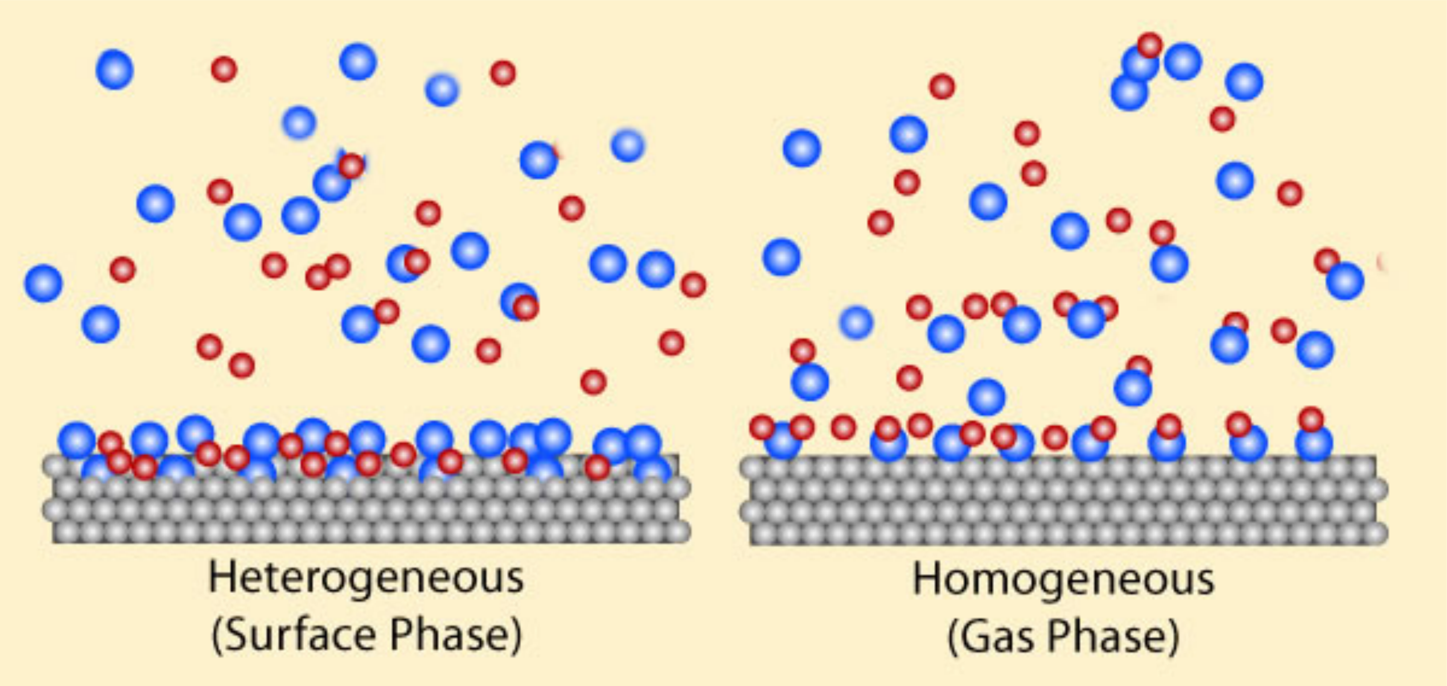
These reactions occur as the reactant gasses reach the heated substrate.

Heterogeneous reactions produce good quality films because of the proximity of the reaction to the wafer's surface.



Heterogeneous Reaction

Heterogeneous or Homogeneous?

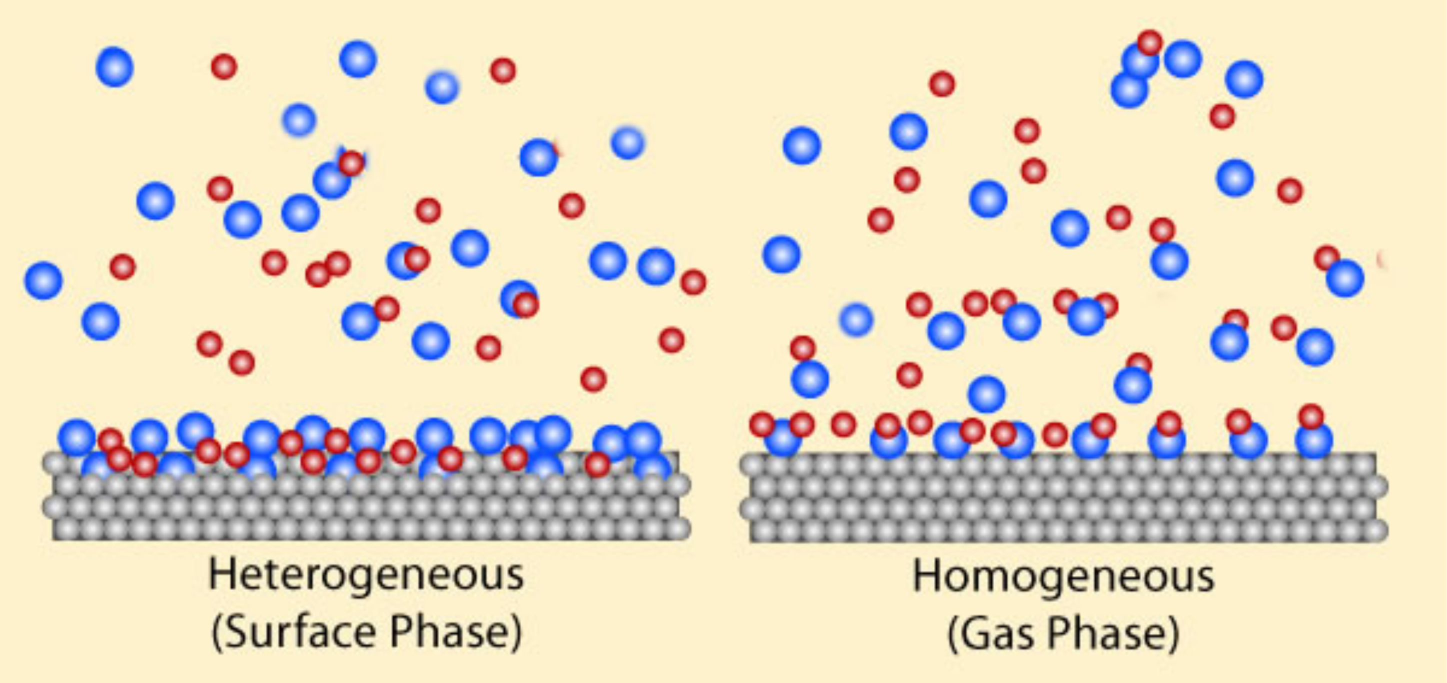


Heterogeneous or Homogeneous?

Which do you think is the preferred method for microsystems?

Why?

Heterogeneous or Homogeneous?



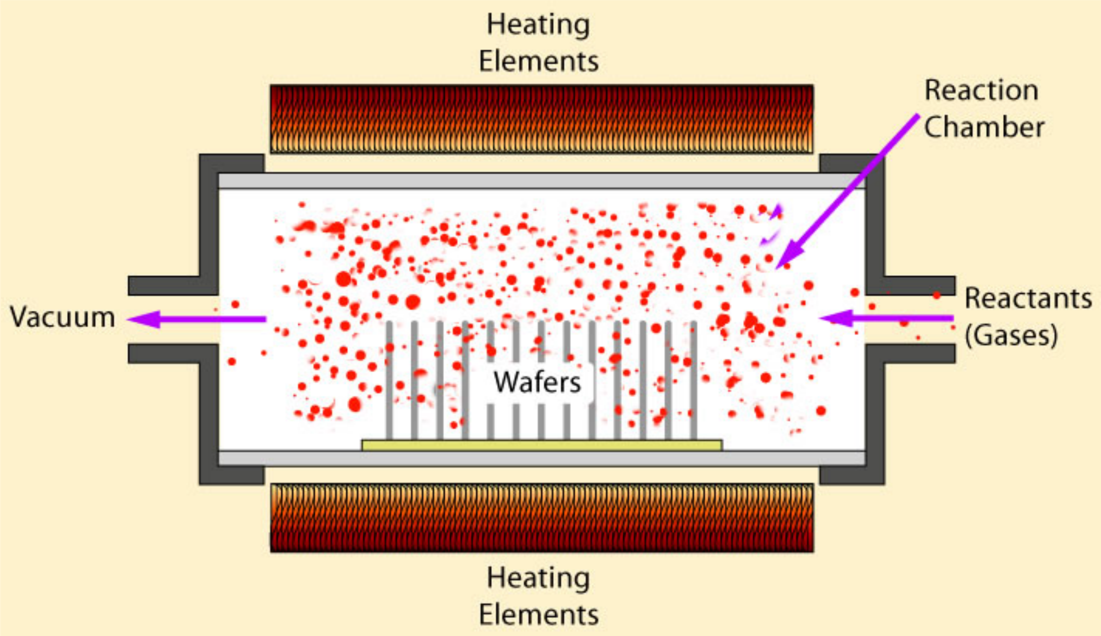
Heterogeneous or Homogeneous?

Which do you think if the preferred method for microsystems?

heterogeneous

Why? Higher quality films

CVD Subsystems



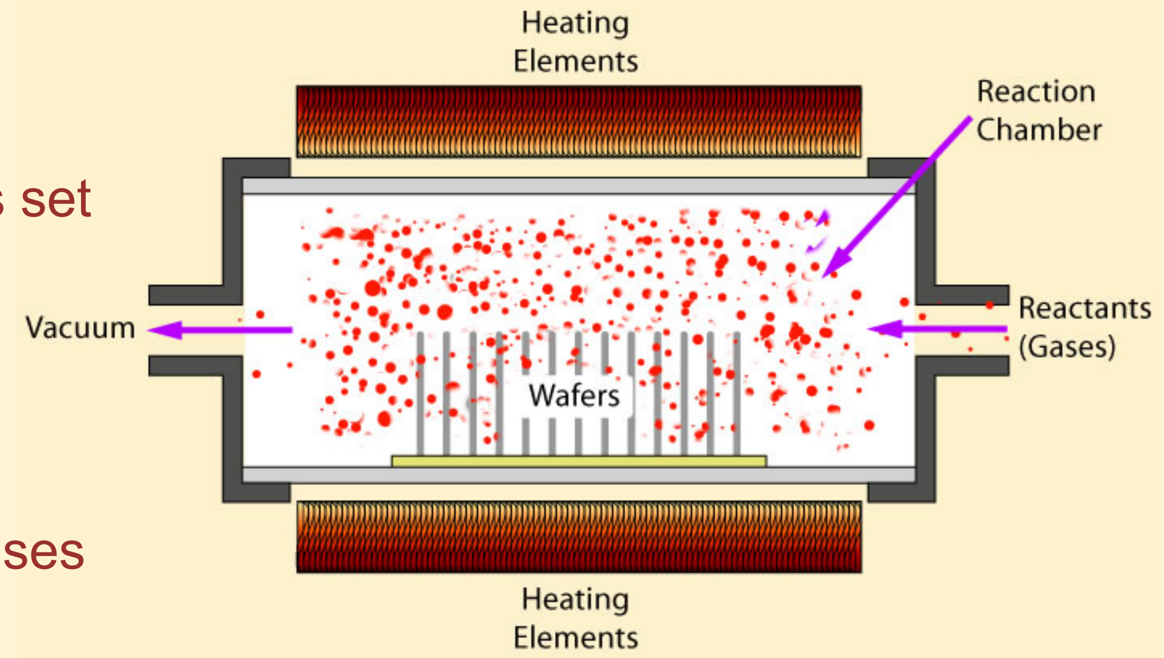
CVD system with gas delivery, gas removal (vacuum), and heat source

All CVD systems consist of the following three subsystems:

- gas delivery to the chamber
- gas removal from the chamber (vacuum system or exhaust)
- a heat source

CVD Process

- Substrate is placed inside reactor
- Chamber pressure is set to process pressure.
- Heat is applied (to substrate or entire chamber)
- Select (reactants) gases are introduced.



- Gas molecules chemically react with each other or with the substrate forming a solid thin film on the wafer surface.
- Gaseous by-products produced by the chemical reaction are removed from the chamber.

Film Thickness

The resulting film's thickness is dependent on process parameters such as

- pressure,
- temperature. and
- the reactant's concentration.

CVD Systems

The differences between CVD systems are the amount of pressure required in the reaction chamber and the energy source.

Four types of CVD systems:

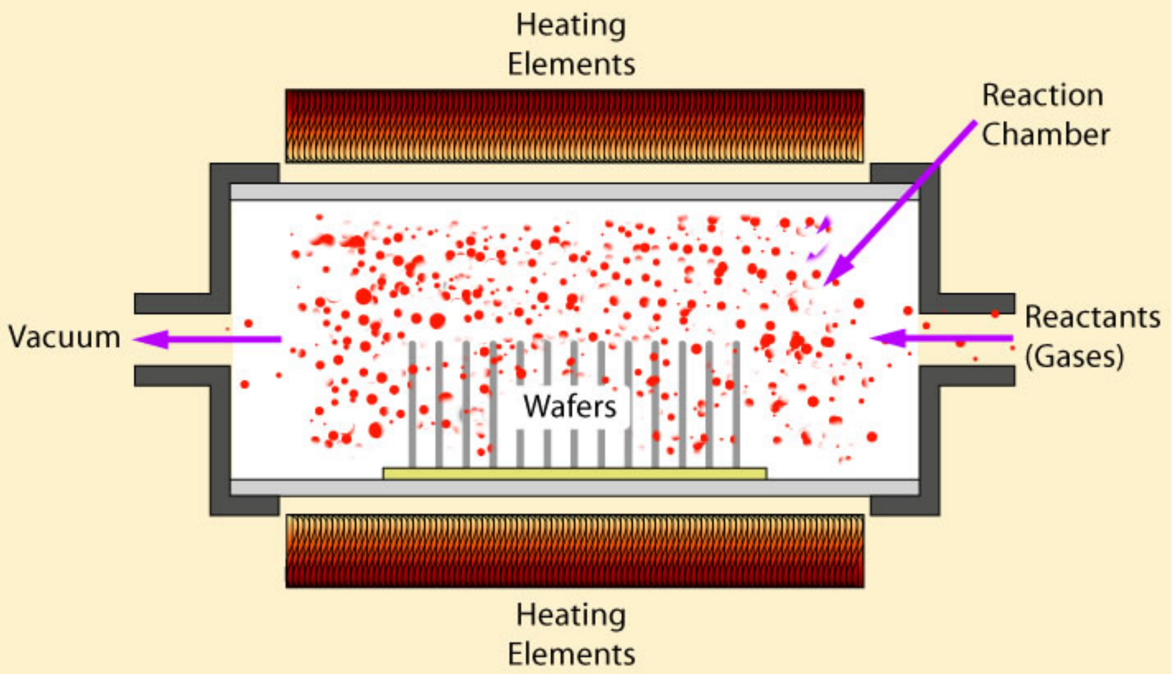
- ❖ Atmospheric Pressure CVD (APCVD)
- ❖ Low Pressure CVD (LPCVD)
- ❖ Plasma-Enhanced CVD (PECVD)
- ❖ High Density PECVD

LPCVD and PECVD are commonly used for microsystems fabrication.

APCVD

Atmospheric Pressure Chemical Vapor Deposition (APCVD) systems use atmospheric pressure or 1 atm in the reaction chamber.

Low Pressure CVD (LPCVD)

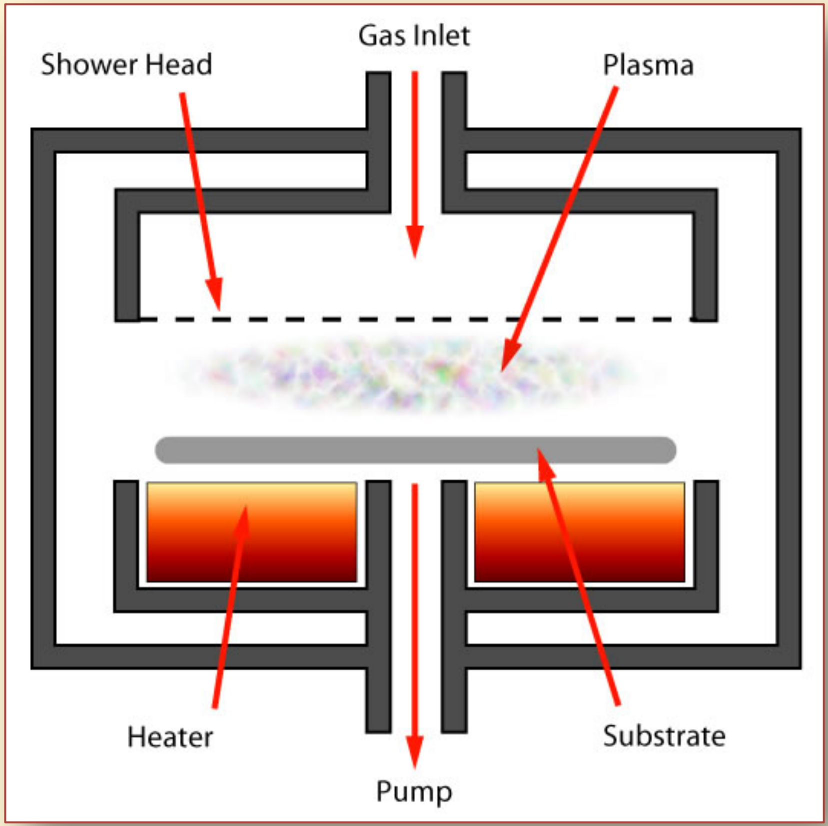


Uses a vacuum to reduce the pressure inside the reaction chamber to a pressure less than 1 atm.

Used for 2-sided films (same film on both sides of wafer) and for phosphosilicate glass (PSG), phosphorus-doped polysilicon, and silicon nitride.

Plasma Enhanced CVD (PECVD)

- Uses low pressure chambers.
- A plasma provides higher deposition rates at lower temperatures than a LPCVD system.
- Used for films or wafers that contain layers of film that cannot withstand the high temperatures of the LPCVD systems.



PECVD System

High Density PECVD (HDPECVD)

HDPECVD uses a magnetic field to increase the density of the plasma, thus further increasing the rate of deposition.

CVD Heat Sources

- 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 (plasma).

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.

PVD is normally used for the deposition of thin films of metals and metal alloys.

PVD Basic Process

There are three basic steps to a PVD process:

- The material to be deposited (the source) is converted into a vapor of source molecules and atoms.
- The vapor travels across a low pressure region from the source to the substrate.
- The vapor condenses on the substrate to form the desired thin film.

The two PVD processes used for microsystems are sputtering and evaporation.

Sputtering

- PVD Sputtering is a 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.

Sputtering Process

- Substrate and film material (target) are placed in the chamber.
- Chamber is evacuated.
- An inert gas (such as argon) is introduced.
- Plasma is generated using an RF power source.
- Gases ionize and ions accelerate toward the target.
- Ions bombard target. Target atoms and molecules break off target material and enter plasma.

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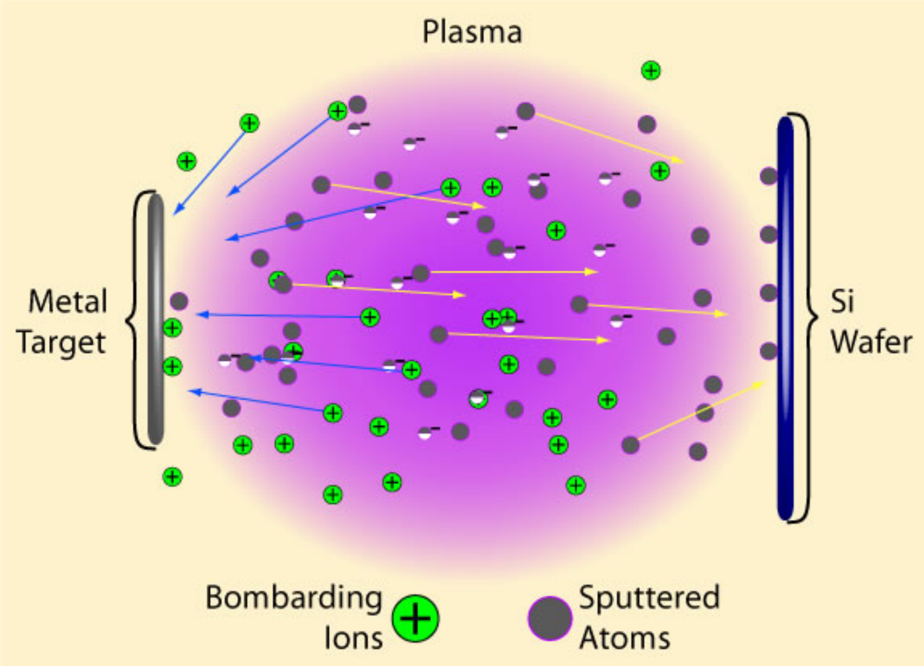
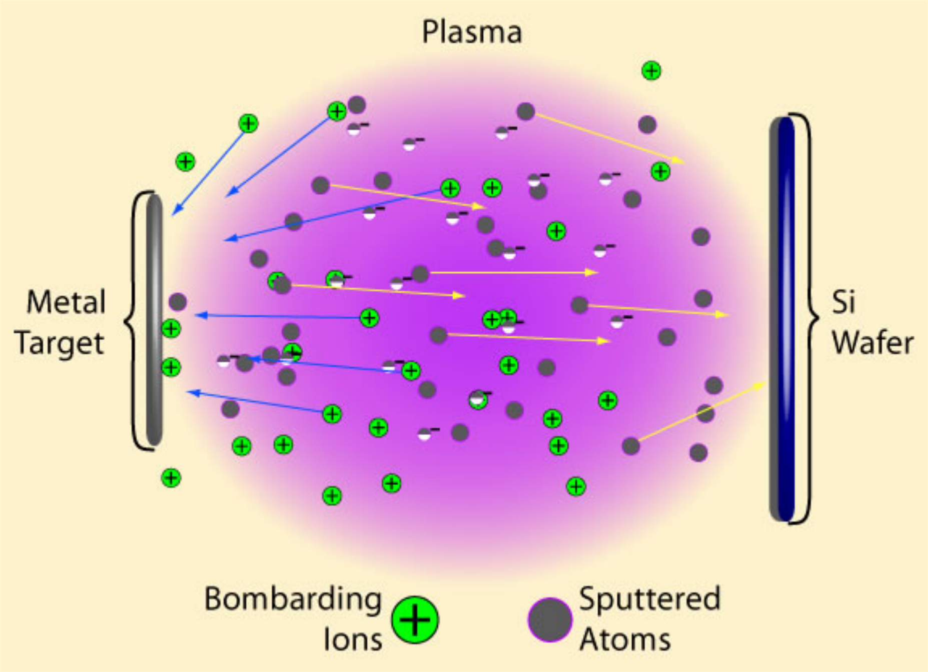


Sputtering Process

The molecules and atoms condense on all surfaces including the substrate.

The desired thin film of source material forms on the surface of the wafer.



Evaporation

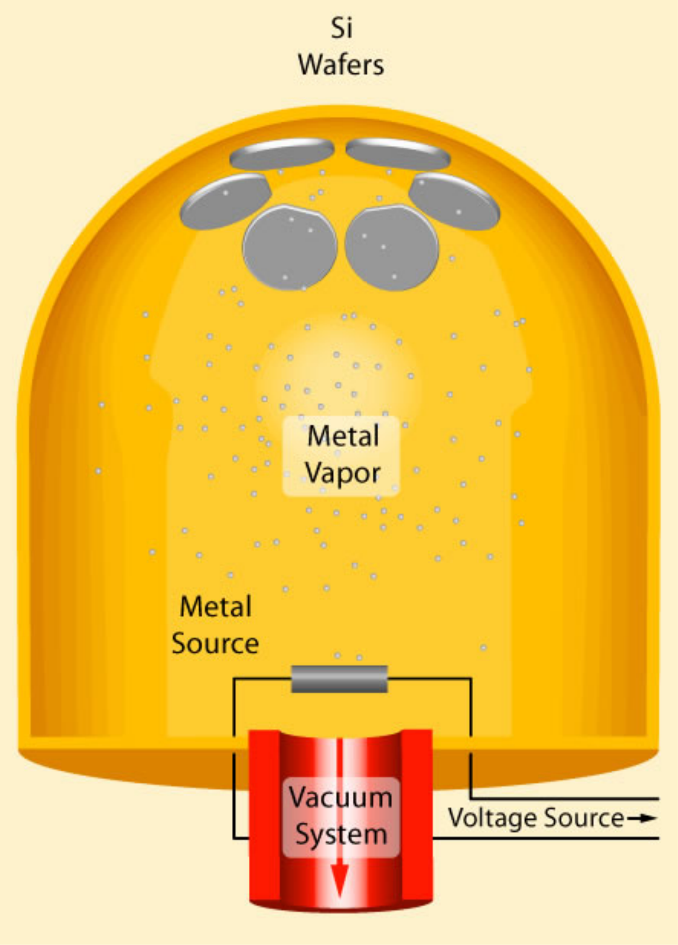
- The source material is vaporized through the application of heat. The high heat causes the source to boil and evaporate.
- High-vacuum environment minimizes collisions as molecules and atoms travel to the substrate. At the substrate the molecules and atoms condense forming the desired thin film.

Single planetary for Evaporator. Evaporator can hold several planetary units.

Evaporators use a planetary system that holds several wafers. This allows for batch processing.

Evaporation Process

- Substrates and source material are placed inside a vacuum chamber.
- Chamber is evacuated to process pressure.
- Source material is heated to its vaporization temperature.
- Source molecules and atoms travel to the substrates. Vacuum allows travel with minimal collisions.
- Molecules and atoms condense on all surfaces including the substrates.



Evaporation Heat Sources

- The primary difference between evaporation processes is the method used to heat (evaporate) 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.

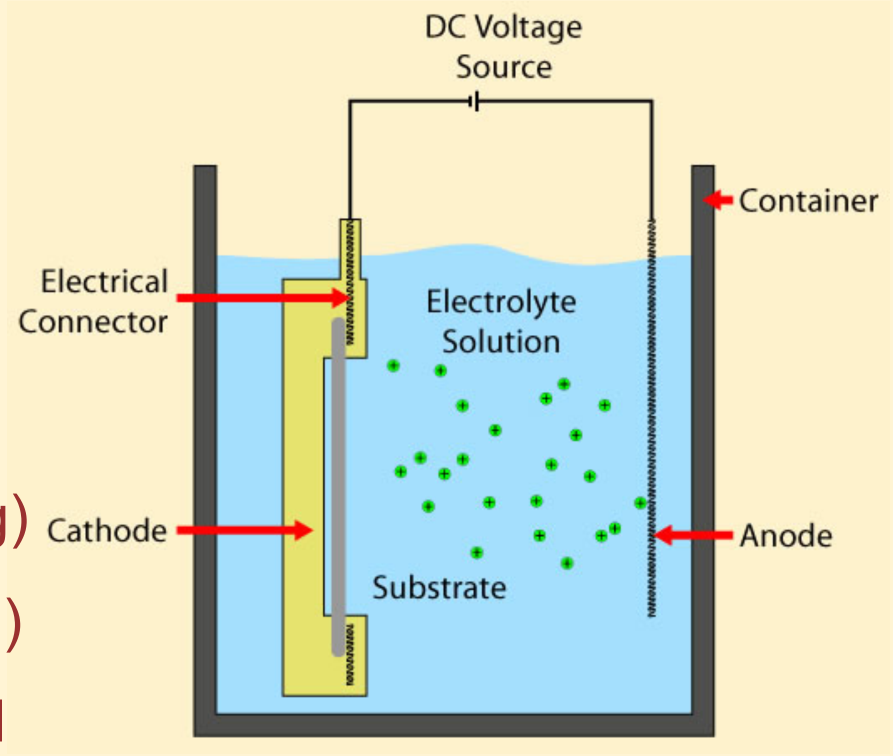
Electroplating

- The process of using electrical current to coat an electrically conductive object with a relatively thin layer of metal.
- A commonly used deposition technique for thousands of everyday objects such as faucets, inexpensive jewelry, keys, silverware and various automobile parts.
- For microsystems, electroplating is used to deposit films of metals such as copper, gold and nickel. The films can be made in any thickness from ~1µm to >100µm.

Electroplating Components

Simple process using very few materials:

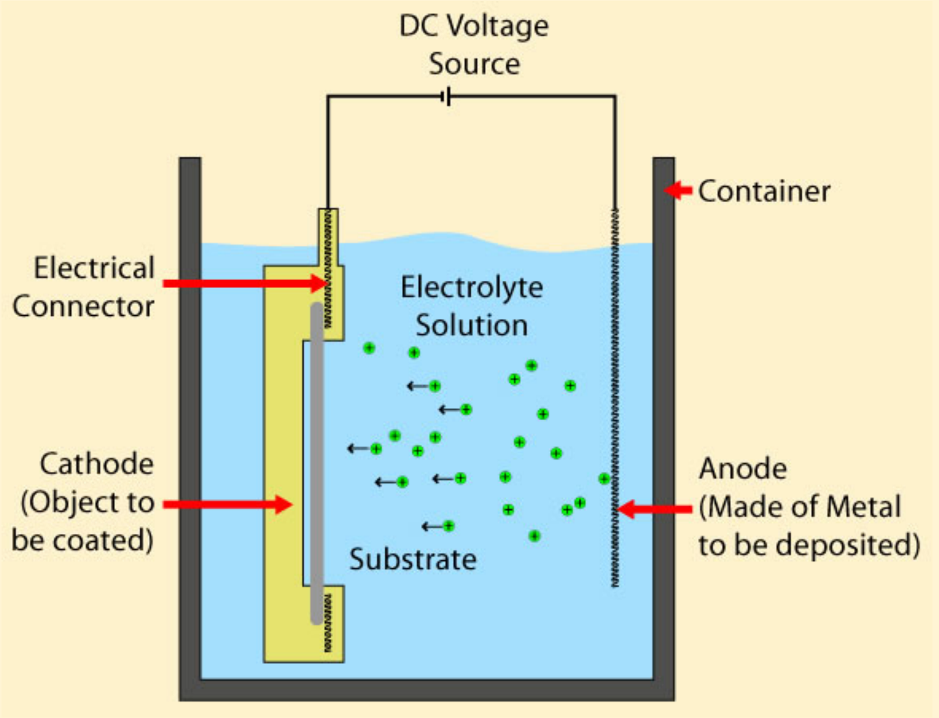
- Container
- Electrolyte Solution
- DC power source
- Anode (Desired metal coating)
- Cathode (Object to be coated)
- Cathode holder with electrical connector



Electroplating Components

Electroplating Process

- Substrate is immersed into electrolyte.
- Negative side of the DC power supply is connected to the cathode.
- Positive side is connected to anode.
- Positively charged metallic ions in electrolyte are attracted to the negatively charged substrate.
- When they reach the substrate, the positive ions are neutralize into metallic form.
- Ions are replenished by release of ions from the anode.
- Process continues until cathode is coated to desired thickness.



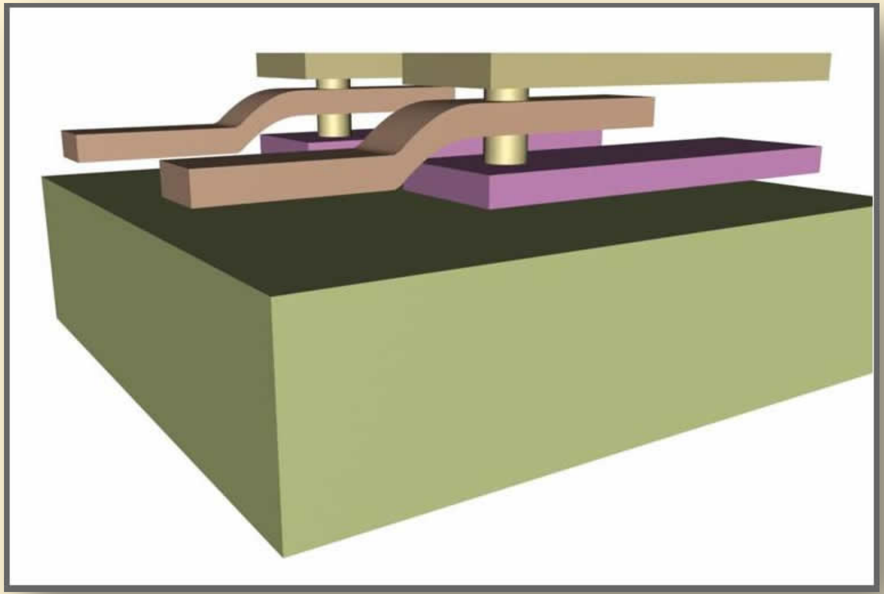
Electroplating Process

Electroplated Examples

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?

How Many Layers?



Microsystems Linkage Assembly
[University of Michigan, Khalil Najafi]

How many different deposition layers were used to construct this linkage assembly?

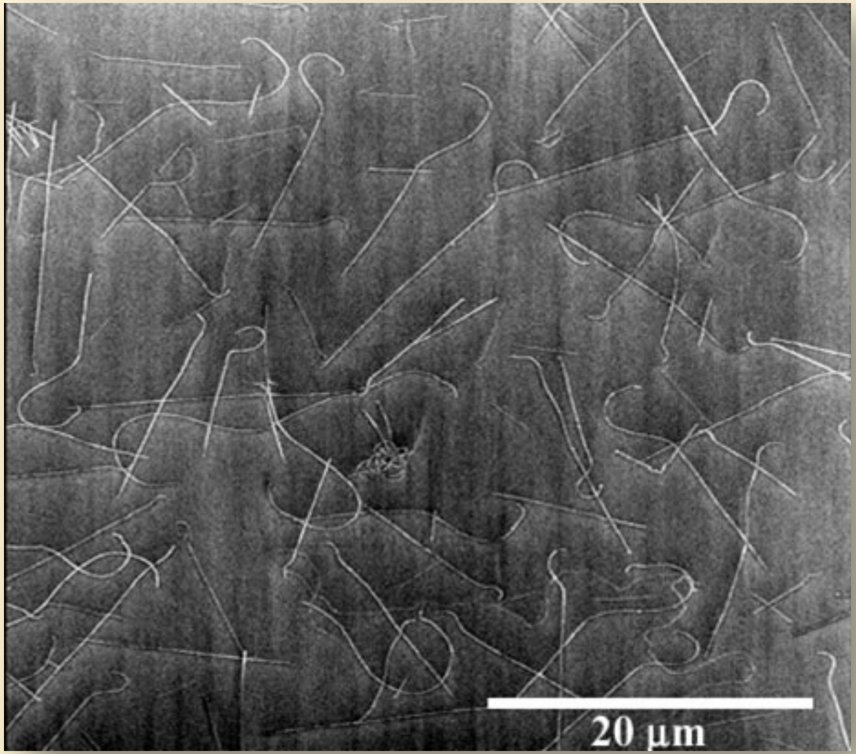
What types of deposition layers were used (insulating, conductive, structural, sacrificial, masking, etc.)?

Deposition and Nanotechnology

Nanotechnology creates new applications for deposition.

Chemical vapor deposition is used for the self-assembly of carbon nanotubes (CNTs), structures that might be used as

- nanowires in integrated circuits,
- tips for scanning-probe microscopy, and
- 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.
- Thin film thickness can range from greater than 100 micrometers to only a few nanometers.
- Microsystems technology uses various types of deposition processes.
- The type of process used depends on the thin film being deposited and the desired thickness.

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