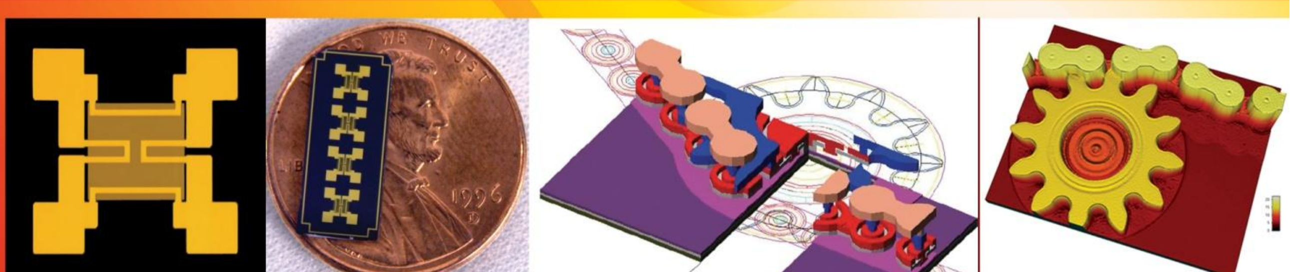
Deposition Overview for Microsystems

Knowledge Probe
Deposition PK
Activities

Participant Guide

SCME
Southwest Center for Microsystems Education



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Southwest Center for Microsystems Education (SCME)
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<u>MEMS Fabrication Topic</u>

Deposition Overview for Microsystems Learning Module

<u>This learning module contains the following units:</u>
Knowledge Probe (Pre learning module quiz)
Deposition Overview – Reading Material
Deposition Terminology Activity
Science of Thin Film Activity
Activity – What Do You Know About Deposition?

Target audiences: High School, Community College, University

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Deposition Overview for Microsystems
Knowledge Probe

Participant Guide

Introduction

The purpose of this assessment is to determine your understanding of the various types of deposition processes used in the fabrication of microsystems. There are 25 questions.

1. Which of the following BEST describes the purpose of the deposition process?
   a. To grow a high quality, insulating thin film on the surface of the wafer
   b. To deposit a high quality, conductive thin film on the surface of the wafer
   c. To deposit or grow a high quality thin film on the surface of the wafer.
   d. To deposit a solid layer of photoresist on the surface of the wafer.

2. Polysilicon is a thin film used in many MEMS applications. This film is used for which of the following layers in the fabrication of a MEMS?
   a. Structural and Piezoresistive layer
   b. Sacrificial and masking layer
   c. Masking and Piezoresistive layer
   d. Electrical and environmental isolation

3. Silicon dioxide is another thin film used in many MEMS applications. This film is used for which of the following layers?
   a. Structural and Piezoresistive layer
   b. Sacrificial and masking layer
   c. Masking and Piezoresistive layer
   d. Electrical and environmental isolation

4. Active piezoresistive and sacrificial applications normally require ________________ thin films.
   a. Silicon nitride
   b. Polysilicon
   c. Phosphosilicate Glass (PSG)
   d. Metal or metal alloy
   e. Photoresist

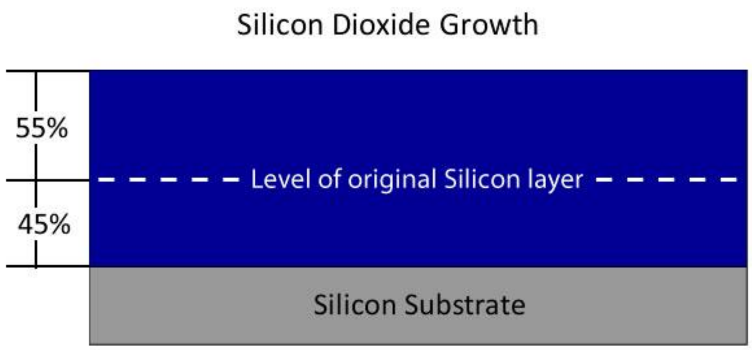
5. Metals are normally deposited using which of the following deposition processes?
   a. Spin-on
   b. Thermal oxidation
   c. Physical vapor deposition
   d. Chemical vapor deposition

6. Which of the following deposition processes is the MOST widely used process for the deposition of thin films such as silicon nitride, silicon dioxide and polysilicon?
   a. Spin-on film
   b. Oxidation
   c. Chemical vapor deposition
   d. Physical vapor deposition
   e. Electroplating

7. Which deposition process "grows" the thin film rather than "deposits" it?
   a. Oxidation
   b. CVD
   c. Sputtering
   d. Evaporation

8. Thermal oxidation is used for which of the following thin films on silicon?
   a. Silicon nitride
   b. Silicon dioxide
   c. Polysilicon
   d. Aluminum

9. Which of the following statements BEST describes the graphic below?
   a. To achieve a high quality silicon dioxide (SiO_2) film, you must first remove some of the silicon substrate (approximately 45% of the desired SiO_2 thickness).
   b. The thermal oxidation process uses a high temperature step to remove some of the silicon substrate (approximately 45% of the desired SiO_2 thickness) before growing SiO_2.
   c. In a thermal oxidation process, the bottom 45% of the SiO_2 layer has a higher concentration of silicon than the top 55%.
   d. In a thermal oxidation reaction the amount of silicon substrate consumed is 45% of the final oxide thickness.

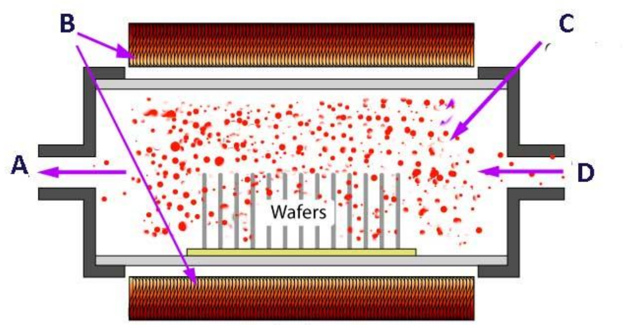


10. The following formula is a reaction that takes place in a specific type of deposition process. In which deposition process does this reaction occur?
    a. Silicon nitride CVD
    b. Wet oxidation of silicon dioxide
    c. Dry oxidation of silicon dioxide
    d. Spin-on of photoresist

$$\mathbf{Si\ (solid) + 2H_2O\ (vapor) \rightarrow SiO_2\ (solid) + 2H_2\ (gas)}$$

11. The films deposited during chemical vapor deposition (CVD) are a result of two types of chemical reactions: homogeneous and heterogeneous. A heterogeneous reaction is between
    a. the reactive gases or reactants used in the process
    b. the reactants and the atoms on the substrate surface
    c. both the reactants and reactants with the atoms on the substrate surface

12. The following diagram represents a low pressure CVD system. Match the labels (A,B,C,D) to the components/process elements, respectively?
    a. Reaction chamber, heating elements, reactants, vacuum/exhaust
    b. Reactants, vacuum/exhaust, heating elements, reaction chamber
    c. Vacuum/exhaust, heating elements, reaction chamber, reactants
    d. Reactants, heating elements, reaction chamber, vacuum/exhaust



13. In a CVD process, which of the following is NOT a process parameter that affects the resulting film thickness and quality?
    a. Pressure
    b. Temperature
    c. Reactant flow rate
    d. Reactant concentration

14. What does the acronym PECVD represent?
    a. Pressure-enhanced chemical vapor deposition
    b. Plasma-enhanced chemical vapor deposition
    c. Partial evaporation chemical vapor deposition
    d. Plating electronically chemical vapor deposition

15. Which of the following deposition processes is used when a film needs to be deposited on both sides of the wafer?
    a. LPCVD
    b. PECVD
    c. Evaporation
    d. Sputtering
    e. Spin-on

16. What is the difference between HDPECVD and PECVD?
    a. PECVD uses a plasma whereas HDPECVD uses only a magnetic field
    b. PECVD uses a low pressure chamber whereas HDPECVD uses a high pressure chamber
    c. HDPECVD uses a magnetic field to increase the density of the plasma in PECVD
    d. HDPECVD uses a higher pressure to increase the density of the plasma in PECVD

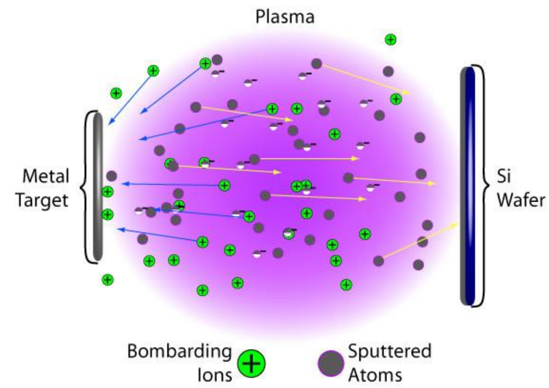
17. __________ systems operate at temperature higher than 600° C, compared to ___________ systems which operate at lower temperatures down to 300°C.
    a. APCVD, LPCVD
    b. LPCVD, APCVD
    c. PECVD, APCVD
    d. LPCVD, PECVD

18. Sputtering and evaporation are deposition processes used primarily to deposit what type of films?
    a. Silicon nitride
    b. Polysilicon
    c. SOG
    d. Silicon dioxide
    e. Metals and metal alloys

19. Which of the following BEST describes the sputtering process?
    a. A high heat source is used to vaporize the material to be deposited. This vapor is then accelerated towards the wafer surface where is solidifies.
    b. A plasma is used to generate high energy ions that bombard a target, causing target atoms to break off as a vapor which expands and condenses on all surfaces, including the substrate.
    c. A plasma is used to generate high energy ions that bombard a source, causing atoms to vaporize, deposit on the substrate and solidify.
    d. Low pressure, high energy molecules collide, creating ions used to react with substrate surface atoms causing these atoms to break after from the substrate.

20. Which of the following processes uses a high heat source to vaporize a source material consisting of the elements of the desired thin film?
    a. LPCVD
    b. PECVD
    c. Evaporation
    d. Sputtering
    e. Thermal oxidation

21. Which of the following processes is illustrated by the graphic?
    a. LPCVD
    b. PECVD
    c. Evaporation
    d. Sputtering



22. Which of the following microsystems processes is BEST for depositing relatively thick films of metal?
    a. CVD
    b. Sputtering
    c. Evaporation
    d. Electrodeposition
    e. Spin-on

23. Which of the following is a unique characteristic of the oxidation process?
    a. Uses ion bombardment on a target
    b. Grows oxide on silicon
    c. Used to deposit a film on both sides of the wafer
    d. Requires an electrically conductive substrate
    e. Melts the source material forming a vapor

24. Which of the following is a unique characteristic of the electroplating process?
    a. Uses ion bombardment on a target
    b. Grows oxide on silicon
    c. Used to deposit a film on both sides of the wafer
    d. Requires an electrically conductive substrate
    e. Melts the source material forming a vapor

25. Which of the following is a unique characteristic of the evaporation process?
    a. Uses ion bombardment on a target
    b. Grows oxide on silicon
    c. Used to deposit a film on both sides of the wafer
    d. Requires an electrically conductive substrate
    e. Melts the source material forming a vapor

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program.

Deposition Overview for Microsystems

Primary Knowledge
Participant Guide

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.

<u>Estimated Time to Complete</u>
Allow at least 20 minutes to complete this unit.

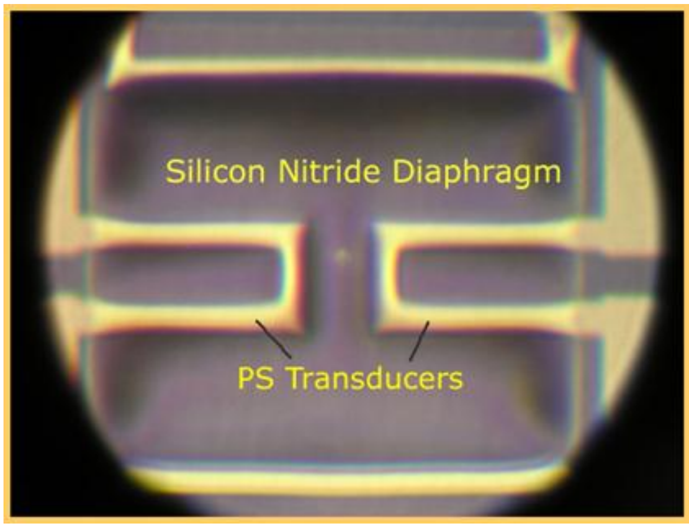
Introduction

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.

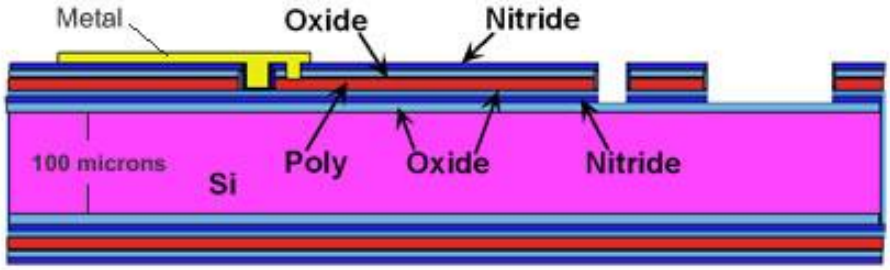
Objectives

- 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

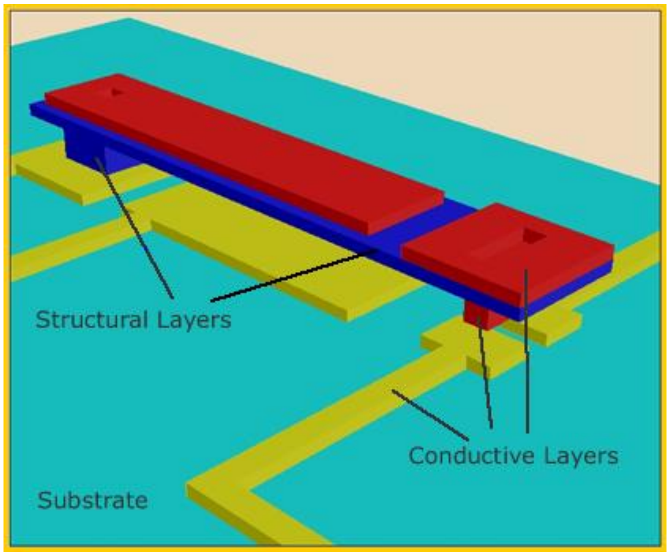
What is Deposition?



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)

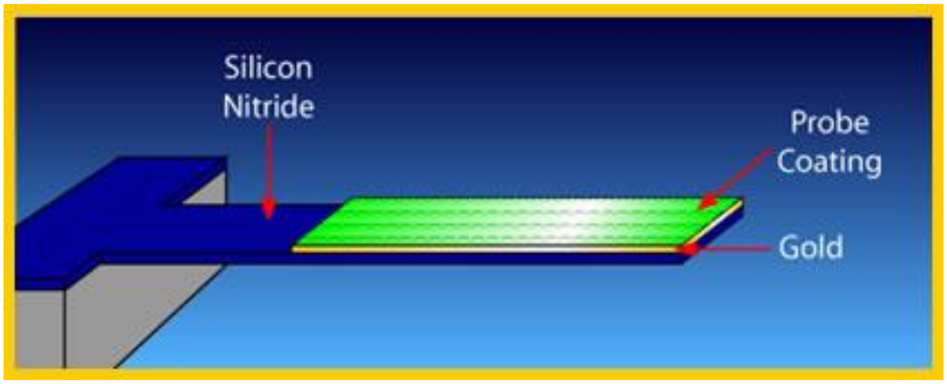
Type of film vs. Application

Different films are used for various applications:

Type of Thin Film	Applications
Silicon Dioxide (oxide)	• Sacrificial Layer • Masking Material
Polysilicon (poly)	• Structural material • Piezoresistive material
Silicon Nitride (nitride)	• 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)	• Structural anchor material to the substrate • Sacrificial Layer
Various metals (Aluminum, gold, platinum)	• Conductive electrodes • Reflective material
Spin-on Glass (SOG)	• Final layer for planarized top surface
Zinc Oxide (ZnO)	• Active piezoelectric film • Sacrificial layer
Photoresist	• 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:

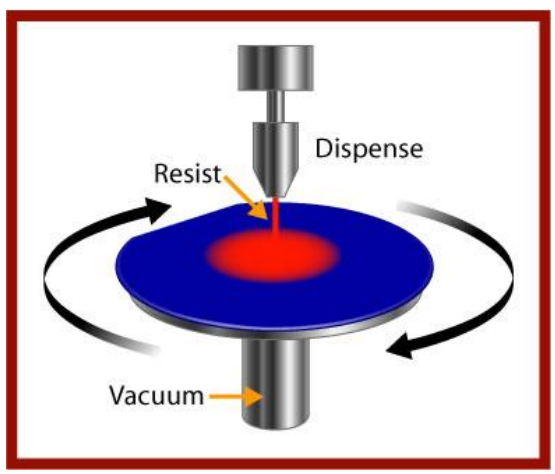
- Spin-on film
- Thermal Oxidation (oxide growth)
- Chemical vapor deposition (CVD)
- Physical vapor deposition (PVD): Evaporation and Sputtering
- Electrodeposition (electroplating/electroforming)

Following is a brief discussion of each of these processes.

Spin-on Films

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.

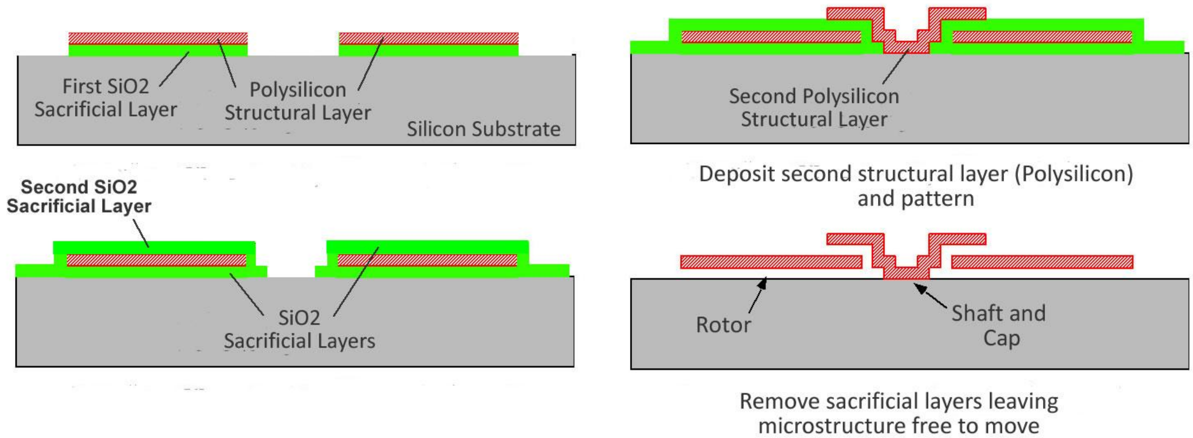


Spin-on Photoresist Layer

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

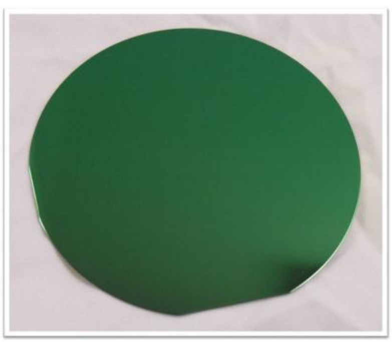


Two silicon dioxide layers used as sacrificial layers for MEMS structure

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.

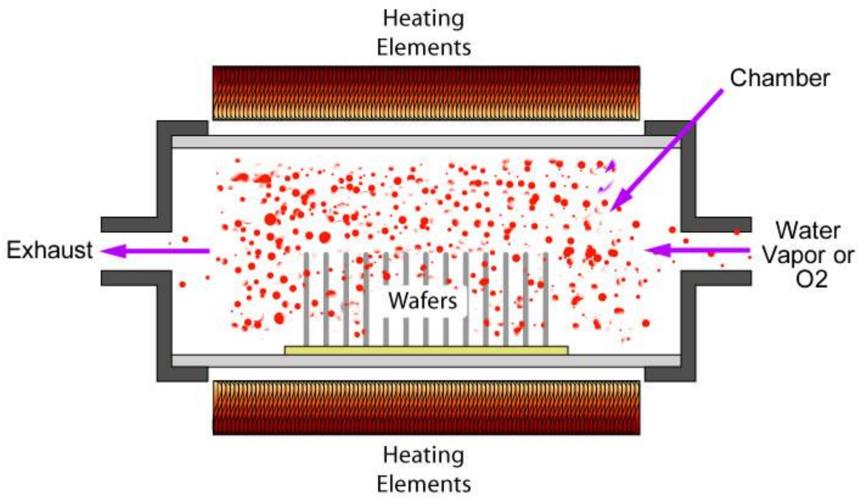


Silicon wafer with a layer of silicon dioxide

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

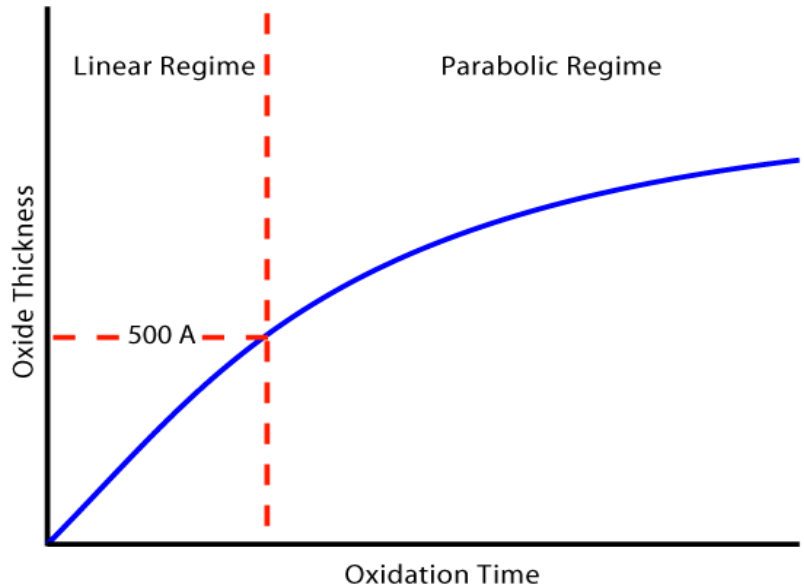
For microsystems fabrication, the thermal oxidation process includes three basic steps:

- 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).

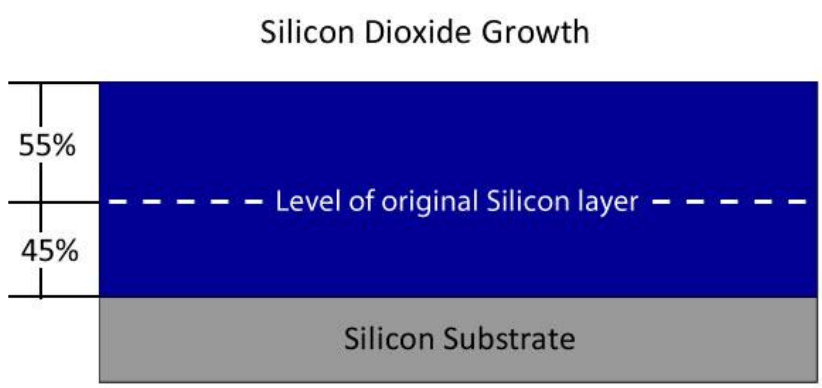
The longer the wafers or metal are exposed to oxygen (O_2), the thicker the oxide layer becomes. The higher the temperature and "humidity", the faster the reaction rate. *More on this later.*

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 SiO_2 begins to grow on the silicon surface, new arriving oxygen molecules must diffuse through the newly formed SiO_2 layer to get to silicon atoms below the surface. At this point (approximately 500 Å thickness) the SiO_2 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 SiO_2 grown, about 0.46 micrometers of silicon is consumed.



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.

$$\mathbf{Si\ (solid) + O_2\ (gas) \rightarrow SiO_2\ (solid)}$$

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

$$\mathbf{Si\ (solid) + 2H_2O\ (vapor) \rightarrow SiO_2\ (solid) + 2H_2\ (gas)}$$

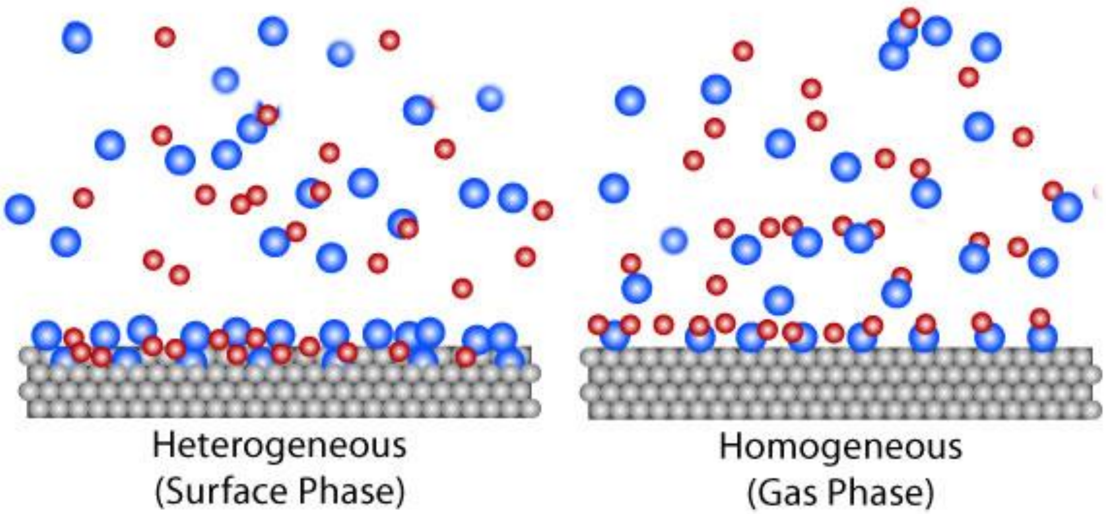
H_2O is much more soluble in SiO_2 than O_2; therefore, this leads to higher oxidation rates (faster oxide growth).

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

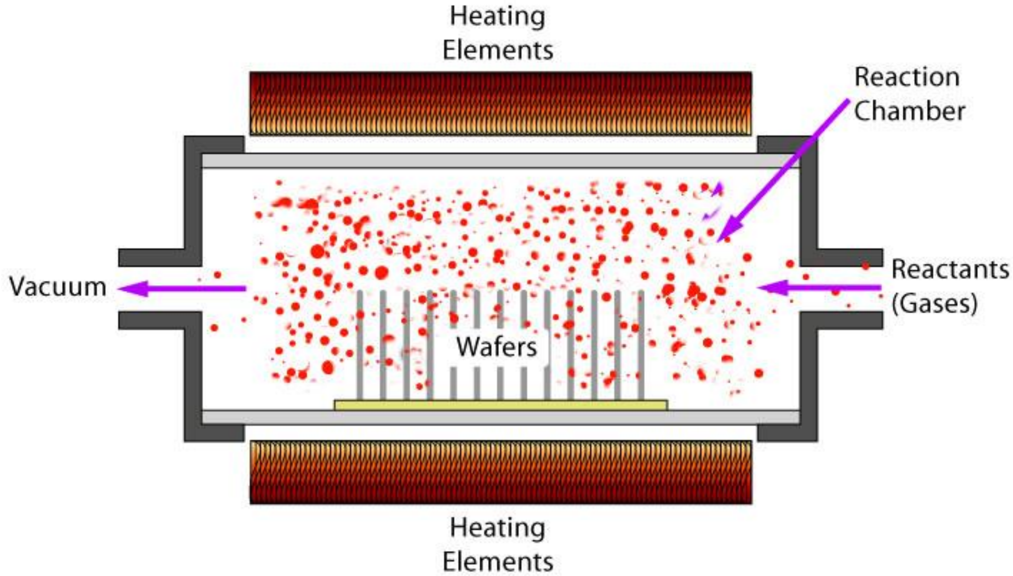
Two types of reactions can occur during the CVD process:
- Homogeneous (gas phase)
- Heterogeneous (surface phase)

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 gasses 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



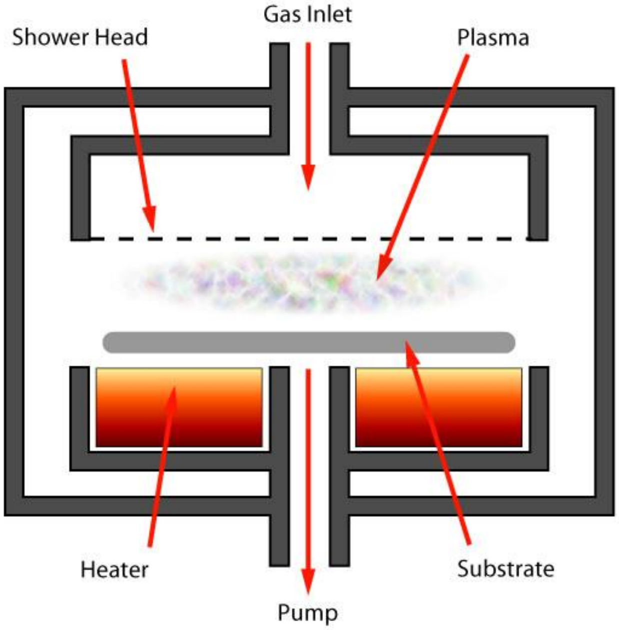
A Low Pressure CVD System

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



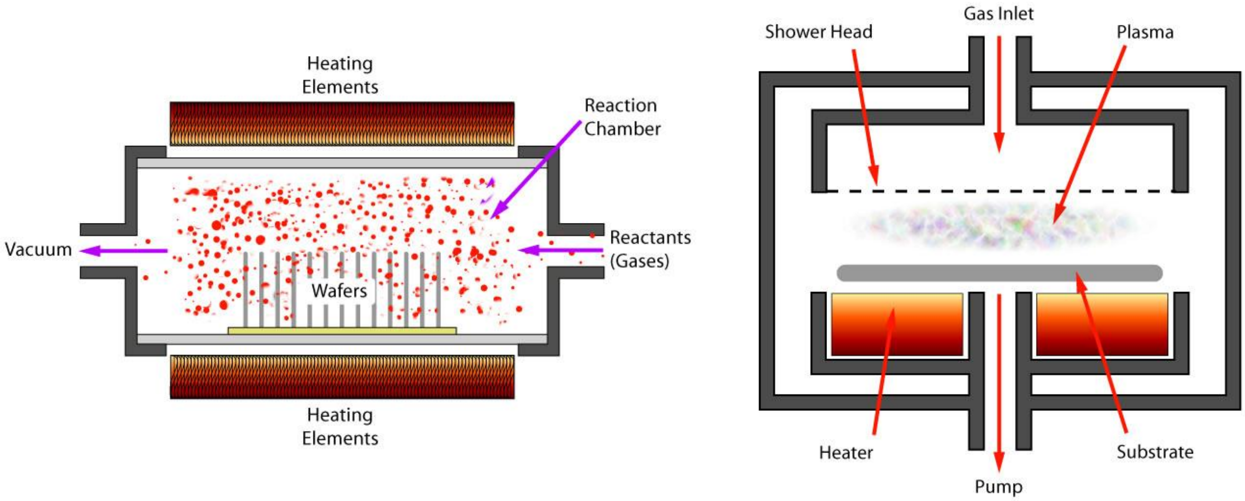
Plasma-enhanced CVD Systems [Image courtesy of UNM-MTTC]

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 PECVD[1]:

- 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.

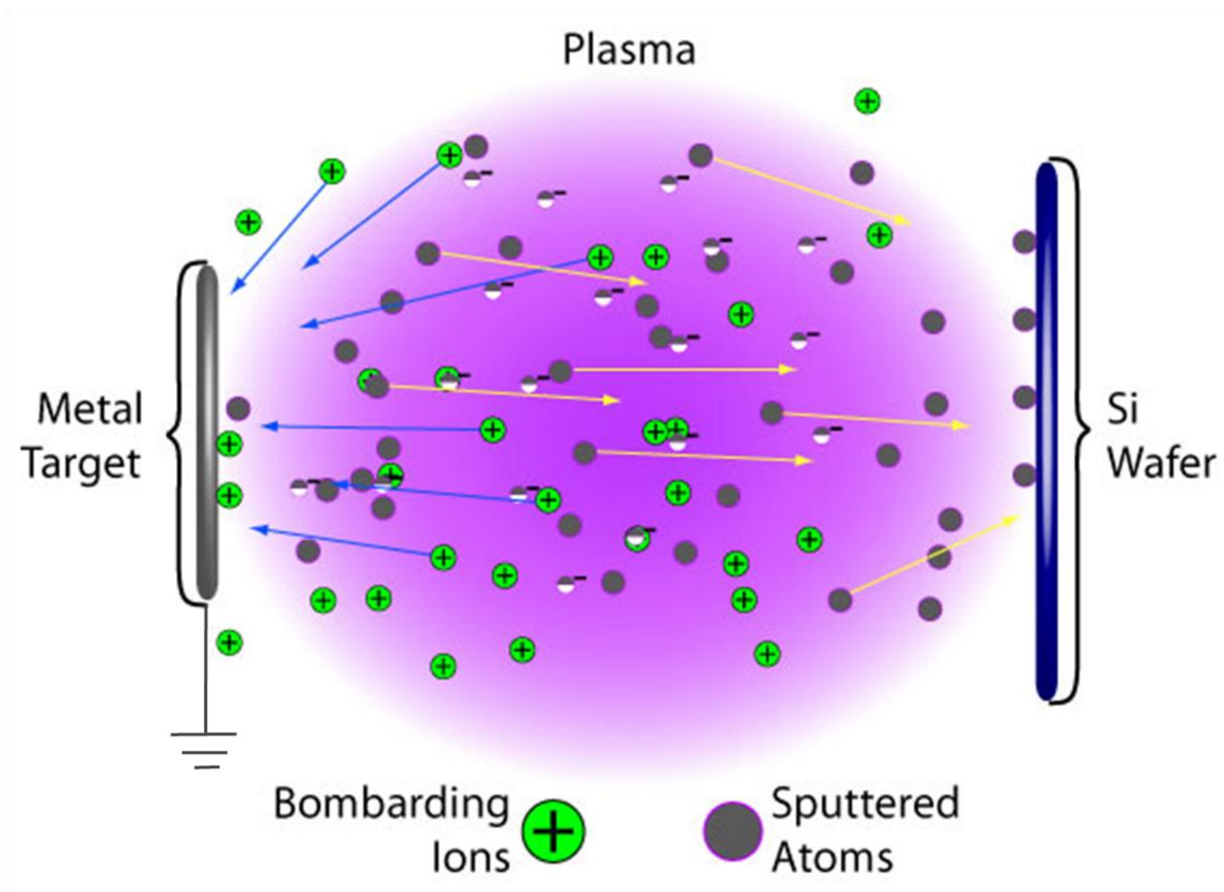
Sputtering

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.

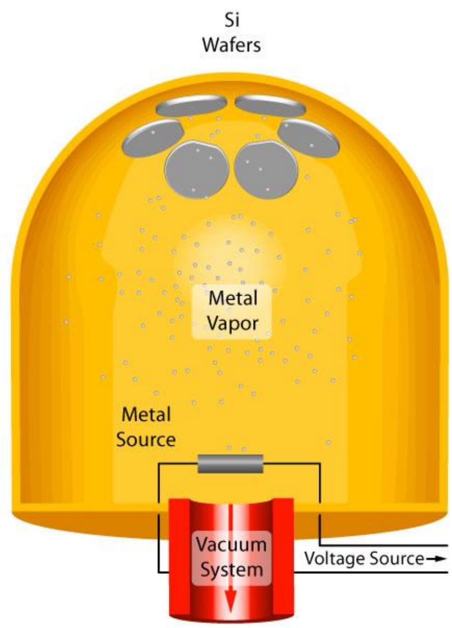
Evaporators use a planetary system *(picture right)* that holds several wafers near the top of the chamber. This planetary system allows for batch processing.

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 electroplating[1])

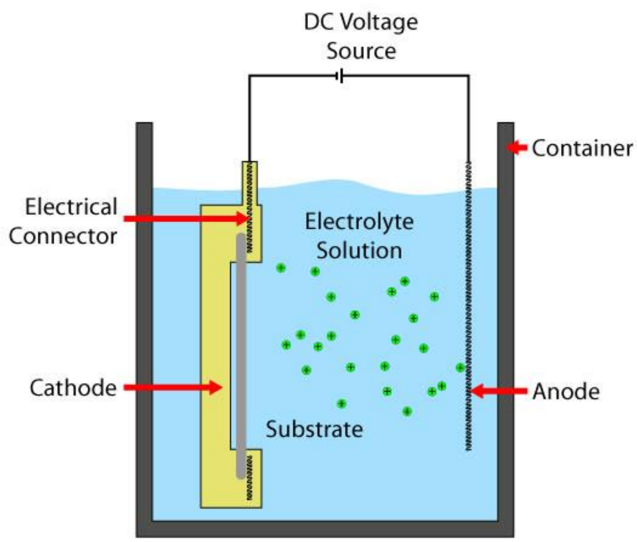
Electrodeposition is a process that uses electrical current to coat an electrically conductive object with a relatively thin layer of metal (electroplating), or to coat and fill a micro-sized cavity with metal (electroforming). Electroplating is a commonly used deposition technique for thousands of everyday 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 ~1µm to >100µm. The LIGA process uses electroforming for the construction of devices with very high aspect ratios, ratios of 100:1 or greater.

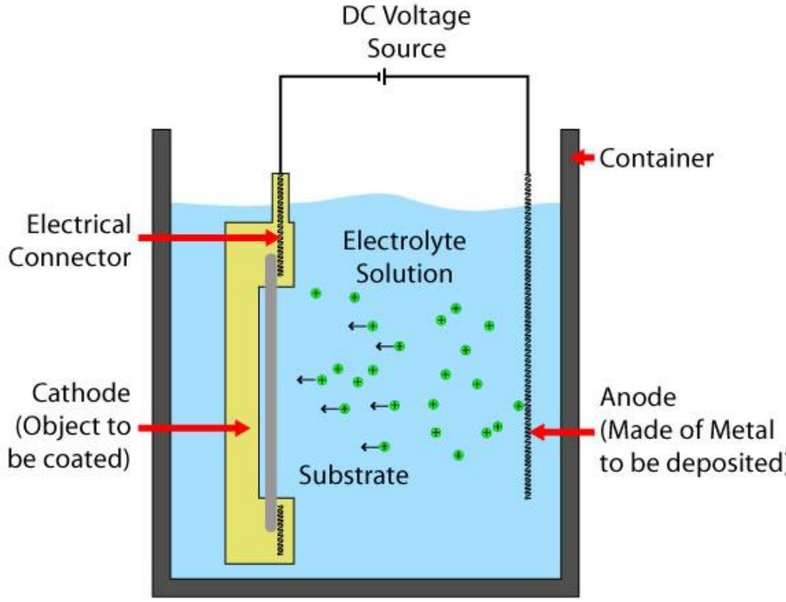
Electroplating Materials

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.

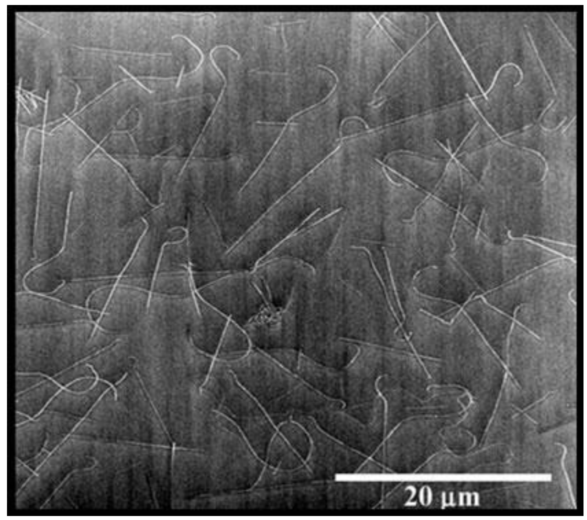
What's What?

Match the following deposition process with its unique characteristic.

		Process		Characteristic
	1	Spin-on	A	Resistive heating for target
	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 2: Processes and Unique Characteristics

Nanotechnology has lead 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.

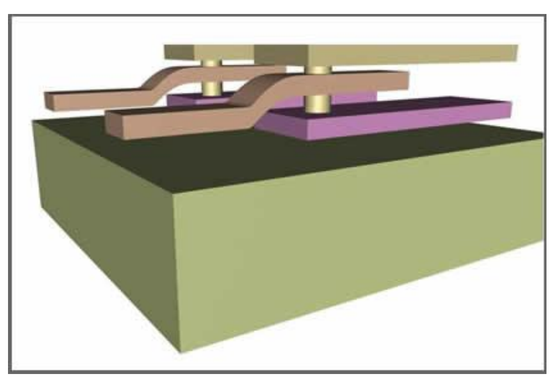


Carbon nanotubes (or hooktubes) grown by the CVD process on a silicon dioxide covered silicon chip. The thin white lines are the nanotubes. [Courtesy of Michael S. Fuhrer, University of Maryland]

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 (stochiometry) being deposited.

Question:
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?

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 wafer 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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Disclaimer

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants.

Deposition Terminology
Activity

Participant Guide

Description and Estimated Time to Complete

In this activity you will demonstrate your understanding of the terminology of deposition for microsystems. This activity consists of a

- **Crossword puzzle** that tests your knowledge of the terminology and acronyms associated with deposition processes.

If you have not reviewed the unit Deposition Overview for Microsystems, you should do so before completing this activity.

Estimated Time to Complete
Allow at least 30 minutes to complete this activity.

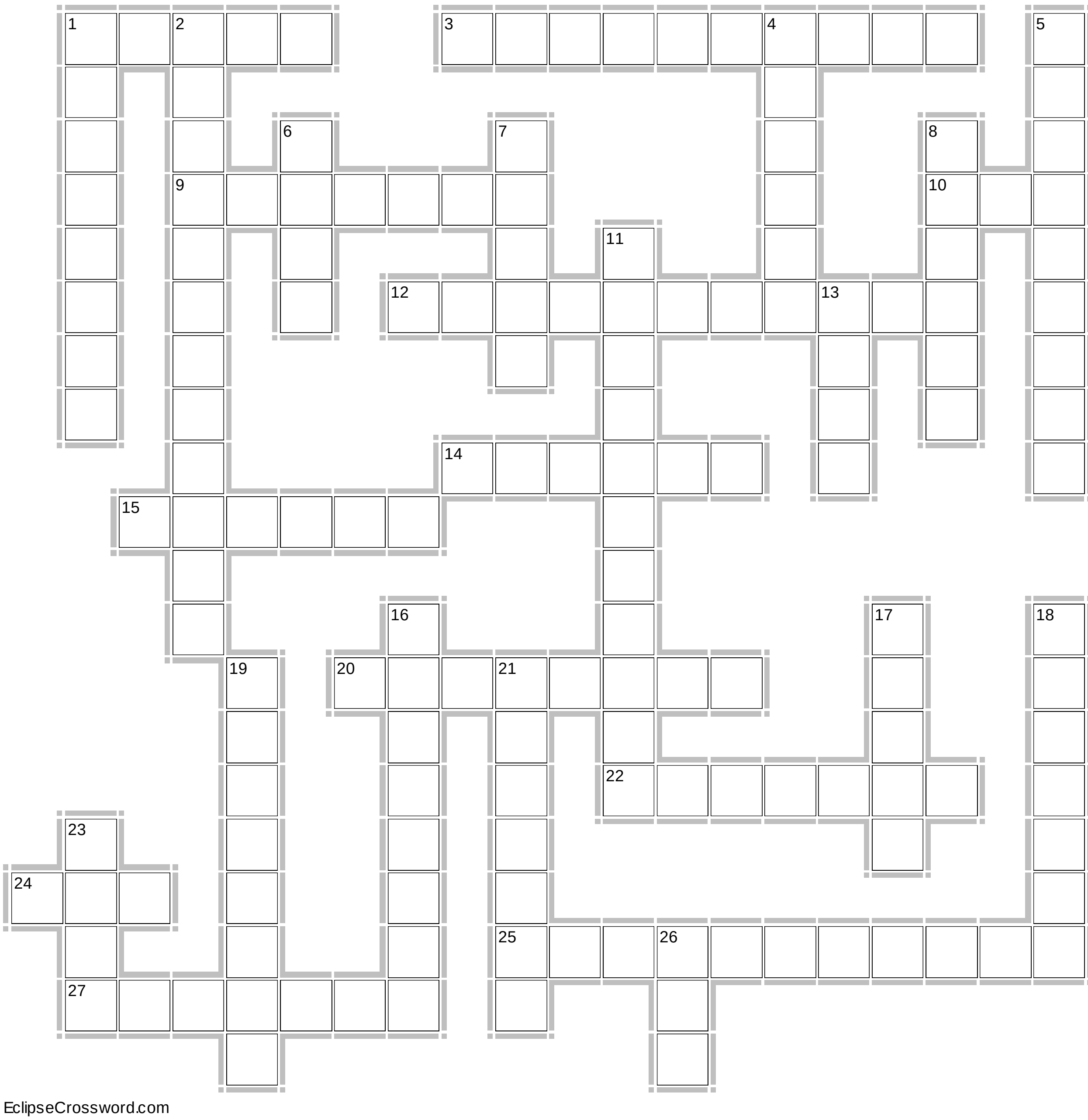
Activity Objective

- Identify the correct terms used for several definitions or statements related to deposition processes.

Activity: Deposition Terminology

Procedure:

Complete the crossword puzzle using the clues on the following page.



ACROSS	ANSWERS
1. To heat the source in an evaporation process a(n) ___________ or resistive component is used.	
3. A process that deposits a thin film of material onto an object.	
9. In electroplating, the ________________ is the electrode that is coated.	
10. Normally used for the deposition of metals and metal alloys.	
12. A deposition process used to deposit a thin film of metal through the use of metal vapors.	
14. The fourth state of matter.	
15. PVD processes require a high _____________ to prevent contamination within the deposited film.	
20. Deposition processes in which the desired film material is vaporized either through heat or sputtering, and deposited on the substrate.	
22. A thin film used for isolation, masking, protection and structural purposes.	
24. In CVD processing, a homogeneous reaction occurs in the ________ phase.	
25. A solution through which an electric current may be carried by the motion of ions.	
27. Oxidation process that uses heat to grow silicon dioxide.	

DOWN	*ANSWERS*
1. Plasma-__________________ CVD process (PECVD)	
2. To use an electric current to coat an electrically conductive object with metal.	
4. In a sputtering system, the source material is called the ____________.	
5. The process that grows a uniform layer of silicon dioxide on a silicon substrate.	
6. Deposition occurs before photolithography and ___________.	
7. A thin film used for conductive and reflective material.	
8. A type of deposition process used primarily to deposit photoresist and SOG.	
11. A structural and piezoresistive thin film.	
13. Plasma consists of electrons, radicals and _________.	
16. The type of reaction that takes place in a CVD process.	
17. A thin film grown to be used as a mask or sacrificial layer.	
18. In CVD processing, a heterogeneous reaction takes place at the _________________ of the wafer.	
19. In CVD, ________________, temperature and the reactant's concentration control the film thickness.	
21. A PVD process by which atoms are ejected from a source material.	
23. In electroplating, the metallic ions of the __________ in the electrolyte carry a positive charge.	
26. Chemical Vapor Deposition	

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 used in integrated circuits are even thinner, on the order of tens of microns. Microsystems technology uses a variety of deposition processes. The type of process used depends on the thin film material, its thickness, and the structure (stochiometry) being fabricated.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program.

What Do You Know About Deposition? Activity

Participant Guide

Description and Estimated Time to Complete

In this activity you will demonstrate your knowledge of deposition for microsystems, by explaining at least two deposition processes, identifying the applications of microsystems in which these processes would be used and studying recent advances and improvements of these processes for microsystems fabrication.

If you have not reviewed the unit Deposition Overview for Microsystems, you should do so before completing this activity.

Estimated Time to Complete
Allow at least 1.5 hours to complete this activity.

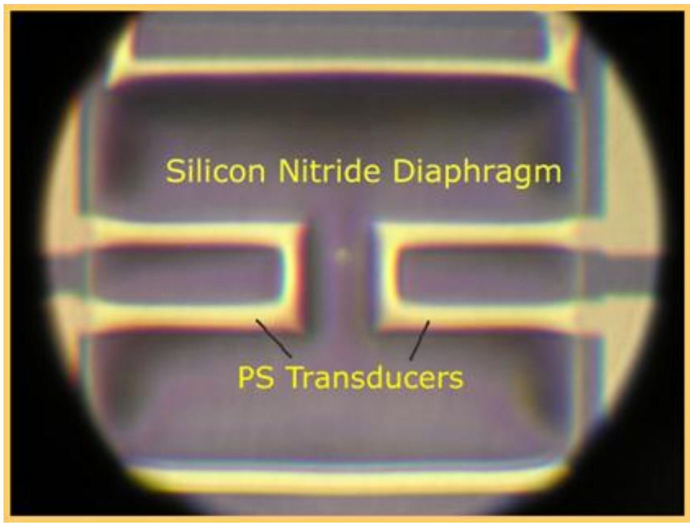
Introduction

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.

The deposition process, which is the focus of this activity, provides the ability to deposit a variet of thin film layers as thick as 100 micrometers or 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 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

Activity Objective

- Identify the type of deposition process associated with different aspects of microsystems fabrication.
- Describe three deposition processes used in microsystems fabrication.
- Discuss at recent research and improvements in at least one of these deposition processes.

Resources

SCME's Deposition Overview for Microsystems PK

Documentation

Present a written paper to your instructor that includes the questions and answers to the following questions as well the information requested on the various deposition processes.

Activity: What Do You Know About Deposition?

Answer each of the following questions and write a brief response for research requests.

1. Why is CVD the most widely used deposition method for most thin films?
2. Write the chemical formulas for the following processes and a brief explanation of each formula.
   a. Wet oxidation process
   b. Dry oxidation process
3. For each of the deposition processes below,
   a. outline the fabrication process,
   b. the types of films deposited, and
   c. at least two microsystem applications for the deposited films. These applications can be current applications as well as applications being researched.

Thermal Oxidation	a.
	b.
	c.
Chemical Vapor Deposition	a.
	b.
	c.
Evaporation	a.
	b.
	c.

4. Which deposition process(es) would be used for the following applications?
    a. conductive layer for RF switches - ______________________________
    b. structural layer for cantilever sensors - __________________________
    c. sacrificial layer between the substrate and the first structural layer - _______________
    d. fill in the cavity of a LIGA mold - ___________________________
    e. a strain gauge on a microcantilever - ____________________________
    f. a silicon nitride hard mask - _____________________________
    g. sacrificial layer between two structural layers - ______________________________
    h. masking layer for photolithography expose - _______________________________

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 used in integrated circuits are even thinner, on the order of tens of microns. Microsystems technology uses a variety of deposition processes. The type of process used depends on the thin film material, its thickness, and the structure (stochiometry) being fabricated.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program.

Science of Thin Films Activity

Deposition Overview for Microsystems
Participant Guide

Description and Estimated Time to Complete

Figure 1. "Rainbow Wafer" [Courtesy of MJ Willis, personal collection.]

Silicon dioxide (oxide) is a thin film used throughout microtechnology fabrication. Its applications include an insulating layer, a sacrificial layer, or a masking layer. A rainbow wafer is a wafer that is initially coated with a layer of silicon dioxide (SiO_2) or oxide (usually less than 6,000 Å). This layer of oxide is then etched or removed in increments over a period of time (5 to 10 minutes). The result is the wafer you see here in the picture. Each layer, etched in equal time increments, appears to have a different color than the other layers. This is due to different thicknesses of oxide for each layer.

In this activity you learn why you see different colors for different thicknesses of oxide and the thickness of oxide that each color represents. Given a rainbow wafer, you estimate the thickness of several layers of silicon dioxide (SiO_2) based on the colors you see, then calculate the etch rate of each layer based on its thickness and time of etch. You also interpret graphs related to oxide growth and temperature.

This activity helps you to better understand the basics of oxidation and etch rate as they apply to the isotropic wet etch of silicon dioxide (SiO_2). It also helps you to begin to recognize oxide thickness based on its color and why the color changes with the oxide thickness.

<u>Estimated Time to Complete</u>
Allow at least 1 hour to complete this activity.

Activity Objectives and Outcomes

Activity Objectives

- Interpret Oxide thickness vs. temperature graphs.
- Using a color chart, estimate the thickness of silicon dioxide removed.
- Using your results, create two graphs showing the relationship between oxide thickness and time.

Activity Outcomes

By the end of this activity you should be able to estimate the thickness of a silicon dioxide layer by its color when viewing it from a specific angle and explain why the color of the oxide changes when viewed from different angles. You should also be able to calculate the time it would take to remove a specific amount of silicon dioxide under certain conditions.

Introduction

Silicon dioxide (SiO_2) is grown on a pure crystalline silicon wafer in a diffusion furnace using high temperatures (~900 to 1200° C). A diffusion furnace consists of a quartz tube large enough to hold several boats of wafers and able to heat to at least 1200° C. The wafers are placed in quartz boats. The boats are then placed on a platen (like a loading dock) which transports the boats into the furnace's quartz tube. Figure 2 shows the manual unloading of 100mm oxidized wafers.

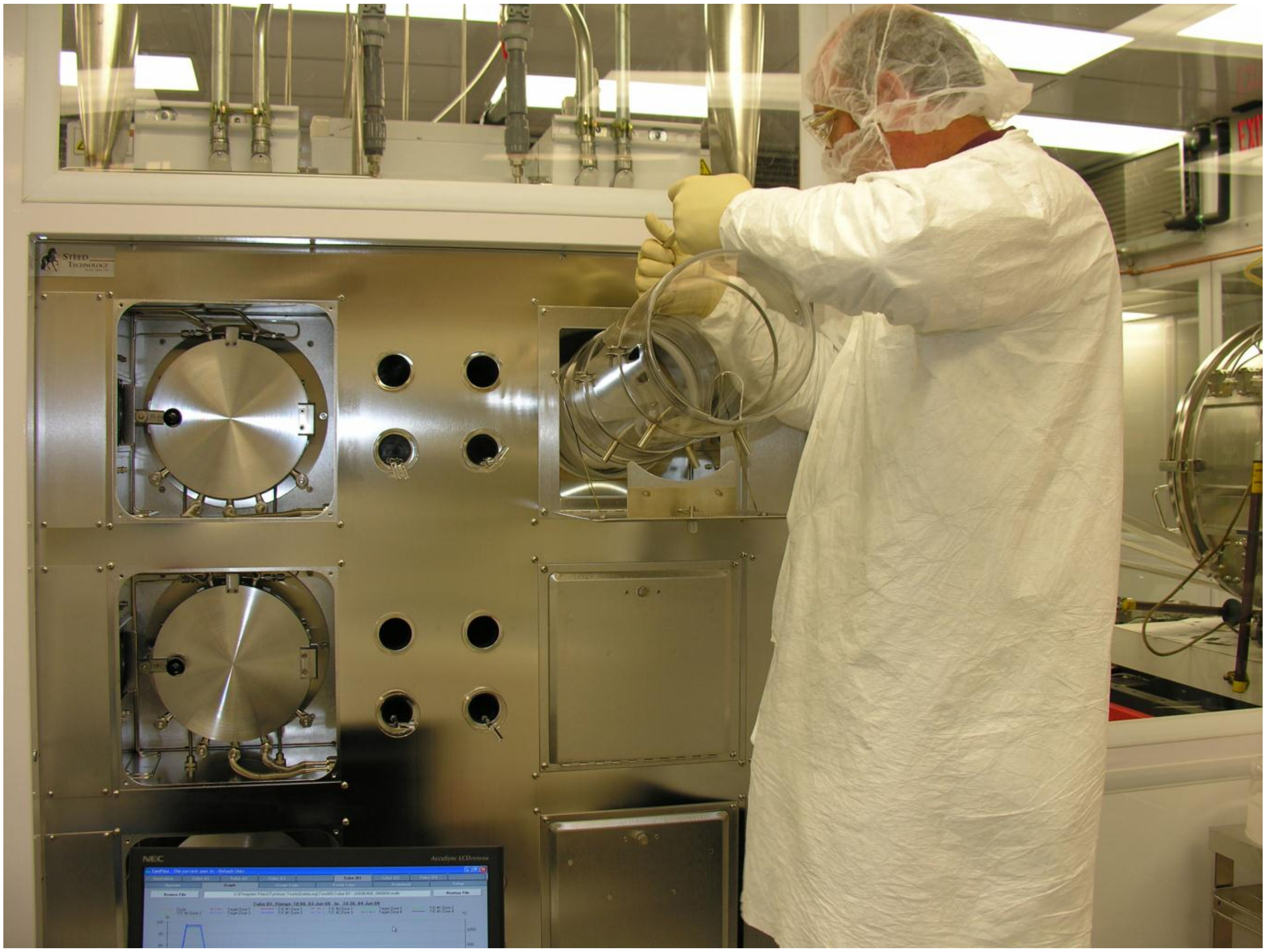


Figure 2. Oxidation furnace being manually unloaded.
[Image courtesy of the University of New Mexico, Manufacturing Training and Technology Center]

Growing Silicon Dioxide (Oxidation)

When exposed to oxygen, pure silicon (Si) oxidizes forming silicon dioxide (SiO_2). Silicon dioxide is also referred to as just "oxide" in the MEMS (microelectromechanical systems) industry. Additional names for silicon dioxide include "quartz" and "silica". Native oxide is a very thin layer of SiO_2 (approximately 1.5 nm or 15 Å) that forms on the surface of a silicon wafer whenever the wafer is exposed to air under ambient conditions. This native oxide coating is a high-quality electrical insulator with high chemical stability making it very beneficial for microelectronics. Other benefits of SiO_2 in microelectronics and microsystems include the following:[1,2]

- sacrificial layer or scaffold for microsystems devices
- structural layer or material for microsystems devices (beams, membranes)
- passivation coatings
- protect the silicon ("hard" mask)
- electrical isolation of semiconductor devices
- diffusion mask, a barrier material or mask during implant or diffusion processes
- gate dielectric and interlayer dielectric in multilevel metallization structures
- a key component in certain wafer bonding applications

SiO_2 naturally grows on a silicon surface at room temperature. However, this growth is very slow and stops at about 15 Å after only two to three days. In semiconductor and microsystems fabrication, SiO_2 is either deposited through a chemical vapor deposition (CVD) process or grown in a high temperature furnace with an oxygen source (gas or vapor). This latter process is called thermal oxidation.

The thermal oxidation process includes three basic steps (***Figure 3***):

- The silicon wafers are placed in a heated furnace tube (typically 900 – 1200 degrees C).
- A source of oxygen (gas or vapor) is pumped into the chamber. This source is either O_2 or H_2O, respectively.
- The oxygen molecules react with the silicon to form a silicon dioxide (SiO_2) layer in and on the substrate.

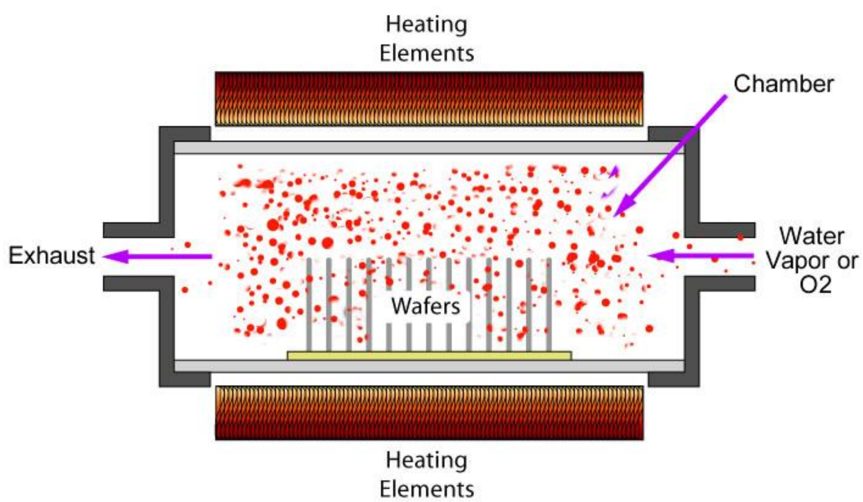


Figure 3. Schematic diagram of an oxidation furnace.

The chemical reactions that take place are

$Si + O_2 \rightarrow SiO_2$ ("dry" oxidation which uses oxygen gas) or

$Si + 2H_2O \rightarrow SiO_2 + 2H_2$ ("wet" oxidation which uses water vapor)

Oxide Growth Kinetics

This oxygen/silicon reaction is analogous to the oxidation or rusting of metal. In the case of iron (Fe), rust (Fe_2O_3) is formed. The rate of formation is dependent on the environment including the presence or absence of water (H_2O) and the temperature. The longer the metal or wafers are exposed to the oxygen source (H_2O or O_2), the thicker the rust (or oxide) layer becomes, to a point. The higher the temperature, the faster the reaction rate and the thicker the oxide. 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. However, after the SiO_2 begins to grow on the silicon surface, new arriving oxygen molecules must diffuse through the SiO_2 layer to get to silicon atoms below the surface. At this point the SiO_2 growth is occurring at the silicon crystal – silicon dioxide interface. As a general principle, the depth of pure silicon consumed in the oxidation process is 45% of the final oxide thickness (***Figure 4***). For every 1 micrometer of SiO_2 grown, about 0.46 micrometers of silicon is consumed.[2]

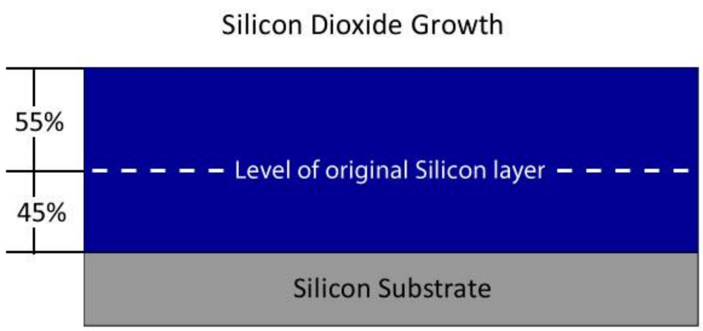
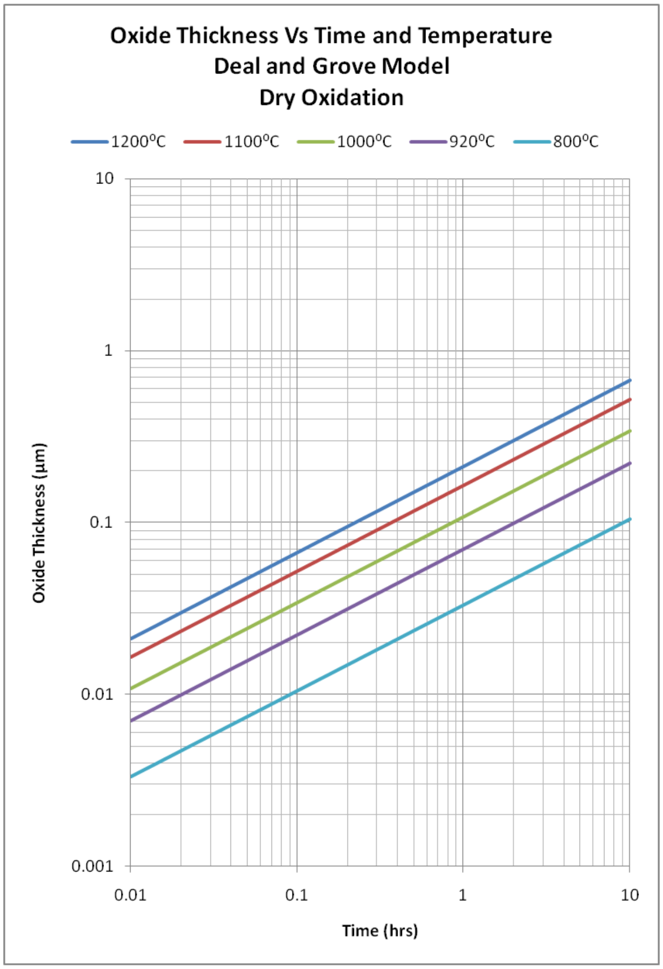


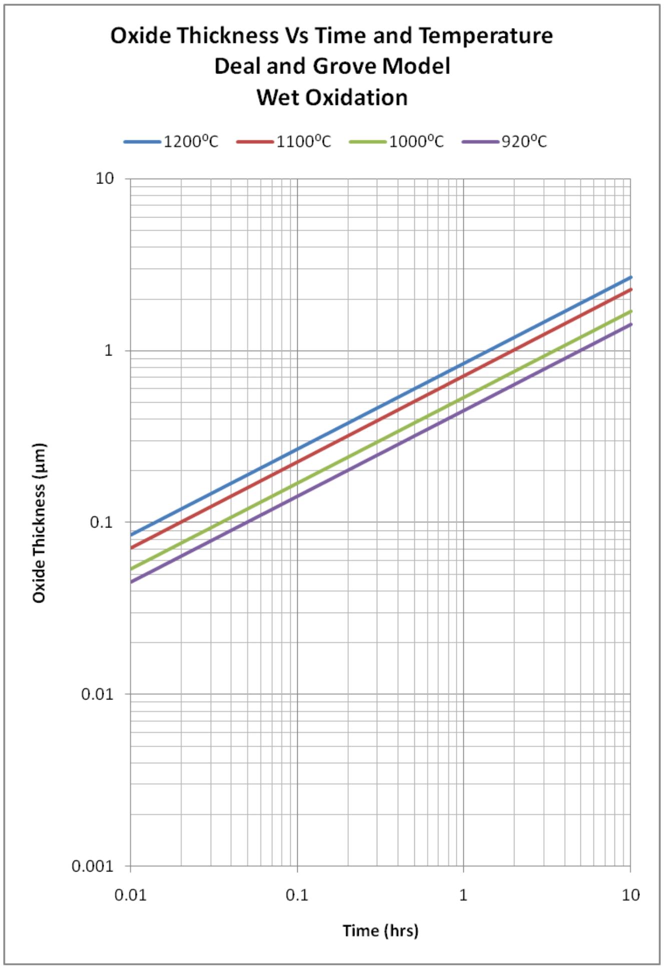
Figure 4. Cross-sectional view showing how silicon dioxide grows into the surface of the wafer surface.

The rate of oxide growth is highly dependent upon temperature. Let's take a look at the relationship between oxide thickness and temperature in dry and wet oxidation growth processes.

Activity Part I: Interpreting Oxide Growth vs. Temperature Graphs

Below are two graphs that demonstrate the growth rate of oxide relative to temperature in a dry oxidation process (*left graph*) and a wet oxidation process (*right graph*). These graphs closely match experimental data and are drawn based on a model by B.E. Deal and A. S. Grove.[3]





Answer each of the following based on your interpretation of the above graphs.

1. In a wet oxidation process, how thick is the oxide after 1 hour when processed at 1200°C?
   a. 0.1 µm
   b. 0.2 µm
   c. 0.9 µm
   d. 2.0 µm
2. In a dry oxidation process, how thick is the oxide after 1 hour when processed as 1200°C?
   a. 0.1 µm
   b. 0.2 µm
   c. 1.0 µm
   d. 2.0 µm

3. In a wet oxidation process of 1000°C, how long would it take to grow an oxide thickness of 1.0 μm?
   a. 1 hour
   b. 2.5 hours
   c. 3.5 hours
   d. More than 10 hours
4. In a dry oxidation process of 1000°C, how long would it take to grow an oxide thickness of 1.0 μm?
   a. 0.1 hours
   b. 1 hour
   c. 4 hours
   d. More than 10 hours
5. Based on your findings, which type of process yields a thicker oxide in a shorter period of time given the same temperatures?
   a. Wet oxidation
   b. Dry oxidation

Etching Silicon Dioxide

Silicon dioxide is readily etched using hydrofluoric acid (HF) according to the following reaction:

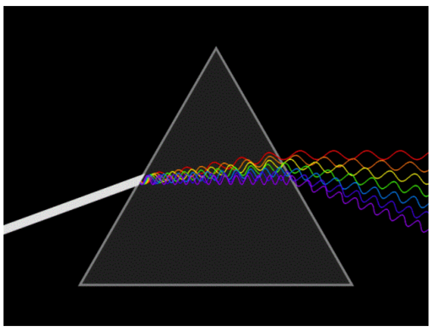
$$SiO_2 \text{ (solid)} + 6HF \text{ (liquid)} \dashrightarrow H_2SiF_6 \text{ (liquid)} + 2H_2O.$$

HF is a weak acid. This means that it only partially dissociates in water. Because of the low value of hydrogen ion concentration $[H^+]$ in weak acids (HF in our case), the pH is quite vulnerable to change. Changes in pH result in changes in etch rate. Small dilutions or consumption of the reactant during etching can significantly alter pH. These alterations can be limited by the technique of buffering the solution. The customary buffer for HF is ammonium fluoride (NH_4F). Ammonium fluoride is a salt that dissociates to form fluoride and ammonium ions. A typical volume ratio is 20 parts NH_4F to one part HF. This mixture is called buffered oxide etch (BOE). BOE is a reasonably selective etch for silicon dioxide. It will not etch bare silicon, but does attack silicon nitride and photoresist to some extent.

Oxide's Color

Oxide is colorless. However, when you look at an oxide wafer, it has color. The color of the oxide coated wafer is caused by the interference of light reflecting off the silicon (below the oxide) and the light reflecting off the top of the oxide surface. As the oxide thickness changes, so does the interference and the oxide's "seen" color. Color charts have been developed that state the oxide's thickness based on its "seen" color. *(See the Oxide Thickness Color Chart attached.)*

Figures 5, 6 and 7 illustrate thin film interference. When studying these figures, don't forget that white light consists of all of the colors of the visible light spectrum. You can see this when you shine white light through a prism *(Figure 5)*.



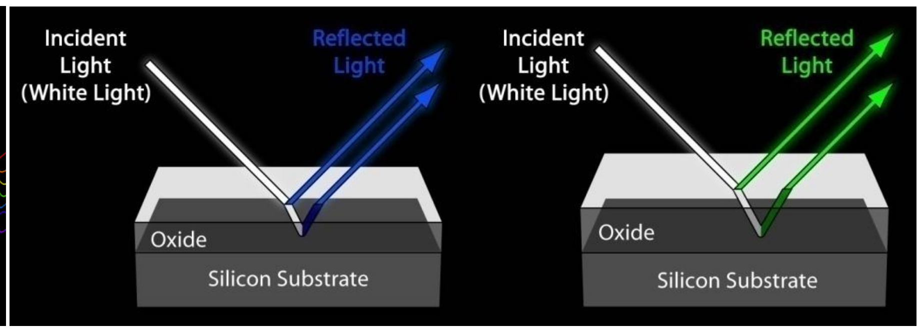


Figure 5. The dispersion of white light as it travels through a triangular prism. [Illustration is Public Domain]

Figure 6. Two wafers with two different oxide thicknesses. The incident ray (or white light) is reflected off both the lower substrate/oxide interface surface and the top air/oxide surface. These two reflected rays of light recombine. Depending on the oxide thickness, only certain colors will constructively recombine, while the other colors which make up the white light will not. These two different thicknesses will reflect two different colors.

When the light reflected off the substrate is in phase with the light reflected off the surface of the oxide, the resultant wave is the sum of the amplitudes. This is *constructive interference.* If the two reflected waves are out of phase, then their amplitudes cancel each other out. This is *destructive interference*.

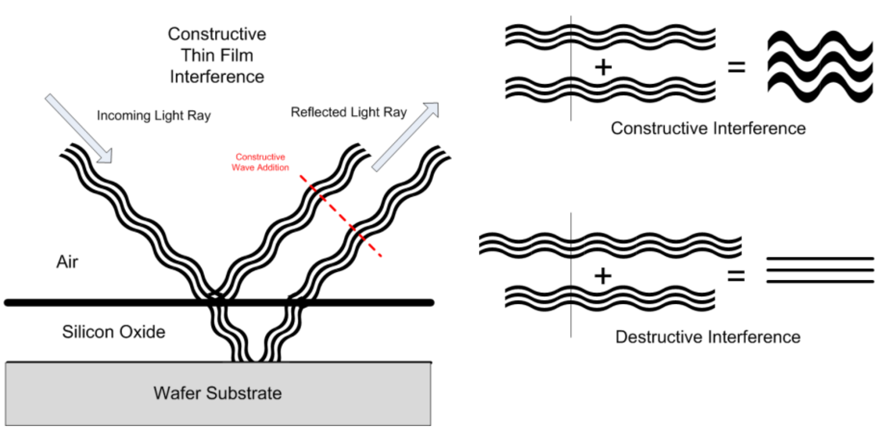


Figure 7. Constructive vs. Destructive Interference. The thin film interference effect is shown on the left for the case of constructive interference of a given wavelength of light and thickness of dioxide. The graphic on the right is a schematic representation of adding two waves which are in phase (constructive) and out of phase (destructive).

However, color can be deceiving. As you tilt the wafer, the color changes. In one wafer, of a specific thickness, you will see different colors as you view the wafer at different angles (tilt). The color you see depends on the angle at which you view the wafer's surface. Figure 8 is a series of photographs taken of the same oxidized wafers, but at three different angles (all of these wafers have had approximately 5700 Angstroms of oxide growth).

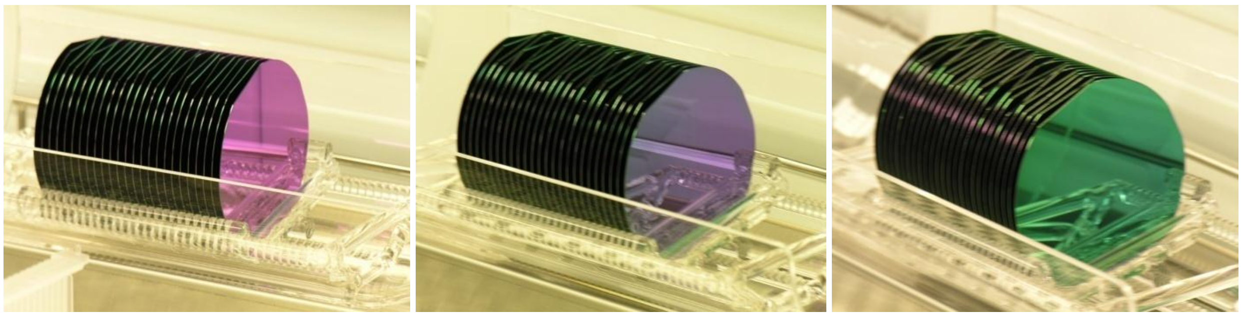


Figure 8. Three photographs taken of the same oxidized wafers at three different angles. [Photos courtesy of the University of New Mexico Manufacturing Training and Technology Center.]

The color you see comes down to the thickness of the film that the light travels through before reaching your eyes; this is called the optical path length. If you look straight down (perpendicular to the surface), the light reflected off the bottom (SiO_2 and Si) will have traveled through two times the thickness of the film. If you look at the same film at an angle, the light will have traveled through more than twice the thickness of the film; the light has therefore traveled through a longer optical path length. Effectively a thicker film is being observed; hence, the color looks different.

Therefore, to use a color chart to estimate oxide thickness consistently, it is very important that your line of sight is perpendicular to the wafer's surface. In other words, look straight down on the wafer, not at an angle.

Keep this in mind when completing this activity. Your outcome will be affected if you do not view the wafer from a direct, top-down perspective in a consistent manner.

Supplies / Equipment

- Rainbow wafer (provided in SCME Science of Thin Films Kit) and/or Rainbow wafer photograph (attached)
- Oxide thickness vs. Color Chart (Attached)
- Rainbow Wafer Calculations Worksheet (attached)

Documentation

- Activity Part I with answers
- Completed Rainbow Wafer Calculations Chart
- Required graphs with a written analysis for each graph
- Answers to the Post-Activity Questions

Activity Part II: The Rainbow Wafer

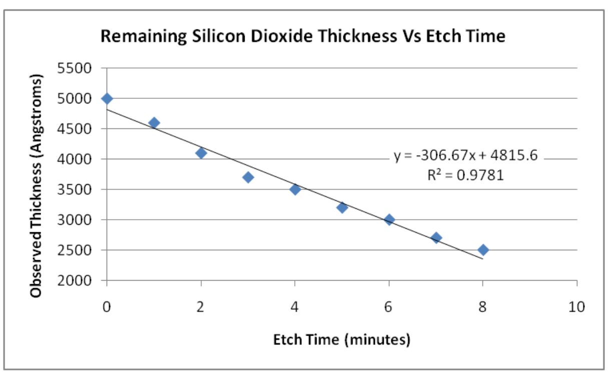
Description

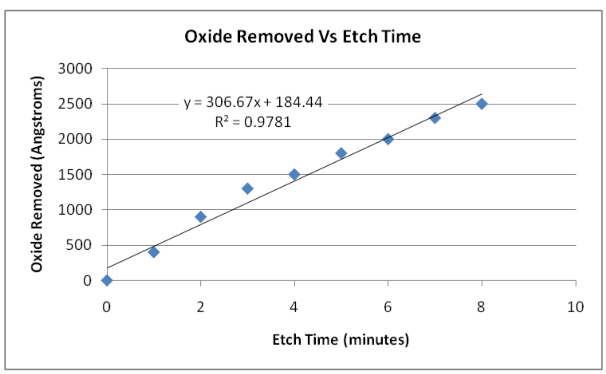
Use a Rainbow Wafer and an Oxide Thickness vs. Color Chart to determine the oxide thickness of each color on the wafer. Develop several graphs from which you can extract the average etch rate. (The etch rate is the amount of oxide etched in a given amount of time.) The average etch rate can be determined by calculating the slope of the straight line through your data points.

Procedure:

1. Using the provided Rainbow Wafer or the Rainbow Wafer photo at the end of this activity, complete the Rainbow Wafer Calculations Worksheet.
   a. **Determine the color of each stripe.** (Refer to Oxide Thickness vs. Color Chart)
   b. **Determine the oxide thickness for each color** based on the color chart.
   c. **Calculate the total amount of oxide etched (removed) for each stripe.**
   d. NOTE: The rainbow wafer in the photograph has a starting oxide thickness of 5000 Å. If you are using the rainbow wafer from the activity kit, the starting oxide thickness will be noted in the kit.
2. **Using Excel or another spreadsheet software, plot a line graph** showing the relationship between "Remaining Oxide Thickness vs. Time Etched". Be sure to indicate units (Å, nm or µm).
3. **Plot a second line graph** showing "Etched Oxide (amount removed) vs. Time Etched". Be sure to indicate units (Å, nm or µm).
4. On each chart, **draw a trend line through your data points**. (If you're using Excel, right click on a point on your chart, select "Add Trend line", then select "linear". If the software doesn't have the capability to add a Trend line, you'll need to estimate it. Draw a straight line through your points that "best fits" the trend of the data points.
5. **Select two points on the line** (points that are NOT your data points) where the line crosses an axis.
6. Use the two points to **determine the slope of the line.**
7. **Answer the Post-Activity Questions**.

Examples of plotted data





Oxide thickness Vs Etch time on the left graph. Oxide thickness removed on the right graph. Both graphs include the fitted straight line trend and corresponding equations with the goodness of fit, R (when R=1, the fit is perfect). The equation follows the $y = mx+b$ equation of a straight line where m is the slope of the line.

Post-Activity Questions

1. What does the slope of the line (m) represent?

2. Refer to your graph for "Remaining Silicon Dioxide Thickness vs. Etch Time".
    a. What is the slope of this line-graph? What is the equation of the line? Make sure you include the units.
    b. The slope should be negative. What does a negative slope mean in this context?

3. Refer to your graph for "Oxide Removed vs. Etch Time".
    a. What is the slope of this line-graph? What is the equation of the line? Make sure you include the units.
    b. The slope should be positive. What does this mean?
    c. How does this compare to question 3) above?

4. Based on your graphs and the slope of the line, how long does it take to etch 0.05 microns (μm) of oxide?

5. Given a silicon wafer substrate with 500 nm layer of oxide, how long would it take to etch to bare silicon based on your data?

6. Refer to the Oxide Thickness vs. Color Chart. What is the thickness(es) of a wafer that looks "yellow-green"? (You may see "yellow-green" more than once. Include all thicknesses.)

7. Why do oxide colors repeat as the oxide continues to grow?

8. In a fabrication facility, estimating the oxide's thickness based on its color is used as an initial verification by the operator that the oxidation process was correct. However, it is not accurate. How is oxide thickness measured in a fabrication facility?

9. Refer to your actual data points. What factors contribute to the variations between data points? (Theoretically, the data points should line up in a straight line with a constant etch rate.)

10. List three other types of thin films used in microtechnology and describe the purpose or applications of each of these thin films.

Summary

When exposed to oxygen, silicon oxidizes forming silicon dioxide (SiO_2). Thermal oxidation is used to grow precise thicknesses of oxide on bare silicon wafers. Even though oxide is transparent, the interference of white light reflected off the silicon crystal/oxide interface with that reflected off the oxide's top surface, creates a variation in color depending on the thickness of the oxide.

Hydrofluoric Acid (HF) can be used to etch SiO_2. The longer the etch time, the more oxide is removed. If you know the etch rate and the initial oxide thickness, you can calculate the amount of time needed to remove a specific thickness of oxide or how long you need to etch an oxide coated wafer to get a specific thickness.

References

1. Silicon Dioxide. MedBib.com - Medicine & Nature. http://www.medbib.com/Silicon_dioxide
2. Silicon Dioxide. Georgia Tech, College of Engineering. http://www.ece.gatech.edu/research/labs/vc/theory/oxide.html
3. "General Relationship for the Thermal Oxidation of Silicon" B. E. Deal and A. S. Grove, Journal of Applied Physics, Vol. 36, No. 12 (1965).
4. "Photolithography (Oxide Etching) Lab". Albuquerque TVI. Mary Jane Willis and Eric Krosche. (1996)
5. "Oxide Growth and Etch Rates". MEMS 1001. Central New Mexico Community College. Matthias Pleil. (2008).

This Rainbow Wafer was created by lowering the wafer into BOE one stripe at a time. Each interval was held (by an operator) for 1 minute, then lowered to the next level. This wafer was created in approximately 9 minutes. The bottom most level was in the BOE solution for the entire 9 minutes. The top most level (5000 angstroms) was never exposed to the BOE.

Oxide Thickness vs. Color Chart

Oxide Thickness [Å]	COLOR	Color and Comments
500		Tan
750		Brown
1000		Dark Violet to red violet
1250		Royal blue
1500		Light blue to metallic blue
1750		Metallic to very light yellow-green
2000		Light gold or yellow slightly metallic
2250		Gold with slight yellow-orange
2500		Orange to Melon
2750		Red-Violet
3000		Blue to violet-blue
3100		Blue
3250		Blue to blue-green
3450		Light green
3500		Green to yellow-green
3650		Yellow-green
3750		Green-yellow
3900		Yellow.
4120		Light orange
4260		Carnation pink
4430		Violet-red
4650		Red-violet
4760		Violet
4800		Blue Violet
4930		Blue
5020		Blue-green
5200		Green (Broad)
5400		Yellow-green
5600		Green-yellow
5740		Yellow to Yellowish (May appear to be light creamy gray or metallic)
5850		Light orange or yellow to pink borderline
6000		Carnation pink

Rainbow Wafer Photo Calculations Worksheet (Use for Rainbow Wafer Photo)				
Level	**Color**	**Oxide Thickness***	**Total Etch Time**	**Å Etched (Starting Oxide – Oxide Thickness)**
Pre-Etch	Bluish Green	5000 Å = 500 nm	0 seconds	0 Å
1			1 minute	
2			2 minutes	
3			3 minutes	
4			4 minutes	
5			5 minutes	
6			6 minutes	
7			7 minutes	
8			8 minutes	

*The values in the answer key are "measured values". Participants will be using "estimated values" based on the color chart.

Rainbow Wafer Calculations Worksheet (Use for Rainbow Wafer in kit)				
Level	**Color***	**Oxide Thickness***	**Total Etch Time**	**Å Etched** (Starting Oxide – Oxide Thickness)
Pre-Etch	Green	5200	0 seconds	0 Å
1			25 seconds	
2			50seconds	
3			75seconds	
4			100seconds	
5			125seconds	

*The values in the answer key are "measured values". Participants will be using "estimated values" based on the color chart.

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