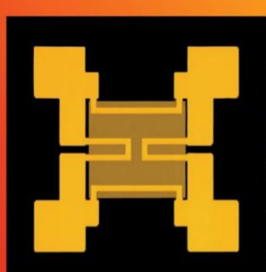
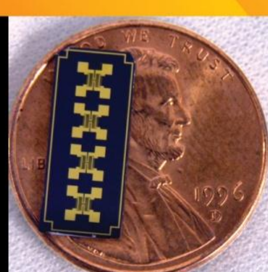



Etch Overview for Microsystems

Learning Module Map
Knowledge Probe
Etch Overview
Activities (3)
Final Assessments

Southwest Center for Microsystems Education

Instructor Guide

www.scme-nm.org

THE UNIVERSITY of NEW MEXICO

What is a SCO?

A SCO is a "shareable-content object" or, what we like to call, a "self-contained object". The term SCO comes from the Shareable Content Object Reference Model (SCORM), first conceived by the Department of Defense in 1999 as part of the Advanced Distributed Learning Initiative (Gonzales, 2005; Advanced Distributed Learning, 2008).

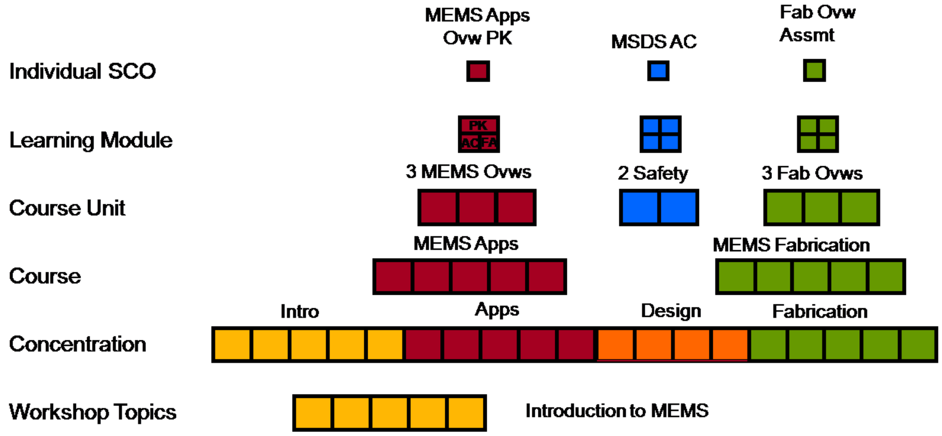
A SCO covers no more than 3 objectives that pertain to one specific topic (e.g., Material Safety Data Sheets or MEMS Applications). A SCO can be used by itself or with other SCOs with common or complementary objectives. We have grouped SCOs that support common objectives into a Learning Module.

<u>Learning Module Organization</u>
Each Learning Module (LM) contains at least one of the following three types of SCOs:

- Primary Knowledge (PK) - Each LM contains at least one PK which contains the basic information supporting the objectives. Most PKs have a supporting PowerPoint presentation.
- Activity (AC) – Each LM can contain one or more activities that provide interactive or hands-on learning that supports the objectives.
- Assessment (KP, FA, AA) – Each LM contains one or more assessments that determines the student's existing knowledge (Knowledge Probe (KP) or pretest) or knowledge gained relative to a particular AC, the PK or both. (Activity Assessment (AA), Final Assessment (FA)).

Each SCO contains an Instructor Guide (IG) and Participant Guide (PG).

Each SCO is self-contained; therefore any one SCO in the Learning Module can be used without the other SCOs, depending upon the needs of the student and the instructor. The instructor or student can pick and choose individual SCOs for select topics, lessons, units, courses or workshops. The graphic below illustrates this concept:



SCME provides SCOs related to Microsystems (MEMS) Technology under many topics including Safety, Introduction to MEMS, Applications of MEMS, BioMEMS, and Fabrication of MEMS.

<u>Why SCOs?</u>
The study of microsystems incorporates many different STEM disciplines: physics, chemistry, biology, lab safety, and mathematics, just to name a few. The goal of SCME is to present MEMS-based lessons that utilize the concepts and principles of these disciplines.

The use of SCOs offers an object-oriented way of presenting materials. Since MEMS education encompasses many subjects, SCME feels that by compartmentalizing materials into small units, it provides flexibility for instructors to introduce MEMS as an application of an existing discipline, to illustrate a concept or principle, or to incorporate MEMS-based education into new or existing curricula.

Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

Etch Overview for Microsystems Learning Module

This booklet contains six (6) Sharable Content Object (SCOs):
Knowledge Probe (KP) / pre-test
Primary Knowledge
Etch Terminology Activity
Science of Thin Films Activity
Bulk Micromachining: An Etch Process Activity
Final Assessment

The following Learning Module Map is a suggested outline on how to use this learning module.

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Learning Module Map for Etch Overview

Learning Module: Etch Overview for Microsystems

Learning Module SCOs (6):

- Knowledge Probe (KP)
- Etch Overview for Microsystems Primary Knowledge (PK)
- Etch Terminology Activity
- Science of Thin Films Activity
- Anisotropic Etch Activity
- Final Assessment Databank
- Final Assessment – short answer (questions from databank)
- Final Assessment – multiple choice (questions from databank)

Following is a suggested map on the implementation of this learning module.

IMPORTANT STEPS	KEY POINTS	REASONS
Pre-test (Knowledge Probe)	Have the participants complete the Knowledge Probe in their booklet or online.	The KP helps to determine the participants' current knowledge of the etch process prior to starting the learning module. The outcome of the KP can be compared against the final assessment to determine the effectiveness of this learning module.
Inquiry – Ask "What is etch or etching? Provide some examples."	It is something they are familiar with, especially in nature. Examples – natural arches, widening river banks, rotting pipe, erosion of any type, sandblasting, sculpturing.	You want the participants to realize that they already know what etch or etching is – it's nothing new. This unit will show how etch is used to make microdevices.
Unit Presentation: Present the Etch Overview for Microsystems PK	Participants should read the PK. A PowerPoint presentation can be downloaded from scme-nm.org and presented to all participants.	An introduction into etch is needed to help participants better understand the etch process. This will lead to more effective learning in the related activities.

<table>
<tr><td>Activity 1:
Complete the “Etch Terminology Activity”.</td><td>This is a crossword puzzle of etch terms and their meanings. This activity could be a homework or classroom assignment. If you have access to the online course, participants can input their answers online.</td><td>Provides participants with a review of the terminology associated with etch processes and equipment.</td></tr>
<tr><td colspan="3">Activity 2: Rainbow Wafer Activity
This activity can be used as a “stand-alone” activity or as part of this Etch Learning Module. It has its own PowerPoint presentation and the introductory material needed to complete this activity. This activity introduces the concepts of etch, oxidation and light interference.
There is a SCME kit for this activity that can be ordered through scme-nm.org.</td></tr>
<tr><td>Activity 2 Inquiry</td><td>Have the participants look at the Rainbow Wafer (from the SCME kits) from different angles.
What colors do they see?
Do the colors of the layers change?
When do they change?
Why do they change?
What are you seeing different colors?</td><td>This inquiry activity gets the participants curious about the wafers, the different colors they see, and how oxide thickness affects the colors on the wafer.</td></tr>
<tr><td>Activity 2 Introduction:
Introduce the “Science of Thin Films Activity” with its presentation.</td><td>The introductory PowerPoint for this activity introduces the participants to three key concepts: etch rates, oxidation rates, and light interference.

The presentation can be downloaded from scme-nm.org.</td><td>The presentation introduces the key concepts of the activity so that the participants gain a better understanding of the data and information gathered during this activity.</td></tr>
</table>

Activity 2: Complete the "Science of Thin Films Activity". **(A kit is available through the SCME website (http://scme-nm.org)** If you do not have a kit, participants can still complete this activity by using the photo of a rainbow wafer that is provided in the SCO.	Correctly interpret oxidation charts. Estimate oxide thicknesses and complete Rainbow Wafer Calculations Worksheet. Calculate and graph etch rates and etch rates vs. oxide thickness. Explain several key concepts, such as *why are several colors seen in oxide thicknesses when oxide is transparent? Why is wet oxidation faster than dry oxidation? What is oxidation? What is etch rate and how can it be controlled?*	This activity helps participants to develop skills for interpreting and developing graphs and tables. Participants learn the relationships between • time and oxide thickness in oxidation processes, • oxide thickness and etch rates, • and oxide thickness and color. They also learn how • light interference affects what color they see on an oxidized wafer, • wafers are oxidized, and how • wafers are etched.
Activity 3: Complete the "Bulk Micromachining: An Etch Process Activity". ***There is a SCME kit for this activity that can be ordered through scme-nm.org.***	This activity uses hazardous chemicals and **requires a fume hood for ventilation.** Participants and instructors are required to wear the proper personal protective equipment. Participants observe the anisotropic etch of silicon using sodium hydroxide (Drain Cleaner).	This activity requires the mixing of sodium hydroxide and water. This activity provides participants with demonstration of bulk etch through the anisotropic etching of silicon on the backside of a MEMS pressure sensor die.
Assessment: Complete one of the Etch Overview Assessment.	Give the participants the final assessment.	Participants are evaluated on what they have learned about etch processes, the types of etch, etch rates, and the application of etch in MEMS fabrication. Compare the results of this assessment with the results of the KP to determine the effectiveness of this learning module in teaching the etch process.

Adapted from Graupp, P. & Wrona, R. (2006) The TWI Workbook: Essential Skills for Supervisors. New York, NY. Productivity Press.

Southwest Center for Microsystems Education (SCME)
University of New Mexico

<u>MEMS Fabrication Topic</u>

Etch Overview Knowledge Probe (Pre-Test)

Shareable Content Object (SCO)

This SCO is part of the Learning Module
<u>Etch Overview for Microsystems</u>

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Etch Overview for Microsystems
Knowledge Probe (Pre-test)

Instructor Guide

Notes to Instructor

This Knowledge Probe (KP) contains 20 questions that can be used assess the participants' current knowledge of the etch processes used for microsystems fabrication. This KP should be given prior to starting the Etch Overview Learning Module. By comparing the results of this KP with the results of the final assessment, you can determine the learning that took place due to the completion of this learning module.

The Etch Overview for Microsystems Learning Module consists of the following SCOs:

- Knowledge Probe (pre-test)
- Etch Overview for Microsystems PK
- Etch Terminology Activity
- Science of Thin Films Activity (SCME Kit available)
- Bulk Micromachining: An Etch Process Activity (SCME Kit available)
- Final Assessment Short Answer – Participant Guide
- Final Assessment Multiple Choice – Participant Guide

This KP is presented as a hand-out (see Participant Guide - PG). Participants and instructors can download the most recent version of this PG from scme-nm.org. Select "Educational Materials" in the side menu.

This companion Instructor Guide (IG) contains both the questions and answers for the KP. The Instructor Guide booklet contains this IG followed by the Participant Guide (PG) assessment which contains only the questions. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

This learning module is now available online as a Moodle course. Contact SCME for access to this course.

Introduction

The purpose of this assessment is to determine your current understanding of the etch processes used in the fabrication of microsystems.

1. For microsystems fabrication, the etch process normally follows which of the following process steps?
    a. Deposition
    b. Photolithography
    c. Oxidation
    d. DRIE

    Answer: b. photolithography

2. There are several types of layers used in the construction of microsystems. Each layer serves a purpose in the device's fabrication. Most of these layers are etched at some point during the process. What type of layer is used to define the pattern to be etched by exposing the areas in the underlying layer that are to be etched and protecting the areas that are not to be etched.
    a. Conductive
    b. Sacrificial
    c. Structural
    d. Etch stop
    e. Etch mask

    Answer: e. etch mask

3. Bulk etch processes are normally used to etch which of the following?
    a. Silicon nitride layers
    b. Silicon substrates
    c. Masking layers
    d. Metal layers

    Answer: b. silicon substrates

4. What type of layer is deposited between structural layers for mechanical separation and isolation, then removed during a "release etch" to free the structural layers and to allow mechanical devices to move.
    a. Conductive
    b. Sacrificial
    c. Structural
    d. Etch stop
    e. Etch mask

    Answer: b. sacrificial

5. What type of etch process is normally used to remove a sacrificial layer from underneath a structural layer without affecting the structural layer?
   a. Physical dry etch
   b. Chemical dry etch
   c. Chemical wet etch
   d. Reactive ion etch (RIE)

   Answer: c. chemical wet etch

6. Which of the following statements BEST describes the difference between surface etch and bulk etch?
   a. Surface etch removes only select material on the surface of the wafer while bulk etch removes material from below the wafer's surface.
   b. Surface etch removes select material from a surface layer on top of the wafer while bulk etch removes select material from within the substrate or bulk of the wafer.
   c. Surface etch removes select material from the masking layer, while bulk etch removes select material from an underlying layer.
   d. Surface etch removes select material from the topmost surface layer, while bulk etch removes select material from an underlying layer.

   Answer: b. *Surface etch removes select material from a surface layer on the wafer while bulk etch removes select material from within the substrate or bulk of the wafer.*

7. Which of the following BEST explains the primary difference between wet etch and dry etch processes?
   a. Wet etch uses a liquid etchant. Dry etch uses a gaseous etchant.
   b. Wet etch is a chemical etch. Dry etch is a physical etch.
   c. Wet etch is a chemical reaction. Dry etch is a physical reaction.
   d. Wet etch yields isotropic profiles. Dry etch yields anisotropic profiles.

   Answer: a. Wet etch uses a liquid etchant. Dry etch uses a gaseous etchant.

8. A wet etch using KOH (potassium hydroxide) is to the silicon substrate as
   a. sandblasting is to patterned glass.
   b. sandpaper is to the surface of wood.
   c. flowing water is to the mud of a river bank.
   d. moisture and heat are to exposed iron.

   Answer: c. flowing water is to the mud of a river bank

9. Surface etch processes are normally NOT used to etch which of the following?
   a. Silicon nitride layers
   b. Silicon substrates
   c. Silicon dioxide layers
   d. Metal layers

   Answer: b. silicon substrates

10. KOH or potassium hydroxide etching is a wet etch process used to ___________________ remove silicon. This type of micromachining etch is referred to as a _________ etch.
    a. Isotropically, surface
    b. Isotropically, bulk
    c. Anisotropically, surface
    d. Anisotropically, bulk

    Answer: d. anisotropically, bulk

11. A plasma is a soup of particles consisting of electrons, positive ions and radicals. During a plasma etch _______________________ are used to physically etch the wafer by striking the wafer with a high acceleration causing a sputtering of surface molecules.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and free radicals
    e. Electrons and free radicals

    Answer: b. positive ions

12. During a plasma etch, _____________________ are adsorbed on the surface and chemically react with surface atoms or molecules creating volatile particles that are removed from the wafer's surface.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and radicals
    e. Electrons and radicals

    Answer: c. free radicals

13. Which of the following does NOT apply to an anisotropic etch profile?
    a. A straight wall profile
    b. Produced by a physical etch process
    c. Produced by a selective wet etch process
    d. High aspect ratios can exist
    e. Shows undercutting below the mask

    Answer: e. shows undercutting below the mask

14. Which of the following statements is always TRUE?
    a. Wet etch produces an anisotropic profile.
    b. Dry etch produces an isotropic profile.
    c. Dry etch is used to etch silicon substrates.
    d. RIE uses both chemical and physical dry etching.
    e. Chemical wet etch is used to strip masking layers.

    Answer: d. RIE uses both chemical and physical dry etching

15. During a RIE process the RF power level and the process pressure are varied to process the desired etch. In order to increase the amount of physical etch within the process the RF power would be ______________________ and/or the process pressure would be _________.
    a. Increased, increased
    b. Decreased, increased
    c. Increased, decreased
    d. Decreased, decreased

    Answer: c. increased, decreased

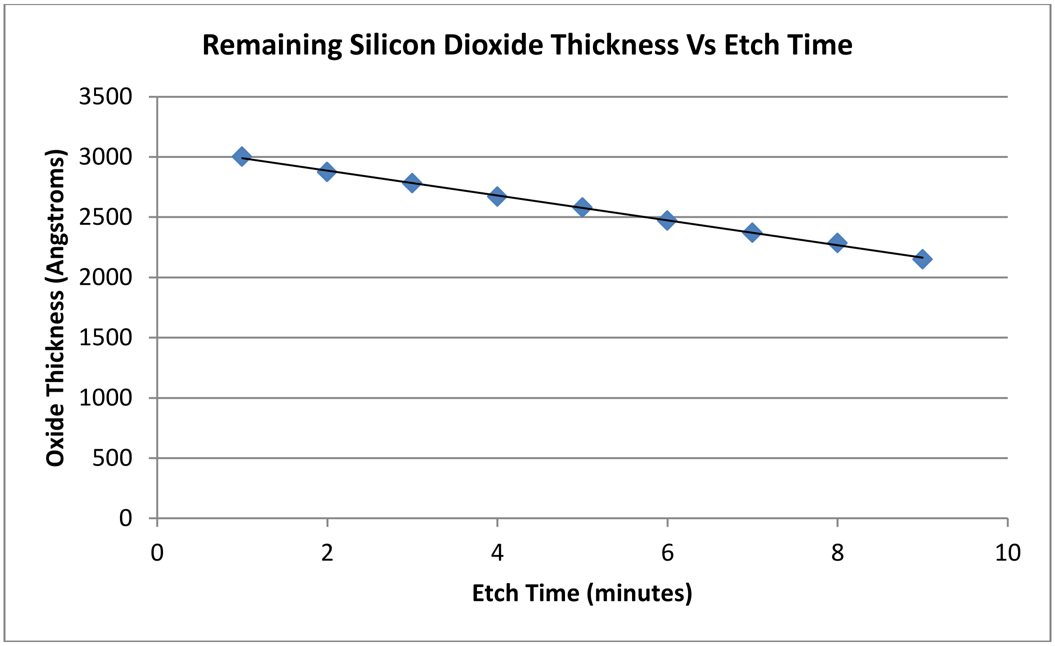
16. What type of dry etch is normally used to fabricate cavities and deep trenches with high aspect ratios?
    a. RIE
    b. DRIE
    c. Ion Milling
    d. KOH

    Answer: b. DRIE

17. Which of the following statements BEST defines "etch rate"?
    a. The rate at which a film is removed from the wafer's substrate during an etching process.
    b. The rate at which a film is deposited on a wafer's surface.
    c. The amount of time it takes to remove a specific thickness of film.
    d. The amount of film removed in a given amount of time.

    Answer: d. the amount of film removed in a given amount of time

18. What is the approximate etch rate of the following process?
   a. 50 angstroms / minute
   b. 100 angstroms / minute
   c. 150 angstroms / minute
   d. 200 angstroms / minute



Answer: b. 100 angstroms / minute

19. Which of the following ratios is the MOST desired selectivity?
   a. 10
   b. 50
   c. 100
   d. 200

Answer: d. 200

20. An etch process is defined by the equation "y = 103x + 90 Å. What does the 103 and 90 represent, respectively?
   a. Etch rate and starting film thickness
   b. Etch rate and total thickness etched
   c. Starting film thickness and etch rate
   d. Total thickness etched and etch rate.

Answer: a. etch rate and starting film thickness

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

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<u>MEMS Fabrication Topic</u>

Etch Overview for Microsystems

Primary Knowledge (PK)
Shareable Content Object (SCO)

This SCO is part of the Learning Module
<u>Etch Overview for Microsystems</u>

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Etch Overview for Microsystems
Primary Knowledge
Instructor Guide

Notes to Instructor

Etch Overview for Microsystems is the introductory primary knowledge SCO for the Etch Overview for Microsystems Learning Module. It is a general overview of various etch processes used in the construction of microsystems. Additional SCOs in this learning module will go into more detail on each type of etch process.

The Etch Overview for Microsystems Learning Module consists of the following SCOs:

- Knowledge Probe (KP) or pre-test
- **Etch Overview for Microsystems PK**
- Etch Terminology Activity
- Science of Thin Films Activity (SCME Kit available)
- Bulk Micromachining: An Etch Process Activity (SCME Kit available)
- Final Assessment
- Final Assessment – Participant Guide

This SCO is presented as a hand-out (Participant Guide - PG). Participants and instructors can download the most recent version of this PG from scme-nm.org. Select “Educational Materials” in the side menu.

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the coaching and review questions at the end of the unit. A PowerPoint presentation is provided for a classroom presentation. The PowerPoint is a summary of the PG. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

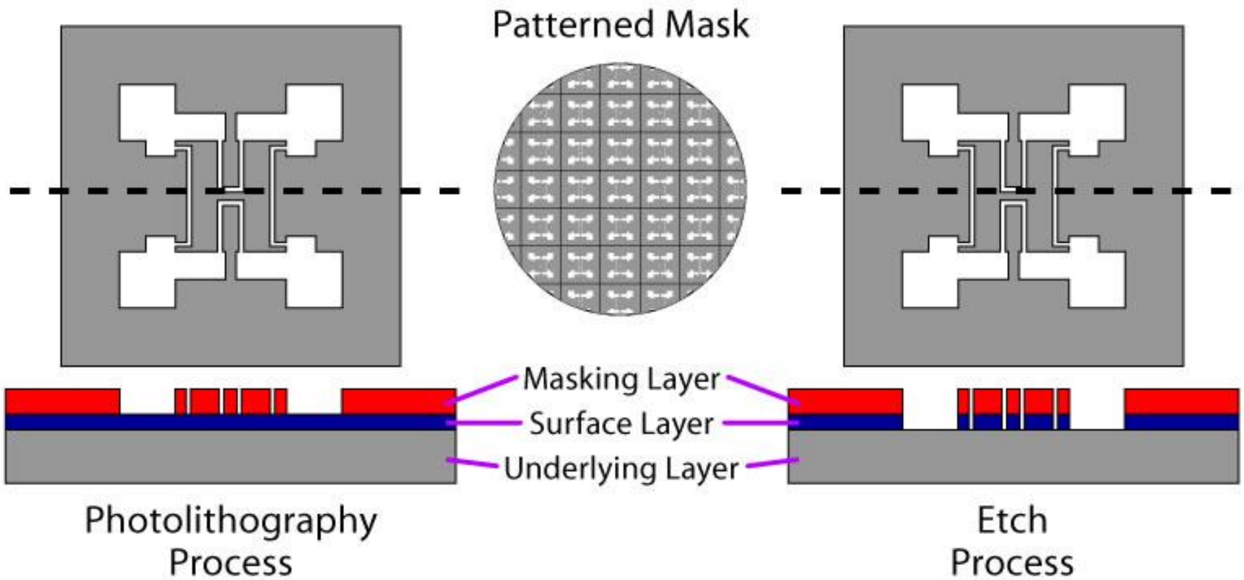
This learning module is now available online as a Moodle course. Contact SCME for access to this course.

Description and Estimated Time to Complete

This unit provides an overview of the etch processes as they apply to the fabrication of Microsystems or Microelectromechanical Systems (MEMS). It is designed to provide basic information on the etch processes and how they are used in the fabrication of MEMS. This unit will introduce you to etch terminology, purpose and processes. Additional instructional units provide more in-depth discussion of the topics introduced in this overview.

Estimated Time to Complete
Allow at least 30 minutes to review.

Introduction



Pattern Transfer

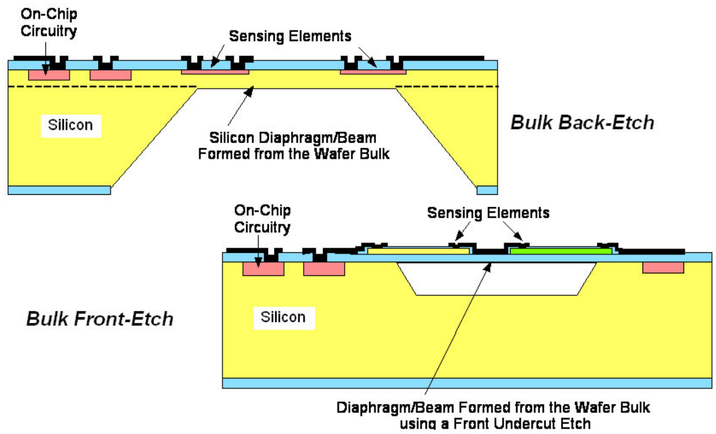
For microsystems fabrication etch is a process that removes select materials from

- the wafer's surface,
- below the wafer's surface, or
- from within the substrate.

The etch process normally follows photolithography or deposition during which a protective masking layer is applied to the wafer's surface. The protective masking layer is used to identify the material to be etched and to protect material that is to remain. The figure labeled "Pattern Transfer," illustrates a mask pattern transferred into a photosensitive layer, shown in red (masking layer), on the wafer's surface (Photolithography Process). During the Etch Process (right), that pattern is transferred into the surface layer, removing exposed areas of the surface layer and leaving areas in the underlying layer open to a subsequent process step.

In microsystems fabrication, the etch process is also used to remove material from underneath a layer or from the backside of the wafer. The graphic to the right illustrates both of these etch processes. In the top graphic (bulk back-etch), the silicon substrate has been selectively removed from the wafer's backside. In the bottom graphic (bulk front-etch), silicon substrate has been removed from underneath a film on the wafer's surface.

A combination of these etch processes allow for the construction of electronic and mechanical devices on the same microchip. These graphics also show the electronics (on-chip circuitry) on the same chip as the mechanical component (diaphragm/beam).



[Graphic courtesy of Khalil Najafi, University of Michigan]

In this unit, you will receive an overview of the two main methods of etching, referred to as wet and dry etch processes. You will also become familiar with the thin films that are etched in the construction of microsystems, and the corresponding etchants (chemicals) used.

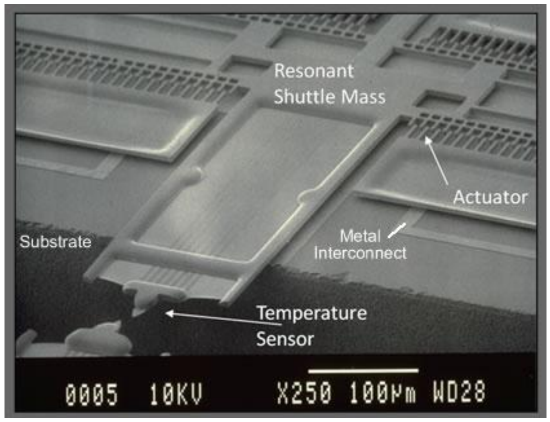
Objectives

- Match microsystem components to the type of etch required to fabricate each component.
- Identify the differences between wet and dry etch.

Key Terms (Definitions are found in the glossary at this end of this unit.)

Adsorption
Anisotropic
Aspect ratio
Chemical etch
Deep Reactive Ion Etch (DRIE)
Desorb
Dry etch
Etch
Etchant
Etch rate
Ion Beam Milling
Isotropic
Physical etch
Plasma
Reactive Ion Etch (RIE)
Selectivity
Wet etch

The Etch Process for Microsystems

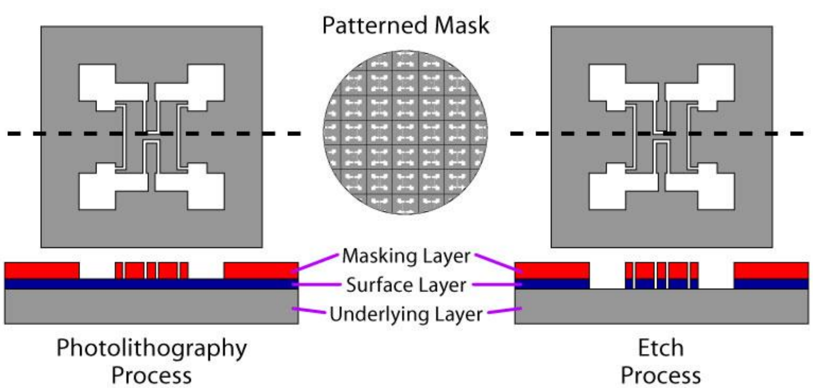


Layers of Micromachined Scanning Thermal Profilometer
[SEM courtesy of Khalil Najafi, University of Michigan]

Microsystems are three-dimensional devices consisting of several thin layers of materials. Each layer is designed to serve a specific role in the system's functionality. A layer may be used as

- part of an electronic circuit (insulator or conductor),
- a structural device for a mechanical component,
- a transducer layer for sensors or
- a sacrificial layer for devices such as cantilevers, diaphragms or beams.

Surface Etch

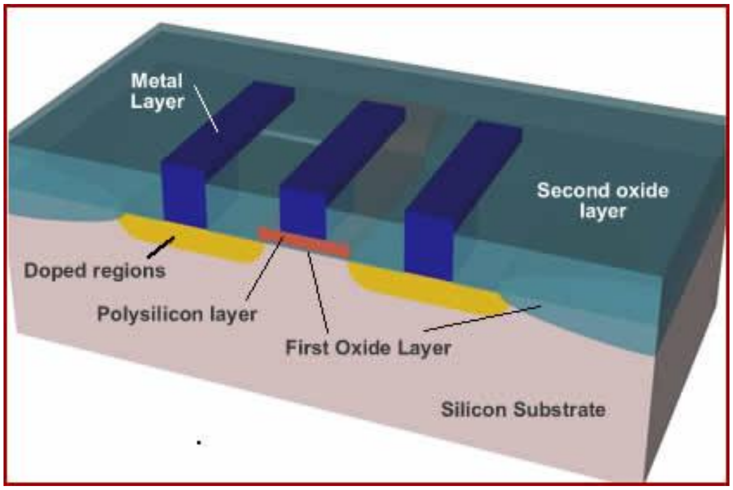


When building the electronics for a microsystem and for outlining mechanical components, the goal of the etch process is the same as that for building integrated circuits:

- Remove selected regions on one layer (the surface layer) of the wafer to create either a structural pattern or to expose an underlying layer of a different material.

For electronic circuits, the underlying layer is now available for conductive interconnects. Connections between different conductive layers can be completed. For mechanical components, the surface layer is now patterned with specific shapes for structural components such as cantilevers, mirrors, or probes. The exposed underlying layer can also allow one to anchor a mechanical structure to it. Mechanical elements can also be conductive as in the case of electrodes or cantilevers.

Transistor etching



Etched layers of a transistor
[Graphic courtesy of Khalil Najafi, University of Michigan]

This graphic illustrates five etched layers which make up the construction of a simple transistor.

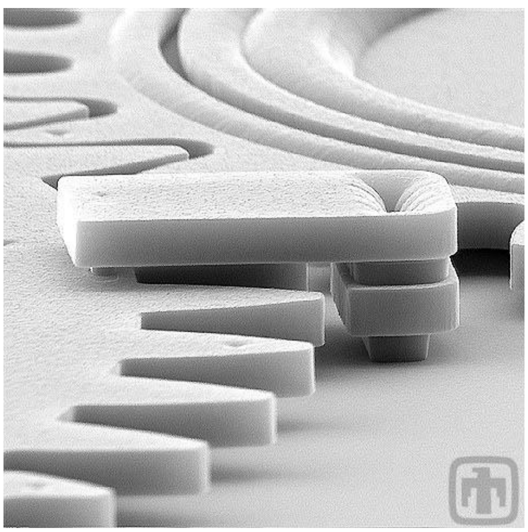
1. The first layer is the silicon substrate.
2. A layer of insulating oxide is deposited on the substrate and openings are etched for the doped regions.
3. A polysilicon layer is deposited and then etched to leave just a small portion for the transistor gate.
4. A second oxide layer is deposited and etched to provide openings for the metal contacts to the doped regions and gate.
5. A metal layer is deposited and etched to form the surface contacts.

Bulk and Release Etch

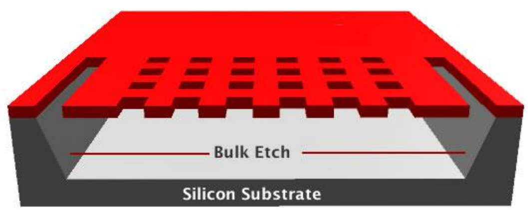
In the construction of a micromechanical part, different components of a structure, such as a rotating gear, are built up layer by layer. Space between parts and layers are created using sacrificial materials which are later removed. This is similar to building scaffolds to hold up a structure during the construction process. At the end of construction, the scaffolding is removed.

In order to release mechanical components, the goal of the etch process changes. The goal is now to remove whatever material is necessary to allow the component to operate according to design, to give it the ability to move freely. The component may be required to move up/down or side-to-side, rotate, vibrate, bend or flex. It may need to be suspended over an open area or formed into a free standing component such as a rotating mirror or oscillating piston.

In such cases, the material underneath the object is removed to "release" the object. In order to do this, etch processes must be able to remove select material from underneath the structural layer without affecting the structural layer itself. This select material (or sacrificial layer) may be another surface layer (left image) or may be bulk material from within the substrate (right graphic). The left image shows the result of a release etch where a sacrificial layer was removed. The image on the right illustrates a bulk etch in which substrate material is removed to provide a void underneath a structural layer.

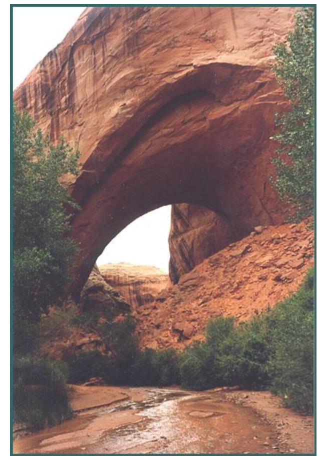


Part of a Gear Train built using Surface Micromachining Technology. Sacrificial layers were etched (removed) in order to create released or moveable devices. [Image courtesy of Sandia National Laboratories, www.mems.sandia.gov]



The above image shows a bulk etch that was used to create an opening under a perforated membrane. This process is called Bulk Micromachining.

Natural Bridges



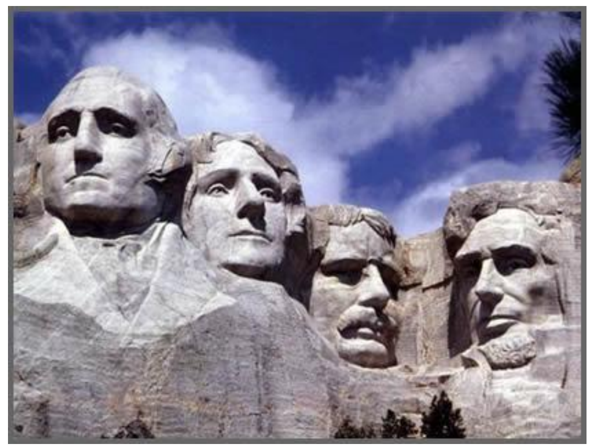
Examples of bulk etching in nature include natural bridges and arches. These structures are formed when the material underneath is etched by wind, rain, water, and natural erosion.

What are some other examples of substrate etching (or bulk etching)?

Natural arch - Coyote Canyon, Utah
[Photo courtesy of Bob Willis]

Other Examples of Etching

Other examples of etching in nature include Mt. Rushmore (right) and cliff dwellings such as Mesa Verde National Park in Colorado below. *[Photos courtesy of the National Park Service]*

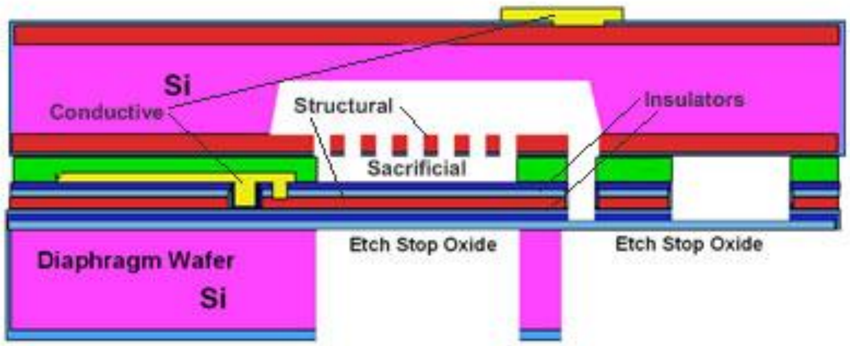


Mt. Rushmore, South Dakota

Mesa Verde National Park

Etched Layers

Each layer of film to be etched for a microsystem has a definitive purpose. Following are the types of functional layers used to construct microsystems and some of the materials used for each type of layer. The actual material used for each layer is dependent on factors such as the application or component being constructed, mechanical and electrical properties needed, previous and subsequent layers, the etch process, and the etchant chemicals.



[Graphic courtesy of Khalil Najafi, University of Michigan]

Conductive Layer – A layer used to construct conductive paths, vias, and electrodes for electronic circuits and components. (Doped Poly-crystalline, metals and metal alloys)
Insulating Layer – A high resistivity layer used to insulate one layer from another. (Silicon nitride, silicon oxide)
Sacrificial Layer - A layer deposited between structural layers for mechanical separation and isolation. This layer is removed during a "release etch" to free the structural layers and to allow mechanical devices to move. (Silicon dioxide, photoresist, polycrystalline silicon)
Structural Layer - A layer having the mechanical and electrical properties needed for the component being constructed. (doped polycrystalline silicon, silicon nitride, some metals such as chrome, gold and aluminum-copper)
Etch Stop Layer – A layer used to define the microstructure thickness by stopping the etch when the etch stop layer is reached. (Boron-doped silicon, silicon dioxide, silicon nitride)
Etch Mask Layer – A layer used to define the pattern to be etched. The mask layer exposes areas to be etched and protects areas that are not to be etched. (photoresist, silicon dioxide, silicon nitride, some metals)

Etchants

Just as different materials are selected for their functional properties in creating the various layers of MEMS, different chemicals are selected to etch those materials. Etchants are chemical compounds which chemically react selectively with the layer to be removed, thereby removing the layer. Great care is exercised in selecting the etchant for a specific layer. Several factors must be considered:

- The etchant must be capable of etching through the select layer at a rate fast enough to complete the etch without under etching the selected area in a desired amount of time.
- The etch rate must not be too fast such that it over etches into the next layer.
- The etchant should not be capable of corroding or etching the protective mask layer.
- The etchant should not react with existing layers that are not to be etched.

Etch Processes

Etching is accomplished though either a wet or dry technique. Wet etching removes the material through a chemical reaction between a liquid etchant and the layer to be etched. Dry etching removes the material through a chemical reaction and/or a physical interaction between etchant gasses and the exposed layer.

Thin Film and Etchant

The table shows some of the thin films used in the construction of microsystems devices, the etch process used (wet or dry), and the etchants for each type of film.

Thin Films removed by Wet Etch	**Etchants**
Aluminum	Phosphoric-based
Crystalline silicon substrate	Potassium Hydroxide (KOH) Ethylene Diamine Pyrocatechol (EDP) Tetramethyl Ammonium Hydroxide (TMAH)
Gold	Iodine-based
Nitride	Phosphoric-based
Noble metals	Mixture of Hydrochloric and nitric acids
Oxide	Hydrofluoric-based
PSG (Phosphosilicate glass)	Hydrofluoric Acid
Thin Films removed by Dry Etch	**Etchants**
Aluminum	Chlorine-based
Silicon	Chlorine and Fluorine-based, with or without oxygen. Cold SF6:02 good for trenching XeF2 (Xenon Difluoride) Bromine/Fluorine
SiO_2, SiNX	Fluorine-based
Polysilicon	Chlorine-based
Photoresist	Oxygen plasma
Tungsten	Fluorine-based

Thin Film materials and Etchants

Factors Affecting Etch Quality

Regardless of the technique used (wet or dry), the etch quality is influenced by several factors. A few important factors for microsystems include etch rate, directional control and selectivity.

Etch rate – The rate at which the material is removed from the wafer.

Directional control – Since etch can occur in all directions, it is important to be able to control the direction of the etch. Directional control results in achieving the desired "shape" through the type of etch profile (isotropic, anisotropic or a combination of both)

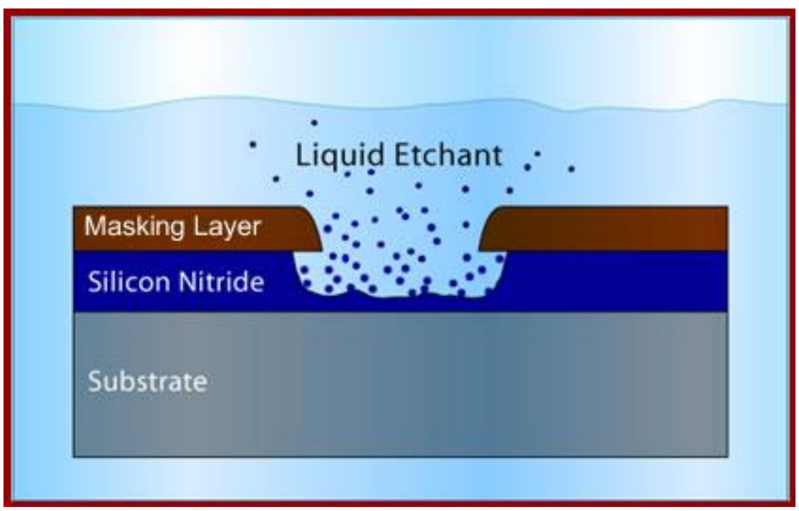
Selectivity – The property of the etchant which permits it to selectively etch specific materials at a faster etch rate than other materials on the wafer. Selectivity is the ratio defined by the following:

$$\text{Selectivity} = \frac{\text{Etch rate of material to be etched}}{\text{Etch rate of material NOT to be etched}}$$

Based on this formula, which is desired in most cases – a high selectivity or low selectivity?

If you said "high selectivity", you are correct! A high selectivity means that, with a correct timed etch, the material to be etched can be completely removed before the masking layer is affected.

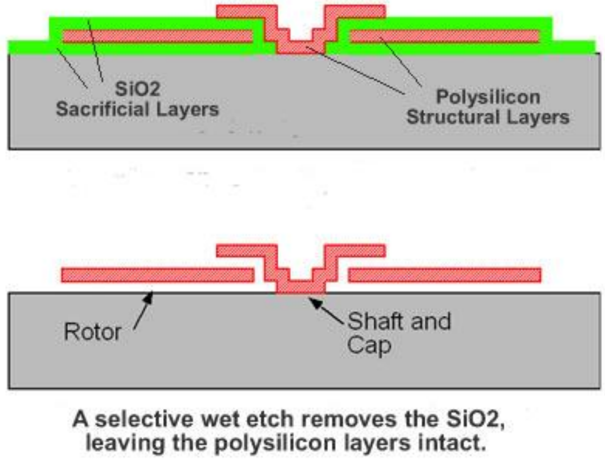
Wet Etch



Wet Etch Process

Wet etch removes the surface layer or bulk material through a chemical reaction between the material to be removed and a liquid etchant. Wet etch chemistry is designed to be highly selective with respect to the mask and substrate. It is a reliable process that uses low cost equipment. However, in most cases, the liquid etchants are expensive and can be quite hazardous.

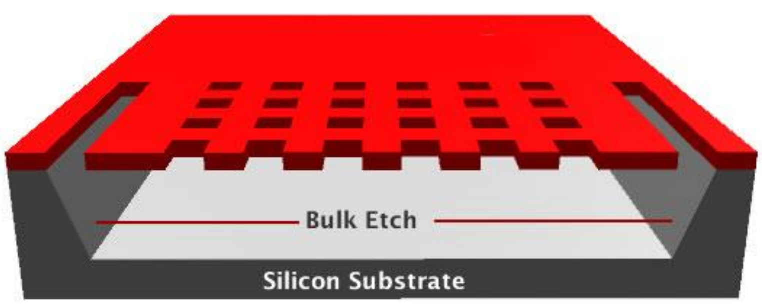
Wet Etch – isotropic or anisotropic?

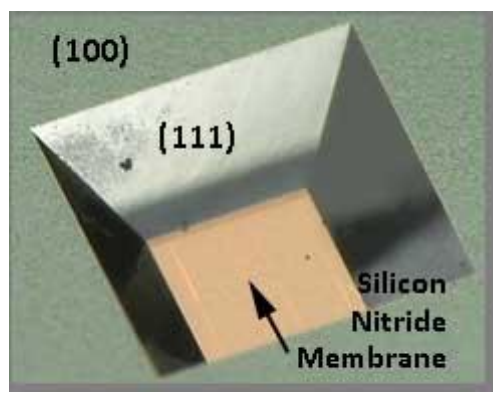


Isotropic Wet Etch

In most applications, wet etch is isotropic. This characteristic makes it very effective at removing a bulk of material such as a sacrificial layer or masking layer. The graphic (Isotropic Wet Etch) shows how structural layers are "released" after the removal of the sacrificial silicon dioxide layers. This requires a selective wet etch process.

Specific wet etches such as potassium hydroxide (KOH) used to etch crystalline silicone, result in an anisotropic etch profile. The KOH etches the silicon along a specific plane. In the figures (Anisotropic Wet Etch), notice the sharpness of the angled edges of the bulk etch. This is due to the high selectivity of KOH (a liquid etchant) and the crystalline structure of silicon. The (111) plane, etches about 400 times slower than the (100) plane. In the photograph of the backside of a pressure sensor, you can see how these planes have been etched forming a well to the silicon nitride membrane (etch stop). An anisotropic wet etch such as KOH can be used to create anisotropic trenches and cavities the full depth of the wafer.





Backside of a Pressure Sensor

Anisotropic Wet Etch

The Wet Etch Process

The wet etch process consists of three primary processing steps:

- Etch
- Rinse
- Dry

Step 1: Etch

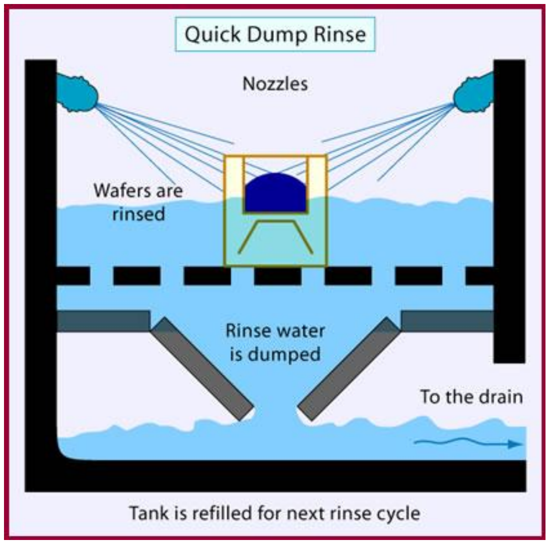
Wet etch is performed in an immersion tank (see photo) containing the etchant solution. Two critical process parameters monitored during wet etch are the concentration of the solution and its temperature. Both directly affect the etch rate. An increase in either parameter increases the etch rate.

- Wafers to be etched are placed in a wafer carrier, also known as a "boat".
- The carrier is lowered into the tank containing the heated etchant solution.
- The wafers are left in the solution for a calculated amount of time.

Etch - The carrier with wafers is lowered into a tank of liquid etchant [Photo courtesy of Bob Willis]

Step 2: Rinse

Once the etch time expires, the wafer carrier is lifted out of the tank and transferred to another tank where it is rinsed with ultra-clean deionized water. The graphic shows a quick-dump-rinse (QDR) in the "rinse" cycle.



Step 3: Dry

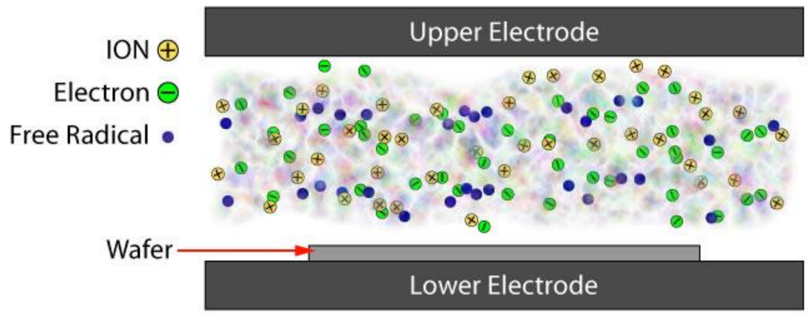
After rinse and before the wafers can be processed further, they must be thoroughly dried. The presence of water, even in miniscule amounts, will interfere with future processing.

Typically, the wafers are placed in a Spin Rinse Dryer (SRD) *(see photo)* where they are rinsed and dried. The SRD's operation is similar to a centrifuge. The wafer carrier is placed in the machine and rotated while being rinsed with deionized water. After the rinse, the water is turned off. The carrier continues to spin but at a higher rotational speed. Heated nitrogen is introduced, removing any remaining water on the wafer.

Loading cassette into Spin-Rinse-Dryer (SRD)
[Photo courtesy of Bob Willis]

Dry Etch

In dry etch the wafer is exposed to a gaseous etchant which is suspended in a RF (radio frequency) energized plasma. Collisions between the gas molecules and energized electrons create a "soup" made up of electrons, ions and radicals. (See graphic below)



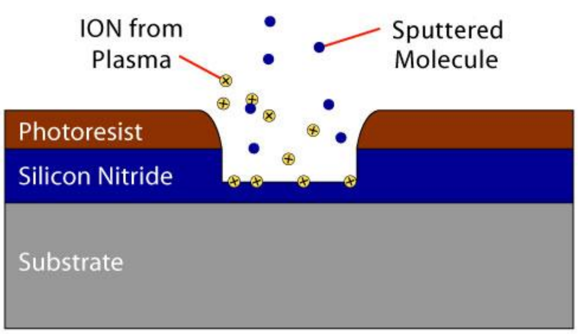
By design, dry etch methods provide more control over the factors which influence etched results. Dry etch processes provide directional control of the etch, anisotropic profiles, and greater control over the process parameters (pressure, temperature, gas flow, power). This control allows very detailed and specific etching to be performed. Because gases are the primary etch medium, and are housed in a sealed chamber, human exposure to dangerous solvents and chemicals is limited. However, the equipment is expensive to purchase and maintain. The application of RF power to the process also poses potential health and safety risks and must be carefully controlled.

Dry Etch

Dry etch is normally used to remove selected areas from the surface layer rather than bulk material of a substrate or a sacrificial layer. Dry etch can be a chemical etch, physical etch or both. Reactive ion etchers (RIE) provide the parameters for both types of etching.

Physical Etch

Physical etch is very similar to the sputtering deposition process. It may be referred to as "ion beam etching", "sputtering" or "ion milling". Ions bombard the surface of the wafer, causing molecules to sputter off the surface. It is entirely a physical process, with no chemical reaction occurring *(see graphic)*.

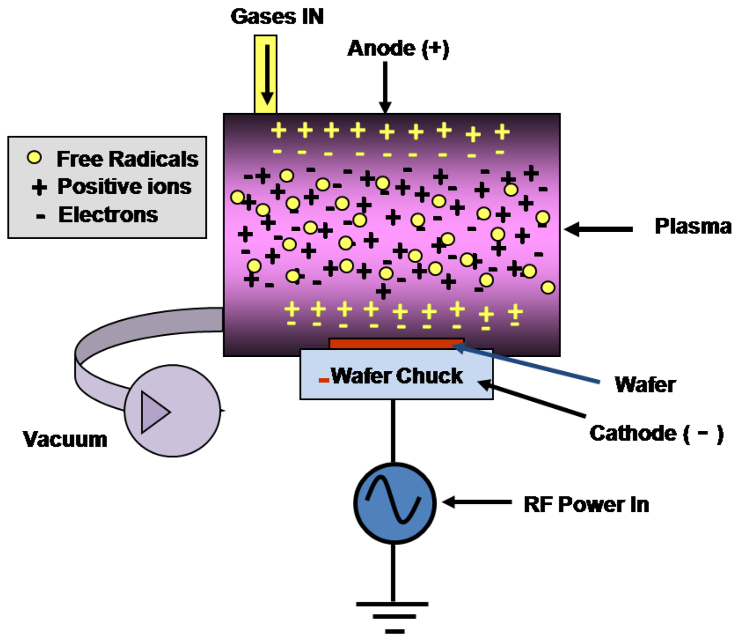


Physical Etch - Ion Bombardment causing molecules to sputter off the exposed surface.

A type of Physical Etch

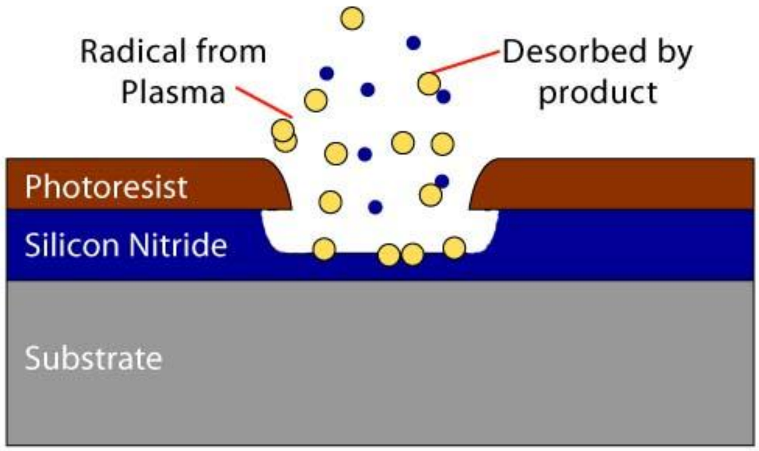
This type of etching is similar to sand-blasting where high velocity sand is used to chip away at an exposed surface. In sand-blasting a picture is formed on a sheet of glass using a strong protective material. This material will stand up to being blasted with high velocity sand particles. The unprotected areas of the glass are etched by the sand which removes particles of glass from the surface. When the desired depth is reached, the blasting stops. The mask is removed and the design exposed.

The Physical Etch Process



- Wafers are placed on a negatively charged cathode inside a vacuum chamber.
- A gas is introduced into the RF-powered chamber under low pressure (e.g., <50 mTorr). A plasma is struck (ignited).
- In the chamber, the gas molecules pass through the plasma and collide with high energy electrons. The energy is transferred from the electrons to the gas etchant molecules.
- These collisions result in high-energy state positive ions and free radicals.
- These positive ions are attracted to the negatively-charged wafer.
- The ions accelerate as they move toward the wafer.
- When the ions hit the wafer, surface layer molecules are removed.
- This process continues until the pattern is etched through the surface layer, exposing the underlying layer.

The Chemical Etch Process



Chemical Dry Etch Process uses radicals from the plasma

Chemical etching requires the presence of plasma energy and a select gas (the chemical etchant) to etch the wafer's surface layer. The process begins the same way as the physical etch process: a plasma is struck and collisions occur between high energy electrons and gas molecules. However, in chemical etching, it is the free radicals formed from the collisions that perform the etch rather than the positive ions. Free radicals are atoms, molecules or ions with unpaired electrons making them highly reactive.

Through the collisions that take place in a plasma, free radicals and positive ions are formed. Because the radicals generate faster and survive longer than ions, more radicals are available in the plasma. Once produced, the free radicals travel towards the wafer where they are adsorbed by the material on the wafer surface. A chemical reaction occurs between the material to be etched and the radicals. By-products of the reaction desorb from the surface and diffuse into the gas present in the chamber. The outcome is an isotropic etch usually with undercutting (a removal of material from beneath the resist mask – as shown in the graphic above.) The adsorption / desorption is the chemical etch.

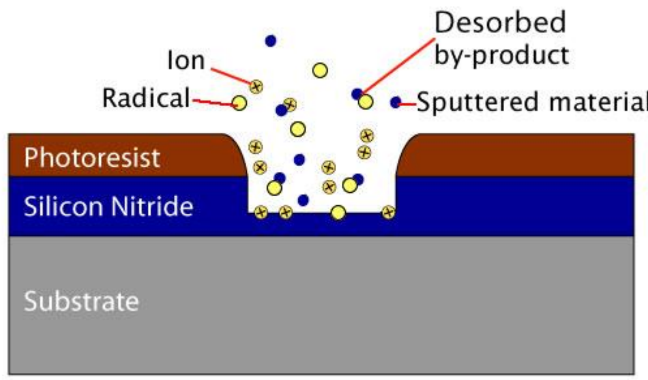
Dry Etch Process Parameters

The two critical parameters in the dry etch process are pressure and RF power.

- Chemical etching requires high-range pressures and low-range RF power levels.
- Physical etching requires low-range pressures and high range RF power levers.

Reactive Ion Etching

Reactive ion etching (RIE) uses mid-level RF power and mid-range pressure to combine both physical and chemical etching in one process. The positive ions from the plasma bombard the wafer's surface (physical etch) at the same time that the free radicals adsorb to the surface (chemical etch). This process program can control the amount of physical vs. chemical etch by adjusting the process pressure or RF power. An increase in RF power will increase the physical etch while an increase in process pressure will increase the rate of chemical etch.



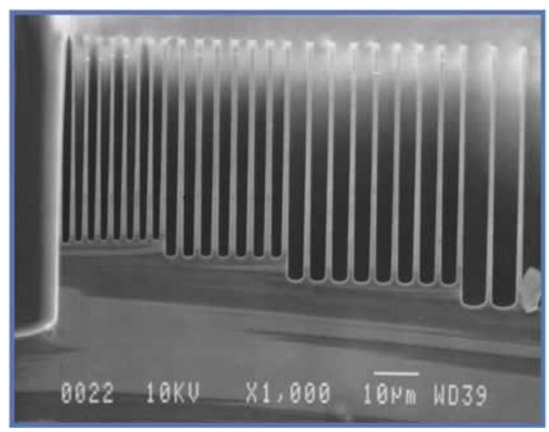
RIE uses both radicals and ions during the etch process

This process provides high selectivity ratios. It also produces anisotropic profiles on features less than 3 microns wide. Its ability to capitalize on the advantages of both physical and chemical etching makes RIE an invaluable tool in the manufacture of microsystems components.

Deep RIE

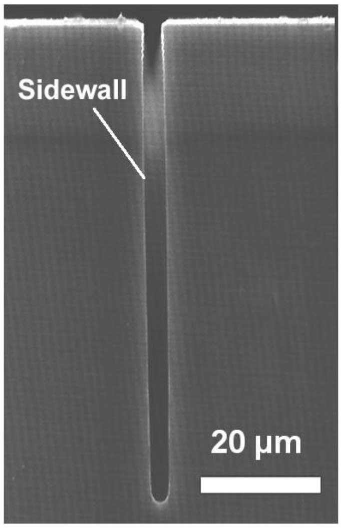
A special subclass of RIE is deep RIE (DRIE). Deep reactive ion etching is used to etch deep cavities (or trenches) in substrates with relatively high aspect ratios (the ratio of a cavity's depth to its width). These cavities can be hundreds of micrometers deep while only a few micrometers wide. Aspect ratios as high as 50:1 can be achieved with DRIE. As new DRIE methods are developed, it is very likely that these aspect ratios will get even higher.

The SEM shows a series of cavities etched using a DRIE process. Notice that the deeper cavities have the wider openings. This means that on the same wafer with a number of different etch openings, the features will achieve different depths. This is not always desirable, but not much can be done about it.



A SEM of cavities etched with DRIE. [SEM courtesy of Khalil Najafi, University of Michigan]

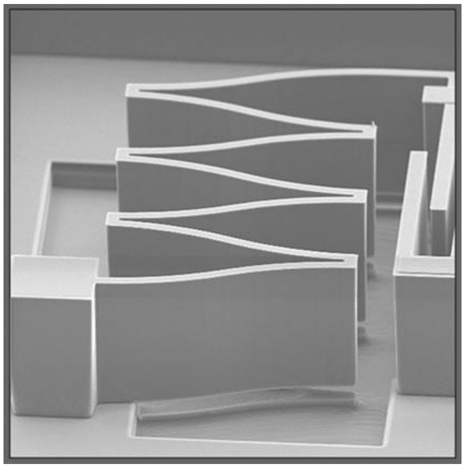
Most systems utilize the so-called "Bosch process" or “switched etching process”, in which a polymer is used to passivate the etching of the sidewalls. This passivation protects the sidewalls from being etched further but not the horizontal surfaces. During the entire etching process, the gas mixture switches back and forth between etchant gasses and passivation gasses. This results in a deep, narrow etch. This process can easily be used to etch completely through a silicon substrate at etch rates 3 to 4 times faster than wet etching.



DRIE Cavity or Trench
[SEM courtesy of Khalil Najafi, University of Michigan]

DRIE Structures

In addition to creating cavities, DRIE can be used to create tall thin objects or components for microsystems devices. These objects can later be "released" through other etch methods. The SEM shows a leaf spring created using DRIE. Notice how the spring is attached to a block at one end (front) and to a slider at the opposite end. The entire spring has been released from the substrate allowing it to expand and contract.



Leaf Spring
[SEM courtesy of Khalil Najafi, University of Michigan]

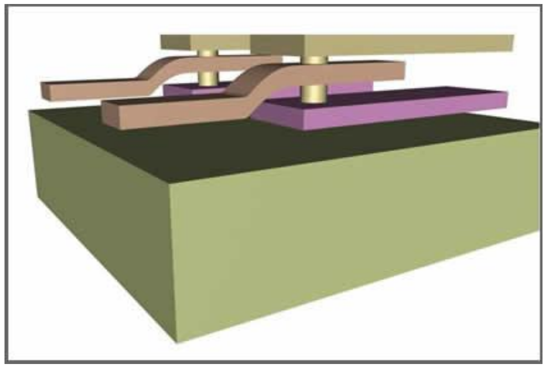
Summary

In microsystems fabrication, etch processes are used to remove bulk material from within a substrate, selectively remove material from within thin film layers, and define structures in layers above and below other thin film layers.

Several different types of etch processes are required to form the various shapes and structures found in microsystems. Such process include
- Wet etch (isotropic and anisotropic)
- Dry etch (physical, chemical, and both)

RIE and DRIE are dry etch processes that use both chemical and physical etch to form the required interleaving shapes. DRIE provides the high aspect ratio cavities required for the advancing technologies of semiconductor, micro and nanosystems.

Review Question



[Image courtesy of Khalil Najafi, University of Michigan]

What types of etch processes were used to form the linkage system in the diagram?

Answer: Dry etch (both plasma and DRIE) to etch the polysilicon layers and the holes for the posts, respectively. Wet etch to remove the sacrificial layers.

References

- MATEC Etch Overview
- University of Michigan MEMS presentations, Prof Khalil Najafi
- Central New Mexico Community College presentations from Matthias Pleil, Fabian Lopez and Mary Jane Willis

Glossary of Key Terms

Adsorption – The accumulation of gases, liquids, or solutes on the surface of a solid of liquid.

Anisotropic - A type of etch that etches at a different rate at the surface and the underlying layers. It results in straight wall geometries

Aspect ratio - The height of an etched feature divided by its width.

Chemical etch – An etch that removes the select material through a chemical reaction between a liquid etchant and the layer to be etched.

Deep Reactive Ion Etch (DRIE) - Deep Reactive-Ion Etching: A highly anisotropic etch process used to create deep, steep-sided holes and trenches in wafers, with aspect ratios of 20:1 or more.

Desorb – The be released from the state of adsorption or absorption.

Dry etch - A process of removing materials from a wafer during the lithography process by using plasma gases.

Etch - The process of removing material from a wafer (such as oxides or other thin films) by chemical, electrolytic or plasma (ion bombardment) means. Examples: nitride etch, oxide etch.

Etchant - An active chemical solution that is used to etching films. It is usually highly selective for etching various films at different etch rates.

Etch rate - The rate at which a film is removed from the wafer surface during an etching procedure.

Ion Beam Milling – A type of dry etch process where a focused beam of ions is used to physical etch selected material on a wafer.

Isotropic - Etching that etches at one rate for the surface as well as the underlying layers. It results in undercutting.

Physical etch – A type of etch where ions bombard the surface of the wafer, causing molecules to sputter off the surface. It is entirely a physical process, with no chemical reaction occurring.

Plasma - An ionized and energized gas consisting of ions, electrons, and radicals used to produce physical and chemical processing of silicon wafers in semiconductor manufacturing tools.

Reactive Ion Etch (RIE) - A dry etching technique that uses a low pressure plasma to remove the etch materials by means of both chemical and physical etch.

Selectivity - The property of the etchant which permits it to selectively etch specific materials at a faster etch rate than other materials on the wafer.

Wet etch - The process of removing materials from a wafer using liquid chemicals.

Disclaimer

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Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

Etch Terminology Activity

Shareable Content Object (SCO)

This SCO is part of the Learning Module
Etch Overview for Microsystems

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Etch Terminology Activity

Etch Overview for Microsystems Learning Module
Instructor Guide

Notes to Instructor

This activity provides the participants an opportunity to better understand the terminology associated with Etch processing. Participants should read the PK SCO before doing this activity in order to get an understanding of Etch terminology.

The Etch Overview for Microsystems Learning Module consists of the following SCOs:

- Knowledge Probe (KP) or pre-test
- Etch Overview for Microsystems PK
- **Etch Terminology Activity**
- Science of Thin Films Activity (SCME Kit available)
- Bulk Micromachining: An Etch Process Activity (SCME Kit available)
- Final Assessment

This activity is presented as a hand-out (Participant Guide - PG). Participants and instructors can download the most recent version of this PG from scme-nm.org. Select "Educational Materials" in the side menu.

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the Post-Activity questions. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

This learning module is now available online as a Moodle course. Contact SCME for access to this course. Answers to this activity can now be submitted online.

Description and Estimated Time to Complete

In this activity you will demonstrate your knowledge of etch for microsystems terminology. This activity consists of two parts:

- A **crossword puzzle** that tests your knowledge of the terminology and acronyms associated with etch processing, and
- **Post-activity questions** that ask you to demonstrate a better understanding of etch and its application to MEMS fabrication.

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

Estimated Time to Complete

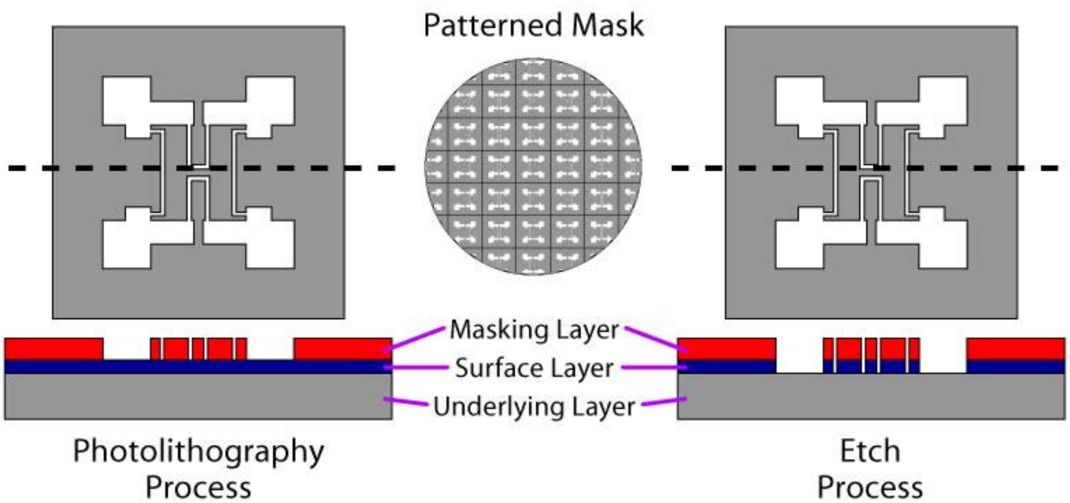
Allow at least 30 minutes to complete this activity.

Introduction

For microsystems fabrication etch is a process that removes select materials from

- the wafer's surface,
- below the wafer's surface, or
- from within the substrate.

The etch process normally follows photolithography or deposition during which a protective mask or layer is applied to the wafer's surface. The protective mask is to identify the material to be etched and to protect material that is to remain. The graphic (Pattern Transfer) illustrates a patterned mask incorporated into a photosensitive layer (or protective mask) on the wafer's surface (Photolithography Process). During the Etch Process (right), that pattern is transferred into the surface layer, exposing areas of the underlying layer.



Pattern Transfer

Activity Objective

Activity Objectives

- Identify the correct terms used for several definitions or statements related to etch.
- Describe the etch process as it applies to microsystems fabrication.

Resources

SCME's Etch Overview for Microsystems PK

Documentation

1. Completed Crossword Puzzle
2. Questions and Answers to the Post-Activity Questions

Activity: Etch Terminology

Answer Key to Crossword Puzzle – Etch Terminology

EclipseCrossword.com

ACROSS	Answers
7. The ratio of the etch rate of material to be etched divided by etch rate of masking material.	**Selectivity**
8. Second step of the wet etch process.	**Rinse**
9. Type of films used for conductive layers.	**Metals**
11. An etch that frees a microsystem component from an underlying layer.	**Release**
14. An etch process that uses a high energy plasma	**Dry**
15. The layer that is completely removed to allow mechanical devices to move.	**Sacrificial**
18. The mask ______ layer determines the endpoint of the etch.	**Stop**
20. The microsystems fabrication process that removes material from a wafer chemically and/or physically.	**Etch**
21. Straight wall geometries result from this type of etch.	**Anisotropic**
22. A layer that defines the pattern to be etched.	**Mask**
24. A type of dry etch process that uses a focused beam of ions to physically etch select material on the wafer.	**Milling**
DOWN	
1. Quick-dump-rinse.	**QDR**
2. Type of etch that removes select material through a chemical reaction.	**Chemical**
3. The ratio of the height of an etched feature divided by its width (2 words)	**Aspect ratio**
4. The type of etch process that uses liquid etchants.	**Wet**
5. An active chemical solution or mixture used to etch films.	**Etchant**
6. Angstroms of film removed divided by time (2 words).	**Etch rate**
10. A layer having the mechanical and electrical properties needed for a MEMS component.	**Structural**
12. Etch process that creates high aspect ratio holes and trenches.	**DRIE**
13. Also called substrate etching (2 words).	**Bulk etch**
16. The type of etch profile that results from a chemical etch.	**Isotropic**
17. A type of etch where ions bombard the surface of the wafer causing a sputter of surface material.	**Physical**
19. An ionized and energized gas consisting of ions, electrons, and radicals.	**Plasma**
23. A process that uses a low pressure plasma allowing for a combination of both chemical and physical etching.	**RIE**

Post-Activity Questions / Answers

1. The etch process can be performed several times during the fabrication of a microsystem; however, the purpose of the etch as well as the type etch process can be different. Describe the purpose(s) and applications of surface etch and bulk/release etch in the fabrication of microsystems.

   Answer:

   Surface Etch: *The purpose of surface etch is to transfer the pattern on a masking layer into the surface layer below. A surface etch will bore through selected regions in the surface layer to expose an underlying layer of a different material. Surface etching is used to pattern microsystem components such as cantilevers, mirrors and probes, and to expose conductive interconnects.*

   Bulk/Release Etch: Bulk etching or bulk micromachining is when a bulk of material is removed from the wafer's surface (a sacrificial layer) or from the substrate material. The purpose of removing a sacrificial layer is to "release" a microsystems component in order for it to "move". This process is used for gears, combdrives, springs or any device that needs to move up and down, side-to-side, rotate, vibrate, bend or flex. Bulk etch removes substrate material in order to provide a "void" underneath a structural object such as a diaphragm or electrode.

2. Discuss the differences between a chemical etch and a physical etch.

   Answer:

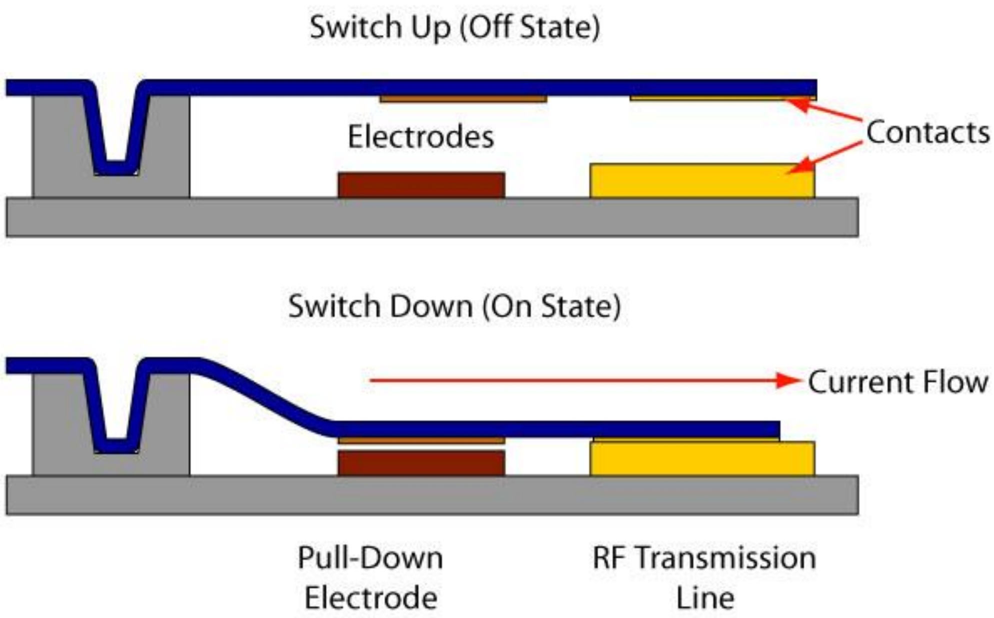
   Chemical etch:

   - *A chemical etch is when select material from a surface layer or from the substrate is removed through a chemical reaction between the material to be removed and a liquid etchant or reactive particle such as a radical.*
   - *A wet etch is always a chemical etch; however, a dry etch, specifically a RIE, can be both chemical and physical.*
   - *A chemical etch is highly selective.*

   Physical Etch:

   - *A physical etch is when high energy positive ions bombard the surface of the wafer causing molecules to sputter off the surface.*
   - *A dry etch is required for physical etching.*
   - *A physical etch has poor or low selectivity.*
   - *It is a physical process with no chemical reaction occurring.*

3. Discuss the etch requirements (types of etch processes and etched layers) required for the RF switch shown in the graphic below.



Answer: *This device would require several layers: anchor, pull-down electrode, contact, sacrificial layer, another electrode layer, another contact layer, structural layer (cantilever). With the exception of the sacrificial layer, all etch processes would probably be dry etch processes. The sacrificial layer between the electrodes and under the cantilever would be a chemical or wet etch.*

Summary

In microsystems fabrication, etch processes are used to remove bulk material from within a substrate, select material from within thin film layers, and complete layers above and below other thin film layers.

Several different types of etch processes are required to form the various shapes and structures found in microsystems. Such process include

- Wet etch (isotropic and anisotropic)
- Dry etch (physical, chemical, and both)

RIE and DRIE are dry etch processes that use both chemical and physical etch to form the required shapes. DRIE provides the high aspect ratio cavities required for the advancing technologies of micro and nanosystems.

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

Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

Science of Thin Films Activity

Shareable Content Object (SCO)

This SCO is part of the Learning Modules
Etch Overview for Microsystems
Deposition Overview for Microsystems

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Science of Thin Films Activity

Etch Overview for Microsystems
Instructor Guide

Notes to Instructor

This activity provides a hands-on study of thin films through a detailed exploration of silicon dioxide (oxide). Participants calculate etch rates as well as identify the color-thickness relationship of silicon dioxide. Participants observe and explore the following:

- The relationship between oxide growth in wet vs. dry oxidation furnaces
- How thin film interference applies to oxide thickness
- How oxide thickness and time is used to determine etch rate
- How the etch rate and oxide thickness determine the time of etch

This activity could also be used as an etch activity or as an oxidation activity. Participants should have a basic understanding of the wet etch process.

To complete this activity, participants will need the "rainbow" wafer provided in the **SCME Science of Thin Films Kit** or, if you do not have a rainbow wafer, a picture of one is provided in this activity. You may also choose to have some students work this activity using the kit Rainbow wafer and other students using the picture of a Rainbow wafer.

This activity is part of the Etch Overview for Microsystems Learning Module as well as the Deposition Overview for Microsystems. This Etch Overview consists of the following SCOs:

- Knowledge Probe (KP) or pre-test
- Etch Overview for Microsystems PK
- Etch Terminology Activity
- **Science of Thin Films Activity (SCME Kit available)**
- Bulk Micromachining: An Etch Process Activity (SCME Kit available)
- Final Assessment

This activity is presented as a hand-out (Participant Guide - PG). Participants and instructors can download the most recent version of this PG from scme-nm.org. Select "Educational Materials" in the side menu.

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the Post-Activity questions. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

This learning module is now available online as a Moodle course. Contact SCME for access to this course. Answers to this activity can now be submitted online.

Description and Estimated Time to Complete

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.

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

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.

Estimated Time to Complete

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.

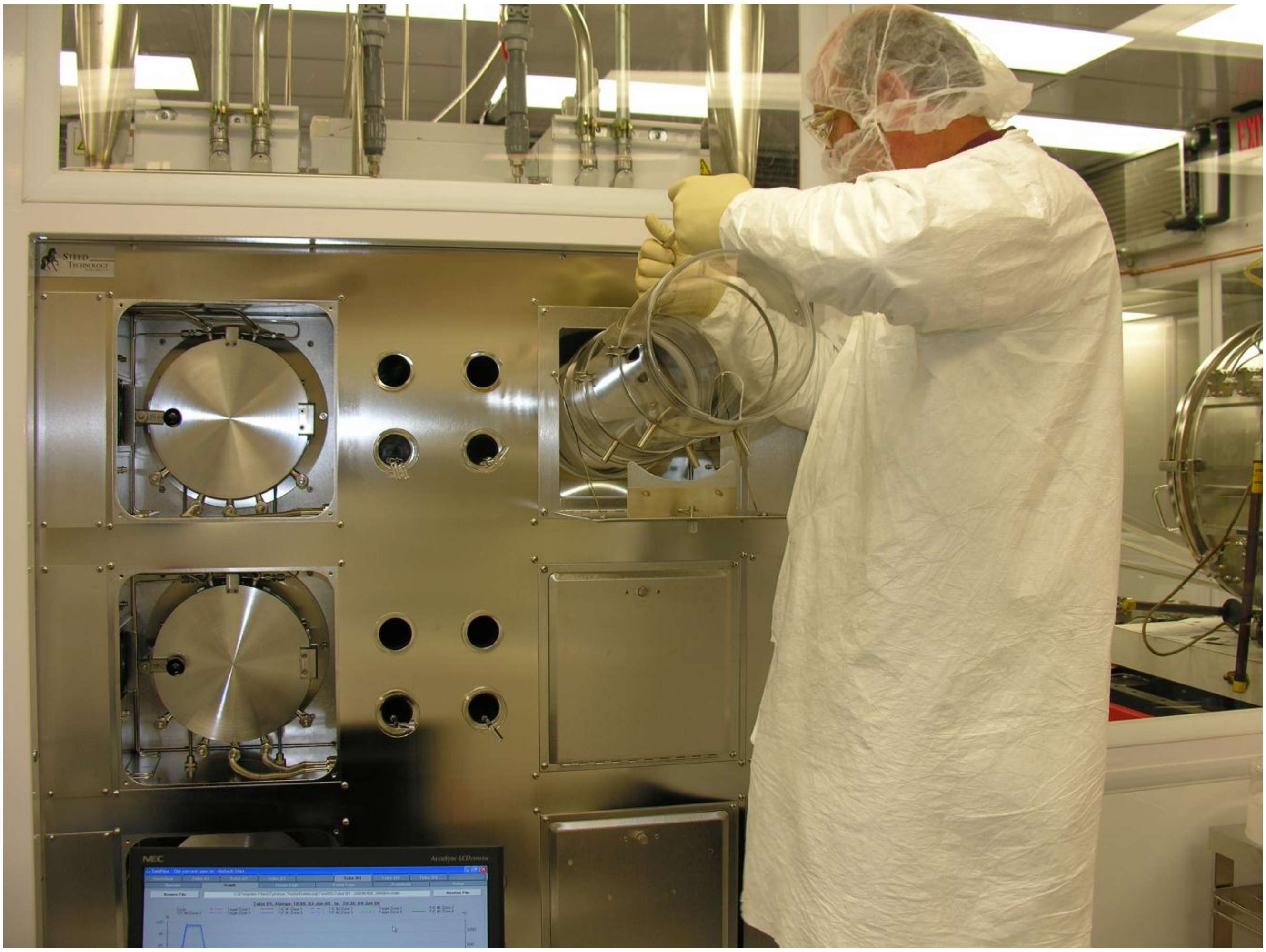


Figure 2. Oxidation furnace being manually unloaded.
[Image courtesy of the University of New Mexico, Manufacturing Training and Technology Center]

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.

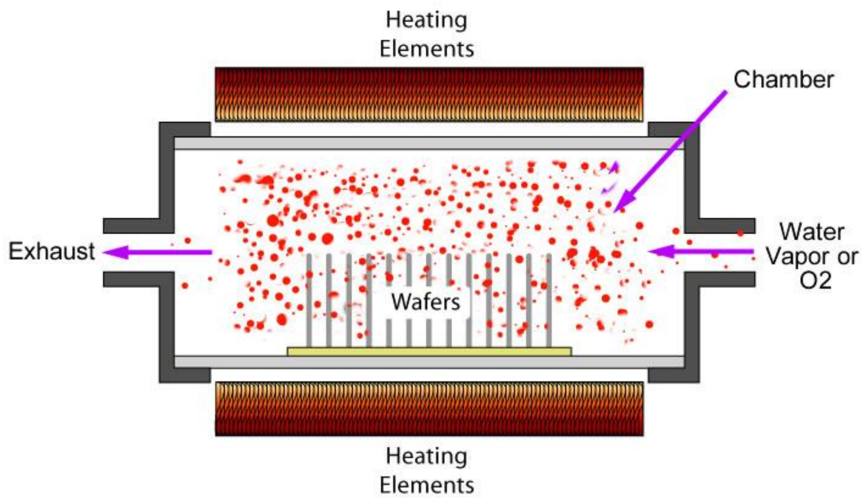


Figure 3. Schematic diagram of an oxidation furnace.

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]

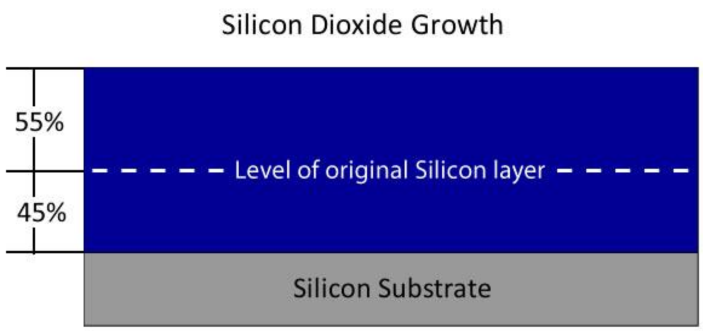
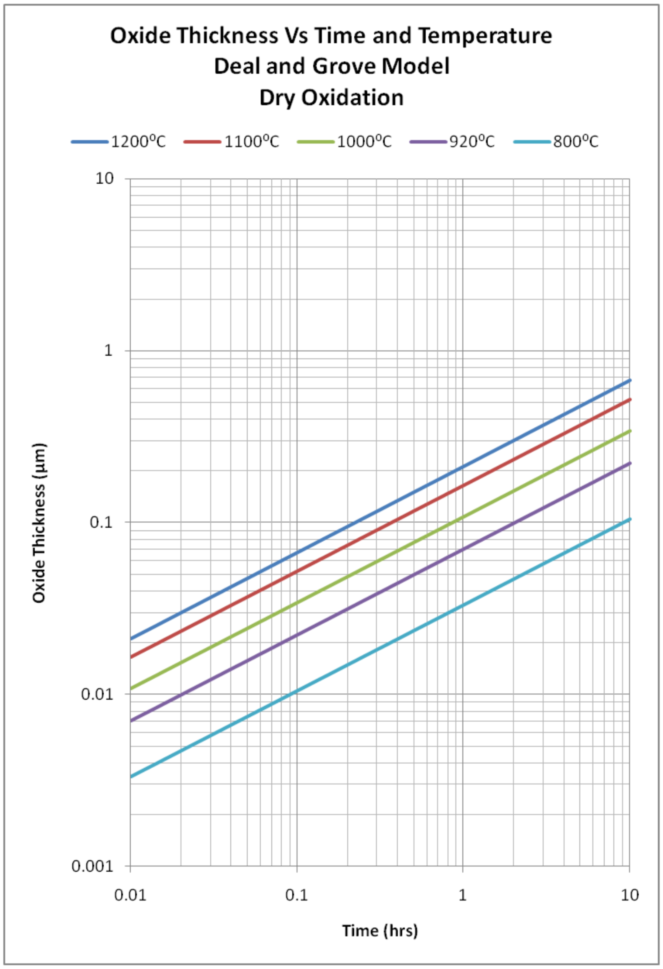


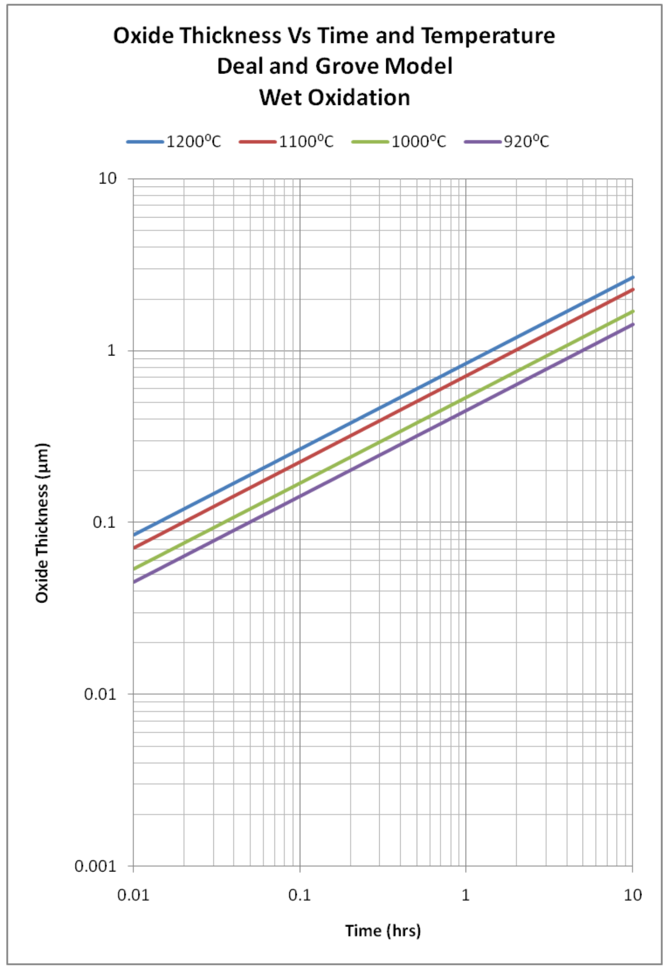
Figure 4. Cross-sectional view showing how silicon dioxide grows into the surface of the wafer surface.

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. ***(Answers in Red)***

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 <u>Oxide Thickness Color Chart</u> 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)*.

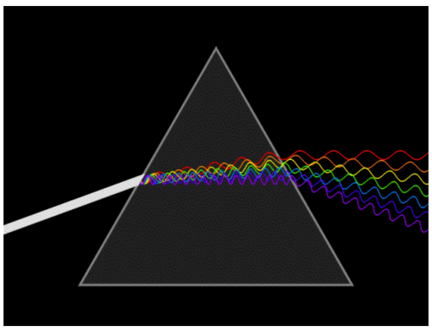


Figure 5. The dispersion of white light as it travels through a triangular prism. [Illustration is Public Domain]

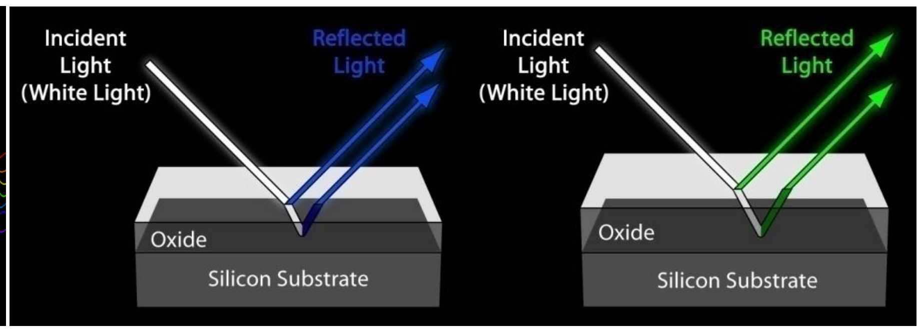


Figure 6. Two wafers with two different oxide thicknesses. The incident ray (or white light) is reflected off both the lower substrate/oxide interface surface and the top air/oxide surface. These two reflected rays of light recombine. Depending on the oxide thickness, only certain colors will constructively 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*.

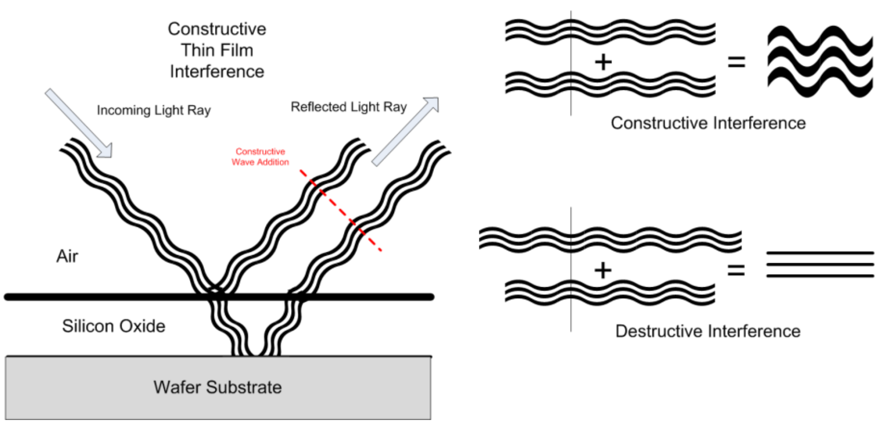


Figure 7. Constructive vs. Destructive Interference. The thin film interference effect is shown on the left for the case of constructive interference of a given wavelength of light and thickness of dioxide. The graphic on the right is a schematic representation of adding two waves which are in phase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

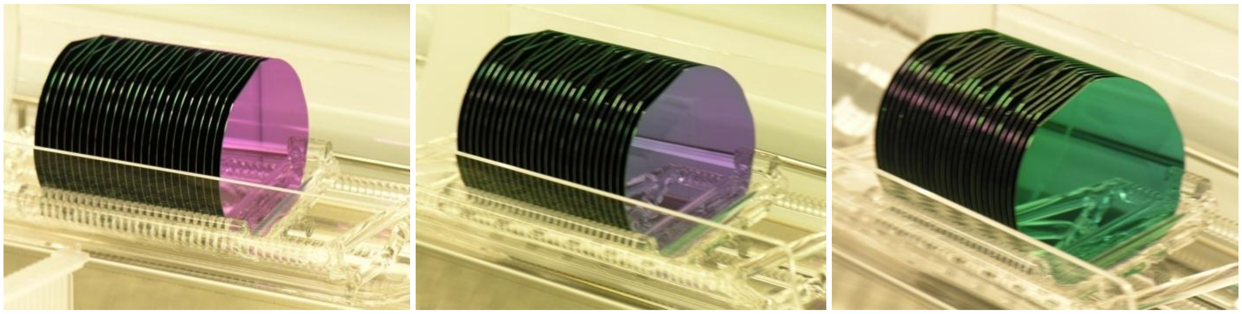


Figure 8. Three photographs taken of the same oxidized wafers at three different angles. [Photos courtesy of the University of New Mexico Manufacturing Training and Technology Center.]

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

- <u>Activity Part I</u> 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

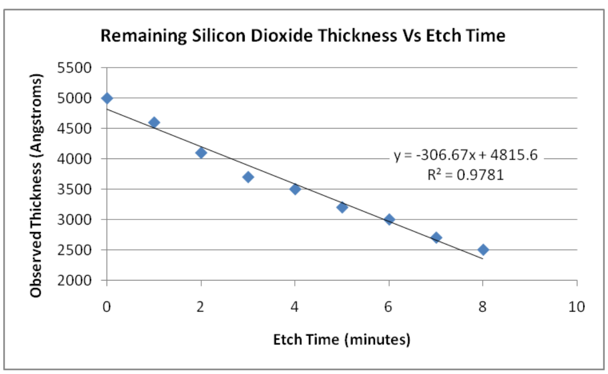
Description

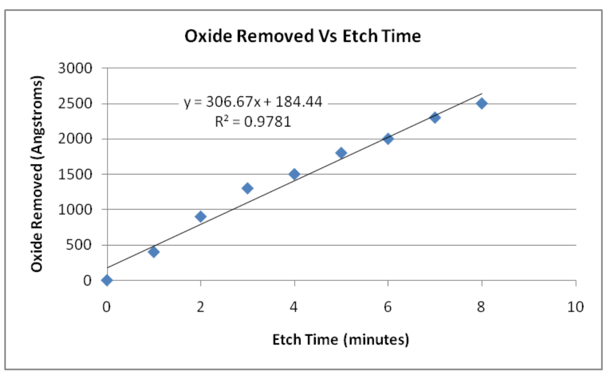
Use a Rainbow Wafer and an Oxide Thickness vs. Color Chart to determine the oxide thickness of each color on the wafer. Develop several graphs from which you can extract the average etch rate. (The etch rate is the amount of oxide etched in a given amount of time.) The average etch rate can be determined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

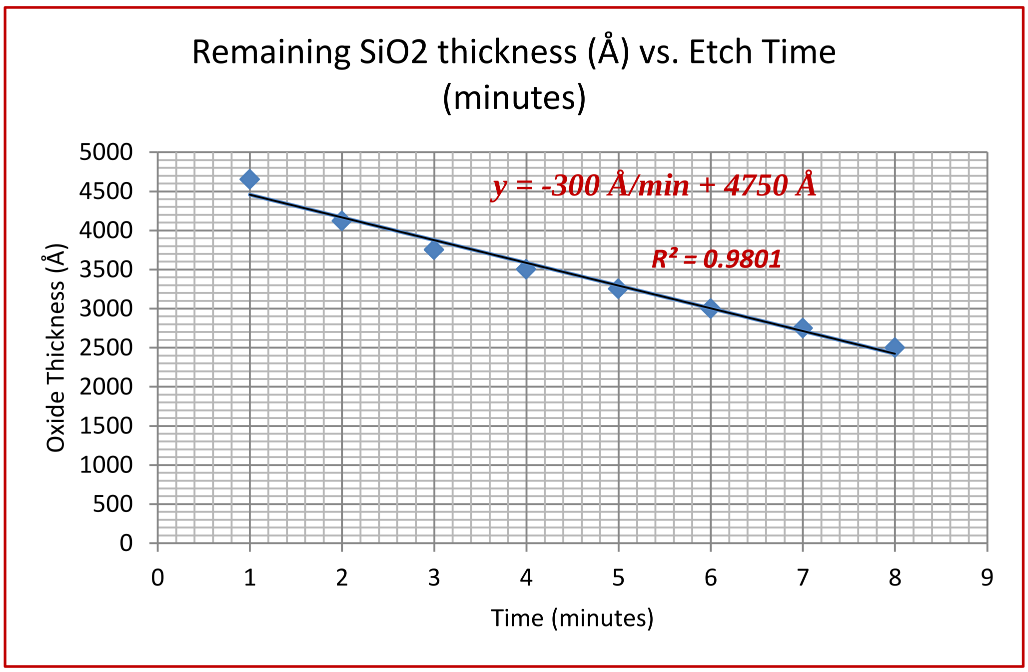
10. List three other types of thin films used in microtechnology and describe the purpose or applications of each of these thin films.

Post-Activity Questions / Answers

1. What does the slope of the line (m) represent?
   Answer: The average etch rate (amount etched over a period of time)

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?

   Answer: (Answers will vary according to how each participant interprets the oxide color at each stripe and the trend line. Therefore, the instructor needs to verify that the worksheet data and graphs support the answers. The following answers and graphs are based on the rainbow wafer photo. NOTE: To get "b" of y = mx + b, the participant will need to extend the trend line to the y-axis intercept, when x=0. What does this mean? At the x=0 point, that is when the etch time is zero. This corresponds to the starting point of the etch, i.e., the original thickness of the oxide.)
   a. Oxide thickness decreases the longer the etch. The slope of the line in the graph below is -300 Å/min. Therefore, the equation of the line is y = -300 Å/min + 4750 Å
   b. In the graph below, a negative slope indicates that the wafer is losing about 300 Angstroms of silicon dioxide every minute of etch time.



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?

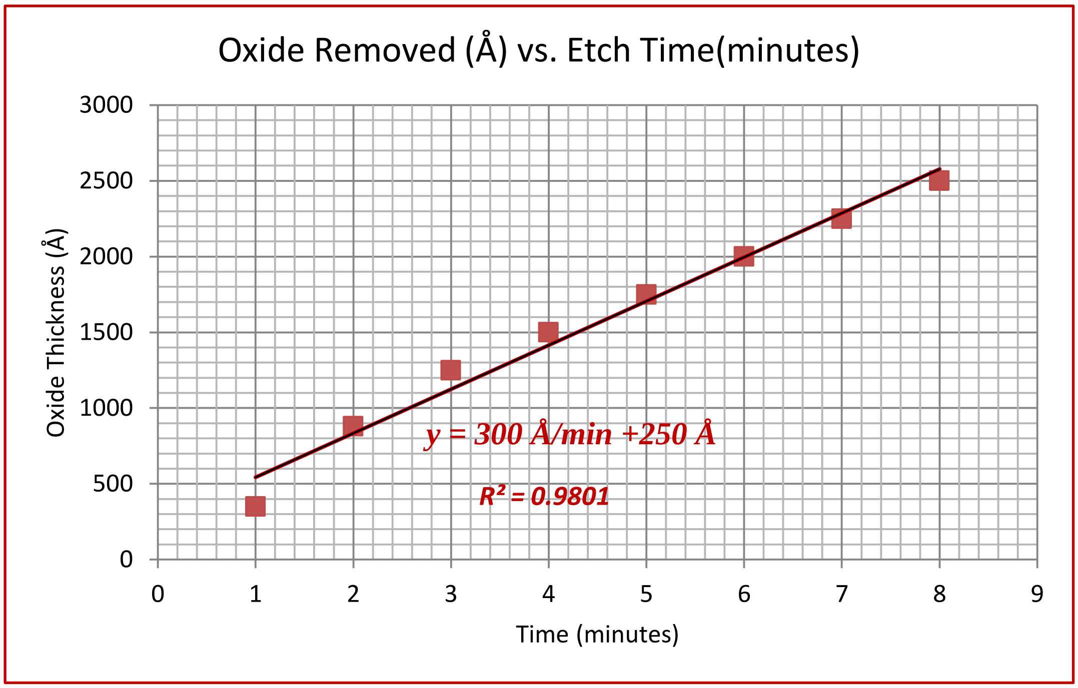
   Answer: : (Answers will vary according to how each participant interprets the oxide color at each stripe and the trend line. Therefore, the instructors needs to verify that the answers are supported by the worksheet data and graphs. The following answers and graphs are based on the rainbow

wafer photo. NOTE: To get "b" of y = mx + b, the participant will need to extend the trend line to the y-axis as mentioned in the answer above.) To get the slope, take the ratio of the amount the line rises over a given period of time (i.e., "rise-over-run"). So, for the graph below, at 1 minute, the oxide removed is about 550Å and at 8 minutes, the oxide removed is about 2600Å. So the rise is 2600Å-550Å=2050Å and the run is 8min-1min=7min. Hence, Rise/Run=slope = 2050Å/7min=293Å/min or about 300Å/min

c. ***Approximately 300 Å/min. y = 300 Å/min x +250 Å. Another way to write this is to say Oxide Removed = 300Å/min * (Etch Time)***
<u>Point of discussion, you should force the line to go through the origin in this case since you can argue that at t=0, you haven't etched anything so the amount removed must be zero! So, why did that fitted curve intercept result in 250Å at t=0?</u>

d. ***As the time of the etch increases, so does the amount of oxide removed. The slope is positive and the units are again in Angstroms per minute.***

e. ***The etch rates (slopes) of the two lines should be equal (very close) but opposite.***



4. Based on your graphs and data, how long does it take to etch 0.05 microns (μm) of oxide?
Answer: Answers will vary, but depend on the participant's graph and the answer to 3a. Using the first graph above with a slope of -300 Å/min, it would take approximately 1.67 minutes (500 Å / 300 Å/min) to etch 0.05 microns (500 Å).

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?
Answer: 500 nm = 5000 Å; therefore 5000 Å/ 300 Å/min = 16.7 minutes

6. Refer to the <u>Oxide Thickness vs. Color Chart</u>. What is the thickness(es) of a wafer that looks "yellow-green"? (You may see "yellow-green" more than once. Include all thicknesses.)
Answer: 3650 Å and 5400 Å.

7. Why do oxide colors repeat as the oxide continues to grow?
Answer: At certain thicknesses the interference of the light reflecting off the crystal silicon

substrate / oxide interface and the oxide's surface repeats itself as multiples of ½ wavelengths of the primary color. The wavelength of the light in the oxide is the wavelength of the light in air divided by the index of refraction of the oxide. Therefore, the observed color will be the same. This is true for 3650 Å and 5400 Å (yellow-green). The reason for this repetition is due to the wave-nature of light. For this example of yellow-green, the wavelength of yellow-green in air is about 5400Å. In oxide, the wavelength is about 5400Å/1.5= 3600Å, half of that is 1800Å which is very close to the difference between the 3650Å and 5400Å oxide thicknesses in the previous question.

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?
   Answer: Tools that utilize ellipsometry or interference methods.

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.)
   Answer: Color observation by a person is subjective to the opinion of the observer. One person may say something looks blue-green and another may call the same material green. The reading of color by observation is not accurate, nor is it very repeatable. Utilizing a calibrated color measurement instrument will yield a more repeatable and accurate result. However, even if you read the colors slightly different than your lab partner and graph it, the slope of the line will be very close to each other even if the exact color determination for a given stripe is not.
   Another reason for the variation in the amount of etch between stripes is that since the wafer was manually handled and timed, this could be operator error. The operator may have kept the wafer at one level for longer than or shorter than one minute.

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

Type of Thin Film	**Applications**
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

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

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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 (Instructor Key) (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	**Red Violet**	**4650 Å = 465 nm**	1 minute	**350 Å**
2	**Light Orange**	**4120 Å = 412 nm**	2 minutes	**880 Å**
3	**Green-Yellow**	**3750 Å = 375 nm**	3 minutes	**1250 Å**
4	**Green to Yellow-Green**	**3500 Å = 350 nm**	4 minutes	**1500 Å**
5	**Blue to Blue-Green**	**3250 Å = 325 nm**	5 minutes	**1750 Å**
6	**Blue to Violet-Blue**	**3000 Å = 300 nm**	6 minutes	**2000 Å**
7	**Red Violet**	**2750 Å = 275 nm**	7 minutes	**2250 Å**
8	**Orange to Melon**	**2500 Å = 250 nm**	8 minutes	**2500 Å**

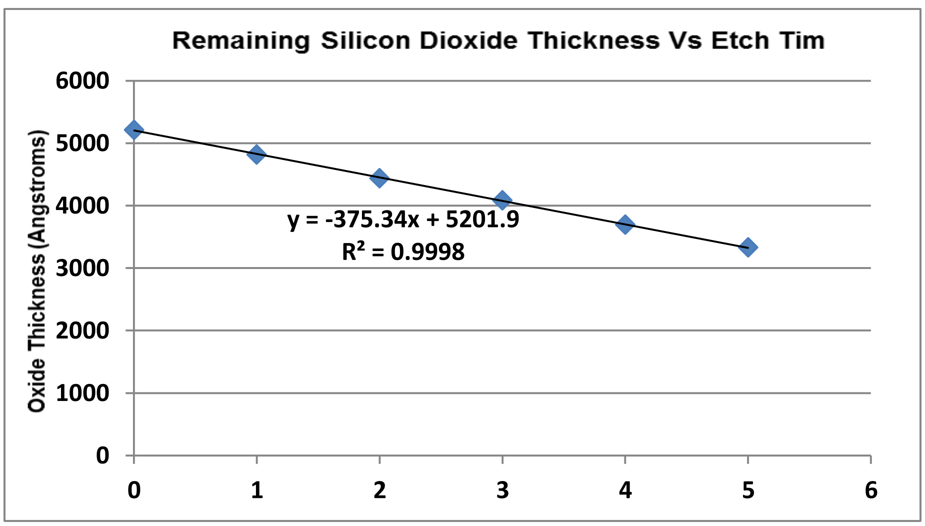
*The values in the answer key are "measured values". Participants will be using "estimated values" based on the color chart.

Rainbow Wafer Calculations Worksheet (Instructor Key) (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	**Blue Violet**	**4820**	25 seconds	**5200-4825=375A**
2	**Violet Red**	**4440**	50seconds	**750**
3	**Light Orange to Yellow**	**4084**	75seconds	**1125**
4	**Green Yellow to Yellow Green**	**3693**	100seconds	**1500**
5	**Light Green to Blue Green**	**3332**	125seconds	**1875**

*The values in the answer key are "measured values" not estimated values. Participants will be using "estimated values" based on the color chart; therefore, their **results should fall within a range around the measured value as indicated in the color column**. For example, for layer 3 the estimated thickness should be between 4120 to 3900 (Light orange to Yellow).

**This value may be different due to different batches of processed wafers. Use the chart to verify an estimation of pre-etch thicknesses.

To the right is the graph for remaining oxide thickness vs. time. Based on the equation, this system had an etch rate of ~375 angstroms / second and a starting oxide thickness estimated at ~5202 angstroms.



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

Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

Bulk Micromachining:
An Etch Process Activity

Shareable Content Object (SCO)

This SCO is part of the Learning Modules
MTTC Pressure Sensor Process and Etch Overview

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384, 0902411, 1205138.
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Bulk Micromachining: An Etch Process Activity
Instructor Guide

Notes to Instructor

The Bulk Micromachining: An Etch Process activity is an activity in the Etch Overview Learning Module and the MTTC Pressure Process Learning Module. This activity demonstrates the bulk etch process used to selectively remove substrate material. This activity should be assigned after the primary knowledge SCO on the MTTC Pressure Sensor Process.

The Etch Overview for Microsystems Learning Module consists of the following SCOs:

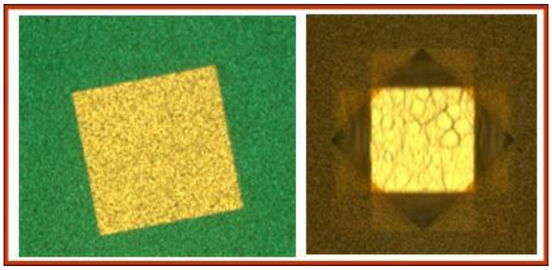
- Knowledge Probe (KP) or pre-test
- Etch Overview for Microsystems PK
- Etch Terminology Activity
- Science of Thin Films Activity (SCME Kit available)
- **Bulk Micromachining: An Etch Process Activity (SCME Kit available)**
- Final Assessment
- Final Assessment – Participant Guide

This activity requires the SCME Bulk Micromachining: An Etch Process Kit. To learn more about this kit, click here for "kit description". To order this kit, go straight to the SCME Kit store.

This activity is presented as a hand-out (Participant Guide - PG). Participants and instructors can download the most recent version of this PG from scme-nm.org. Select "Educational Materials" in the side menu.

This companion Instructor Guide (IG) contains all of the information in the PG as well as answers to the Post-Activity questions. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

Introduction



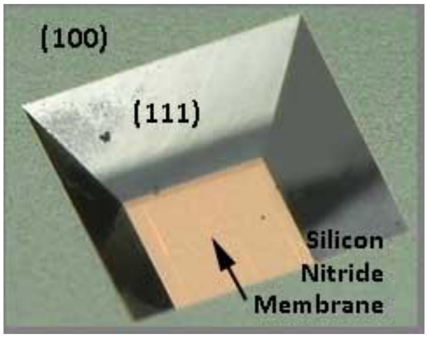
Backside of Pressure Sensor before and After Anisotropic Etch

This activity demonstrates the anisotropic etch process, which is considered a bulk micromachining process because it removes a select bulk of silicon wafer. It is the last step in a 10 step process* for making a micro pressure sensor. The micro pressure sensor design used in this process incorporates a Wheatstone bridge configuration on a silicon nitride membrane on the frontside of the chip. The backside of the chip is etched to remove a bulk of the silicon from beneath the membrane, forming a cavity. This cavity or chamber is used by the micro pressure sensor as the reference pressure chamber.

The micro pressure sensor process used at the Manufacturing Technology Training Center (MTTC) at the University of New Mexico uses KOH (potassium hydroxide) as the etchant. This activity uses a high concentration drain cleaner (sodium hydroxide), as a substitute for KOH. In this etch process wafers are submerged in a heated bath of a drain cleaner mixture. The drain cleaner is used because, like KOH, it produces an anisotropic etch with silicon by etching along the planes of the silicon.

Silicon nitride on the non-metal side (backside) of the chip acts as a hard mask on the chip. This mask leaves select areas of the silicon exposed to the drain cleaner. The exposed silicon is etched anisotropically by the drain cleaner. The etch continues until all of the exposed silicon is removed and the silicon nitride membrane on the front side of the chip is reached. KOH cannot etch silicon nitride; therefore, the etch stops when the silicon nitride layer is reached.

The image shows a backside etch. The brown indicates the silicon nitride membrane on the frontside of the chip. As you can see the backside (or silicon) has been etched to create an opening or chamber beneath the membrane. The top of the wafer is the (100) plane whiles the etched sides of the chamber are formed by the (111) plane of the silicon.



Drain Cleaner Description and Parameters

In this activity a single die from a processed wafer is submerged in drain cleaner to anisotropically etch the exposed silicon. It is very important to purchase the right kind of drain cleaner. It is highly recommended that you use 100% Sodium Hydroxide (lye) crystal drain cleaner as the etchant. The drain cleaner will be diluted during the experiment with de-ionized (DI) or distilled water. Many drain cleaners have concentrations of sodium hydroxide that are less than 100% and they contain other additives. These drain cleaners should be avoided.

It is also very important to note that this etchant will be heated and will emit toxic fumes. It will also emit hydrogen gas.

Therefore, you MUST perform this experiment under a fume hood. There should be no exceptions.

Experiment Preparation: Approximately 30 minutes
Process Time: Approximately 2.5 to 3.5 hours
Chemicals Used: 100% Sodium Hydroxide ($NaOH$) in crystal form

*The 10 step process was developed jointly by the University of New Mexico (UNM) and Central New Mexico Community College (CNMCC)

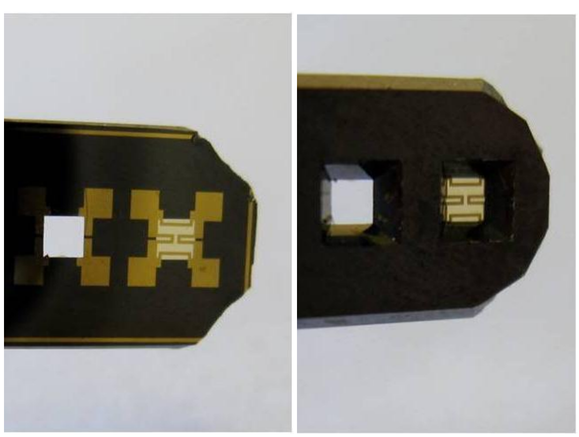
Activity Objectives and Outcomes

Activity Objectives

- Describe the process of wet anisotropic etch of silicon.
- Identify the safety requirements when performing the wet anisotropic etch process.

Activity Outcomes

Upon examination, the exposed silicon is etched anisotropically leaving a thin silicon nitride membrane on the front side of the wafer. The images below are what you should see upon completion of the etch process.



Frontside of an Individual Chip after Processing is Complete (far left) Backside of an Individual Chip after Processing is Complete (right image)

Safety

This activity uses sodium hydroxide drain cleaner. It is important to study the Material Safety Data Sheet (MSDS) prior to performing this activity and to follow safe chemical handling procedures when performing this activity. All participants should wear impervious protective clothing including shoes, gloves, and lab coat / apron. Safety goggles and/or a full face shield are required. This experiment should be performed in an area with an eye wash station and safety rinse area.

This experiment must be performed in a laboratory with a fume hood.

The following personal protective equipment (PPE) is required when performing this activity:

- Latex or nitrile gloves
- Safety goggles

Supplies/Equipment

This activity requires the SCME kit called Bulk Micromachining: An Etch Process.

Supplies provided by instructor

- Crystal Drain Cleaner – 100% Sodium Hydroxide (NaOH) or lye (can be purchased from a home improvement center)
- DI (de-ionized) or Distilled water (a gallon of distilled water can be obtained from a grocery store)
- Paper cup
- Plastic spoon
- Plastic glass
- Hotplate with thermocouple control and ceramic top (if possible)*
- Microscope
- Latex or nitrile gloves
- Safety goggles

*Sodium hydroxide does react with certain metals.

Kit supplies

- 1 Liter beaker
- 6 Pre-processed etch chip
- 1 - 6 in Teflon tubing with additional chip
- 1 Weighing Scale (with 100g weight for calibrating)
- 1 Etch Overview for Microsystems Learning Module - Instructor Guide
- 1 Etch Overview for Microsystems Learning Module – Participant Guide

Preparation/setup

Before performing this activity, put on your latex or nitrile gloves and your safety goggles. Make sure you work under a fume hood and that the work surface is well protected in case of spills.

Facility

This activity MUST be performed under a working fume hood and in a facility with an eye wash station and rinse area (e.g., safety shower).

Activity: Anisotropic Etch of Silicon

Description: Perform a wet anisotropic etch of silicon using sodium hydroxide to create a cavity on the backside of a silicon chip.

Material Safety Data Sheet (MSDS)

1. From the Internet, download the MSDS for sodium hydroxide. Study the MSDS and answer the following questions.

2. Answer the following question before proceeding with this procedure.
   a. Why is it important to wear goggles, gloves and protective clothing when working with sodium hydroxide?

      Answer: Sodium hydroxide is a corrosive and can cause severe burns on contact with the skin and can result in corneal damage or blindness with eye contact.

   b. Why is it important to perform this activity under a fume hood?

      Answer: When mixed with water, sodium hydroxide forms hydrogen gas that can be explosive and should not be inhaled.

   c. What measures should you take if sodium hydroxide comes in contact with your skin?

      Answer: Get medical aid immediately. Flush skin with plenty of water for at least 15 minutes while removing contaminated clothing / shoes. Wash clothing before reuse.

NOTE: Anytime you work with chemicals, it is your responsibility to know the chemical you are working with, know the necessary precautions, and follow ALL safety procedures (i.e., handling, personal protective clothing, first aid measures, disposal) when working with the chemical.

Note to Instructor: *Because this activity deals with a hazardous chemical (sodium hydroxide), be sure to follow the safety requirements of your institution.*

Anisotropic Etch Procedure

1. Set the hot plate to 105ºC. It takes some time for the hotplate to reach this temperature.

2. While the hotplate is heating, place the pressure sensor die in the Teflon holder. Ensure that the die is placed with the corner in the holder and the backside facing out *(as shown below).*

Pressure Sensor Die in Teflon Tubing Holder

3. Measure 600 mL of DI or distilled water into the 1 Liter beaker.

4. Place the paper cup on the scale. The scale might need to be calibrated. If so, use the instructions included with the scale to calibrate the scale.

5. Scoop enough crystal drain cleaner (NaOH) into the paper cup to measure 100 g.

6. VERY slowly add the 100 g of NaOH to the water in the 1 Liter beaker.

    - Remember, **Always Add Acid (AAA)** to water, and never the reverse. NaOH is a very strong base, but it should be treated as an acid. When NaOH is mixed with water, the reaction is highly exothermic. A large amount of heat is released. If you add water to NaOH, you initially form an extremely concentrated solution. Before you can completely add all of the water, the released heat from the NaOH and H_2O causes the solution to boil very violently, splashing concentrated NaOH out of the container! If you add the NaOH to water, the initial solution is very dilute and the small amount of heat released is not enough to vaporize and spatter it. AAA allows the heat to be released and to dissipate, preventing a violent reaction. This is the same reaction that can occur for acids and water; therefore, treat NaOH as an acid. Remember – it's also highly corrosive.

7. Once all of the NaOH has been added to the water, place the Teflon tube with die side down into the NaOH solution.

8. Swirl the Teflon tube in the solution to further dissolve the NaOH crystals.

9. Place the beaker with the solution and the Teflon tube with the die on the hotplate.

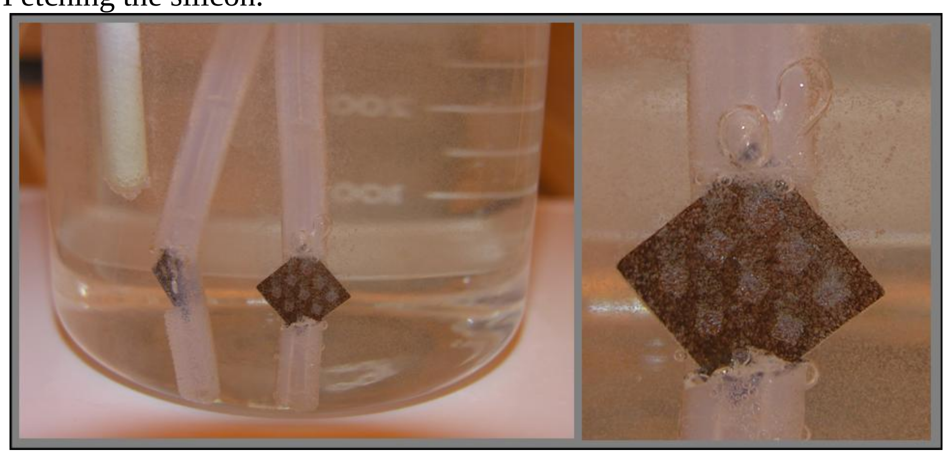
10. Insert the hotplate's thermocouple into the flask.

11. Monitor the temperature and allow the solution to come to 105ºC.

    - Even though the solution should already be hot due to the exothermic reaction between the NaOH crystals and the water, it may take some time for the solution to reach 105ºC.

12. The temperature should be monitored and should maintained at 105ºC.

13. Notice the bubbles forming as the silicon is being etched. (See image below). This is the NaOH etching the silicon.



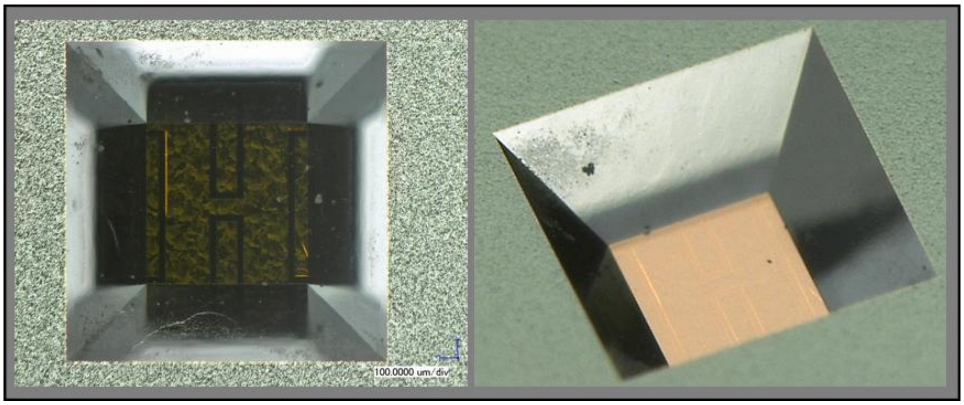
Pressure Sensor Die in KOH Solution

14. It should take between 2.5 to 3.5 hours for the bulk of the silicon on the back side of the die to be removed or etched away. You can tell the process is complete if you can see light through the holes in the die.

15. Once you can see light through the devices, carefully remove the die from the solution.

16. Pour DI or distilled water into the plastic glass. Gently rinse the die in the DI or distilled water.

17. Through a microscope, view the etch on the backside of the die.



Backside of Pressure Sensor Illustrating the Bulk Etch of the Silicon
Courtesy of Keyence

Post Activity Questions

1. What is meant by "anisotropic etch"?

2. What characteristic of silicon allows for its anisotropic etch with KOH (or NaOH)?

3. What type of micromachining process does this activity simulate (surface, bulk, or LIGA)?

4. What are the important safety procedures that must be followed when performing this experiment?

5. This process is just one type of anisotropic etching. Some anisotropic etching occurs within a plasma etcher and affects a thin film on the surface of a wafer, thus being a "surface" micromachining process. However, the process you just performed is considered a "bulk" micromachining process. Explain why.

Post Activity Questions / Answers

1. What is meant by "anisotropic etch"?
   Answer: Straight walled etch or etch that follows the crystalline structure of the silicon

2. What characteristic of silicon allows for its anisotropic etch with KOH (or NaOH)?
   Answer: The crystalline structure of the silicon

3. What type of micromachining process does this activity simulate?
   Answer: Bulk Micromachining

4. What are the important safety procedures that must be followed when performing this experiment?
   The experiment must be performed under a fume hood.
   Latex or Nitrile gloves should be worn.
   Goggles should be worn.
   Always Add Acid to water, never the reverse.

5. This process is just one type of anisotropic etching. Some anisotropic etching occurs within a plasma etcher and affects a thin film on the surface of a wafer, thus being a "surface" micromachining process. However, the process you just performed is considered a "bulk" micromachining process. Explain why.
   Answer: This is a bulk process because it removes material from within the substrate or silicon wafer.

Disclaimer

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

Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

Etch Overview Final Assessment

Shareable Content Object (SCO)

This SCO is part of the Learning Module
Etch Overview for Microsystems

Target audiences: High School, Community College, University

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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Etch Overview for Microsystems
Final Assessment

Instructor Guide

Notes to Instructor

This assessment contains twenty (20) questions to assess the participants' knowledge of the etch processes used for microsystems fabrication. This assessment should be given upon completion of the Etch Overview Learning Module. By comparing the results of this assessment with the KP, you can determine the learning that took place due to the completion of this learning module.

The Etch Overview for Microsystems Learning Module consists of the following SCOs:

- Knowledge Probe (pre-test)
- Etch Overview for Microsystems PK
- Etch Terminology Activity
- Science of Thin Films Activity (SCME Kit available)
- Bulk Micromachining: An Etch Process Activity (SCME Kit available)
- Final Assessment Multiple Choice – Participant Guide

This assessment is presented as a hand-out. The participant guide for this assessment is in the Instructor Guide (IG).

This companion Instructor Guide (IG) contains both the questions and answers for this FA. The Instructor Guide booklet contains this IG followed by the Participant Guide (PG) assessment which contains only the questions. The most recent version of the IG can be downloaded from scme-nm.org by registered users.

This learning module is now available online as a Moodle course. Contact SCME for access to this course.

Introduction

The purpose of this assessment is to determine your understanding of the etch processes used in the fabrication of microsystems.

1. For microsystems fabrication, the etch process normally follows which of the following process steps?
   a. Deposition
   b. Photolithography
   c. Oxidation
   d. DRIE

   Answer: b. photolithography

2. There are several types of layers used in the construction of microsystems. Each layer serves a purpose in the device's fabrication. Most of these layers are etched at some point during the process. What type of layer is used to define the pattern to be etched by exposing the areas in the underlying layer that are to be etched and protecting the areas that are not to be etched.
   a. Conductive
   b. Sacrificial
   c. Structural
   d. Etch stop
   e. Etch mask

   Answer: e. etch mask

3. Bulk etch processes are normally used to etch which of the following?
   a. Silicon nitride layers
   b. Silicon substrates
   c. Masking layers
   d. Metal layers

   Answer: b. silicon substrates

4. What type of thin film layer is used by the etch process to determine the depth of an etch by preventing further etching?
   a. Conductive
   b. Sacrificial
   c. Structural
   d. Etch stop
   e. Etch mask

   Answer: d. etch stop

5. What type of etch process is normally used to remove a sacrificial layer from underneath a structural layer without affecting the structural layer?
   a. Physical dry etch
   b. Chemical dry etch
   c. Chemical wet etch
   d. Reactive ion etch (RIE)

   Answer: c. chemical wet etch

6. Which of the following statements BEST describes the difference between surface etch and bulk etch?
   a. Surface etch removes only select material on the surface of the wafer while bulk etch removes material from below the wafer's surface.
   b. Surface etch removes select material from a surface layer on top of the wafer while bulk etch removes select material from within the substrate or bulk of the wafer.
   c. Surface etch removes select material from the masking layer, while bulk etch removes select material from an underlying layer.
   d. Surface etch removes select material from the topmost surface layer, while bulk etch removes select material from an underlying layer.

   Answer: b. *Surface etch removes select material from a surface layer on the wafer while bulk etch removes select material from within the substrate or bulk of the wafer.*

7. Which of the following BEST explains the primary difference between wet etch and dry etch processes?
   a. Wet etch uses a liquid etchant. Dry etch uses a gaseous etchant.
   b. Wet etch is a chemical etch. Dry etch is a physical etch.
   c. Wet etch is a chemical reaction. Dry etch is a physical reaction.
   d. Wet etch yields isotropic profiles. Dry etch yields anisotropic profiles.

   Answer: a. Wet etch uses a liquid etchant. Dry etch uses a gaseous etchant.

8. A wet etch using KOH (potassium hydroxide) is to the silicon substrate as
   a. sandblasting is to patterned glass.
   b. sandpaper is to the surface of wood.
   c. flowing water is to the mud of a river bank.
   d. moisture and heat are to exposed iron.

   Answer: c. flowing water is to the mud of a river bank

9. Surface etch processes are normally NOT used to etch which of the following?
   a. Silicon nitride layers
   b. Silicon substrates
   c. Silicon dioxide layers
   d. Metal layers

   Answer: b. silicon substrates

10. KOH or potassium hydroxide etching is a wet etch process used to ___________________

remove silicon. This type of micromachining etch is referred to as a _________ etch.

a. Isotropically, surface
b. Isotropically, bulk
c. Anisotropically, surface
d. Anisotropically, bulk

Answer: d. anisotropically, bulk

11. A plasma is a soup of particles consisting of electrons, positive ions and radicals. During a plasma etch ______________________ are used to physically etch the wafer by striking the wafer with a high acceleration causing a sputtering of surface molecules.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and free radicals
    e. Electrons and free radicals

    Answer: b. positive ions

12. During a plasma etch, ____________________ are adsorbed on the surface and chemically react with surface atoms or molecules creating volatile particles that are removed from the wafer's surface.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and radicals
    e. Electrons and radicals

    Answer: c. free radicals

13. Which of the following does NOT apply to an anisotropic etch profile?
    a. A straight wall profile
    b. Produced by a physical etch process
    c. Produced by a selective wet etch process
    d. High aspect ratios can exist
    e. Shows undercutting below the mask

    Answer: e. shows undercutting below the mask

14. Which of the following statements is always TRUE?
    a. Wet etch produces an anisotropic profile.
    b. Dry etch produces an isotropic profile.
    c. Dry etch is used to etch silicon substrates.
    d. RIE uses both chemical and physical dry etching.
    e. Chemical wet etch is used to strip masking layers.

    Answer: d. RIE uses both chemical and physical dry etching

15. During a RIE process the RF power level and the process pressure are varied to process the desired etch. In order to increase the amount of physical etch within the process the RF power would be ______________________ and/or the process pressure would be _________.
    a. Increased, increased
    b. Decreased, increased
    c. Increased, decreased
    d. Decreased, decreased

    Answer: c. increased, decreased

16. What type of dry etch is normally used to fabricate cavities and deep trenches with high aspect ratios?
    a. RIE
    b. DRIE
    c. Ion Milling
    d. KOH

    Answer: b. DRIE

17. Which of the following statements BEST defines "etch rate"?
    a. The rate at which a film is removed from the wafer's substrate during an etching process.
    b. The rate at which a film is deposited on a wafer's surface.
    c. The amount of time it takes to remove a specific thickness of film.
    d. The amount of film removed in a given amount of time.

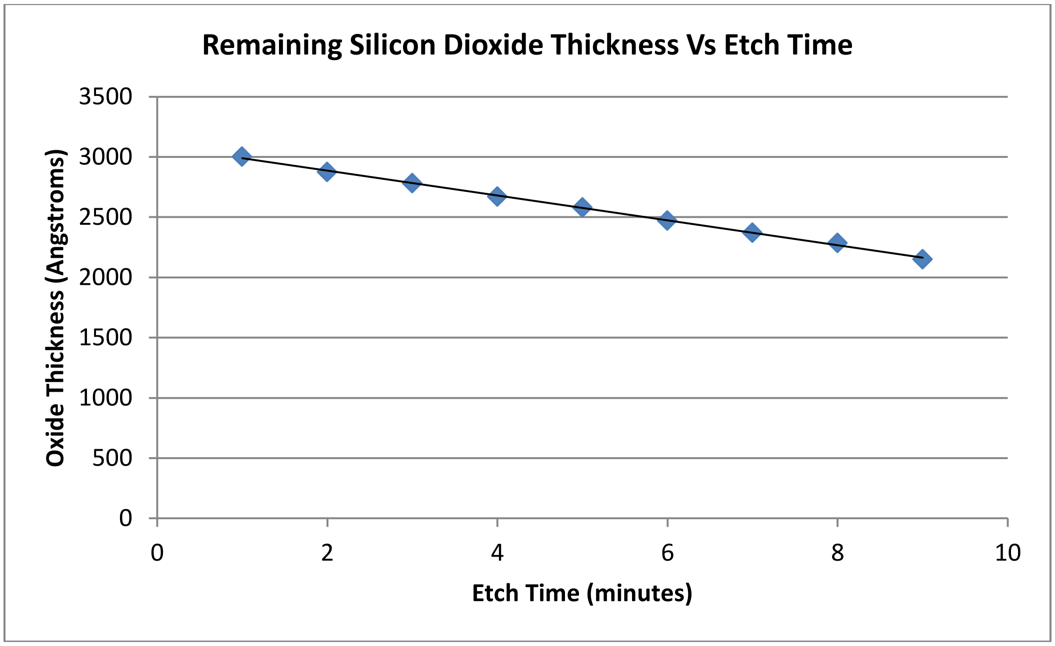
    Answer: d. the amount of film removed in a given amount of time

18. The process parameter that compares the etch rate of the material to be etched to the etch rate of the material that is not to be etched is called ________________.
    a. Aspect ratio
    b. Directional control
    c. Selectivity
    d. Etchant comparison

    Answer: c. selectivity

19. What is the approximate etch rate of the following process?

   a. 50 angstroms / minute
   b. 100 angstroms / minute
   c. 150 angstroms / minute
   d. 200 angstroms / minute



Answer: b. 100 angstroms / minute

20. An etch process is defined by the equation "y = 103x + 90 Å. What does the 103 and 90 represent, respectively?

   a. Etch rate and starting film thickness
   b. Etch rate and total thickness etched
   c. Starting film thickness and etch rate
   d. Total thickness etched and etch rate.

Answer: a. etch rate and starting film thickness

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

Etch Overview for Microsystems
Final Assessment

Participant Guide

The purpose of this assessment is to determine your understanding of the etch processes used in the fabrication of microsystems. There are 20 questions.

1. For microsystems fabrication, the etch process normally follows which of the following process steps?
    a. Deposition
    b. Photolithography
    c. Oxidation
    d. DRIE

2. There are several types of layers used in the construction of microsystems. Each layer serves a purpose in the device's fabrication. Most of these layers are etched at some point during the process. What type of layer is used to define the pattern to be etched by exposing the areas in the underlying layer that are to be etched and protecting the areas that are not to be etched.
    a. Conductive
    b. Sacrificial
    c. Structural
    d. Etch stop
    e. Etch mask

3. Bulk etch processes are normally used to etch which of the following?
    a. Silicon nitride layers
    b. Silicon substrates
    c. Masking layers
    d. Metal layers

4. What type of thin film layer is used by the etch process to determine the depth of an etch by preventing further etching?
    a. Conductive
    b. Sacrificial
    c. Structural
    d. Etch stop
    e. Etch mask

5. What type of etch process is normally used to remove a sacrificial layer from underneath a structural layer without affecting the structural layer?
   a. Physical dry etch
   b. Chemical dry etch
   c. Chemical wet etch
   d. Reactive ion etch (RIE)

6. Which of the following statements BEST describes the difference between surface etch and bulk etch?
   a. Surface etch removes only select material on the surface of the wafer while bulk etch removes material from below the wafer's surface.
   b. Surface etch removes select material from a surface layer on top of the wafer while bulk etch removes select material from within the substrate or bulk of the wafer.
   c. Surface etch removes select material from the masking layer, while bulk etch removes select material from an underlying layer.
   d. Surface etch removes select material from the topmost surface layer, while bulk etch removes select material from an underlying layer.

7. Which of the following BEST explains the primary difference between wet etch and dry etch processes?
   a. Wet etch uses a liquid etchant. Dry etch uses a gaseous etchant.
   b. Wet etch is a chemical etch. Dry etch is a physical etch.
   c. Wet etch is a chemical reaction. Dry etch is a physical reaction.
   d. Wet etch yields isotropic profiles. Dry etch yields anisotropic profiles.

8. A wet etch using KOH (potassium hydroxide) is to the silicon substrate as
   a. sandblasting is to patterned glass.
   b. sandpaper is to the surface of wood.
   c. flowing water is to the mud of a river bank.
   d. moisture and heat are to exposed iron.

9. Surface etch processes are normally NOT used to etch which of the following?
   a. Silicon nitride layers
   b. Silicon substrates
   c. Silicon dioxide layers
   d. Metal layers

10. KOH or potassium hydroxide etching is a wet etch process used to ___________________ remove silicon. This type of micromachining etch is referred to as a __________ etch.
   a. Isotropically, surface
   b. Isotropically, bulk
   c. Anisotropically, surface
   d. Anisotropically, bulk

11. A plasma is a soup of particles consisting of electrons, positive ions and radicals. During a plasma etch ______________________ are used to physically etch the wafer by striking the wafer with a high acceleration causing a sputtering of surface molecules.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and free radicals
    e. Electrons and free radicals

12. During a plasma etch, ____________________ are adsorbed on the surface and chemically react with surface atoms or molecules creating volatile particles that are removed from the wafer's surface.
    a. Electrons
    b. Positive ions
    c. Free radicals
    d. Positive ions and radicals
    e. Electrons and radicals

13. Which of the following does NOT apply to an anisotropic etch profile?
    a. A straight wall profile
    b. Produced by a physical etch process
    c. Produced by a selective wet etch process
    d. High aspect ratios can exist
    e. Shows undercutting below the mask

14. Which of the following statements is always TRUE?
    a. Wet etch produces an anisotropic profile.
    b. Dry etch produces an isotropic profile.
    c. Dry etch is used to etch silicon substrates.
    d. RIE uses both chemical and physical dry etching.
    e. Chemical wet etch is used to strip masking layers.

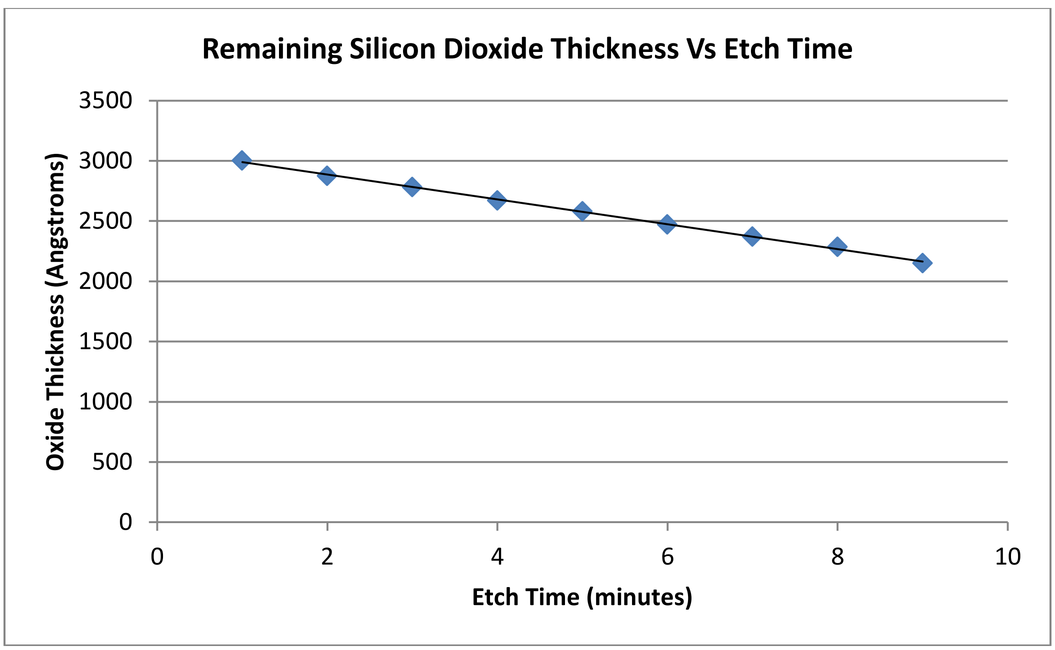
15. During a RIE process the RF power level and the process pressure are varied to process the desired etch. In order to increase the amount of physical etch within the process the RF power would be ______________________ and/or the process pressure would be _________.
    a. Increased, increased
    b. Decreased, increased
    c. Increased, decreased
    d. Decreased, decreased

16. What type of dry etch is normally used to fabricate cavities and deep trenches with high aspect ratios?
    a. RIE
    b. DRIE
    c. Ion Milling
    d. KOH

17. Which of the following statements BEST defines "etch rate"?
    a. The rate at which a film is removed from the wafer's substrate during an etching process.
    b. The rate at which a film is deposited on a wafer's surface.
    c. The amount of time it takes to remove a specific thickness of film.
    d. The amount of film removed in a given amount of time.

18. The process parameter that compares the etch rate of the material to be etched to the etch rate of the material that is not to be etched is called ________________.
    a. Aspect ratio
    b. Directional control
    c. Selectivity
    d. Etchant comparison

19. What is the approximate etch rate of the following process?
    a. 50 angstroms / minute
    b. 100 angstroms / minute
    c. 150 angstroms / minute
    d. 200 angstroms / minute



20. An etch process is defined by the equation "y = 103x + 90 Å. What does the 103 and 90 represent, respectively?
    a. Etch rate and starting film thickness
    b. Etch rate and total thickness etched
    c. Starting film thickness and etch rate
    d. Total thickness etched and etch rate.

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