
Etch Overview for Microsystems

Primary Knowledge Participant Guide

Description and Estimated Time to Complete

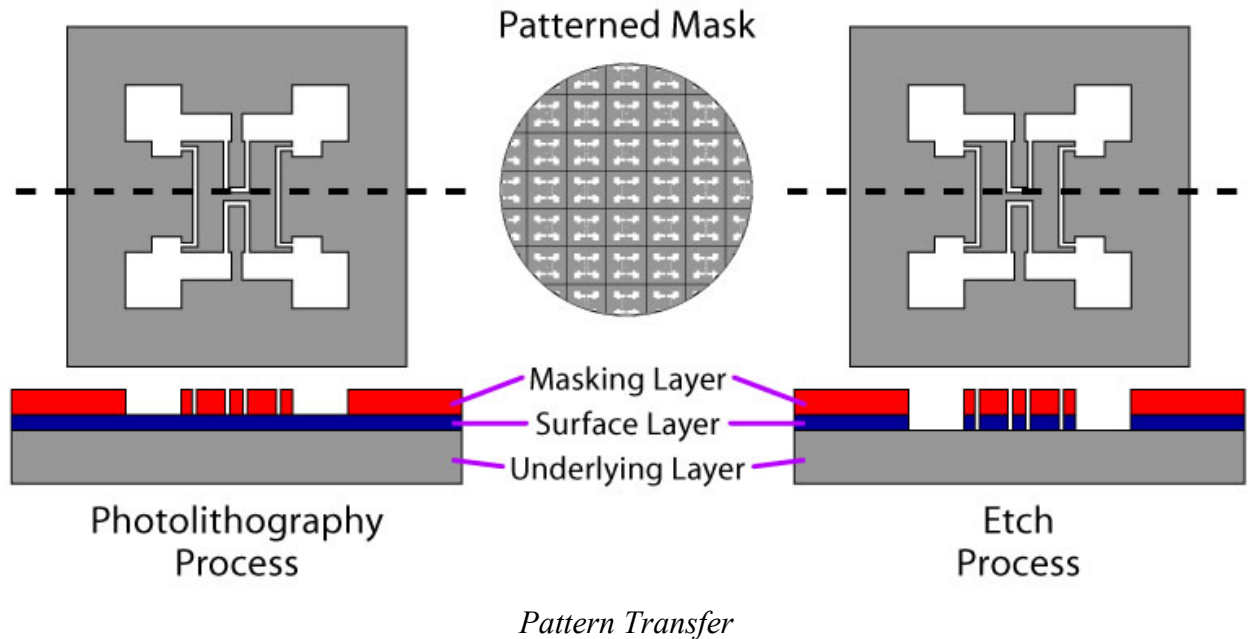
This Learning Module introduces the most common etch processes used in the fabrication of microsystems. Activities allow you to demonstrate your understanding of the terminology and basic concepts of these processes.

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



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

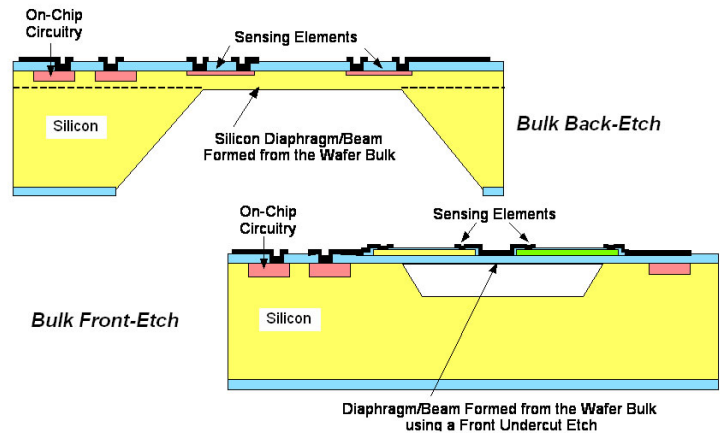
- the wafer's surface,
- below the wafer's surface, or
- from within the substrate.

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).

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.



[Graphic courtesy of Khalil Najafi, University of Michigan]

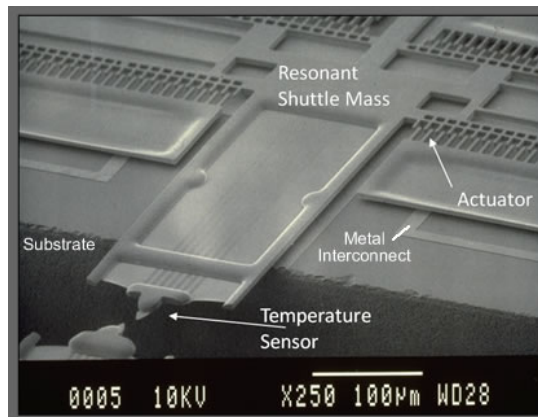
Objectives

- 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]*

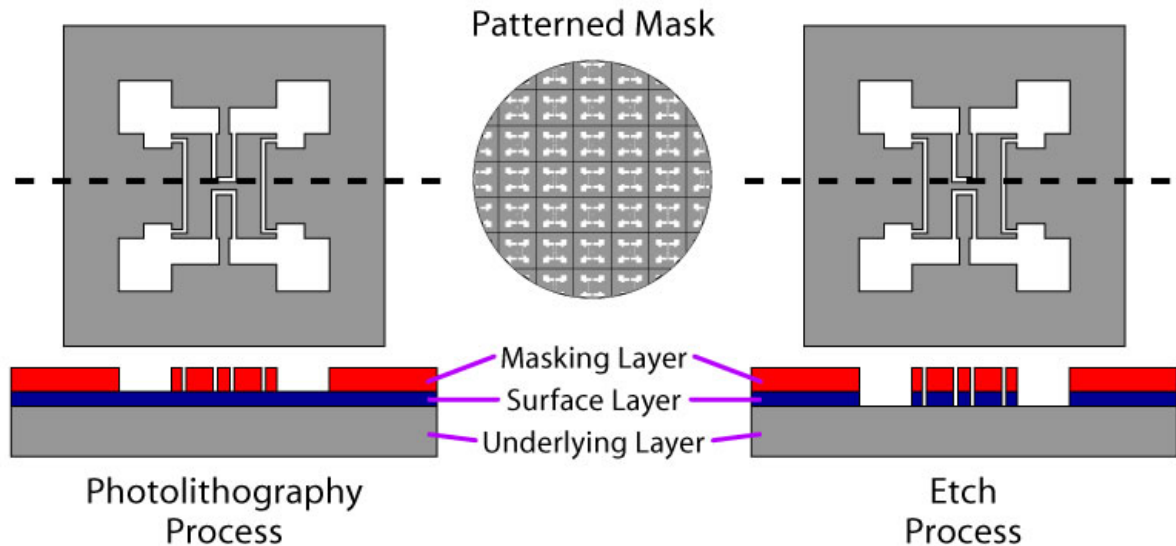
Microsystems are three-dimensional devices consisting of several thin layers of materials. Each layer is designed to serve a specific role in the system's functionality. A layer may be used as

- 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

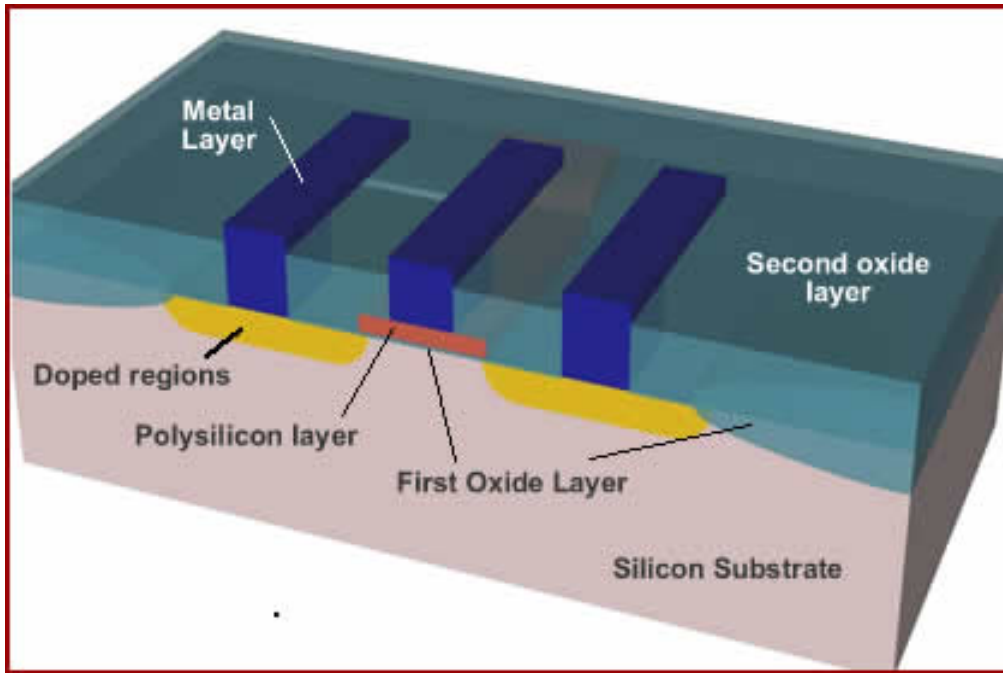
When building the electronics for a microsystem and for outlining mechanical components, the goal of the etch process is the same as that for building integrated circuits:

- 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.

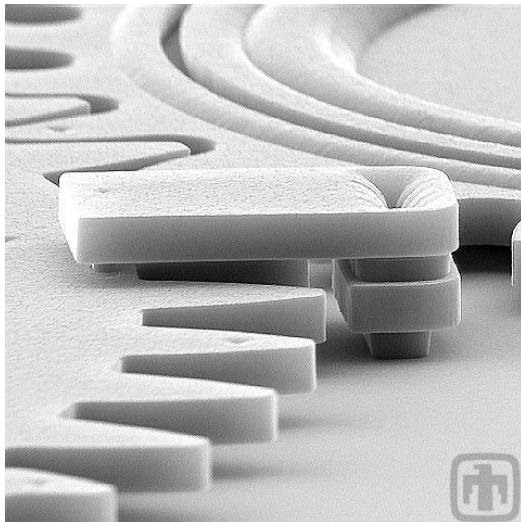
1. The first layer is the silicon substrate.
2. A layer of insulating oxide is deposited on the substrate and openings are etched for the doped regions.
3. A polysilicon layer is deposited and then etched to leave just a small portion for the transistor gate.
4. A second oxide layer is deposited and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

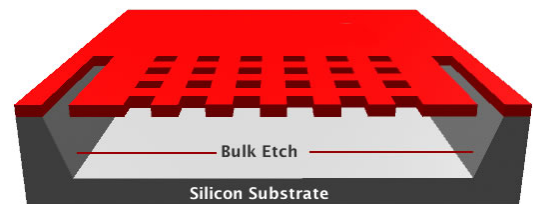
In the construction of a micromechanical part, different components of a structure, such as a rotating gear, are built up layer by layer. Space between parts and layers are created using sacrificial materials which are later removed. This is similar to building scaffolds to hold up a structure during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



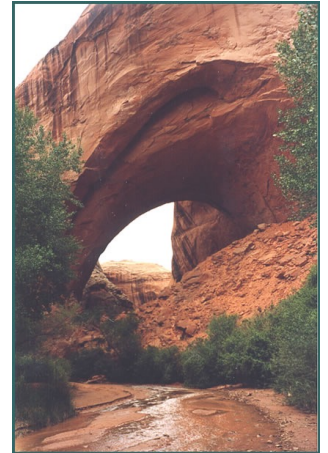
The above image shows a bulk etch that was used to create an opening under a perforated membrane. This process is called Bulk Micromachining.

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]*



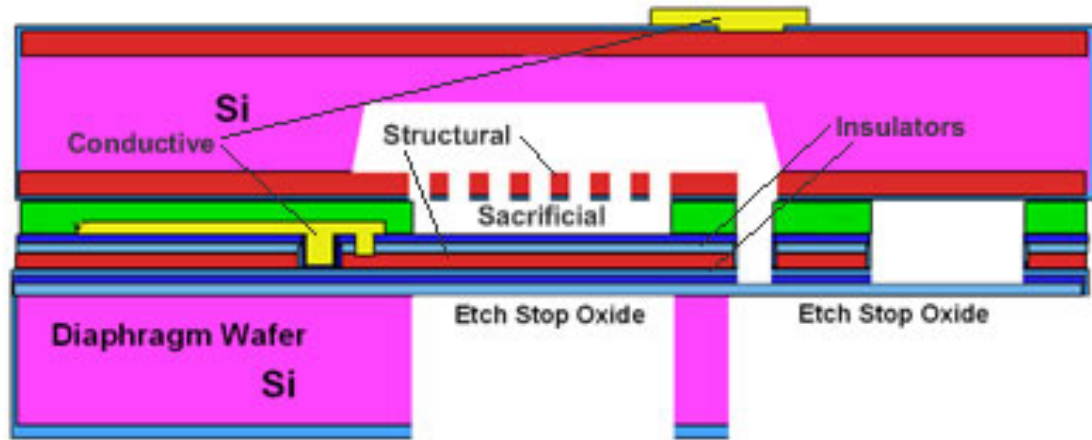
Mt. Rushmore, South Dakota



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 and Etch Process

Just as different materials are selected for their functional properties in creating the various layers of MEMS, different chemicals and processes 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.

Etching is accomplished though either a wet or dry process. 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 SF ₆ :O ₂ good for trenching XeF ₂ (Xenon Difluoride) Bromine/Fluorine
SiO ₂ , Si ₃ N ₄	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)

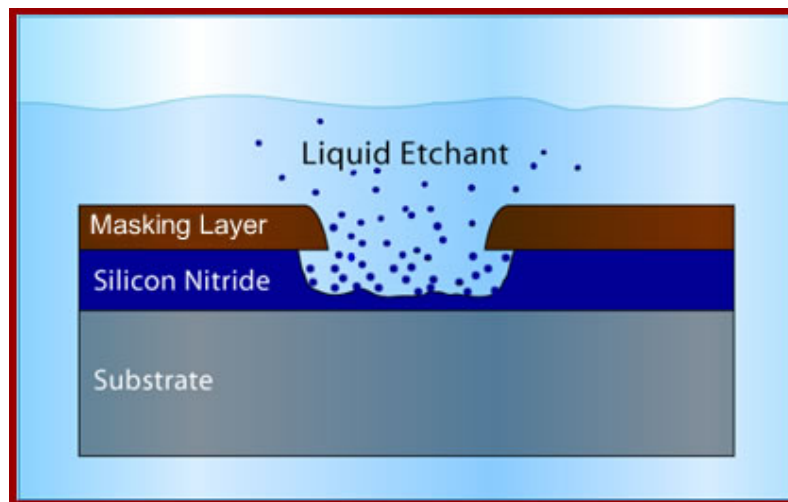
Selectivity – The property of the etchant which permits it to selectively etch specific materials at a faster etch rate than other materials on the wafer. Selectivity is the ratio defined by the following:

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

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.

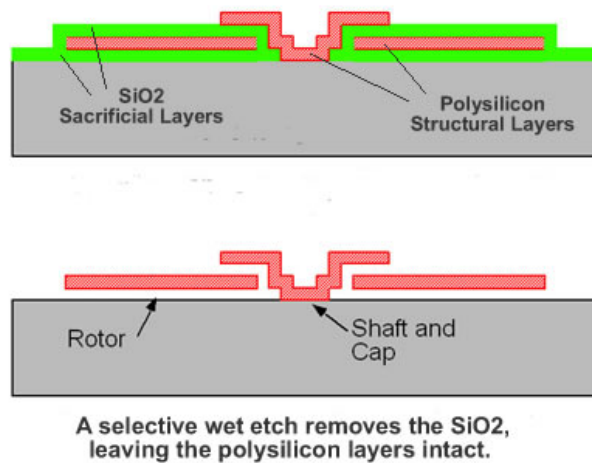
Wet Etch



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.

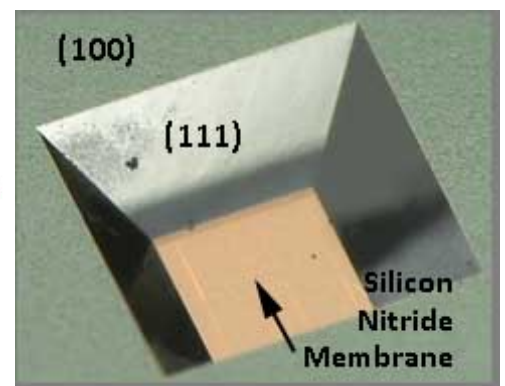
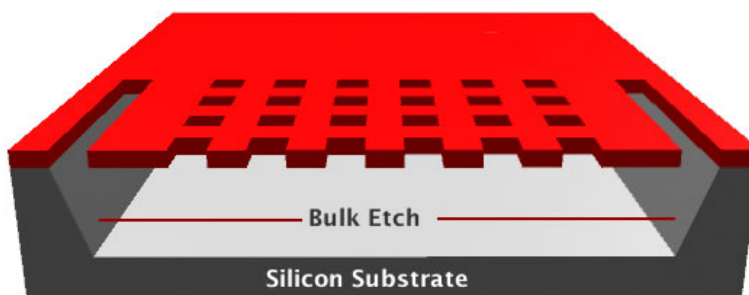
Wet Etch – isotropic or anisotropic?



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 silicon, 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.

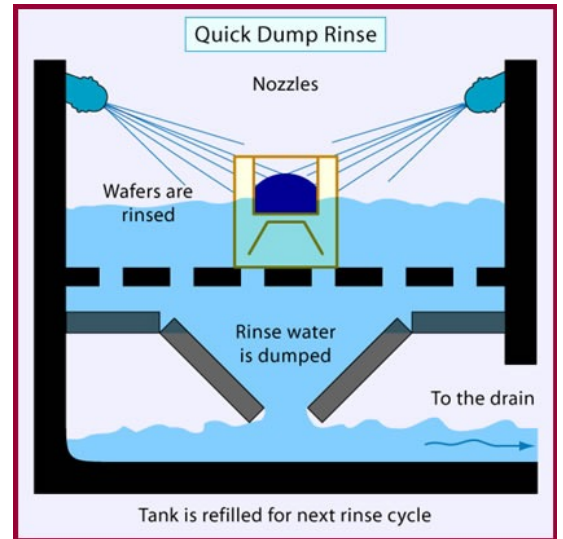
- Wafers to be etched are placed in a wafer carrier, also known as a "boat".
- The carrier is lowered into the tank containing the heated etchant solution.
- The wafers are left in the solution for a calculated amount of time.

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.

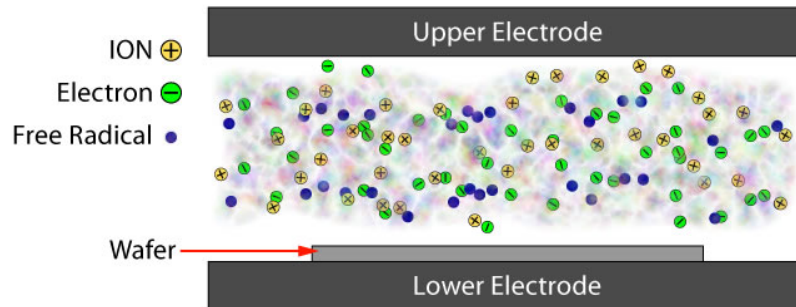
Typically, the wafers are placed in a Spin Rinse Dryer (SRD) (*see photo*) where they are rinsed and dried. The SRD's operation is similar to a centrifuge. The wafer carrier is placed in the machine and rotated while being rinsed with deionized water. After the rinse, the water is turned off. The carrier 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.

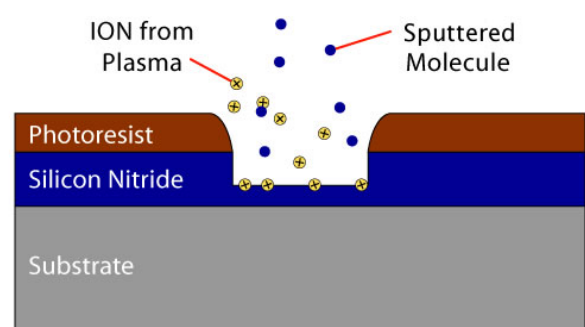
Dry Etch

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*).

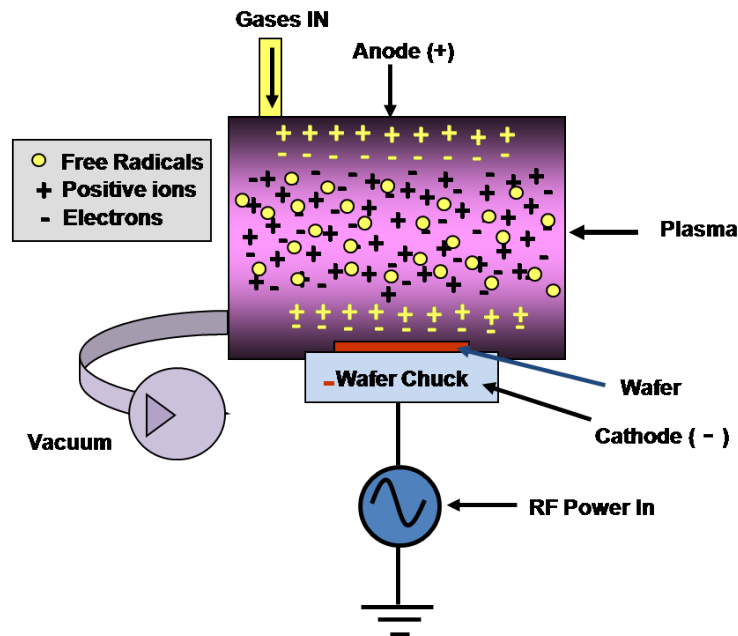


Physical Etch - Ion Bombardment causing molecules to sputter off the exposed surface.

A type of Physical Etch

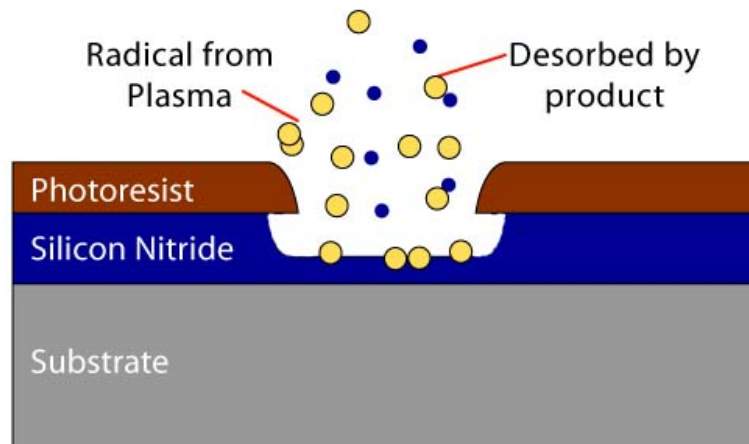
This type of etching is similar to sand-blasting where high velocity sand is used to chip away at an exposed surface. In sand-blasting a picture is formed on a sheet of glass using a strong protective material. This material will stand up to being blasted with high velocity sand particles. The unprotected 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.

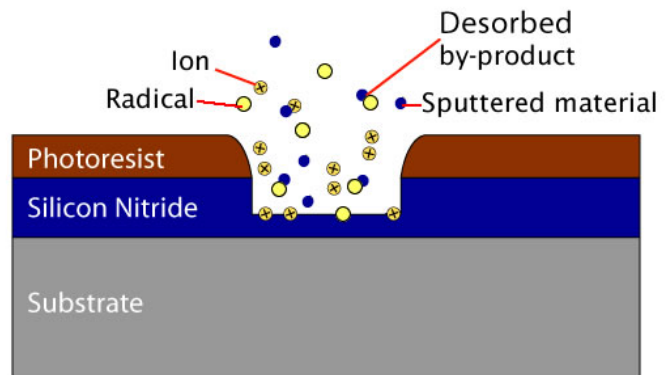
Dry Etch Process Parameters

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 levels.

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.



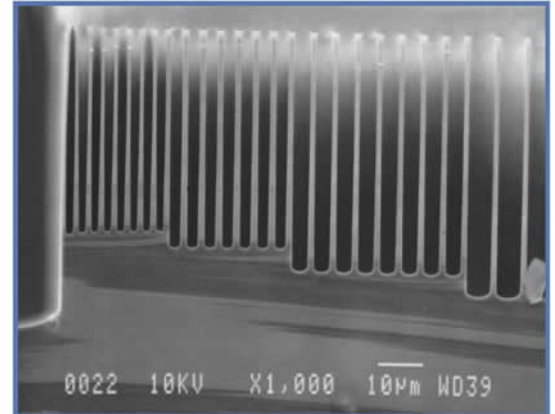
RIE uses both radicals and ions during the etch process

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

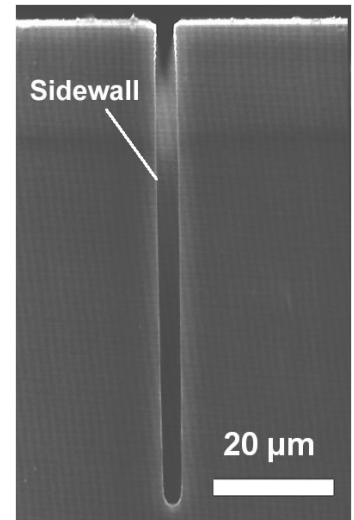
A special subclass of RIE is deep RIE (DRIE). Deep reactive ion etching is used to etch deep cavities (or trenches) in substrates with relatively high aspect ratios (the ratio of a cavity's depth to its width). These cavities can be hundreds of micrometers deep while only a few micrometers wide. Aspect 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]*

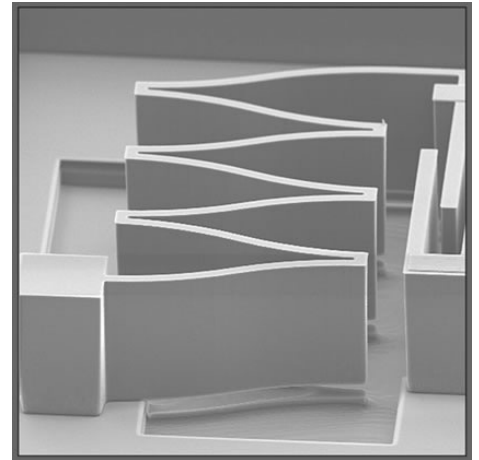
Most systems utilize the so-called "Bosch process" or "switched etching process", in which a polymer is used to passivate the etching of the sidewalls. This passivation protects the sidewalls from being etched further but not the horizontal surfaces. During the entire etching process, the gas mixture 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

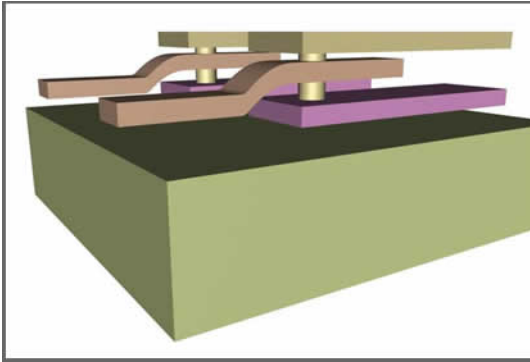
In microsystems fabrication, etch processes are used to remove bulk material from within a substrate, selectively remove material from within thin film layers, and define structures in layers above and below other thin film layers.

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?

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 or 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.

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