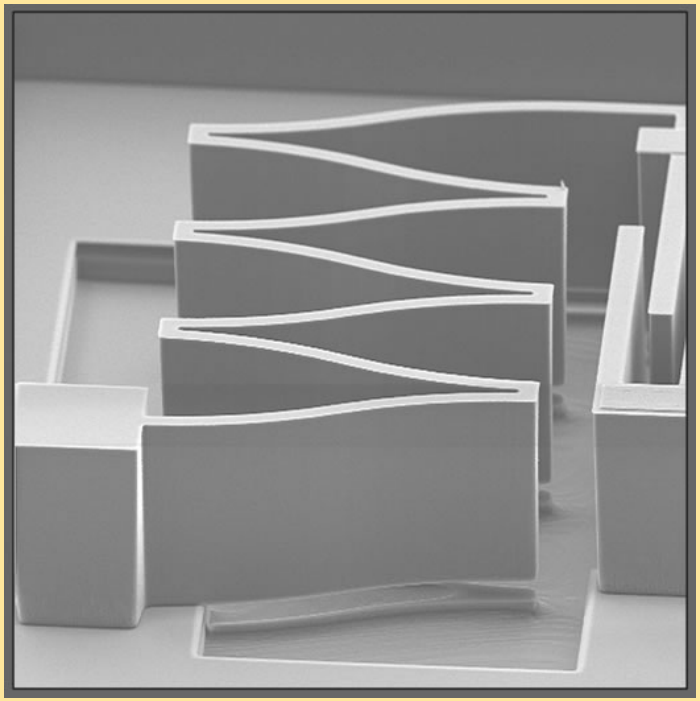
ETCH OVERVIEW FOR MICROSYSTEMS



MEMS Leaf Spring - expands and contracts above the substrate [Graphics courtesy of Khalil Najafi, University of Michigan]

Unit Overview

This unit is an overview of the wet and dry etch processes, the various thin films that are etched in the construction of microsystems, and the etchants (chemicals) used.

Objectives

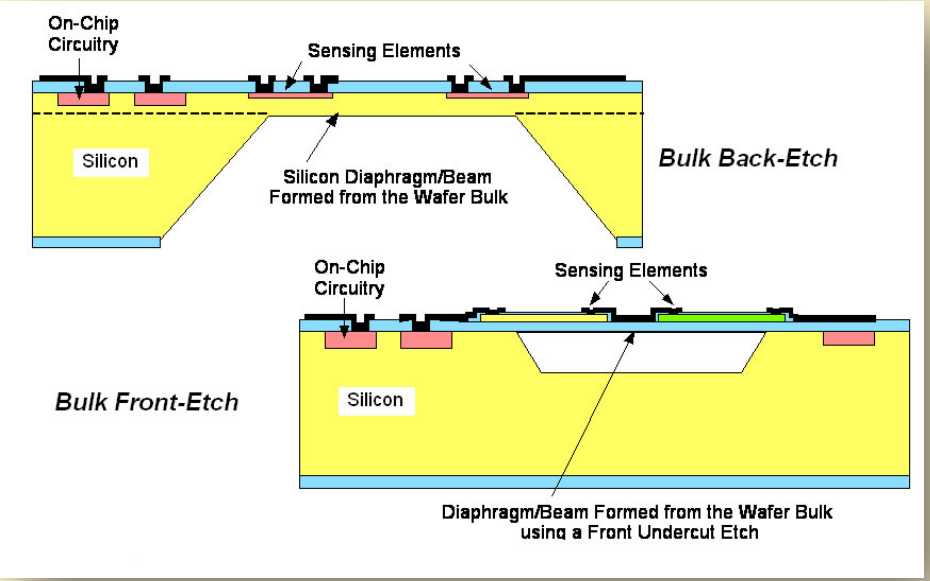
- Match microsystem components to the type of etch required to fabricate each component.
- Identify the differences between wet and dry etch.

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.

A combination of these etch processes allows for the construction of electronic (on-chip circuitry) and mechanical devices (diaphragm / beam) on the same microchip.



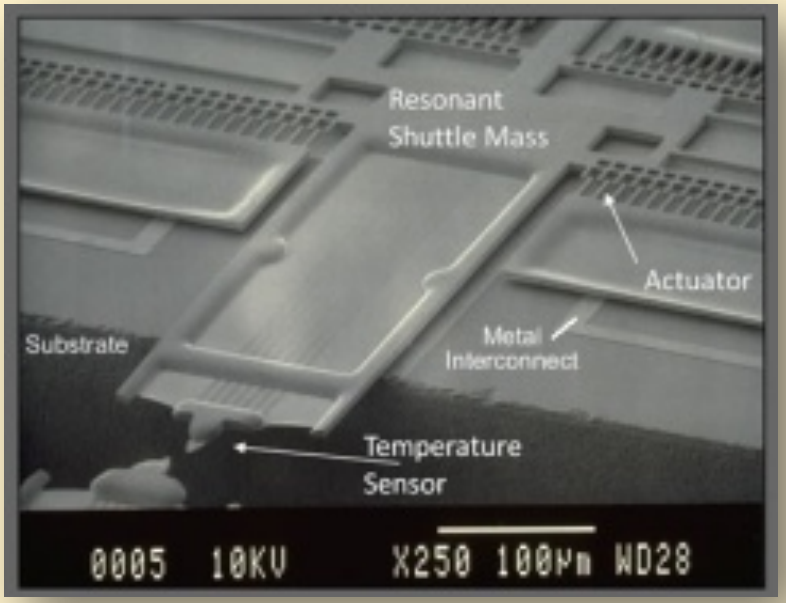
[Graphic courtesy of Khalil Najafi, University of Michigan]

The Etch Process for Microsystems

Microsystems are 3-D devices consisting of several thin layers of materials.

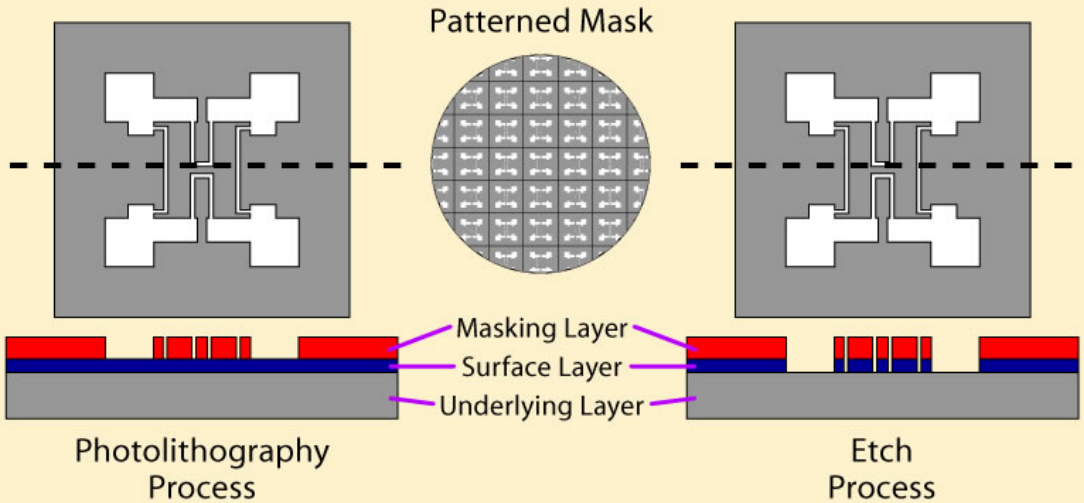
A layer may be used as

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



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

Surface Etch



Surface etch for microsystems is the same as for integrated circuits:

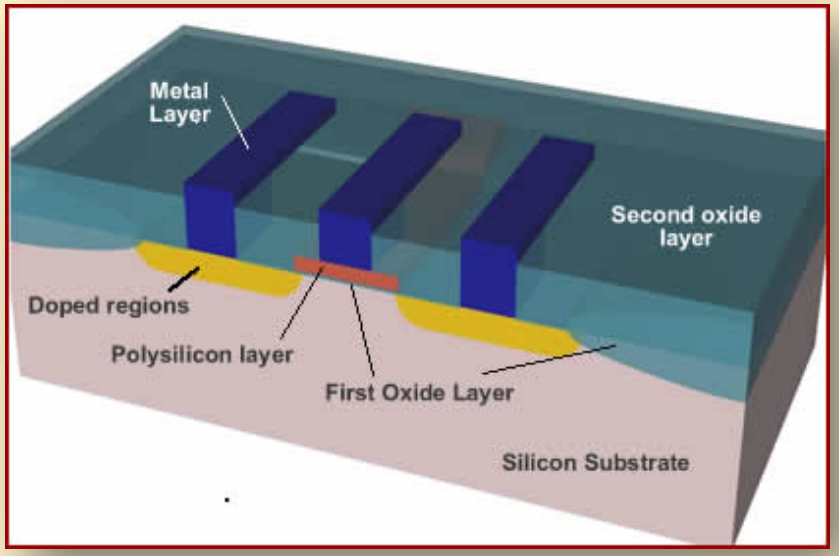
- *Remove selected regions on one layer (the surface layer) of the wafer to create either a structural pattern or to expose an underlying layer of a different material.*

For integrated circuits the underlying layer is for conductive interconnects. For mechanical components, the surface layer is patterned with specific shapes for structural components such as cantilevers, mirrors, or probes.

Transistor Etching

This graphic illustrates five etched layers:

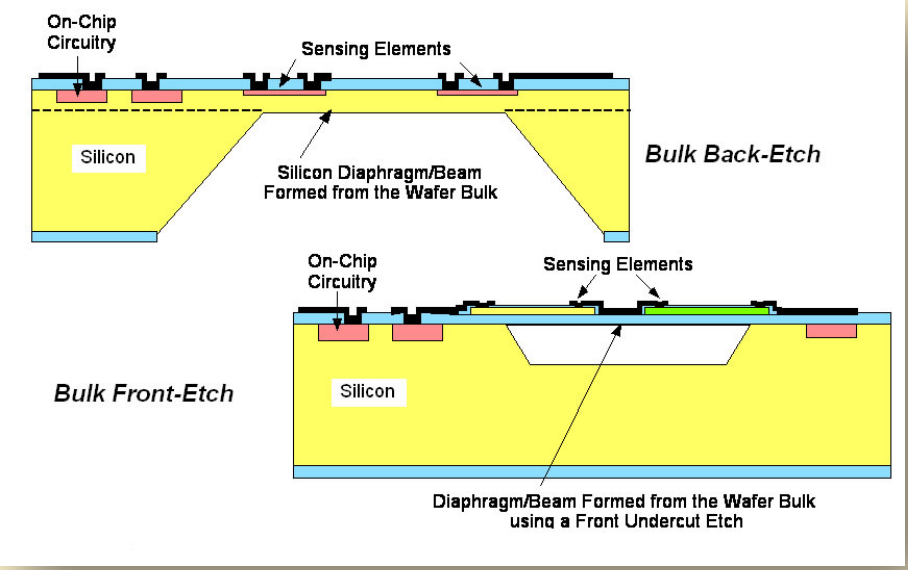
- Silicon substrate
- Insulating oxide or first oxide layer (openings are etched for the doped regions)
- Polysilicon layer (etched to leave just a small portion for the transistor gate)
- Second oxide layer (etched to provide openings for metal contacts to the doped regions and gate)
- Metal layer (etched to form the surface contacts)



Etched layers of a transistor

Bulk Etch

In microsystems fabrication, the etch process is also used to remove material from underneath the mask or from the backside of the wafer.

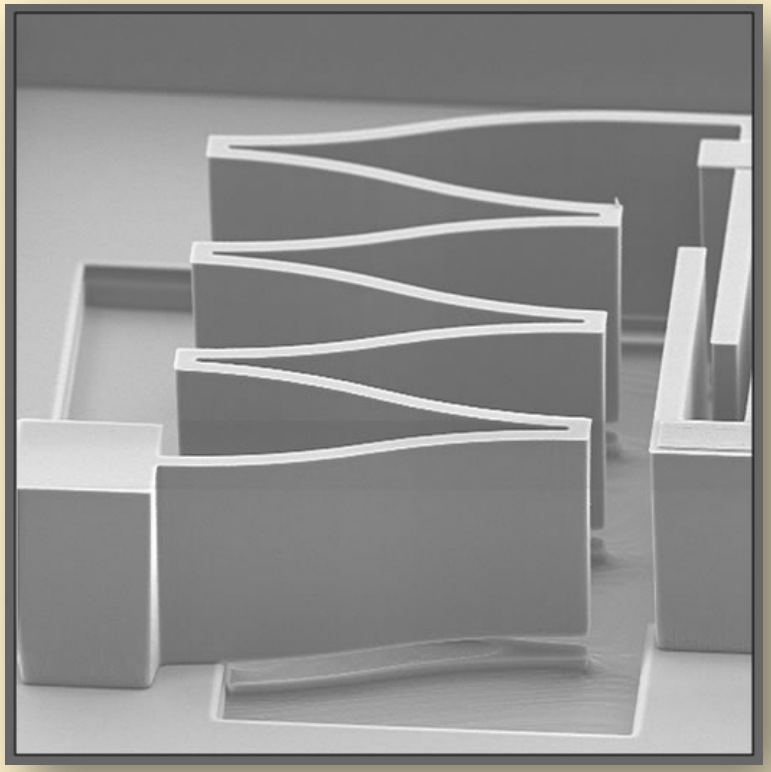


[Graphic courtesy of Khalil Najafi, University of Michigan]

In *Bulk Back-Etch*, the silicon substrate has been selectively removed from the wafer's backside.
In *Bulk Front-Etch*, the silicon substrate has been removed from underneath a film on the wafer's surface.

Release Etch

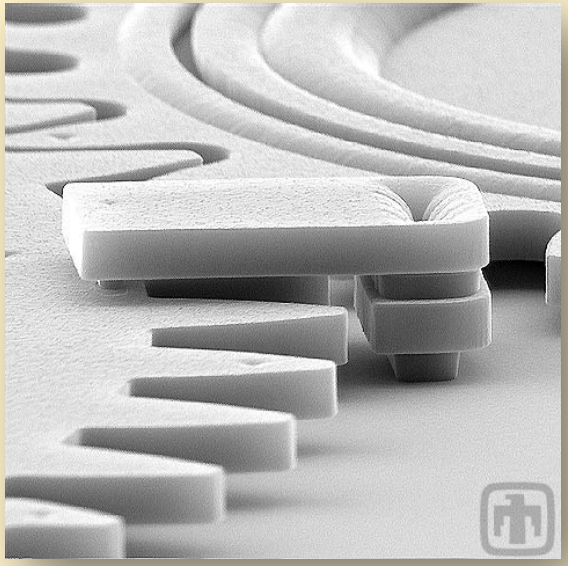
- To release mechanical components, etch is used to remove whatever material is necessary to allow the component to operate according to design.
- The component may be required to move up/down or side-to-side, rotate, vibrate, bend or flex. It may need to be suspended over an open area or formed into a free standing component such as a rotating mirror, oscillating piston, or spring *(see SEM to right)*.



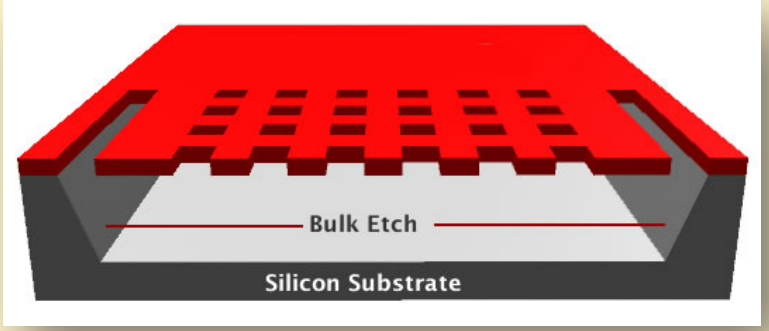
Leaf Spring - expands and contracts above the substrate [SEM courtesy of Khalil Najafi, University of Michigan]

Release Etch

- The material underneath the object is removed to "release" the object.
- Specific etch processes remove select material from underneath the structural layer without affecting the structural layer.
- The etched material (or sacrificial layer) may be another surface layer (left graphic) or bulk material from within the silicon substrate (right graphic).



A bulk etch was used to create an opening under a perforated membrane. This process is called Bulk Micromachining.

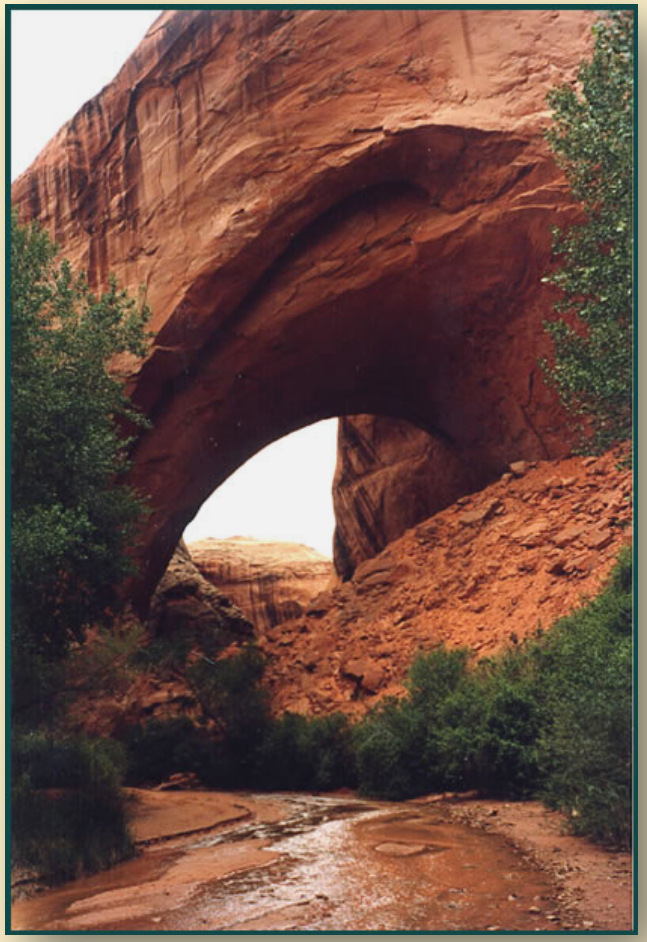


Part of a Gear Train built using Surface Micromachining Technology. Sacrificial layers were etched (removed) in order to create released or moveable devices. [Image courtesy of Sandia National Laboratories, www.mems.sandia.gov]

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]

Another Example

Mt. Rushmore [Photo courtesy of the National Park Service]

Mt. Rushmore in South Dakota

And Yet Another Example

Mesa Verde [Photo courtesy of the National Park Service]

Mesa Verde National Park in Colorado

Etched Layers

Each layer of film to be etched for a microsystem has a definitive purpose.
Following are types of functional layers used for microsystems and some of the materials for each type of layer.

The actual material used is dependent on various factors:

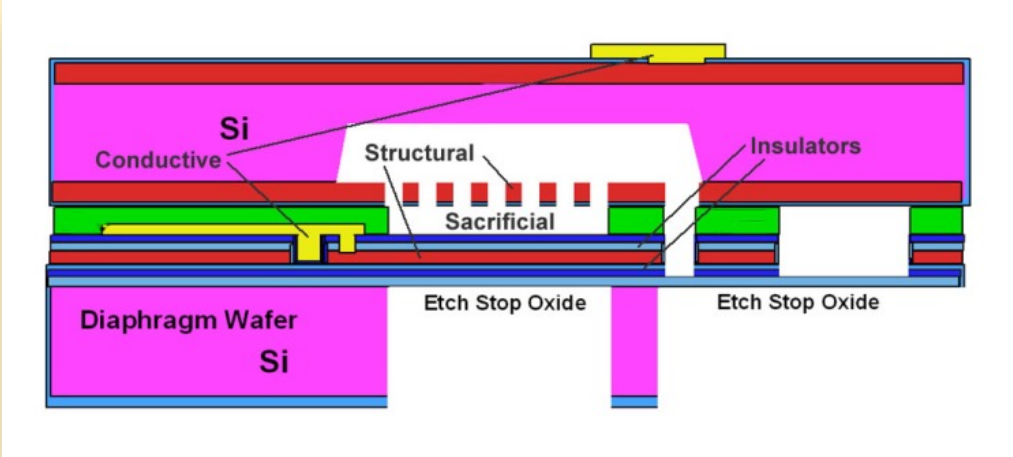
- application or component being constructed
- mechanical and electrical properties needed
- previous and subsequent layers
- the etch process
- the etchant chemicals

Etched Layers

Conductive Layer – A layer for conductive paths, vias, and electrodes for electronic circuits / components. (*Doped Poly-crystalline, metals and metal alloys)*

Insulating Layer – high resistivity layer to insulate one layer from another. *(Silicon nitride, silicon oxide)*

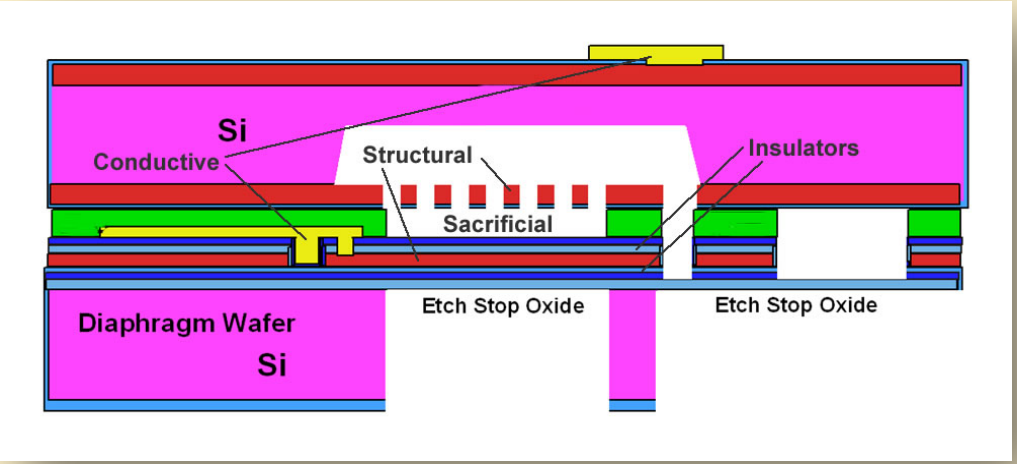
Sacrificial Layer - layer deposited between structural layers for mechanical separation and isolation. Removed during a "release etch" to free the structural layers and allow devices to move. *(Silicon dioxide, photoresist, polycrystalline silicon)*



Types of Etched Layers
[Graphic courtesy of Khalil Najafi, University of Michigan]

Etched Layers

Structural Layer - layer having mechanical /electrical properties needed for microdevices. *(doped polycrystalline silicon, silicon nitride, some metals)*



Etch Stop Layer – layer that stops the etch when this layer is reached. *(Boron-doped silicon, silicon dioxide, silicon nitride)*

Etch Mask Layer – layer that defines the pattern 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 a MEMS, different chemicals are selected to etch those materials.

- Etchants are chemical compounds which chemically react with the layer to be removed, thereby removing the layer.

Selecting Etchants

Factors to consider when selecting etchants:

- Must be capable of etching through the select layer at a rate fast enough to complete the etch in a desired amount of time.
- Etch rate must not be too fast such that it overetches into the next layer.
- Should not be capable of corroding or etching the protective mask layer.
- Should not react with existing layers that are not to be etched.

Etch Processes

Etching is accomplished with either a wet or dry technique.

Wet etch removes the material through a chemical reaction between a liquid etchant and the layer to be etched.

Dry etch removes the material through a chemical reaction and/or a physical interaction between etchant gasses and the exposed layer.

Factors Affecting Etch Quality

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" or etch profile (isotropic, anisotropic or a combination of both)

Selectivity

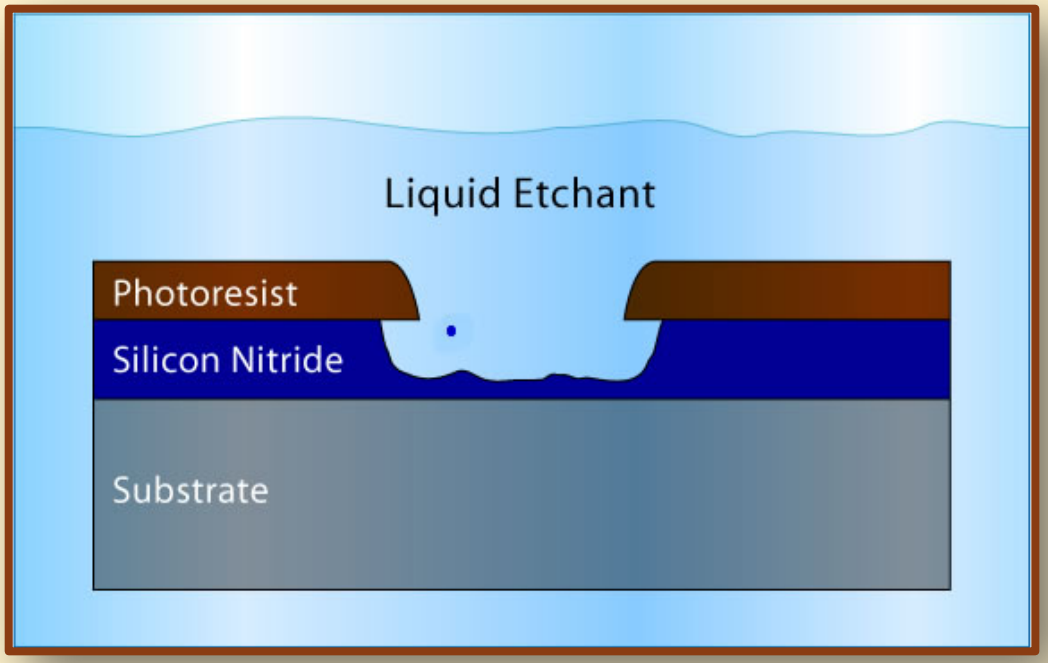
Selectivity – The property of the etchant which permits it to selectively etch a specific material at a faster etch rate than other materials on the wafer.

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?

Wet Etch

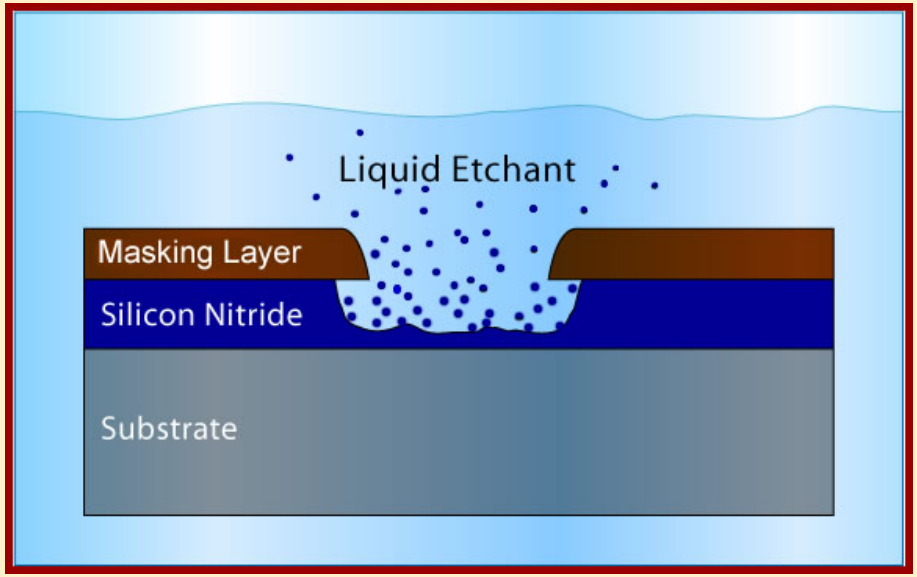


The Wet Etch Process

- 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.
- A reliable process using low cost equipment. However, the liquid etchants are usually expensive and quite hazardous.

Isotropic Wet Etch

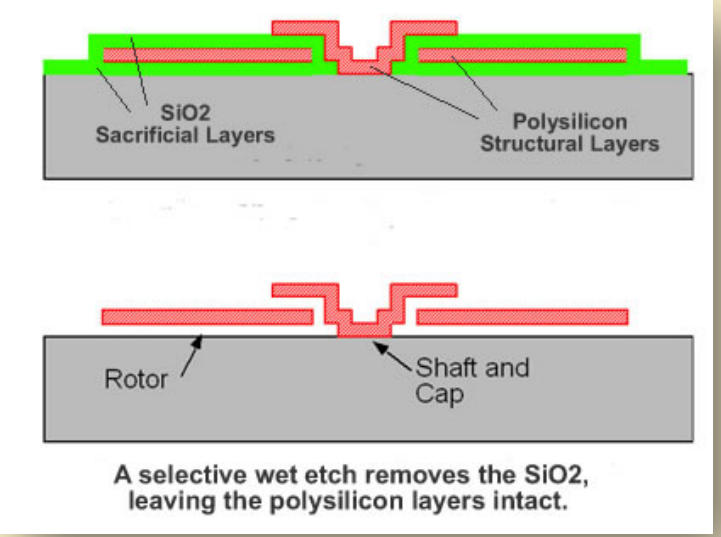
- In most wet etch processes, the etch is isotropic.
- An isotropic etch is a chemical etch that etches the selected layer in all directions.
- The graphic shows the silicon nitride layer being etched vertically as well as horizontally (undercutting the masking layer).



Isotropic Wet Etch

Isotropic Wet Etch

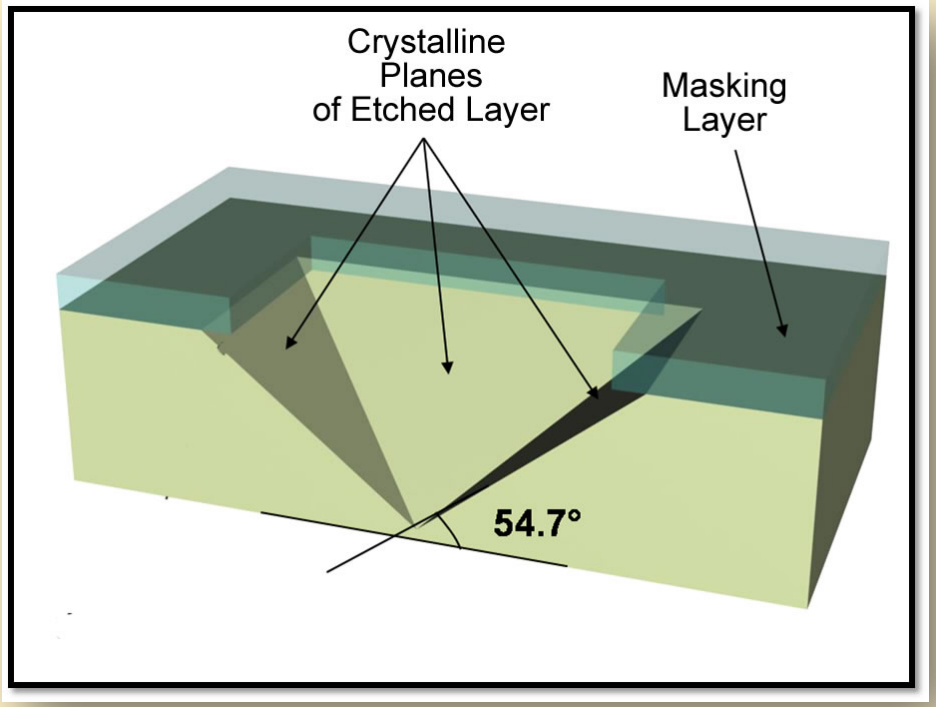
- This characteristic makes it very effective at removing a entire layer of material such as a sacrificial or masking layer.
- The graphic shows how structural layers are "released" after the removal of the sacrificial silicon dioxide layers.
- This requires a selective wet etch process.



Isotropic Wet Etch

Anisotropic Etch

- Specific wet etches such as silicon and potassium hydroxide (KOH) result in an anisotropic etch profile.
- An anisotropic etch is a straight wall edge or an etch that edges along a crystalline plane of the substrate or materials to be etched. *(See graphic)*

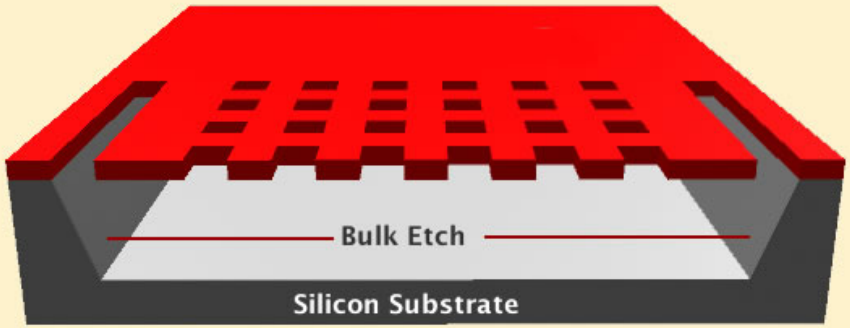


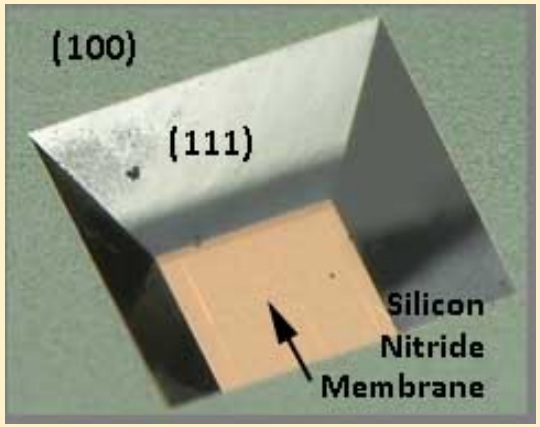
KOH Anisotropic Etch

In a bulk etch process, KOH is used to etch the silicon substrate along a specific crystalline plane.

In the graphic, notice the sharpness of the angled edge within the silicon substrate. This edge is the result of the high selectivity of KOH (a liquid etchant) and the crystalline structure of silicon.

Bulk Anisotropic Etch





Backside of MTTC Pressure Sensor illustrating anisotropic etch

The Wet Etch Process

The wet etch process consists of three primary processing steps:

1. Etch
2. Rinse
3. Dry

Step 1: Etch

- Wafers to be etched are placed in a wafer carrier or “boat”.
- Carrier is lowered into a tank of the etchant solution.
- Wafers are left in the solution for a calculated amount of time.

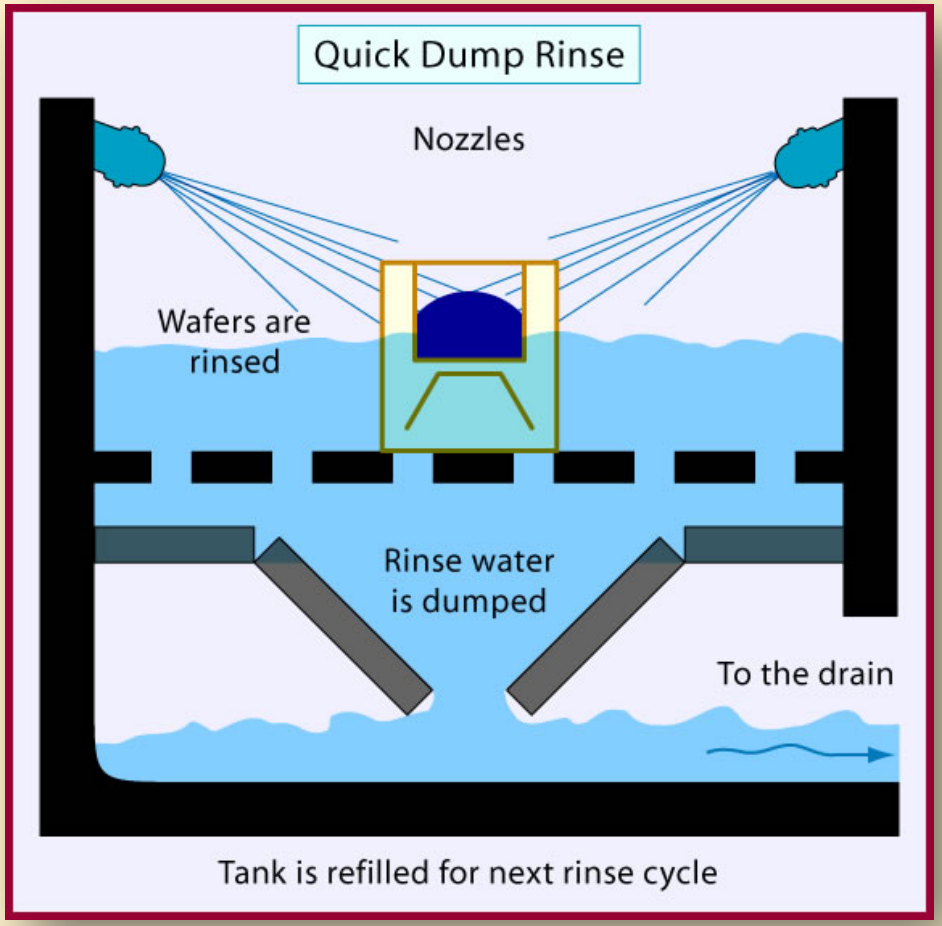
Wafer Carrier in Etchant Solution
[Photo courtesy of Bob Willis]

The concentration of the solution and its temperature are constantly monitored, because both directly affect the etch rate.

An increase in either parameter increases the etch rate.

Step 2: Rinse

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



Quick-Dump-Rinse (QDR) Tank

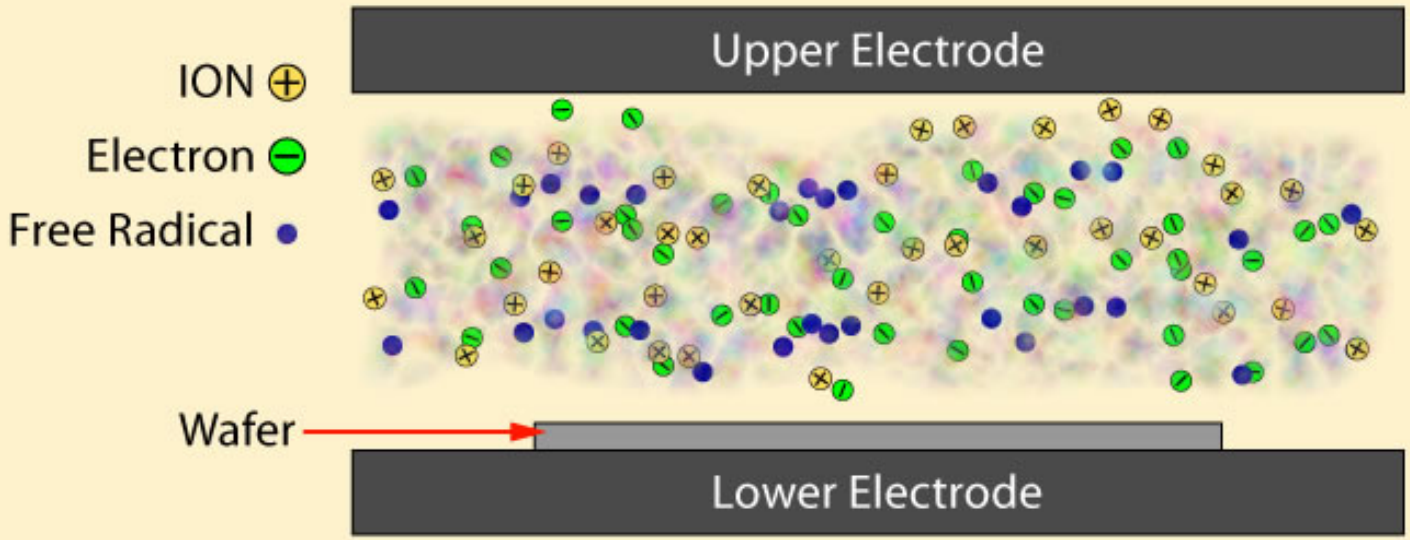
Step 3: Dry

- After rinse, wafers must be thoroughly dried to prevent problems 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:

SRD [Photo courtesy of Bob Willis]

- Carrier is placed in the machine and rotated while being rinsed with deionized water.
- The water is turned off but the carrier continues to spin at a higher rotational speed.
- Heated nitrogen is introduced, removing any remaining water on the wafer.

Dry Etch Process



Plasma soup consisting of electrons, ions and radicals

- In dry etch the wafer is exposed to a gaseous etchant 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.

Dry Etch

By design, dry etch methods provide more control over the factors which influence etched results:

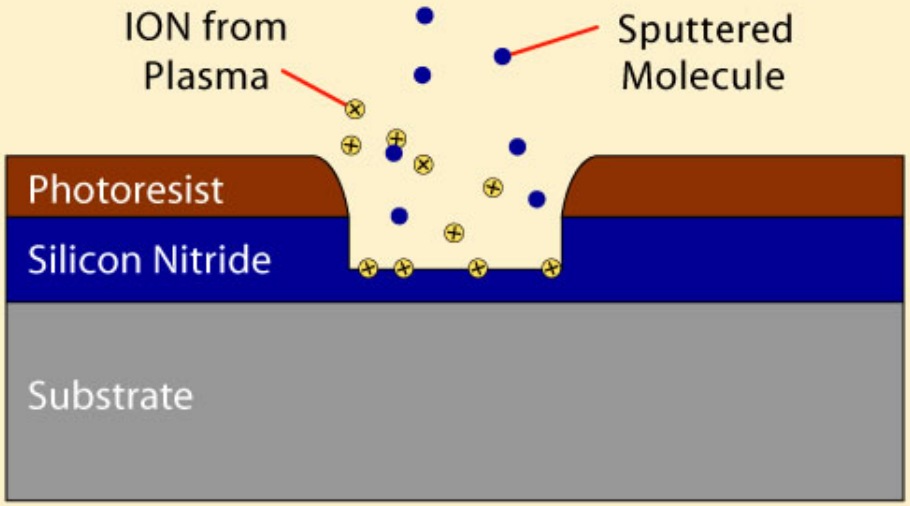
- directional control of the etch,
- anisotropic profiles, and
- process parameters (pressure, temperature, gas flow, power).

This control allows for a very selective and specific etch.

Types of 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 combination of the two.
- Reactive ion etchers (RIE) provide the parameters for both types of etching.

Physical Etch



Physical Dry Etch
uses ions to sputter molecules from surface

- Physical etch is very similar to the sputtering deposition process. It is entirely physical. No chemical reaction occurs.
- Physical etch is referred to as "ion beam etching", "sputtering" or "ion milling".
- Ions bombard the surface of the wafer, causing molecules to sputter off the surface. *(See graphic)*

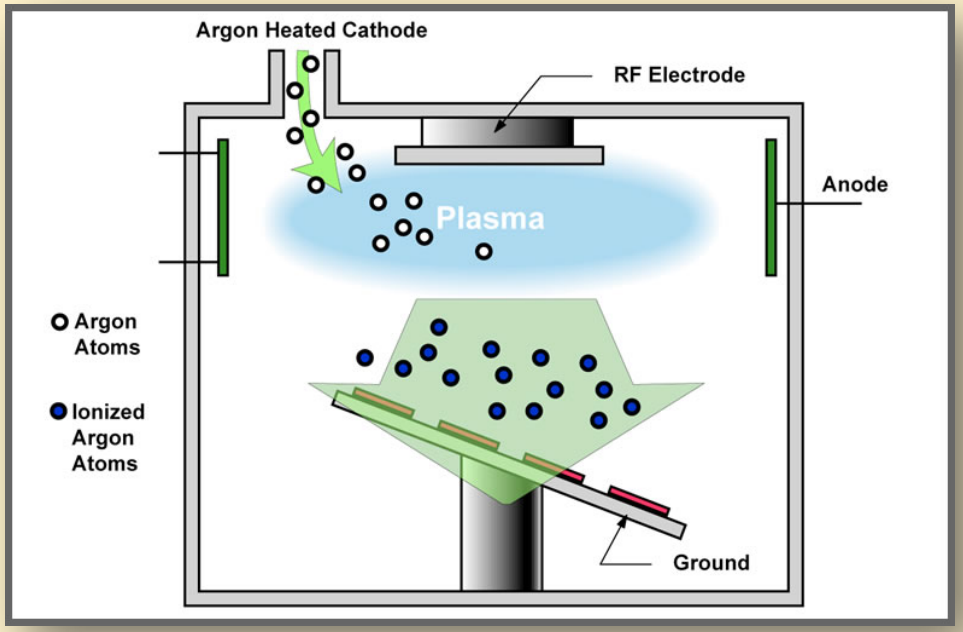
A Type of Physical Etch

- Sand blasting is a type of physical etch process.
- A design is placed on a sheet of glass using a strong protective material.
- This material stands up to the bombardment of 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.

Dry Physical Etch

Wafers are placed on a negatively grounded holder in a vacuum chamber.

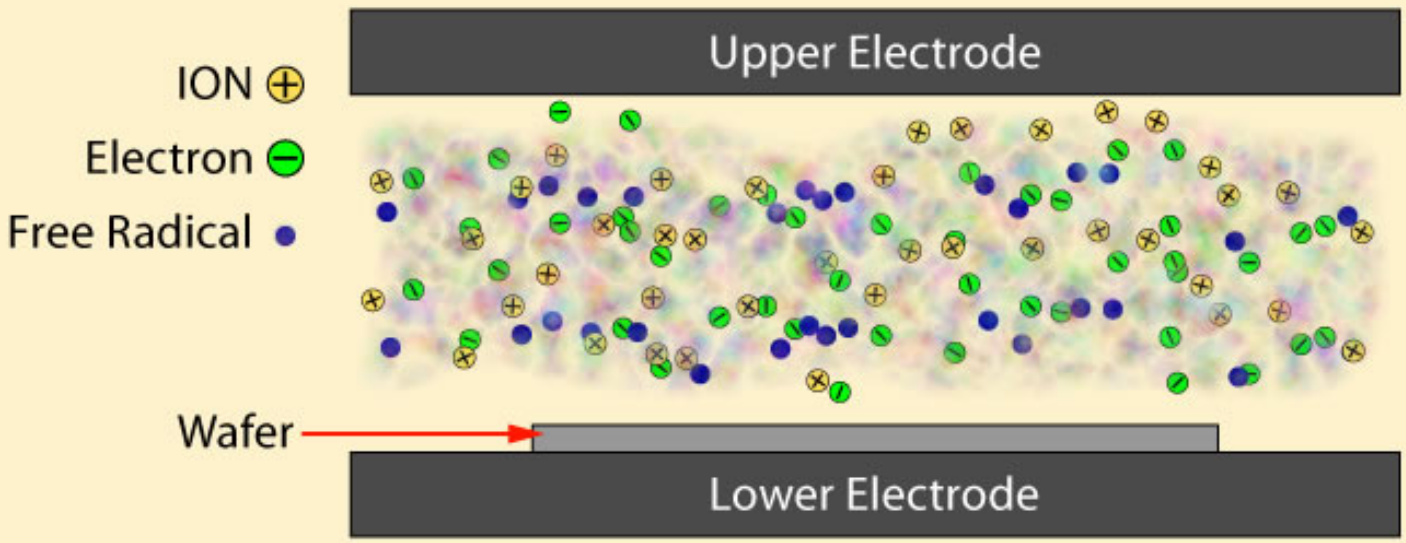
- A gas is introduced, chamber pressure reduced (e.g., <50 mTorr) and RF turned on. A plasma is struck (ignited).
- Gas molecules enter the plasma and collide with high energy electrons resulting in positive ions.



Ion Beam Milling Process (Physical Etch)
[Graphic courtesy of MATEC]

- Ions are attracted to the negatively-grounded wafer holder.
- Ions accelerate as they move toward the wafer holder.
- Ions hit the wafer, sputtering molecules from the surface.
- Process continues until pattern is etched exposing the underlying layer.

Dry Chemical Etch

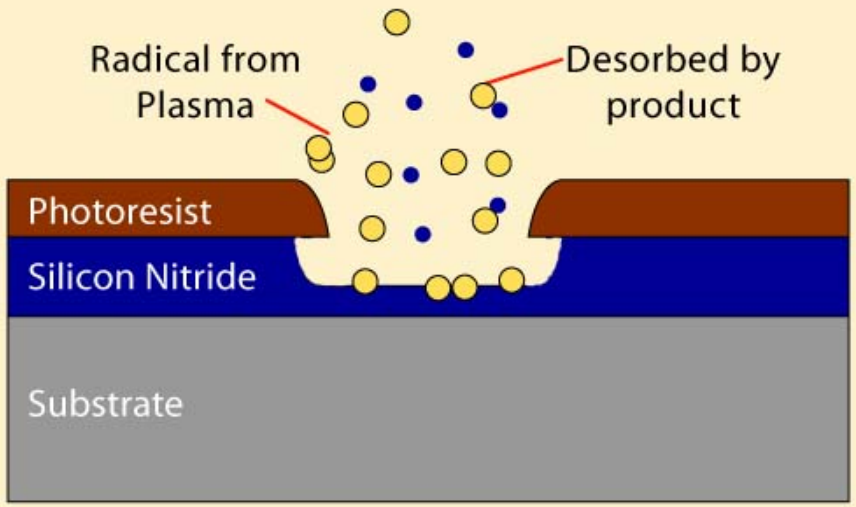


Plasma Collisions

- 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 as the physical etch process: a plasma is struck and collisions occur between high energy electrons and gas molecules.
- However, in dry chemical etch, the radicals formed by the collisions perform the etch rather than the positive ions.

The Chemical Dry Etch Process

- Because radicals generate faster and survive longer than ions, more radicals are available in the plasma.
- Radicals travel towards the wafer and are adsorbed by the surface material that is to be etched.



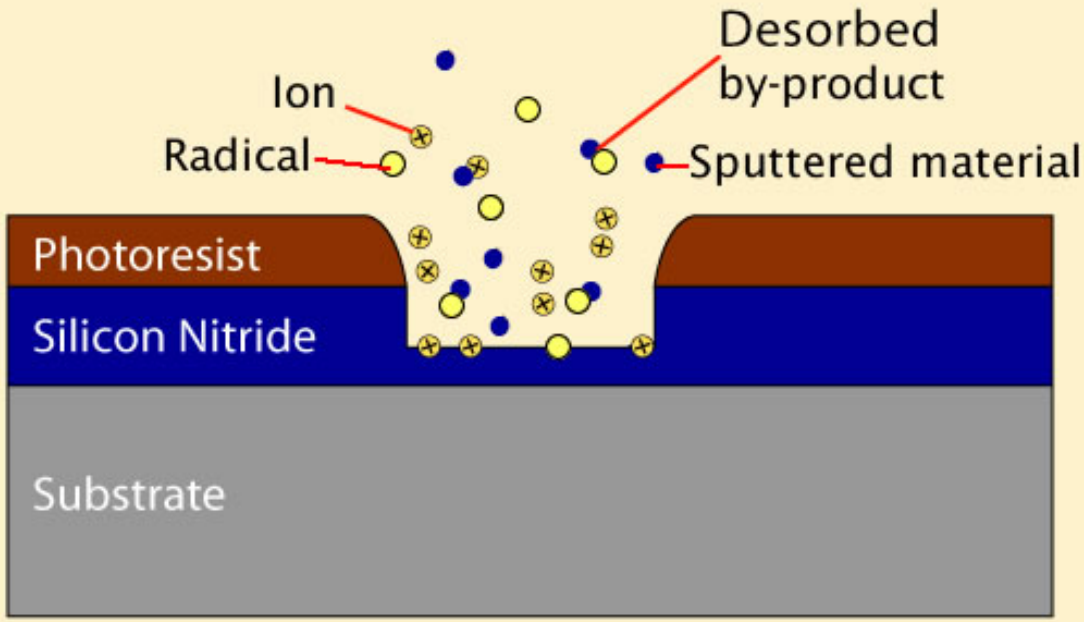
Chemical Dry Etch Process

A chemical reaction occurs between the atoms of the material and the radicals. By-products of this reaction desorb from the surface and diffuse into the gas present in the chamber.
The reaction / desorption is the chemical etch.

Dry Etch Process Parameters

- The two critical parameters in the dry etch process are Pressure and RF power level.
- 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 Etch (RIE)



RIE process uses both ions and radicals

- 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 at the same time that the radicals adsorb to the surface.

RIE

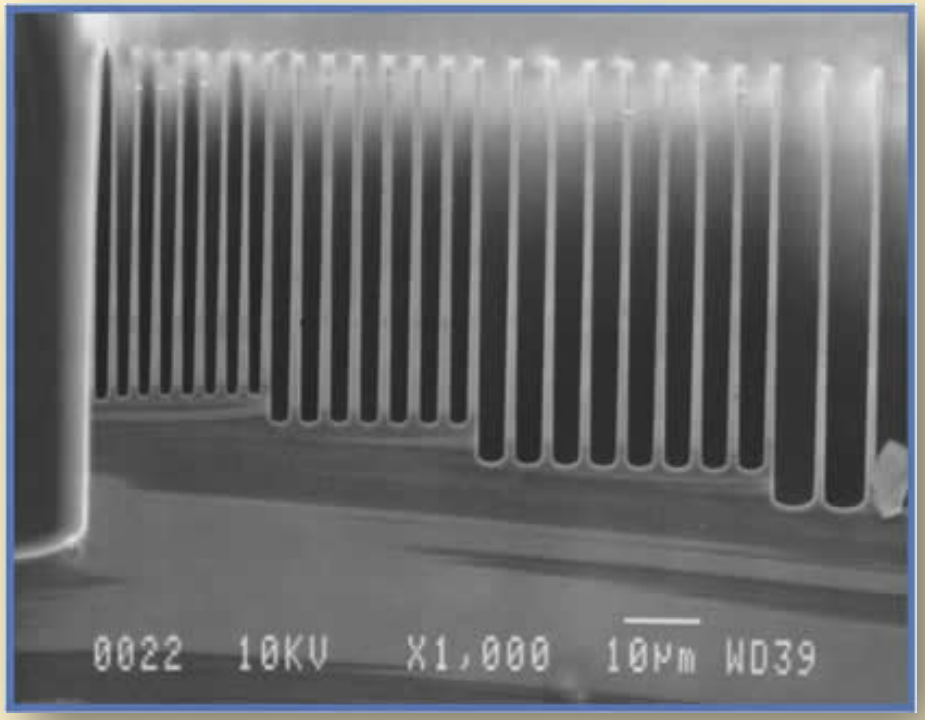
- This process provides high selectivity ratios.
- It also produces anisotropic profiles on features less than 3 microns wide.
- Its ability to capitalize on the advantages of both physical and chemical etching makes RIE an invaluable tool in the manufacture of microsystems components.

Deep RIE

- A special subclass of RIE is Deep RIE (DRIE).
- DRIE is used to etch deep cavities (or trenches) in substrates with relatively high aspect ratios, such as 50:1 (The aspect ratio is the ratio of a cavity's depth to its width).
- These cavities can be hundreds of micrometers deep while only a few micrometers wide.

Deep RIE (DRIE)

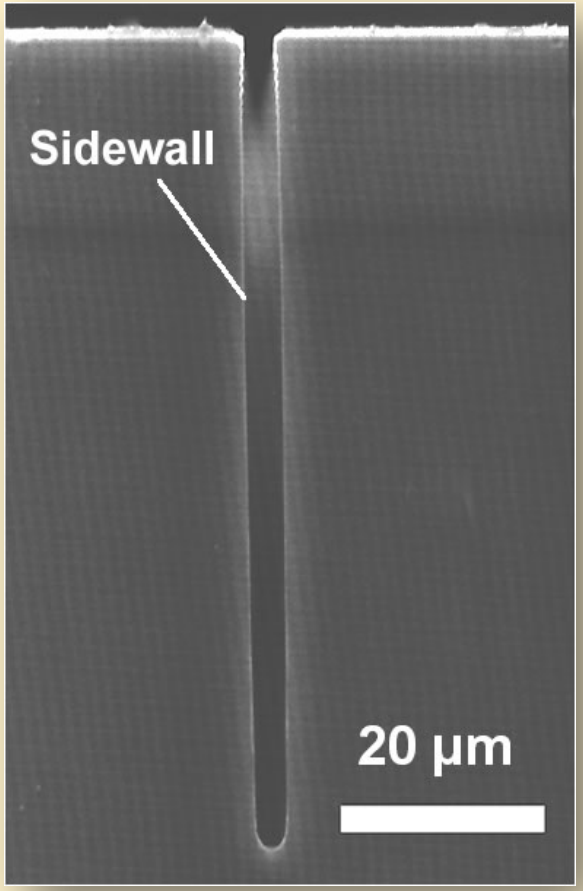
- The SEM image to the right shows a series of cavities etched using a DRIE process.
- Notice that the deeper cavities have the wider openings. This means that on the same wafer with a number of different etch openings, different widths will achieve different depths.



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

Deep RIE – Bosch Process

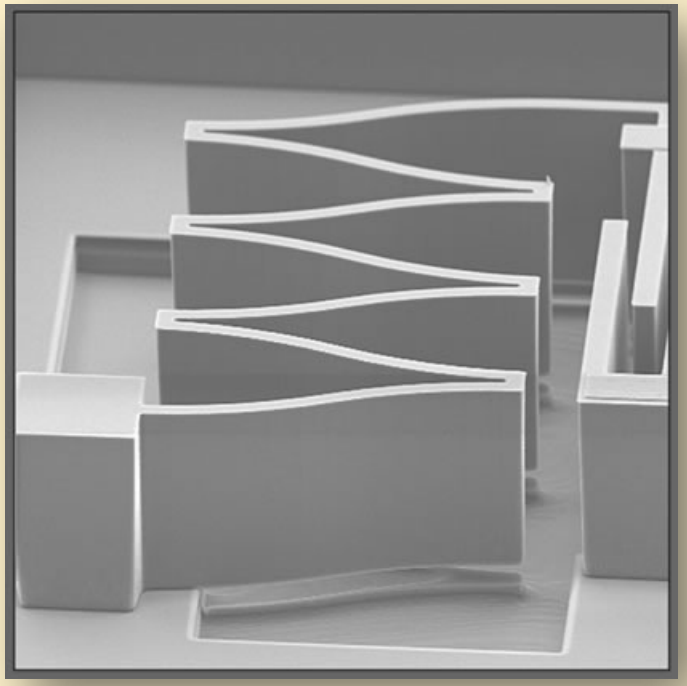
- Most systems use "Bosch process":
- The Bosch process uses a fluor polymer to passivate the etching of the sidewalls. This passivation protects the sidewalls from being etched but not the horizontal surfaces.
- During the entire etching process, the gas mixture switches back and forth between etchant gasses and passivation gasses. This results in a deep, but narrow etch.



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

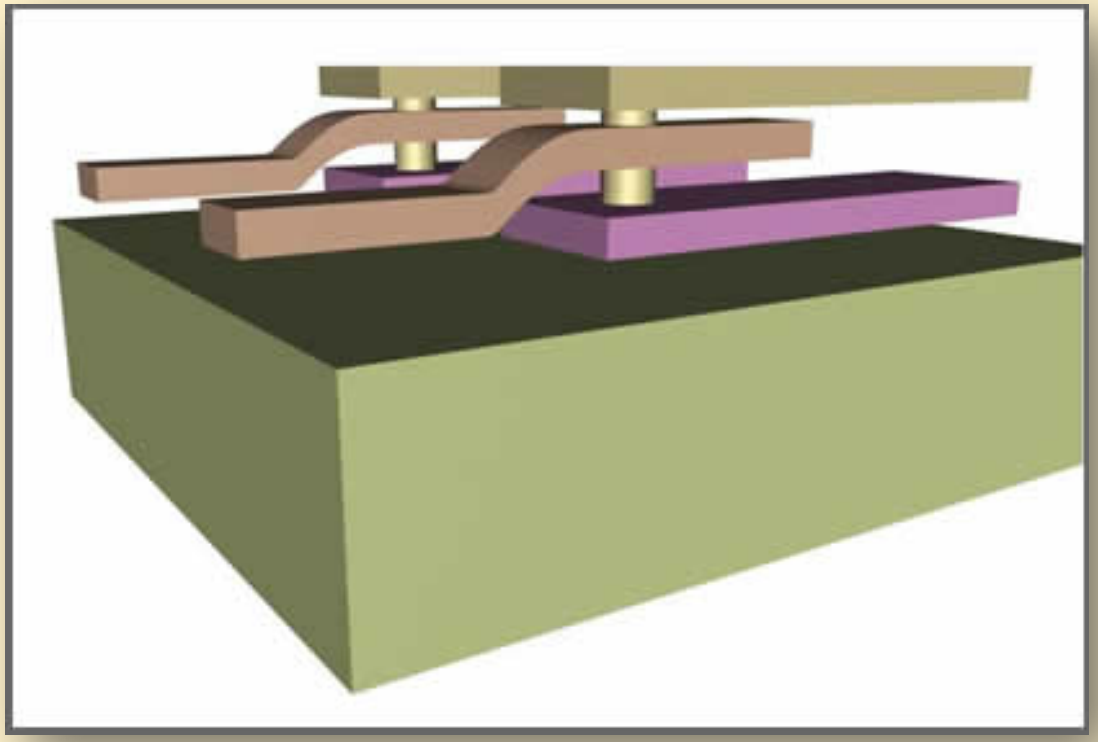
DRIE Structures

- In addition to creating cavities, DRIE can be used to create tall objects or components for microsystems devices which can later be "released" through other etch methods.
- The SEM image on the right 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]

Let's Review



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

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:

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

Disclaimer

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Acknowledgements

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