
MEMS Micromachining Overview

Primary Knowledge Unit

Instructor Guide

Note to Instructor:

This Primary Knowledge (PK) provides an overview of three widely used micromachining processes for fabricating microsystems or MEMS: bulk, surface and LIGA.

The *MEMS Micromachining Learning Module* consists of the following:

- Knowledge Probe (KP)
- **MEMS Micromachining Overview PK**
- Terminology Activity
- Research Activity
- LIGA Activities (4) – These activities can be found in the LIGA Micromachining Activities Module. A SCME kit is required for 2 of these activities*.
- Final Assessment

**The LIGA Micromachining kit can be ordered through the SCME website (<http://scme-nm.org>) while supply lasts and center is funded.*

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 (when applicable).

Description and Estimated Time to Complete

This learning module provides an overview of three micromachining processes (bulk, surface, LIGA) used for the fabrication of microsystems or MEMS (microelectromechanical systems). Activities are provided that contribute to a better understanding of these processes and that encourage further exploration.

The fabrication of microelectromechanical systems (MEMS) uses some of the same processes and tools used to fabricate integrated circuits (IC) (e.g., deposition, photolithography, etch). However, MEMS technology has altered or enhanced some of these processes, as well as added new processes, in order to build mechanical devices such as microfluidic channels, gears, cantilevers, micro motors, comb drives and gyroscopes. Because of the techniques used in some of these new processes and methods, MEMS fabrication is also called micromachining. This unit provides an overview of three widely used MEMS micromachining methods:

- Surface Micromachining
- Bulk Micromachining
- LIGA (Lithography, Galvanoformung (electroforming), and Abformung (molding))

Each of these processes requires a clean environment to reduce particle contamination during fabrication.

Estimated Time to Complete

Allow approximately 60 minutes to read through this unit.

Introduction

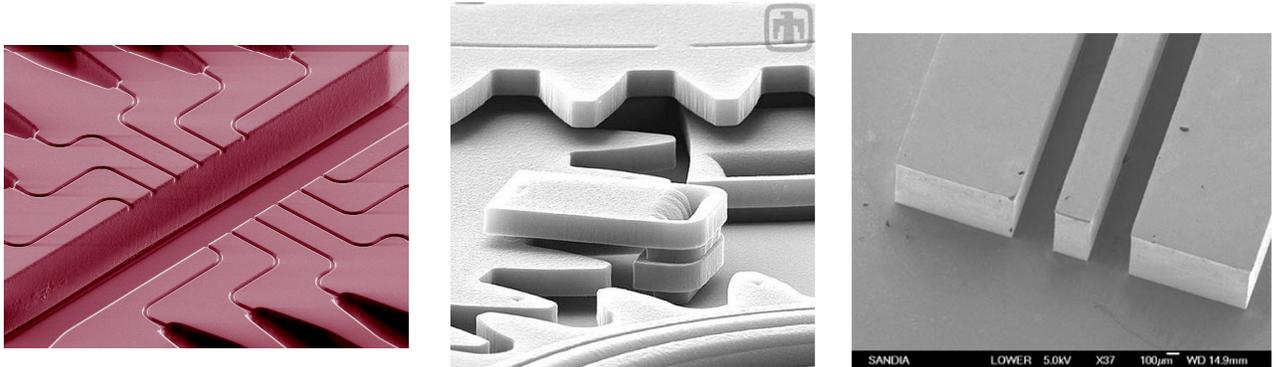
Many of MEMS fabrication processes use batch fabrication techniques where more than one wafer is processed at a time, as well as tools and infrastructure similar to that used in the manufacturing of integrated circuits or computer chips. By incorporating this existing technology, MEMS fabrication (also called micromachining) has allowed for the manufacturing of micro and nano-sized devices at lower cost and increased reliability when compared to macro-sized equivalent components. This is especially true for sensors and actuators.¹ These microdevices also tend to be quite rugged. They respond quickly while consuming little power and they occupy very small volumes.²

MEMS micromachining techniques allow for the construction of three-dimensional (3D) micro-sized structures, components, and various elements on or within a substrate (usually silicon). In some cases, micromachining is the utilization of modified IC manufacturing processes in conjunction with other processes such as deep bulk etching, laser assisted chemical vapor deposition, electroplating, and molding techniques.

Three widely used MEMS fabrication methods are

- surface micromachining,
- bulk micromachining, and
- LIGA (Lithography, Galvanoformung (electroforming), and Abformung (molding)).

Below are scanning electron microscope (SEM) images of products from each type of micromachining process. The far left SEM shows microchambers and channels fabricated using bulk micromachining. The middle SEM shows layers of gears made possible through surface micromachining. The left SEM is a waveguide produced by Sandia National Laboratories using LIGA. *[The SEMs of the gears and waveguide are courtesy of Sandia National Laboratories. The microfluidic channels are courtesy of BioPOETS Lab, Berkeley]*



Surface micromachining constructs thin mechanical components and systems on the surface of a substrate by alternately depositing, patterning and etching thin films. Bulk micromachining etches into a substrate to form 3D mechanical elements such as channels, chambers and valves. When combined with wafer bonding, surface and bulk micromachining allow for the fabrication of complex mechanical devices.² LIGA processes combine collimated x-ray lithography with electroplating and molding techniques to create high aspect ratio (tall and thin) structures or deep cavities needed for certain types of MEMS devices.

This unit takes a closer look at each of three widely used micromachining processes: bulk, surface and LIGA.

Objectives

- Identify the distinguishing elements of bulk micromachining, surface micromachining and LIGA.
- Identify microsystems and microsystem components that are constructed using each of the three micromachining processes.

Terminology *Definitions for these key terms are found in the glossary at the end of this unit.*

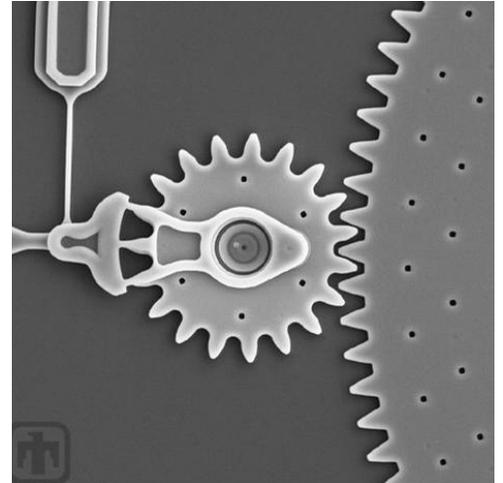
Anisotropic etch
Aspect Ratio
Bulk etch
Bulk Micromachining
Chemical Mechanical Polishing (CMP)
Deposition
Electroforming
Electroplating
Isotropic etch
LIGA
Oxidation
Photolithography
Release etch
Sacrificial Layer
Structural Layer
Surface micromachining

Surface Micromachining

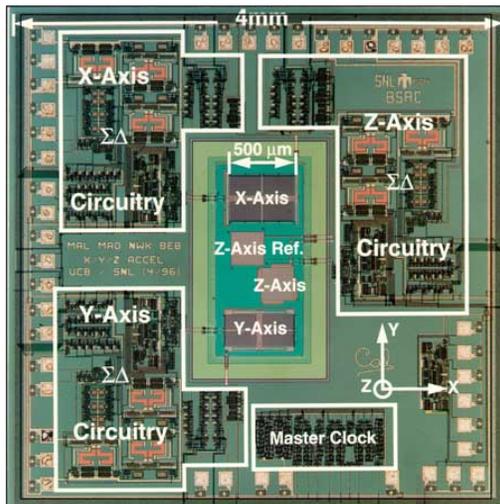
Surface micromachining is a process that uses thin film layers deposited on the surface of a substrate to construct structural components for MEMS. Unlike bulk micromachining that builds components within a substrate, surface micromachining builds on top of the substrate. The scanning electron microscope (SEM) image shows microgears that were fabricated using surface micromachining.

These gears are very thin, 2 to 3 microns in thickness (or height), but can be hundreds of microns wide. Each gear tooth is smaller than the diameter of a red blood cell (8 to 10 microns). These gears rotate above the surface of the substrate.

[SEM courtesy of Sandia National Laboratories]

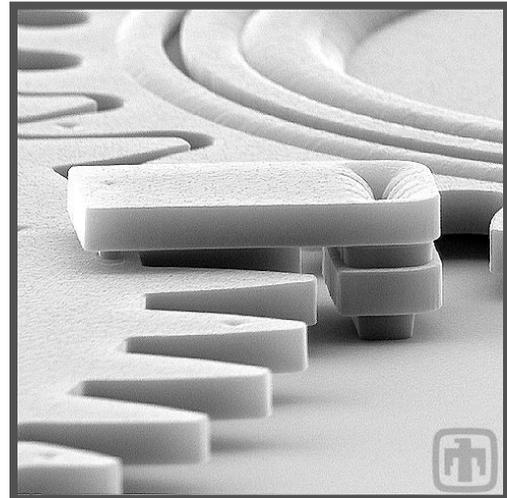
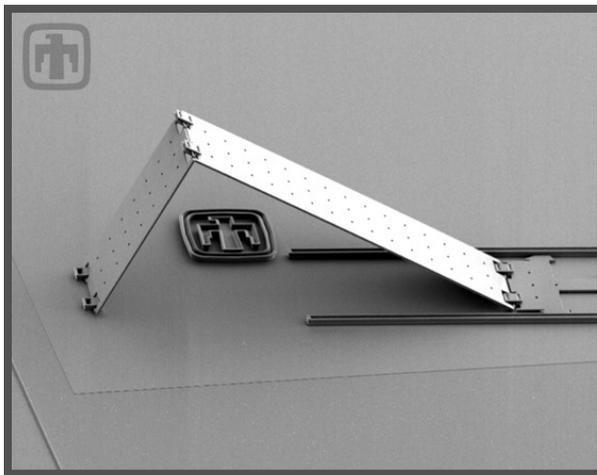


Surface micromachining uses many of the same techniques, processes, and tools as those used to build integrated circuits (ICs) or more specifically CMOS (Complementary Metal Oxide Semiconductor) components. This process is used to fabricate micro-size components and structures by depositing, patterning, and etching a series of thin film layers on a silicon substrate. This creates an ideal situation for integrating microelectronics with micromechanics. Electronic logic circuits can be fabricated at the same time and on the same chip as the mechanical devices. The 3-axes MEMS accelerometer below shows three surface micromachined accelerometers (mechanical components) on the same chip as their electronic control circuits.



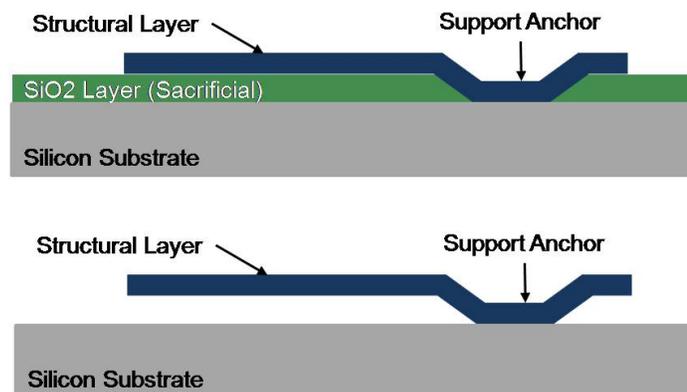
Integrated 3-axis silicon microaccelerometer [Image courtesy of Sandia National Laboratories]

The main difference between CMOS fabrication and surface micromachining is that the circuits constructed for CMOS allow for the movement or flow of electrons while the structures constructed with surface micromachining (e.g., cantilevers, gears, mirrors, switches) move matter. In order to move matter and to create moveable structures, spaces must be incorporated between moveable components during the fabrication process. For example, optical flip mirrors (*below left*) cannot move nor can a gear (*below right*) rotate on an axis unless there is space to allow for movement.



*Pop-up Mirror (left) and geartrain with alignment pin (right)
[SEM images courtesy of Sandia National Laboratories]*

The spaces between components are fabricated using sacrificial layers. A sacrificial layer is deposited between two structural layers to provide the needed gap. Once the device is complete and all of the structural layers are formed, the sacrificial layers are removed, *releasing* the component(s) so that it is free to move. The graphic below shows the construction of a microcantilever. A sacrificial layer is deposited on top of the substrate. A structural layer is then deposited on top of the sacrificial layer. Once the structure is defined and etched, the sacrificial layer is removed; the cantilever is *released* and is free to flex.



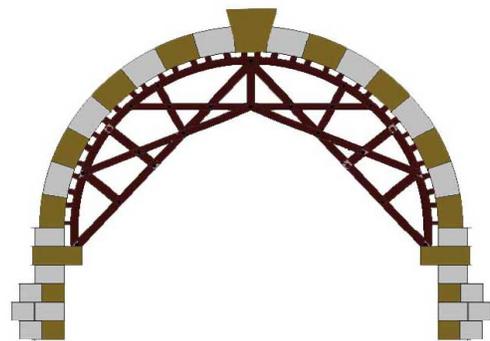
Some of the moving parts in the structural layers are so thin (2 to 3 microns) and have such a low aspect ratio (ratio of height to width) that they are sometimes referred to as "2.5 D" rather than 3 D.

Surface micromachining is based on the deposition and etching of alternating structural and sacrificial layers on top of a substrate. The most commonly used substrate is silicon; however, less expensive substrates such as glass and plastic are also used. Glass substrates are used for MEMS applications such as DNA microarrays, implantable sensors, components for flat screen displays, and solar cells. Plastic substrates are used for various microfluidics applications and bioMEMS applications as well as for the fabrication of surface micromachined beams, diaphragms and cantilevers.⁴

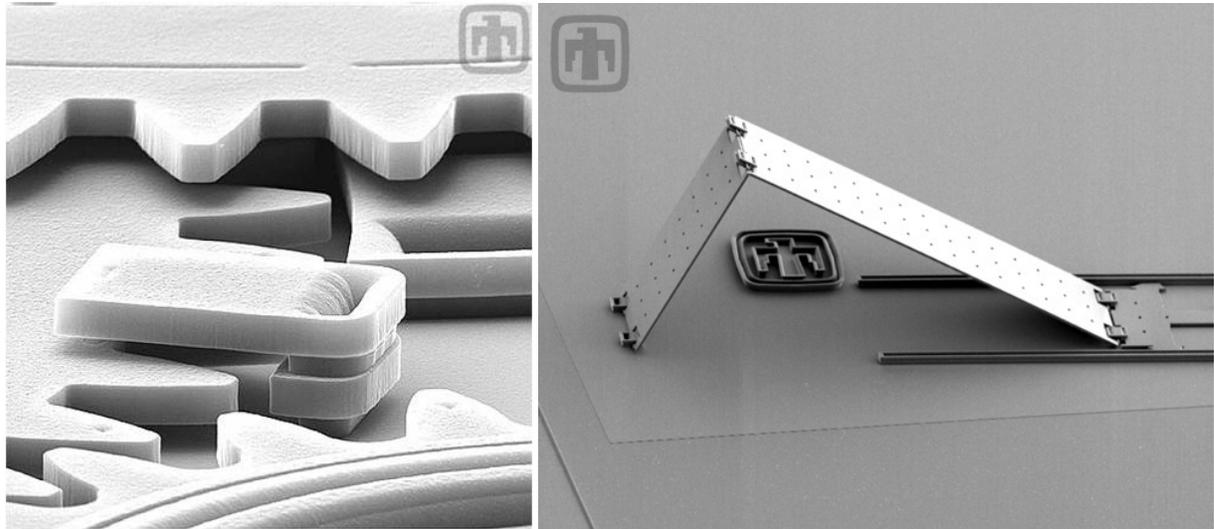
What is a Sacrificial Layer?

Complicated components such as movable gear transmissions and chain drives can be constructed using surface micromachining because of its use of the sacrificial layer. Let's take a look at how sacrificial devices are used to construct macro-size structures.

The image to the right shows a cross-sectional view of a keystone bridge. This structure is made by first constructing a wooden scaffold. Cut stones are placed on top of the scaffold, following its outline. The final stone at the apex is called the keystone, thus the name – Keystone bridge. Once this stone is in place, the scaffolding is removed and the bridge remains in place. The scaffold is only used to provide support and shape during the construction process, and then it is sacrificed (removed). Thus the term sacrificial layer.



When constructing MEMS there are many possible combinations of sacrificial and structural layers. The combination used is dependent upon the device(s) being constructed. Below are two surface micromachined MEMS that require different process flows. Notice the layering required for the gears and the gear with its alignment clip (*left*) vs. the pop-up mirror (right). Obviously, the gears would require more structural/sacrificial layers than the pop-up mirror.



[SEM images courtesy of Sandia National Laboratories]

Surface Micromachining Materials

Materials used in surface micromachining are generally the same as those used in CMOS processing techniques but they serve a different function in the mechanical components.

- Silicon dioxide (SiO_2 or oxide) is the film most commonly used as a sacrificial layer and hard mask.
- Polysilicon crystalline (poly) is the most commonly used film as a structural layer.
- Silicon nitride is a thin film used for membranes (in devices such pressure sensors), as insulating material, and as a hard mask.
- Self-assembled monolayer (SAM) coatings are deposited at different steps to make the surfaces hydrophobic, and to reduce friction and wear of rubbing parts.

Surface Micromachining Layers and Processes

Silicon Dioxide (SiO₂ or oxide)

The first step of surface micromachining is to grow a thin film of silicon dioxide into the surface of the silicon wafer (substrate). This first SiO₂ layer acts as an insulator and a scaffold (space). It is thermally grown in a thermal oxidation furnace. The picture on the left is of a six (6) process chamber horizontal oxidation furnace. The graphic on the right illustrates the components of each chamber. This is a batch process; therefore, several cassettes (boats) of wafers are processed at one time.

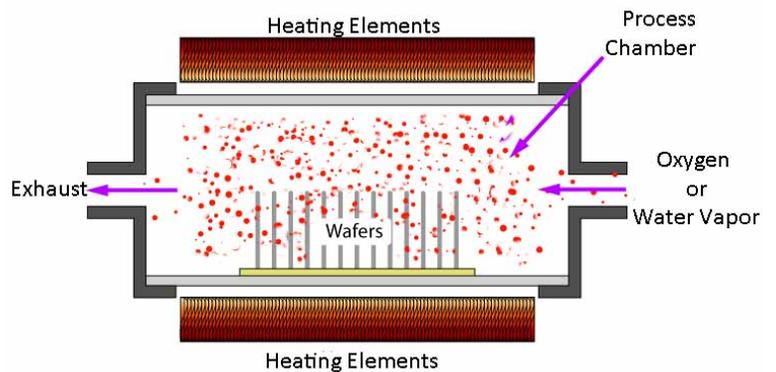


Diagram of an oxidation furnace's process chamber

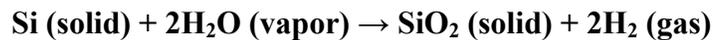
Horizontal Thermal Oxidation Furnace

[Photo courtesy of University of New Mexico, Manufacturing Training and Technology Center (UNM/MTTC)]

Two oxidation methods are used in thermal oxidation: dry and wet oxidation. Dry oxidation uses oxygen gas (O₂) to form SiO₂.



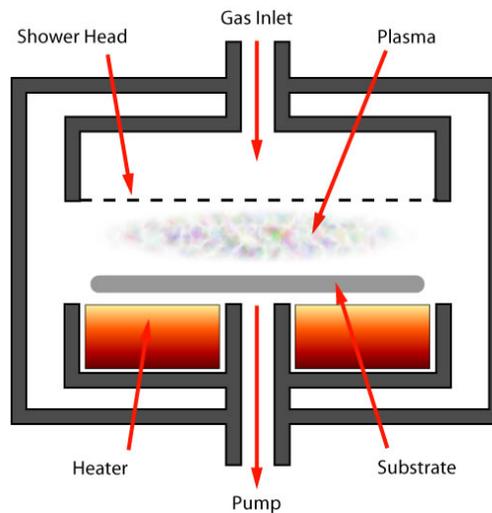
Wet oxidation uses steam or water vapor to form SiO₂.



In both processes, dry and wet, the process temperature affects the rate of oxidation (the rate at which the SiO₂ layer grows). The higher the temperature, the greater the oxidation rate (amount of oxide growth / time). Also, wet oxidation has a higher oxidation rate than dry oxidation at any given temperature. This effect can be seen in the oxidation of iron and the formation of rust (iron oxide). Rust grows much faster in humid climates than in dry climates (Florida vs. New Mexico); thus, the oxidation rate is higher in Florida than in New Mexico.

A variety of Chemical Vapor Deposition (CVD) processes are used to deposit subsequent structural and sacrificial layers. CVD is the most widely used deposition method. The films deposited during CVD are a result of the chemical reaction between the reactive gas(es) and between the reactive gases and the atoms of the substrate surface. CVD processes used in surface micromachining include the following:

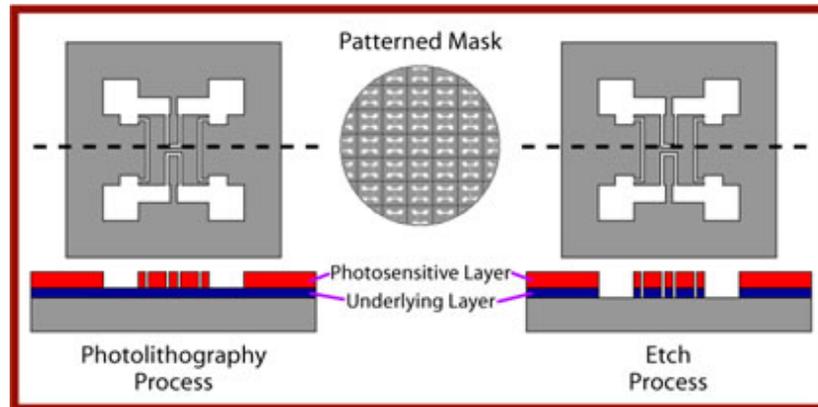
- Atmospheric pressure chemical vapor deposition (APCVD) system - uses atmospheric pressure or 1 atm in the reaction chamber.
- Low pressure CVD (LPCVD) system - uses a vacuum pump to reduce the pressure inside the reaction chamber to a pressure less than 1 atm.
- Plasma-enhanced CVD (PECVD) - uses a low pressure chamber and a plasma to provide higher deposition rates at lower temperatures than a LPCVD system. (*see graphic below of a PECVD*)
- High Density, Plasma Enhanced, CVD (HDPECVD) uses a magnetic field to increase the density of the plasma within the chamber resulting in much higher deposition rates.



Plasma-enhanced CVD System

Metal layers which are used as conductive layers are deposited using Physical Vapor Deposition (PVD) processes such as sputtering and evaporation.

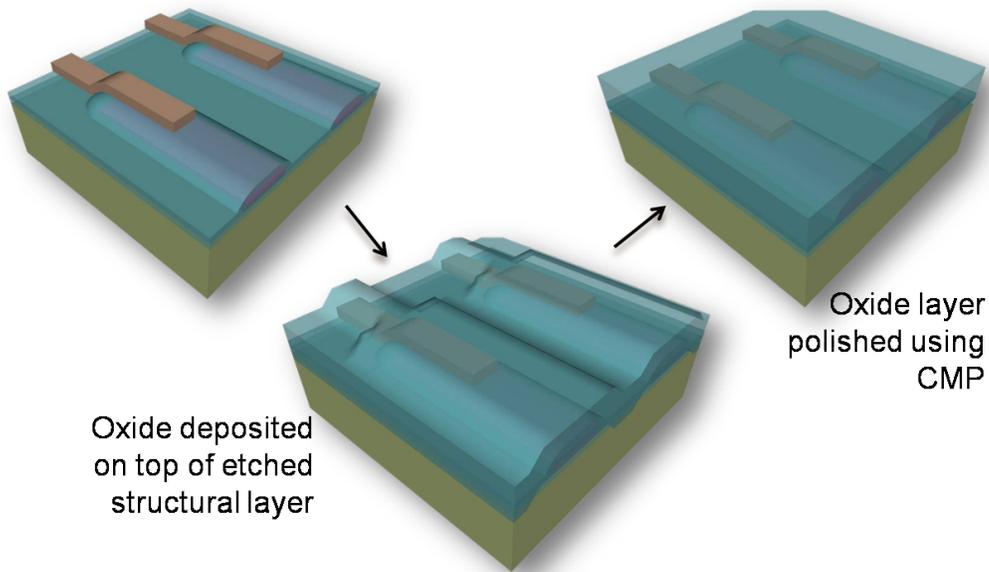
Once a layer has been deposited, it needs to be patterned. This is done through photolithography, a process used to transfer the pattern on a reticle or mask to a thin coating on the wafer's surface. Photolithography uses a coating of light sensitive material called photoresist which is developed after exposure to patterned light. When a positive photoresist is used, the exposed resist is removed during develop. The resist which is not exposed, remains on the wafer surface and protects the underlying surface from the subsequent etch. (See graphic below)



After the develop process, the exposed areas of the underlying layer are etched (removed) using either a wet or dry etch process. Once the resist pattern has been transferred to the underlying material layer, the remaining resist is removed (resist strip) leaving the patterned material layer.

Chemical Mechanical Polishing (CMP)

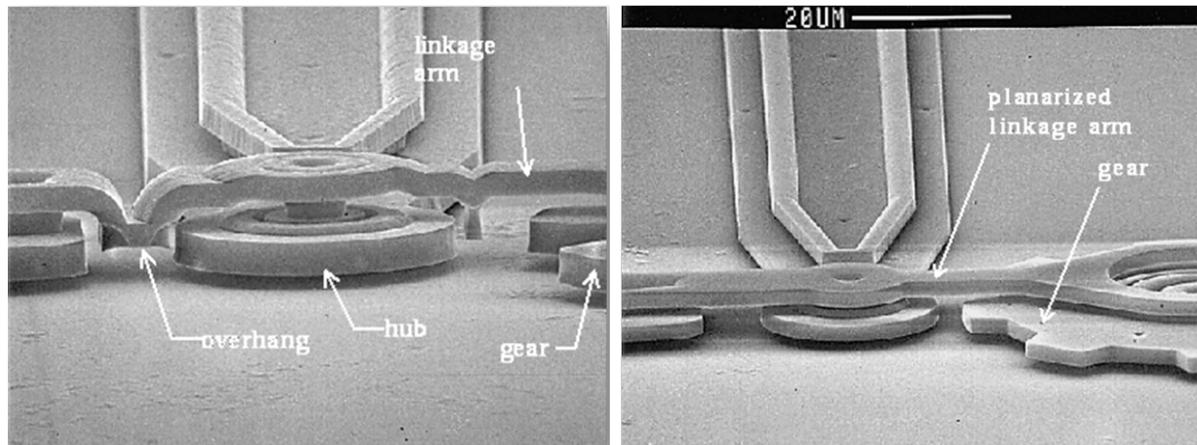
As you add layers, the topography at the surface gets bumpy or uneven. This unevenness can affect subsequent processes such as deposition and photolithography, but it can also affect the movement of components upon release. The more layers a MEMS device requires, the more uneven the surface becomes after each new layer. Remember that each layer usually requires a deposition, photolithography, and etch step. Therefore, some processes require that an oxide deposition be followed by chemical mechanical polish (CMP). The CMP removes the “bumpiness” of the oxide surface prior to the deposition of the next layer. The graphics below show the bumpiness of an oxide layer after being deposited on top of an etched structural layer and its “flatness” after a CMP.



[Graphic images courtesy of Khalil Najafi, University of Michigan]

CMP is used to flatten the topography. Sandia National Laboratories developed a CMP process for MEMS which is similar to that used in CMOS manufacturing. A thick layer of sacrificial oxide is deposited followed with a polish (CMP). The polish removes the topography making the top of the sacrificial layer very smooth. The next structural layer is then deposited. This structural layer is flat on the bottom allowing the structure to move freely once the sacrificial layer is removed.

The image in the left shows the severe topography resulting if no CMP is done. Compare this to the image on the right. In this case a polish is performed between the sacrificial and structural layer depositions. The conformal nature of oxide deposition is negated by polishing the surface prior to the structural layer deposition.



*Without CMP (left image), With CMP (right image)
[Scanning Electron Microscope (SEM) images courtesy of Sandia National Laboratories]*

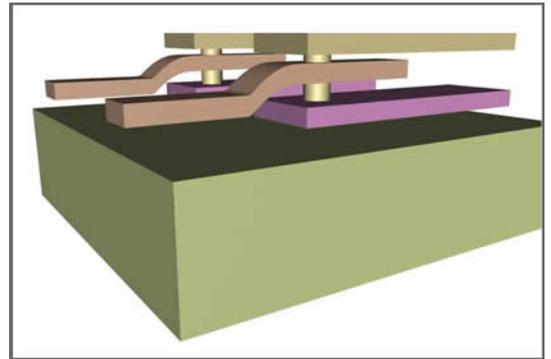
Building a MEMS using Surface Micromachining

The linkage system in the graphic is an example of a surface micromachining process that requires several structural and sacrificial layers. During fabrication, the sacrificial oxide layers define the components' topographical shapes (structural layers) and the vertical spaces between them. Let's take a look at how such a device is fabricated.

- A sacrificial (oxide) layer is first deposited on the substrate.
- The first polysilicon layer is deposited on top of the oxide layer.
- This polysilicon layer is patterned and etched and forms the first set of cantilevers.
- A second oxide layer is deposited on top of the etched polysilicon layer.
- The second structural layer or polysilicon layer is deposited, patterned and etched. This forms the second set of cantilevers.
- The third oxide layer (sacrificial layer) is deposited.
- At this point, the surface has become extremely bumpy; therefore, this oxide deposition is followed by a CMP.
- Two holes are etched through the top oxide layer providing an opening to the polysilicon layer below it. These holes are needed to begin forming the posts which support the cantilevers and allow rotation.
- To continue fabricating the posts, holes are etched into the second polysilicon layer.
- Another layer of oxide is deposited on the surface and into the two holes. This is the last sacrificial layer.
- The third polysilicon layer is now deposited, patterned and etched. This layer forms the top set of cantilevers.
- The oxide films below each structural layer provide the necessary space for the middle cantilever to move after all of the oxide layers have been removed and the cantilevers released.
- The last step of this process is to remove the oxide layers from between the structural layers using a wet etch process of a hydrofluoric acid (HF) solution.
- Once the sacrificial layers are removed, the middle cantilever is free to rotate.

These steps - 1) oxide deposition, 2) structural layer deposition, pattern, etch, 3) sacrificial etch – can be repeated several times when fabricating a complex moving structure such as the linkage system, a gear transmission, an accelerometer, and other MEMS devices.

To view a step-by-step presentation of this process, stop here and watch the narrated presentation “Linkage Assembly Fabrication”.



[Graphic image courtesy of Khalil Najafi, University of Michigan]

An important advantage of using surface micromachining over bulk micromachining is that it is very compatible with CMOS processing. This compatibility allows mechanical devices to be built at the same time as the electronic logic circuits. Also, the cost of fabrication is generally lower since this technology uses the same equipment as the semiconductor industry. Many MEMS startup companies purchase used equipment from the semiconductor industry allowing for lower startup costs. MEMS component parts are generally 1 micron or larger in scale which is compatible with 1990's semiconductor equipment capabilities. *(Note: Simultaneous fabrication of electronic logic circuits and mechanical components require the logic circuits to be encapsulated before the mechanical release step of the process; otherwise, the silicon dioxide insulation for the logic circuits would be etched along with the sacrificial layers for the mechanical components.)*

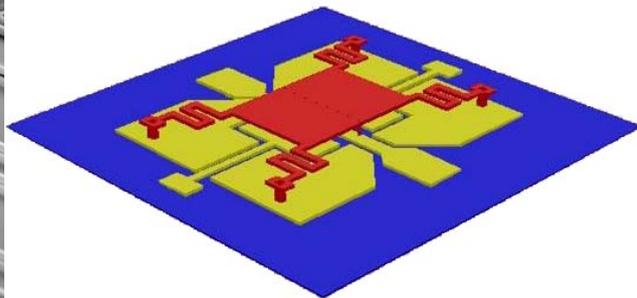
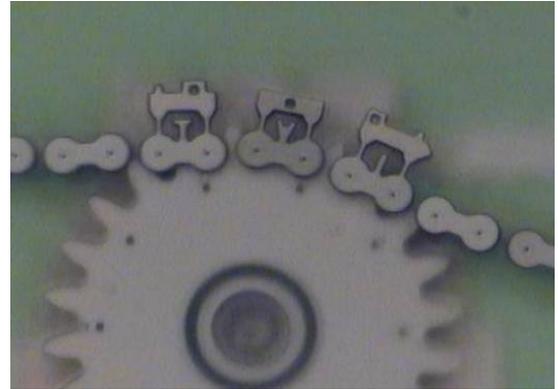
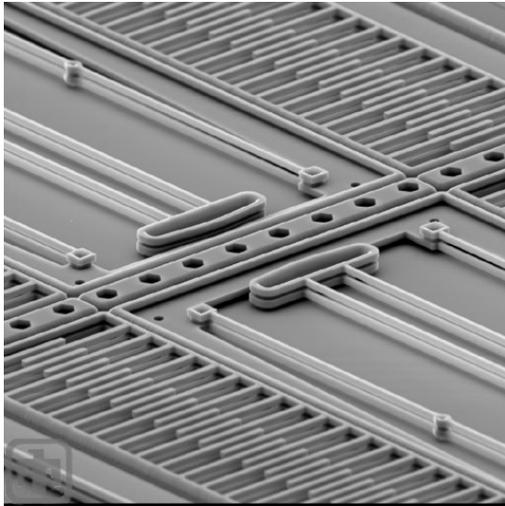
The downside of surface micromachining is that the mechanical components are very close together (a few microns) and they are flat. This can cause stiction. Stiction occurs when two, very flat surfaces come into contact and stick together; often, the two parts cannot be separated.

A limitation of surface micromachining is that its processes can generally create only low aspect ratio devices, which is ideal for comb drives and gear drives. However, MEMS devices such as micro-channels and reservoirs require high aspect ratios; therefore, other micromachining processes are required.

Surface Micromachining Components

In spite of its limitations, surface micromachining is used to fabricate many MEMS components:

- Comb Drives (*Below left*)
- RF Switch (*center*)
- Gears and chains (*Right*)
- Surface acoustical wave (SAW) sensors
- Inertial sensors
- Cantilevers
- Torsional Ratcheting Actuators (TRA)

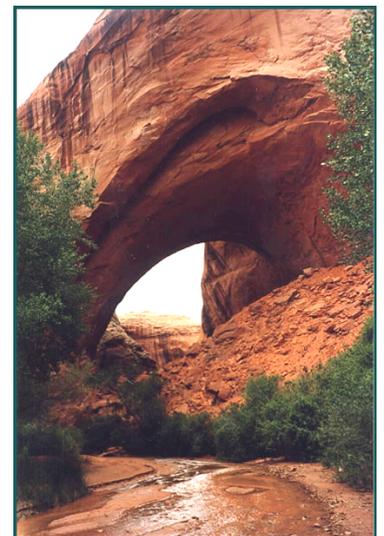


[Comb Drive SEM courtesy of Sandia National Laboratories, Gear and chain image courtesy of SCME, designed by CNM student, Paul Tafoya, RF Switch graphic courtesy of SCME]

Bulk Micromachining

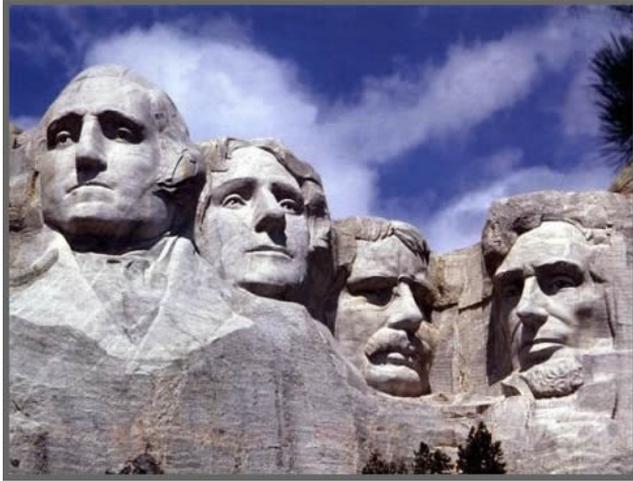
Bulk micromachining is a process that defines structures by selectively removing or etching into a substrate. This is not a new concept. In fact, bulk etch has existed in nature for eons. Have you ever seen a natural bridge or arch like the natural arch shown in the picture to the right? This arch was formed by water and wind eroding (or etching) into and eventually, through the sandstone.

*Natural Arch, Coyote Canyon, Utah
[Photo courtesy of Bob Willis]*

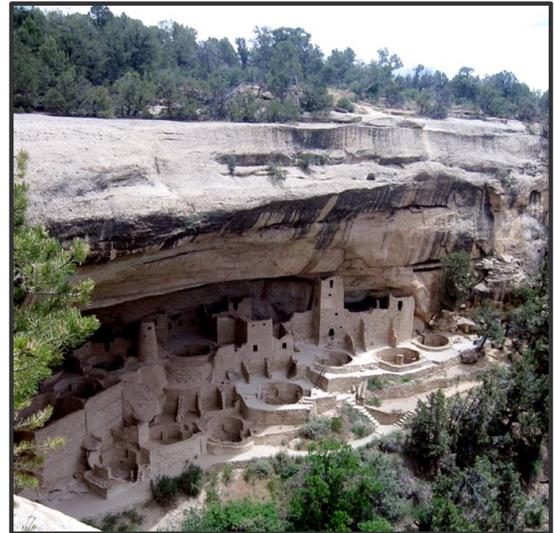


The men that carved the faces into Mt. Rushmore (*below left*) and the native Americans that constructed cliff dwellings (*below right*) into the side of mountains used an bulk etch process. Imagine what it took to start with a flat surface like the side of a mountain and end up with such definitive structures as the ones seen in the pictures below. When you look carefully at these pictures you can see that bulk etching is a subtractive

process as well as a highly selective process. These are not random carvings.



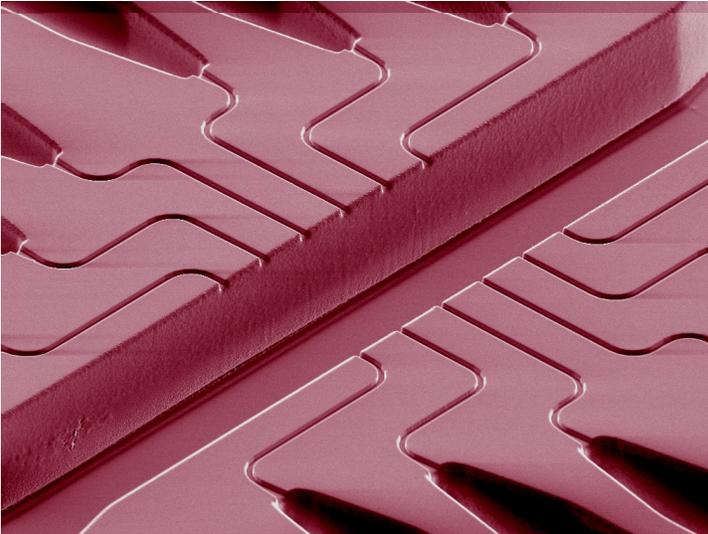
*Mt. Rushmore, South Dakota
[Photo courtesy of the National Park Service]*



*Mesa Verde National Park, Colorado
[Photo courtesy of the Barbara Lopez]*

In MEMS fabrication bulk micromachining uses the entire thickness of the silicon wafer (or substrate) to form microsystem structures that can result in high aspect ratios. In bulk micromachining monocrystalline silicon wafers are selectively etched to form 3-D MEMS devices. Bulk micromachining is used to

- remove relatively large amounts of a silicon substrate,
- construct high aspect ratio structures such as fluidic channels and chambers (*see image below*), alignment grooves, and
- construct sensors including micro pressure sensors, cantilever arrays, and accelerometers. Some of these latter components are fabricated using both bulk and surface micromachined components.

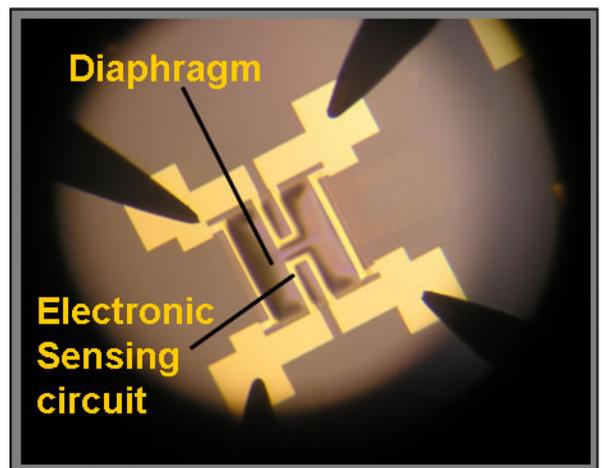


Microfluidic channels with high aspect ratio fluidic chambers [SEM Image courtesy of Berkeley. Ref: C. Ionescu-Zanetti, R. M. Shaw, J. Seo, Y. Jan, L. Y. Jan, and L. P. Lee (PNAS, 2005)]

The Bulk Micromachining Process

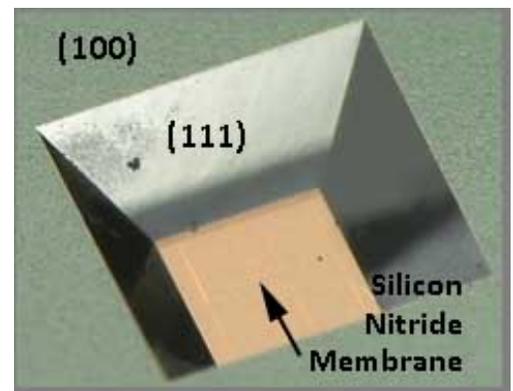
Bulk etch is a subtractive process in which the silicon substrate is selectively removed. Specific etchants are chosen that remove substrate material either isotropically (the same in all directions) or anisotropically (not the same in all direction). The anisotropic wet etching of silicon takes advantage of the crystalline structure of the silicon wafer to remove select material following the planes of the silicon crystal. This selectivity is possible due to the knowledge that certain plane orientations etch much faster than other planes (e.g., the (100) plane etches approximately 400 times faster than the (111) plane).

An example of bulk etching in MEMS fabrication is in the construction of a MEMS pressure sensor. A MEMS pressure sensor (*right*) consists of a silicon nitride thin film deposited onto the surface of a silicon substrate. This layer of silicon nitride acts as the diaphragm or membrane of the pressure sensor. A thin film of gold is deposited on top of the silicon nitride, then patterned and etched to form a Wheatstone bridge sensing circuit. In order for the membrane to move up and down with changes in pressure, it must be “released”. To release the membrane, the silicon substrate beneath the membrane is removed by etching the backside of the wafer.



[Pressure Sensor image courtesy of MTTC/UNM]³

The picture to the right shows the backside of a MEMS pressure sensor and the result of a bulk etch using a solution of potassium hydroxide (KOH) and water. The KOH etchant solution selectively etches the crystalline silicon along a specific plane. In the picture you can see that the etchant preferentially etched the (100) plane of the silicon (the wafer surface in this case) while simultaneously etching the (111) plane. The (111) plane etches about 400 times slower than the (100) plane. This allows for a controlled etch in which an inverted pyramid shaped opening of a specific size is created. The etch of the (100) plane stops when it hits the silicon nitride which is impervious to the KOH. For the purpose of this etch, the silicon nitride layer is the etch stop layer. For the purpose of the pressure sensor, the silicon nitride serves as the membrane or diaphragm on which the sensing circuit is constructed.

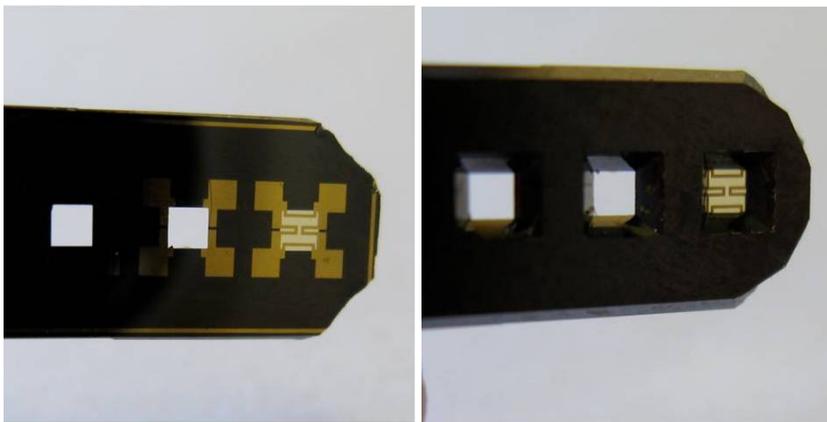


Bulk Combined with Surface Micromachining

The previous example of the pressure sensor is actually a MEMS fabrication process that uses both bulk micromachining and surface micromachining. Bulk etch is used to remove a select section the thickness of the substrate from beneath a patterned thin film (silicon nitride). Surface micromachining is used to pattern the backside as well as to create a metal electronic sensing circuit on the frontside of the wafer. Below is the process used to fabricate this MEMS pressure sensor.

- A thin film of silicon nitride is deposited onto both sides (frontside / backside) of the wafer.
- The backside nitride is patterned and plasma etched creating the openings for the chamber (the inverted pyramid shown in a previous image). In this application the silicon nitride is used as a hard mask.
- Prior to creating the chambers within the substrate, the metal electronic sensing circuit is fabricated on the frontside silicon nitride. The surface micromachining processes - deposition, pattern and etch – are used to create the electronic sensing circuit by depositing chrome, then gold thin films on top of the silicon nitride, patterning the chrome/gold layers, then etching the chrome/gold to form the electronic circuit.
- The last step is to anisotropically etch the backside chambers using a potassium hydroxide (KOH) solution. For this bulk etch process, the backside silicon nitride acts as a patterned mask, while the frontside silicon nitride is the etch stop (i.e., the anisotropic etch stops when all of the silicon is removed within the holes of the mask and the frontside silicon nitride is reached).
- The frontside silicon nitride directly over the backside chamber operates as the pressure sensor's diaphragm because it can now deflect up or down with changes in pressure.

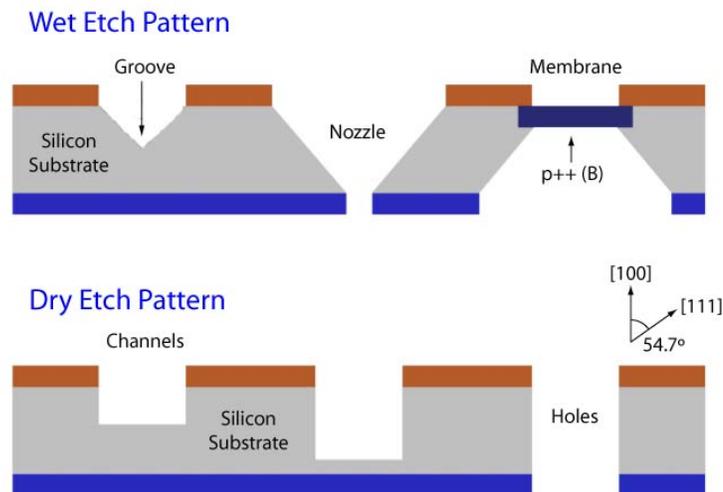
The images below show the frontside and backside, respectively, of a finished pressure sensor (far right circuit in both images).



MEMS pressure sensor frontside (left) showing electronic sensing circuit etch in a gold film layer and backside (right) showing the chamber (look closely and you can see the beveled edges). [Images courtesy of UNM/MTTC]

Wet and Dry Etch in Bulk Micromachining

Wet and dry etch techniques have been developed to provide the various shapes needed for MEMS devices. (See graphic below) Grooves and slots are used in assembly, such as putting multiple wafers together with different devices on each wafer. V-shaped grooves are also used to finely align fiber optics to micro optical components. Nozzles are used for devices such as inkjet printheads, cavities for open volumes or chambers in pumps or voids under membranes, and channels to pass fluids through. These shapes are formed by using different processes that create either an isotropic or anisotropic profile.

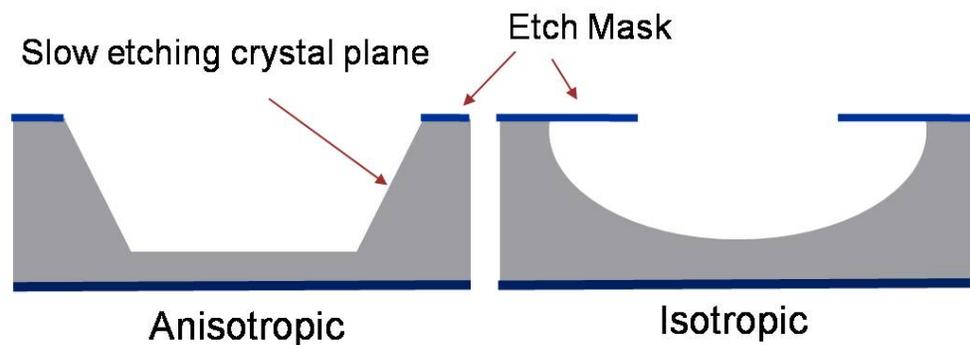


Anisotropic vs. Isotropic Profiles

Bulk micromachining uses etch processes that result in both isotropic and anisotropic etch profiles. The result (isotropic or anisotropic) depends on the etchant used and the selectivity of that etchant to the material being etched.

Anisotropic etches prefer one direction over another and may be dependent upon the crystalline structure (crystal orientation) of the substrate. As you saw previously with the backside etch of the pressure sensor, the etch process etches certain planes more rapidly than others (i.e., the (100) plane faster than the (111) plane). This etch rate selectivity where the selectivity varies with crystal plane orientation, provides the ability to use anisotropic etching techniques to produce specific shapes such as pyramidal cavities and v-shaped trenches.

Isotropic etch does not prefer a given direction over another. This is an etch equal in all directions as illustrated in the graphic. The typical cross sectional profile is that of a champagne glass or concave shape. It is not dependent upon crystal orientation, but rather upon the ability of the etchant to react with the material to be etched creating a volatile by-product that detaches from the wafer. Isotropic etching is characterized by its distinct profile and its undercutting of the thin film used as the etch mask. Isotropic profiles can be achieved using both wet and dry etch processes. A wet isotropic etch is used to removed the sacrificial layer from underneath a structural layer. A dry isotropic etch is used to create some of the structures and shapes needed for MEMS. The graphic below illustrates the isotropic profile versus the anisotropic profile. Anisotropic profiles can also be the result of a dry plasma reactive ion etch. The side-walls can be vertical or at an angle to the wafer plane.



Wet Etch Anisotropic Etchants

In bulk micromachining wet etching can result in either isotropic or anisotropic structures depending upon the etchant and the material being etched. The following etchants yield anisotropic profiles when etching crystalline material such as silicon:

- Potassium Hydroxide (KOH)
- Ethylene Diamine Pyrocathechol (EDP)
- Tetramethyl Ammonum Hydroxide (TMAH)
- Sodium Hydroxide (NaOH)
- $N_2H_4-H_2O$ (Hydrazine)

Costs, etch rates (i.e., how fast something etches), resulting surface roughness, selectivity between the mask material and material to be etched, relative etch ratios between the different crystal planes, safety issues, and process compatibility are some of the variables used when selecting one etchant over another.

Dry Etch

Dry etch bulk processes use reactive vapor etchants usually in a plasma environment, or through bombarding the exposed substrate by sputtering with high energy particles. Dry etch is generally well controlled and capable of higher resolutions than wet etch. Dry etch can produce both isotropic and anisotropic profiles with critical dimensions much less than 1 μm .

Compared to wet etch tools, tools used for dry etching are more expensive and usually have a larger footprint, taking up more space in the manufacturing area. Dry etch does not leave large quantities of hazardous liquids needing to be properly disposed of; however, some of the etchants and the etched by-product (exhaust gasses) can be quite hazardous, requiring filters and neutralization systems..

Four dry etch processes used in bulk micromachining include the following:

- Deep Reactive ion etch (DRIE)
- Isotropic Plasma Etching
- Sputter Etching (ion milling)
- Vapor Phase Etching

Bulk Micromachining Components

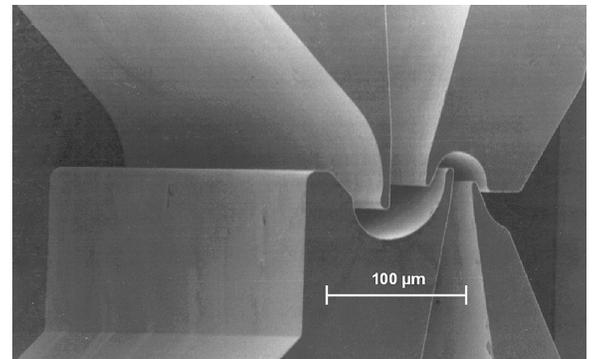
The following components are MEMS structures that are possible only through the use of bulk micromachining processes.

- Cantilever Arrays
- Nozzles
- Microfluidic channels
- Needle Arrays
- AFM Probes
- Membranes
- Chambers
- Through wafer connections

LIGA

(Lithographie (Lithography), Galvanoformung (electroforming), and Abformung (molding)).

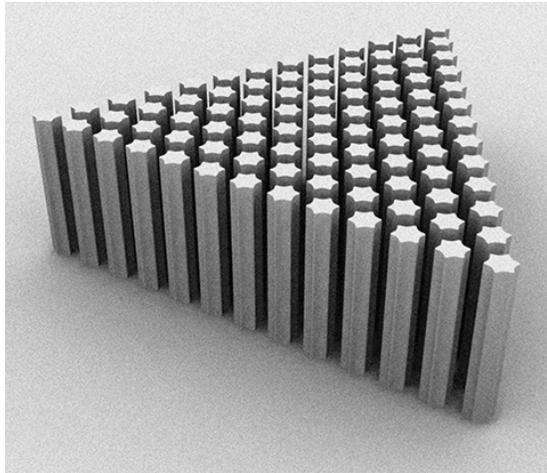
LIGA was developed in the early 1980's at the Karlsruhe Nuclear Research Center in Germany to produce nozzles for uranium enrichment processes. The image to the right is a SEM of one of these nozzles.⁵



LIGA micromachined nozzles
[Image courtesy of Wenn du Benutzer Captain Bligh,
Source: Wikipedia]

LIGA is an additive, lithographic process which allows for the fabrication of complex, three dimensional structures with very high aspect ratios exceeding 100:1.⁶ These structures can have sub-micron size features with heights of several millimeters and widths of only a few microns (e.g., probes, pin, electrodes, gears, waveguides, and molds). LIGA is also a type of HARMST process – High Aspect Ratio Micro-Structure Technology. LIGA molds allow for mass-production of micro-sized HARMST components. These components as well as other LIGA components can be fabricated using polymers, metals and moldable materials.

The graphic below illustrates high aspect ratio posts that can be fabricate using the LIGA process and made from a variety of different materials.



LIGA uses the collimated x-rays produced by synchrotron radiation to illuminate thick x-ray sensitive materials such as PMMA (polymethylmethacrylate), also known as acrylic glass or Plexiglas. As with a basic photolithography process, the PMMA layer is patterned under a lithographic mask using an x-ray exposure. Instead of a mask consisting of a chrome pattern on quartz as in UV photolithography, LIGA utilizes gold on beryllium as the mask materials. Gold blocks x-rays while the beryllium is transparent to x-rays. The PMMA is exposed by the x-rays and the pattern is developed (like photoresist). Since the x-rays are well collimated, they travel in a straight line and have a large depth of focus. This results in patterning sharp, tall, thin or deep structures or cavities within the PMMA after the develop process. Nickel and other metals are electroplated into these cavities. After electroplating, the PMMA is removed leaving the metal structures. These structures can be used individually, or as stamps, or molds to create thousands of like structures in plastic. Hot plastic embossing and injection molding are used with the LIGA fabricated molds.



*This LIGA micromachined gear is used for a mini electromagnetic motor
[Image courtesy of Sandia National Laboratories]*

LIGA Process

The LIGA process consists of the following basic steps:

- Expose
- Develop
- Electroform (Electroplate)
- Strip
- Replicate or Release

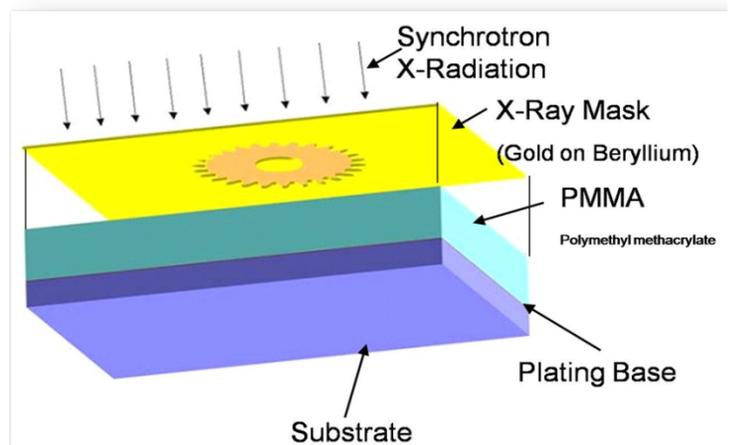
Let's take a look at each of these steps.

Expose

Once the PMMA is applied to the substrate or base, synchrotron radiation patterns the PMMA through a gold on beryllium mask. Like photoresist, the radiation modifies the PMMA so that the exposed material can be removed with a suitable or selective developer solution.

The graphic shows the radiation, the mask and the PMMA layer. The mask has the pattern of a micro-gear.

[Graphic courtesy of HT MicroAnalytical, Inc.]



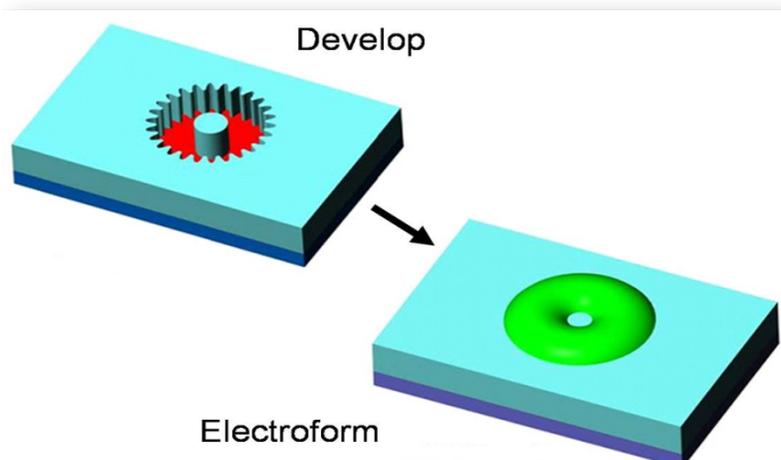
Develop

With the use of a developer solution, the exposed PMMA is removed leaving a mold with high aspect ratio cavities, holes, or trenches. *[Top graphic]*

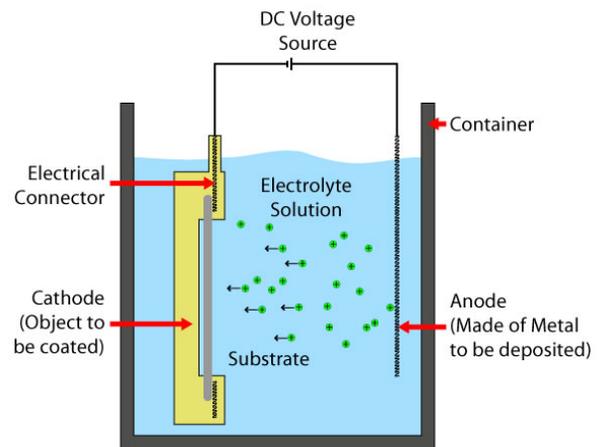
Electroform

The cavities created in the develop step are filled with a metal (e.g., nickel, copper, gold, or various alloys) through electroforming processes.

[Graphics courtesy of HT MicroAnalytical, Inc.]



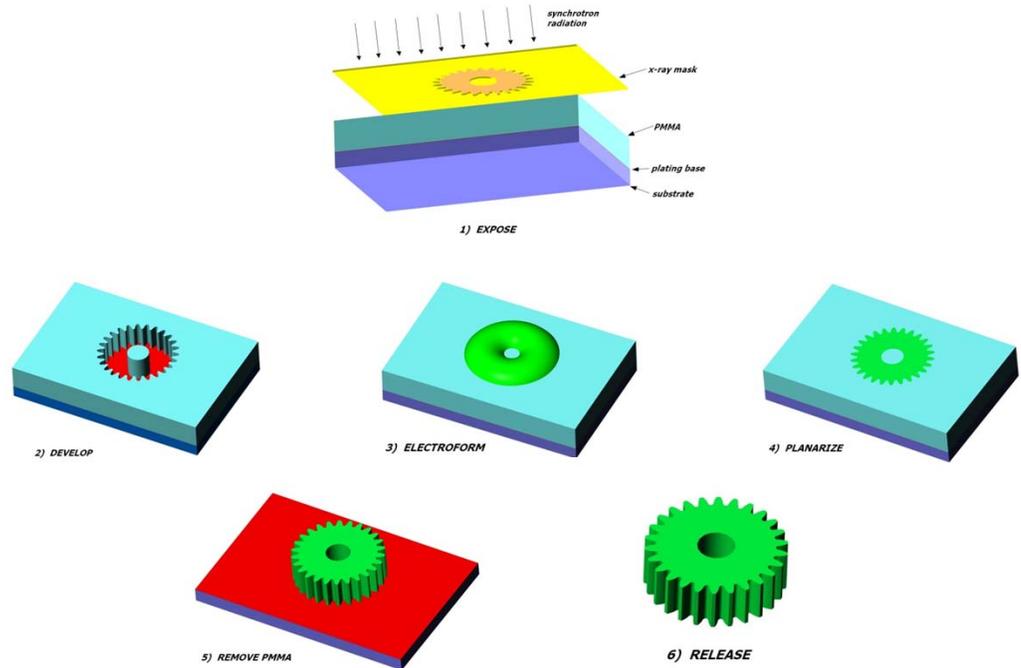
Electroforming is “the fabrication of simple and complicated components by means of electroplating.”² Electroplating (*graphic right*) is a process in which a positive and a negative electrode are submerged in an electrolyte solution. The negative electrode (i.e., cathode) is the object or holds the object or substrate to be coated. In LIGA fabrication the cathode (also referred to as the mandrel) is the 3-D PMMA structure that is formed by the expose and develop processes.



During electroplating metallic positive ions (cations) released from the anode are attracted to the negatively charged cathode. When the cations reach the substrate they are neutralized by the electrons of the cathode, reducing them to metallic form. This process continues until the substrate is coated with the desired thickness.

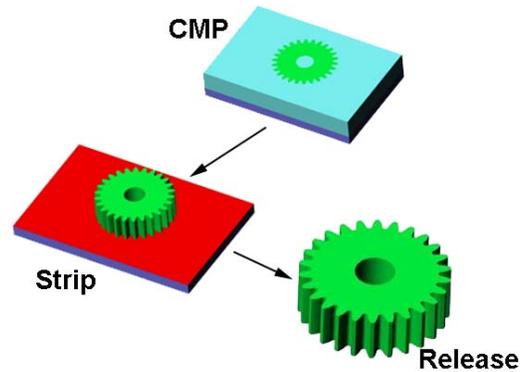
Electroforming differs from electroplating in that it yields a much thicker layer of metal on the substrate or mandrel than the electroplating processes. In electroforming a metal object is produced (or reproduced) by coating the mandrel with the desired thickness of metal. At the end of the process, the mandrel may be removed, resulting in a self-supporting object. In electroplating the substrate is coated with a thin layer of metal that adheres to the substrate becoming a permanent part of the object (e.g., chrome faucet, jewelry, hardware).

The following graphic illustrates how the mandrel takes shape after the develop step (2) of LIGA fabrication. In the electroforming process, metal is deposited within the cavity using the process of electroplating. However, the electroplating process continues (in this case) until the cavity is completely filled. Once the surface has been planarized, the PMMA removed and the metal form released, a self-supporting object remains, in this case – a metal microgear. [Graphic courtesy of HT MicroAnalytical, Inc.]



Strip

After electroforming a CMP may be performed to flatten the surface. Once the surface has been polished (planarized), the PMMA is removed or stripped. Depending on the component, the remaining structure could be used to make molds or the end product. The graphic shows these three steps (CMP, strip, release) for a microgear.



[Graphics courtesy of HT MicroAnalytical, Inc.]

View an animation of this entire process at <https://youtu.be/CbN7h3o51Zo> .

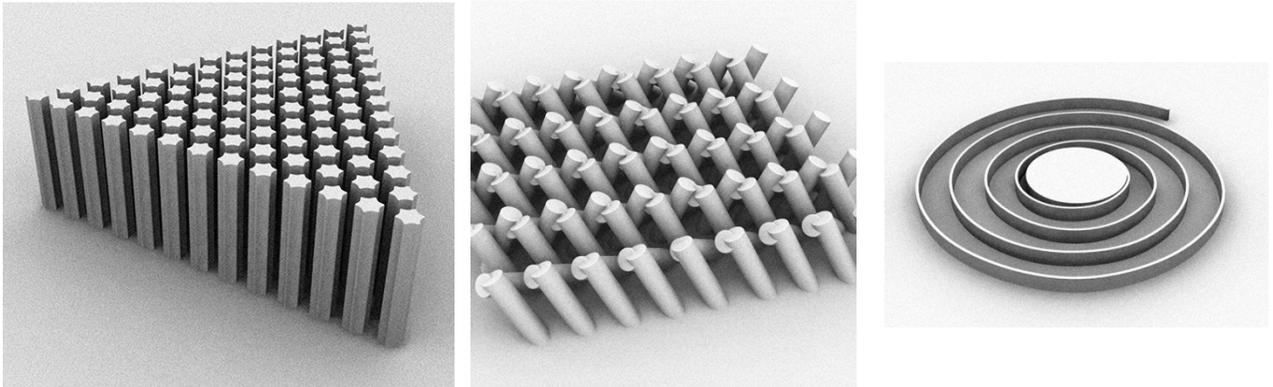
The LIGA process enables the creation of micro-sized high aspect ratio components that are

- free-standing,
- attached to the substrate, or
- metal inserts for injection molding.

LIGA's ability to incorporate “multi-layer wafer-scale processing extends the additive approach to accommodate interfaces and packaging.” LIGA components require extensive, unique metrology to ensure quality products.⁸

What type of MEMS components would fall into these three categories and would probably be fabricated using LIGA processing?

Here are some graphics of parts and structures that can be build using LIGA micromachining processes. Note the very high aspect ratios. What are some of the applications that would require such tall structures?



The left image represents high aspect ratio posts. Such posts can be fabricated from a LIGA mold or build into the PMMA and released. The middle image represents angled structures that can be fabricated using a LIGA process. Again, notice the high aspect ratio of the components. The right image is of a coiled spring. This would be a very difficult component to fabricate using surface or bulk micromachining. However, such components are possible with a LIGA process.

Just for fun - This is probably the most famous LIGA SEM in the world – it has been attributed to Rorschungzentrum Karlsruhe, Germany.



Ant with a LIGA micro-gear. [Image courtesy of Rorschungzentrum Karlsruhe, Germany]

Summary

MEMS fabrication (also called micromachining) has allowed for the manufacturing of micro-sized devices which has also enabled nanotechnology, at lower cost and increased reliability when compared to macro-sized equivalent components. Such devices can be fabrication on top of substrates, within substrates, or molded and bonded depending on the micromachining processes used. Three widely used micromachining processes are

- surface micromachining
- bulk micromachining, and
- LIGA (**L**ithography, **G**alvano**f**ormung, and **A**bformung).

Food for Thought

Discuss the differences and similarities between the three micromachining processes discussed in this unit. Include details as to the pro's and con's of the processes: relative cost of each process, complexity, types of structures etc.

For each micromachining process, identify at least three MEMS or MEMS components that could be fabricated.

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Glossary

Anisotropic etch – this etch is highly directional. The etch rate varies with direction resulting in straight or sloped sidewalls. An example of a wet anisotropic etch is the application of KOH solution to silicon crystal; the etch rate of the (110) plane is approximately 400 times faster than the etch rate along the (111) plane.

Aspect ratio - The height of an etched feature divided by its width in the case of a tall structure, or the width divided by the depth in the case of a channel.

Bulk etch - A subtractive process in which the silicon substrate is selectively removed in relatively large amounts.

Bulk Micromachining - A process that defines structures by selectively removing or etching inside a substrate. This results in deep channels, or large, free-standing structures.

Chemical Mechanical Polishing (CMP) – A process used to flatten the topography of the wafer's surface as new layers are deposited.

Deposition - A process that deposits a material onto an object. Typically, thin films are deposited in Microsystems fabrication using chemical vapor deposition, physical vapor deposition (evaporation) or even oxide growth.

Electroforming – A process used to coat an object with a metal or metal alloy. This process uses a positive and negative electrode submerged in an electrolyte solution. This is similar to electroplating but provides for thicker coatings. The resulting structures are often used as a stamp or mold used in hot-plastic embossing or injection molding, respectively.

Electroplating - The process of using electrical current to coat an electrically conductive object with a layer of metal. The film is typically much thinner than what is done in electroforming.

Isotropic Etch – Etching is done at the same rate in all directions. Resulting structures have concave cross-sections, bowl-shaped.

LIGA (Lithography, Galvanoförmung, and Abförmung) - An additive, lithographic process which allows for the fabrication of complex, three dimensional structures with very high aspect ratios exceeding 100:1.

Oxidation - The process used to grow a uniform, high quality layer of silicon dioxide (SiO₂) on the surface of a silicon substrate.

Photolithography - The transfer of a pattern or image from one medium to another, as from a mask to a thin film deposited on a silicon wafer.

Release etch – An etch process designed to remove material (sacrificial layer or bulk material) from underneath the structural layer without affecting the structural layer itself. The removed sacrificial layers provide space so the mechanical parts can move.

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)

Surface micromachining - A micromachining process that uses layers of thin films deposited on the surface of a substrate to construct structural components for MEMS.

Synchrotron – A type of cyclic particle accelerator that synchronizes a magnetic field and electric field with a traveling particle beam.

Synchrotron radiation – The electromagnetic radiation emitted by charged particles moving close to the speed of light within a synchrotron.

x-ray – A form of electromagnetic radiation having a wavelength in the range 0.01 nanometer (nm) to 10 nm.

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