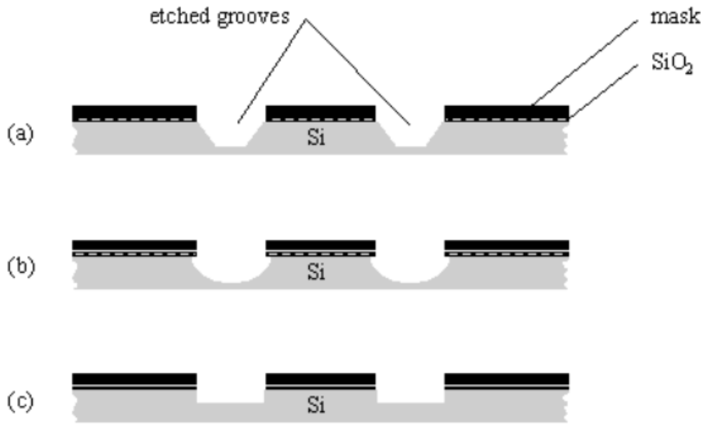
BULK MICROMACHINING

Bulk micromachining is the oldest paradigm of silicon based MEMS. The whole thickness of a silicon wafer is used for building the micro-mechanical structures.Silicon is machined using various etching processes. Anodic bonding of glass plates or additional silicon wafers is used for adding features in the third dimension and for hermetic encapsulation. Bulk micromachining has been essential in enabling high performance pressure sensors and accelerometers.

The term bulk micromachining comes from the fact that this type of micromachining is used to realize micromechanical structures within the bulk of a single-crystal silicon wafer by selectively removing ('etching') wafer material. The microstructures fabricated using bulk micromachining may cover the thickness range from submicron to full wafer thickness (200–500 μm), and the lateral size range from submicron to the lateral dimensions of a full wafer. Bulk micromachining technique allows to selectively remove significant amounts of silicon from a substrate to form membranes on one side of a wafer, a variety of trenches, holes, or other

Bulk micromachining technique can be divided into wet etching and dry etching of silicon according to the phase of etchants. Liquid etchants, almost exclusively replying on aqueous chemicals, are referred to as wet etching. Vapor and plasma etchants are referred to as dry etching. For etching such thick silicon substrate, anisotropic wet etchants such as solutions of potassium hydroxide (KOH), ethylene diamine and pyrocatechol (EDP), tetramethylammonium hydroxide (TMAH), and hydrazine-water are used. These etchants have different etch rates in different crystal orientation of the silicon . Wet etching in mostcase is done from the back side of the wafer while the plasma etching is being applied to front side.Etch process can be made selective by the use of dopants (heavily doped regions etch slowly) or may even be halted electrochemically (e.g., etching stops upon encountering a region of different polarity in a biased p–n junction). A region at which wet etching tends to slow down or diminish is called an etch-stop. Wet etching occurs by dipping substrate into an etching bath or spraying it with etchants that may be acid or alkaline. Wet etching can either be isotropic etching or anisotropic etching depending on the structure of the materials or the etchants used. If the material is amorphous or polycrystalline, wet etching is always isotropic etching. During isotropic etching (etchants used are acid solution), resist is always undercut, implying that the deep etching is not practical for MEMS.



Etched grooves using (a) anisotropic etchants, (b) isotropic etchants, (c) Reactive Ion Etching (RIE)

Isotropic Etching

Isotropic etching uses very strong acids for attacking the Si, resulting in rounded patterns grooved into the substrate material because of the equal etch rate in all directions. Rates of up to 50 microns per minute can be achieved (about 100 times faster than anisotropic etching). The rate depends on the concentration of the acid used and the processing temperature as well as on the grade of agitation applied to the sample while etching. Because the etch rate depends on agitation, difficulties occur when controlling the exact extend of the etched structure.

The most common etchants are mixtures of hydrofluoric acids (HF) and nitric acid (HNO_3) with either water or rather acetic acid being used as diluent. A solution of this kind is often referred to as *HNA*system. Since the etch rate of SiO_2 is high (300 to 800 Å/min), either thick layers of oxide or alternative masking layers like silicon nitride (Si_3N_4) are needed when etching deeper patterns into the substrate. Otherwise the accuracy of the mask could be affected in a negative way, resulting in poor resolution of the etched profile.

Since the etchant attacks the Si equally in every direction, it takes away the material horizontally as well, thus undercutting the masking layer on top. The longer the sample remains in the etch bath, the stronger this effect, since the etch rate is all the same in every direction, making masking a difficult task when etching isotropically.

A common means for cleaning a plain wafer before doing any kind of process is immersing it in a piranha etch (H_2O_2:H_2SO_4, concentration varying between 1:1 and 4:1) to remove impurities on top of the sample. The acid does not affect Si itself, developing a thin film of oxide instead when brought in contact.

The *BHF* solution mentioned above for patterning the oxide mask also belongs to the category of isotropic etchants.

Anisotropic Etching

Anisotropic etching techniques were developed later than their isotropic relatives. The most important attribute of anisotropic etch is their ability to control the lateral extensions of the etched profile. In contrast to the isotropic etchants, anisotropic etchants attack the substrate material depending on its crystalline structure, thus revealing very precise structures when applied correctly. They were developed in the 1960s by Bell Laboratories.

Common chemicals used in anisotropic etching processes are:

Potassium hydroxide (KOH)/H_2O solutions, sometimes with ispropyl alcohol (IPA) additive at 65-85°C

Ethylene diamine pyrocatechol (EDP), diluted with water at 115ºC

Tetramethyl ammmonium hydroxide (TMAH) and water at 90ºC

Hydrazine N_2H_4/H_2O/IPA at 115ºC

The etchants differ with respect to their specifications regarding handling, toxicity, and appropriate masking material. Again, the etch rate depends on the concentration of the solution used, higher concentrations generally slow down the etching process, since the water is needed in the etching process as an oxidizing agent for silicon.

KOH is the most popular etchant. It can be used in near saturated solutions with processing temperatures of up to 80°C; higher temperatures affect the etch uniformity and produce unwanted fumes. A disadvantage of this chemical is the fact that its etch selectivity between Si an SiO_2 is too low, resulting in mask layers made of oxide being attacked quickly. Therefore, for this process, alternative masking materials are needed, adding additional process steps to the fabrication process. Like applying to the isotropic HNA etching system, Si_3N_4 is an appropriate material for masking, staying untouched by the KOH etchant. While the etching is in progress, the development of bubbles that consist of hydrogen set free by the reaction occurs. When too great in numbers, these bubbles can prevent parts of the solution from keeping in touch with the substrate's surface, leading to an increase in surface roughness. This especially happens at long etch times when using solutions of high concentration. Agitation of the immersed sample reduces this problem. KOH can cause blindness in contact with the eyes, but is less hazardous than most of the other etching solutions.

TMAH is the newest of the etching solutions mentioned above. Being non-toxic, its handling is easy compared to the other etchants. The appropriate concentration is chosen by weighing surface smoothness against etch rate, since the first is better with more saturated solutions, whereas the latter rises with the amount of water present in the solution. A value of approximately 22 wt% is usually a reasonable compromise between these two factors. The disadvantage of TMAH is its lower etch rate of Si, compared to the other chemicals.

Hydrazine was the first anisotropic etchant. It is explosive at concentrations of 50 % and above in solution with water and very toxic (suspected to cause cancer). For this reason it is hardly in use anymore, having been replaced by EDP in most cases which is less hazardous. The surface quality of the produced structures is very good, depending on the water concentration and the temperature of the solution. Silicon oxide nearly is not attacked and therefore often used as masking material, as well as many metallic films.

The organic etchant EDP was developed to replace the hard to handle hydrazine, providing a more stable and less toxic means for anisotropic etching processes. SiO_2 can be used as masking material, since with EDP the etch selectivity between Si and its oxide is very good. Selectivity is also good between Si and various other materials, e. g., gold, chromium, silver, copper or silicon nitride, making this etchant pretty flexible in this respect. But the solution is toxic and has to be handled with great care. It ages fast, especially in the presence of oxide, resulting in an optically denser liquid with considerably lower etch activity.

In general, etch rates of anisotropic etchants are considerably lower than those of isotropic processes, mostly being slower than 1 μm/s. Etching deep structures of some 100 microns into the bulk of a substrate material therefore is far more time consuming when using anisotropic etchants, demanding processing times of several hours. This requires a careful choice of the masking material to prevent the etched structure to get too imprecise due to the mask layer being attacked to hard by the etchant. In some cases, surface roughness is too high, making a short isotropic etch advisable after the anisotropic process for smoothing purposes.

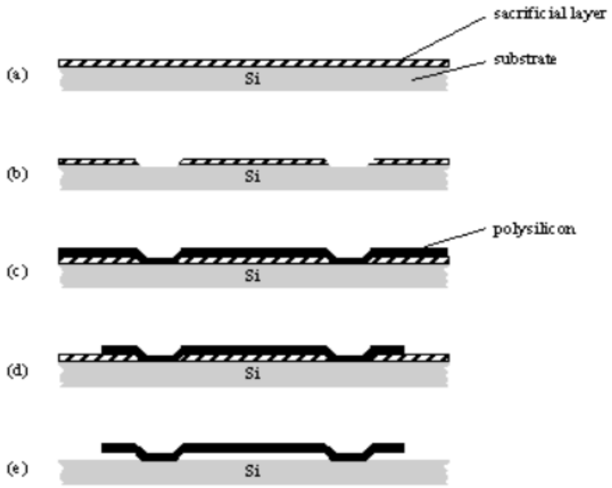
For both isotropic and anisotropic etching proper protection of the backside of the wafer is required. This can be done mechanically by keeping it in a special holder that prevents the backside to get exposed to the liquid. Or, it is possible to coat it with a chemical protection layer, e. g., waxes.

SURFACE MICRO MACHINING

In contrast to the bulk micromachining described above, where three-dimensional structures are etched into the substrate wafer, surface micromachining consists of building them by layering thin films of new material onto the surface of the substrate. Usually, sacrificial spacer layers are used to create freestanding structures like air-bridges; after depositing such a sacrificial layer and patterning it using microlithographic steps described above, the material for the final structure is deposited. Afterwards, the spacer layer is removed by an appropriate etchant, freeing the desired structure.

Surface micromachining was invented in the late 1960s, when a cantilever beam was produced by underetching the applied material on top of a sacrificial layer. The techniques used in this area emerged in the early 1980s, using polysilicon as structural material. Many different structures created using surface micromachining have been demonstrated, e. g., springs, gears, sliders and sealed cavities. However, the first commercial application based on this process was announced 1991 by Analog Devices (an accelerometer for the automobile industries).

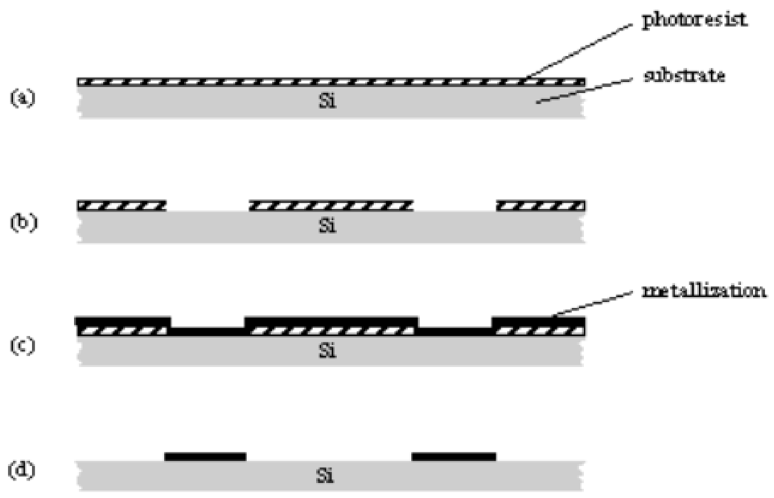
Surface micromachining uses layers deposited on the surface of a substrate as the structural materials, rather than using the substrate itself. Surface micromachining was created in the late 1980s to render micromachining of silicon more compatible with planar integrated circuit technology, with the goal of combining MEMS and integrated circuits on the same silicon wafer. The original surface micromachining concept was based on thin polycrystalline silicon layers patterned as movable mechanical structures and released by sacrificial etching of the underlying oxide layer. Interdigital comb electrodes were used to produce in-plane forces and to detect in-plane movement capacitively. This MEMS paradigm has enabled the manufacturing of low cost accelerometers for e.g. automotive air-bag systems and other applications where low performance and/or high g-ranges are sufficient. Analog Devices has pioneered the industrialization of surface micromachining and has realized the co-integration of MEMS and integrated circuits.



Basic surface micromachining process. (a) Spacer layer deposition. (b) Pattering of the spacer layer. (c) Deposition of the microstructure layer. (d) Patterning of desired structure. (e) Stripping of the spacer layer resolves final structure.

The steps for producing the air-bridge are clearly visible. Different materials can be used for the spacer layer, with photoresist being the simplest choice, reducing the steps necessary for patterning. Photoresist can be exposed with an appropriate mask and simply developed, revealing the structure needed for the following deposition of the microstructure layer. If a metallic material is used for this purpose, often a seed layer is deposited in order to enable the final structure to be applied via electrodeposition. This seed layer can be evaporated to a thickness of ~100 Å; afterwards, the sample is electroplated for an appropriate time in order to achieve the desired thickness of the final structure.

A variation of the standard surface micromachining process is called lift-off. Its aim is to apply a (metallic in most cases) layer to the substrate only in specific areas. Therefore, a sacrificial layer (usually photoresist) is applied and patterned, opening the regions that are to be covered with the metal film. After deposition of the metal, it contacts the substrate only in those regions. By removing the photoresist with a solvent that does not attack the metal layer, the material on top of the sacrificial layer is "lifted off", leaving the metal only at the desired areas



Principle of the lift-off process

Important for the success of the lift-off procedure is the use of relatively thick photoresist in order to provide a very thin metallic layer on the sidewalls of the opening. This allows the lift-off to be completed without breaking the metallic film too easily. This is also the main difference between lift-off and normal surface micromachining, where thicker sidewalls are required in order to provide stability of the free structure.

The advantage of the lift-off procedure is the ability to work with metallic layers such as platinum or gold that are difficult to pattern by etching directly.

COATING TECHNOLOGY

Stiction is a major problem in MEMS devices. Stiction (i.e.,unintentional adhesion) occurs when surface adhesion forces (viz., capillary, van derWaals and electrostatic) are higher than the mechanical restoring force of the miniaturized surfaces of the structural components. As a result of stiction, surfaces can permanently adhere to each other causing device failure- a phenomenon known as in-use stiction.

The application of low-energy surface coatings would be required to eliminate or reduce capillary, chemical bonding and electrostatic forces between the contacting microstructure surfaces of the MEMS device.

Coatings should have the following characteristics.-

- The coating should have excellent adhesion on the surfaces of the micro-components
- It should be hydrophobic in nature and thin enough not to bridge structural features of the MEMS device.

- The coating also has to permeate through microscopically small openings and diffuse onto under surfaces.
- The coating film should have stability in MEMS operating environments (viz. air and vacuum)
- It should retain its lubricating properties for longer periods. This is specially critical in MEMS devices for biomedical applications.

Techniques:

Spin coating

Spin coating of photoresist is the standard coatingmethod for flat wafers in MEMS technology. First, photoresist is flooded onto thewafer in order to cover the whole surface. A pause afterthe dispense step allows additional time for the solutionto flow into the deep features. A slow acceleration andspin speed is applied in the first step. This allows timefor the solution to flow and spread prior to drying. Asecond step with a fast spin speed promotes the drying ofthe film and reduces the further flowing of photoresistthat can result in non-uniformal coating.

Spray Coating

The direct spray system includes an ultrasonic spray nozzle, which generates a distribution of droplets of micrometer size. It can reduce the effect of fluid dynamics of photoresist on the wafer as the resist droplets are supposed to stay where they are being deposited. The central part of the aerosol is forwarded to the dispense nozzle which is constructed to reduce the carrier gas pressure and to redirect the resist spray perpendicular to the substrate surface. During spray coating, the wafer is rotated slowly while the swivel arm of the spray coating unit is moved across the wafer. The low spinner speed (30-60rpm) is to minimize the centrifugal force. The rotating also allows resist coverage in all the angle of the cavities. Photoresist AZ4562 diluted with a solvent is used for this spray system as it results in good coverage and uniform layer

Electrodeposition

It requires a special plating equipment and cataphoretic resist emulsion. To deposit a photoresist layer, the wafer surface must be coated with an electrically conductive material. The wafer to be coated faces an inert, planar stainless steel anode at a distance of 50 mm.

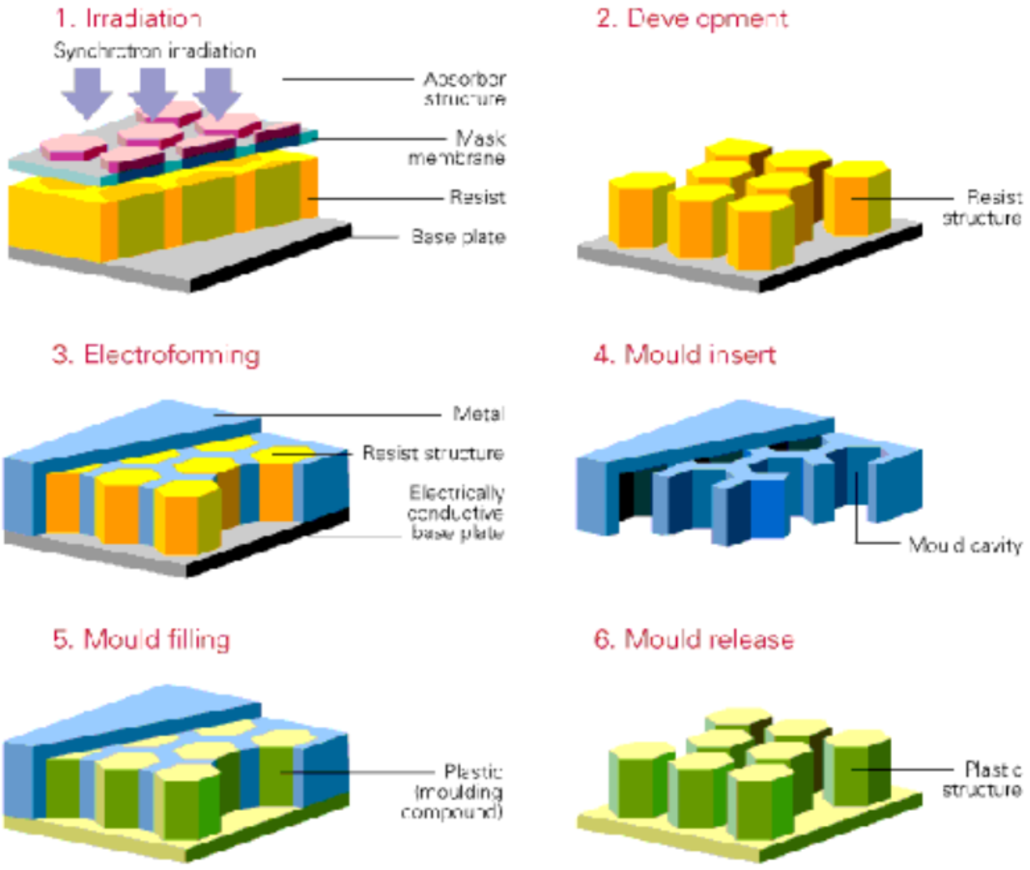
CVD-LIGA PROCESS

The LIGA Fabrication process provides the possibility to produce micromechanical structures with very high aspect ratios compared to other microelectromechanical technologies (up to 300:1). The height of the manufactured pieces can be 100 microns to a couple of millimeters. By using molding, different materials (metal, ceramics as well as plastic) can be used to produce the final structure.

LIGA is a German abbreviation and stands for Lithographie, Galvanoformung and Abformung (lithography, electrodeposition and molding). The process was developed in the 1980s by the Kernforschungszentrum Karlsruhe, Germany (KfK) to provide a technique for producing large numbers of micron sized nozzles.

The principle of the LIGA process consists of depositing a relatively thick layer of a polymer sensitive to X-rays on top of a conductive substrate or one covered with a conductive seed layer. This can be done by applying multiple coats of photoresist during spinning the substrate wafer for thicknesses of up to a few hundred microns. For thicker polymer layers (millimeters) it is common to buy prefabricated plates of PMMA (polymethylmethacrylate, a polymer often used as photoresist), attach them to the substrate plate and mill them back to the desired thickness.

After exposure through an appropriate X-ray-mask, a developer removes either the exposed (positive photoresist) or the unexposed (negative) areas of polymer, and metal layers are grown by electroplating in the spaces now free from cover. Often the metal is grown higher than needed and then milled back to the desired thickness together with the photoresist. Having removed the unwanted areas of the polymer, the resulting metallic structure can be used. Free mechanical structures can be manufactured by using a sacrificial layer between the wafer substrate and the grown metal film and dissolving this layer, thus yielding the structure in the end of the process; this technique is called sacrificial LIGA (SLIGA).



For the purpose of mass production, the metal can serve as a mould or embossing tool for pieces made of various materials such as metals, polymers, ceramics or glass.

The major advantages of the LIGA process are the high aspect ratios made possible and therefore the larger heights of the pieces, very sharp vertical sidewalls as well as the possibility to produce three-dimensional structures by using a sacrificial layer as described above.

The main disadvantage of LIGA is the need of high-energy X-rays that can only be achieved with a synchrotron. This and the expensive X-ray masks needed for exposure make the cost for the process high. On the other hand, the mass production of microstructures by using the produced structures as mold for other materials becomes very inexpensive per produced device, since the expensive exposure step only needs to be done once in the beginning of the fabrication process.

To reduce the cost of LIGA, especially the investment costs for the synchrotron, the usage of traditional lithography light sources in the UV range is being investigated in combination with other photoresist materials (rather polyamides or standard photoresists than the polymers used in X-ray lithography). Using these processes, structures of up to 80 microns in height can be produced with this technique.

Alternatively companies providing the necessary tools for LIGA to multiple users can reduce the production cost, too. MCNC in Research Triangle Park, NC offers LIGAMUMPs™, a "Multi-user MEMS Process that involves the fabrication of high aspect ratio MEMS in a low-cost environment"