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INTRODUCTION TO MICROENGINEERING
by Danny Bank

What is Microengineering ?

Microengineering refers to the technologies and practice of making three dimensional structures and devices with dimensions in the order of micrometers.

The two constructional technologies of microengineering are microelectronics and micromachining. Microelectronics, producing electronic circuitry on silicon chips, is a very well developed technology. Micromachining is the name for the techniques used to produce the structures and moving parts of microengineered devices.

One of the main goals of Microengineering is to be able to integrate microelectronic circuitry into micromachined structures, to produce completely integrated systems (microsystems). Such systems could have have the same advantages of low cost, reliability and small size as silicon chips produced in the microelectronics industry.

When considering such small devices, a number of physical effects have different significance on the micrometer scale compared to macroscopic scales. Interest in microengineering has spawned or renewed interest in a number of areas dealing with the study of these effects on microscopic scales. This includes such topics as micromechanics, which deals with the moving parts of microengineered devices, and microfluidics, etc.

The remainder of this document introduces three of the micromachining techniques that are in use / under development.

Silicon micromachining is given most prominence, since this is one of the better developed micromachining techniques. Silicon is the primary substrate material used in the production microelectronic circuitry (ie, bettersilicon chips), and so is the most suitable candidate for the eventual production of microsystems.

The Excimer laser is an ultraviolet laser which can be used to micromachine a number of materials without heating them, unlike many other lasers which remove material by burning or vaporising it. The Excimer laser lends itself particularly to the machining of organic materials (polymers, etc).

LIGA is a technique that can be used to produce moulds for the fabrication of micromachined components. Microengineered components can be made from a variety of materials using this technique, however it does suffer the disadvantage that currently the technique requires X-rays from a synchrotron source.

A quick introduction to mask design is provided following discussion of techniques and structures, rather than directly following the photolithography section. This is so that the reader is able to become acquainted with the concept of creating structures by sequential photolithography and machining steps first, which hopefully makes it easier to understand what mask design software is trying to achieve.

Photolithography

Photolithography is the basic technique used to define the shape of micromachined structures in the three techniques outlined below. The technique is essentially the same as that used in the microelectronics industry, which will be described here. The differences in the photolithographic techniques for Excimer laser micromachining and LIGA will be outlined in the relevant sections.

Figure 1a shows a thin film of some material (eg, silicon dioxide) on a substrate of some other material (eg, a silicon wafer). It is desired that some of the silicon dioxide (oxide) is selectively removed so that it only remains in particular areas on the silicon wafer (figure 1f).

Firstly a mask is produced. This will typically be a chromium pattern on a glass plate. The wafer is then coated with a polymer which is sensitive to ultraviolet light (figure 1b), called a photoresist. Ultraviolet light is then shone through the mask onto the photoresist (figure 1c). The photoresist is then developed which transfers the pattern on the mask to the photoresist layer (figure 1d).

There are two types of photoresist, termed positive and negative. Where the ultraviolet light strikes the positive resist it weakens the polymer, so that when the image is developed the resist is washed away where the light struck it - transferring a positive image of the mask to the resist layer. The opposite occurs with negative resist. Where the ultraviolet light strikes negative resist it strengthens the polymer, so when developed the resist that was not exposed to ultraviolet light is washed away - a negative image of the mask is transferred to the resist.

A chemical (or some other method) is then used to remove the oxide where it is exposed through the openings in the resist (figure 1e). Finally the resist is removed leaving the patterned oxide (figure 1f).

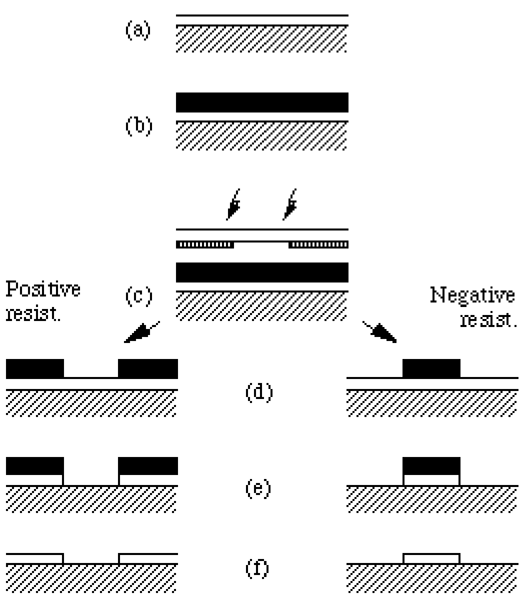

Figure 1.

Silicon micromachining

There are a number of basic techniques that can be used to pattern thin films that have been deposited on a silicon wafer, and to shape the wafer itself, to form a set of basic microstructures (bulk silicon micromachining). The techniques for depositing and patterning thin films can be used to produce quite complex microstructures on the surface of silicon wafer (surface silicon micromachining). Electrochemical etching techniques are being investigated to extend the set of basic silicon micromachining techniques. Silicon bonding techniques can also be utilised to extend the structures produced by silicon micromachining techniques into multilayer structures.

Basic techniques

There are three basic techniques associated with silicon micromachining. These are the deposition of thin films of materials, the removal of material (patterning) by wet chemical etchants, and the removal of material by dry etching techniques. Another technique that is utilised is the introduction of impurities into the silicon to change its properties (ie, doping). Doping is only mentioned very briefly below.

It should be noted that all the techniques are outlined very briefly. Behind each outline hides a number of different methods, each with different advantages and disadvantages.

Thin films

There are a number of different techniques that facilitate the deposition or formation of very thin films (of the order of micrometers, or less) of different materials on a silicon wafer (or other suitable substrate). These films can then be patterned using photolithographic techniques and suitable etching techniques. Common materials include silicon dioxide (oxide), silicon nitride (nitride), polycrystalline silicon (polysilicon or poly), and aluminium.

A number of other materials can be deposited as thin films, including noble metals such as gold. Noble metals will contaminate microelectronic circuitry causing it to fail, so any silicon wafers with noble metals on them have to be processed using equipment specially set aside for the purpose. Noble metal films are often patterned by a method known as "lift off", rather than wet or dry etching.

Often, photoresist is not tough enough to withstand the etching required. In such cases a thin film of a tougher material (eg, oxide or nitride) is deposited and patterned using photolithography. The oxide / nitride then acts as an etch mask during the etching of the underlying material. When the underlying material has been fully etched the masking layer is stripped away.

Wet etching

Wet etching is a blanket name that covers the removal of material by immersing the wafer in a liquid bath of the chemical etchant. Wet etchants fall into two broad categories; isotropic etchants and anisotropic etchants.

Isotropic etchants attack the material being etched at the same rate in all directions. Anisotropic etchants attack the silicon wafer at different rates in different directions, and so there is more control of the shapes produced. Some etchants attack silicon at different rates depending on the concentration of the impurities in the silicon (concentration dependent etching).

Isotropic etchants are available for oxide, nitride, aluminium, polysilicon, gold, and silicon. Since isotropic etchants attack the material at the same rate in all directions, they remove material horizontally under the etch mask (undercutting) at the same rate as they etch through the material. This is illustrated for a thin film of oxide on a silicon wafer in figure 2, using an etchant that etches the oxide faster than the underlying silicon (eg, hydroflouric acid).

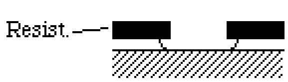

Figure 2.
This illustrates the isotropic wet etching of a thin film of material.

The photoresist is black, and the substrate yellow. The film is etched through, and the etching continues to further under-cut the mask.

Anisotropic etchants are available which etch different crystal planes in silicon at different rates. The most popular anisotropic etchant is potassium hydroxide (KOH), since it is the safest to use.

Silicon wafers are slices that have been cut from a large ingot of silicon that was grown from a single seed crystal. The silicon atoms are all arranged in a crystalline structure, so the wafer is monocrystalline silicon (as opposed to polycrystalline silicon mentioned above). When purchasing silicon wafers it is possible to specify that they have been sliced with the surface parallel to a particular crystal plane.

The simplest structures that can be formed using KOH to etch a silicon wafer with the most common crystal orientation (100) are shown in figure 3. These are V shaped groves, or pits with right angled corners and sloping side walls. Using wafers with different crystal orientations can produce grooves or pits with vertical walls.

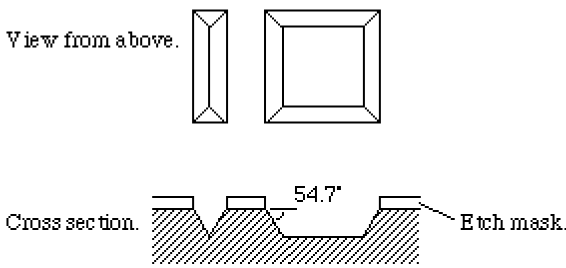

Figure 3.

Both oxide and nitride etch slowly in KOH. Oxide can be used as an etch mask for short periods in the KOH etch bath (ie, for shallow grooves and pits). For long periods, nitride is a better etch mask as it etches more slowly in the KOH.

Concentration Dependent Etching. High levels of boron in silicon will reduce the rate at which it is etched in KOH by several orders of magnitude, effectively stopping the etching of the boron rich silicon.

The boron impurities are usually introduced into the silicon by a process known as diffusion. A thick oxide mask is formed over the silicon wafer and patterned to expose the surface of the silicon wafer where the boron is to be introduced (figure 4a). The wafer is then placed in a furnace in contact with a boron diffusion source. Over a period of time boron atoms migrate into the silicon wafer. Once the boron diffusion is completed, the oxide mask is stripped off (figure 4b).

A second mask may then be deposited and patterned (figure 4c) before the wafer is immersed in the KOH etch bath. The KOH etches the silicon that is not protected by the mask, and etches around the boron doped silicon (figure 4d).

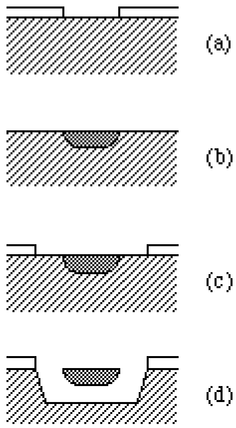

Figure 4.

Boron can be driven into the silicon as far as 20µm over periods of 15 to 20 hours, however it is desirable to keep the time in the furnace as short as possible. With complex designs, etching the wafer from the front in KOH may cause problems where slow etching crystal planes prevent it from etching beneath the boron doped silicon. In such cases the wafer can be etched from the back, however this is not without disadvantages (longer etching times, more expensive wafers, etc). The high concentration of boron required means that microelectronic circuitry cannot be fabricated directly on the boron doped structure.

Dry etching

The most common form of dry etching for micromachining applications is reactive ion etching (RIE). Ions are accelerated towards the material to be etched, and the etching reaction is enhanced in the direction of travel of the ion. RIE is an anisotropic etching technique. Deep trenches and pits (up to ten or a few tens of microns) of arbitrary shape and with vertical walls can be etched in a variety of materials including silicon, oxide and nitride. Unlike anisotropic wet etching, RIE is not limited by the crystal planes in the silicon.

Lift off

Lift off is a stencilling technique often used to pattern noble metal films. There are a number of different techniques, the one outlined here is an assisted lift off method.

A thin film of the assisting material (eg, oxide) is deposited. A layer of resist is put over this and patterned, as for photolithography, to expose the oxide in the pattern desired for the metal (figure 5a). The oxide is then wet etched so as to undercut the resist (figure 5b). The metal is then deposited on the wafer, typically by a process known as evaporation (figure 5c). The metal pattern is effectively stencilled through the gaps in the resist, which is then removed lifting off the unwanted metal with it (figure 5d). The assisting layer is then stripped off too, leaving the metal pattern alone (figure 5e).

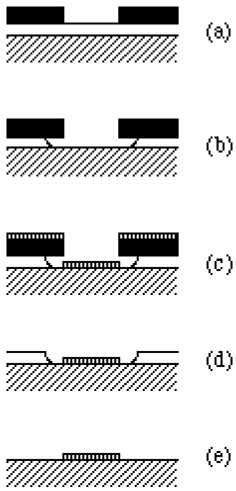

Figure 5.

There are lift off techniques in which only photoresist is used as the stencil. In the assisted lift off, an intermediate layer assists in the process to ensure a clean lift off and well defined metal pattern. When noble metals are used it is desirable to deposit a thin layer of a more active metal (eg, chrome) first, to ensure good adhesion of the noble metal.

Basic structures

Bulk silicon micromachining

One of the simplest possible, and most obvious, structures is the patterning of insulated electrical conductors. One possible application of this could be to use electric fields to manipulate individual cells.

Anisotropic etching with KOH can easily form V shaped grooves, or cut pits with tapered walls into silicon (figure 3 and figure 6).

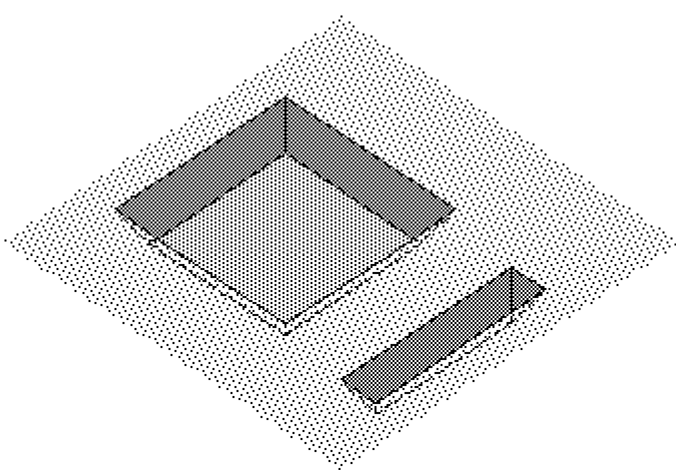

Figure 6.

KOH can also be used to produce mesa structures (figure 7a). When etching mesa structures the corners can become bevelled (figure 7b), rather than right angle corners. This has to be compensated for in some way. Typically the etch mask is designed to include additional structures on the corners. These compensation structures are designed so that they are etched away entirely when the mesa is formed to leave 90 degree corners. One problem with using compensation structures to from right angled mesa corners is that they put a limit on the minimum spacing between the mesas.

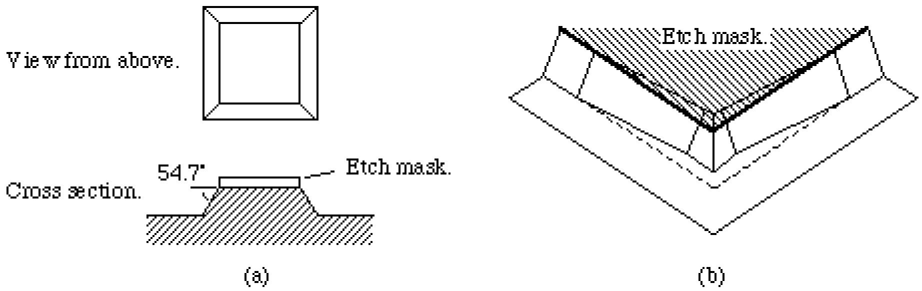

Figure 7.

Silicon diaphragms from about 50µm thick upwards can be made by etching through an entire wafer with KOH (figure 8). The thickness is controlled by timing the etch, and so is subject to errors.

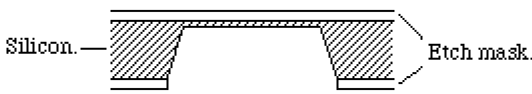

Figure 8.

Thinner diaphragms, of up to about 20µm thick, can be produced using boron to stop the KOH etch (figure 9) - Concentration dependent etching. The thickness of the diaphragm is dependent on the depth to which the boron is diffused into the silicon, which can be controlled more accurately than the simple timed KOH etch.

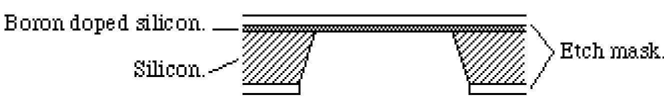

Figure 9.

The silicon diaphragm is the basic structure used in microengineered pressure sensors, for example. It can also be adapted for use as an acceleration sensor.

Concentration dependent etching can also be used to produce narrow bridges, or cantilever beams. Figure 10a shows a bridge, defined by a boron diffusion, spanning a pit that was etched from the front of the wafer in KOH. A cantilever beam (a bridge with one end free) produced by the same method is shown in figure 10b.

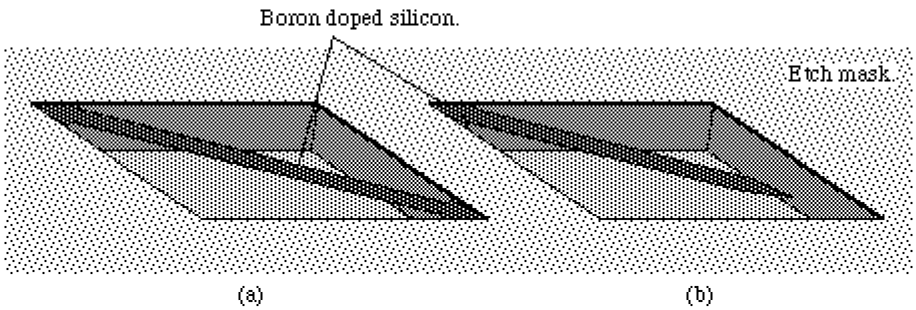

Figure 10.

The bridge and beam in figure 10 project across the diagonal of the pit to ensure that they will be etched free by the KOH. More complex structures are possible using this technique, but care must be taken to ensure that they will be etched free by the KOH.

If it is desired to make beams or bridges of a different orientation, the wafer can be etched through from the back in KOH (figure 11). This will ensure that the structure is released from the silicon. During such etching, it is necessary to ensure that the front of the wafer is adequately protected from the long KOH etch. Another alternative could be to produce a diaphragm, and etch the desired bridge or beam shape using a reactive ion etcher (dry etching).

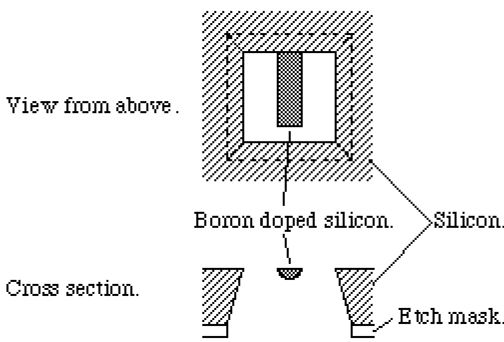

Figure 11.

One of the applications for these beams and bridges is as resonant sensors. The structure can be set vibrating at it's fundamental frequency. Anything causing a change in the mass, length, etc, of the structure will register as a change frequency. Care has to be taken to ensure that only the quantity to be measured causes a significant change in frequency.

A combination of dry etching and isotropic wet etching can be used to form very sharp points. First a column with vertical sides is etched away using an RIE (figure 12a). A wet etch is then used, which undercuts the etch mask leaving a very fine point (figure 12b), the etch mask is then removed.

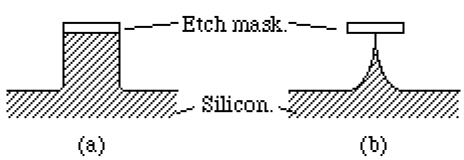

Figure 12.

Very fine points like this can be fabricated on the end of cantilever beams as probes for use in atomic force microscopy. The technique can also be used to produce sharp, small blades.

Surface micromachining

The anisotropic wet etching, and concentration dependent etching techniques discussed in the "Basic Techniques" section are generally called bulk silicon micromachining techniques. This is because the microstructures are formed by etching away the bulk of the silicon wafer to achieve the desired result. Surface micromachining techniques build up the structure in layers of thin films on the surface of the silicon wafer (or any other suitable substrate).

The process would typically employ films of two different materials, a structural material (commonly polysilicon) and a sacrificial material (oxide). These are deposited and dry etched in sequence. Finally the sacrificial material is wet etched away to release the structure. The more layers, the more complex the structure, and the more difficult it becomes to fabricate.

A simple surface micromachined cantilever beam is shown in figure 13. A sacrificial layer of oxide is deposited on the surface of the wafer. A layer of polysilicon is then deposited, and patterned using RIE techniques to a beam with an anchor pad (figure 13a). The wafer is then wet etched to remove the oxide layer under the beam, freeing it (figure 13b). The anchor pad has been under etched, however the wafer was removed from the etch bath before all the oxide was removed from under the pad leaving the beam attached to the wafer.

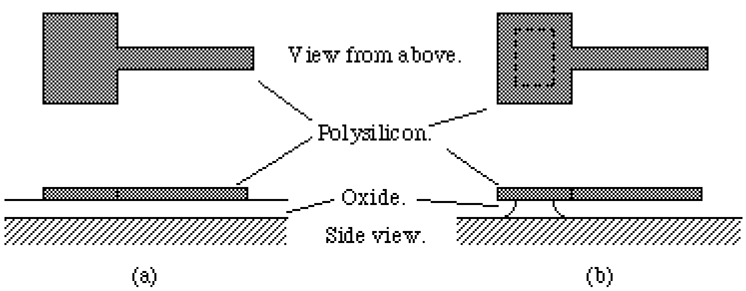

Figure 13.

A variety of different chambers can be fabricated on the surface of silicon wafers using surface micromachining techniques. In figure 14, the chamber is defined by a volume of sacrificial oxide (figure 14a). A layer of polysilicon is then deposited over the surface of the wafer (figure 14b). A window is dry etched (RIE) through the polysilicon, and the wafer is then immersed in a wet etch that removes the oxide, leaving a windowed chamber (figure 14c).

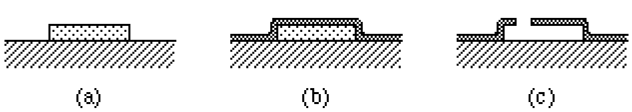

Figure 14.

Surface micromachining can potentially produce quite complicated structures; such as microengineered tweezers, and gear trains.

Electrochemical etching of silicon

A variety of electrochemical silicon etching techniques are under development. One of these is the electrochemical passivation technique.

A wafer with a particular impurity concentration is used, and different impurities are diffused (or implanted) into the wafer. This is done to form a diode junction at the boundary between the differently doped areas of silicon. The junction will delineate the structure to be produced. An electrical potential is then applied across the diode junction, and the wafer is immersed in a suitable wet etch (KOH). This is done in such a way that when the etch reaches the junction an oxide layer (passivation layer) is formed which protects the silicon from further etching.

This is another bulk silicon micromachining technique, and is essentially similar to the boron etch stop technique (concentration dependent etching). The structures that can be produced are similar to those produced by the boron etch stop technique. The main advantage of the electrochemical method is that much lower concentrations of impurities are required, so the resulting structure is more compatible with the fabrication of microelectronic circuitry.

Wafer bonding

There are a number of different methods available for bonding micromachined silicon wafers together, or to other substrates, to form larger more complex devices.

A method of bonding silicon to glass that appears to be gaining in popularity is anodic bonding (electrostatic bonding). The silicon wafer and glass substrate are brought together and heated to a high temperature. A large electric field is applied across the join, which causes an extremely strong bond to form between the two materials. Figure 15 shows a glass plate bonded over a channel etched into a silicon wafer (RIE), forming a pipe through which fluid can flow.

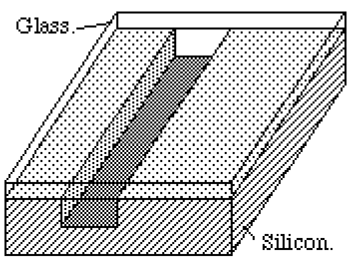

Figure 15.

It is also possible to bond silicon wafers directly together using gentle pressure, under water (direct silicon bonding).

Other bonding methods include using an adhesive layer, such as a glass, or photoresist. Whilst anodic bonding and direct silicon bonding form very strong joins they suffer from some disadvantages, including the requirement that the surfaces to be joined are very flat and clean.

Wafer bonding techniques can potentially be combined with some of the basic micromachined structures to form the valves, pumps, etc, of a microfluid handling system.

Excimer laser micromachining

Excimer lasers produce relatively wide beams of ultraviolet laser light. One interesting application of these lasers is their use in micromachining organic materials (plastics, polymers, etc). This is because the excimer laser doesn't remove material by burning or vaporising it, unlike other types of laser, so the material adjacent to the area machined is not melted or distorted by heating effects.

When machining organic materials the laser is pulsed on and off, removing material with each pulse. The amount of material removed is dependent on the material itself, the length of the pulse, and the intensity (fluence) of the laser light. Below a certain threshold fluence, dependent on the material, the laser light has no effect. As the fluence is increased above the threshold, the depth of material removed per pulse is also increased. It is possible to accurately control the depth of the cut by counting the number of pulses. Quite deep cuts (hundreds of microns) can be made using the excimer laser.

The shape of the structures produced is controlled by using a chrome on quartz mask, like the masks produced for photolithography. In the simplest system the mask is placed in contact with the material being machined, and the laser light is shone through it (figure 16a). A more sophisticated and versatile method involves projecting the image of the mask onto the material (figure 16b). Material is selectively removed where the laser light strikes it.

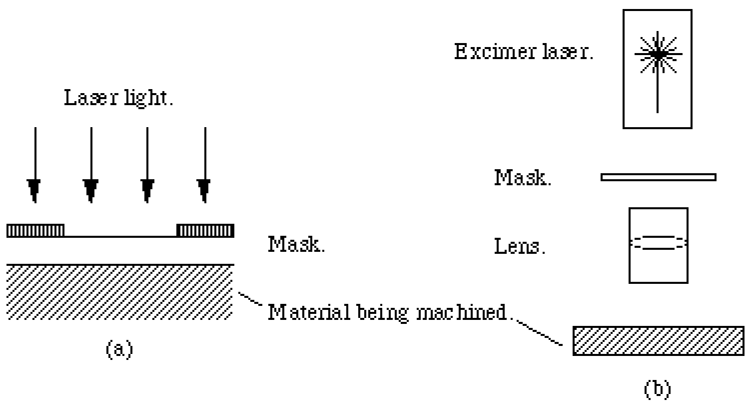

Figure 16.

Structures with vertical sides can be created. By adjusting the optics it is possible to produce structures with tapered sidewalls (figure 17).

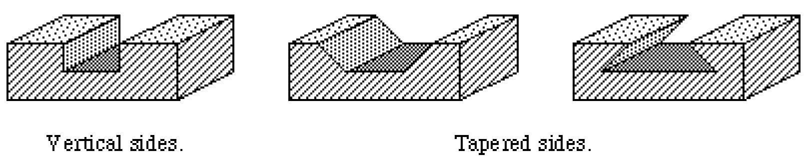

Figure 17.

Excimer lasers have a number of applications beyond those mentioned here. One area of application is in machining the cornea of the eye to change its optical properties; correcting for short sight.

LIGA

The acronym LIGA comes from the German name for the process (Lithographie, Galvanoformung, Abformung). LIGA uses lithography, electroplating, and moulding processes to produce microstructures. It is capable of creating very finely defined microstructures of up to 1000µm high.

In the process as originally developed, a special kind of photolithography using X-rays (X-ray lithography) is used to produce patterns in very thick layers of photoresist. The X-rays from a synchrotron source are shone through a special mask onto a thick photoresist layer (sensitive to X-rays) which covers a conductive substrate (figure 18a). This resist is then developed (figure 18b).

The pattern formed is then electroplated with metal (figure 18c). The metal structures produced can be the final product, however it is common to produce a metal mould (figure 18d). This mould can then be filled with a suitable material, such as a plastic (figure 18e), to produce the finished product in that material (figure 18f).

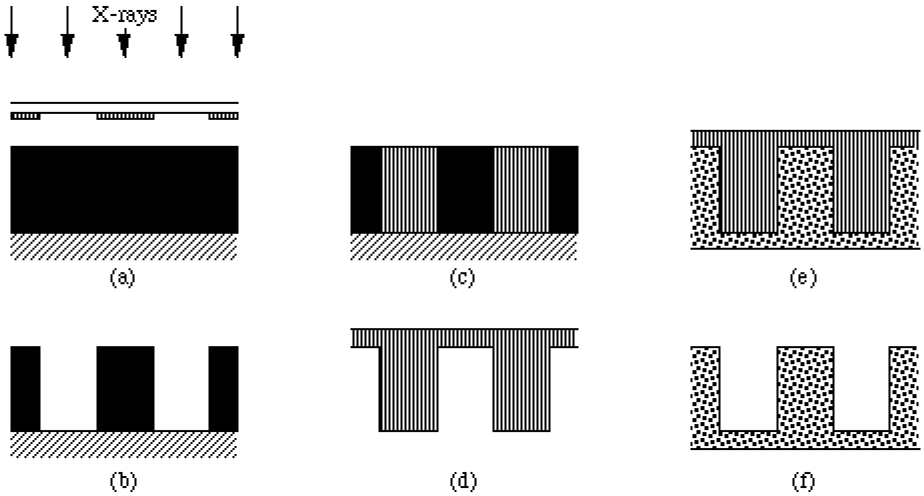

Figure 18.

As the synchrotron source makes LIGA expensive, alternatives are being developed. These include high voltage electron beam lithography which can be used to produce structures of the order of 100µm high, and excimer lasers capable of producing structures of up to several hundred microns high.

Electroplating is not limited to use with the LIGA process, but may be combined with other processes and more conventional photolithography to produce microstructures.

General LIGA Process Information

LIGA Process Flow

The overall process for the multi-project LIGA runs is shown in Figures 1-4 and has the following structure. Please note some
changes since the last LIGA run.

Starting material: 4 inch silicon substrate
Oxidize to 5,000 Angstroms; unpatterned
Sputter plating base; unpatterned - 300 Angstroms of titanium followed by 5000 Angstroms of copper followed by
another 300 Angstroms of titanium. The titanium and copper layers also act as sacrifical layers. The titanium and copper
layers can be etched simultaneously to release the plated structures if desired.
Apply thick photoresist (PMMA) and mill to thickness.
Expose and develop the photoresist using the nickel level mask.
Electroplate with pure nickel. For the thick nickel process, the metal is overplated and then milled to achieve a height of
200 +/- 5 microns. The photoresist is then removed to produce nickel structures with a height of 200 +/- 5 microns. For
the thin nickel process, the metal is plated to 30 microns with no subsequent milling. The surface roughness will be that
of the as-plated nickel. Estimated height control is +/- 5 microns and is pattern dependent.
Released nickel structures can be produced by etching away the sacrificial titanium layer in a fresh solution of 1 part

Ammonium Hydroxide, 1 part Hydrogen Peroxide, and 6 parts of Deionized Water, at room temperature. This release step is not necessary if only fixed structures are desired. Note: The structures on a die are either all fixed or all released as the sacrificial layer is not patterned. For released structures, the final release step must be performed by the user at the customer site.

Hints for Good Mask Design

Mechanical milling generates shear stresses on the photoresist and metal. This affects both photoresist and metal adhesion. Yield improves if retained photoresist areas are large. Yield decreases when the developed photoresist pattern contains mechanically weak structures. In the thick nickel process, the nickel and photoresist are milled after plating. Yield is better on larger nickel areas than on smaller ones. However, during milling the photoresist itself can also support milling stress and certain geometries are better than others. For example, a hexagonal nickel post can be milled easier than a circular one which will tend to rotate since it has no PMMA support. Uniformity in metal plating is pattern dependent. A good layout is one in which 50% of the chip area is covered with metal.

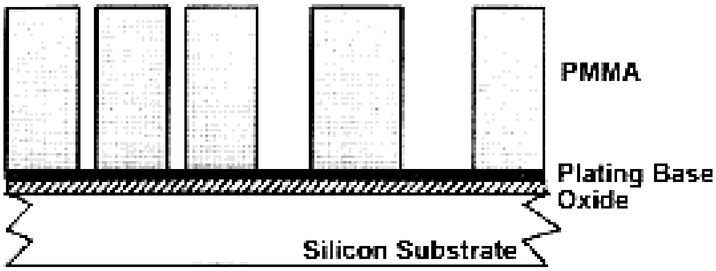

Fig. 1 Fabrication is done on a (100) silicon wafer with a 0.5μm oxide layer. A plating base is formed by sputtering 300nm of Ti and 5000A of Cu with a top layer of 300A Ti. The Ti and Cu also act as a release layer. Thick photoresist is applied and exposed using x-rays from a synchotron and developed with a solvent.

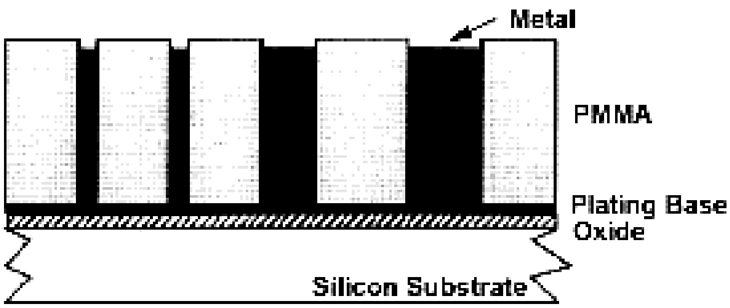

Fig. 2 The desired metal, in this case nickel, is electroplated onto the substrate, filling the voids in the PMMA.

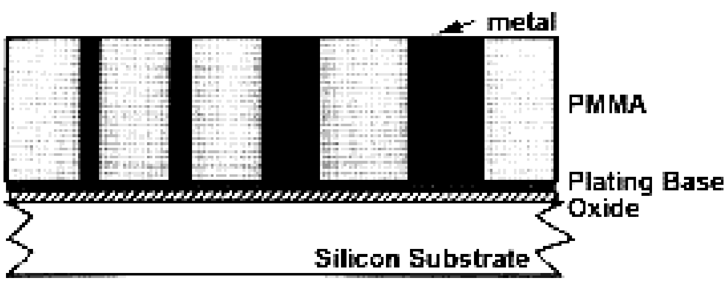

Fig. 3 The metal and PMMA are milled back to produce a uniform top surface.

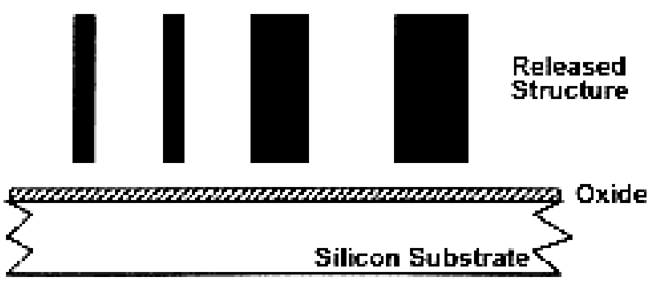

Fig. 4 Finally, the PMMA is removed. If desired, the customer can release the structures from the substrate by etching away the plating base in an NH_4O_2/H_2O_2 solution.