Lecture 5: Microfabrication and micromachining methods

Material deposition methods

1) Surface micromachining

Surface micromachining involves processing above the substrate, mainly using it as a foundation layer on which to build. Material is added to the substrate in the form of layers of thin films on the surface of the substrate (typically a silicon wafer). These layers can either by structural layers or act as spacers, later to be removed, when they are known as sacrificial layers. Hence the process usually involves films of two different materials: a structural material out of which the free standing structure is made (generally polycrystalline silicon or polysilicon, silicon nitride and aluminum) and a sacrificial material, deposited wherever either an open area or a free standing mechanical structure is required (usually an oxide).

These layers (or thin films) are deposited and subsequently dry etched in sequence, with the Sacrificial material being finally wet etched away to release the final structure. Each additional layer is accompanied by an increasing level of complexity and a resulting difficulty in fabrication. A typical surface micromachined cantilever beam is shown in Figure 1. Here, a sacrificial layer of oxide is deposited on the silicon substrate surface using a pattern and photolithography.

A polysilicon layer is then deposited and patterned to form a cantilever beam with an anchor pad. The wafer is then wet etched to remove the oxide (sacrificial) layer releasing and leaving the beam on the substrate.

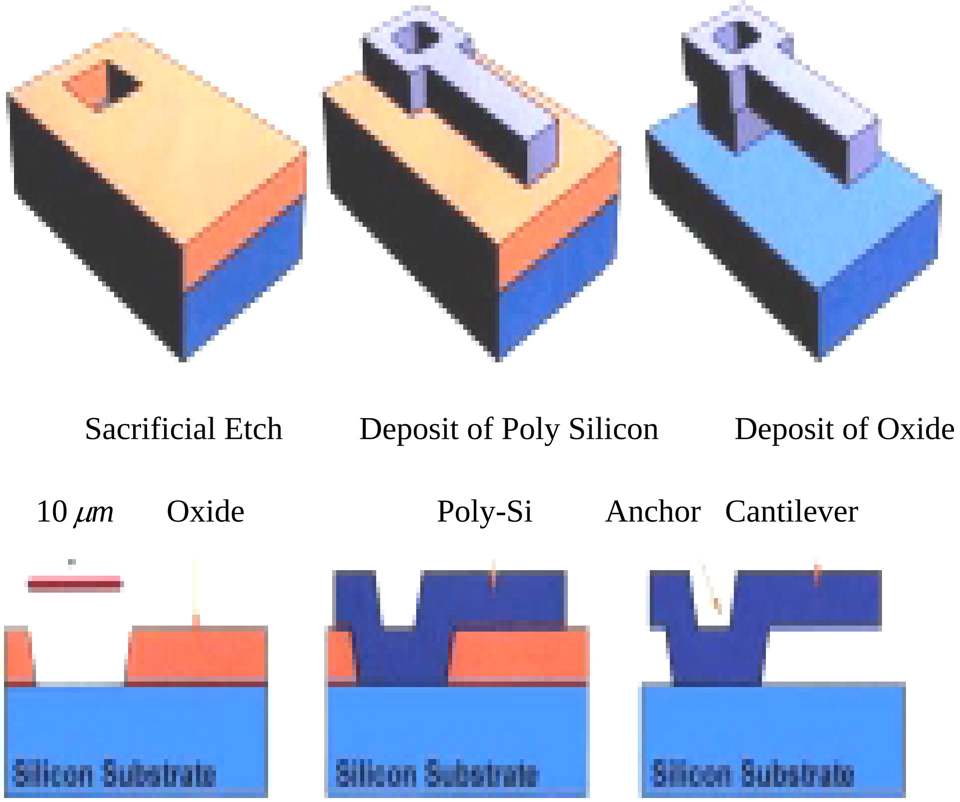

Figure1: Surface micromachining of a cantilever beam using a sacrificial layer

More complex MEMS structures can be achieved using structural polysilicon and sacrificial silicon dioxide, including sliding structures, actuators and free moving mechanical gears. Figures 2 show the process flow for the fabrication of a micromotor.

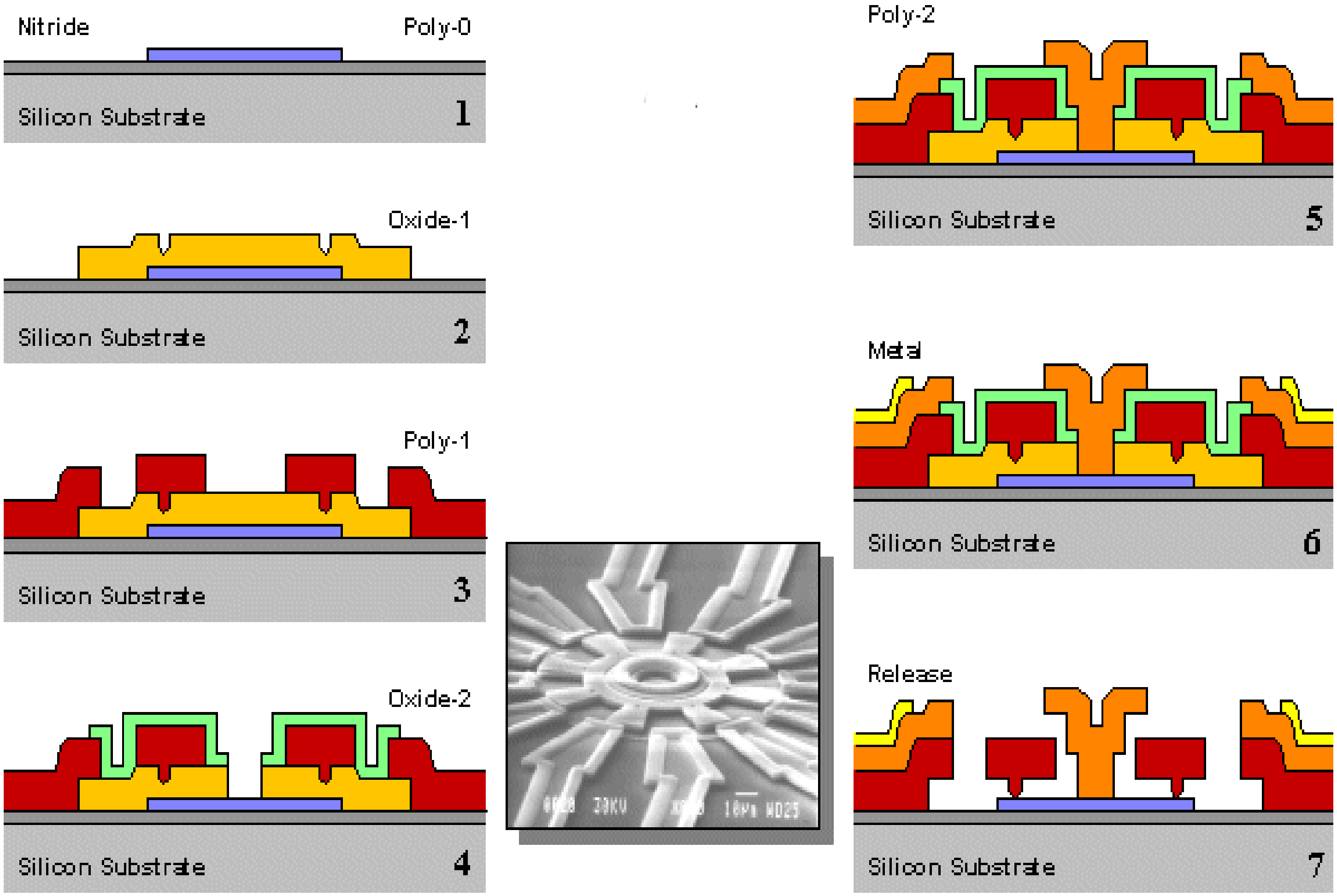

Figure 2: Surface micromachining of a micromotor

The advantages of surface micromachining are:

1) Structural features, especially thicknesses, can be smaller than 10 µm in size.

2) The device footprint can often be much smaller than bulk wet-etched devices.

3) It is easier to integrate electronics below surface microstructures.

4) Surface microstructures generally have superior tolerance compared to bulk wet-etched devices.

Surface micromachining is used in a lot of applications like:

1- Shear stress sensors

2- Oscillators.

3- Accelerometer.

4- Communication filters.

5- Optical scanner.

6- Micro relays.

2) Micro stereo lithography

This technique is used for generating 3D structure by constructing 2D sliced thin plane from liquid. The light source used is laser or Xenon lamp. UV curing polymer liquid is used. We have two methods:

a) Constrained surface, here we focus on liquid surface, the slice thickness defined by the distance to glass. This method can be used to transfer, but hard to remove. It need support, and long time because it made layer by layer, it gives a resolution of 5 µm.

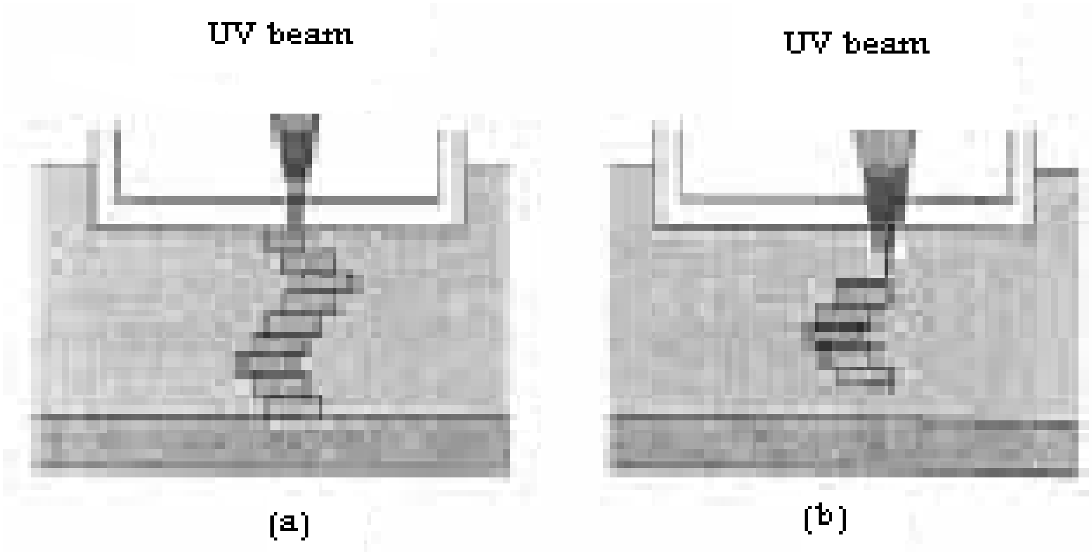

Figure 3: Constrained surface micro stereo lithography

b) Free surface, it used to form solid in 3D liquid space. This method can make freely moveable structures, but gives resolution <1 µm

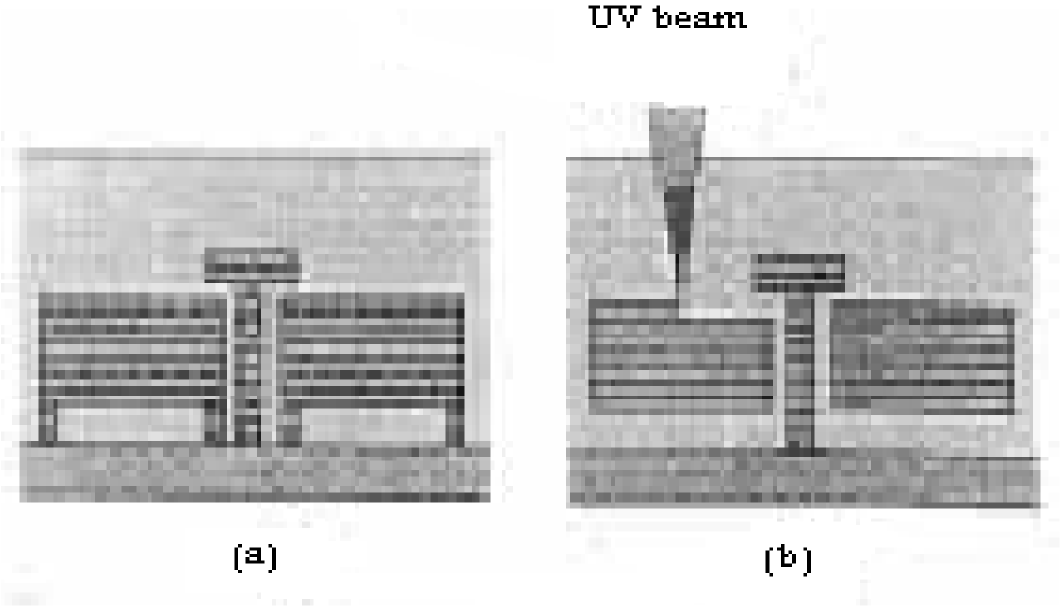

Figure 4: Free surface micro stereo lithography

3) LIGA

LIGA is a German acronym for (lithograpie Galvanoformung Abformung), developed at the Karlsruhe Research Center in the early 80’s. This method allows 3D microstructure of several hundred µm high and laterally in 0.2 µm. This process includes three major fabrication steps:

1) X-ray lithography

2) Electroforming

3) Molding

In the process, 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 5 a). This resist is then developed (figure 5 b).

The pattern formed is then electroplated with metal (figure 5 c). The metal structures produced can be the final product; however it is common to produce a metal mould (figure 5 d). This mould can then be filled with a suitable material, such as a plastic (figure 5 e), to produce the finished product in that material (figure 5 f).

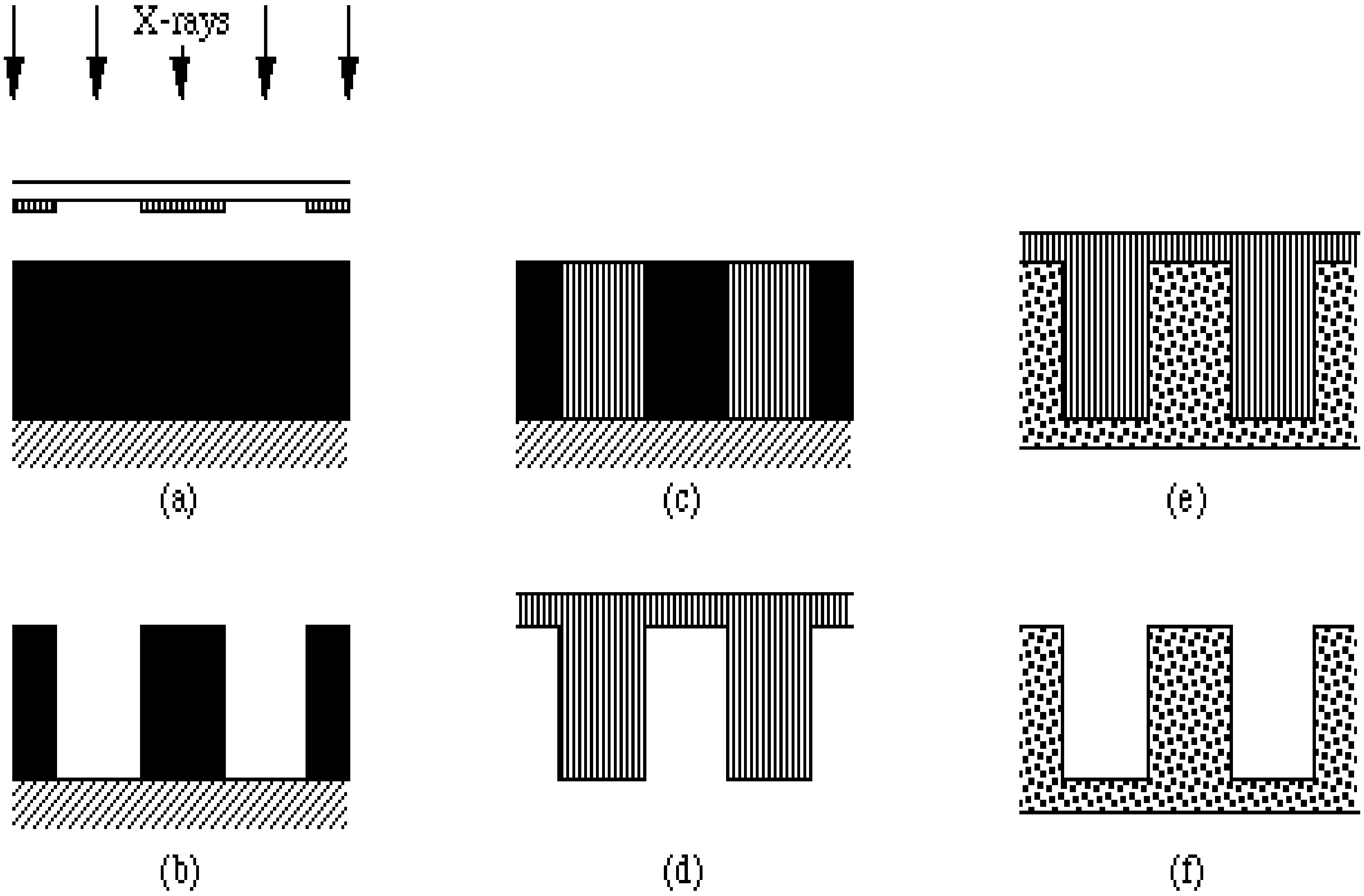

Figure 5: LIGA

A drawback to the LIGA process is the cost, both of the masks and of access to the X-ray facilities.. The figures below show some examples of microstructures made by the LIGA process.

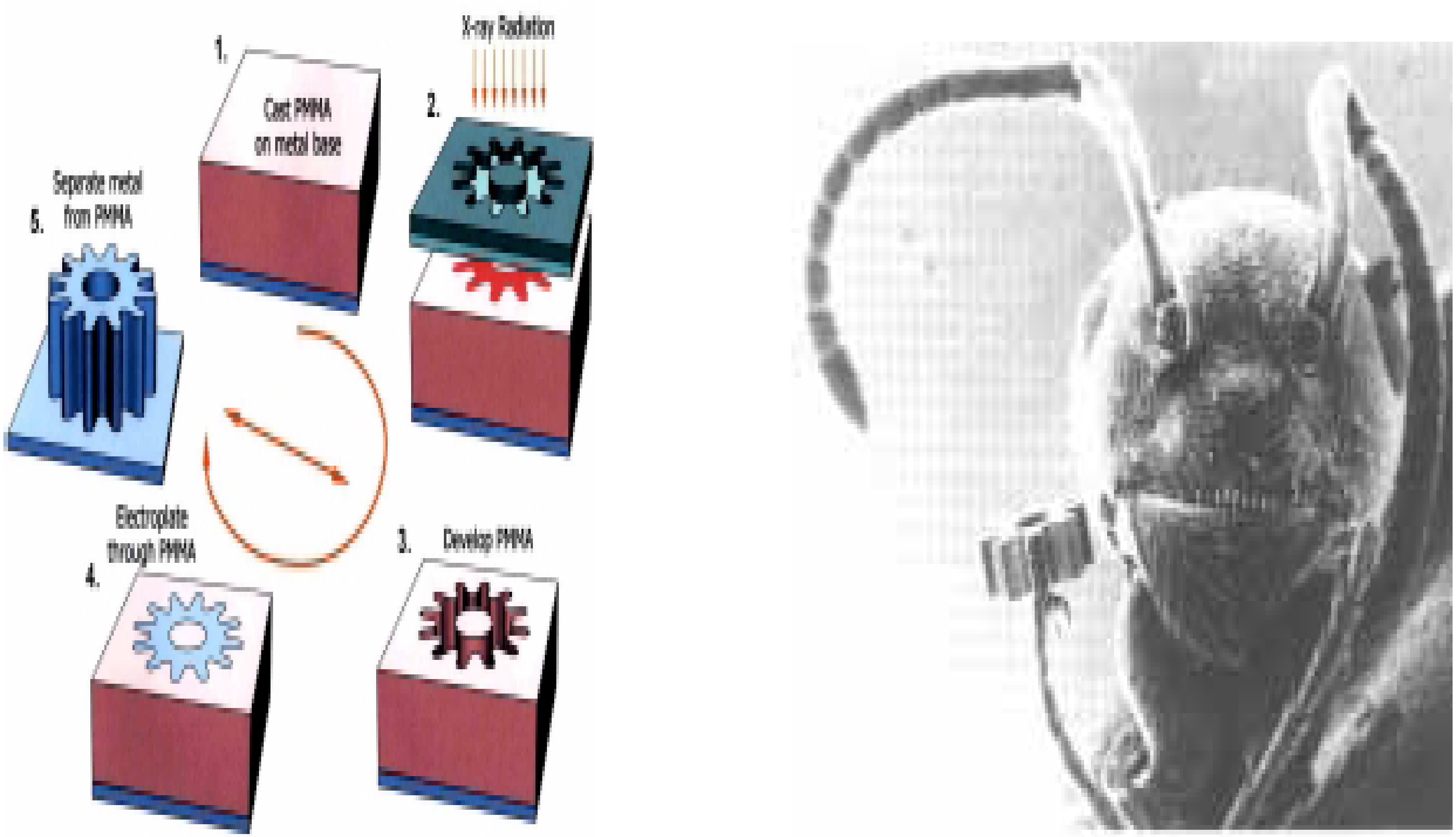

Figure 6: LIGA microturbine impeller

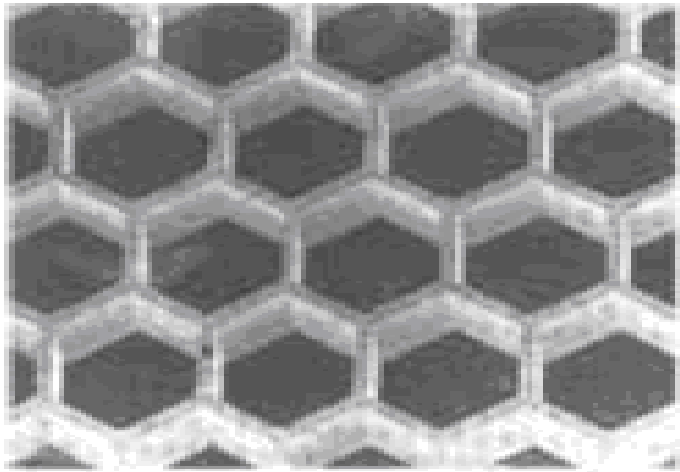

Figure 7: LIGA high pass optical filter

Figure 8: LIGA micromotor

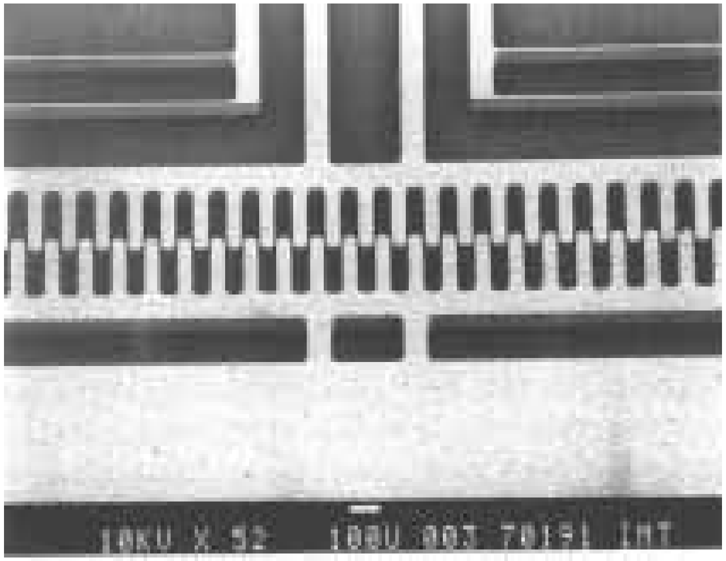

Figure 9: LIGA Comb Drive

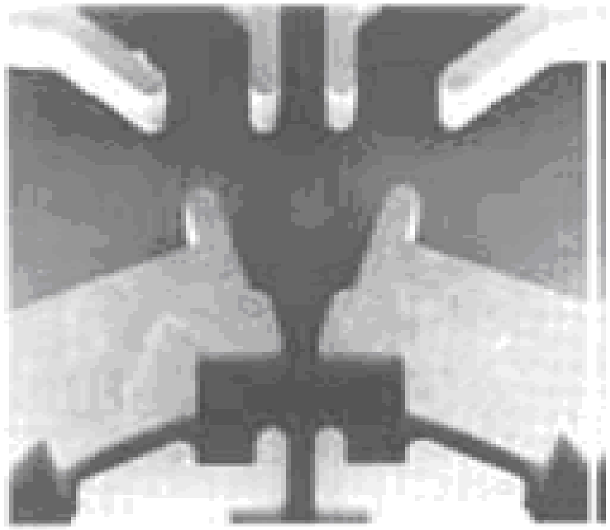

Figure 10: LIGA fluidic switch

4) Laser-Assisted Chemical Vapor Deposition (LCVD)

It is a chemical vapor deposition from vapor phase assisted by laser, the laser used mainly the Nd-YAG (neodymium yttrium aluminum garnet) or Ar+. This method gives 3-D structures, on different kinds of substrates as silicon, carbon, boron, oxides, nitrides, carbides, borides and metals. In fabrication, a high pressure LCVD If the pressure is higher than 1 bar, this method gives high growth rate (>1.1 mm/s max). If pressure is lower than 1 bar then it is called low pressure LCVD, this method gives low growth rate (<100 µm/s).

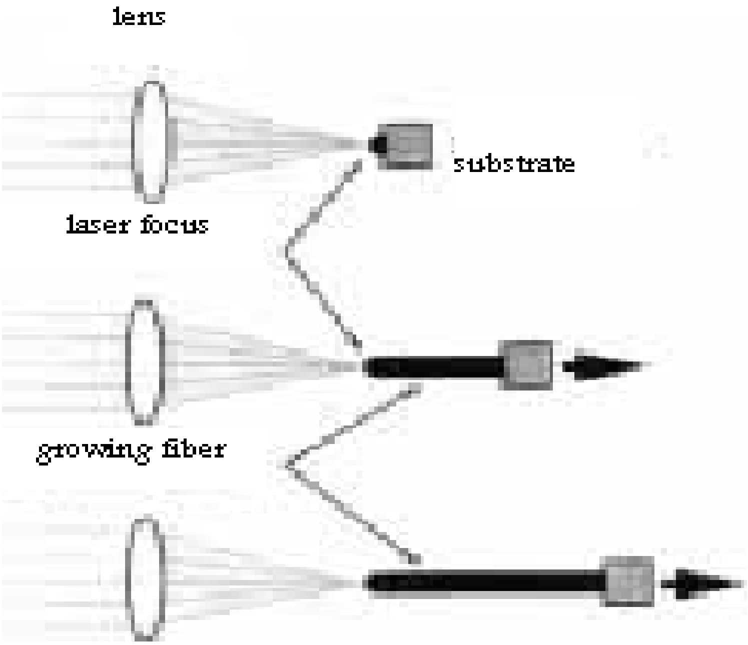

Figure 11: LCVD

5) Localized electrochemical deposition (LECD)

Opposite effect of EDM, the localized growth is defined by a sharp microelectrode. We use it to made 3-D structures. The figure 8 shows some examples of microstructures made by the LECD process.

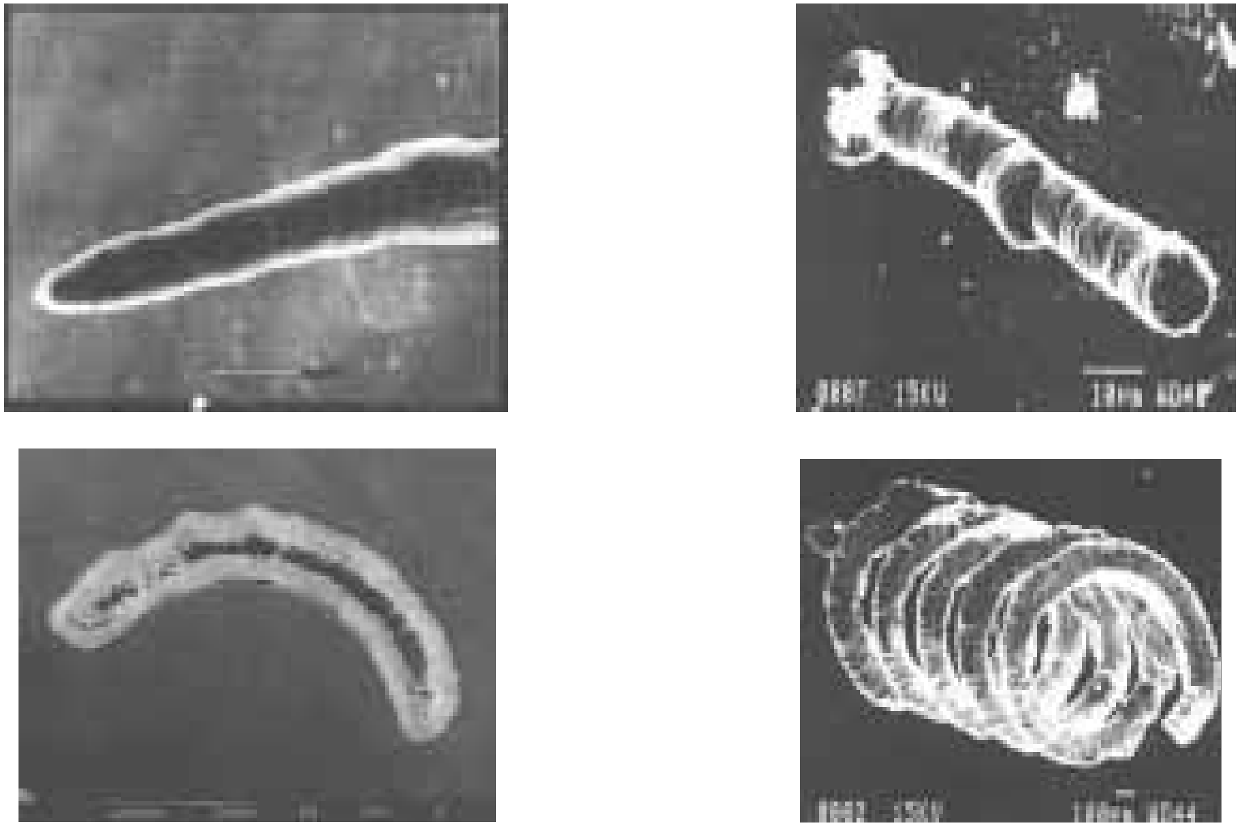

Figure 12: Some LECD structures

Material removal methods

1) Bulk micromachining

Bulk micromachining is the most used in silicon micromachining technology. It is emerged in the early 1960s and has been used since then in the fabrication of many different microstructures. Bulk micromachining is utilized in the manufacture of the majority of commercial devices – almost all pressure sensors and silicon valves and 90 percent of silicon acceleration sensors. The term Bulk micromachining expresses 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 the wafer material.

The microstructure fabricated using Bulk micromachining may cover the thickness range from submicrons to the thickness of the full wafer (200 to 500 μm) and the lateral size ranges from microns to the full diameter of a wafer (75 to 200 mm), where etching is the key technological step for bulk micromachining. Anisotropic etching with KOH can easily form V shaped grooves, or cut pits with tapered walls into silicon (Figure 13).

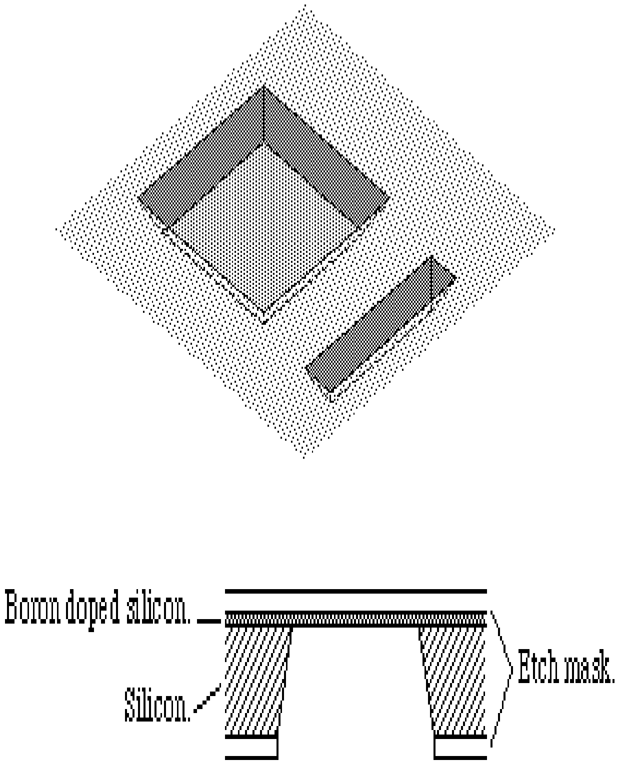

Figure 13: Wet etching of a thin film of material

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 14 shows a bridge, defined by boron diffusion, spanning a pit that was etched from the front of the wafer in KOH.

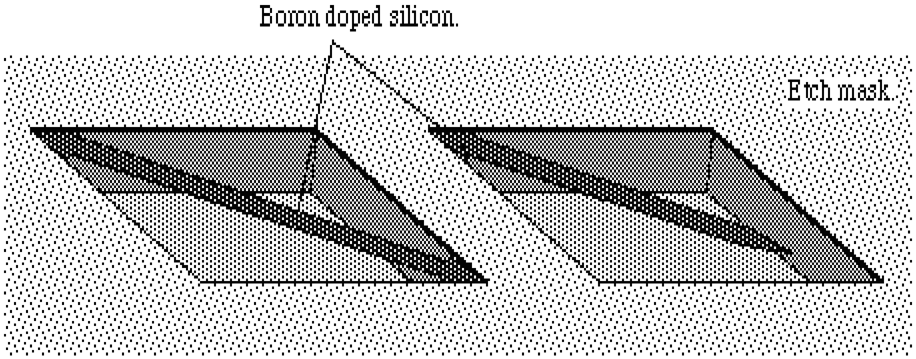

Figure 14: Bulk micromachining in producing bridge

A cantilever beam (a bridge with one end free) produced by the same method is shown in Figure 15.

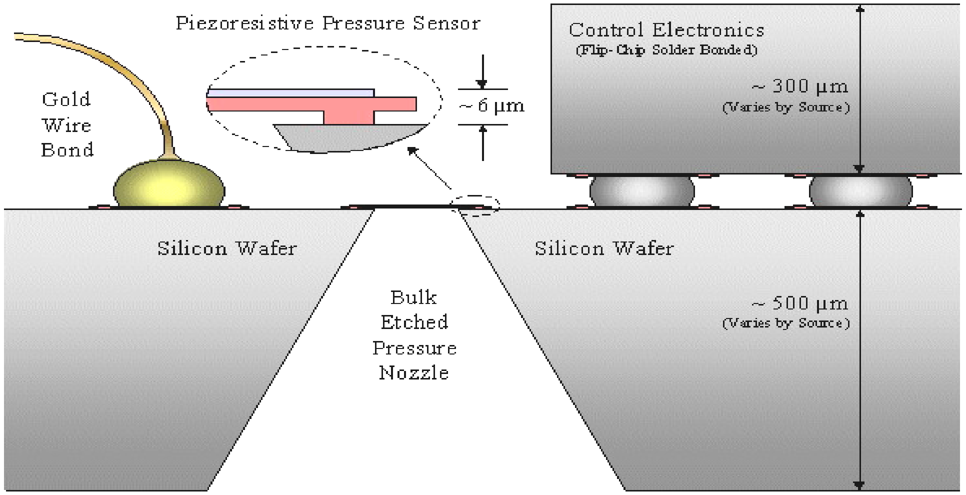

Figure 15: Bulk micromachining in producing cantilever beam

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 16). 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).

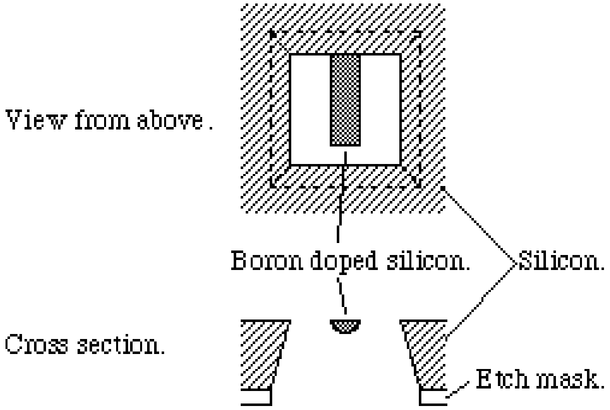

Figure 16: (Cantilever) by using wet etching

One of the applications for these beams and bridges is as resonant sensors. The structure can be set vibrating at its 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 17 (a)). A wet etch is then used, which undercuts the etch mask leaving a very fine point (Figure 17 (b)), the etch mask is then removed.

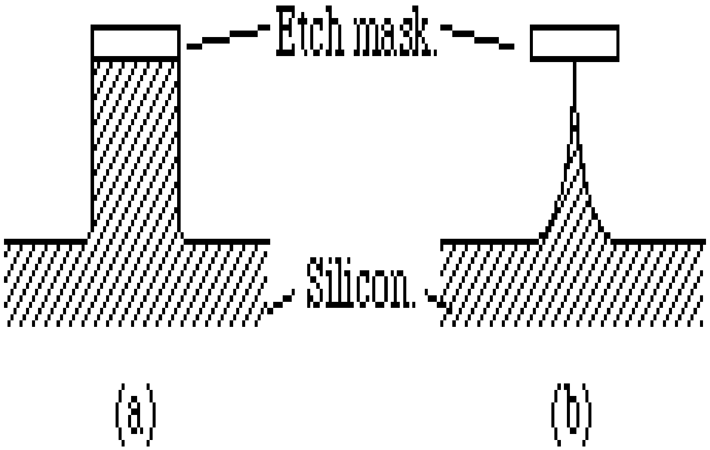

Figure 17: A combination of wet and dry etch to form very fine points

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

2) Laser micromachining

Most laser micromachining processes are not parallel and hence not fast enough for effective MEMS fabrication. Nonetheless, they have utility in specialty micromachining or making moulds. One of the most kinds of lasers used in microfabrication is Excimer (Excited Dimer), this type was invented in 1975, by using a diatomic molecules like N2 and H2 as lasing materials. Excimer laser wavelength is in the ultraviolet range (157 nm, 193 nm, 248 nm, 308 nm, 353 nm). Excimer laser micromachining is used particularly for the micromachining of organic materials (plastics, polymers etc.), as material is not removed by burning or vaporization. Hence, material adjacent to the machined area is not melted or distorted by heating effects. Lasers have found other applications in MEMS but only in a limited capacity, laser drilling, laser annealing and etching are the most common forms. 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 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 18 (a)). A more sophisticated and versatile method involves projecting the image of the mask onto the material (Figure 18 (b)). Material is selectively removed where the laser light strikes it.

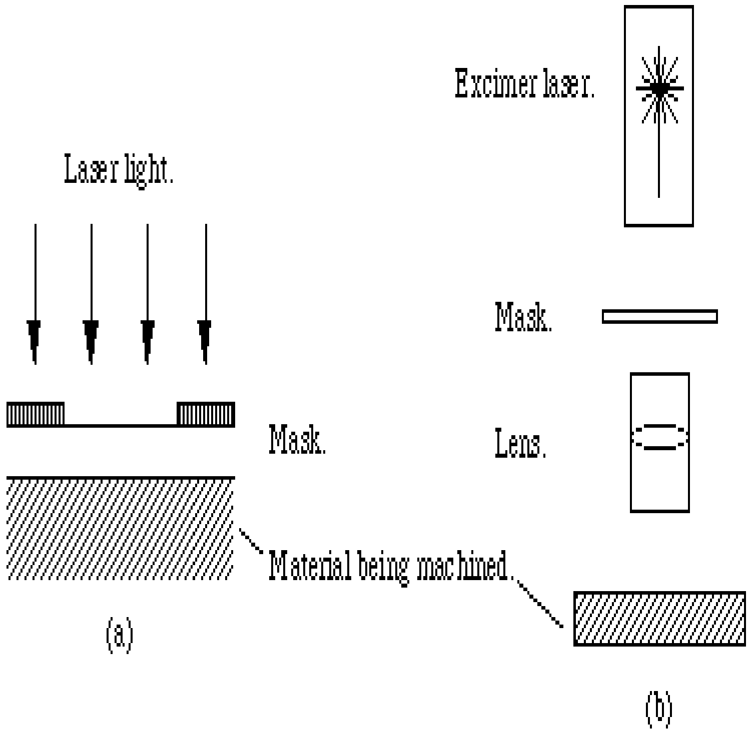

Figure 18: Excimer Laser used in micromachining

3) Milling

A) Focused ion beam milling

The beam is ejected from a liquid metal ion source (e.g. gallium), this ion beam is applied directly onto substrate through a mask, with no resist layer. This process is Anisotropic, and possible to make thick microstructure (about 100 mm), with spot size < 10 nm.

B) Plasma beam milling

The simplest plasma reactor consists of two plate electrodes in a chamber with low pressure adjusted to 0.01 to 1 mbar (1-100 Pa) (Figure 19). The electrodes are connected with a high frequency voltage source. If the voltage is applied to the electrodes, a current flow forming plasma, which emits a characteristic glow. At the same time reactive species are formed from the feedstock gas or gas mixture. Samples placed on one of the electrodes are exposed to the plasma and in consequence to reactive neutrals and charged particles. Milling of the samples takes place if the reactive species are able to react with the sample material under formation of volatile products, which are pumped away. Other materials which will not form volatile products will not be removed and can be used as masking layer.

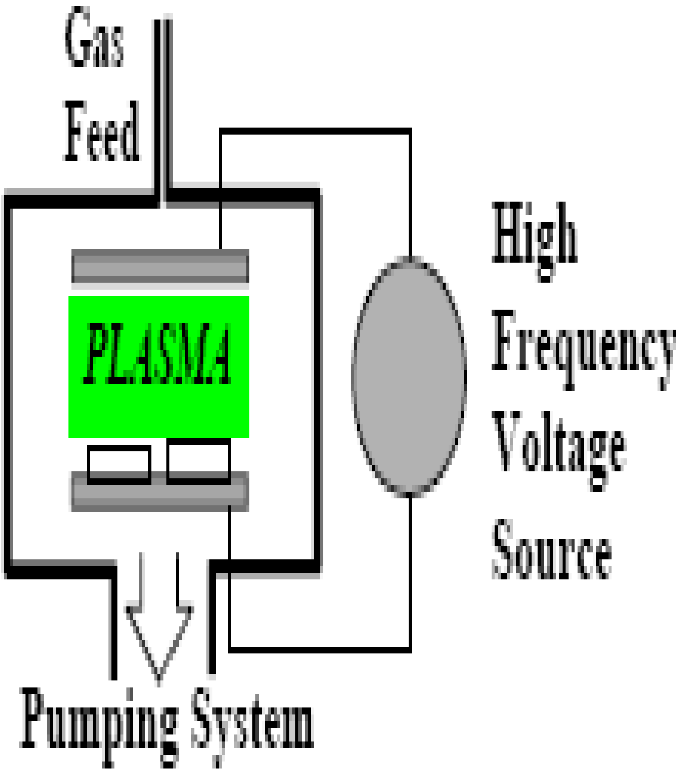

Figure 19: Plasma reactor used in micromachining

C) Diamond milling

Diamond machining uses an extremely sharp diamond cutting tool to machine extremely accurate surfaces. Diamond tools can be used in especially made laths, fly cutters, boring machines, NC machines and other machine shop tools to generate complex surfaces.

4) Micro Electro-Discharge Machining

Also called spark erosion, first experiment at the end of 60's, then it rediscovered at later 80's. This method removes material through erosive action. Structures, which can be made, are micro holes and micro shafts.

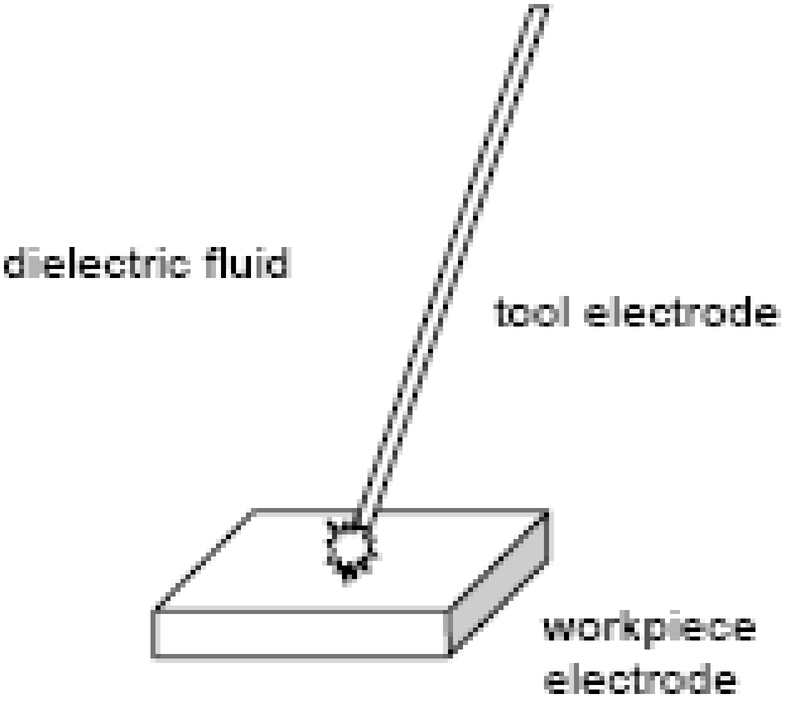

Figure 20: EDM micromachining

This method has a lot of benefits, like the low installation cost, flexibility, ideal for prototypes, easy to make complex 3D structure and has high aspect ratio. There are different types of EDM, in Die-sinking EDM; the tool material used is Copper and graphite, which is a complex and expansive tool. For the Wire EDM, the tool material is tungsten and copper, which make it cheaper, easy to renew tool, and can make complex parts with shorter machining time. A drawback is that wire may bend, which reduced accuracy.

5) Micro ultrasonic Machining

Here we use the ultrasonic as vibrated tool (i.e. mechanical effect), with an abrasive slurry added. Oscillation type is 20 MHz, which can penetrate hard materials such as glass and Si. Machined part becomes an exact counterpart of the tool.

6) Powder Blasting

It is an erosion technique, where the powder particles generate cracks and remove material. Erosion rate is 1 mm/min; with a particle speed is from 80 – 200 m/s. The smallest cut $\simeq$ 3x particle size. The masks used are metals and thick foils.

7) Soft lithography

It is a non-optical transfer technique, with an elastomeric stamp with patterned relief structures on its surface. The pattern added by microcontact printing or replica micromolding. Figure 21 shows some structures made by soft lithography.

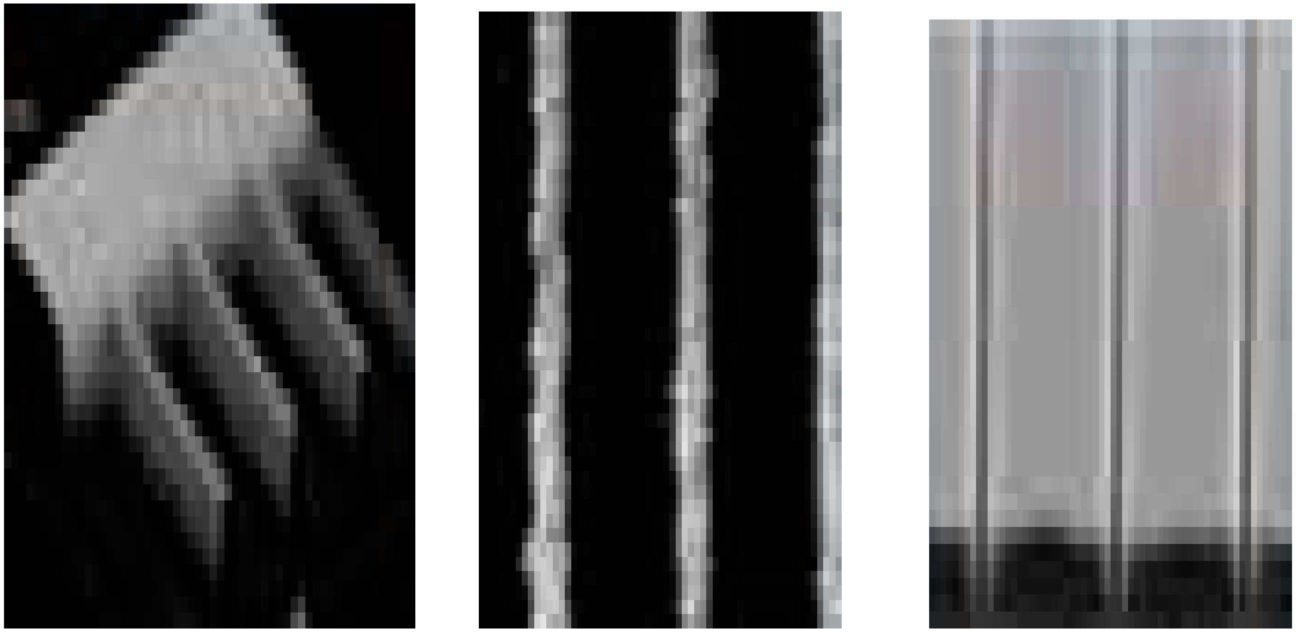

Figure 21: Soft lithography structures