This chapter will offer an overview of the application of the various fabrication techniques described in Chapter 8 in the manufacturing micrometer scaled devices and systems of complicated geometry delivering electromechanical functions.

Three distinct micromanufacturing techniques will be presented:

- **Bulk micromanufacturing**
- **Surface micromachining**
- **The LIGA process**
• Bulk micromanufacturing technique involves creating **3-D components** by **removing materials** from thick substrates (silicon or other materials) using primarily **etching** method.

• **Etching** - dry or wet etching is the principal technique used in bulk micromanufacturing.

• Substrates that can be etched in bulk micromanufacturing include:
  - Silicon
  - SiC
  - GaAs
  - special polymers

• **Wet etching** involves the use of chemical solvents (called **etchants**)

• **Dry etching** uses **plasma** to remove materials at the desired locations on a substrate.
Isotropic and Anisotropic Etching

- Pure silicon crystals are not isotropic in their properties due to non-uniform distribution of atoms at their interior.
- Such anisotropic properties are represented by three distinct planes:

  - The (100) plane
  - The (110) plane
  - The (111) plane

- The (111) plane makes an angle of 54.74° with the (100) plane.
- Corresponding to these (3) planes are 3 distinct directions in which etching takes place: <100>, <110> and <111>.
- The <100> is the easiest direction for etching, and the <111> is the hardest direction for etching.
Anisotropic etching of silicon

- Anisotropic etching is **easier** to control of the etched shape of the substrates.
- **Disadvantages:**
  - Slower in rate of etching (< 1 µm/minute)
  - The rate is **temperature-sensitive**.
  - Best performance at elevated temperature, e.g. 100°C → temperature-resistant mask materials.
Wet etchants for silicon and silicon compounds

- **HNA** for isotropic etching at room temperature.
- **Alkaline chemicals** with ph > 12 for anisotropic etching.
- **Popular anisotropic etchants** are:
  - KOH (potassium hydroxide)
  - EDP (ethylene-diamine and pyrocatecol)
  - TMAH (tetramethyl ammonium hydroxide)
  - Hydrazine
- **Most etchants** are used with 1:1 by weight mixture with water.
- **Typical etching rates** are:

<table>
<thead>
<tr>
<th>Materials</th>
<th>Etchants</th>
<th>Etch Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon in &lt;100&gt;</td>
<td>KOH</td>
<td>0.25 –1.4 µm/min</td>
</tr>
<tr>
<td>Silicon in &lt;100&gt;</td>
<td>EDP</td>
<td>0.75 µm/min</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>KOH</td>
<td>40 – 80 nm/hr</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>EDP</td>
<td>12 nm/hr</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>KOH</td>
<td>5 nm/hr</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>EDP</td>
<td>6 nm/hr</td>
</tr>
</tbody>
</table>
Selectivity Ratios of Etchants

- Silicon compounds are much stronger etching resistive materials than silicon.
- These materials can thus be used as masks for etching of silicon substrates.
- The resistivity to etchants is measured by **Selectivity Ratio** of a material.
- The **selectivity ratio** of a material is defined by:

\[
Selectivity\ Ratio = \frac{Etching\ rate\ of\ silicon}{Etching\ rate\ of\ the\ material}
\]

- Selectivity ratio of etchants to two silicon compound substrates is:

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Etchants</th>
<th>Selectivity Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide</td>
<td>KOH</td>
<td>(10^3)</td>
</tr>
<tr>
<td></td>
<td>TMAH</td>
<td>(10^3 - 10^4)</td>
</tr>
<tr>
<td></td>
<td>EDP</td>
<td>(10^3 - 10^4)</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>KOH</td>
<td>(10^4)</td>
</tr>
<tr>
<td></td>
<td>TMAH</td>
<td>(10^3 - 10^4)</td>
</tr>
<tr>
<td></td>
<td>EDP</td>
<td>(10^4)</td>
</tr>
</tbody>
</table>

- The higher the selectivity ratio, the better the mask material is.
A. On etching geometry:

- **Timing** and agitated **flow patterns** can affect the geometry of etched substrate geometry:

  - Ideal etching
  - Under etching
  - Under cutting

- **Endurance of the masks** is another factor that affects the etching geometry.
Control of wet etching – Cont’d

B. Etch stop:
Etching may be stopped by the following two methods, both related to doping of the silicon substrates.

- **Controlled by doping:**
  Doped silicon dissolved faster in etchants than pure silicon.

- **Controlled by electrochemical etch stop:**

  ![Diagram of electrochemical etch stop]

  Etching stops at the interface of p- and n-type of the doped silicon.
Dry etching involves the removal of substrate materials by *gaseous etchants*. It is more a physical than chemical process.

**3 dry etching techniques:**
- Ion etching.
- **Plasma etching**.
- Reactive ion etching.  →  Deep reactive ion etching (DRIE)

**Plasma etching:**

*Plasma* is a neutral ionized gas carrying a large number of free electrons and positively charged ions.

A *common source of energy* for generating plasma is the *radio frequency* (RF) source.

*Chemical reactive gas*, e.g. CCl₂F₂, is mixed with plasma in etching process. Other chemical reactive gases for different substrates are given in Table 9.3.
Plasma etching – Cont’d

The working principle:

- Plasma etching operates on both high kinetic energy and chemical reactions between neutrals (N) and the substrate materials.
- The reactive gas, e.g. CF₂ in the carrier gas ions produces reactive neutrals (N).
- The reactive neutrals (N) attacks both the normal surface and the side walls.
- The ions (+) only attack the normal surface only.
- As result, the etching front advances much faster in the depth than on the sides.

Rate of dry etching:

- Conventional dry etching by ions is slow in rates at about 0.1 µm/min, but plasma etching may increase this rate to 2 µm/min.
- The rate of dry etching can be “stretched” to 5 µm/min. It is much faster and cleaner than wet etching.
Deep Reactive Ion Etching (DRIE)

Why DRIE?

- Plasma etching can produce deeper trenches, than wet etching, but with tapered angles.
- Tapered trenches are not desirable in many applications such as resonators that involve pairs of “centipedes-like” micro devices with overlapped “fingers”:
  - DRIE process may produce deep trenches with $\theta \approx 0$. 
Deep Reactive Ion Etching (DRIE)

Working principle:
- The DRIE process provides thin films of a few microns protective coatings on the sidewalls during the etching process.
- It involves the use of a high-density plasma source.
- The process allows alternating process of plasma (ion) etching of the substrate material and the deposition of etching-protective material on the sidewalls.
- Special polymers are frequently used for side-wall protective films.

What DRIE can do:
- The DRIE process has produced MEMS structures with $A/P^{**} = 30$ with virtually vertical walls of $\theta = \pm 2^\circ$ for several years.
- Recent developments have used better sidewall protecting materials. For example, silicon substrates with $A/P$ over 100 was achieved with $\theta = \pm 2^\circ$ at a depth of up to 300 $\mu$m. The etching rate, however, was reduced to 2-3 $\mu$m/min.

** $A/P = \text{Aspect ratio} = \text{the dimension in vertical to horizontal directions} $
Recent development:

- Recent developments have substantially improved the performance of DRIE with better sidewall protecting materials.

- Silicon substrates with A/P over 100 was with $\theta = \pm 2^{\circ}$ at a depth of up to 300 $\mu$m was achieved. The etching rate, however, was reduced to 2-3 $\mu$m/min.

Popular side wall protecting materials:

<table>
<thead>
<tr>
<th>Sidewall protection materials</th>
<th>Selectivity ratio</th>
<th>Aspect ratio, A/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td></td>
<td>30:1</td>
</tr>
<tr>
<td>Photoresists</td>
<td>50:1</td>
<td>100:1</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>120:1</td>
<td>200:1</td>
</tr>
</tbody>
</table>
### Wet vs. dry etching:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dry etching</th>
<th>Wet etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directionality</td>
<td>Good for most materials</td>
<td>Only with single crystal materials (aspect ratio up to 100)</td>
</tr>
<tr>
<td>Production-automation</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Masking film adherence</td>
<td>Not as critical</td>
<td>Very critical</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Poor</td>
<td>Very good</td>
</tr>
<tr>
<td>Materials to be etched</td>
<td>Only certain materials</td>
<td>All</td>
</tr>
<tr>
<td>Process scale up</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Conditionally clean</td>
<td>Good to very good</td>
</tr>
<tr>
<td>Critical dimensional control</td>
<td>Very good (&lt; 0.1 μm)</td>
<td>Poor</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>Expensive</td>
<td>Less expensive</td>
</tr>
<tr>
<td>Typical etch rate</td>
<td>Slow (0.1 μm/min) to fast (6 μm/min)</td>
<td>Fast (1 μm/min and up)</td>
</tr>
<tr>
<td>Operational parameters</td>
<td>Many</td>
<td>Few</td>
</tr>
<tr>
<td>Control of etch rate</td>
<td>Good in case of slow etch</td>
<td>Difficult</td>
</tr>
</tbody>
</table>
Surface Micromachining

- **Etching** process creates 3-D microstructures by removing material from substrates.
  - Removed substrate materials are wasted.

- **Surface micromachining** creates 3-D microstructures by adding material to the substrate.
  - Added materials may not be same as the substrate material – flexibility.
  - Added material layers can be 2-5 µm thick each, or as high as 5-20 µm thick each – much more than most etching process can achieve.
  - There is little waste of substrate materials.

  - Deposition processes are commonly used methods – expensive.
  - Requires multiple masks – expensive and time consuming.
  - Requires sacrificial layers to create cavities – wasteful with technical problems.
Illustration of micromachining process – creation of a polysilicon cantilever beam on silicon substrate base:

- Deposit a sacrificial layer of PSG (Phosphosilicate glass) using LPCVD process.
- Cover the PSG layer with Mask 1 (made of Si$_3$N$_4$) for subsequent etching away the PSG for beam’s support area as shown in Step C.
- Produce a Mask 2 (Si$_3$N$_4$) with opening of the size of the beam length and width. Cover this Mask on top of the PSG layer.
- Deposit polysilicon over the masked region using CVD to thickness of the beam.
- Remove the sacrificial PSG by etching (see blow) and creates the free-standing cantilever beam.
Etching of sacrificial layers:

Three (3) commonly used sacrificial layer materials:
- **PSG** (Phosphosilicate glass)
- **SiO₂**
- **BPSG** (Boronphosphosilicate)

**Etching process:** 1:1 HF:H₂O + 1:1 HCℓ:H₂O. Rising with deionized water and dried under Infrared lamp.

**Etching rates for sacrificial layers**

<table>
<thead>
<tr>
<th>Thin Oxide Films</th>
<th>Lateral Etch Rate (µm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVD SiO₂ (densified at 1050°C for 30 min.)</td>
<td>0.6170</td>
</tr>
<tr>
<td>Ion-implanted SiO₂ (at 8x10¹⁵/cm², 50 KeV)</td>
<td>0.8330</td>
</tr>
<tr>
<td>Phosphosilicate (PSG)</td>
<td>1.1330</td>
</tr>
<tr>
<td>5%-5% Boronphosphosilicate (BPSG)</td>
<td>4.1670</td>
</tr>
</tbody>
</table>
Mechanical problems

(1) Quality of adhesion of layers:

- The interfaces of layers are the vulnerable areas for structural failures.
- Two possible failures:

  ![Peeling off](image1)  ![Severing along the interface by shear](image2)

(2) Interfacial stresses due to mismatch of CTE:

At 1000°C:

- During oxidation by CVD

At 20°C:

- After oxidation
(3) **Stiction:**

- It is the **most serious technical problem** in surface micromachining.
- It occurs in structures separated by **narrow gap** that is supported by sacrificial layer, e.g. with PSG.
- Stiction phenomenon is the **collapsing of the layers** supported by the sacrificial layers once they are removed by etching.
- Stiction may occur in the example of the cantilever beam fabricated by surface micromachining:

![Diagram of cantilever beam]

- Once stiction takes place, there is **little chance to separate the parts again**.
- Stiction occurs due to **Van der Waals and chemical forces** between surfaces with narrow gaps.
The term **LIGA** is an acronym for German term in “Lithography (Lithographie), electroforming (Galvanoformung), and molding (Abformung)”.

- The technique was first developed at the Karlsruhe Nuclear Research Center in Karlsruhe, Germany.

- LIGA process is **radically different** from silicon-based micro manufacturing.

- The major difference is that LIGA can produce microstructures that have **high aspect ratio**.

- There is no restriction on using silicon or silicon compounds as substrate. **Nickel** is a common material for LIGA products.

- It is easier to be produced in large volumes.

- **Major disadvantage** of LIGA process is the requirement of special facility - **Synchrotron radiation (X-ray) source**, a very expensive facility.
The LIGA Process – Cont’d

Major steps in LIGA process

- Deep x-ray lithography
  (Provided by Synchrotron radiation facility)

- Photoresist with desired patterns
  (Using a mask made of Quartz with gold plating)

- Electroplating of metal on patterns

- Metal product
  (Usually with nickel linings)

- Metal molds

- Plastic products by injection molding
The LIGA Process – Cont’d

Fabrication of a square tube using LIGA

The desired product: a tube

Gold plated region (For blocking x-ray)

Mask (Si$_3$N$_4$) (Transparent to x-ray)

X-ray

1 - 1.5 $\mu$m tk

Thick film Photoresist PMMA

Substrate

(a) X-ray lithography

(b) Resist after lithography

Plated metal layers (Normally Ni)

Metal tube (Made of Ni)

Substrate

(c) After electroplating

(d) After removing resist
The LIGA Process – Cont’d

**Materials for substrates**
- Substrates in LIGA process must be electrical conductive to facilitate subsequent electroplating over photoresist mold.
- Metals such as: steel, copper plates, titanium and nickel, or
- Silicon with thin titanium or silver/chrome top layer; glass with thin metal layers.

**Photoresist materials**

**Basic requirements:**
- Must be sensitive to x-ray radiation.
- Must have high resolution and resistance to dry and wet etching.
- Must have thermal stability up to 140°C.
- The unexposed part must be absolutely insoluble during development.
- Good adhesion to substrate during electroplating.
- PMMA appears most popular for LIGA process, but other polymers are available:

<table>
<thead>
<tr>
<th></th>
<th>PMMA</th>
<th>POM</th>
<th>PAS</th>
<th>PMI</th>
<th>PLG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Bad</td>
<td>Good</td>
<td>Excellent</td>
<td>Reasonable</td>
<td>Reasonable</td>
</tr>
<tr>
<td>Resolution</td>
<td>Excellent</td>
<td>Reasonable</td>
<td>Very bad</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Sidewall smoothness</td>
<td>Excellent</td>
<td>Very bad</td>
<td>Very bad</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Stress corrosion</td>
<td>Bad</td>
<td>Excellent</td>
<td>Good</td>
<td>Very bad</td>
<td>Excellent</td>
</tr>
<tr>
<td>Adhesion on substrate</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Bad</td>
<td>Good</td>
</tr>
</tbody>
</table>
The inner surfaces of the photoresist mold produced by X-ray lithography need to be plated with thin metal layers for securing permanent microstructure geometry.

Metals available for the plating are: Ni, Cu, Au, NiFe and NiW.

In the case of plating with Ni, the process is:

- **Nickel ions** \((\text{Ni}^{2+})\) are produced from electrolysis of \(\text{NiCl}_2\) solution.

- They are attracted to the electrons at the cathode:

  \[
  \text{Ni}^{2+} + 2\text{e}^- \rightarrow \text{Ni}
  \]

- There could be \(\text{H}^+\) ions presence at the same cathode in the process.
- These \(\text{H}^+\) ions may form \(\text{H}_2\) bubbles on the cathode, and thus Ni plate.
- Proper control of the pH in the solution is important to mitigate this effect.
Summary on Micromanufacturing

A. Bulk micromanufacturing:
- Less expensive in the process, but material loss is high.
- Suitable for microstructures with simple geometry.
- Limited to low-aspect ratio in geometry.

B. Surface micromachining:
- Requires the building of layers of materials over the substrate.
- Complex masking design and productions.
- Etching of sacrificial layers is necessary – not always easy and wasteful.
- The process is tedious and more expensive.
- There are serious engineering problems such as interfacial stresses and stiction.
- Major advantages:
  - Not constrained by the thickness of silicon wafers.
  - Wide choices of thin film materials to be used.
  - Suitable for complex geometry such as micro valves and actuators.

C. The LIGA process:
- Most expensive in initial capital costs.
- Requires special synchrotron radiation facility for deep x-ray lithography.
- Micro injection molding technology and facility for mass productions.
- Major advantages are:
  - Virtually unlimited aspect ratio of the microstructure geometry.
  - Flexible in microstructure configurations and geometry.
  - The only technique allows the production of metallic microstructures.