ME 189 Microsystems Design and Manufacture

Chapter 9

Micromanufacturing

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

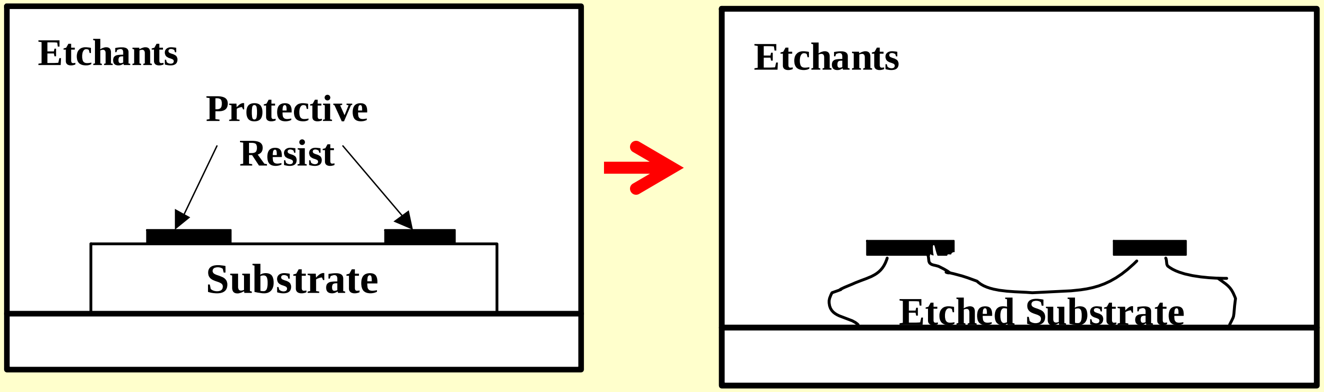
Bulk Micromanufacturing

- 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)

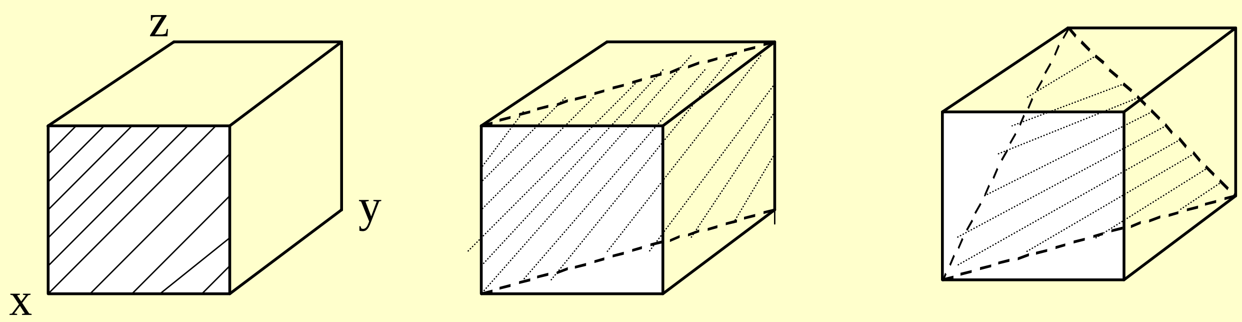


- Dry etching uses plasma to remove materials at the desired locations on a substrate.

Bulk Micromanufacturing- Cont'd

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:

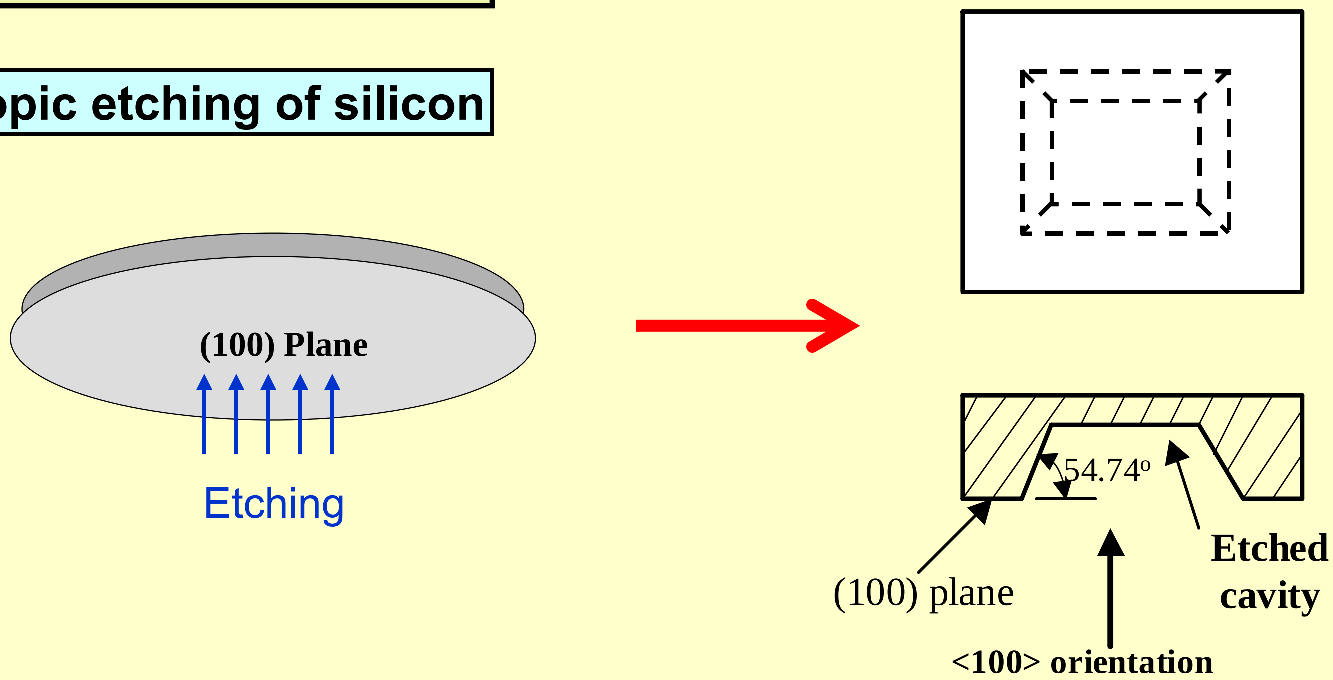


The (100) plane The (110) plane The (111) plane

- 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.

Bulk Micromanufacturing- Cont'd

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^oC → temperature-resistive mask materials.

Bulk Micromanufacturing- Cont’d

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:**

Materials	Etchants	Etch Rates
Silicon in <100> Silicon in <100>	KOH EDP	0.25 –1.4 μm/min 0.75 μm/min
Silicon dioxide Silicon dioxide	KOH EDP	40 – 80 nm/hr 12 nm/hr
Silicon nitride Silicon nitride	KOH EDP	5 nm/hr 6 nm/hr

Rate drops
Harder to etch

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:

$$Selectivity\ Ratio = \frac{Etching\ rate\ of\ silicon}{Etching\ rate\ of\ the\ material}$$ using same etchant

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

Substrates	Etchants	Selectivity Ratios
Silicon dioxide	KOH TMAH EDP	10^3 $10^3 – 10^4$ $10^3 - 10^4$
Silicon nitride	KOH TMAH EDP	10^4 $10^3 – 10^4$ 10^4

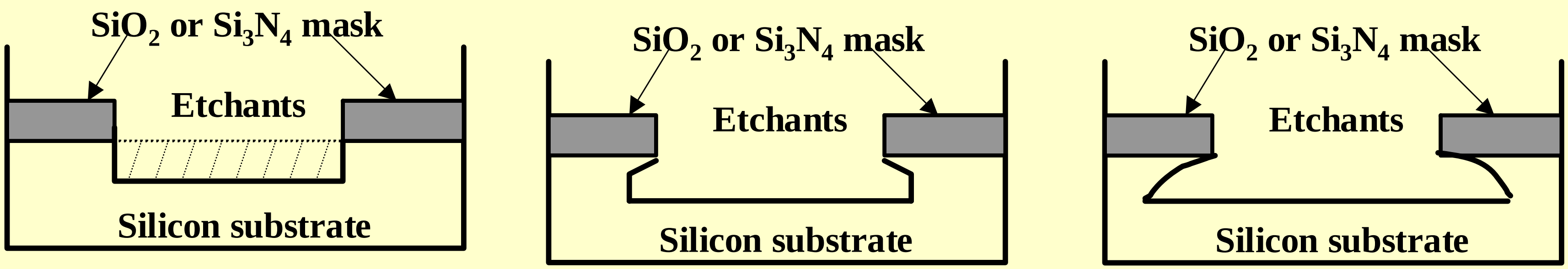
- **The higher the selectivity ratio, the better the mask material is**.

Bulk Micromanufacturing- Cont'd

Control of wet etching

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.

Bulk Micromanufacturing- Cont'd

Control of wet etching – Cont'd

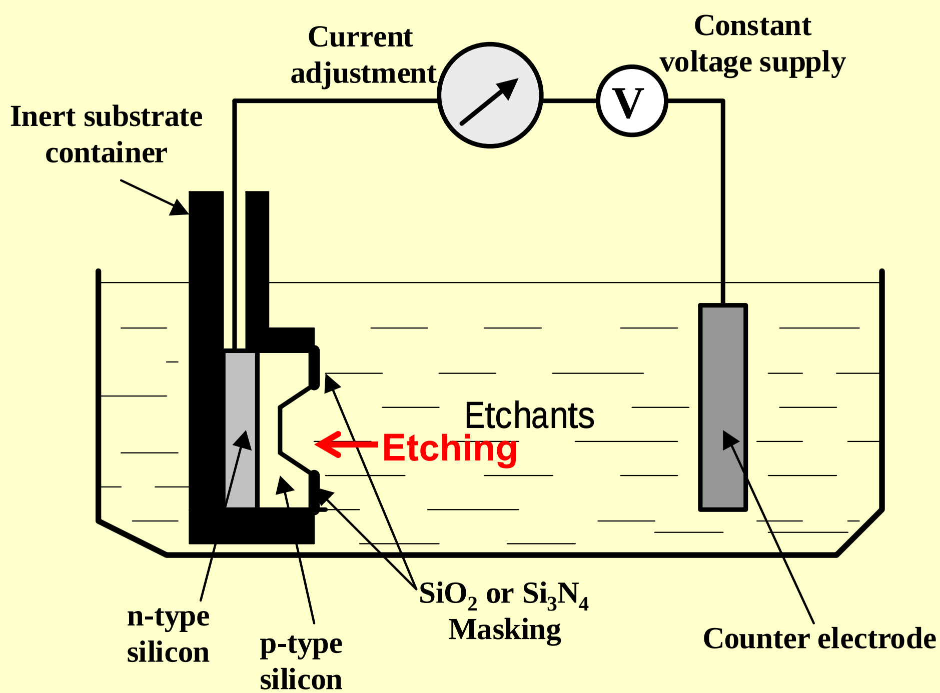
B. Etch stop:

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:**



Etching stops at the interface of p- and n-type of the doped silicon.

Dry Etching

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.

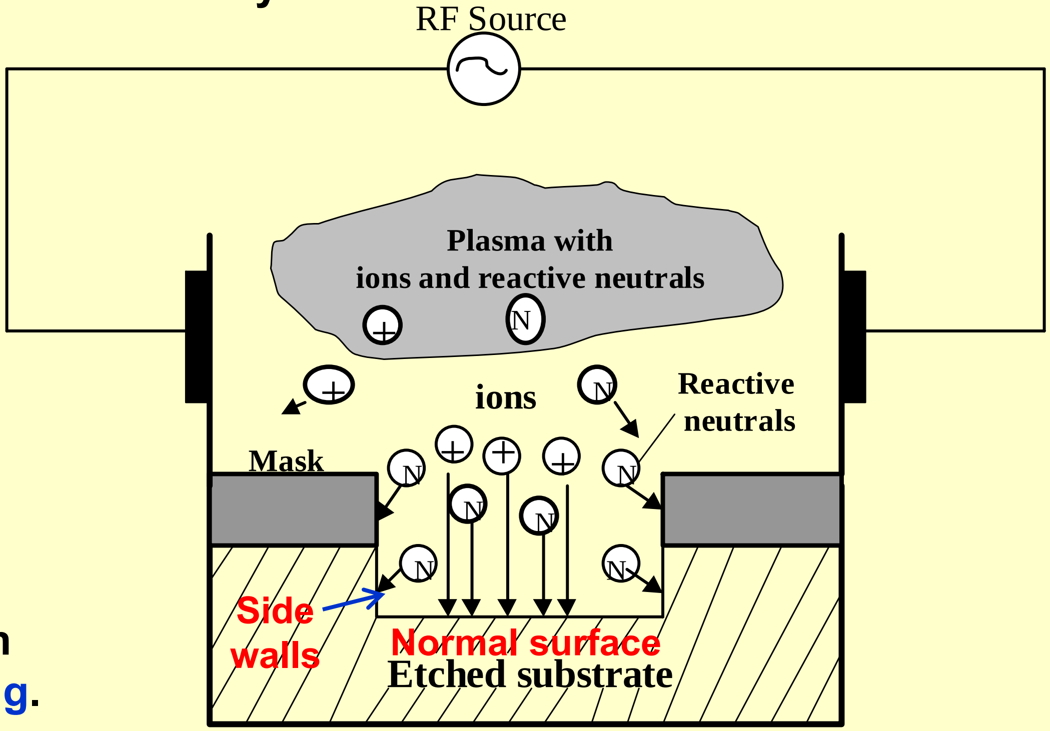
A common source of energy for generating plasma is the radio frequency (RF) source.

Chemical reactive gas, e.g. $CC\ell_2F_2$, is mixed with plasma in etching process. Other chemical reactive gases for different substrates are given in Table 9.3.

Bulk Micromanufacturing- Cont'd

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. $CC\ell_2F_2$ 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:

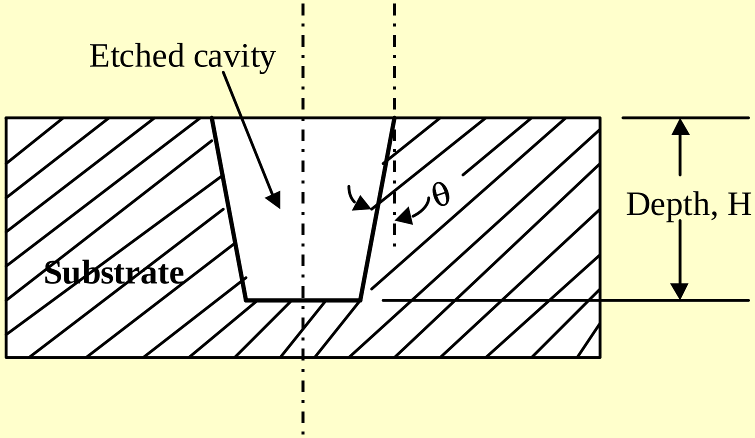
- Conventional dry etching by ions is slow in rates at about 0.1 μm/min, but plasma etching may increase this rate to 2 μm/min.
- The rate of dry etching can be "stretched" to 5 μm/min. It is much faster and cleaner than wet etching.

Bulk Micromanufacturing- Cont'd

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":



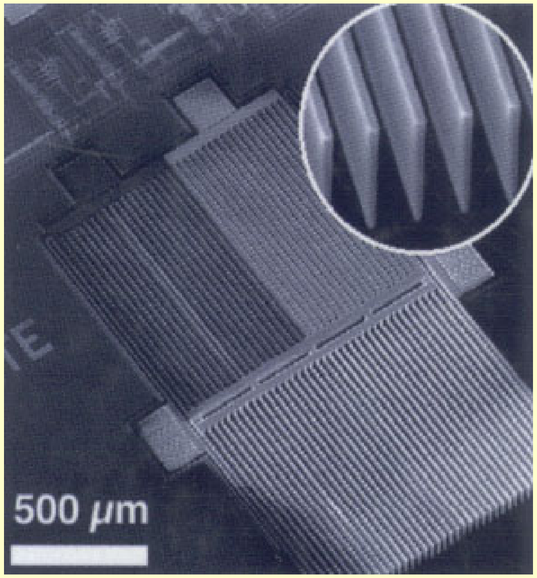
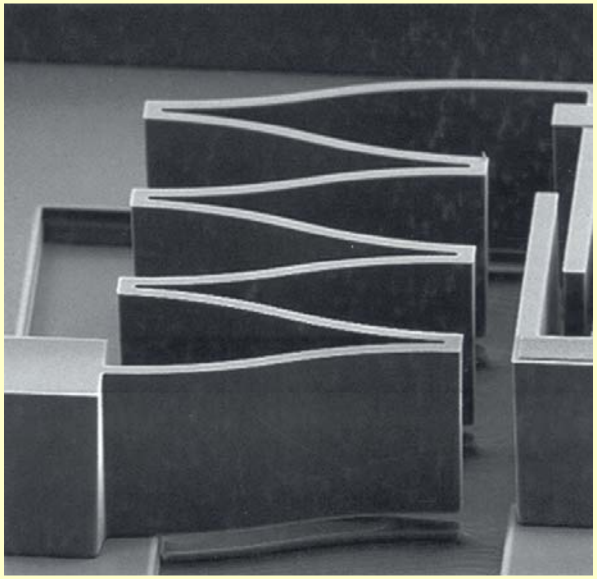


Plate- resonators



Spring resonator

- **DRIE process may produce deep trenches with $\theta \approx 0$.**

Bulk Micromanufacturing- Cont'd

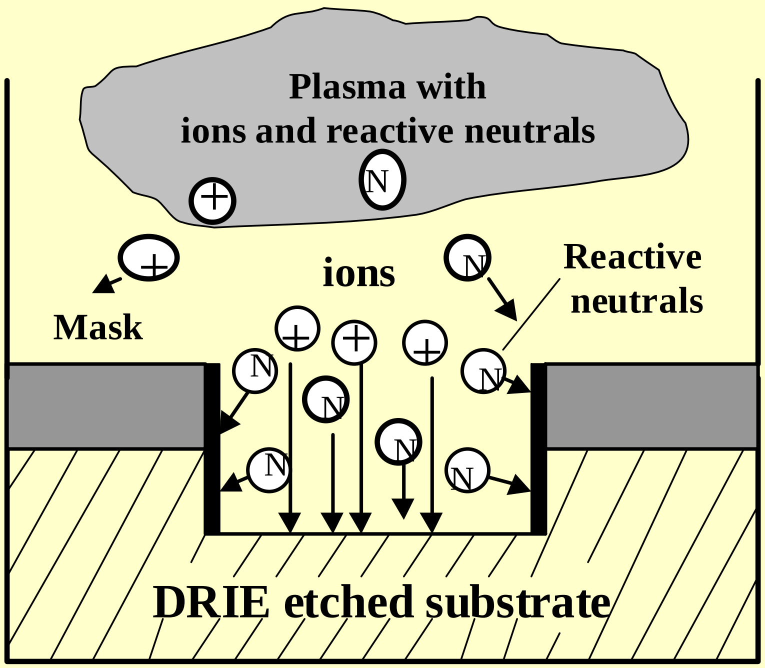
Deep Reactive Ion Etching (DRIE)

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 $\theta = \pm 2^o$ for several years.
- Recent developments have used better sidewall protecting materials. For example, silicon substrates with A/P over 100 was achieved with $\theta = \pm 2^o$ at a depth of up to 300 μm. The etching rate, however, was reduced to 2-3 μm/min.



** **A/P** = **Aspect ratio** = the dimension in vertical to horizontal directions

Deep Reactive Ion Etching (DRIE)- Cont'd

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 $\theta = \pm 2^o$ at a depth of up to 300 μm was achieved. The etching rate, however, was reduced to 2-3 μm/min.

Popular side wall protecting materials:

Sidewall protection materials	Selectivity ratio	Aspect ratio, A/P
Polymer		30:1
Photoresists	50:1	100:1
Silicon dioxide	120:1	200:1

Bulk Micromanufacturing- ends

Wet vs. dry etching:

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

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.**

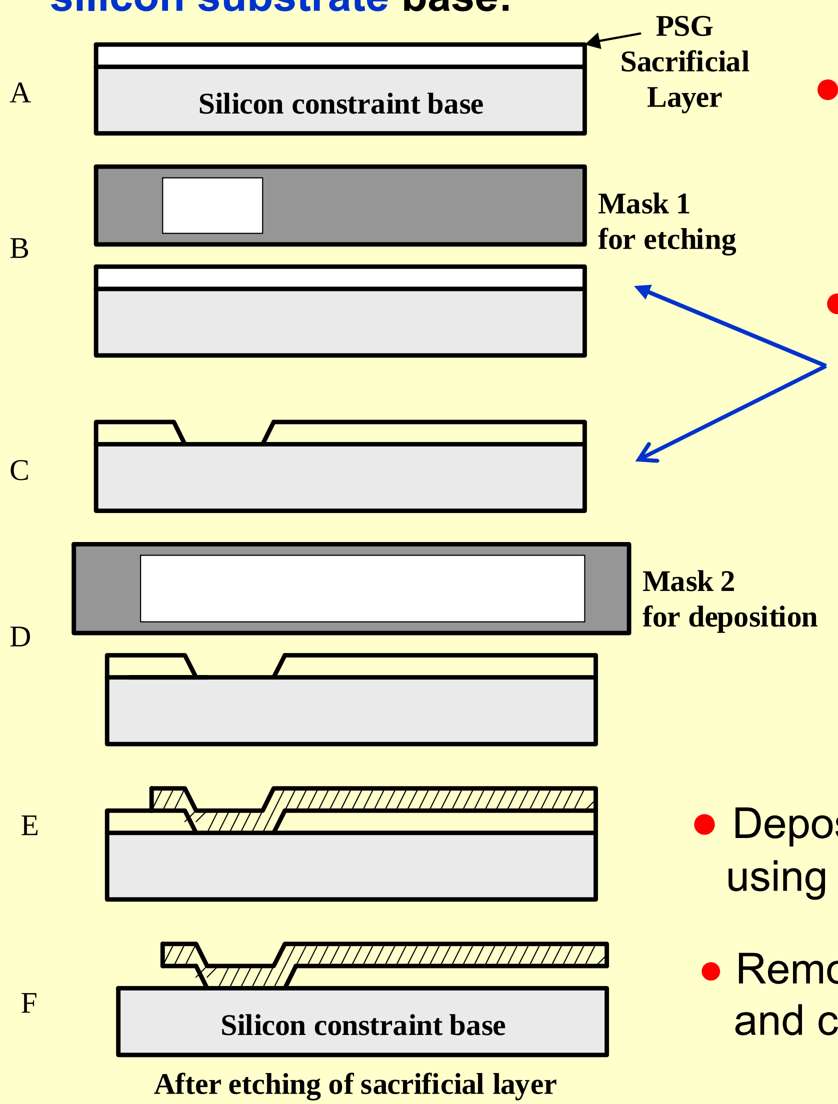
- **Added materials may not be same as the substrate material – flexibility.**
- **Added material layers can be 2-5 μm thick each, or as high as 5-20 μm thick each – much more than most etching process can achieve.**
- **There is little waste of substrate materials.**

- **Deposition processes are commonly used methods – expensive.**
- **Requires multiple masks – expensive and time consuming.**
- **Requires sacrificial layers to create cavities – wasteful with technical problems.**

Surface Micromachining – Cont'd

General description of process

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_3N_4) for subsequent etching away the PSG for beam's support area as shown in Step C.
- Produce a Mask 2 (Si_3N_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.

Surface Micromachining – Cont'd

General description of process- Cont'd

Etching of sacrificial layers:

Three (3) commonly used sacrificial layer materials:
- **PSG** (Phosphosilicate glass)
- **SiO_2**
- **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

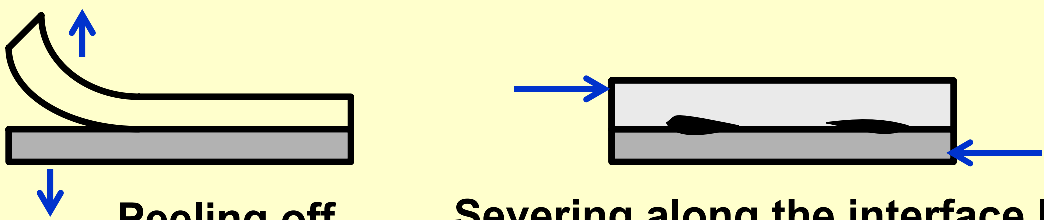
Thin Oxide Films	Lateral Etch Rate (μm/min)
CVD SiO_2 (densified at 1050°C for 30 min.)	0.6170
Ion-implanted SiO_2 (at $8x10^{15}/cm^2$, 50 KeV)	0.8330
Phosphosilicate (PSG)	1.1330
5%-5% Boronphosphosilicate (BPSG)	4.1670

Surface Micromachining – Cont'd

Mechanical problems

(1) Quality of adhesion of layers:

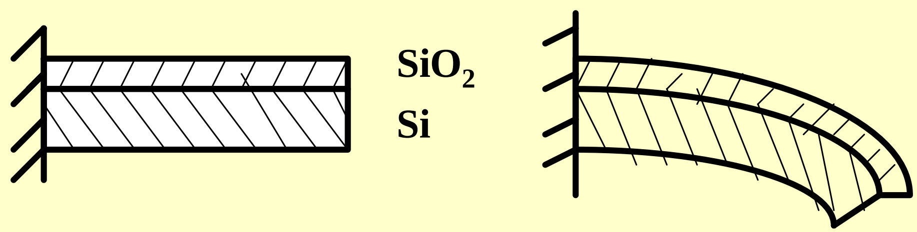
- The interfaces of layers are the vulnerable areas for structural failures.
- Two possible failures:



Peeling off

Severing along the interface by shear

(2) Interfacial stresses due to mismatch of CTE:



During oxidation by CVD

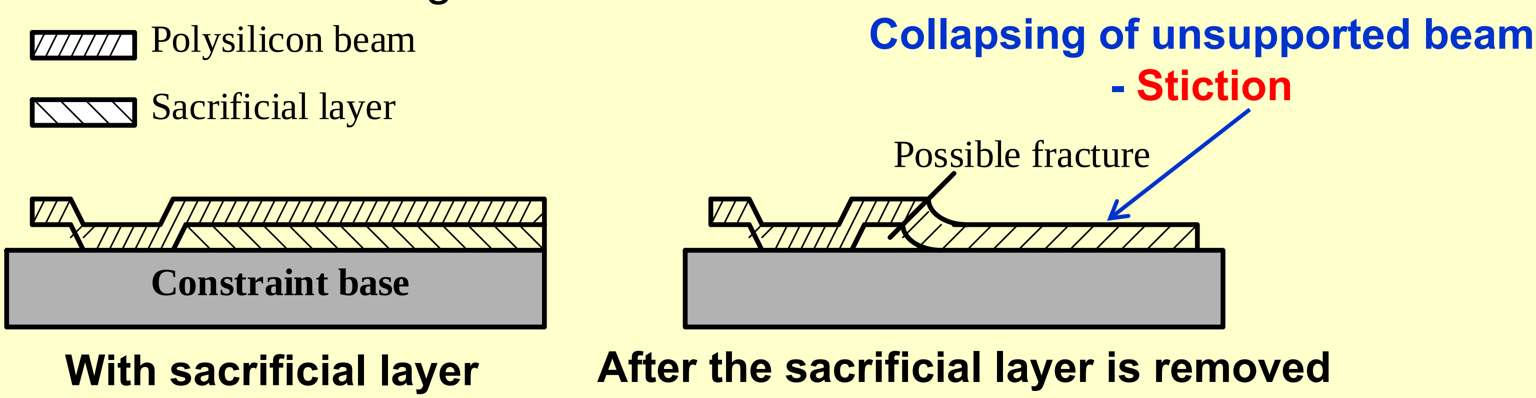
After oxidation

Surface Micromachining – Ends

Mechanical problems – Cont'd

(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:



- 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 LIGA Process

- 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.

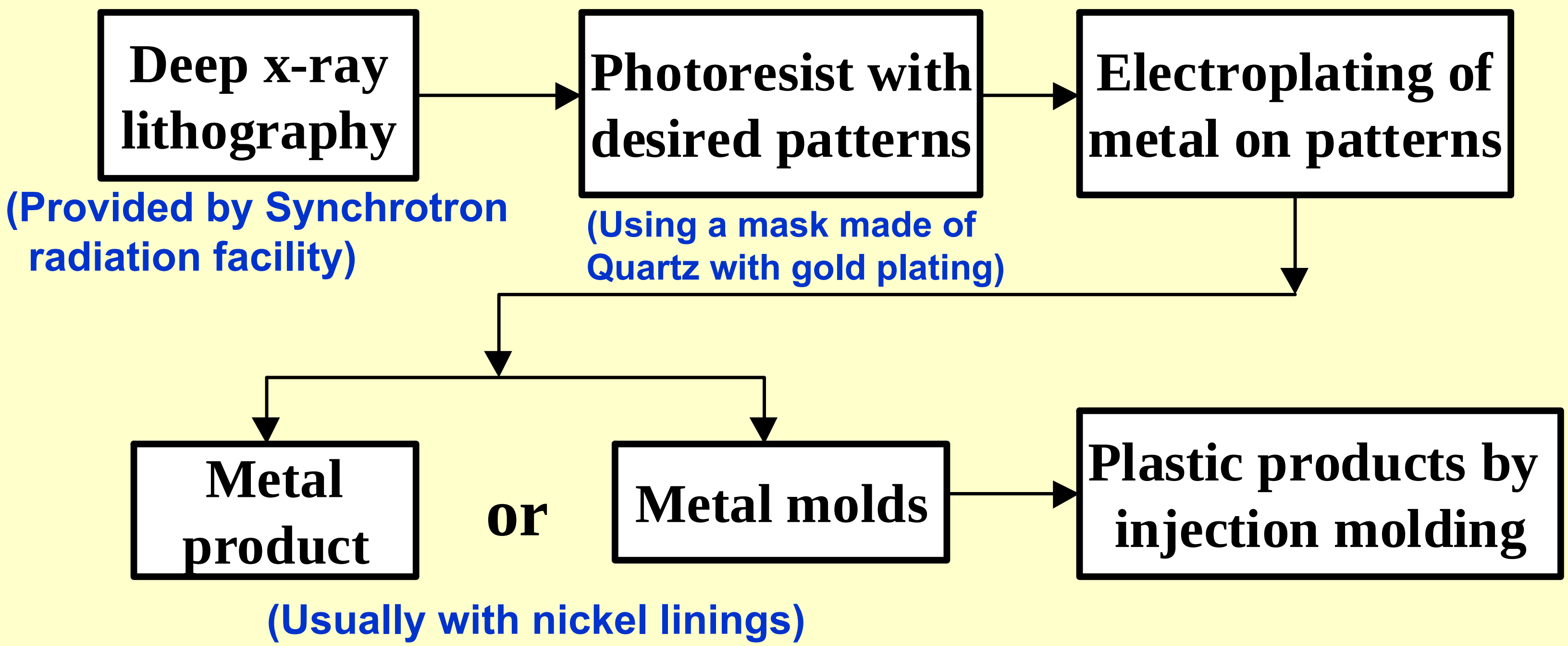
- There is no restriction on using silicon or silicon compounds as substrate. Nickel is a common material for LIGA products.

- 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.

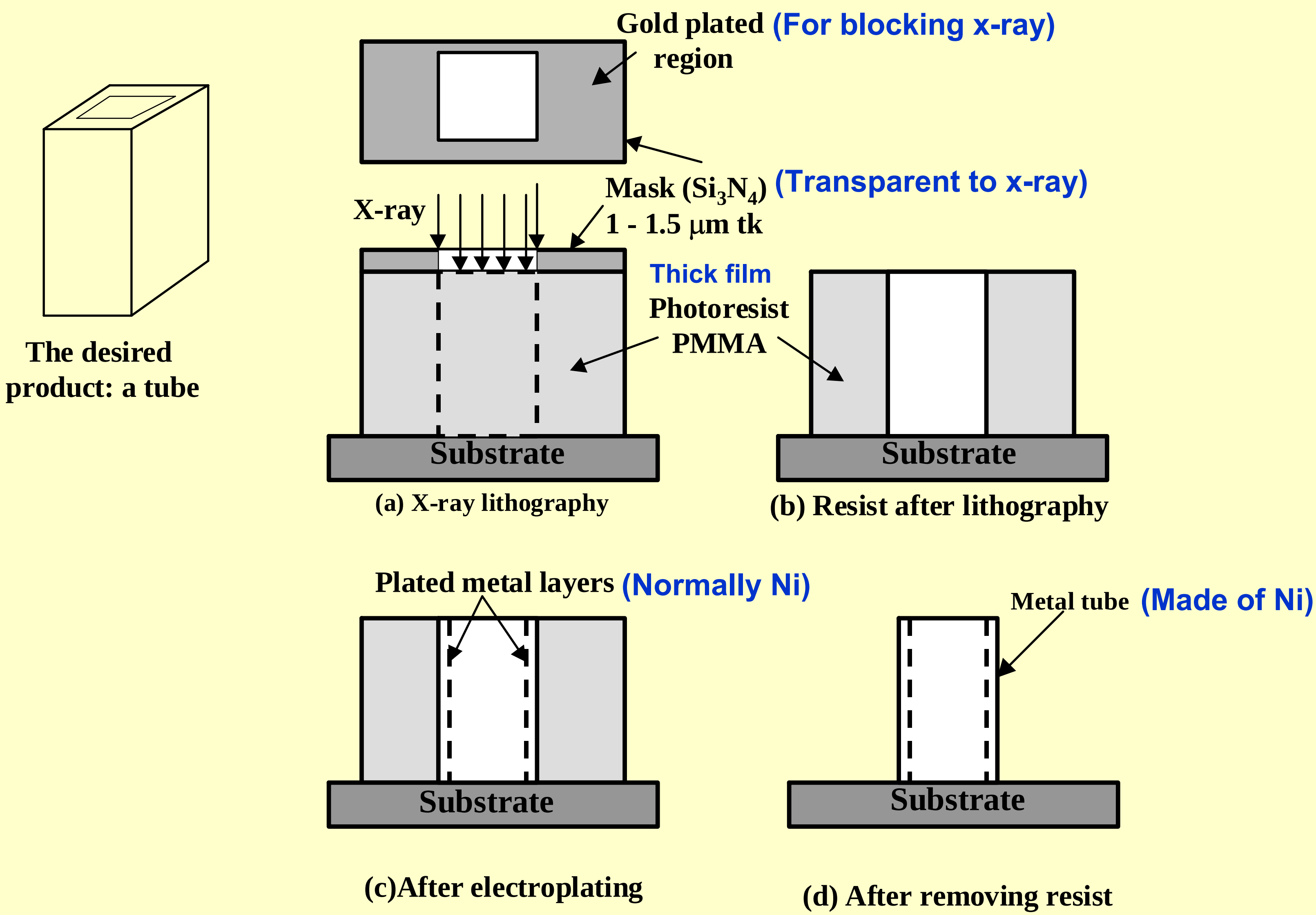
The LIGA Process – Cont'd

Major steps in LIGA process



The LIGA Process – Cont'd

Fabrication of a square tube using LIGA



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:

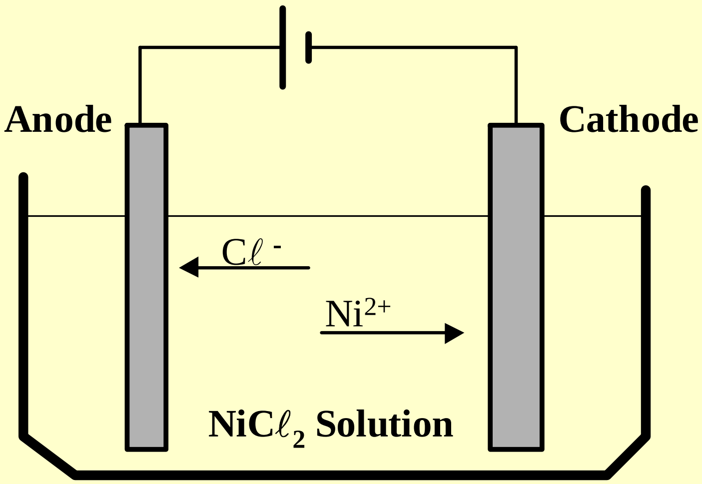
- Must be sensitive to x-ray radiation.
- Must have high resolution and resistance to dry and wet etching.
- Must have thermal stability up to 140oC.
- The unexposed part must be absolutely insoluble during development.
- Good adhesion to substrate during electroplating.
- PMMA appears most popular for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

	PMMA	POM	PAS	PMI	PLG
Sensitivity	Bad	Good	Excellent	Reasonable	Reasonable
Resolution	Excellent	Reasonable	Very bad	Good	Excellent
Sidewall smoothness	Excellent	Very bad	Very bad	Good	Excellent
Stress corrosion	Bad	Excellent	Good	Very bad	Excellent
Adhesion on substrate	Good	Good	Good	Bad	Good

The LIGA Process – Ends

Electroplating

- 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 (Ni^{2+}) are produced from electrolysis of $NiC\ell_2$ solution.

- They are attracted to the electrons at the cathode:

$$Ni^{2+} + 2e^- \rightarrow Ni$$

- There could be H^+ ions presence at the same cathode in the process.
- These H+ ions may form 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.