Chemical Vapor Deposition

- Chemical vapor deposition (CVD) is the most important process in microfabrication.

- It is used extensively for producing thin films by depositing many different kind of foreign materials over the surface of silicon substrates, or over other thin films that have already been deposited to the silicon substrate.

- Materials for CVD may include:
  (a) Metals: Al, Ag, Au, W, Cu, Pt and Sn.
  (b) Organic materials: Al_2O_3, polysilicon, SiO_2, Si_3N_4, piezoelectric ZnO, SMA TiNi, etc.

- There are three (3) available CVD processes in microfabrication:
  (a) APCVD: (Atmospheric-pressure CVD);
  (b) LPCVD (Low-pressure CVD), and
  (c) PECVD (Plasma-enhanced CVD).

- CVD usually takes place at elevated temperatures and in vacuum in high class clean rooms.

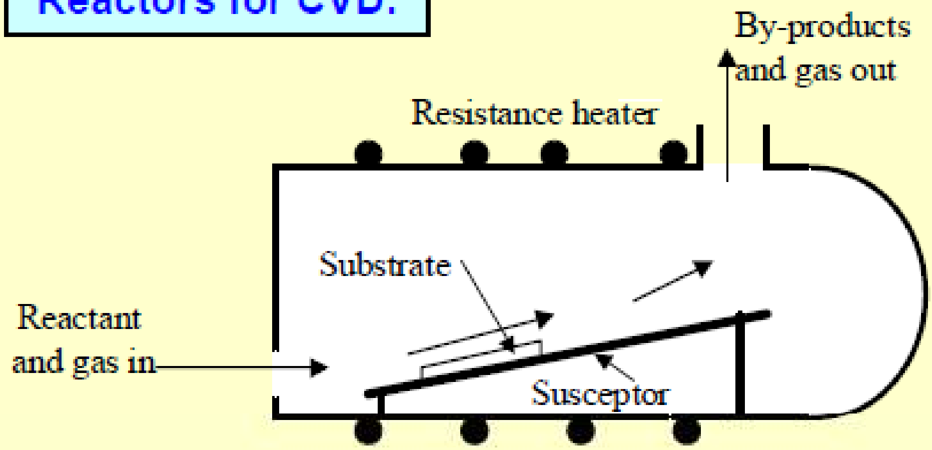
Chemical Vapor Deposition

Working principle of CVD:

- CVD involves the flow of a **gas containing diffused reactants** (normally in vapor form) over the **hot** substrate surface
- The gas that carries the reactants is called "***carrier gas***"
- The "diffused" reactants are foreign material that needed to be deposited on the substrate surface
- The carrier gas and the reactant flow over the hot substrate surface, the energy supplied by the surface temperature provokes **chemical reactions of the reactants** that form films during and after the reactions
- The **by-products** of the chemical reactions are then let to the vent
- Various types of **CVD reactors** are built to perform the CVD processes

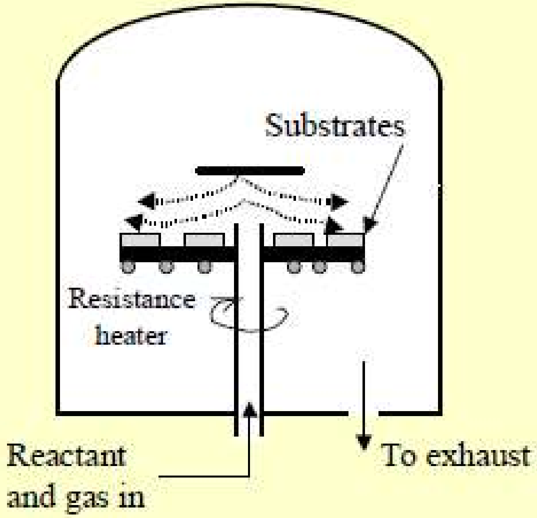
Chemical Vapor Deposition

Reactors for CVD:



Horizontal Reactor

Vertical Reactor



Chemical Vapor Deposition

Chemical reactions in CVD:

- **CVD of SiO_2 on silicon substrates:**

$$SiH_4 + O_2 \rightarrow \mathbf{SiO_2} + 2H_2 \qquad \text{at } 400 - 500^{\circ}C$$

Carrier gases are: O_2 (such as in the above reaction), NO, NO_2, CO_2 and H_2.
The diffused reactant in the reaction is **Silane (SiH_4)** -a common reactant in CVD.

- **CVD of Si_3N_4 on silicon substrates:**

$$3SiH_4 + 4NH_3 \rightarrow \mathbf{Si_3N_4} + 12\,H_2 \qquad \text{at } 650 - 750^{\circ}C$$
$$3SiCl_4 + 4NH_3 \rightarrow \mathbf{Si_3N_4} + 12\,HCl$$
$$3SiH_2Cl_2 + 4NH_3 \rightarrow \mathbf{Si_3N_4} + 6HCl + 6H_2$$

- **CVD of polysilicon on silicon substrates:**

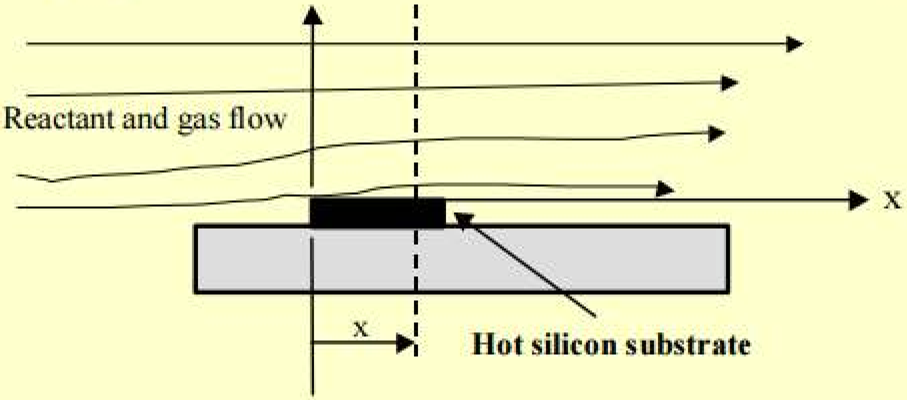
It is essentially a pyrolysis process of Silane at 600 – 650°C.

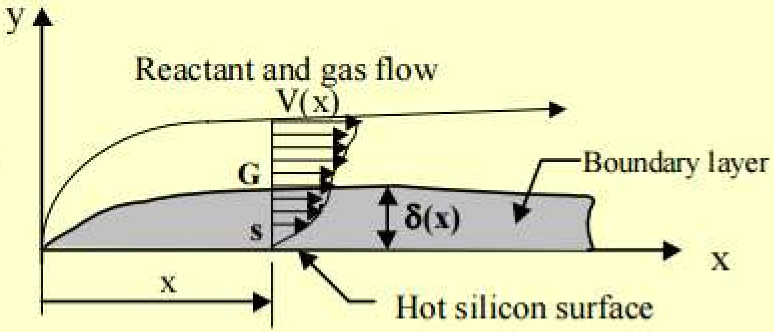
$$SiH_4 \rightarrow \mathbf{Si} + 2H_2$$

Chemical Vapor Deposition

Rate of CVD Build-up:

- CVD is the principal technique for building the desired 3-D geometry of many MEMS and microsystems by means of thin film deposition.
- The rate of the build-up of these thin films obviously is a concern to process design engineers.
- Quantification of the rate of CVD is extremely complicated. A quasi-quantitative assessment of such rate of build-up may begin with the understanding of the physical-chemical principles on which CVD operates.
- Two major factors affect the rate of CVD:
  - (a) The velocity of carrier gas and the diffused reactant, as measured by the Reynold's number (Re) and the associated boundary layer (δ) thickness at the substrate-gas interface.
  - (b) The Diffusion flux of the reactant (N).





Chemical Vapor Deposition

The Reynolds number:

$$R_e = \frac{\rho L V(x)}{\mu} \qquad (8.18)$$

where L = length of the substrate

The thickness of boundary layer:

$$\delta(x) = \frac{x}{\sqrt{\mathrm{Re}(x)}} \qquad (8.17)$$

The diffusion flux of reactant ($\vec{N}$) across the boundary layer is:

$$\vec{N} = \frac{D}{\delta}(N_G - N_S) \quad \text{atoms or molecules/m}^2\text{-s}$$

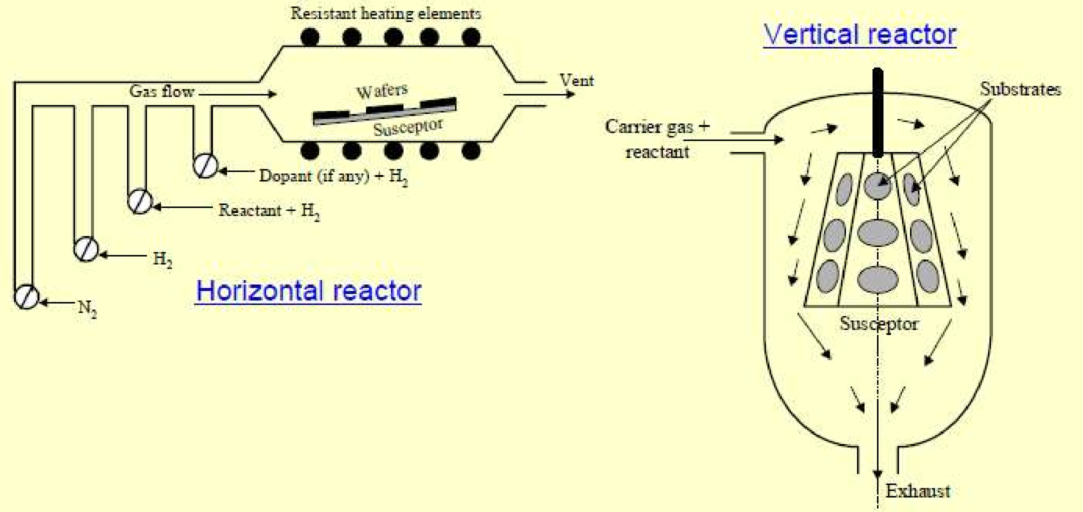
where D = diffusivity of reactant in the carrier gas (cm^2/s)

N_G = Concentration of reactant at the top of boundary layer ($molecules/m^3$)

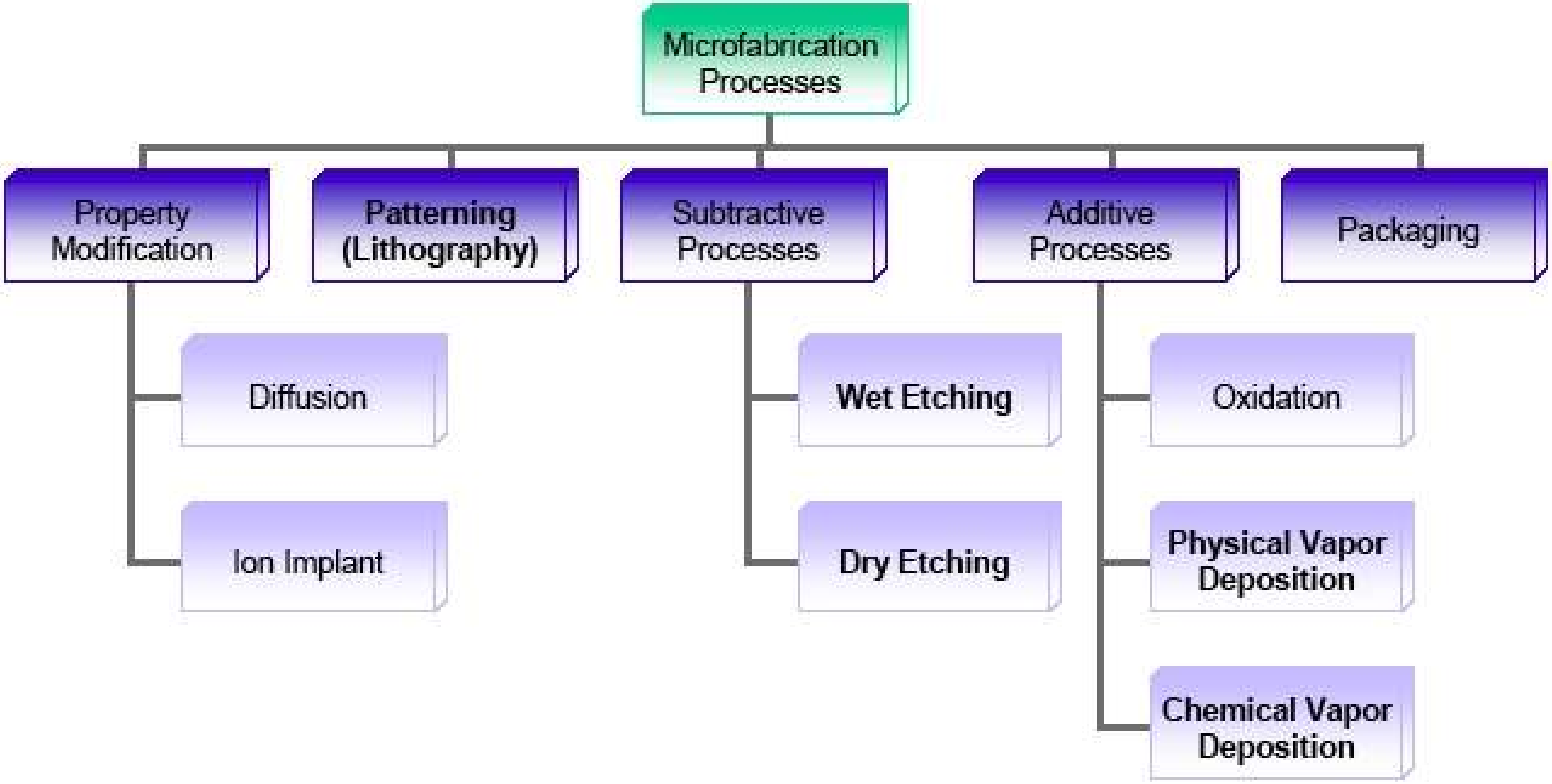
N_s = concentration of reactant at the substrate surface ($molecules/m^3$)

Deposition by Epitaxy

- Both CVD and PVD processes are used to deposit dissimilar materials on the silicon substrate surfaces.
- Epitaxy deposition process is used to deposit **polysilicon** films on **silicon substrate** surfaces.
- Most polisilicons are doped pure silicon crystals randomly oriented. They are used to conduct electricity at desired locations on silicon substrates.
- This process is similar to CVD with carrier gas with **reactants that release the same material as the substrates.**
- One may deposit GaAs to GaAs substrates using this technique.



Taxonomy of Microfabrication Processes



- Microfabrication Processes
  - Property Modification
    - Diffusion
    - Ion Implant
  - Patterning (Lithography)
  - Subtractive Processes
    - Wet Etching
    - Dry Etching
  - Additive Processes
    - Oxidation
    - Physical Vapor Deposition
    - Chemical Vapor Deposition
  - Packaging

Etching

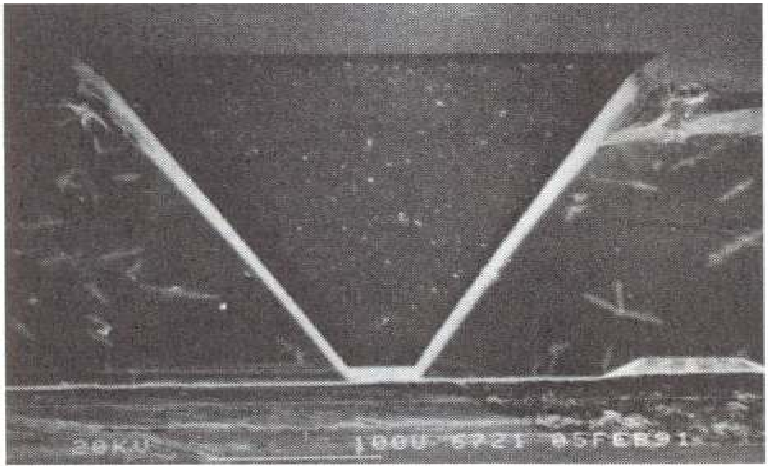
- MEMS and microsystems consist of components of 3-dimensional geometry.

- There are two ways to create 3-dimensional geometry:

    - by **adding** materials at the desired locations of the substrates using vapor deposition techniques, or
    - by **removing** substrate material at desired locations using the etiching methods.

- There are two types of etching techniques:
    - **Wet etching** involving the use of strong chemical solvents (**etchants**), or
    - **Dry etching** using high energy **plasmas**.

- In either etching processes, **masks** made of strong-resisting materials are used to protect the parts of substrate from etching.



Anisotropic Etchants

Isotropic Etchants

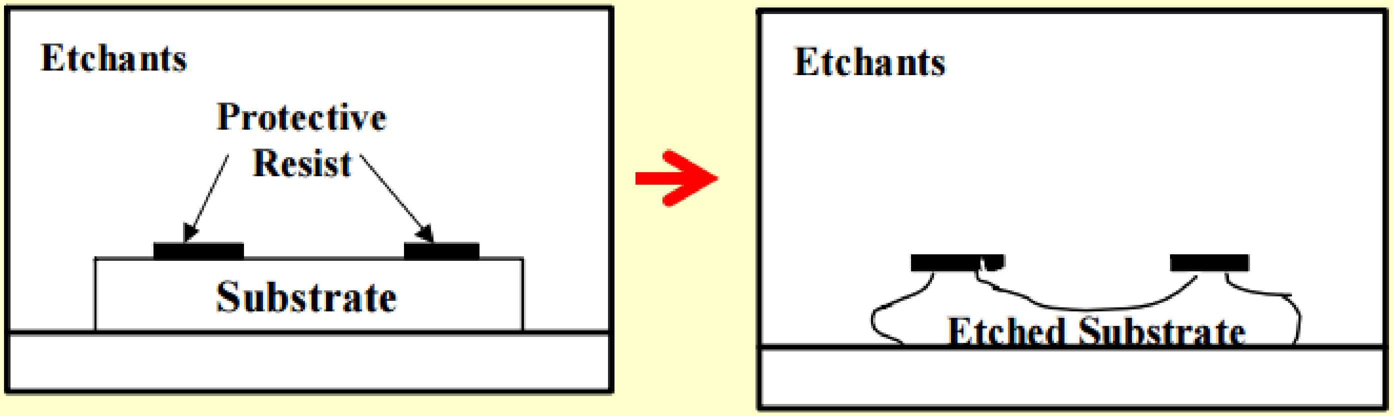
Bulk Micromanufacturing

- 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)

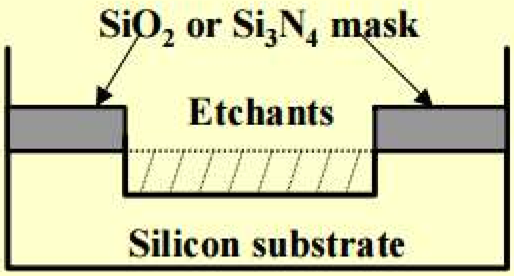


- Dry etching uses plasma to remove materials at the desired locations on a substrate.

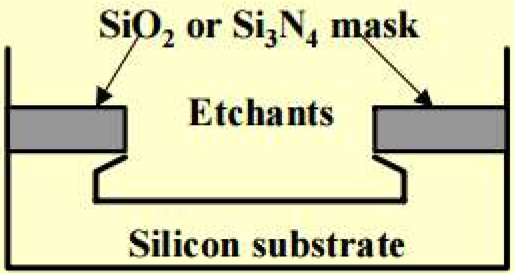
Bulk Micromanufacturing

A. On etching geometry:

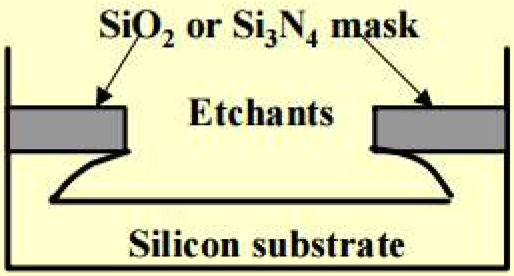
- Timing and agitated flow patterns can affect the geometry of etched substrate geometry:



Ideal etching



Under etching



Under cutting

- Endurance of the masks is another factor that affects the etching geometry.

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:**

Bulk Micromanufacturing

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)

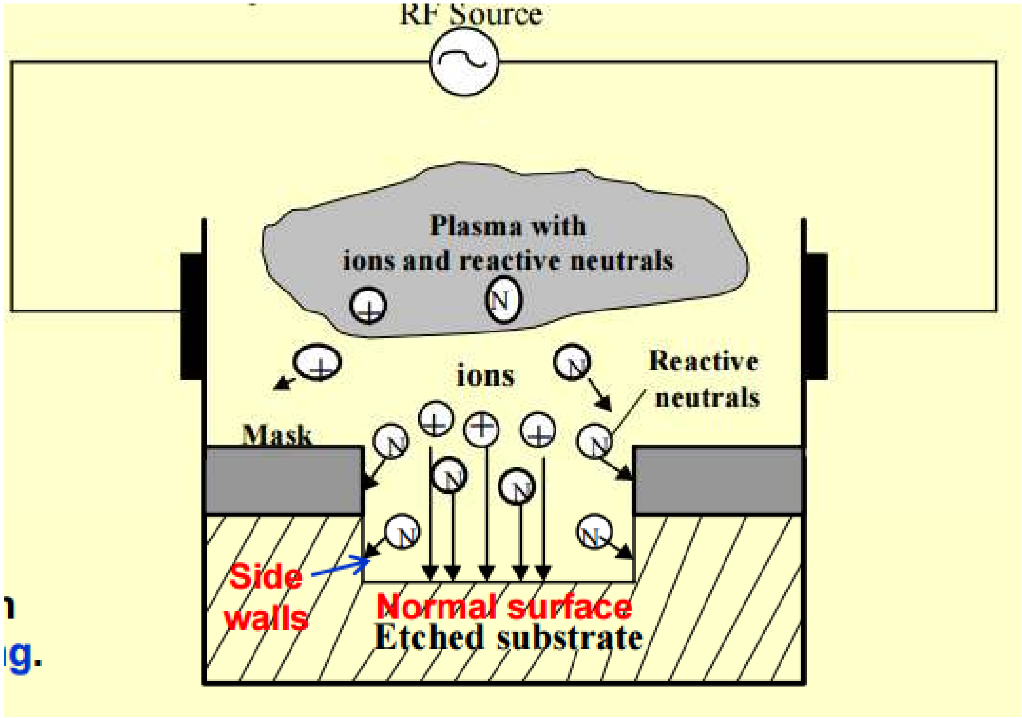
Plasma etching:

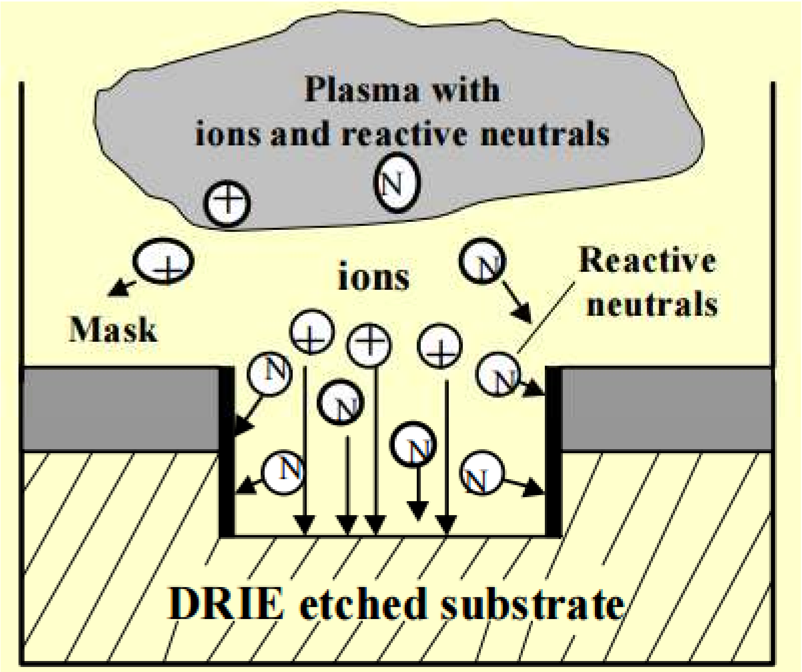
Plasma is a neutral ionized gas carrying a large number of free electrons and positively charged ions.

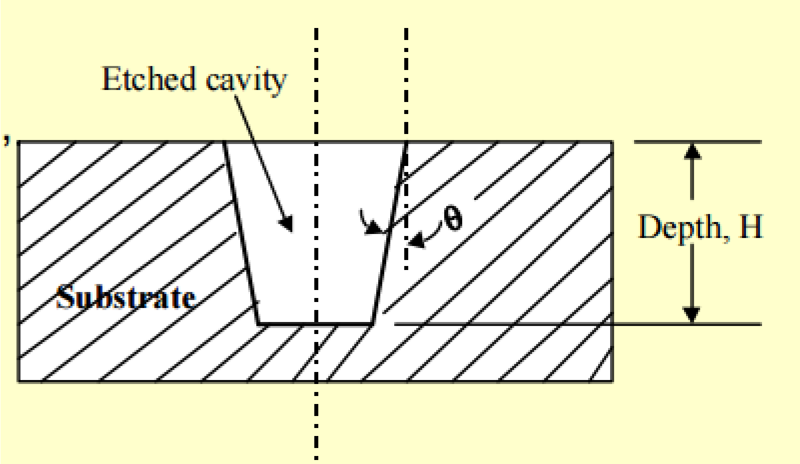
A common source of energy for generating plasma is the radio frequency (RF) source.

Chemical reactive gas, e.g. $CC\ell_2F_2$, is mixed with plasma in etching process.

Bulk Micromanufacturing







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.**

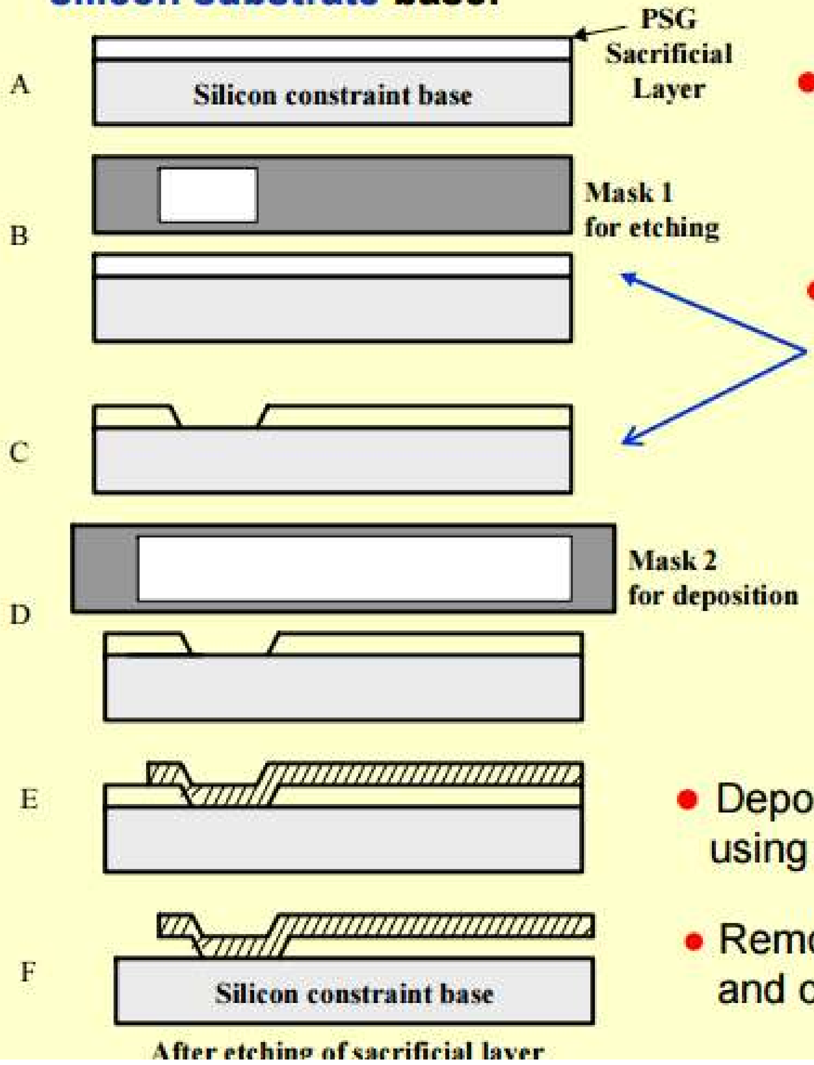
- **Added materials may not be same as the substrate material – flexibility.**
- **Added material layers can be 2-5 μm thick each, or as high as 5-20 μm thick each – much more than most etching process can achieve.**
- **There is little waste of substrate materials.**

- **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

General description of process

Illustration of micromachining process – creation of a polysilicon cantilever beam on silicon substrate base:



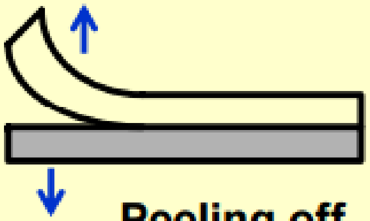
- Deposit a sacrificial layer of **PSG** (Phosphosilicate glass) using LPCVD process.
- Cover the PSG layer with Mask 1 (made of Si_3N_4) for subsequent etching away the PSG for beam's support area as shown in Step C.
- Produce a Mask 2 (Si_3N_4) with opening of the size of the beam length and width. 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

Mechanical problems

(1) Quality of adhesion of layers:

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

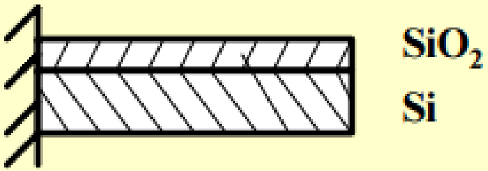


Peeling off

Severing along the interface by shear

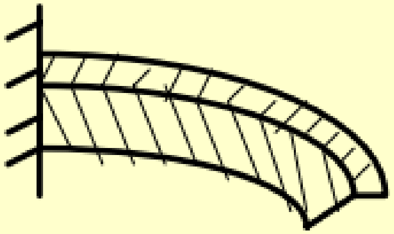
(2) Interfacial stresses due to mismatch of CTE:

At 1000°C:



During oxidation by CVD

At 20°C:

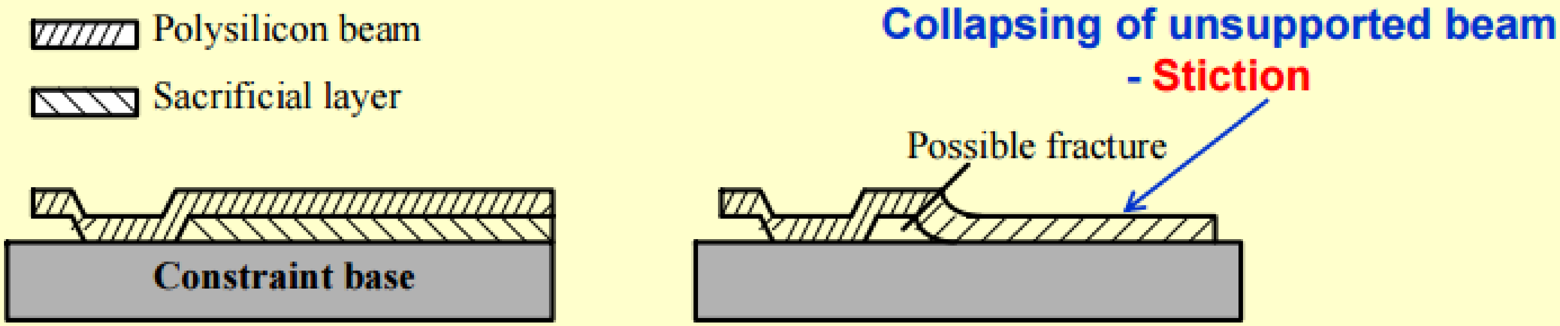


After oxidation

Surface Micromachining

(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:



Collapsing of unsupported beam - Stiction

With sacrificial layer **After the sacrificial layer is removed**

- 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.

LIGA (Lithographie, Galvanoformung, Abformung) (Lithography, Electroplating, and Molding)