Introduction to MEMS/NEMS FABRICATION

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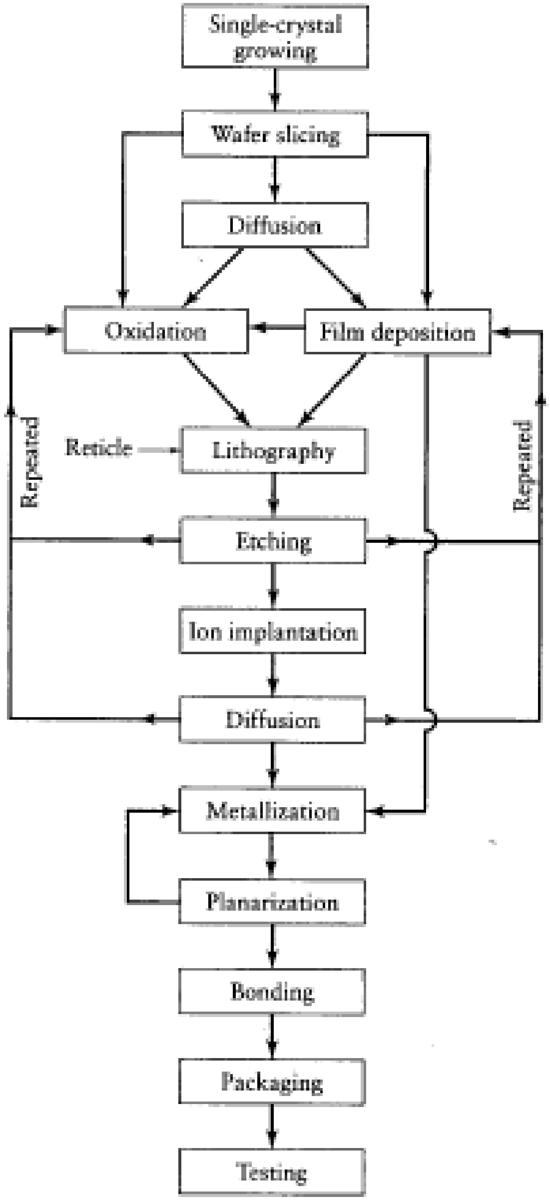
Outline

- General Fabrication Processes (For ICs Fabrication)
  - Photolithography
  - Oxidation
  - Chemical Vapor Deposition
  - Etching
- Techniques (For Microsystems Fabrication)
  - Surface Micromachining
  - Bulk Micromanufacturing (Micromachining)
  - LIGA process

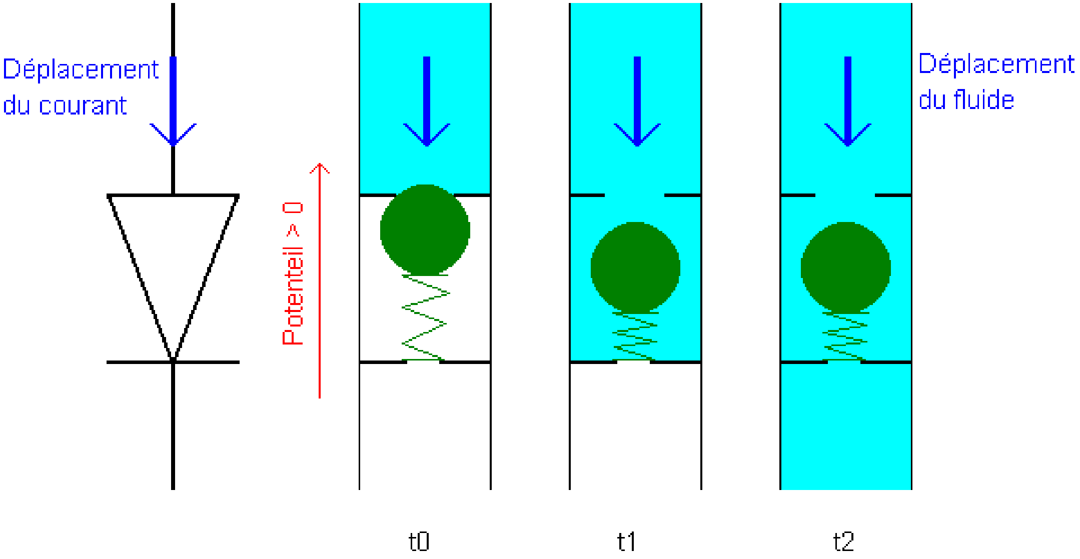
What is IC?

- In electronics, an **integrated circuit** (also known as **IC**, **microcircuit**, **microchip**, **silicon chip**, or **chip**) is a miniaturized electronic circuit (consisting mainly of semiconductor devices, as well as passive components) that has been manufactured in the **surface** of a thin substrate of semiconductor material

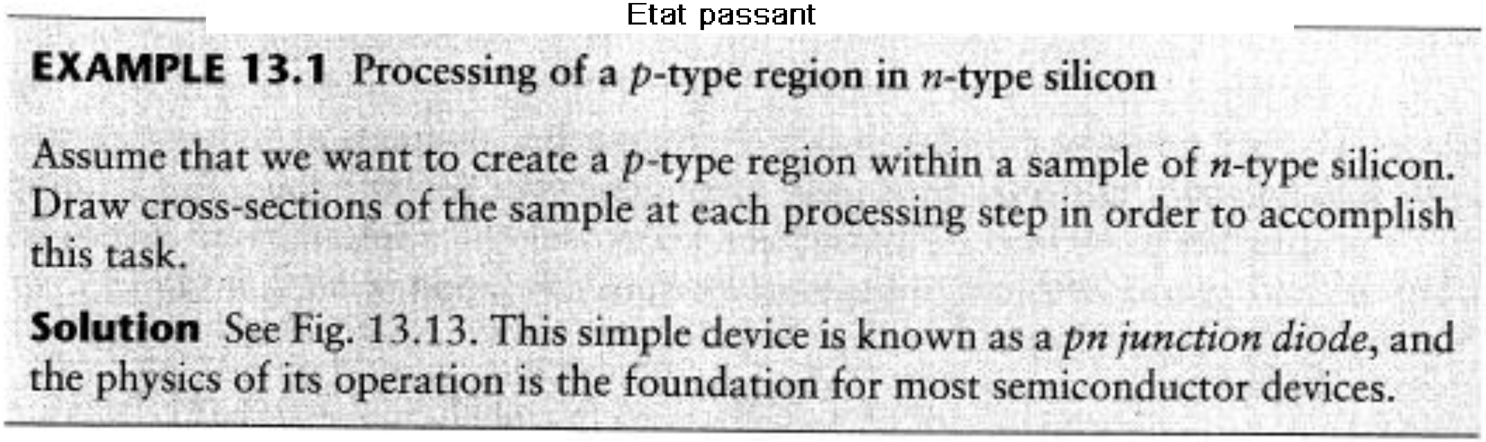
General fabrication sequence for ICs



Pn junction diod



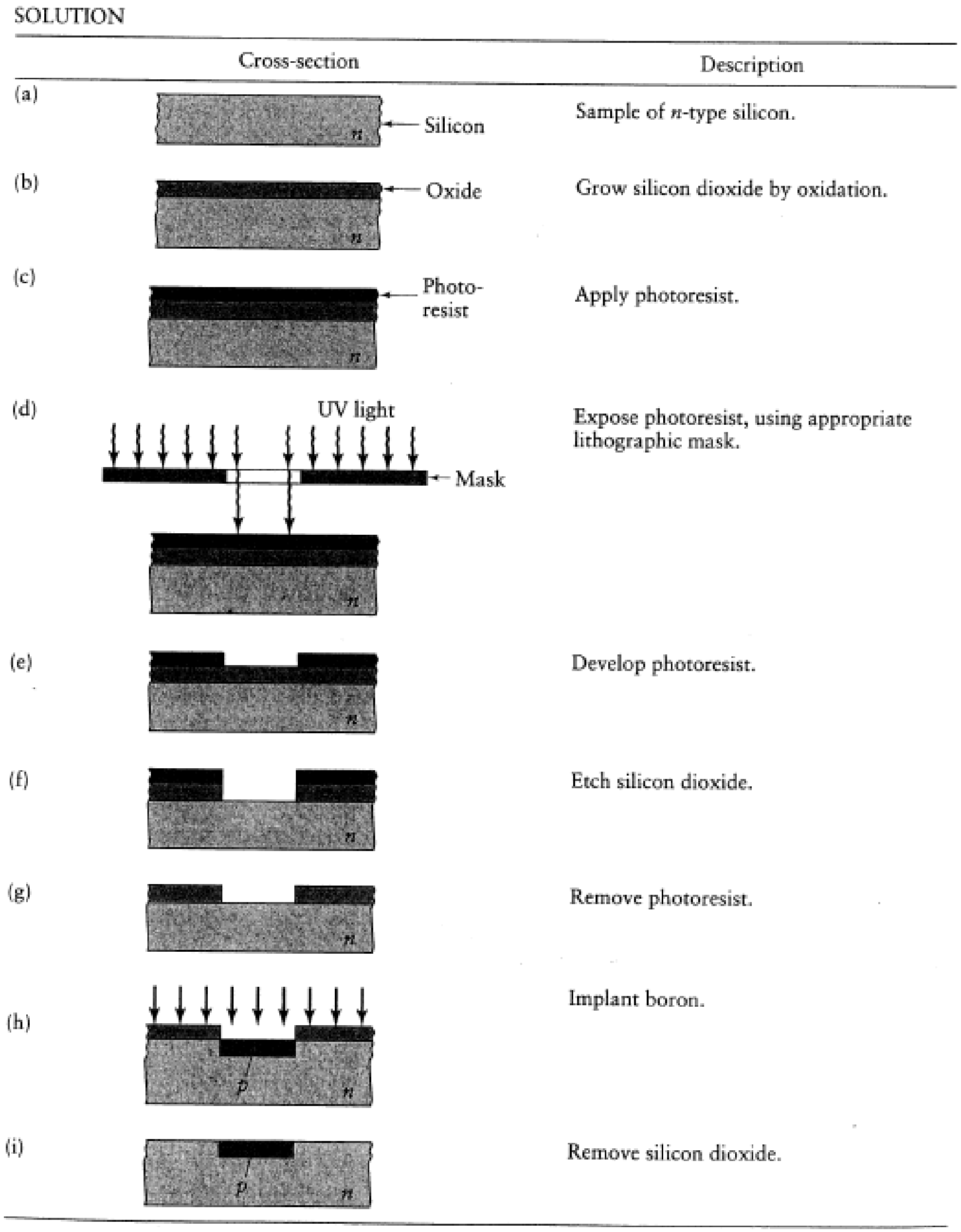
Etat passant



EXAMPLE 13.1 Processing of a *p*-type region in *n*-type silicon

Assume that we want to create a *p*-type region within a sample of *n*-type silicon. Draw cross-sections of the sample at each processing step in order to accomplish this task.

Solution See Fig. 13.13. This simple device is known as a *pn junction diode*, and the physics of its operation is the foundation for most semiconductor devices.



SOLUTION

	Cross-section	Description
(a)	Silicon	Sample of *n*-type silicon.
(b)	Oxide	Grow silicon dioxide by oxidation.
(c)	Photo-resist	Apply photoresist.
(d)	UV light Mask	Expose photoresist, using appropriate lithographic mask.
(e)		Develop photoresist.
(f)		Etch silicon dioxide.
(g)		Remove photoresist.
(h)		Implant boron.
(i)		Remove silicon dioxide.

FIGURE 13.13 Processing of a *p*-type region in *n*-type silicon.

Lithography in general

- In Greek it is a combination of Lithos means “stone” and graphein means “to write”
- It was invented in 1796 by Aloys Senefelder
- It was used for Engraving on that time

Photolithography in MEMS

- The Photolithography process involves the use of an optical image and photosensitive film to produce a pattern on the substrate. A photoresist is first coated onto the flat surface of the substrate. The substrate with photoresist is then exposed to a set of lights through a transparent mask with the desired pattern. Patterns on the mask are photographically reduced from macro or mesosizes to the desired microscale.
- http://video.google.com/videoplay?docid=8848737050367959402&q=microfabrication&total=15&start=0&num=10&so=0&type=search&plindex=9

Photolithography steps

1-**Making mask (usually 5 to 20X larger)**

2-The wafer is cleaned and coated with an organic Photoresist (0.5 – 2.5 µm)

3-Prebaking the wafer to remove the solvent from the PR and harden it

4-Registration of reticle on the wafer (alignment) and expose to light

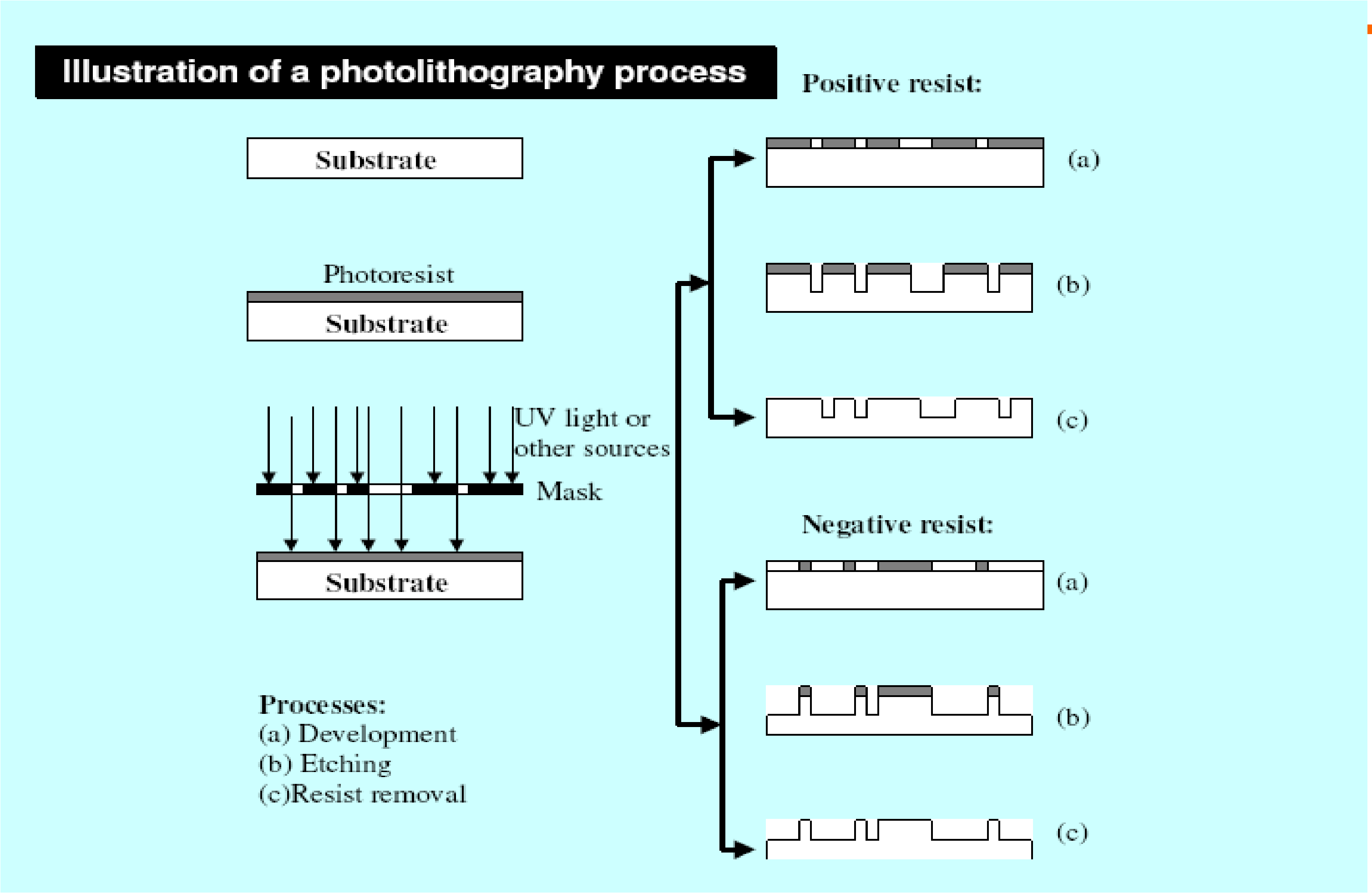
5-Enlarged images are then focused onto a wafer through a lens system in a process known reduction lithography

6-Postbaking to drive off solvent and toughen the adhesion of the remaining resist

7-Etching

https://wecanfigurethisout.org/VL/IC_process.htm

General Procedure of photolithography



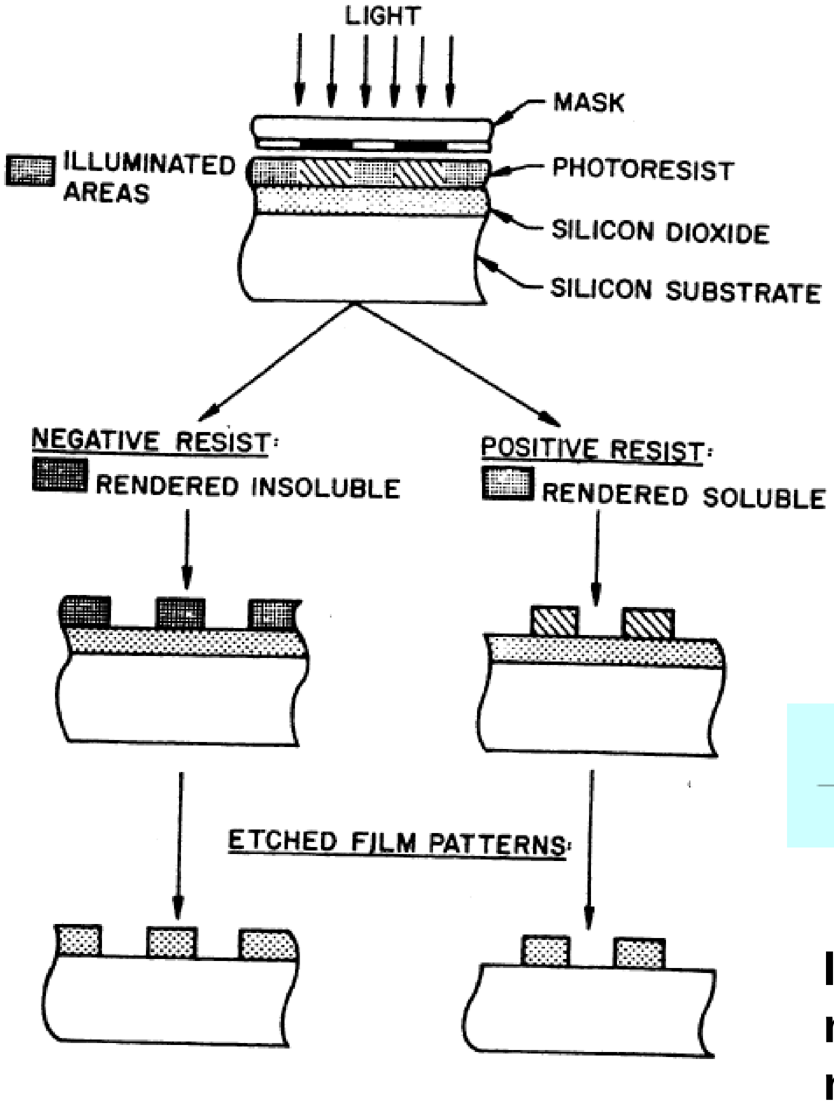
در positive هر جا که نور uv به maskant برخورد کند آن را شل می کند ولی در negative هرجا نور uv به maskant برخورد کند آن را سفت می کند.

Photoresist; positive & Negative

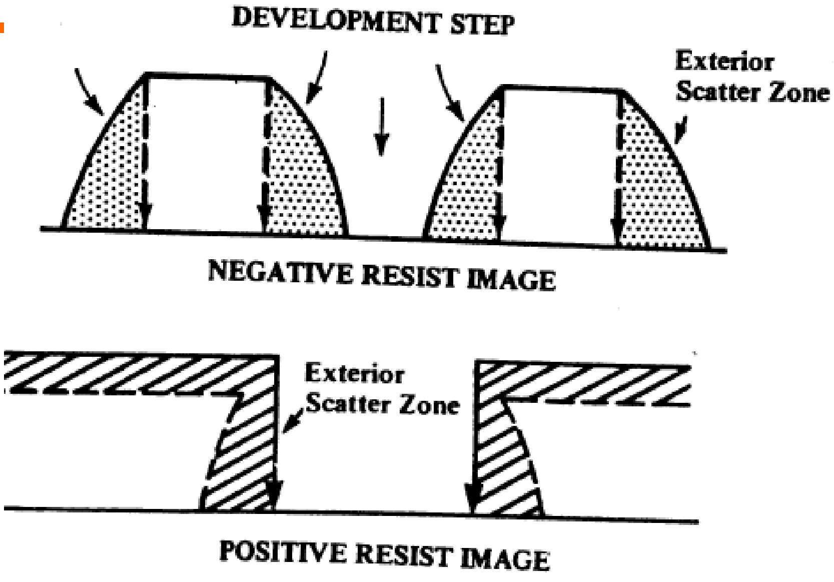
•**Photoresist materials change their solubility when they are exposed to light**

- Positive resist
  - PMMA polymer (polymethlmethacrylate)
  - DQN copolymer Diazoquinone ester and phenolic novolak resin
  - They are sensitive to UV light, (220 nm)
  - They can be developed in alkaline solvent such as KOH , TMAH & ACETAE
  - More commonly used method
- Negative resist
  - Bis (aryle)azide rubber resist
  - Kodak KFTR
  - They are sensitive to electron beam rather than optical and X-ray exposure
  - Xylene is the most commonly used solvent for developing negative resist
  - PR can swell and distort, making it unsuitable for small geometry

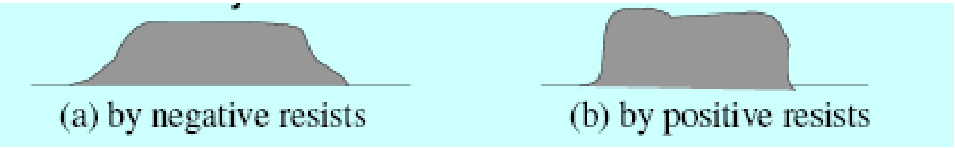
Photoresist : positive and negative



A



B



(a) by negative resists

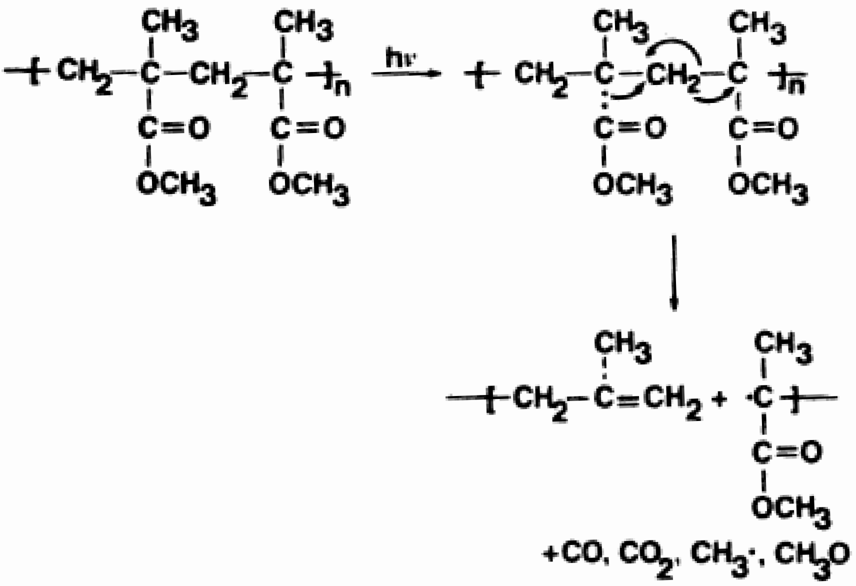
(b) by positive resists

In general, positive resists provide more clear edge definition than the negative one

PR materials

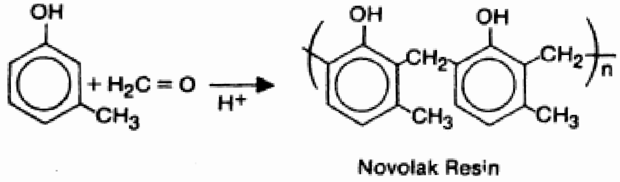
Poly(methylmethacrylate) or PMMA

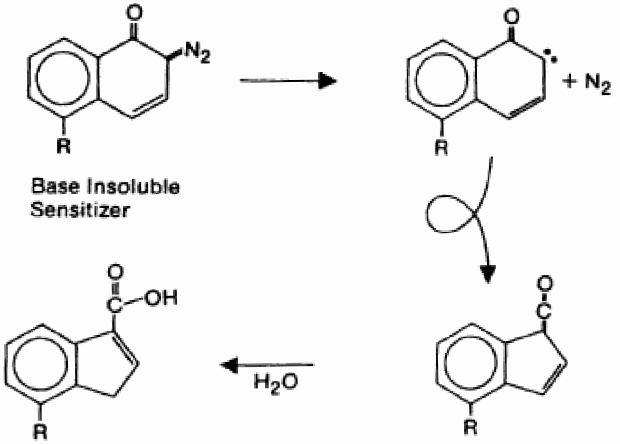
Photo-induced chain scission of PMMA resist.



Diazoquinone ester (DQ) and phenolic novolak resin (N), i.e., DQN

The novolak (Novolak) matrix resin (N) is prepared by acid copolymerization of cresol and formaldehyde. The base insoluble sensitizer, a diazoquinone (DQ), undergoes photolysis to produce a carbene which then undergoes a rearrangement to form a ketene. The ketene reacting with water present in the film forms a base-soluble, indenecarboxylic acid photoproduct.





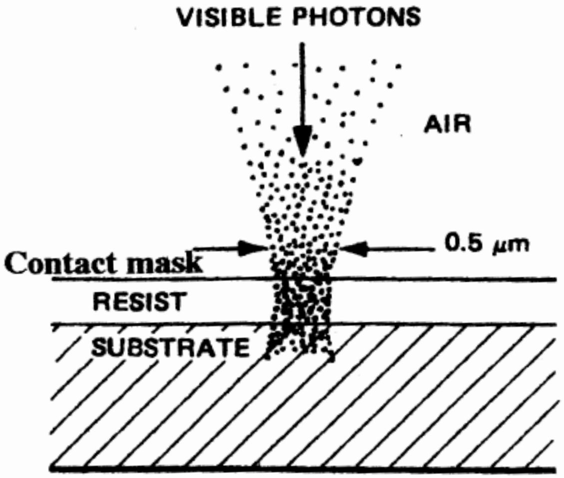
Critical Dimension (CD) or Line-Width

- Line width is the major issue in lithography. It is the smallest feature obtainable on the silicon surface.
- The absolute size of a minimum feature in an IC or micromachine, whether it involves a line-width, spacing, or contact dimension, is called the critical dimension.
- It is a key factor on the final price. Difference b/w Intel and Celeron processors depend on their overall resolution

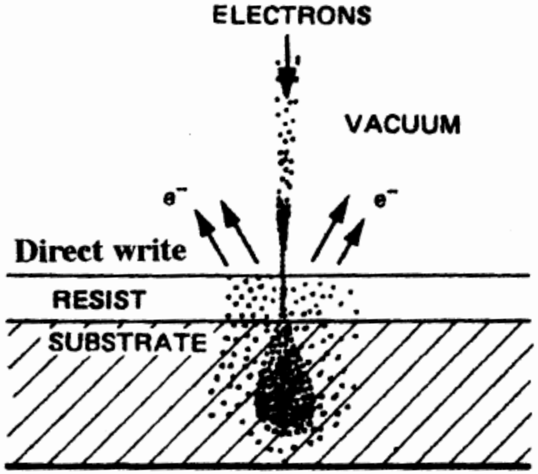
Alternative Lithography processes

- X-ray lithography
  - It has a shorter wavelength of radiation and very large path of focus (Line-Width of 0.2 µm)
  - It doesn’t need vacuum environment
  - Aspect ratio of more than 100 is obtainable
- Electron beam lithography
  - It can register accurately over small areas of a wafer (Line-Width of 0.1 µm)
  - It is a direct writing technique (doesn’t need mask)
  - Mask fabrication opportunity
- Ion-beam Lithography
  - It can register over small area of a wafer (Line-Width of 0.1 µm) without back scattering effect
  - It can be used for direct write and mask fabrication
  - It is a direct writing technique (doesn’t need mask)
  - It has the smallest possible size, smaller than UV, X-ray and e-beam (currently reached about 8 nm by FIB)

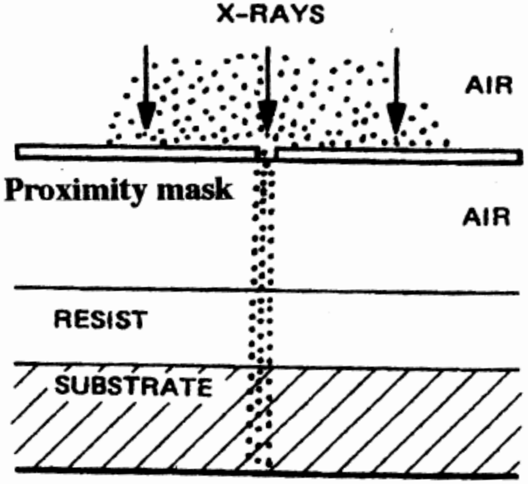
A comparison of photolithography, E-beam, I-beam and X-ray lithography



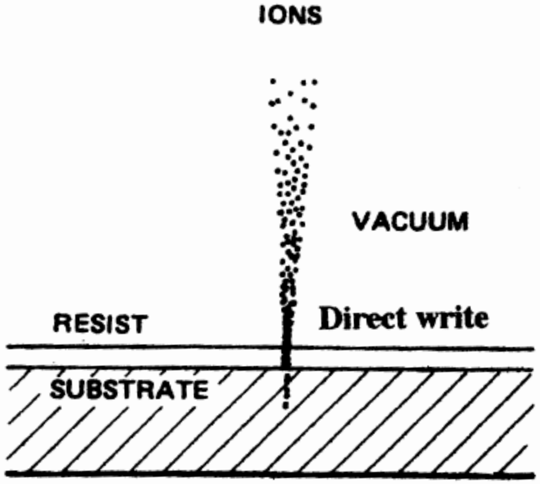
(a) PHOTOLITHOGRAPHY
Routinely linewidths of 2-3 μm



(b) ELECTRON-BEAM LITHOGRAPHY
Linewidths of 0.1 μm



(c) X-RAY LITHOGRAPHY
Linewidths of 0.2 μm

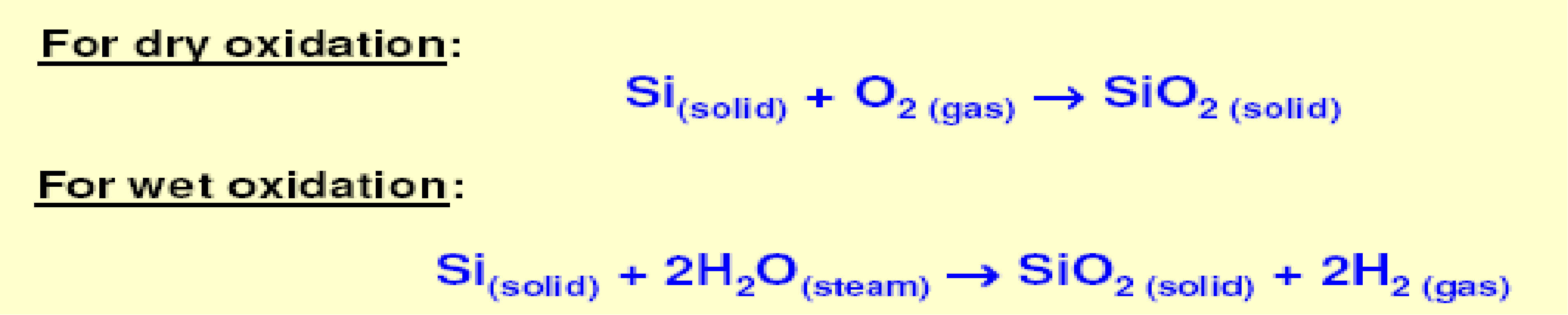


(d) ION-BEAM LITHOGRAPHY
Linewidths of 0.1 μm

http://cnfcornell.itx.net/cnf5_courses.html

Oxidation

- Silicone dioxide is used as an electric insulator as well as etching mask in surface micromachining
- The least expensive way to produce SiO2 film on the silicon substrate is by thermal oxidation



For dry oxidation:

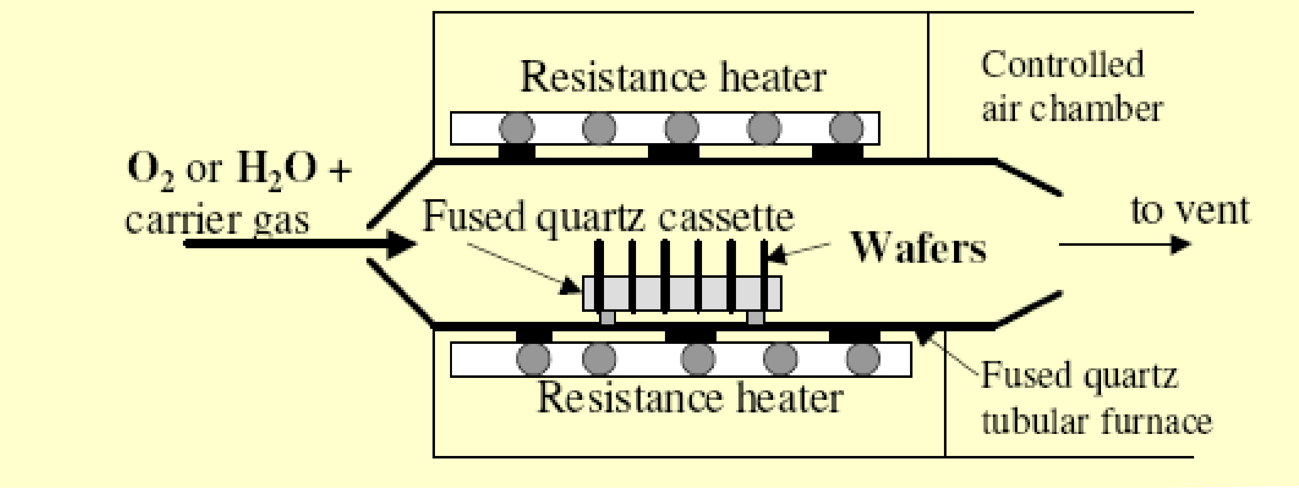
$$Si_{(solid)} + O_{2\ (gas)} \rightarrow SiO_{2\ (solid)}$$

For wet oxidation:

$$Si_{(solid)} + 2H_2O_{(steam)} \rightarrow SiO_{2\ (solid)} + 2H_{2\ (gas)}$$

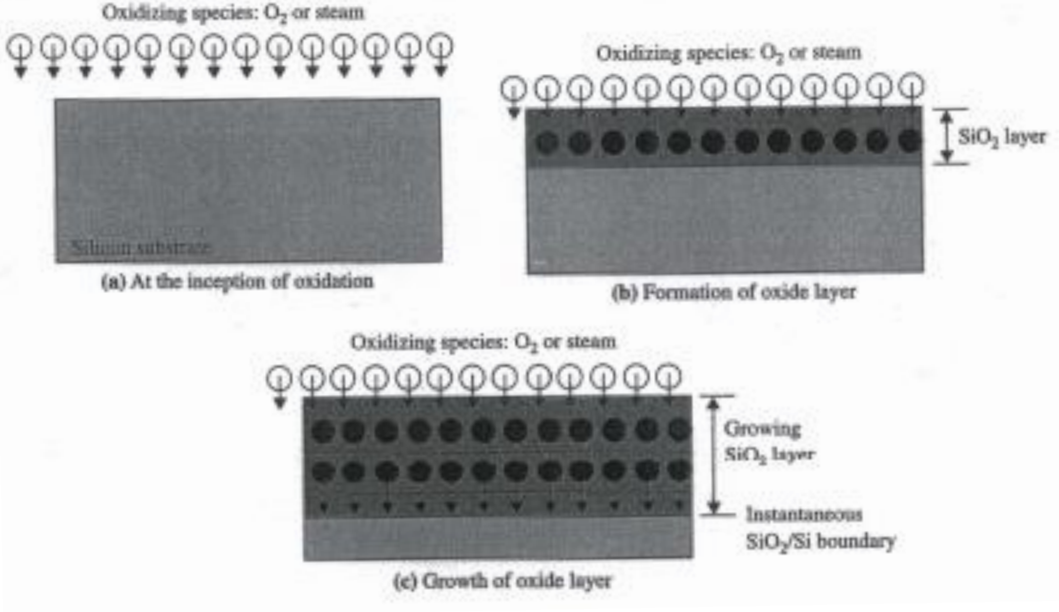
- The temperature is in the range of 900-1200 ˚C

Oxidation facility and growth mechanism



There is a simultaneous diffusion of SiO2 molecules and chemical reaction b/w the SiO2 molecules and the silicon substrate, which creates new SiO2/silicon boundaries.

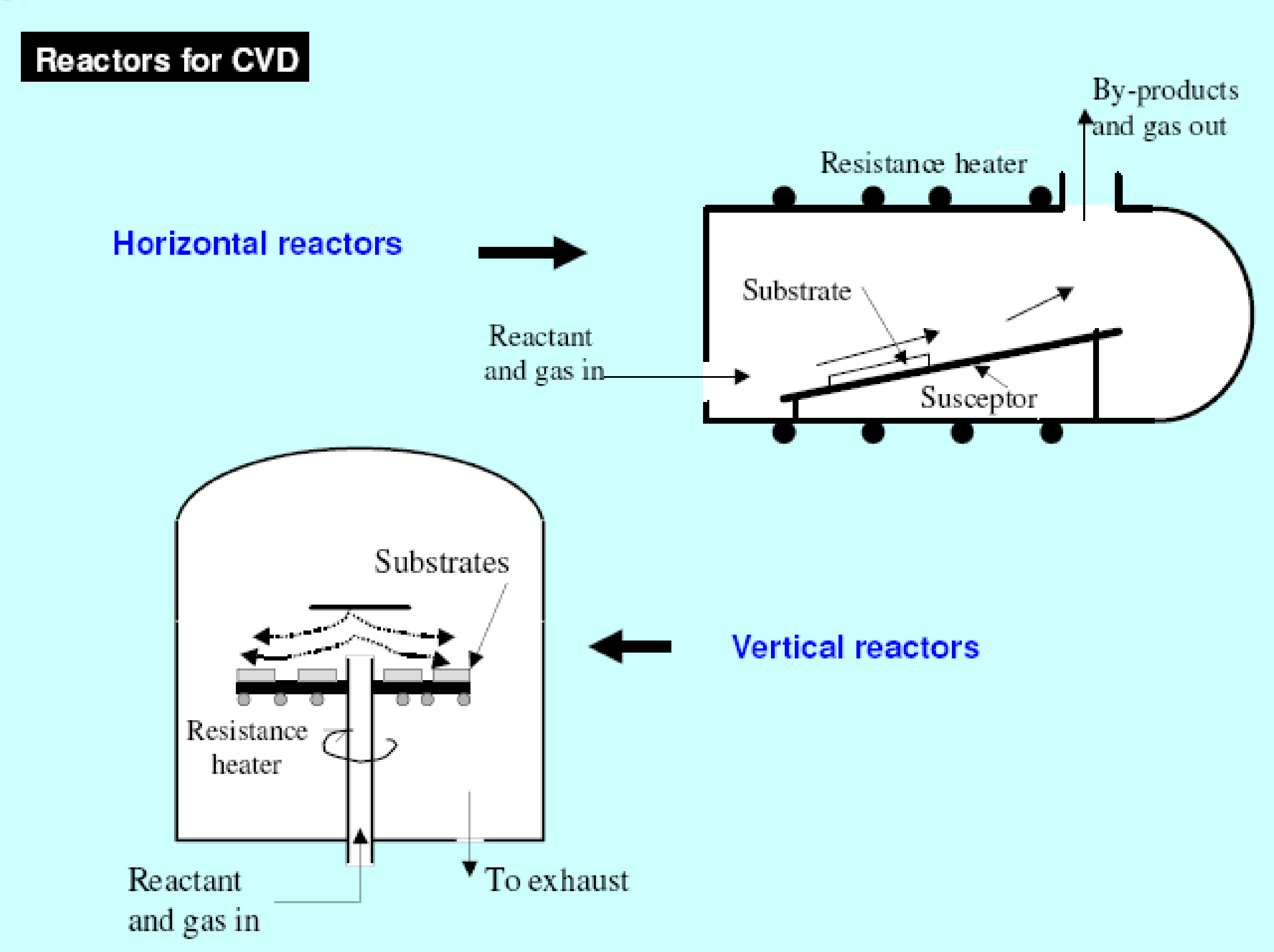
Figure 8.8 | The kinetics of SiO_2 in silicon substrates.



Chemical Vapor Deposition (CVD)

- Unlike thermal oxidation, CVD adds thin films to substrate
- It involves the flow of gas with diffused reactant over a hot substrate surface. The heat from the hot substrate surface prompt chemical reaction b/w the reactant and carrier gas to form the desire thin film on the substrate surface
- It can be used for deposition of organic or inorganic material in silicon substrate such as silicon dioxide, silicon nitride and polycrystalline silicon

Typical CVD reactor



Chemical reaction in CVD

For SiO_2: **Reactant is silane, SiH_4**

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

For Si_3N_4:

$$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2 \text{ at } 700\text{-}900^{\circ}C$$

$$3SiCl_4 + 4NH_3 \rightarrow Si_3N_4 + 12\,HCl \text{ at } 850^{\circ}C$$

$$3SiH_2Cl_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2 \text{ at } 650 - 750^{\circ}C$$

For Polysilicon, Si by pyrolysis:

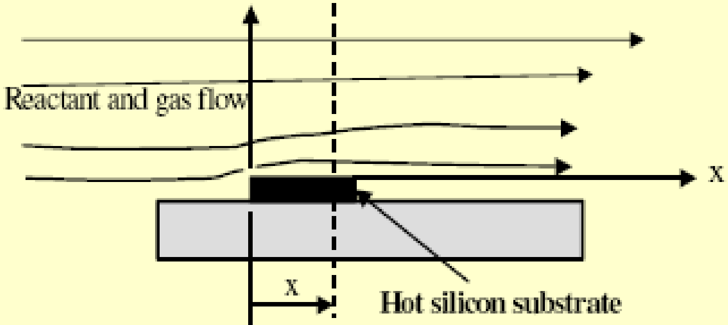
$$SiH_4 \rightarrow Si + 2H_2 \text{ at } 600 - 650^{\circ}C$$

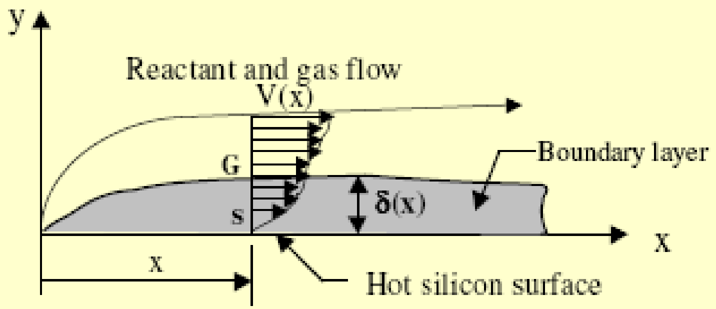
Rate of deposition in CVD

CVD is a common way to produce thin films over substrates. The rate of production is of a prime concern to process and design engineers.

Since CVD processes involve carrier gas flow over the substrate's surface, the issue of "fluid/solid interface" must be dealt with in assessing the effectiveness of CVD.

Whenever a fluid flowing over a solid surface, a "boundary layer" is created:





The boundary layer acts as a barrier to transfer of heat or transport of medium.

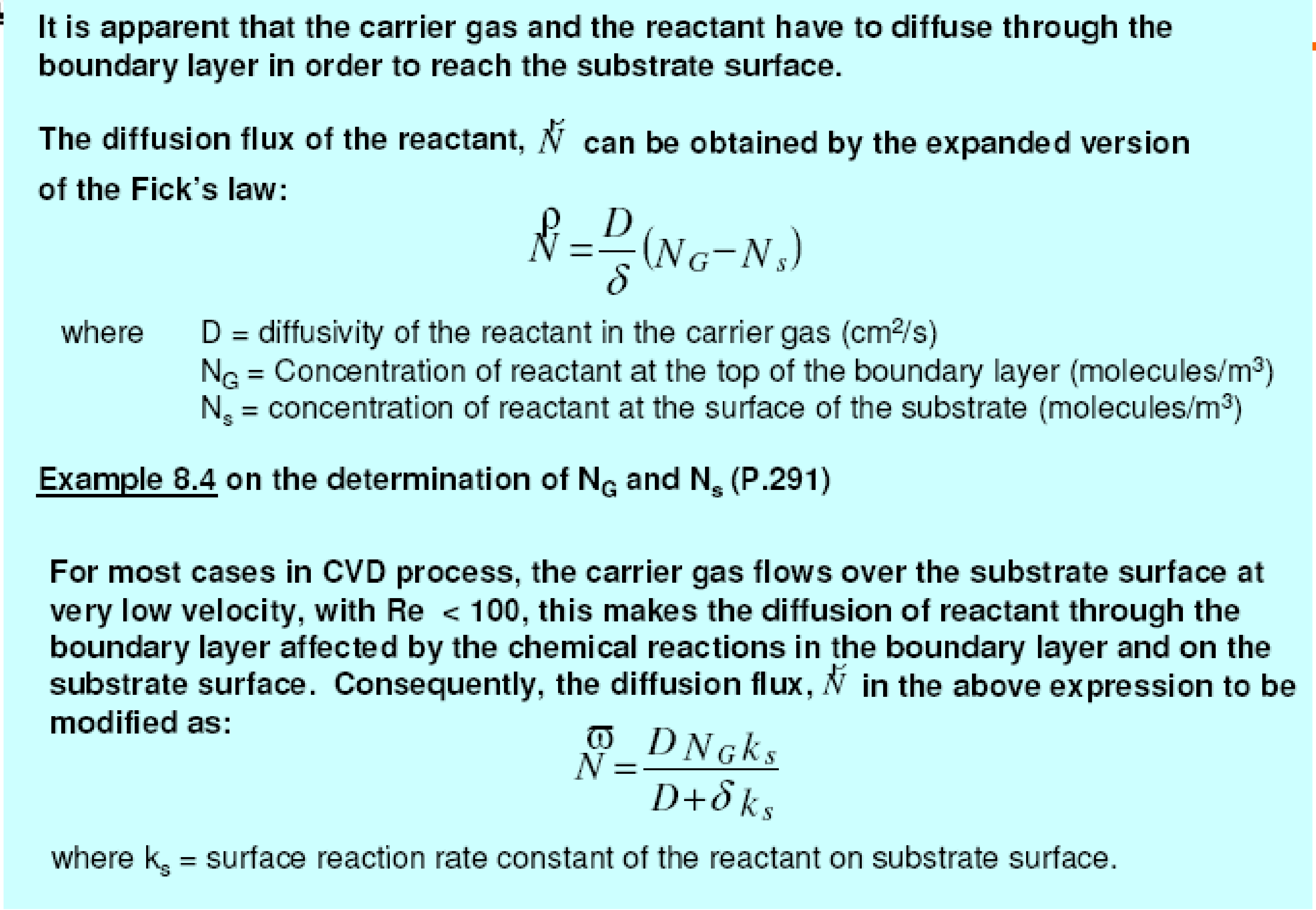
In the case of CVD, the boundary layer plays a significant role in the rate of deposition.

The thickness of the boundary layer over the substrate surface at a distance x from the leading edge can be evaluated by:

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

Re(x) = Reynolds number at x

Rate of deposition



It is apparent that the carrier gas and the reactant have to diffuse through the boundary layer in order to reach the substrate surface.

The diffusion flux of the reactant, $\vec{N}$ can be obtained by the expanded version of the Fick's law:

$$\overset{\rho}{N} = \frac{D}{\delta}(N_G - N_s)$$

where D = diffusivity of the reactant in the carrier gas (cm^2/s)
N_G = Concentration of reactant at the top of the boundary layer ($molecules/m^3$)
N_s = concentration of reactant at the surface of the substrate ($molecules/m^3$)

<u>Example 8.4</u> on the determination of N_G and N_s (P.291)

For most cases in CVD process, the carrier gas flows over the substrate surface at very low velocity, with Re $<$ 100, this makes the diffusion of reactant through the boundary layer affected by the chemical reactions in the boundary layer and on the substrate surface. Consequently, the diffusion flux, $\vec{N}$ in the above expression to be modified as:

$$\overset{\varpi}{N} = \frac{D N_G k_s}{D + \delta k_s}$$

where k_s = surface reaction rate constant of the reactant on substrate surface.

Rate of deposition

The rate of thin film growth over the substrate surface can be obtained by the following expressions:

A. For $\delta k_s \geq D$:

$$r = \frac{D N_G}{\gamma \delta}$$

B. For $\delta k_s << \mathrm{D}$:

$$r = \frac{N_G k_s}{\gamma}$$

in which γ = number of atoms (or molecules) per unit volume of the thin film.

We may use the following expression for estimating the value of γ :

$$\gamma = \frac{1}{\frac{4}{3}\pi a^3}$$

where a = radius of atoms or molecules of the thin film on the substrate surface.

Enhanced CVD

Low-pressure CVD (LPCDV)

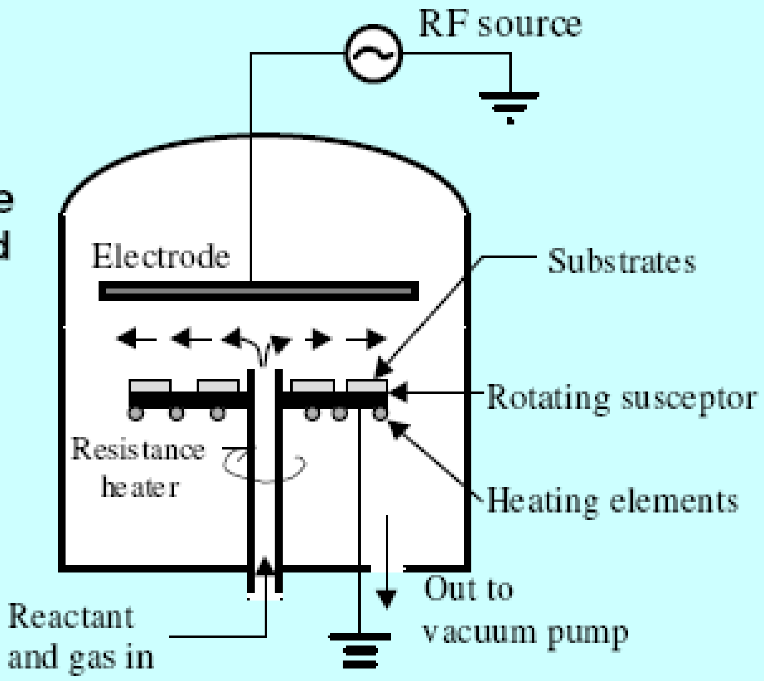
LPCVD is a very popular CVD. It operates in vacuum at about 1 torr (1 mm of Hg). The reactor used for LPCVD is similar to that for APCVD (atmospheric pressure CVD) except the chamber is made leak-proof.

LPCVD offers better quality thin film deposition with more uniform thickness than those by APCVD.

Plasma-enhanced CVD (PECVD)

Unlike APCVD and LPCVD, PECVD can operate at relatively lower temperature, as the required energy for CVD is provided by RF plasma with RF at 3 KHz to 300 GHz. Lower operating temperature means less possibility of damaging the deposited thin films and the substrate.

PECVD usually operates at high vacuum for fast growth of thin films.



Etching

- It involves the removal of materials in desire area by physical or chemical means. It is a way to establish permanent patterns developed at the substrate surface by photolithography.
- It is the process by which the particular section of the film or substrate are removed. It must selectively remove one layer without affecting another layer
- Two common types:
  - Dry (Plasma) etching- physical method
  - Wet (chemical) etching-chemical method

We will discuss about etching in bulk manufacturing section

Summery

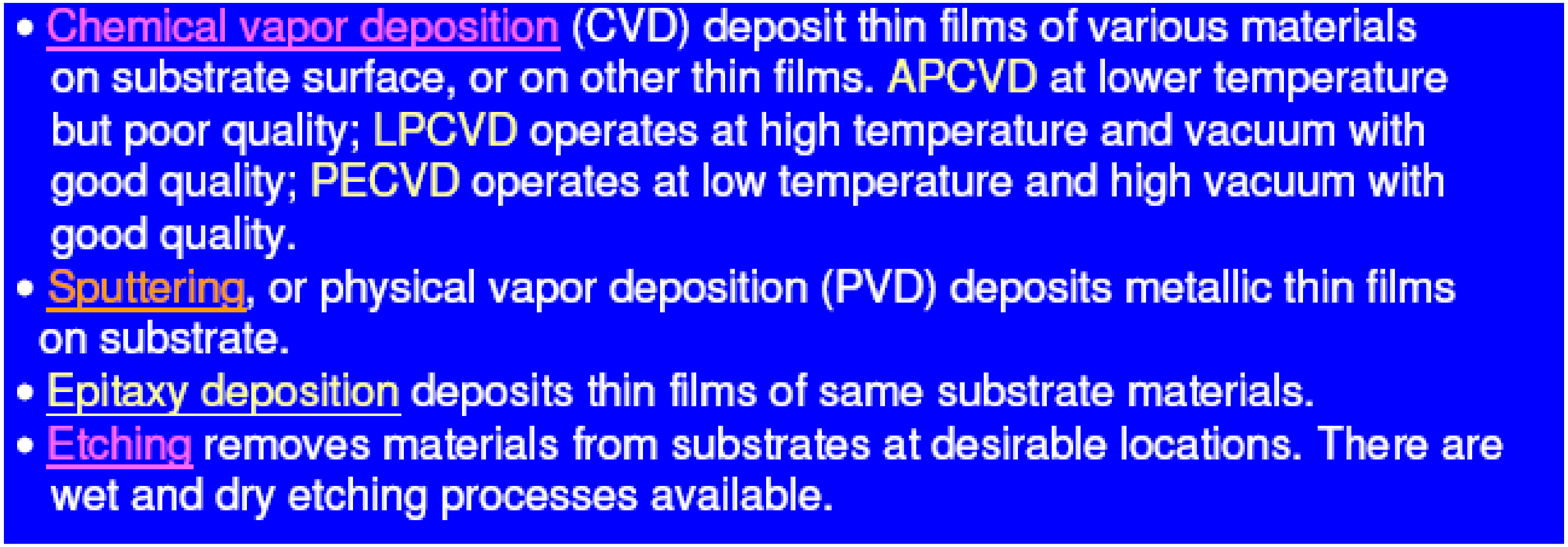
1- All microfabrication techniques have been implemented by Physical-Chemical means, which is radically different from conventional manufacturing process.

2- Most of these techniques are imported from those used in micoelectronic.

3- Photolithography is the most important process in microfabrication. It is the only way establishing the micro scale pattern from the mesoscale mask.

4- Oxidation is a process to produce a thermal insulator or dielectric layer on silicon substrate. The process is strongly temperature dependent

5- Diffusion is similar to oxidation but it gives more uniform dispersion of molecules on silicon substrate.

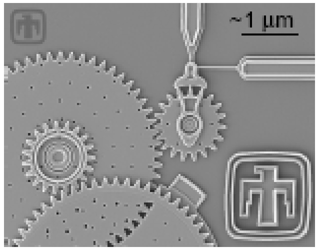


- Chemical vapor deposition (CVD) deposit thin films of various materials on substrate surface, or on other thin films. APCVD at lower temperature but poor quality; LPCVD operates at high temperature and vacuum with good quality; PECVD operates at low temperature and high vacuum with good quality.
- Sputtering, or physical vapor deposition (PVD) deposits metallic thin films on substrate.
- Epitaxy deposition deposits thin films of same substrate materials.
- Etching removes materials from substrates at desirable locations. There are wet and dry etching processes available.

Microfabrication techniques

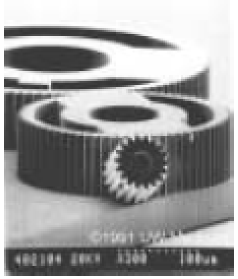
- According to Wikipedia, **Microfabrication** or **Micromanufacturing** are the terms to describe processes of fabrication of miniature structures, of sizes measured in microns and smaller.
- Historically the earliest micromanufacturing was used for semiconductor devices in integrated circuit fabrication and these processes have been covered by the term "semiconductor device fabrication," "semiconductor manufacturing," etc.
- Practical advances in microelectromechanical systems (MEMS) and other nanotechnology, where the technologies from IC fabrication are being re-used, adapted or extended have led to the extension of the scope and techniques of microfabrication.
- Miniaturization of various devices presents challenges in many areas of science and engineering: physics, chemistry, material science, computer science, ultra-precision engineering, fabrication processes, and equipment design.

MEMS fabrication techniques



http://www.mdl.sandia.gov
/Micromachine/vision.html

Klasseen et al., 1995



- Surface micromachining
  - LPCVD polysilicon used for vast majority of MEMS applications.
  - Thickness limited to 3-5 microns.

    http://www.memsrus.com/figs/surface.micro.dcr
- Bulk micromachining
  - Allows for “thicker” structures
  - DRIE of single crystalline Si wafers is most popular

    http://www.memsrus.com/figs/bulk.micro.dcr
- Electrodeposited (LIGA)
  - Allows for “thicker” metallic structures
  - Ni most popular

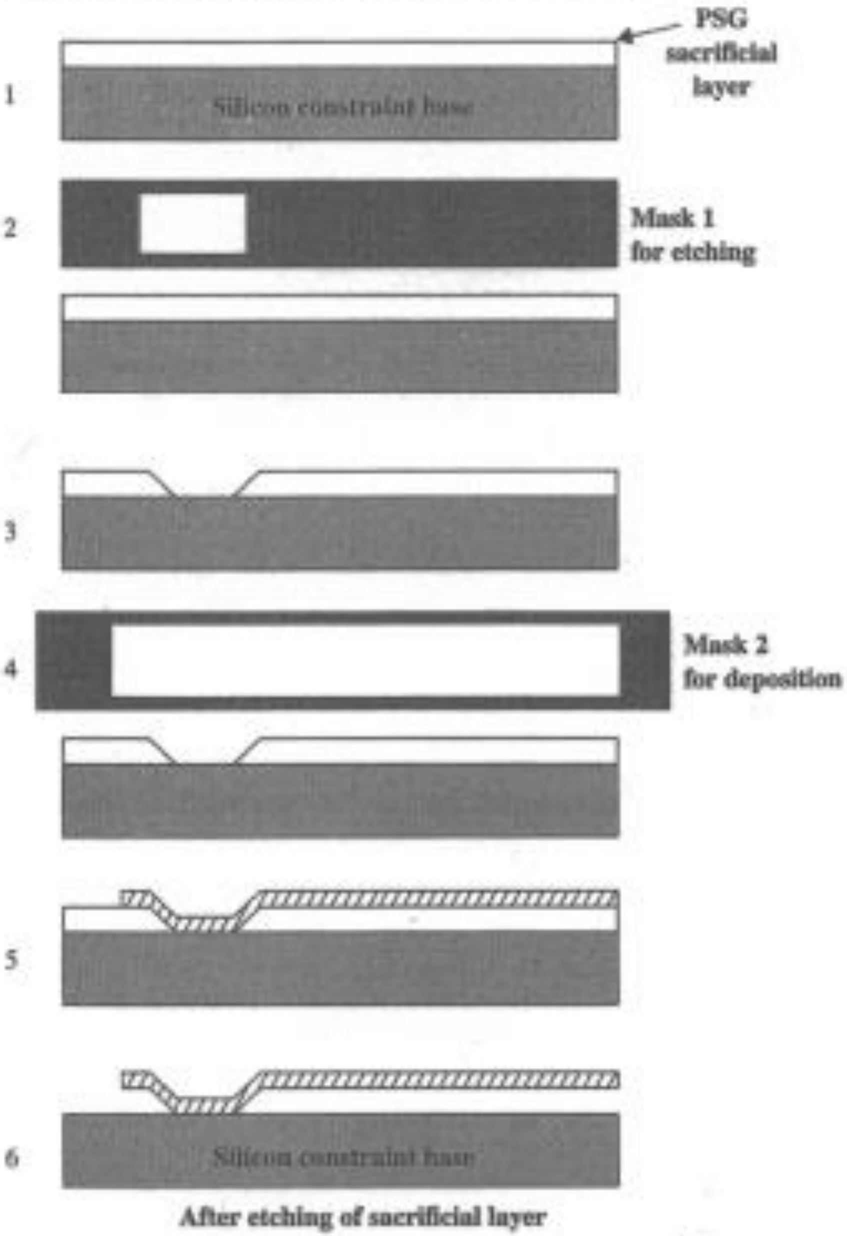
    http://www.memsrus.com/figs/liga.dcr

Surface micromachining

- It typically made up three types of component:
  - Sacrificial component (spacer layer)
    - It is PSG (phosphosilicate glass) or SiO2 deposited on substrate by LPCVD
  - Microstructural component: polysilicon is a popular material
  - Insulator component: can be SiO2 or polysilicon

adding material layer by layer on the top of substrate

Figure 9.10 | Surface micromachining process.



Step1: deposition of PSG on the silicon substrate

Step 2: using mask 1 to make the anchor for microcantilever (photolithography)

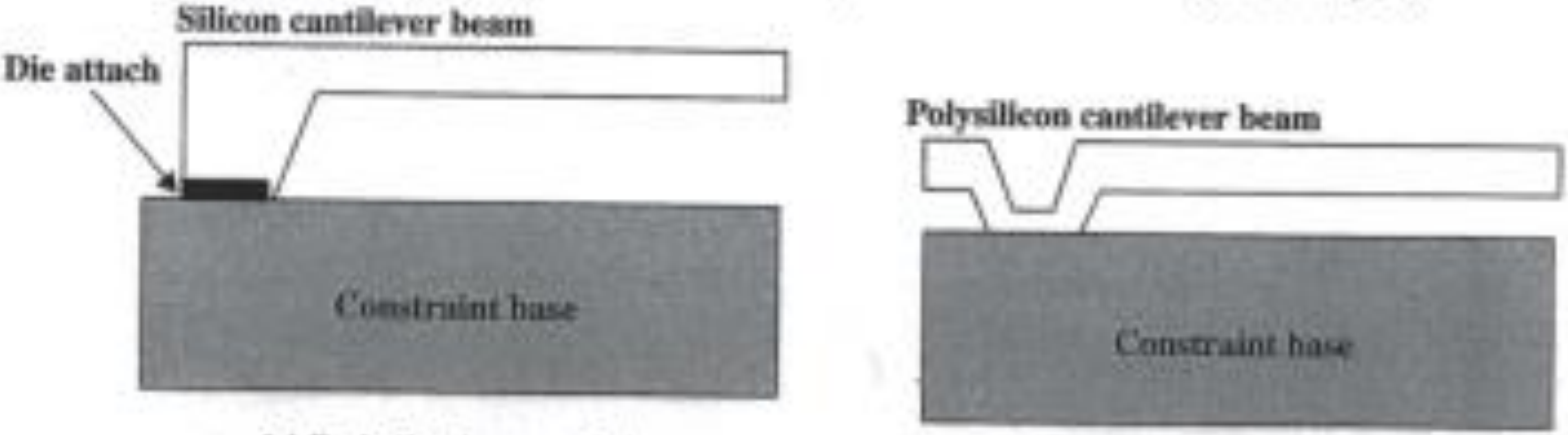
Step 3: using mask 2 for deposition of polysilicon microstructural material

Step 4: etch away the PSG sacrificial layer by 1:1 HF

Step 5: rinsed the structure in deionized water followed by drying under infrared lamp

Selection of micromachining techniques

Figure 9.8 | Microcantilever beams produced by two micromachining techniques.



(a) By bulk micromachining

(b) By surface micromachining

Bulk micromanufacturing

- In contrast to surface micromachining in which the microstructure is built by adding material layer by layer on the top of substrate, bulk micromanufacturing builds microstructure by removing the substrate material using physical and chemical means.
- Physical and chemical techniques, either by dry or wet etching, are the only practical solutions.
- **Orientation-independent isotropic etching or orientation-dependent anisotropic etching are the key technology used in bulk micromanufacturing**

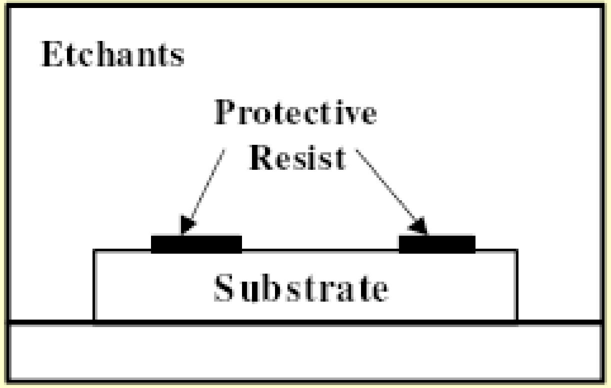
Chemical or wet etching

- The chemical solutions used in etching, or etchant, attack the parts of the substrate that are not protected by the mask. The mask may be either the PR for SiO_2 substrate in HF or mask made of SiO_2 for the protection of silicon substrate in KOH etchant
- It is a fast and cheap process
- It can be isotropic (etch in all direction at the same rate) or anisotropic
- Undercut beneath the mask material can be happen
- For anisotropic etching there will be a need for a better masking such as silicone nitride instead of silicon dioxide

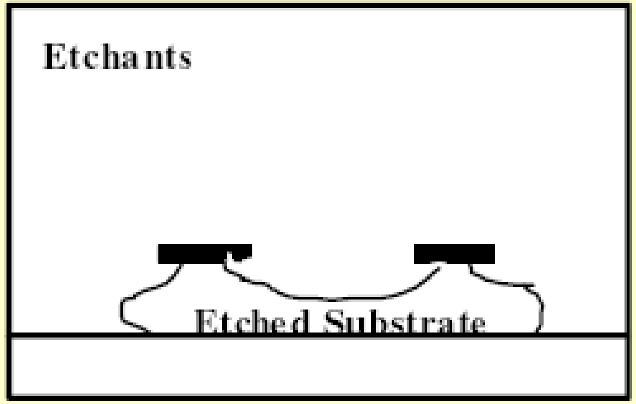
Isotropic etching

Isotropic wet etching or Isotropic plasma etching means the chemistry (etchant or plasma gas) etches the substrates with total disregard for their crystal planes.

It etches in all directions at the same rate.



(a) Substrate in wet etching

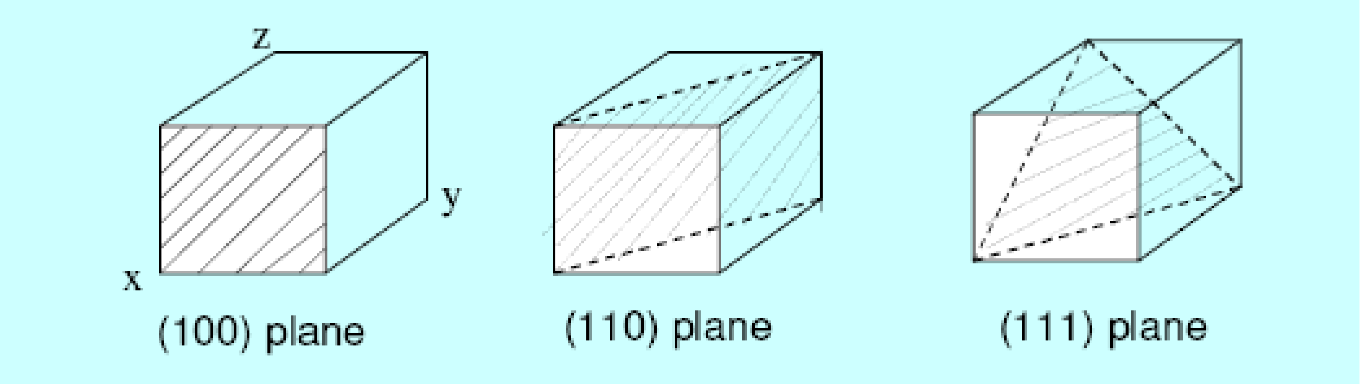


(b) Partially etched substrate

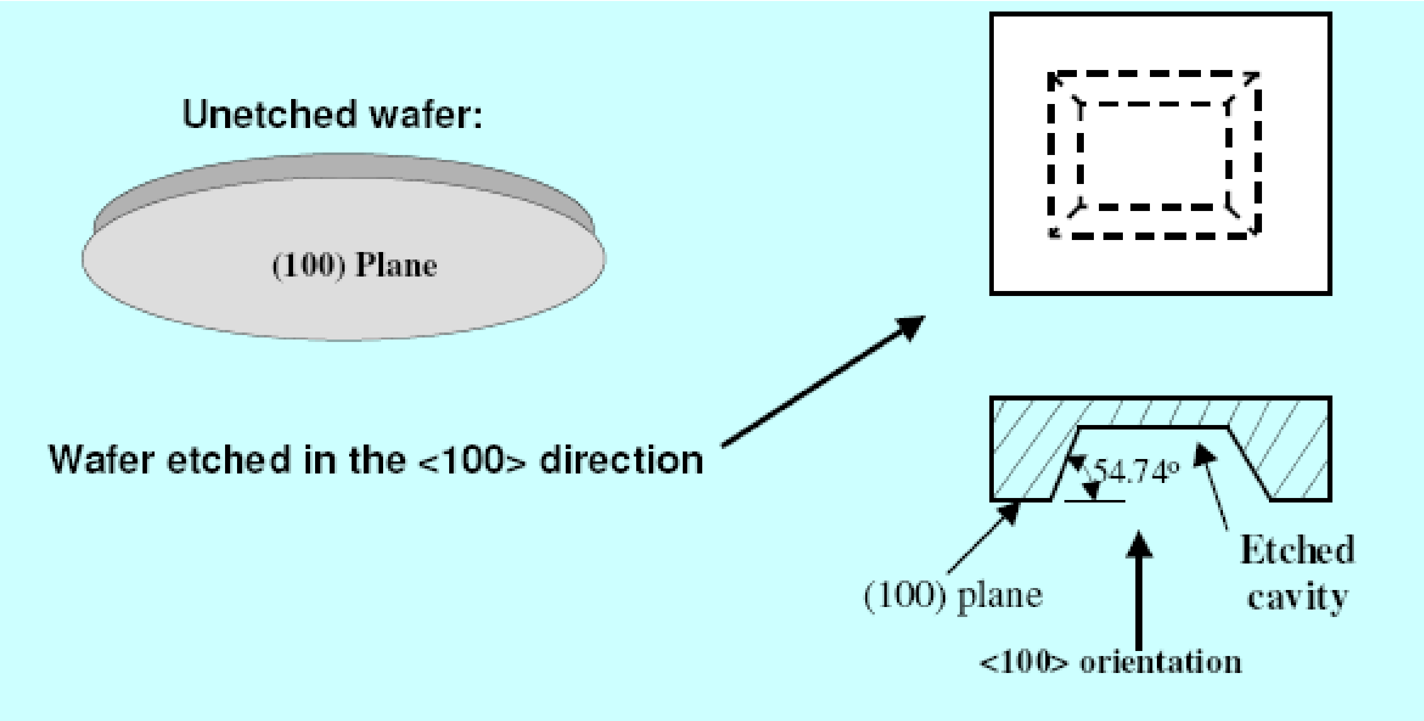
Isotropic etchants are available for oxide, nitride, aluminum, polysilicon, gold and silicon. Hydrofluoric acid (HF) is the most commonly used chemistry for silicon.

Isotropic etching is not desirable in micromanufacturing because lack of control of the geometry of the finished product.

Anisotropic etching



Anisotropic etching


Unetched wafer:

Wafer etched in the <100> direction

Etchant

Etchants are the chemicals that dissolve or remove materials from substrates.

Etchants in wet etching are chemicals in solvents, whereas etchants used in dry etching are plasmas that contains charge-carrying ions.

Wet etchants for silicon substrates

For isotropic etching: HNA (acidic agents, e.g. $HF/HNO_3/CH_3COOH$) at room temperature.

For anisotropic etching: Alkaline chemicals with PH > 12. Popular etchants:
Potassium hydroxide (KOH)
Ethylene-diamine and pyrocatecol (EDP)
Tetramethyl ammonium hydroxide (TMAH)

Most wet etchants are diluted with water, normally 1:1 by weight.

The selectivity ratio of etchants is defined as the ratio of etching rate of silicon to the etching rate of another material using the same etchant.

It is of great importance to the process design engineers in selecting the suitable material for the mask used in the etching process.

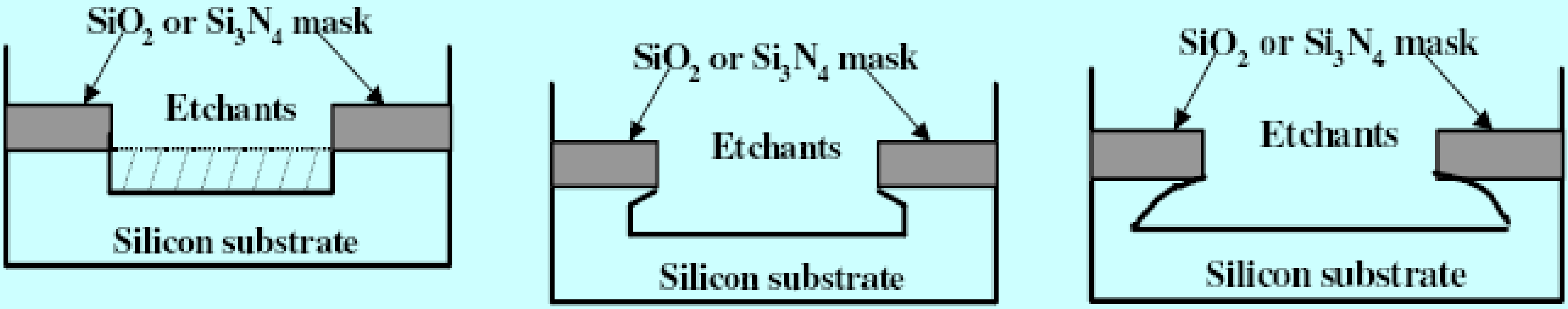
Selectivity ratio of etchants to two silicon substrates is given below:

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

- We notice that the selectivity of SiO_2 has selectivity ratio of > 10^3 that means that SiO_2 has more than 1000 time slower etching rate than that in the silicon substrate.
- This feature makes SiO_2 as less expensive but an attractive candidate material for using as an etching mask.
- Si_3N_4 would have been a better choice for mask material, but it is more costly to produce than SiO_2.

Inadequate selection of mask

The following undesirable situations may occur in etching with the use of improper mask materials:



(a) Ideal etching (b) Under-etching (c) Under cutting

In general SiO_2 is used as a masking material with KOH etchant for relatively shallow trenches.

Si_3N_4 is used for etching processes for deep trenches, in which long periods in etching is a common practice.

Microcantilever bulk micromachining

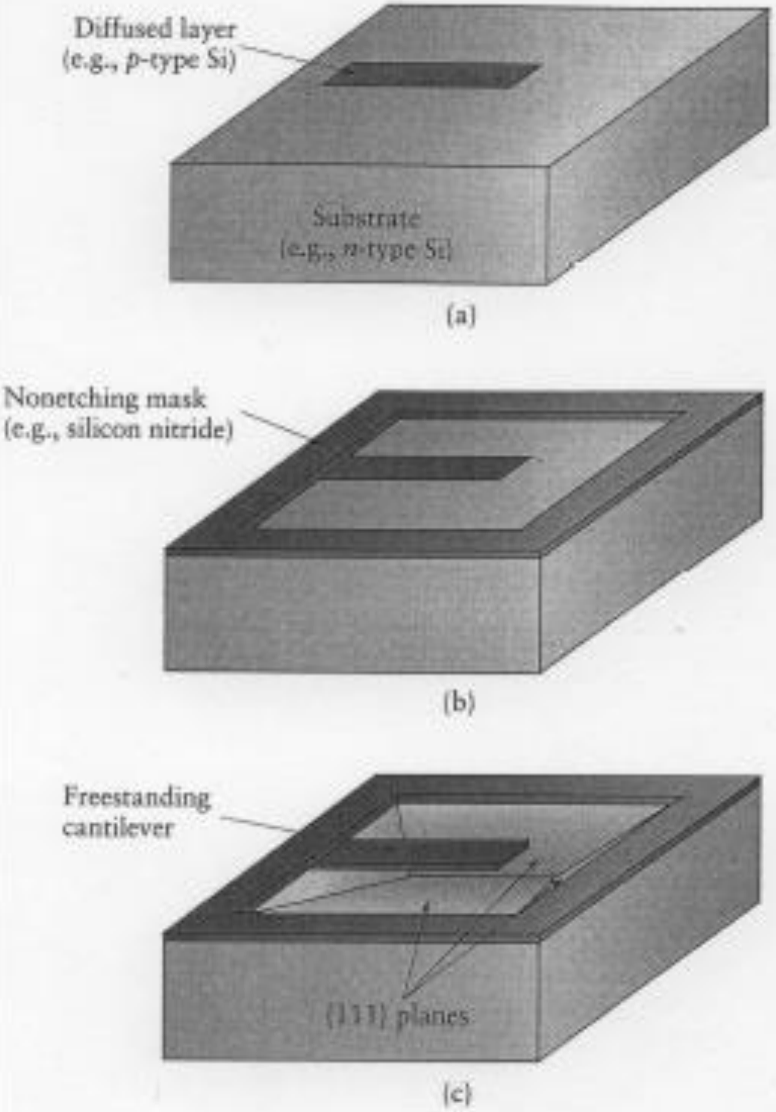


FIGURE 13.27 Schematic illustration of bulk micromachining. (a) Diffuse dopant in desired pattern. (b) Deposit and pattern masking film. (c) Orientation-dependent etch, leaving behind a freestanding structure. *Source:* K. R. Williams.

Step 1: by using the masking technique, a rectangle patch of the n-type silicone substrate is changed to p-type silicon

Step 2: a mask Is then produced , such as with silicon nitride on silicon

Step 3: etching with KOH will remove the undoped and unmasked silicon rapidly

Dry etching

Dry etching involves the removal of substrate materials by gaseous etchants without wet chemicals or rising.

There are generally 3 dry etching techniques:
(1) Plasma. (2) Ion milling. (3) Reactive ion etch.

Common practice, however, involves Plasma and Reactive ion etch.

Relatively recent develop has been in the Deep Reactive Ion Etching, or DRIE.

- Dry etching of silicon substrates typically is faster and cleaner than wet etching. A typical dry etching rate is 5 μm/min, which is about 5 times faster than that by wet etching.
- However, dry etching requires more costly equipment.
- On the other hand, it is the only way to produce deep trenches with near-vertical side walls using the DRIE process, which is critical for many MEMS and microsystems components.

Plasma Etching

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

Radio frequency (RF) is a common energy source for the production of plasma.

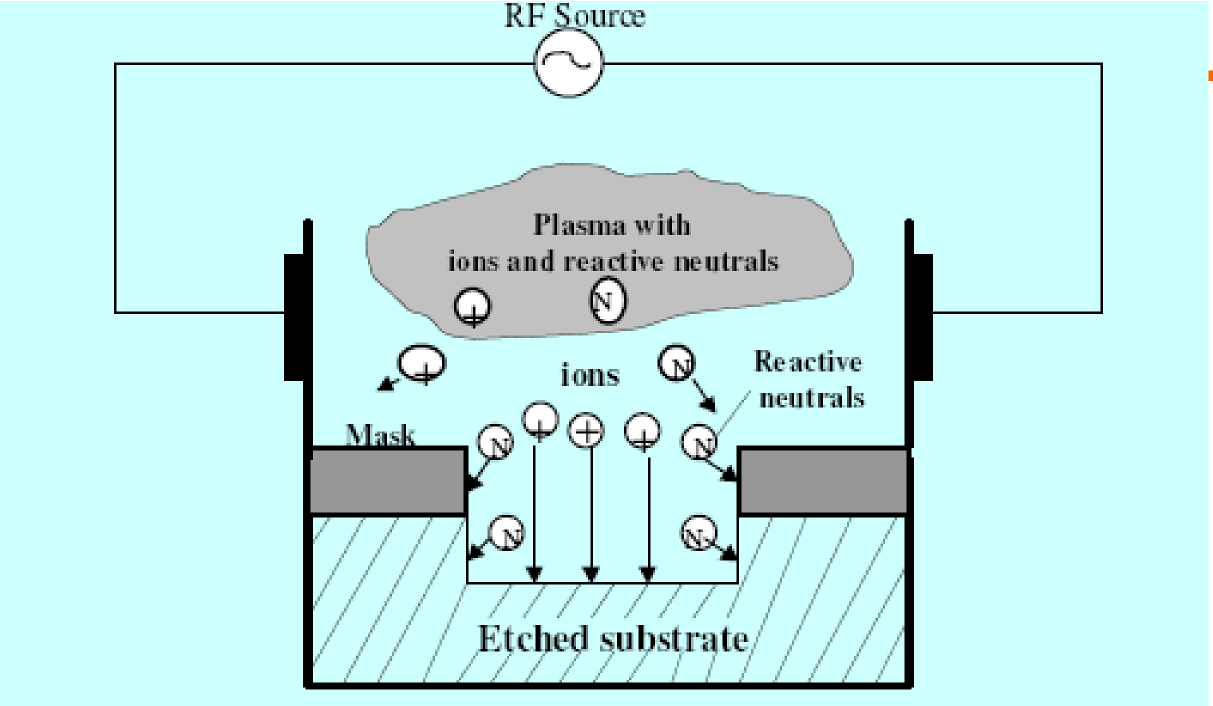
To etch silicon or silicon-compound substrates, one needs to add chemically reactive gas, e.g. CCL_2F_2 to the plasma.

The added reactive gas produces reactive neutrals when it is ionized in the plasma.

Both the reactive neutrals and the ions in the plasma carry high kinetic energies.

They attack the substrate materials by bombarding the surfaces of the substrate as illustrated in the next slide.

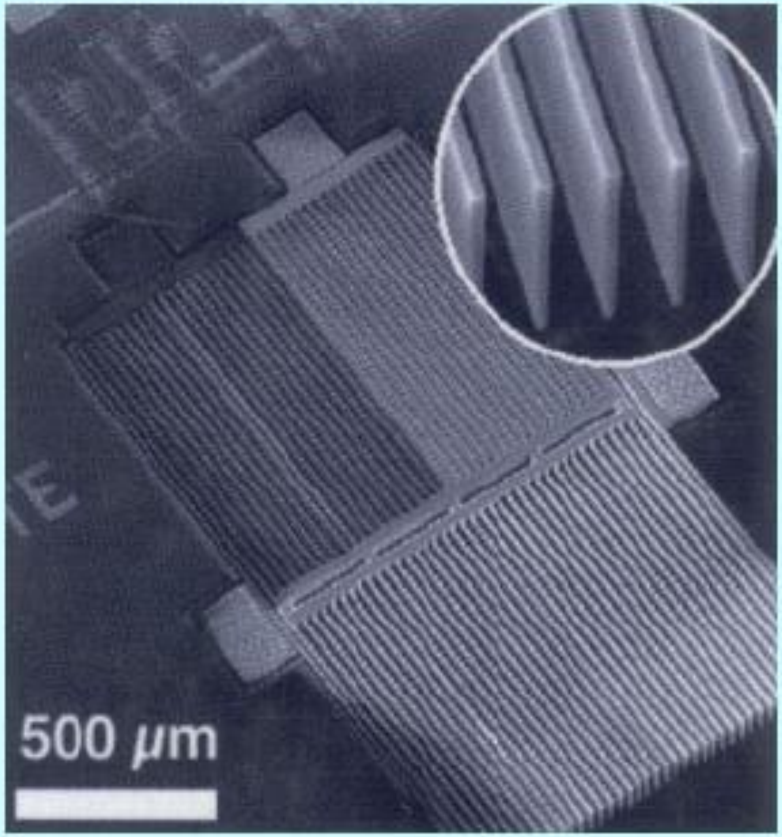
Plasma etching process

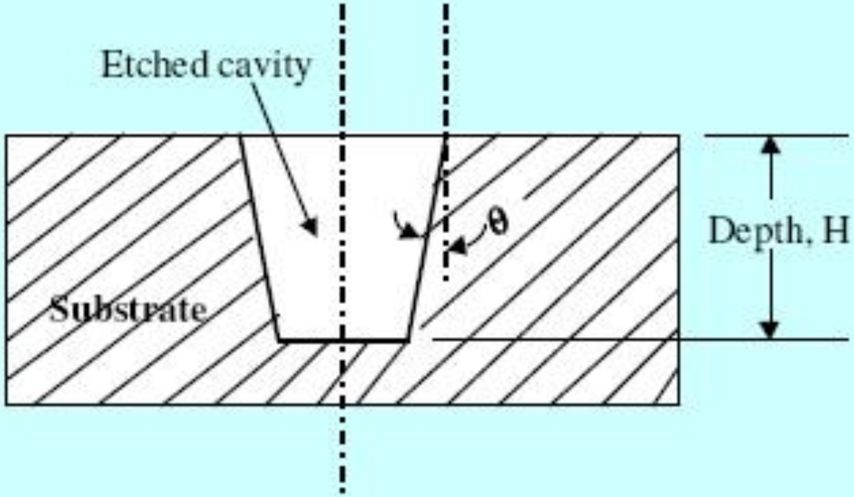


- The plasma used is a stream of positive-charge-carrying ions of a substance with a large no of electrons
- High energy plasma containing gas molecules, free electrons, and gas ions bombards the surface of the target substrate
- The ions (+) in the plasma itself attack the substrate only in the normal direction. Etching of substrate material is accomplished by instant local evaporation of substrate material after high energy impingement of (N) neutral and (+) ions.

Deep Reactive Ion Etching

Many MEMS components, such as resonators and micro accelerometers require etching trenches in the silicon substrates with sufficient depth (H) and vertical side walls, i.e. $\theta \approx 0$ in the figure below to the right.





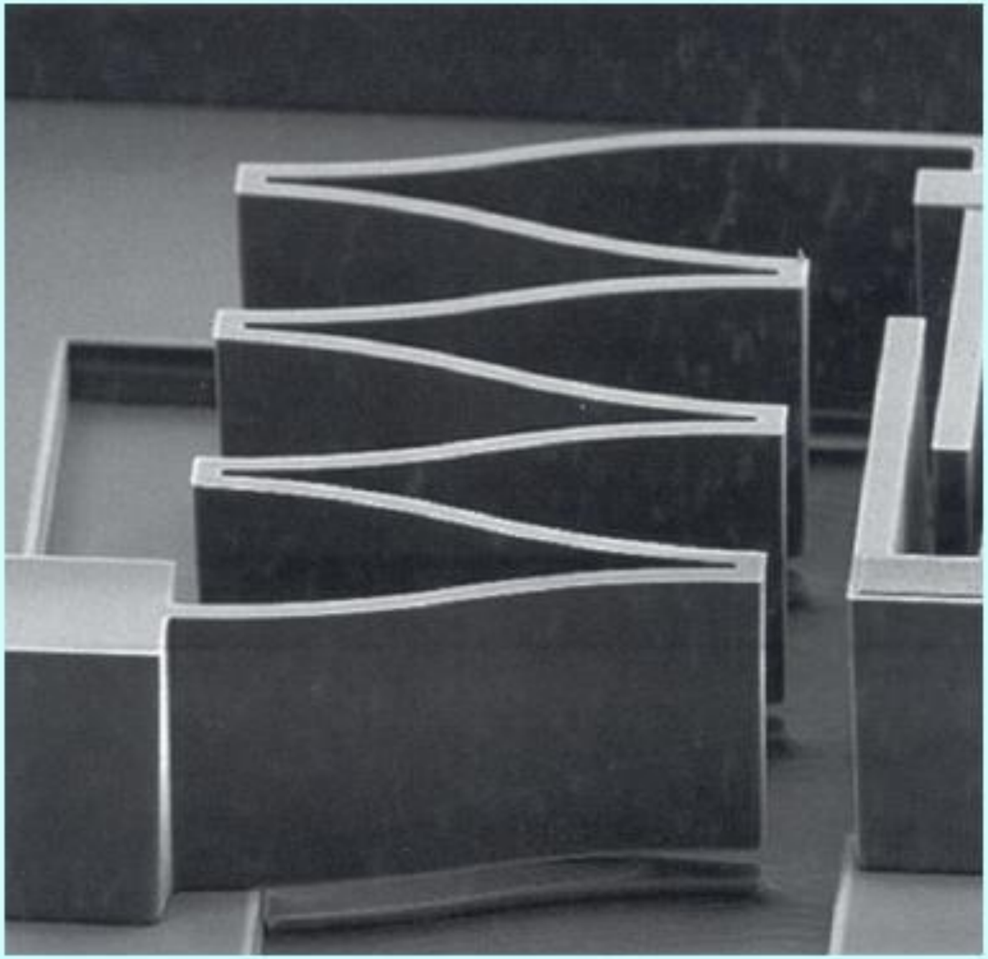
These trenches are of typically high aspect ratio (The ratio of the dimension in the thickness (H) to those of the surface).

Wet etching and conventional dry etching could not accomplish deep etching with vertical walls.

MEMS with high aspect ratio by DRIE

DRIE is the only etching technique that is capable of producing trenches with aspect ratio up to 300 and a near vertical walls at θ = ±2°.

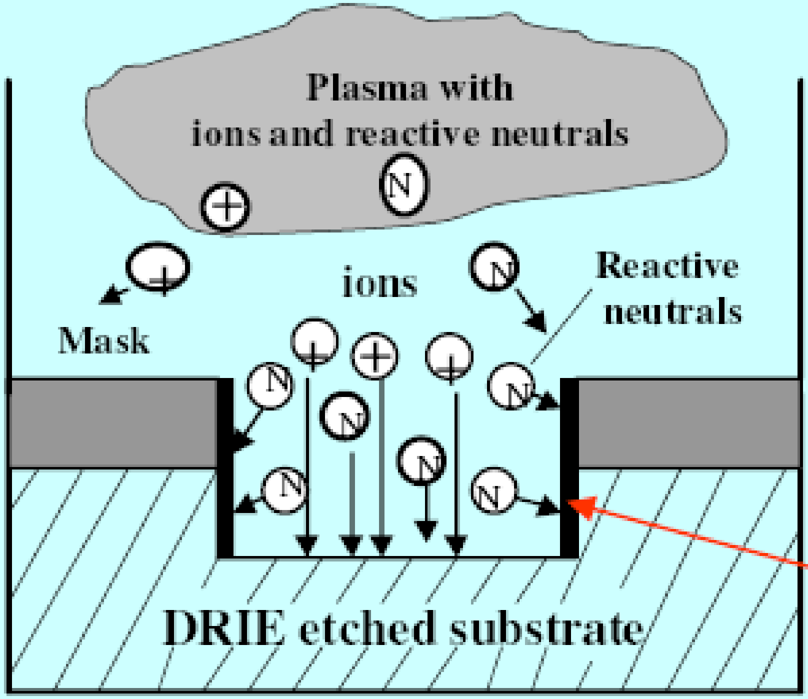
A micro spring



Principle of DRIE

DRIE works on a similar principle as the plasma etching. A major difference, however, is that DRIE involves the production of thin protective polymer films on the side walls during the etching process. These thin protective films prevent etching of the side walls. As result etching can only take place in the normal (the depth) direction in the trench.

The DRIE process is illustrated below:



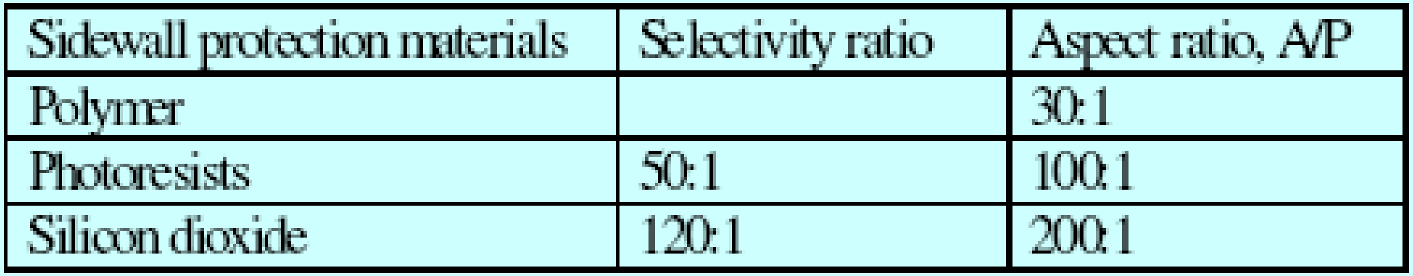
Thin protective polymer films

Principle of DRIE

The reactants that can produce thin protective polymer films is fluoropolymers (nCF2) in the plasma Argon gas ions.

The rate of DRIE is in the range of 2 - 3 μm/min.

Examples of high aspect ratio of trenches produced by DRIE are:



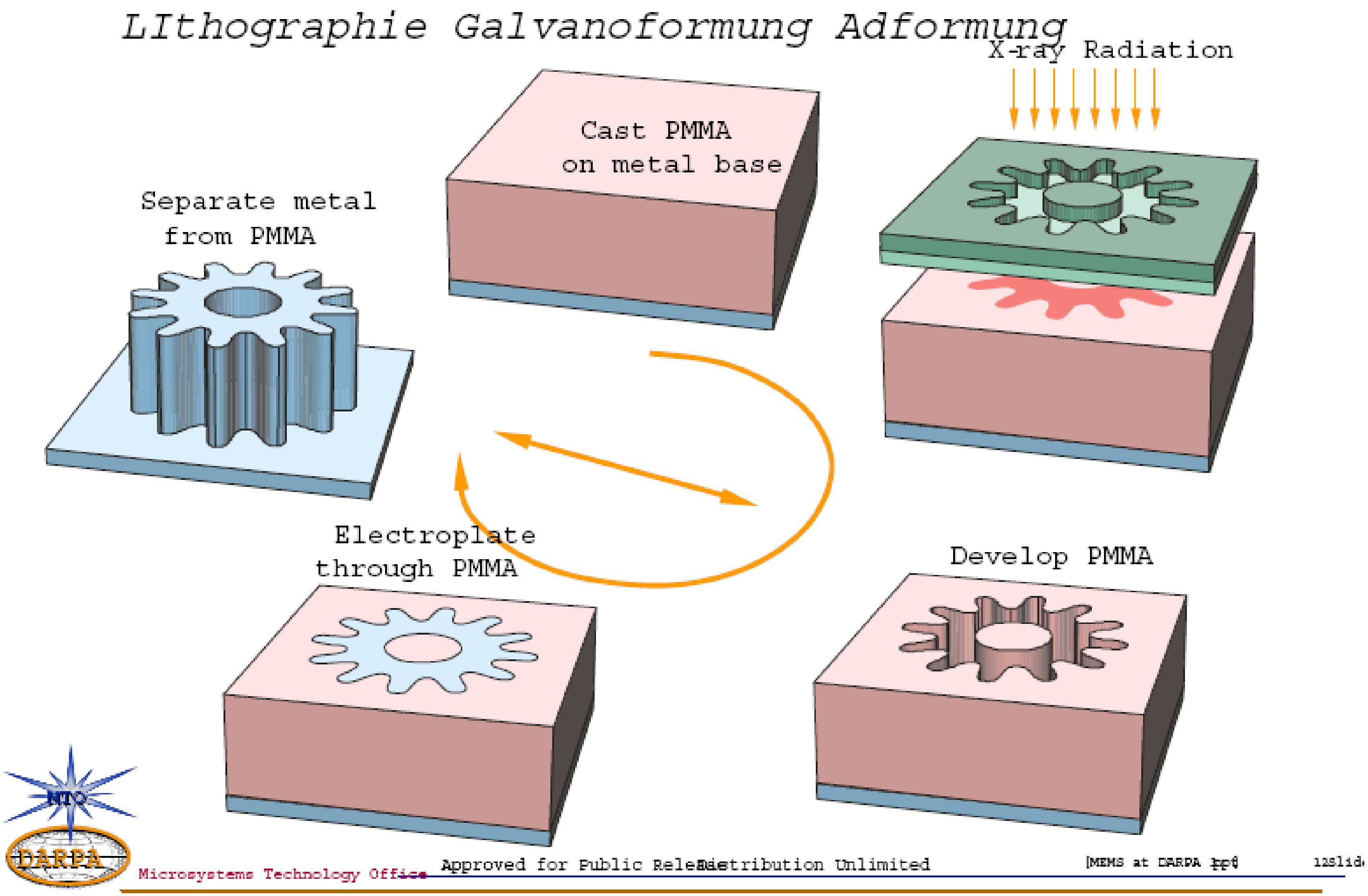
Sidewall protection materials	Selectivity ratio	Aspect ratio, A/P
Polymer		30:1
Photoresists	50:1	100:1
Silicon dioxide	120:1	200:1

Depth of trenches at 300 μm with vertical walls at ±2o were produced in silicon substrates.

LIGA process

- **LIGA**, a German acronym for (X-ray) lithography (**Li**thographie), Electroplating (**G**alvanoformung), and Molding (**A**bformung), is a process in microtechnology that was developed to manufacture non-silicon-based microstructure
- The single most important feature of this process is that it can produce “thick” microstructure that have extremely flat and parallel surfaces such as microgear made of metal or plastic.

LIGA process



Electrodeposition

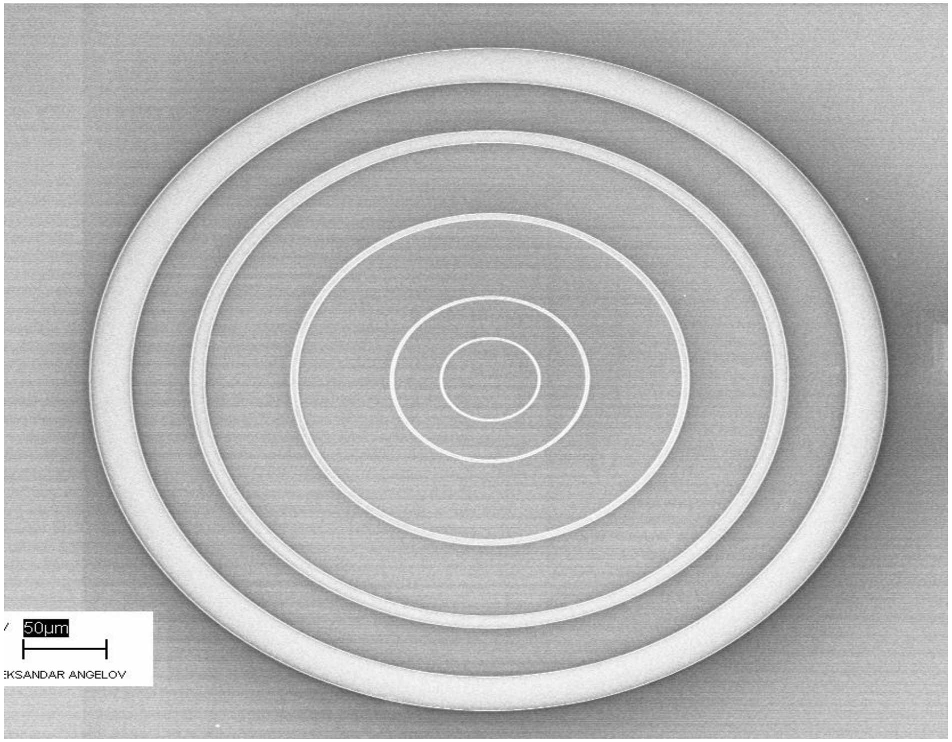
- E.g. Ni, Cu, Au, Cr, FeNi
  - Metal ions in solution are deposited on a substrate in an electrochemical process.
- Key parameters:
  - Current density, bath T, chemisty and pH.
  - Hard to plate uniform thickness and smooth surfaces.
- Main uses:
  - Cu interconnects
  - LIGA Ni - high aspect ratio MEMS

Molding Trials

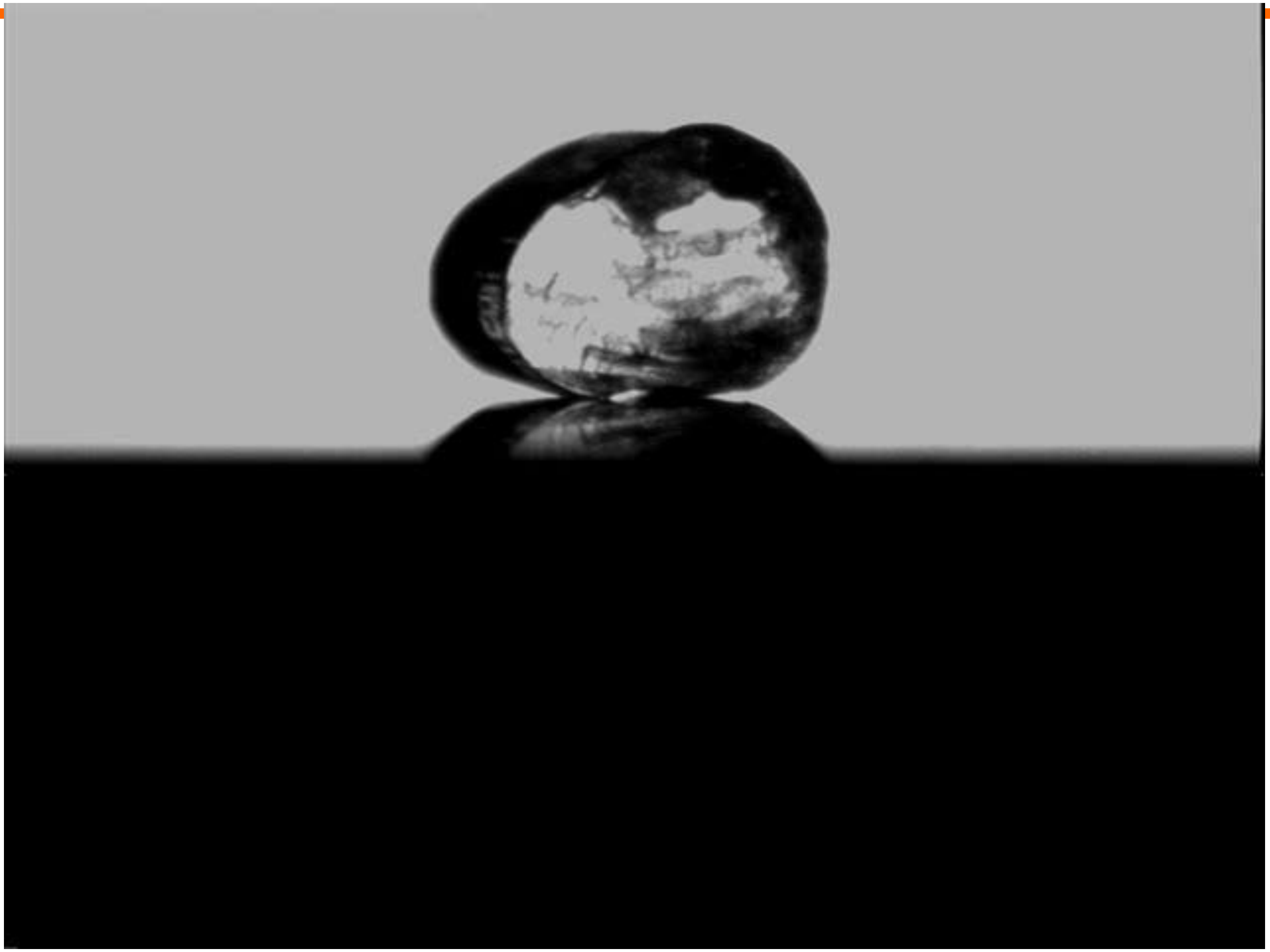
Nano-featured parts with dimension ranging up to a few hundred nanometers on Si Wafer using Deep Reactive Ion Etching. (Aspect Ratio ranging from 0.01 to 0.5) (Feature depth ~ 400 nm)

Ring 0	710
Ring 1	1509
Ring 2	3753
Ring 3	8723
Ring 4	25000

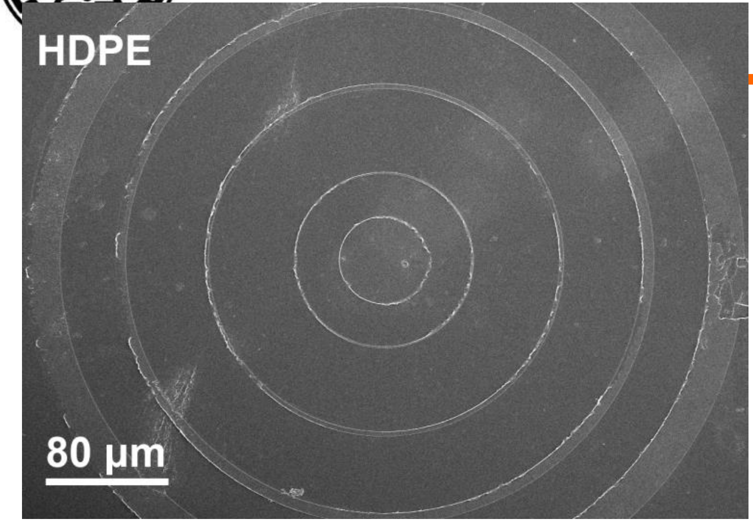
Ring dimension in nm

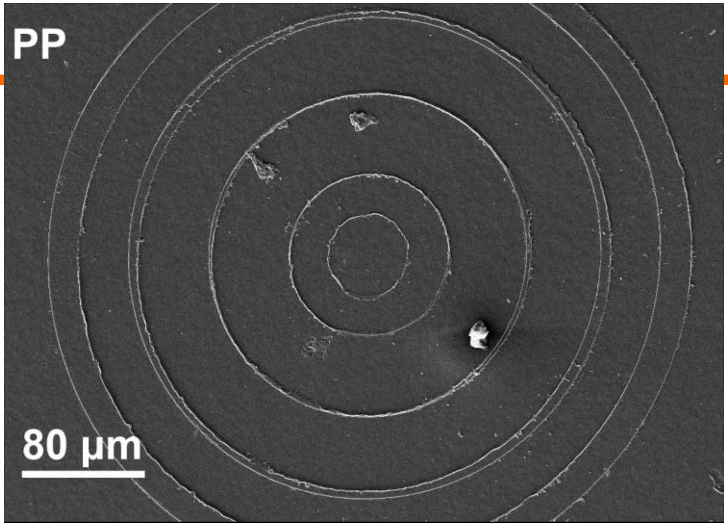


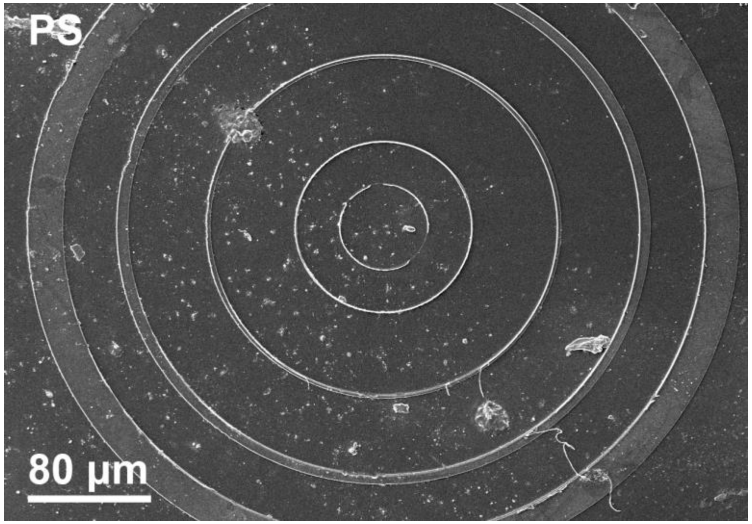
- Spreading observed in “Cap with Foot” shape observed with PMMA and PS

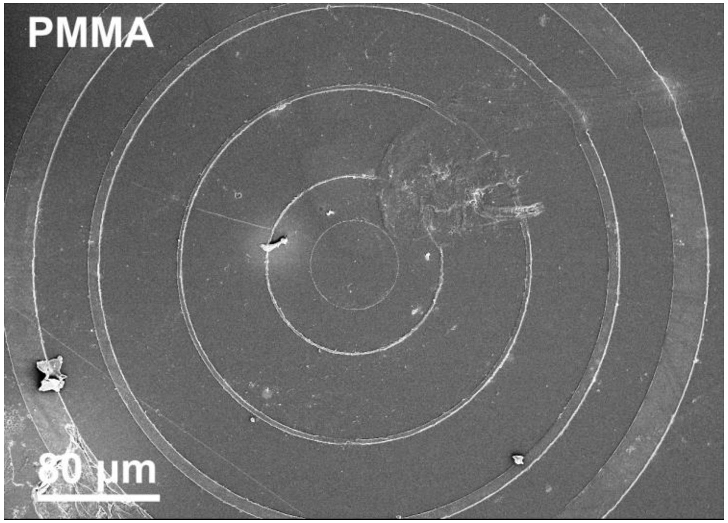


SEM Image of molded parts









Thank you for your attention!

Questions ????