PC 3242 Part II

Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	8
RBS	Extra material provided	9
Light ions in lithography	Extra material provided	10
Etching	Chapter 7	10, 11
Nano Imprint Lithography	Chapter 6	12
3DP Three Dimensional Printing	Extra material provided	13

JA van Kan 2024

Degree of Anisotropy

r_{lat} : lateral etch rate
r_{ver} : vertical etch rate

A_f : degree of anisotropy

$$\boxed{A_f \equiv 1 - \frac{r_{lat}}{r_{ver}}}$$

$$0 \le A_f \le 1$$

Isotropic

Anisotropic

Isotropic Etching

Isotropic etching was used first. Here the etch rate is the same in all directions: **Depth and lateral**

Wafer is in contact with liquid, reactive gas or plasma.

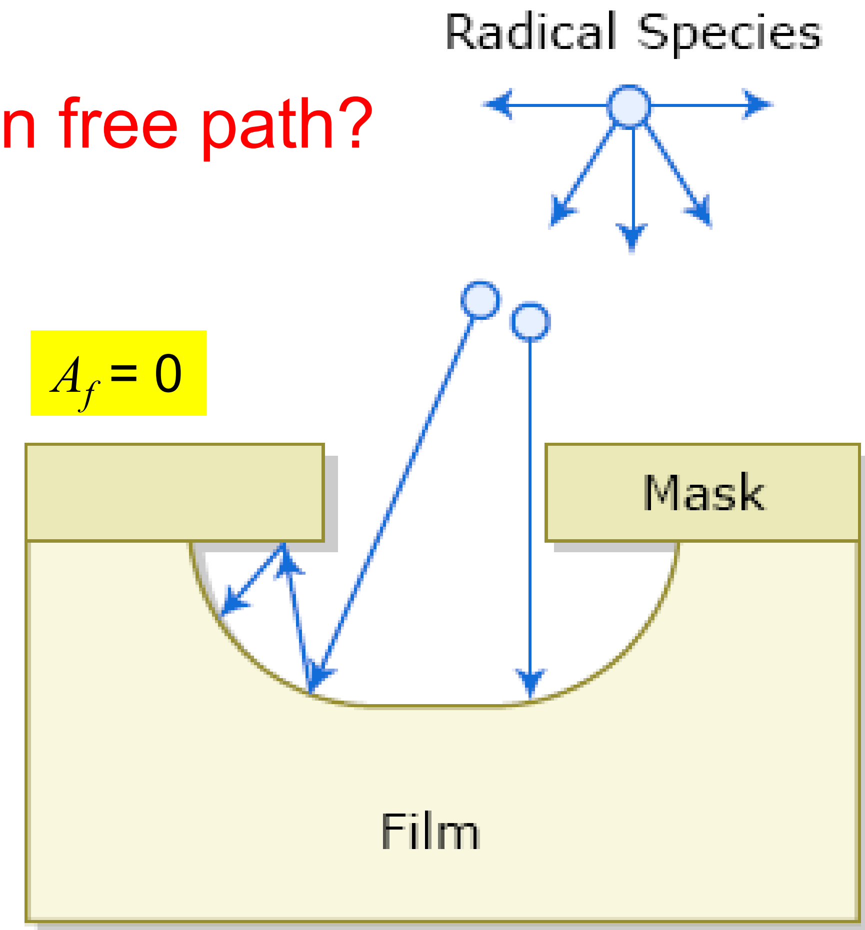
If you use gas what is the mean free path?

Etching is the result of a chemical reaction and is therefore:

1 Isotropic

2 Highly selective

3 Rate is thermally activated



Physical Etching (anisotropic)

Wafer exposed to inert gas and or plasma

Etch is from **momentum transfer** of accelerated ions acting **anisotropic**

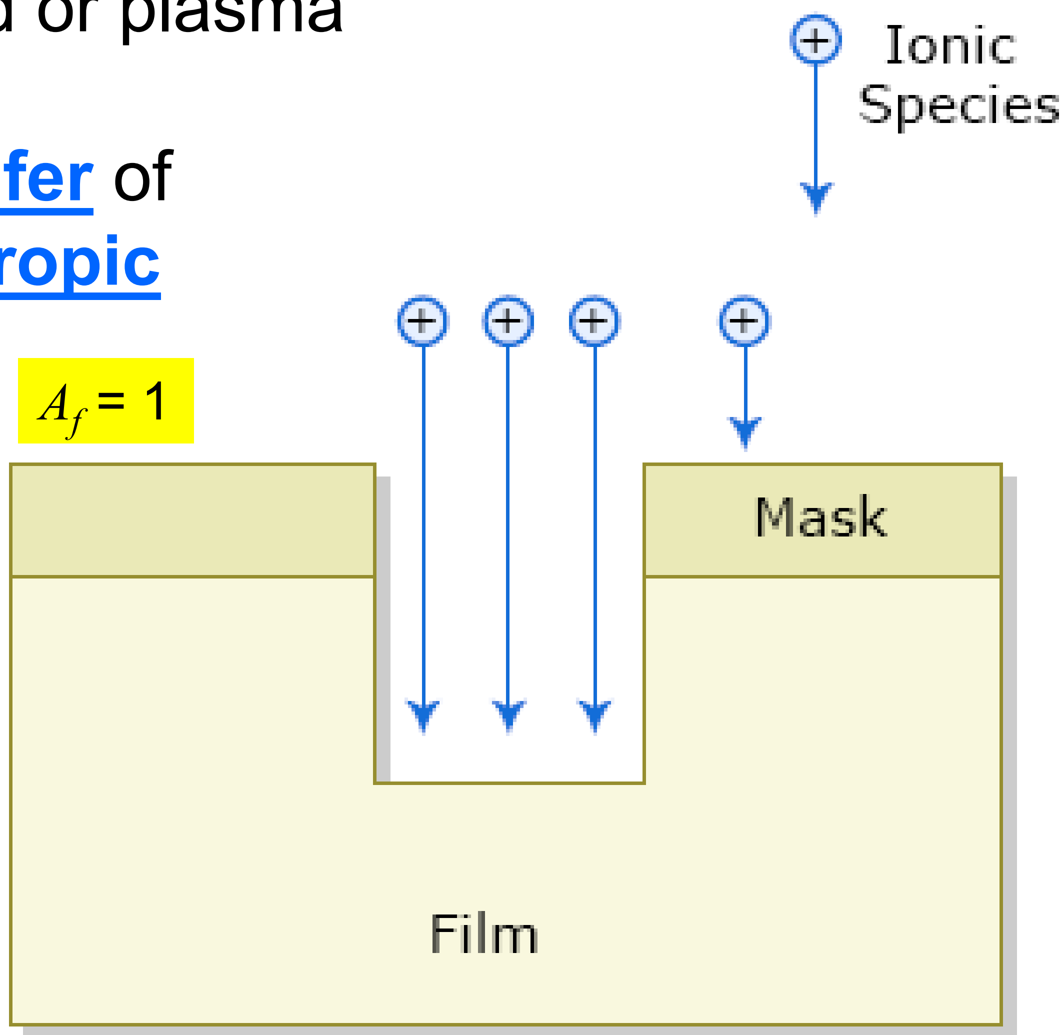
$A_f = 1$

1 Good edge definition

2 Anisotropic

3 Low selectivity

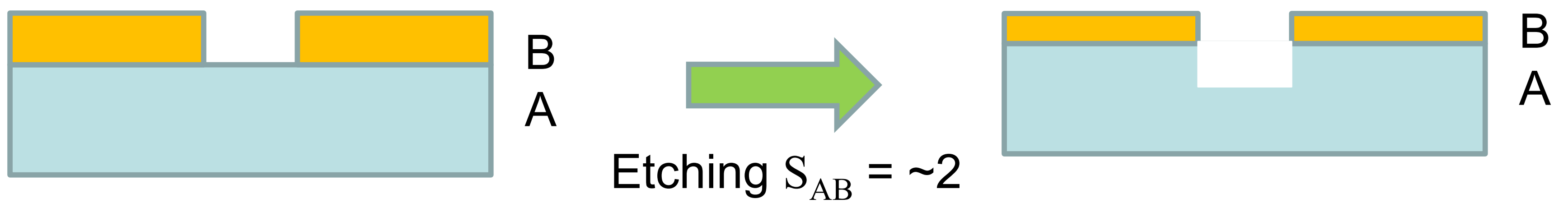
4 Rate is mass transport dependent (by products)



Most preferred is dry anisotropic etching since the structures don't shrink
But wet etching is very commonly used in industry (Cheap).

Etching Selectivity S

$$S_{AB} = \frac{r_A\,(\text{vertical etching velocity of intended material A})}{r_B\,(\text{vertical etching velocity of mask B})}$$



Chemical reactions are highly selective (20-50)

<u>S is controlled by:</u>

Chemicals, concentration, temperature

Physical etch processes less so (1-5)

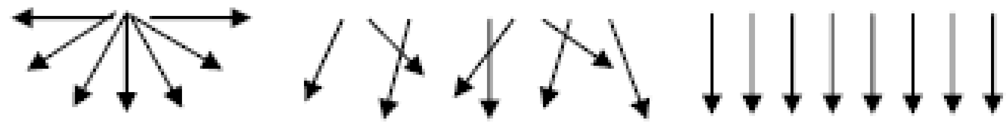
RIE (reactive ion etching)

<u>S is controlled by:</u>

Plasma parameters, plasma chemistry, gas pressure, flow rate & temperature.

Etching Selectivity S

***Directionality*: From Isotropic to Anisotropic**



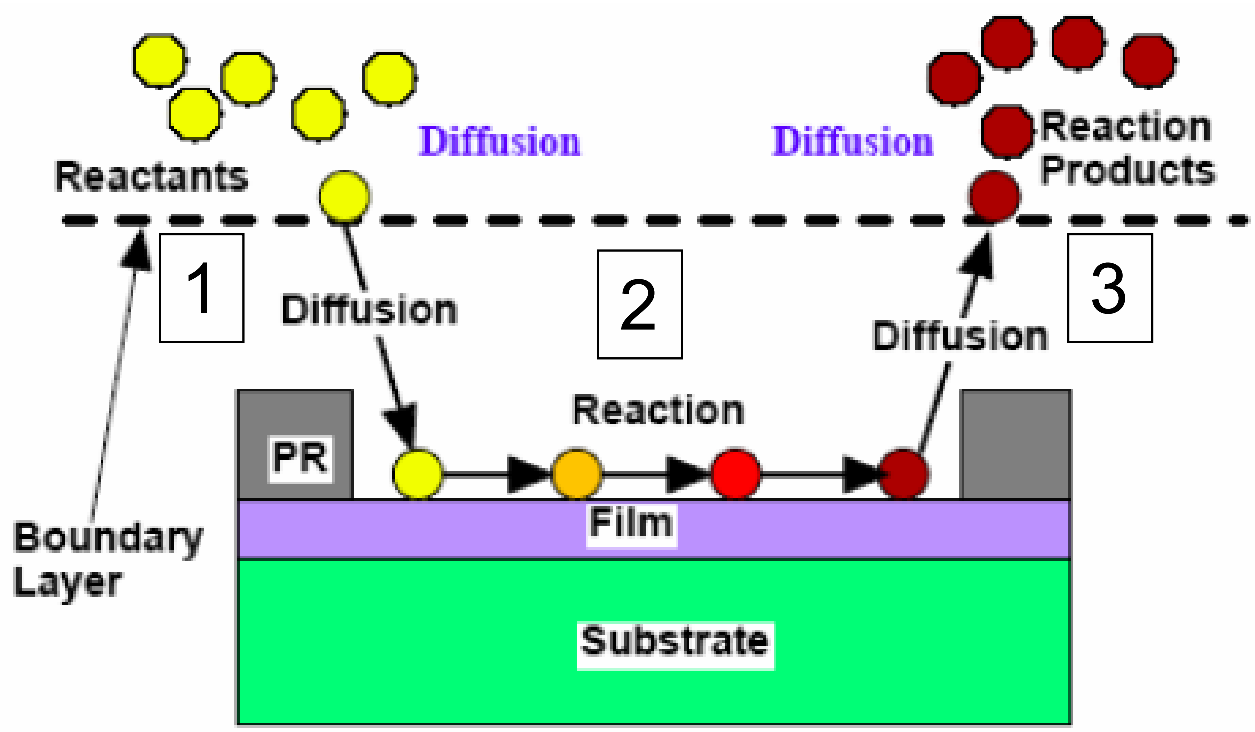
	Wet etch (*Chemical*)	Dry etch (*Physical*)
Selectivity	**25 - 50**	**1 - 5**
Directionality	**low**	**high**

Etch Process - Figures of Merit

- **Etch rate** fast enough to be practical, slow enough to be controllable.
- **Etch rate uniformity** across wafer
- **Selectivity** rate of etching target material relative to mask-etch rate (should be large)
- **Anisotropy** directional dependence of etch rate
- **By products** volatile or otherwise easily removed, Are they safe?

Wet Etching

Wafer in solution that attacks film to be etched, but not mask



Advantages:
High selectivity due to chemical reactions

Disadvantages:
- Isotropic (except for Si)
- Poor process control
- Strong T-dependence
- Excessive particulates

1 Reactant diffuse through boundary layer to surface

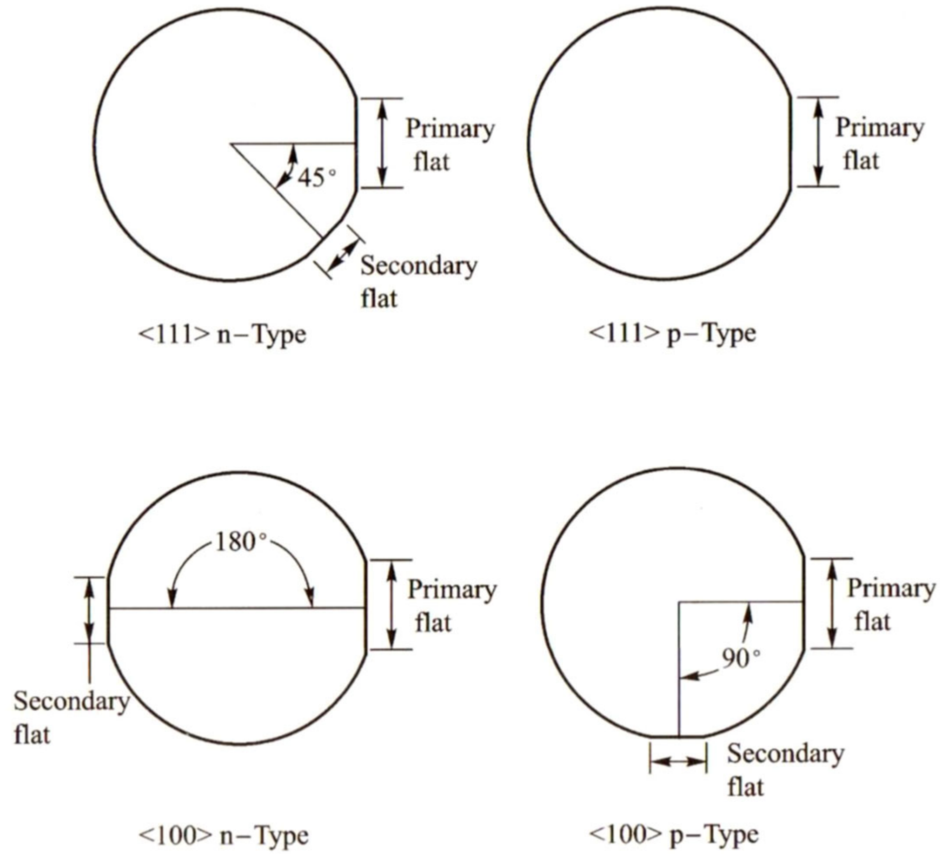
2 Thermally activated, selective reaction at the surface of etchant with the film to be etched gives soluble species

3 Diffusion of by-products through boundary layer away from surface

Wet Bulk Surface Micromachining

<u>Wet etching is mainly isotropic</u>. The anisotropic etching of Si by alkaline (eg KOH) is an exception.

In wet bulk micromachining features are sculptured in bulk materials like Si, SiO2, sapphire, ceramics, SiC, GaAs, InP and Ge by **isotropic** or **anisotropic** wet etchants.



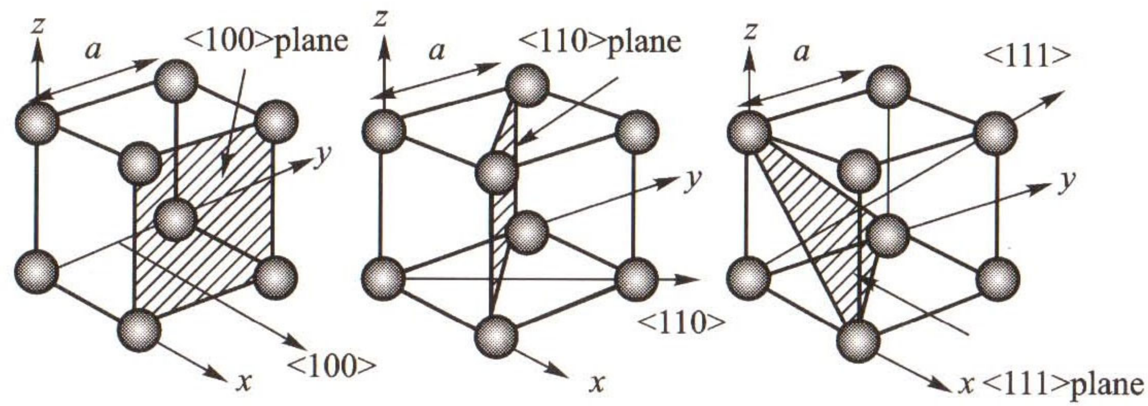
Standard markings can help to align within 0.01 degree!

Good etch masks are Si3N4 (silicon nitride deposited by low pressure- or plasma enhanced Chemical vapour deposition) 40 nm is typically enough. Au and Cr are also acceptable.

Si3N4 has 0.1 nm/min etch rate in KOH ➔
Si has 1 um/min etch rate
Selectivity ?
➔ 10,000

Importance of Orientation

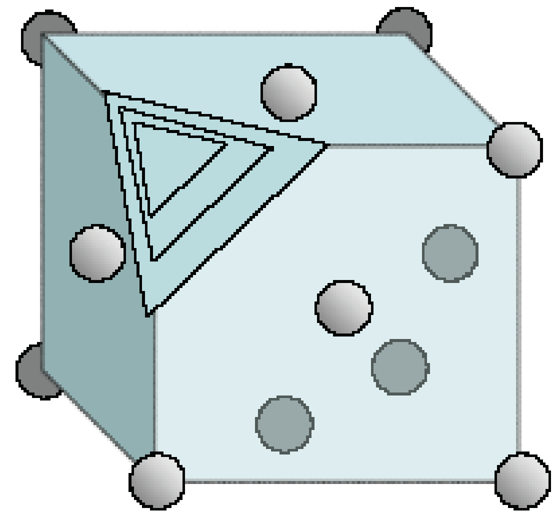
Orientation is important because of different characteristics and etching speeds in different planes and resulting etching angles.



In Si the **etch rate** depends on crystallography

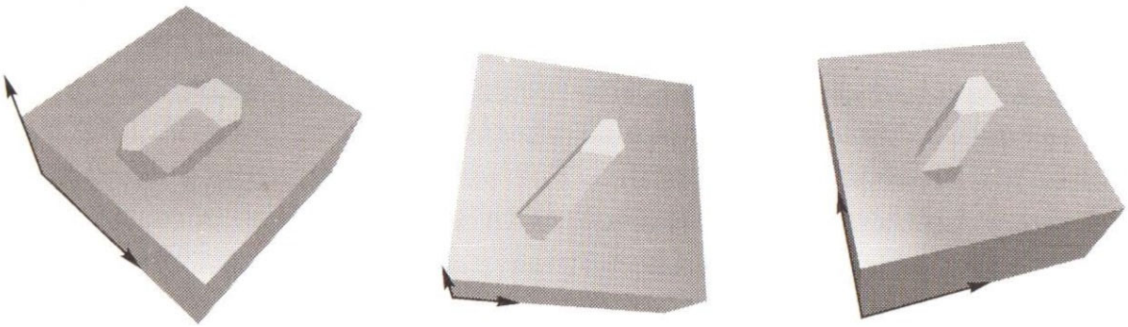
Fastest normal to low-in-plane-bond direction <110> then <100>

Slowest normal to high-in-plane-bond direction <111>



Si planes <100> <110> <111>
High atomic planar density ≡ low etch rate

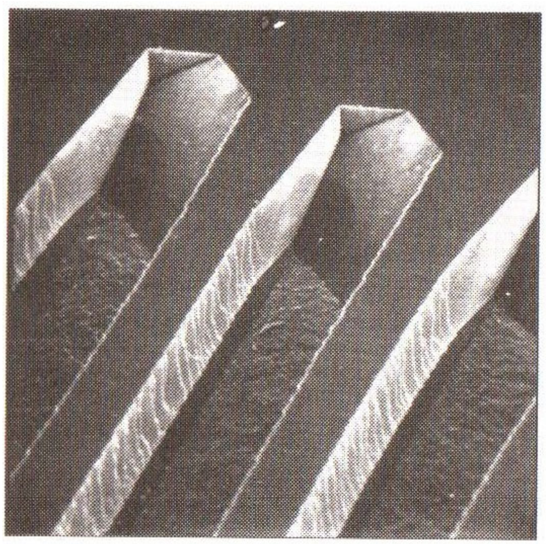
Importance of Orientation



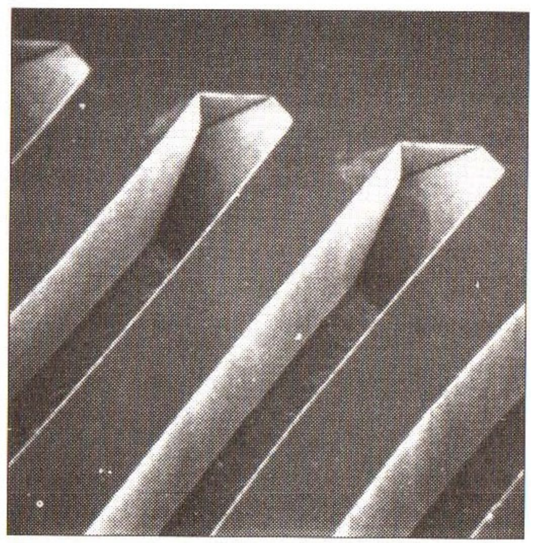
Misaligned Aligned Misaligned

Effect of mask misalignment
with the Si crystal axis

Computer simulations are good to get an idea how to etch and get desired final structures.



Misaligned



Aligned

Experimental results showing misaligned and aligned KOH etching

We need alignment of the etch mask with respect to the crystal planes. Otherwise, we don't follow the etch mask but the crystal planes.

➔ Rough edges

Controlled Etching

- **Si** etches preferentially along preferred crystallographic directions (commonly used in MEMS fabrication)

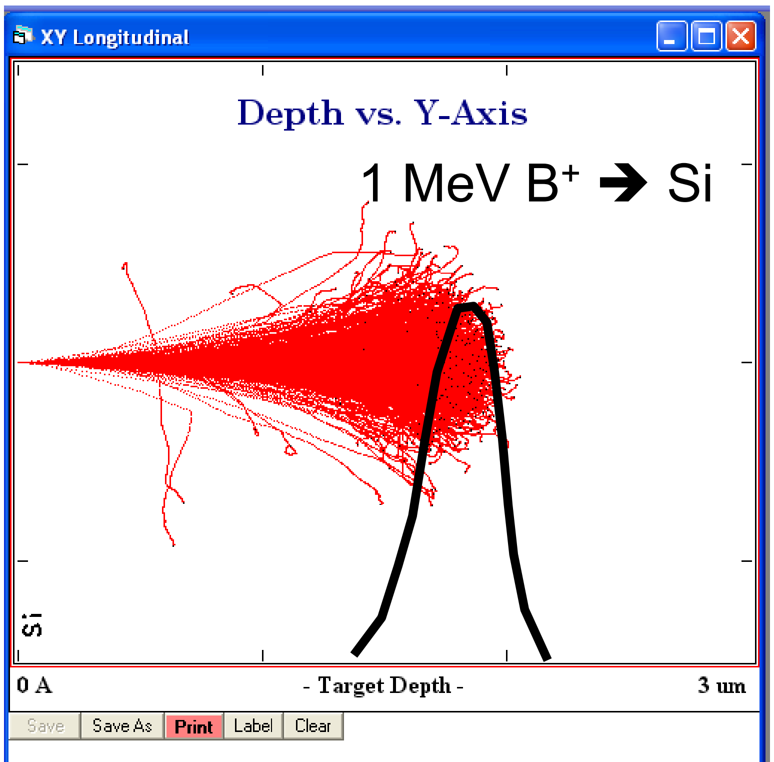
- Si shows a reduction of etch rate in heavily doped p-type regions

•Etch control: Boron typically is incorporated using ion implantation or diffusion for this purpose

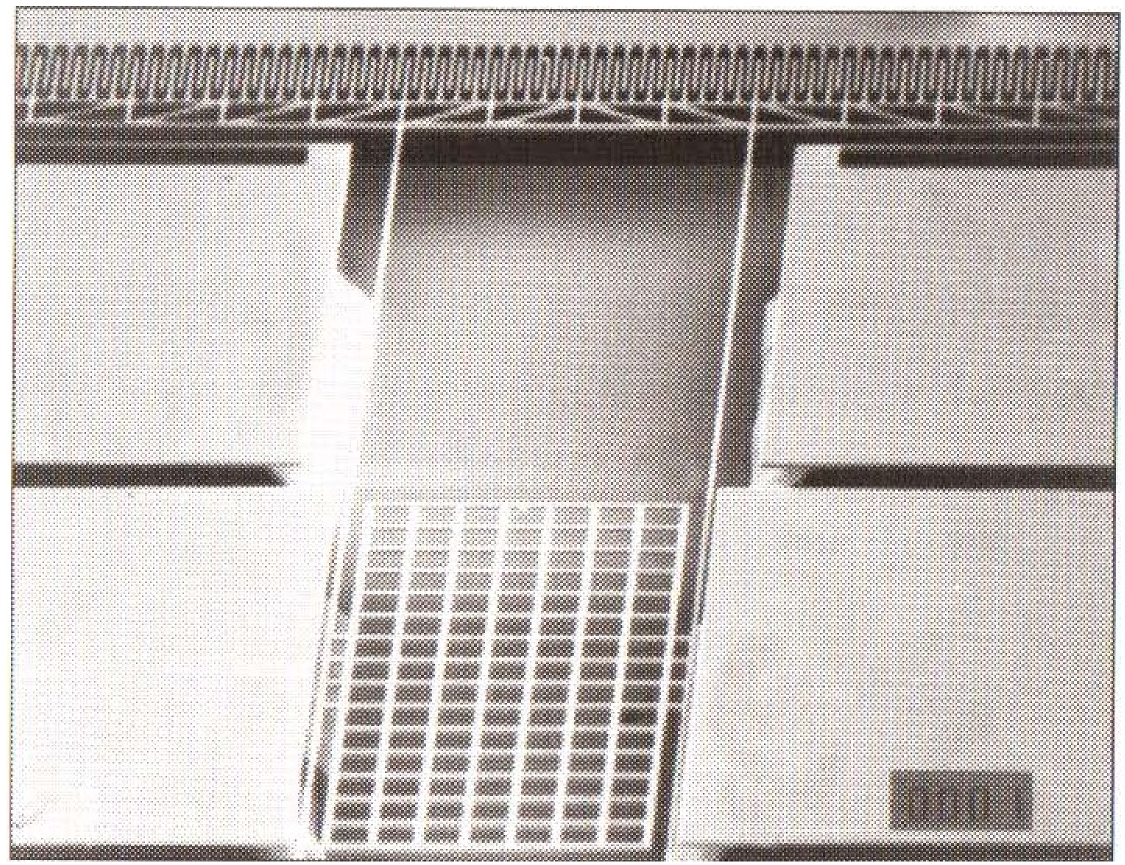
B as etch stop

Si etch rate in EDP (Ethylenediamine Pyrocatechol) depends strongly on B^+ concentration in the Si

➔The Si etch rate will drop 140 times if we have a B concentration of ~$10^{20}/cm^3$ This can be achieved either through implanting or diffusion of B^+ in Si



ION STATS	Range	Straggle
Longitudinal	1.74 um	1573 A
Lateral Proj.	1660 A	2138 A
Radial	2691 A	1532 A



Electrostatic micro-actuator. Here the Si is under etched using EDP. The Si was im-planted with B+ to form an etch stop layer

Importance of Orientation

Ion = Beryllium [4] , Mass = 9.012 amu

Target Density = 2.3212E+00 g/cm3 = 4.9770E+22 atoms/cm3

======= Target Composition ========

Atom Name	Atom Numb	Atomic Percent	Mass Percent
Si	14	100.00	100.00

====================================

Bragg Correction = 0.00%
Stopping Units = MeV / (mg/cm2)
See bottom of Table for other Stopping units

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
100.00 keV	9.099E-01	7.489E-02	4668 A	1334 A	1298 A
110.00 keV	9.558E-01	7.043E-02	5046 A	1384 A	1365 A
120.00 keV	1.000E+00	6.654E-02	5413 A	1429 A	1426 A
130.00 keV	1.043E+00	6.311E-02	5770 A	1469 A	1483 A
140.00 keV	1.085E+00	6.006E-02	6116 A	1507 A	1537 A
150.00 keV	1.127E+00	5.732E-02	6453 A	1541 A	1587 A
160.00 keV	1.167E+00	5.486E-02	6781 A	1572 A	1633 A
170.00 keV	1.207E+00	5.262E-02	7101 A	1601 A	1678 A
180.00 keV	1.246E+00	5.058E-02	7412 A	1628 A	1719 A
200.00 keV	1.323E+00	4.700E-02	8014 A	1677 A	1796 A
225.00 keV	1.415E+00	4.324E-02	8727 A	1730 A	1881 A
250.00 keV	1.504E+00	4.011E-02	9404 A	1775 A	1957 A
275.00 keV	1.590E+00	3.744E-02	1.00 um	1815 A	2025 A
300.00 keV	1.673E+00	3.514E-02	1.07 um	1849 A	2086 A
325.00 keV	1.752E+00	3.313E-02	1.13 um	1880 A	2141 A
350.00 keV	1.829E+00	3.137E-02	1.18 um	1907 A	2191 A
375.00 keV	1.902E+00	2.980E-02	1.24 um	1932 A	2238 A
400.00 keV	1.973E+00	2.840E-02	1.29 um	1954 A	2281 A
450.00 keV	2.104E+00	2.599E-02	1.39 um	1995 A	2357 A
500.00 keV	2.225E+00	2.399E-02	1.49 um	2030 A	2424 A
550.00 keV	2.335E+00	2.230E-02	1.58 um	2061 A	2484 A
600.00 keV	2.435E+00	2.086E-02	1.67 um	2087 A	2537 A
650.00 keV	2.525E+00	1.961E-02	1.75 um	2111 A	2586 A
700.00 keV	2.607E+00	1.851E-02	1.83 um	2132 A	2630 A
800.00 keV	2.749E+00	1.667E-02	1.99 um	2175 A	2709 A
900.00 keV	2.864E+00	1.519E-02	2.14 um	2212 A	2777 A
1.00 MeV	2.956E+00	1.398E-02	2.28 um	2245 A	2839 A

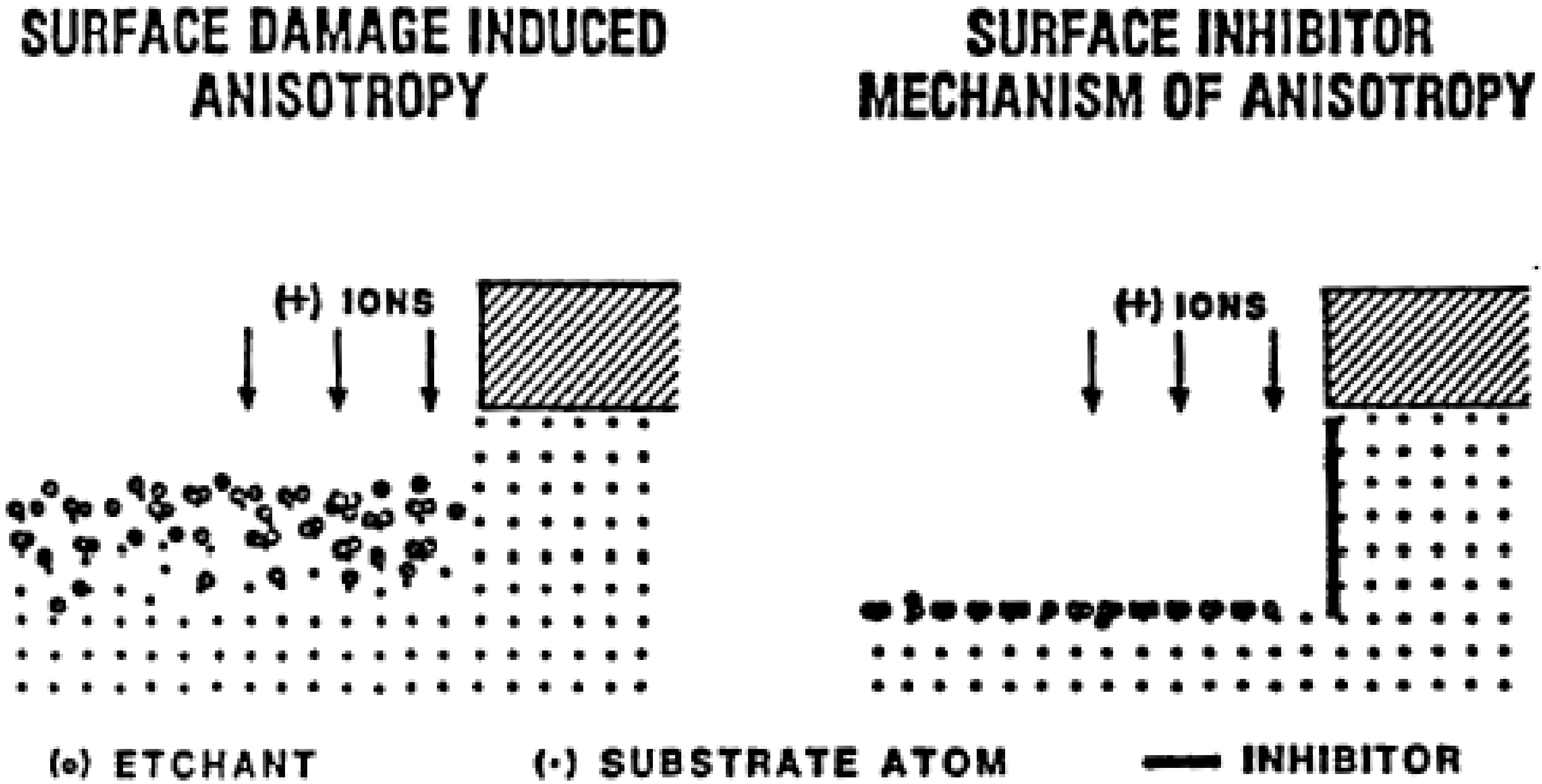
Multiply Stopping by	for Stopping Units
2.3211E+01	eV / Angstrom

Mainly electronic stopping since B is a low Z element

Bosch Process or DRIE

How to Control Anisotropy ?

1) ionic bombardment to damage expose surface.
2) sidewall coating by inhibitor prevents sidewall etching.

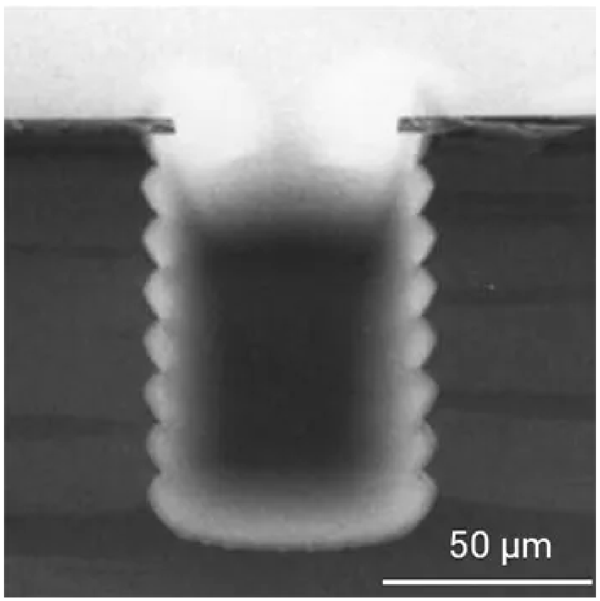


Bosch Process or DRIE

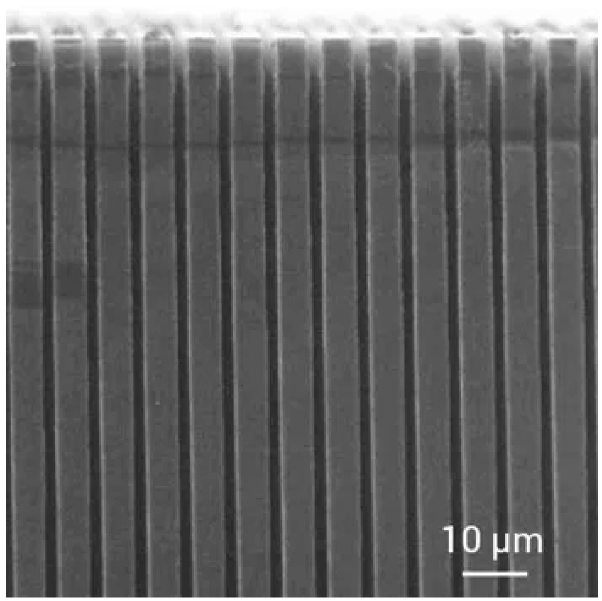
Silicon Deep Reactive Ion Etching (DRIE) for Etching Si and SiO_2

The Bosch process is a deep silicon etch which was developed and patented by Robert Bosch GmbH.

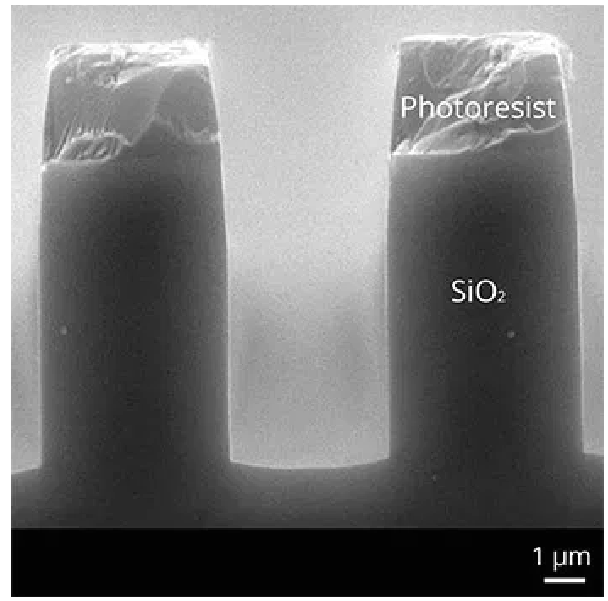
- Two step plasma process which **alternates between deposition** and etching
- The result is an anisotropic etch that can have a vertical sidewall regardless of the orientation of the silicon crystal.



High-rate Si deep etching
Etch Rate : 55 μm/min
Pattern Width : 50 μm



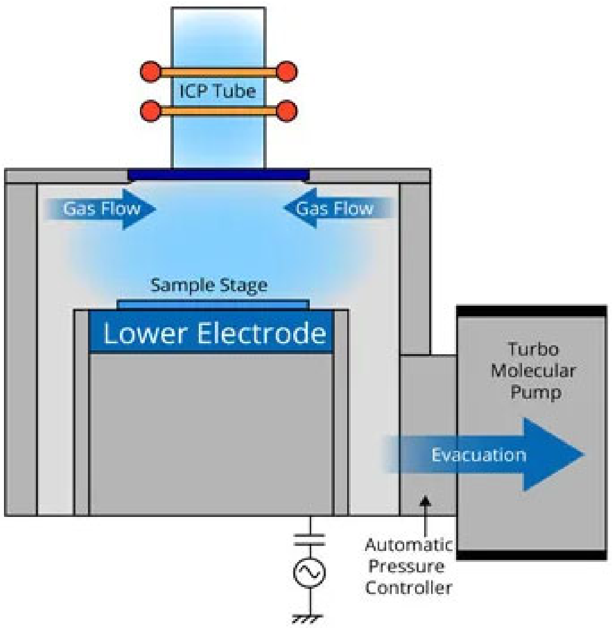
Si etching with high aspect ratio
Aspect Ratio : 40
Pattern Width : 2.5 μm
Etch Depth : 100 μm
Scallop Size : less than 100 nm



Anisotropic SiO_2 etching
4 μm width L/S pattern
Etch Depth : 6.5 μm
Etch Rate : 325 nm/min

Bosch Process or DRIE

High-density ICP plasma source

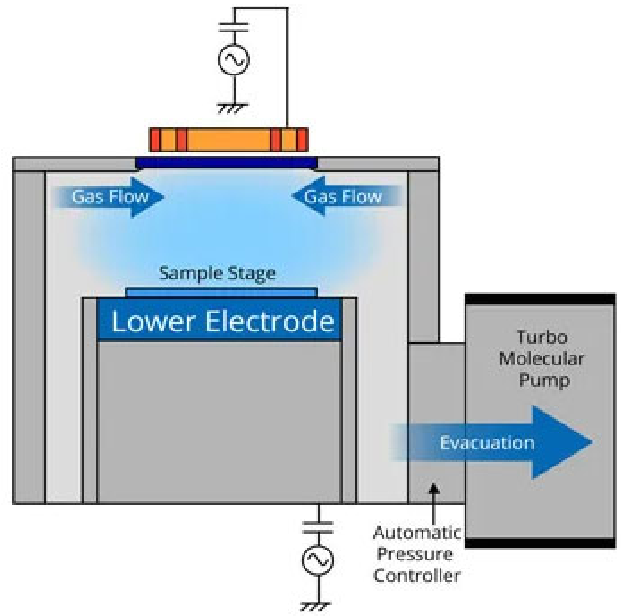


High power ICP source generates a repeatable high density plasma and enables high-rate Si etching of max. 55 µm/min .

High-speed Gas Switching

Fast gas switching (~ 0.1 sec) allows smooth sidewalls with less scallops.

Optional SiO_2 Etch Kit

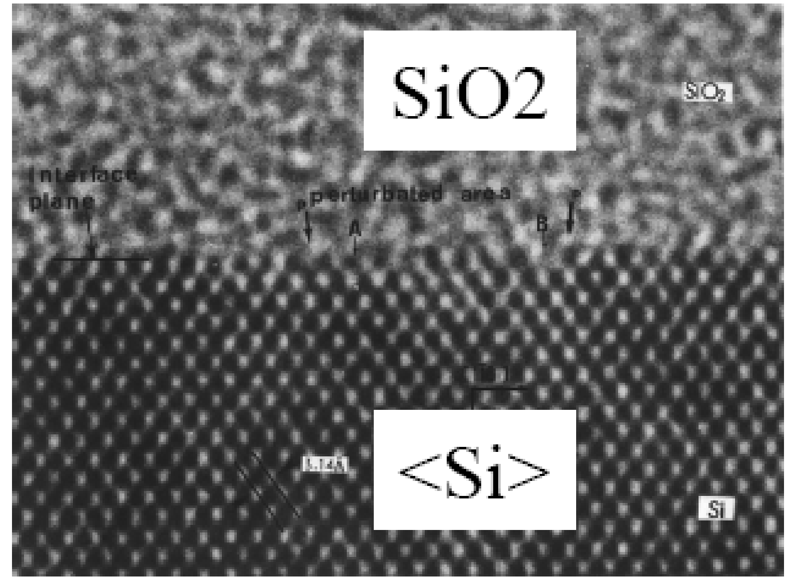


Optional ICP coil enables high-speed SiO_2 etching.

Process consist of the cyclic isotropic etching; Inductively Coupled Plasma (ICP) and fluorocarbon-based protection film deposition by quick gas switching

Properties of SiO_2

Thermal SiO_2 is **amorphous**.
Weight Density = 2.20 gm/cm^3
Molecular Density = 2.3E22 molecules/cm^3



Crystalline SiO_2 [Quartz] = 2.65 gm/cm^3

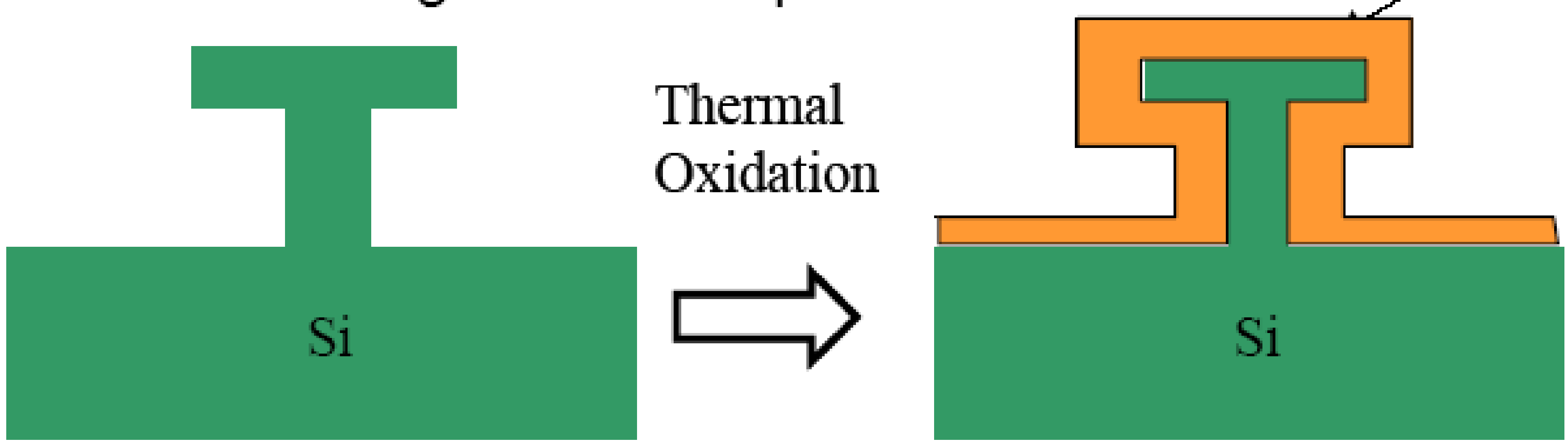
(1) Excellent Electrical Insulator
Resistivity > 1E20 ohm-cm   Energy Gap ~ 9 eV

(2) High Breakdown Electric Field
> 10MV/cm

(3) Stable and Reproducible Si/SiO_2 Interface

Properties of SiO_2 (cont'd)

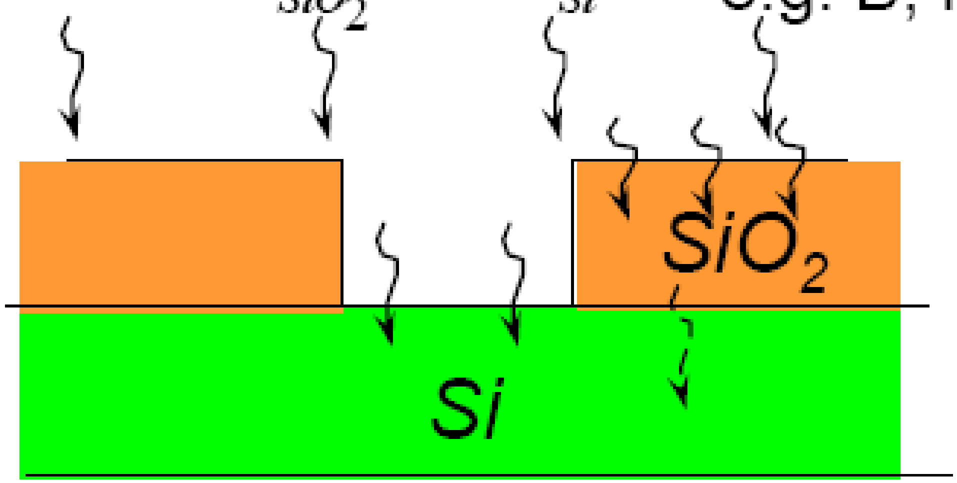
(4) Conformal oxide growth on exposed Si surface



(5) SiO_2 is a good diffusion mask for common dopants

$$D_{SiO_2} \ll D_{Si}$$

e.g. B, P, As, Sb.



*exceptions are Ga (a p-type dopant) and some metals, e.g. Cu, Au

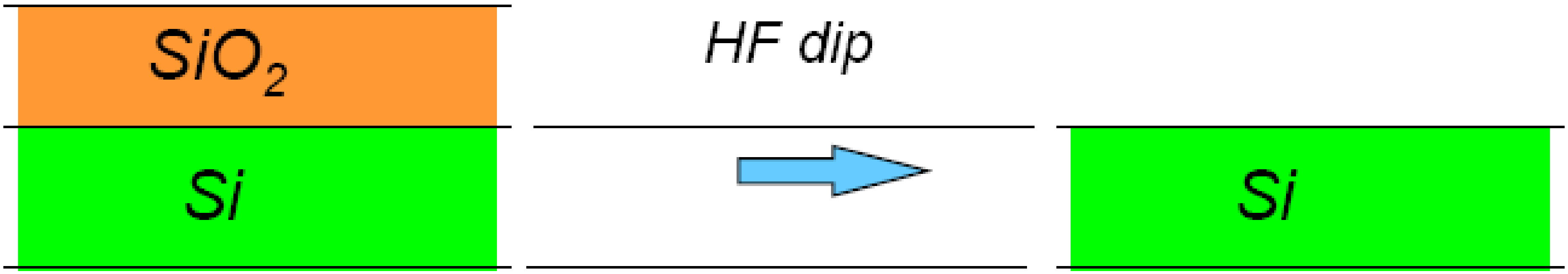
Thermal Oxidation Equipment

Horizontal Furnace

Vertical Furnace

Properties of SiO_2

SiO_2 has very good etching selectivity compared to Si



SiO_2 also called oxide is a popular material in IC industry

Controlled Etching

<u>Anisotropic etchants</u>

- Potassium hydroxide (**KOH**) Etches Si,
- Ethylene diaminepyrochatechol (**EDP**)
- Tetramethyl ammonium hydroxide (**TMAH**)

- Etch **<u>silicon</u>** preferentially along preferred crystallographic directions (commonly used in MEMS fabrication)

- Shows a reduction of etch rate in heavily doped p-type regions

- Etch control: Boron typically is incorporated using ion implantation or diffusion for this purpose

Applications of SiO_2

Sacrificial layer
➔ Movable structures
➔ Fluidics lab on a chip

Pyrex glass has expansion coefficient close to Si and can be bonded nicely to form closed fluidic channels. Structure with photo resist (thin layers) Au or Cr for deeper etched structures, etchant buffered HF (9% of HCl) can improve smoothness.

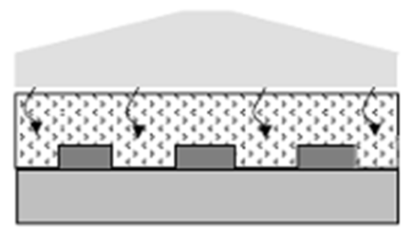
SiO_2 is removed using wet isotropic etching. ➔ HF (49%) has an etch rate of 1.8um/min

There are different forms of Nano imprint lithography (NIL)

I Soft Lithography
or
μ-contact printing

Inking and Au coating

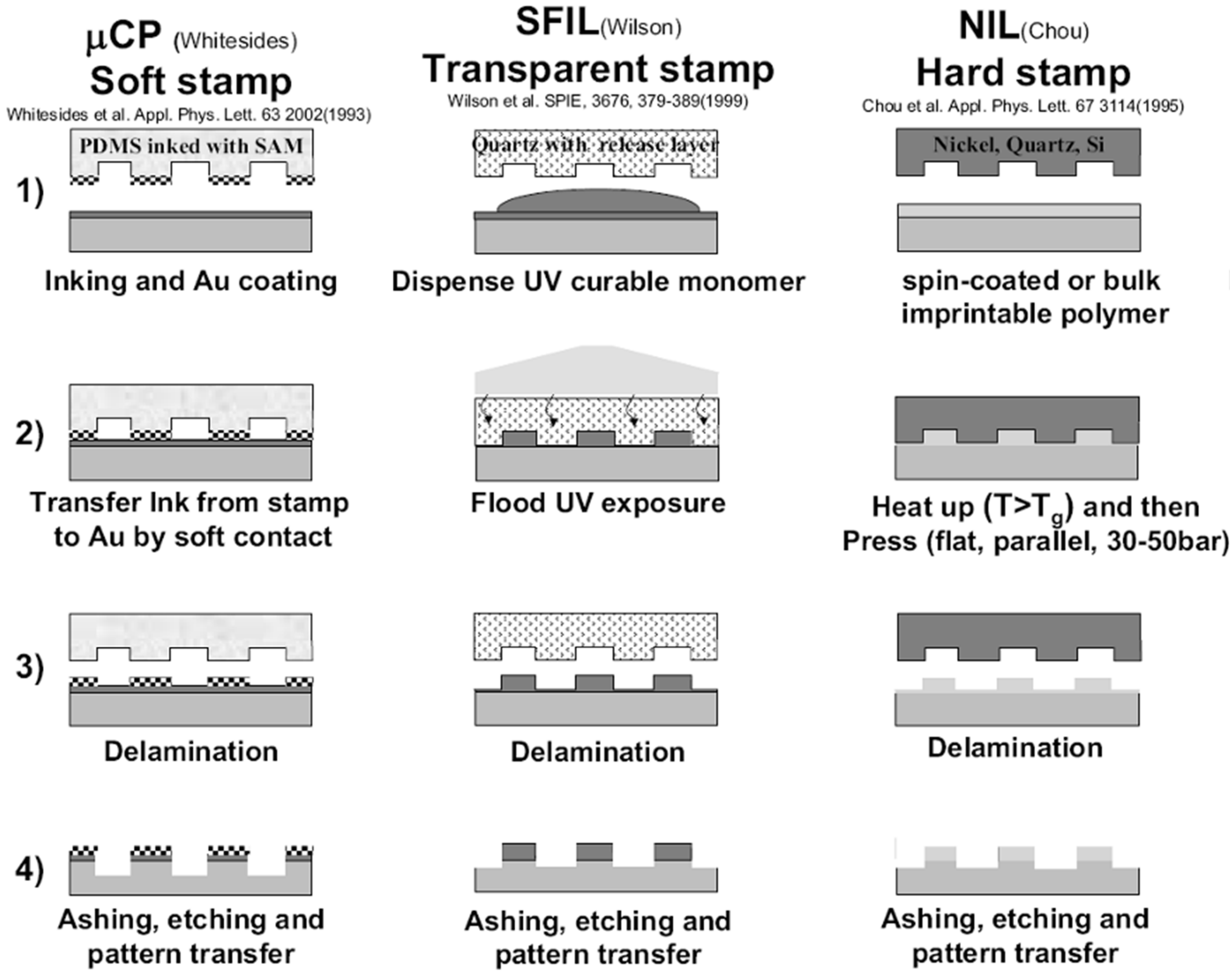
II SFIL Step and Flash nanoimprint lithography



Flood UV exposure

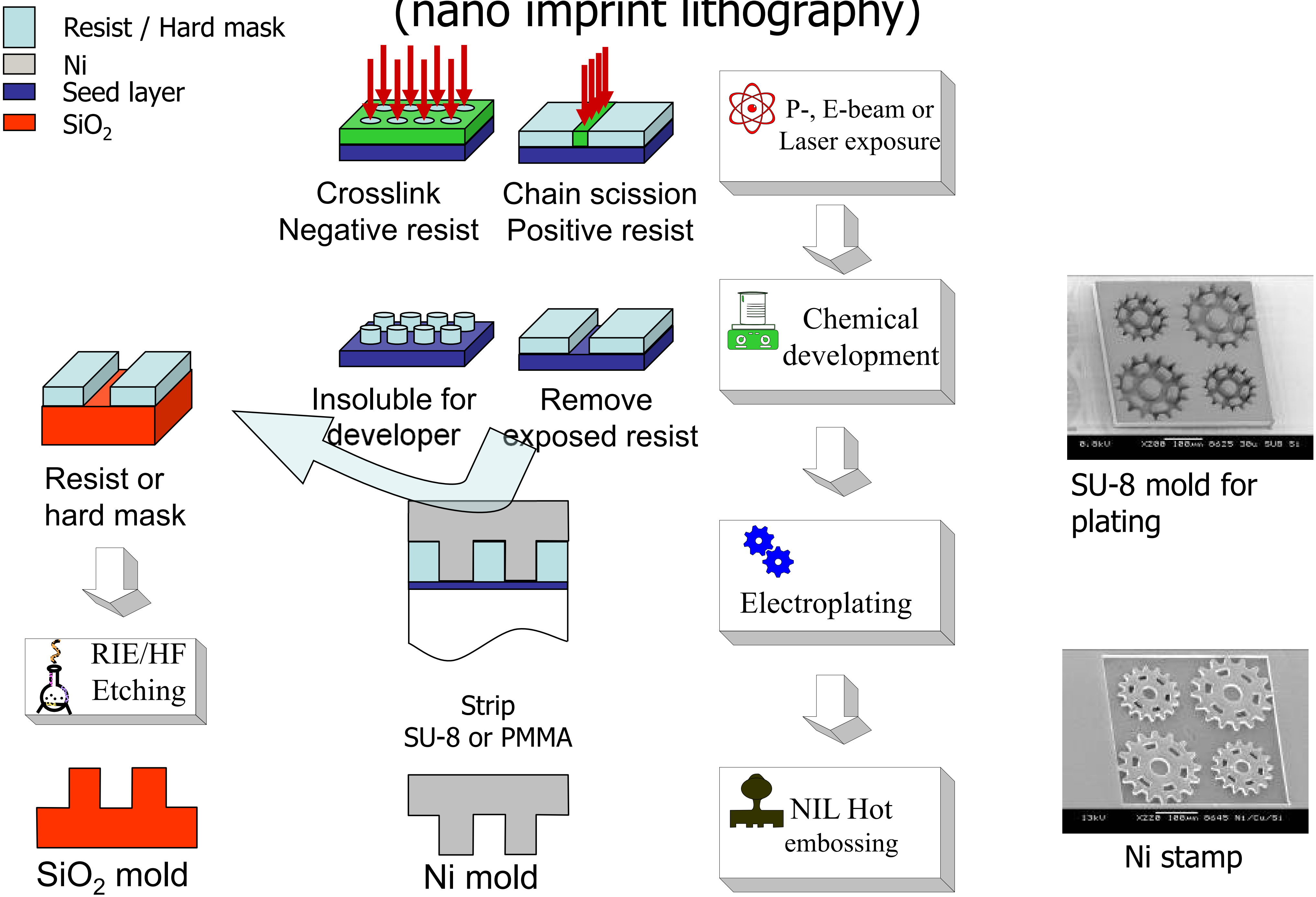
III NIL (some people call this Hot embossing)

Heat up ($T>T_g$) and then Press (flat, parallel, 30-50bar)


μCP (Whitesides)
Soft stamp
Whitesides et al. Appl. Phys. Lett. 63 2002(1993)
SFIL(Wilson)
Transparent stamp
Wilson et al. SPIE, 3676, 379-389(1999)
NIL(Chou)
Hard stamp
Chou et al. Appl. Phys. Lett. 67 3114(1995)
PDMS inked with SAM
Quartz with release layer
Nickel, Quartz, Si
1)
Inking and Au coating
Dispense UV curable monomer
spin-coated or bulk imprintable polymer
2)
Transfer Ink from stamp to Au by soft contact
Flood UV exposure
Heat up ($T>T_g$) and then Press (flat, parallel, 30-50bar)
3)
Delamination
Delamination
Delamination
4)
Ashing, etching and pattern transfer
Ashing, etching and pattern transfer
Ashing, etching and pattern transfer

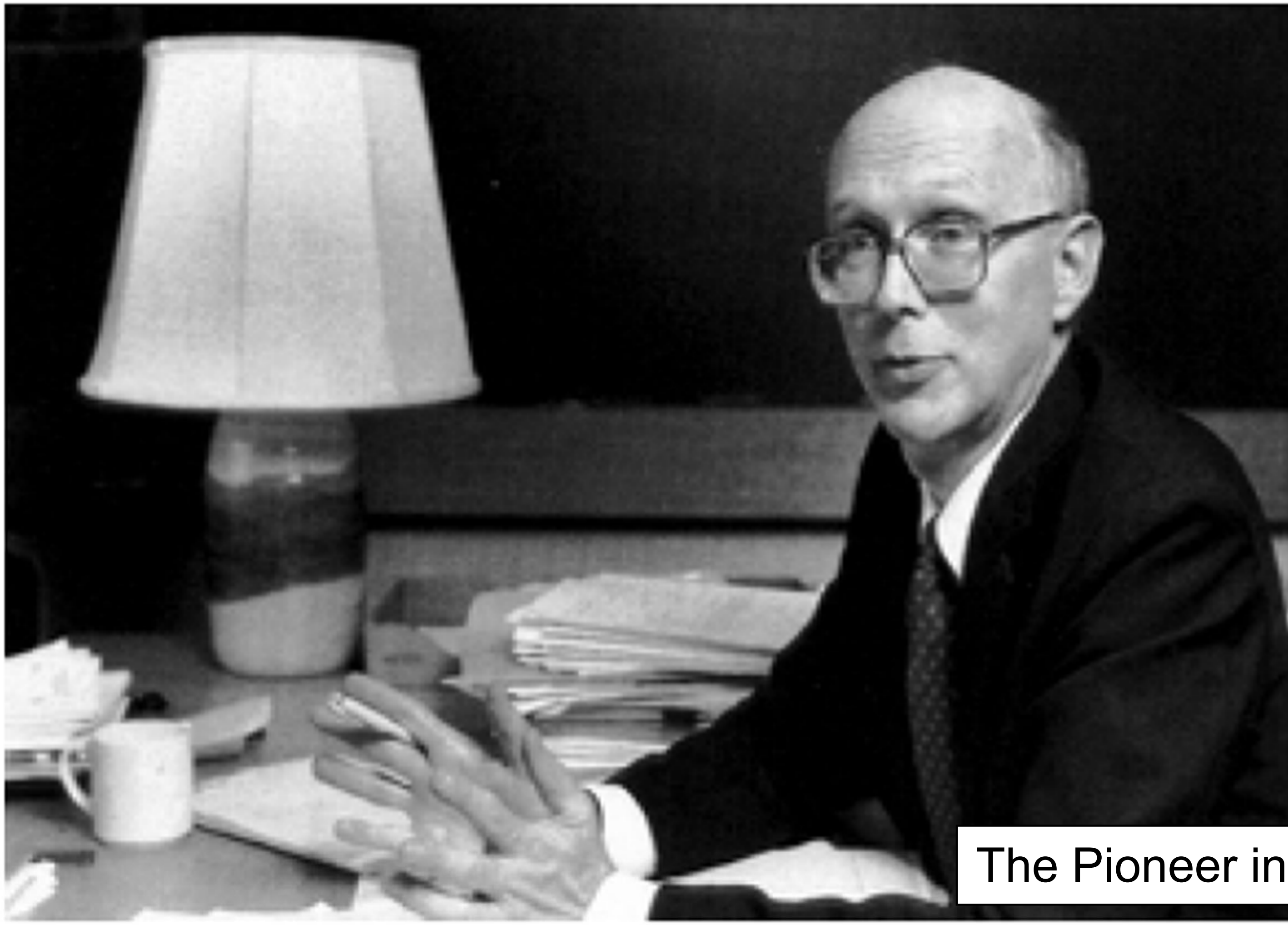
Stamp fabrication for NIL

(nano imprint lithography)



Soft Lithography µ-contact printing

PDMS fabrication for Soft lithography

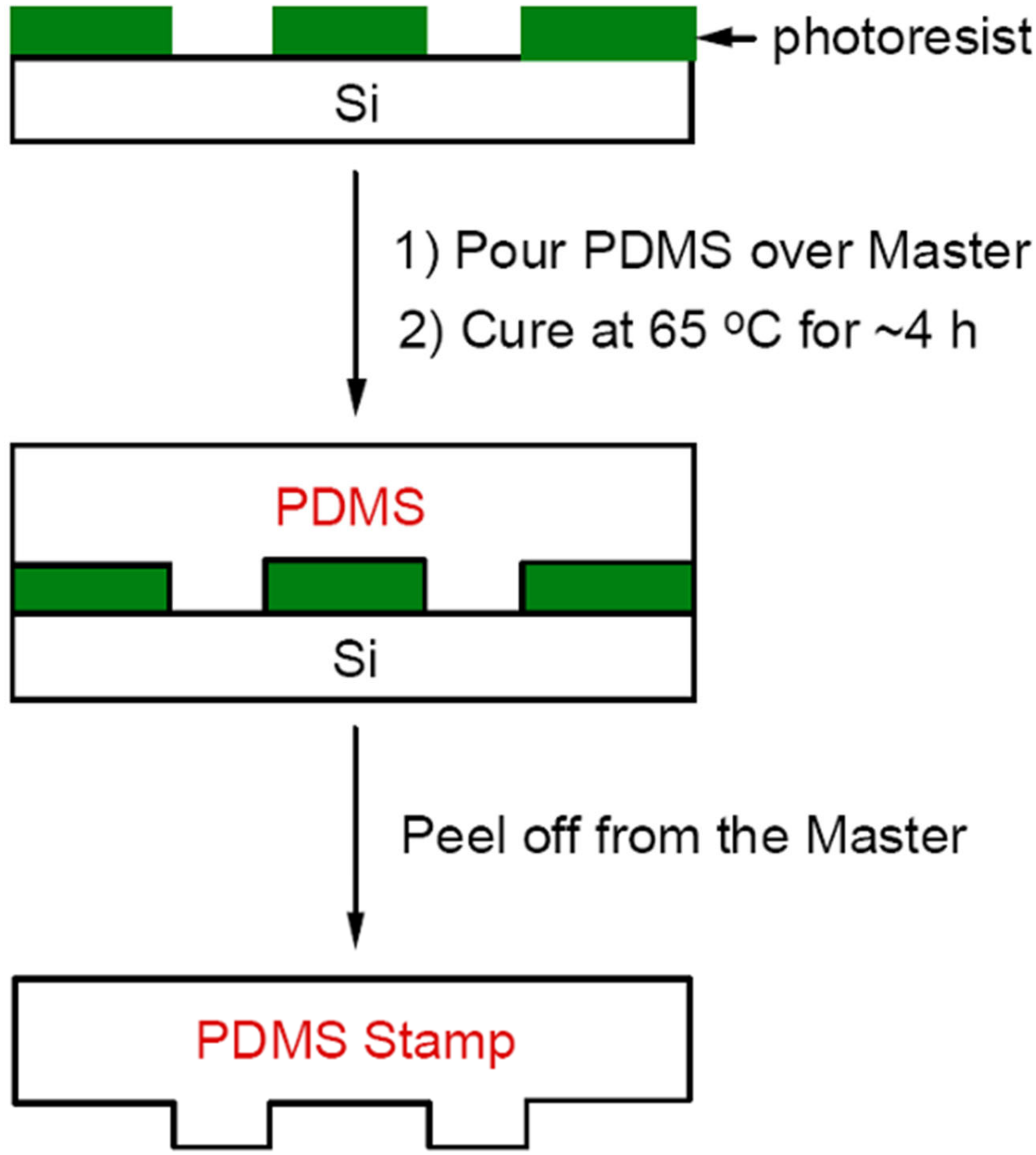


The Pioneer in Soft Lithography

George M. Whitesides Group
Harvard University

Soft Lithography μ-contact printing

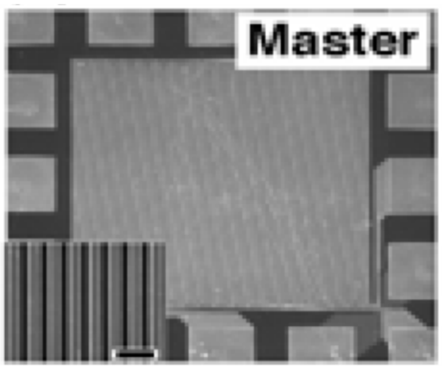
PDMS Fabrication

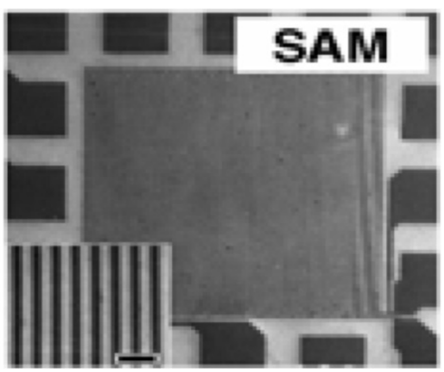


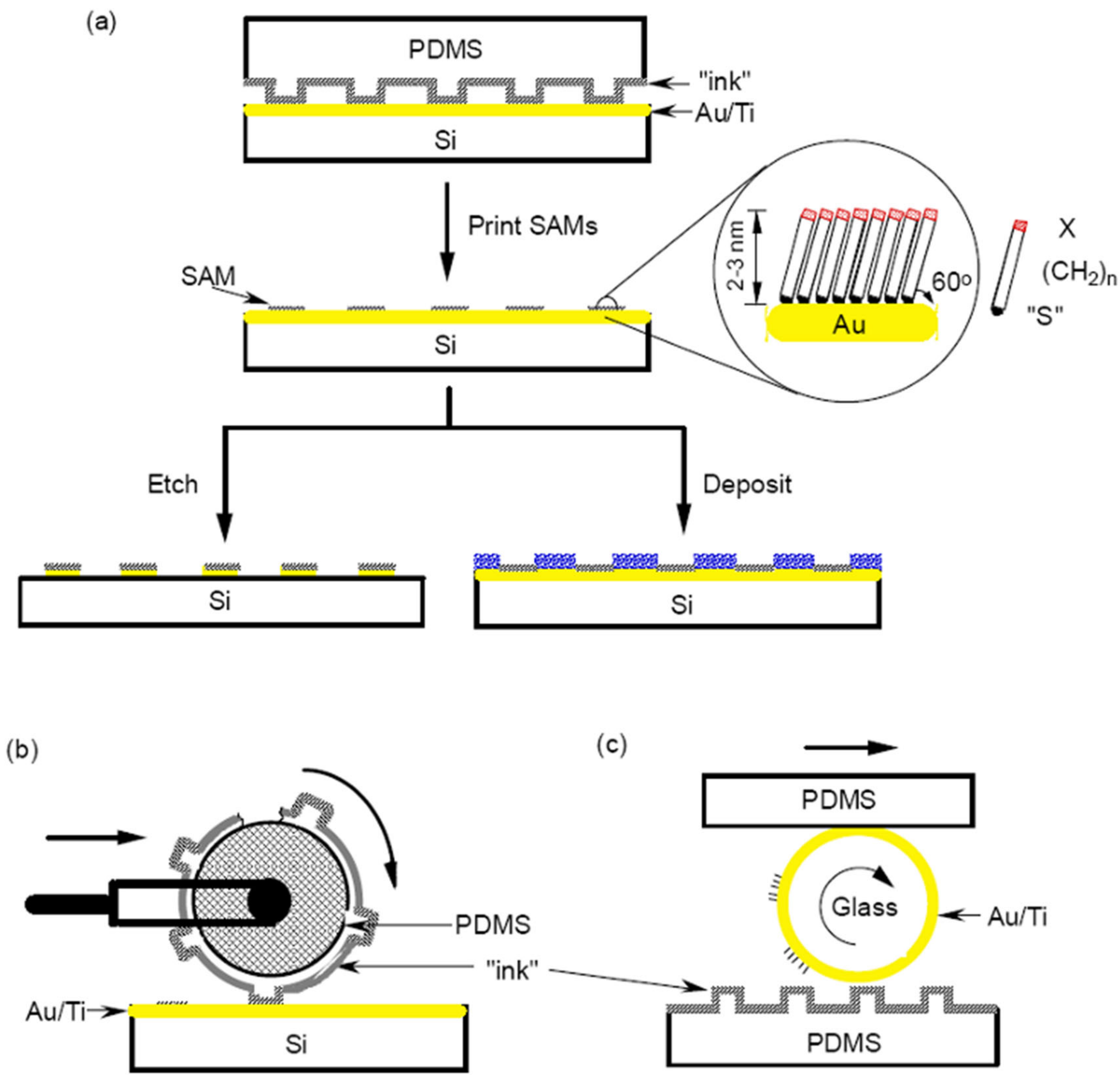
(PDMS: Polydimethylsiloxane)

Soft Lithography μ-contact printing

Micro contact Printing



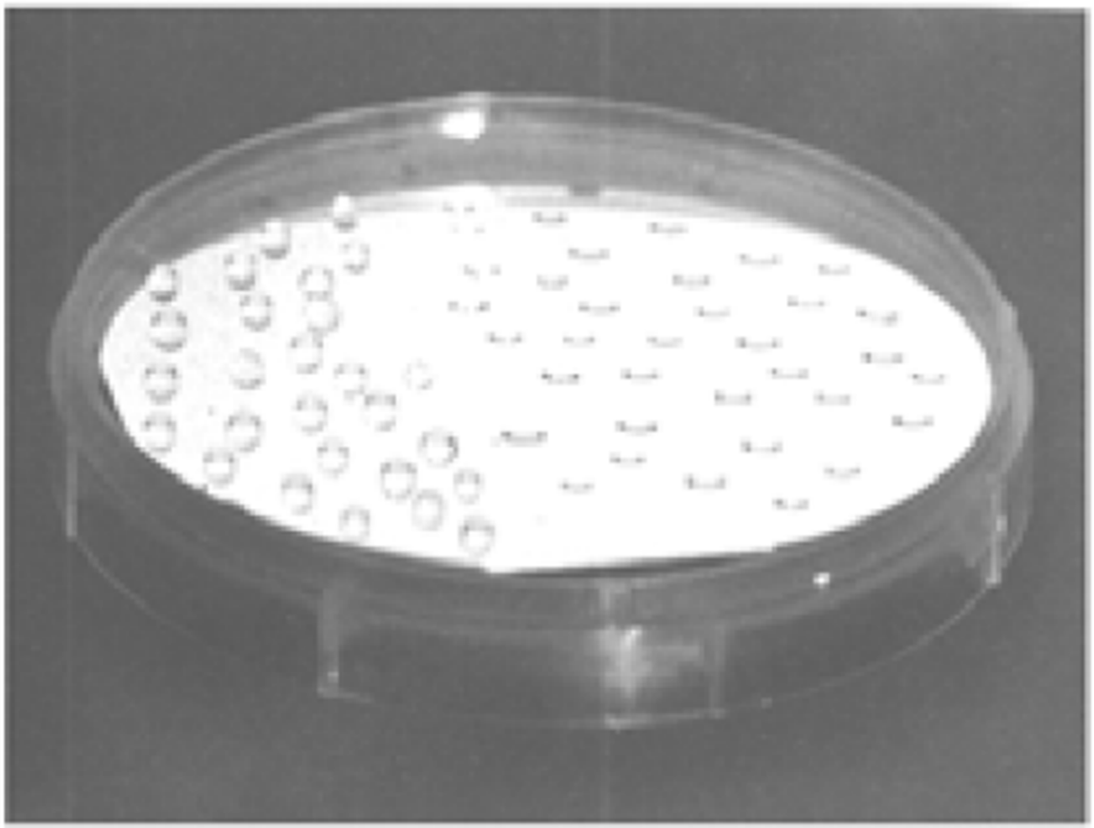


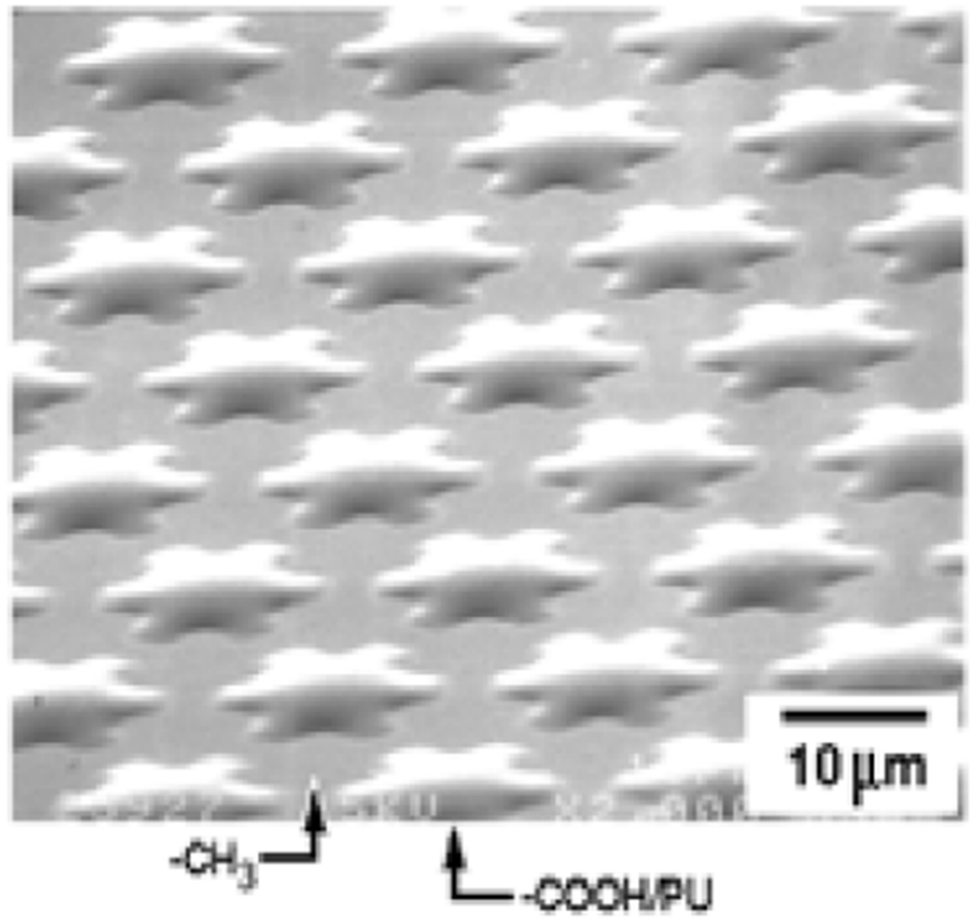


Soft Lithography μ-contact printing

Wetting Dewetting

Hydrophilic / Hydrophobic coating





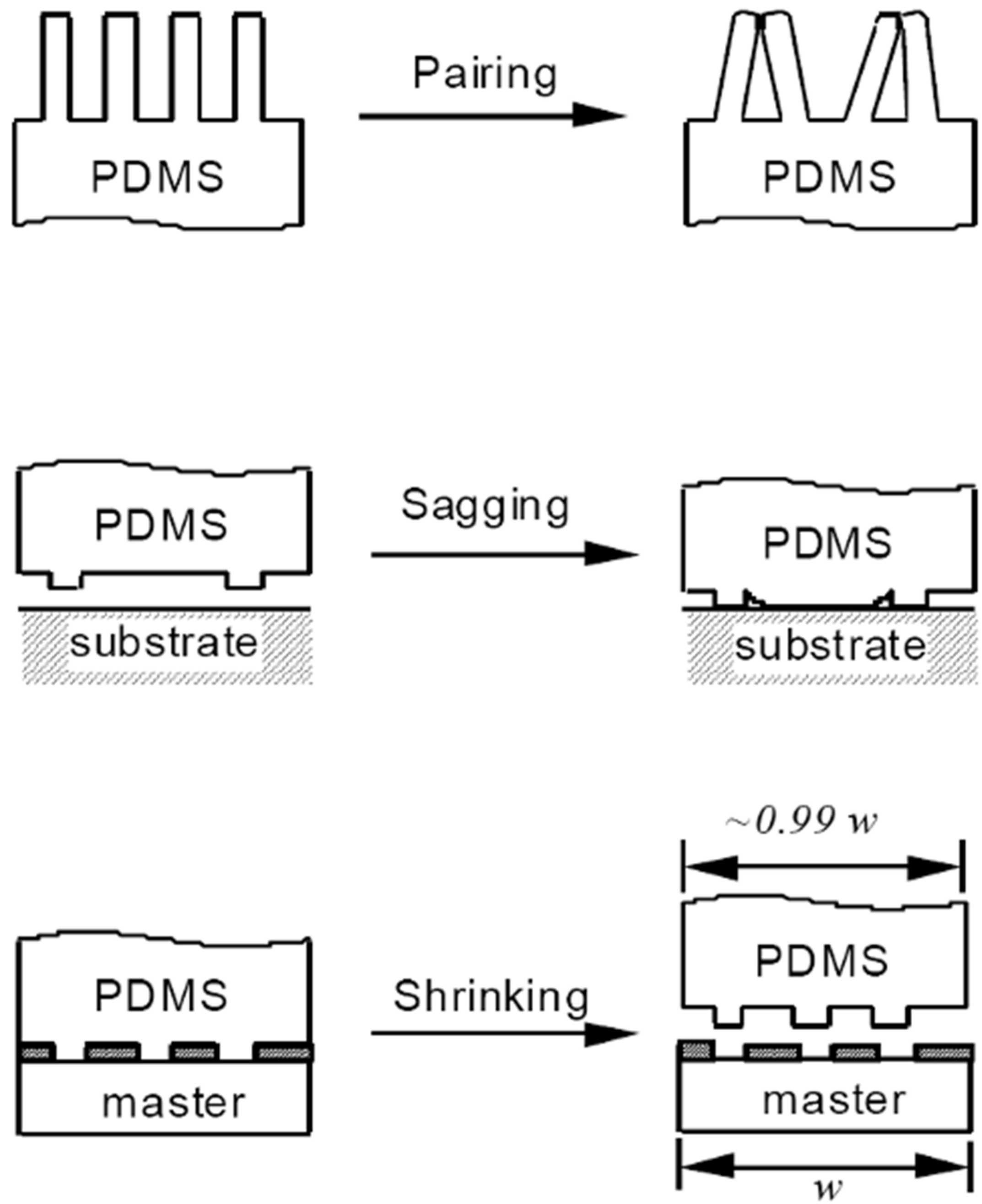
Soft Lithography μ-contact printing

Considerations

Limit the Aspect ratio to 3!

1/3 > Height / Width <3

Multi layer printing is possible



Soft Lithography µ-contact printing

Large area Printing