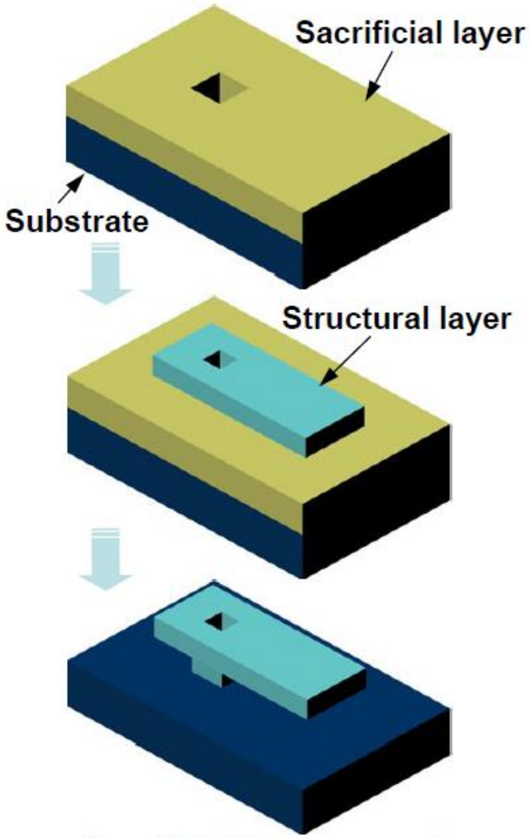
Lecture#7:

Etching (1)

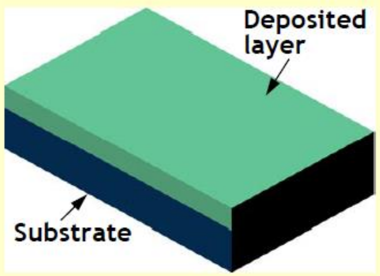
:Bulk Micromachining

Reminder: General Step

Etching (1): Bulk Micromachining

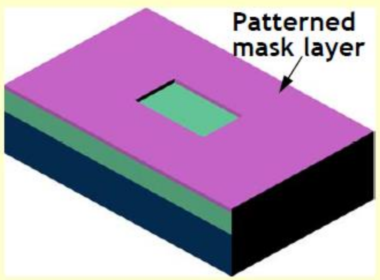


Deposition



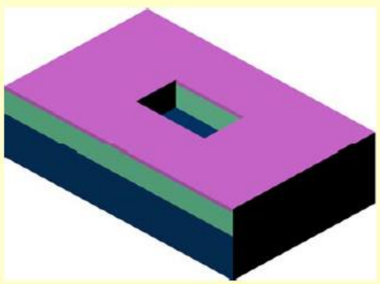
- CVD
- Coating
- Sputtering
- Evaporation
- Bonding
- Plating

Patterning



- UV lithography
  - Stepper
  - Contact aligner (Double side)
- E-beam lithography
- X-ray lithography

Etching



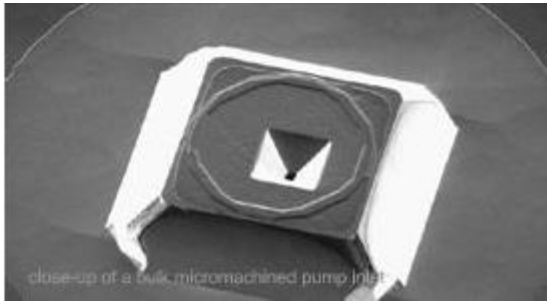
- Dry etching
  - Anisotropic
  - Isotropic
- Wet etching
  - Anisotropic
  - Isotropic

Etching (1): Bulk Micromachining

- **Bulk micromachining**

; Bulk micromachining was developed in the late 70's essentially for the fabrication pressure sensor membranes from a silicon monocrystal.

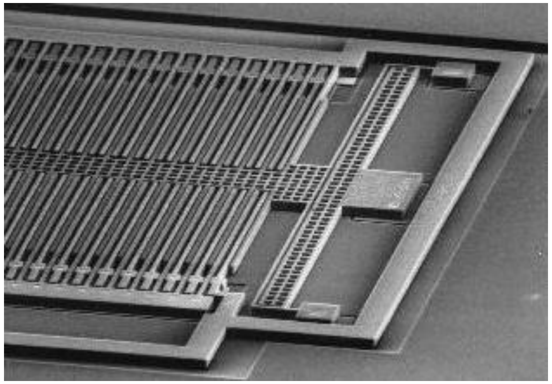
; It is nowadays commonly used to fabricate a variety of mechanical structures (e.g. membranes, valves, and cantilevers) and fluid handling devices (e.g. channels, cavities)



- **Surface micromachining**

; Surface micromachining uses several deposition, lithography, and etching processes to build up mechanical features, layer by layer, on a wafer surface.

; It usually requires the use of a sacrificial layer to form cavities or free-standing and moving structures.



Micromachining (2)

Etching (1): Bulk Micromachining

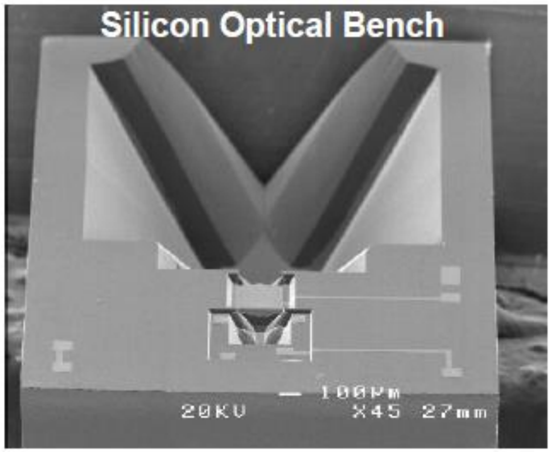
- **Summary: micromachining**

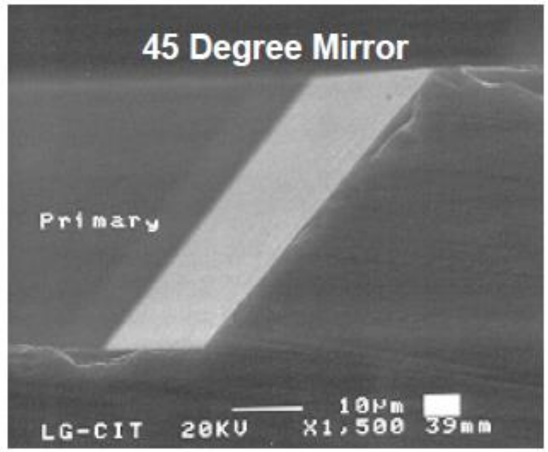
	Bulk-micromachining	Surface-micromachining
Birth	1960's	1980's
Structure (Material)	Single crystal silicon wafer	Thin film on wafer
Etching	Wet/Dry etching	Wet/Dry etching
Etch control	Crystal orientation, Diffusion layer	Material selectivity

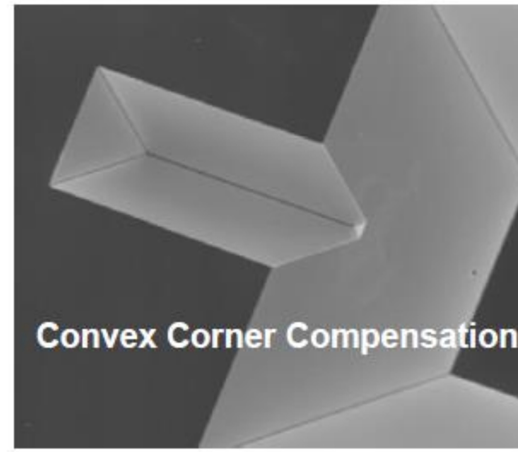
Bulk Micromachining (1)

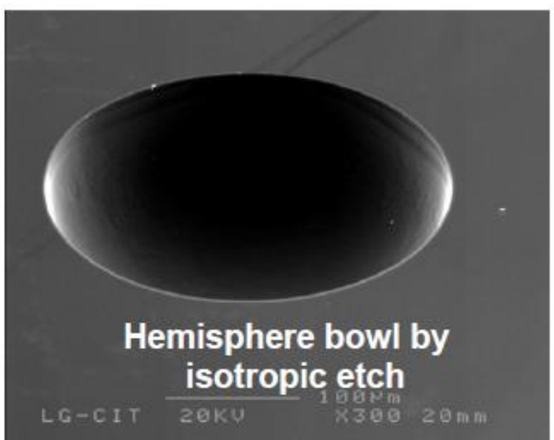
Etching (1): Bulk Micromachining

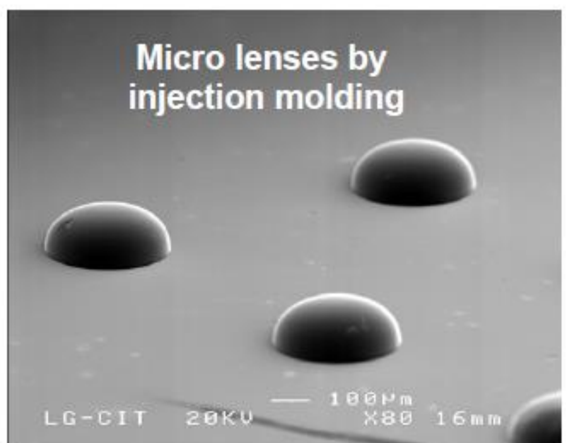
- **Applications**

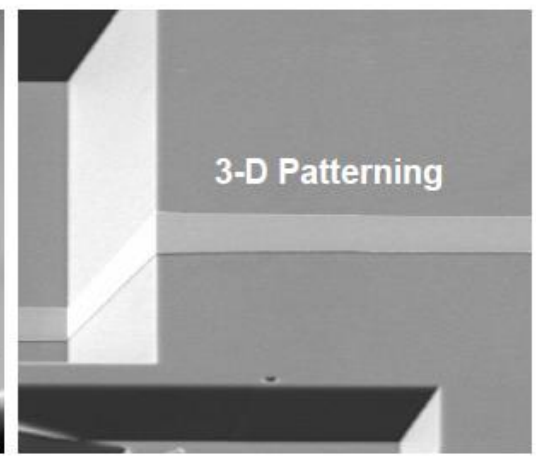








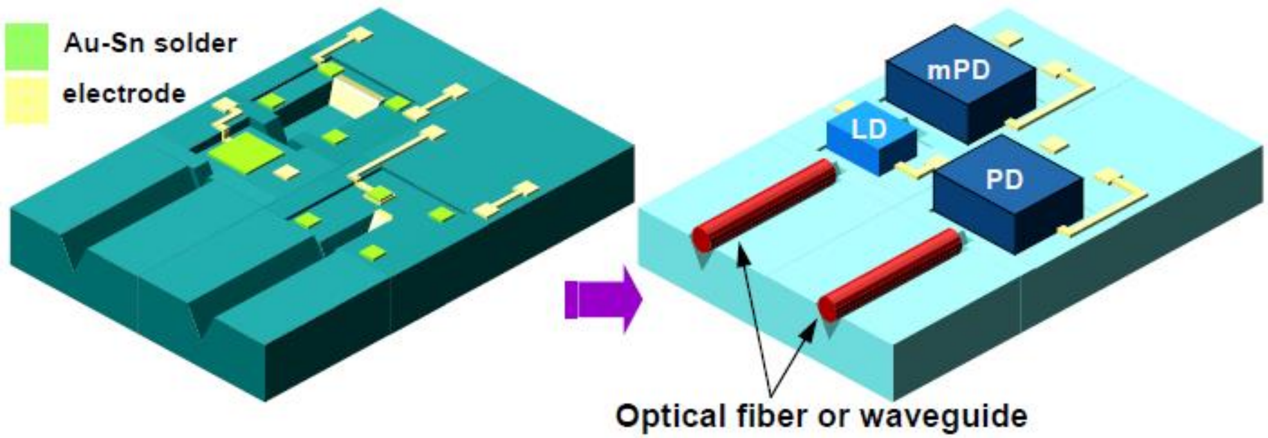


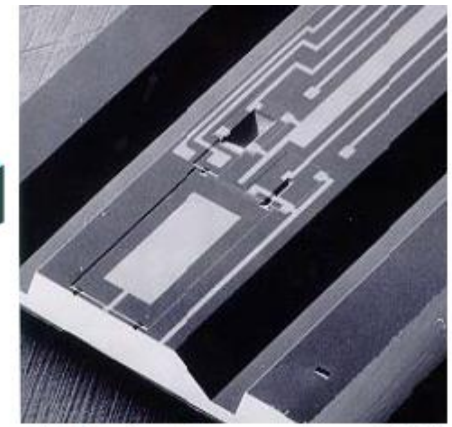


Bulk Micromachining (2)

Etching (1): Bulk Micromachining

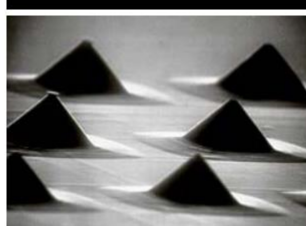
- SiOB for transceiver

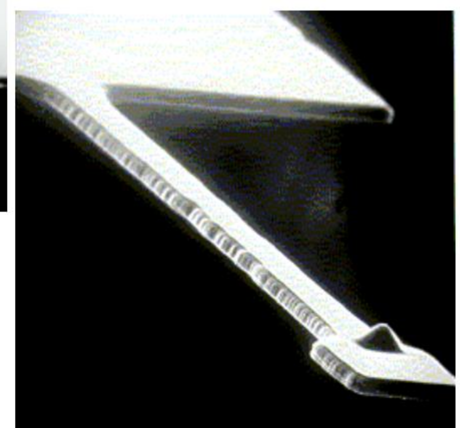




SiOB for Transceiver (LG)

- AFM probe tip

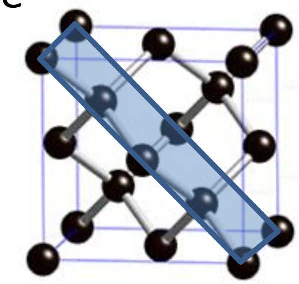


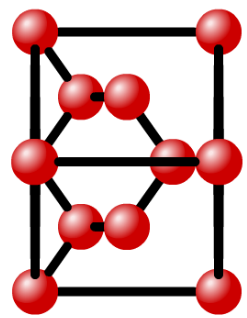


Reminder: Silicon Crystallography

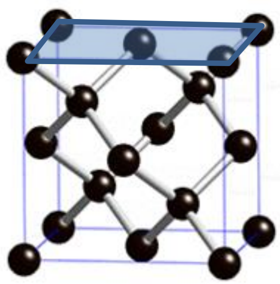
Etching (1): Bulk Micromachining

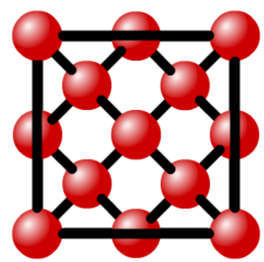
(110) plane



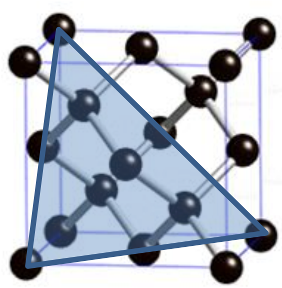


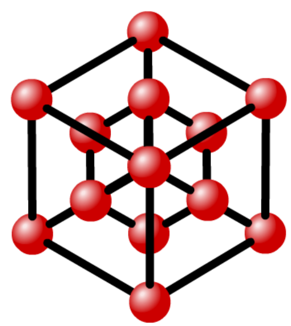
(100) plane





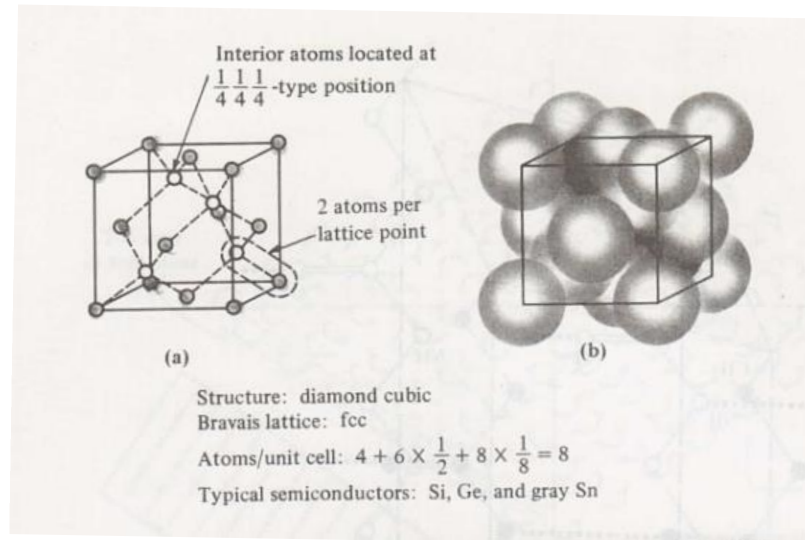
(111) plane





- **Silicon wafer**

Single crystal → Surface density difference



(100) → $6.8 \times 10^{14}/cm^2$
(110) → $9.6 \times 10^{14}/cm^2$
(111) → $11.8 \times 10^{14}/cm^2$

http://www.dawgsdk.org/crystal/en/library/diamond#0001

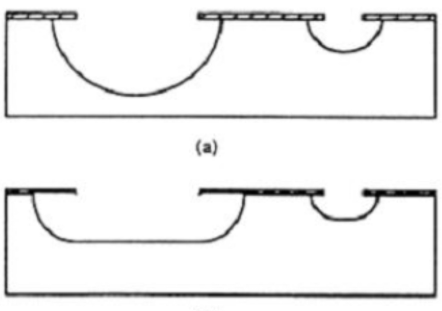
Wet Chemical Etching

Etching (1): Bulk Micromachining

Wet etching

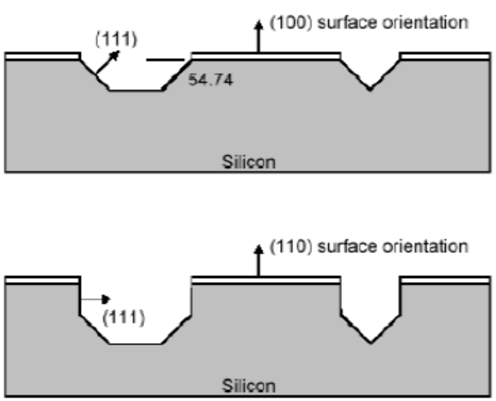
- **Immersion etching**; Wafer is immersed in the etch solution
- Wet chemical etching provides a higher degree of selectivity and faster than dry etching technique.

Etching profile



- **Isotropic etching**: etch in all crystallographic directions at the same rate

  - *Note: agitation during etching creates more rounded features, but does not significantly change the undercutting.*



- **Anisotropic etching**: directionally dependent on crystallographic directions

Wet Chemical Etching: Isotropic (1)

Etching (1): Bulk Micromachining

- **Isotropic etching**
  - They usually are acidic, such as $HF/HNO_3/CH_3COOH$ (hydrofluoric acid / nitric acid / acetic acid), called **HNA system** and lead to rounded isotropic features in single crystalline silicon.

- **HNA system**
  - The overall reaction of HNA system with silicon is

$$Si + 4HNO_3 \rightarrow \boxed{SiO_2} + 2H_2O + 4NO_2 \text{ ---- (1)}$$

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O \text{ ---- (2)}$$

Etchant (Diluent)	Reagent Quantities	Temp. °C	Etch Rate (μm/min)	(100)/(111) Etch Ratio	Dopant Dependence	Masking Films (etch rate)
HF	10 ml				$\leq 10^{17}$ cm^{-3} n or p reduces etch rate ≈150×	
HNO_3	30 ml	22	0.7 to 3.0	1:1		SiO_2 (30 nm/min)
(water, CH_3COOH)	80 ml					
HF	25 ml					
HNO_3	50 ml	22	4	1:1	no dependence	Si_3N_4
(water, CH_3COOH)	25 ml					
HF	9 ml					
HNO_3	75 ml	22	7	1:1	---	SiO_2 (70 nm/min)
(water, CH_3COOH)	30 ml					

Wet Chemical Etching: Isotropic (2)

- **Masking for isotropic silicon etchant**
  - SiO_2 has an appreciable etch rate of 300 to 800 A / min in the HNA system.
  - A mask of nonetching Au or Si_3N_4 is needed for deeper etching.
  - Photoresists do not stand up to strong oxidizing agents such as HNO_3.

<Masking materials for acidic etchants>

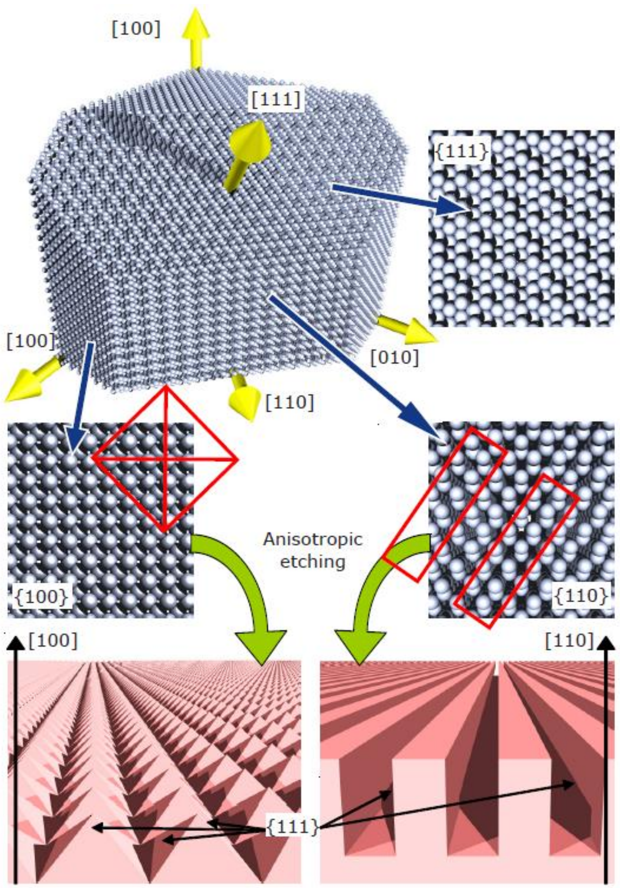
Masking	Piranha (4:1, H2O2: H2SO4)	Buffered HF (5:1NH4F: conc. HF)	HNA
Thermal SiO_2		0.1 μm/min	300–800 Å /min. Limited etch time, thick layers often are used due to ease of patterning.
CVD (450°C) SiO_2		0.48 μm/min	0.44 μm/min
Corning 7740 glass		0.063 μ/min	1.9 μ/min
Photoresist	Attacks most organic films	OK for short while	Resists do not stand up to strong oxidizing agents like HNO_3 and are not used.
Undoped Si polysilicon	Forms 30 Å of SiO_2	0.23 to 0.45 Å/min	0.7 to 40 μm/min at RT [at a dopant concentration < 10^{17} cm^{-3} (n or p)].
Black wax			Usable at room temperature.
Au/Cr	OK	OK	OK
LPCVD Si_3N_4		1 Å/min	Etch rate is 10–100 Å/min. Preferred masking material.

Note: The many variables involved necessarily mean that the given numbers are approximate only.

Wet Chemical Etching: Anisotropic (1)

Etching (1): Bulk Micromachining

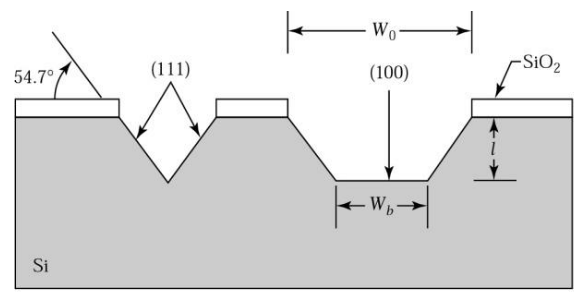
- **Anisotropic etching**
  - In the usual application, the wafer is selectively thinned with precisely controlled lateral dimensions and a thickness control.



e.g.) Etchant : 19wt % KOH in deionized (DI) water at 80℃

Etch rate (100) : (110) : (111) = 100 : 16 : 1

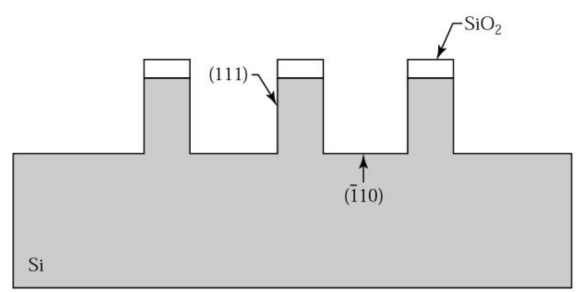
- **Orientation dependent (<100>-oriented silicon)**



(a)

$$W_b = W_0 - 2l\cot(54.7°)$$

$$W_b = W_0 - \sqrt{2}l$$

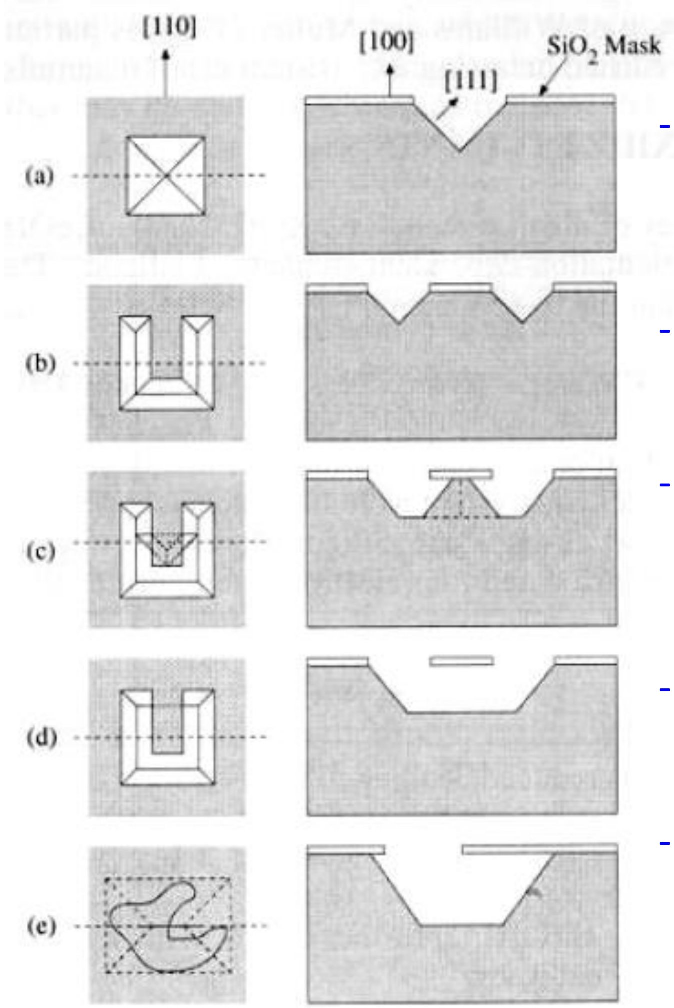


(b)

Wet Chemical Etching: Anisotropic (2)

Etching (1): Bulk Micromachining

Various etching profile

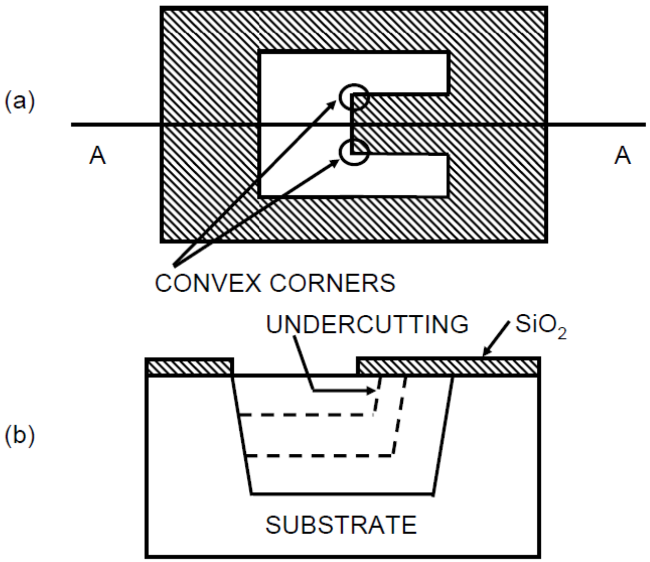


- (a) Typical pyramidal pit, bounded by the (111) planes, etched into (100) silicon with an anisotropic etch through a square hole in an oxide mask.
- (b) Type of pit which is expected from an anisotropic etch with a slow convex undercut rate.
- (c) The same mask pattern can result in a substantial degree of undercutting using an etchant with a fast convex undercut rate.
- (d) Further etching of (c) produces a cantilever beam suspended over the pit.
- (e) Illustration of the general rule for anisotropic etch undercutting assuming a "sufficient time"

Wet Chemical Etching: Anisotropic (3)

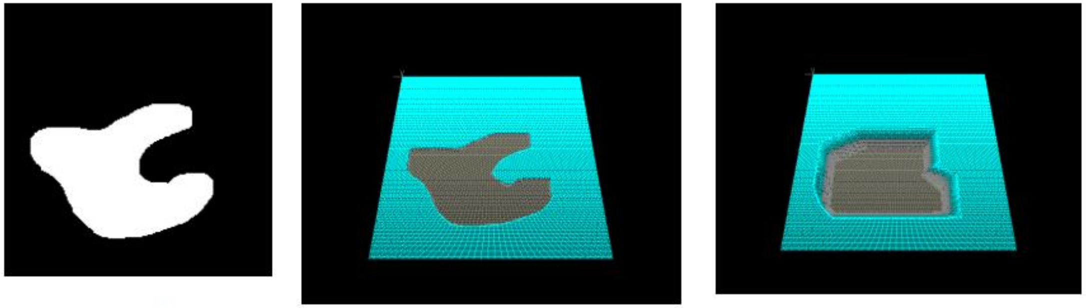
Etching (1): Bulk Micromachining

Convex corner compensation



- For **convex corners, the fastest etching planes** dominate the three-dimensional shape.
- For **concave corners, the slowest etching planes** dominate the three dimensional shape.

- For an arbitrary shaped mask with transparent opening, the pyramidal shape is bound by the outside boundary.



mask

Wet Chemical Etching: Anisotropic (4)

Etching (1): Bulk Micromachining

Mainly used anisotropic etchants

Etchant/diluent/ additives/temperature	Etch stop	Etch rate (100), μm/min	Etch rate ratio	Remarks	Mask (etch rate)
KOH (water) 85°C 44 g/100 mL	B > 10^{20} cm^{-3} reduces etch rate by 20	1.4	400 for (100)/(111)	IC incompatible, avoid in eyes, etches oxide fast, lots of H_2 bubbles	Photoresist (shallow etch at room temperature); Si_3N_4(<1 nm/min) SiO_2 (28 Å/min)
Ethylenediamine pyrocatechol (water) 115°C 750 mL /120 g/240 mL (EDP)	$=7\times10^{19}$ cm^{-3} reduces the etch rate by 50	1.25	35 for (100)/(111)	Toxic, ages fast, O_2 must be excluded, few H_2 bubbles, silicates may precipitate	SiO2 (2–5 Å/min) Si_3N_4 (1 Å/min) Ta, Au, Cr, Ag, Cu are not attacked Al at a 0.33 μm/min
Tetramethyl ammonium hydroxide (TMAH) (water) 90°C	$>4\times10^{20}$ cm^{-3} reduces etch rate by 40	1	from 12.5 to 50 (100)/(111)	IC compatible, easy to handle, smooth surface finish, few studies	SiO_2 etch rate is four orders of magnitude lower than (100) LPCVD Si_3N_4
N_2H_4 (water, isopropyl alcohol) 100°C 100 mL/100 mL	$>1.5\times10^{20}$ cm^{-3} practically stops the etch	2.0	10(100)/(111)	Toxic and explosive, OK at 50% water	SiO_2 (<2 Å/min) and most metallic films; does not attack Al

Note: Given the many possible variables, the data in the table are only typical examples.

- **KOH**: (Good) High etching rate, Nontoxic
  (Bad) Contaminate the MOS process (Potassium ion), Temperature sensitive, Stratified etching rate
- **EDP**: (Good) MOS process compatible (Sodium free), Good uniformity, Abrupt stop at etching stop
  (Bad) Toxic, Low etching rate
- **TMAH**: (Good) Nontoxic, MOS process compatible (Sodium free), Will not attack the silicon doped Aluminum, Stable (will not decompose under 130 degree C)
  (Bad) Bad surface roughness on the bottom <100>, High undercutting ratio

Wet Chemical Etching: Anisotropic (5)

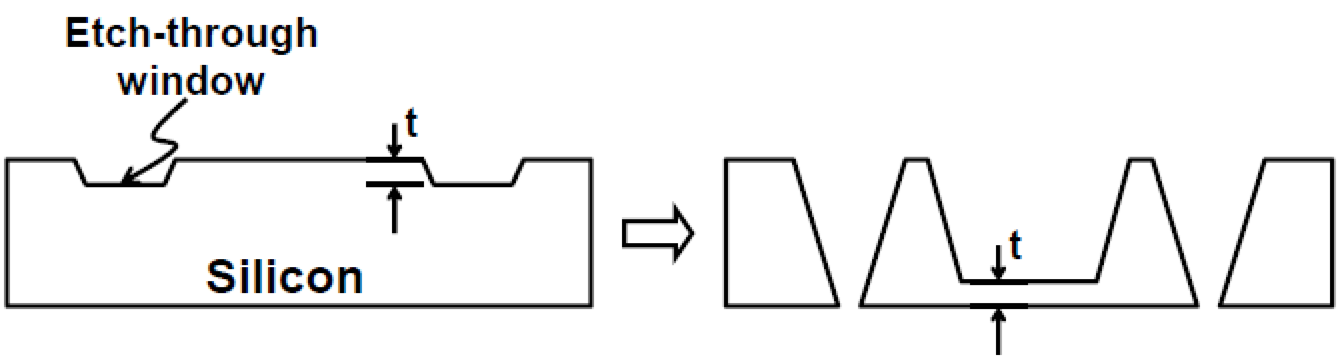
- **Etch stop methods**

1) Dopant dependent etch stop

   → EDP : Boron { 10^{20} /cm^3 - 1:50 (Si : p+)
   7×10^{19} /cm^3 – 1:20 (Si:p+)

2) Electrochemical etch stop
3) Timed etch stop
4) Etch-through window

   → Thickness of a commercial silicon wafer = 525μm ±



Wet Chemical Etching: Anisotropic (6)

Etching (1): Bulk Micromachining

Etching for SiO_2, Si_3N_4, poly-Si (a-Si), and Al

- **SiO_2 etching**: Hydrofluoric acid (HF)
  : Buffered oxide etch (BOE or BHF)
  HF + NH_4F (ammonium fluoride)

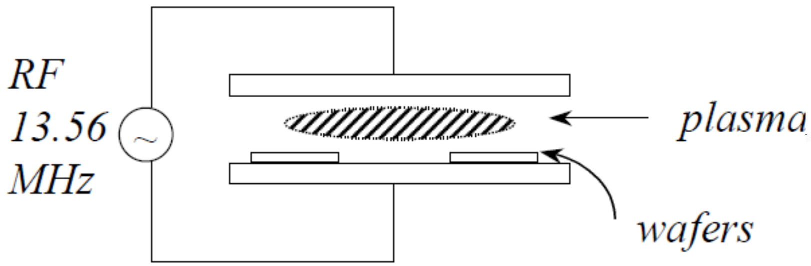
- **Si_3N_4 etching**: HF + boiling H_3PO_4 (phosphoric acid)
  : BOE or BHF + boiling H_3PO_4
  85% H_3PO_4 at 180°C
  → etching selectivity for SiO_2
  ; PR has problems as etching mask
  → Using SiO_2 mask

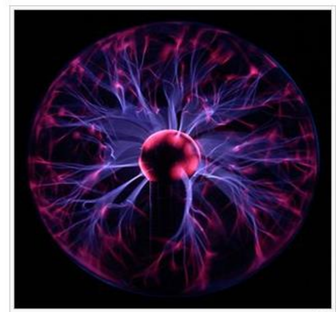
- **Poly & a-Si**: Same etchant of Single crystal Si
  : Etch rate is faster than SC Si
  : Almost isotropic etching

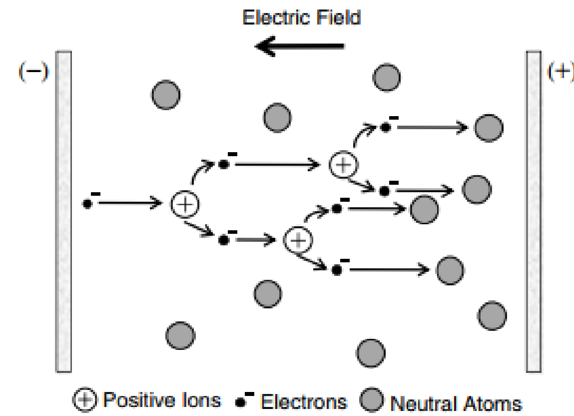
- **Al etching**: 73% H_3PO_4 + 4% HNO_3 (nitric acid) + 3.5% CH_3COOH (acetic acid)
  +19.5% DI water
  : Generally, developer can etch pure Al easily
  → Al alloy can solve this problem (AlNd)

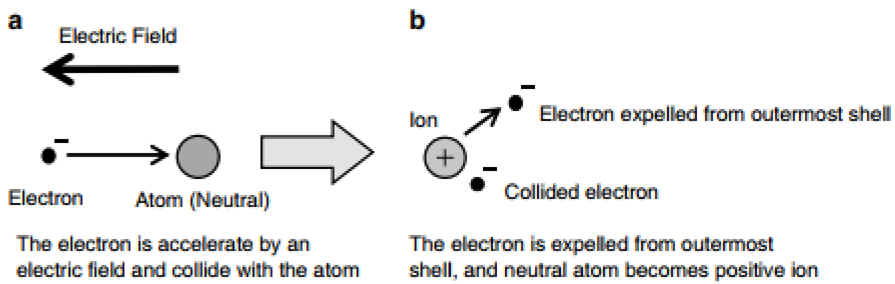
Ref: Michael Köhler "Etching in Microsystem Technology" Wiley

Dry etching (Plasma assisted etching)

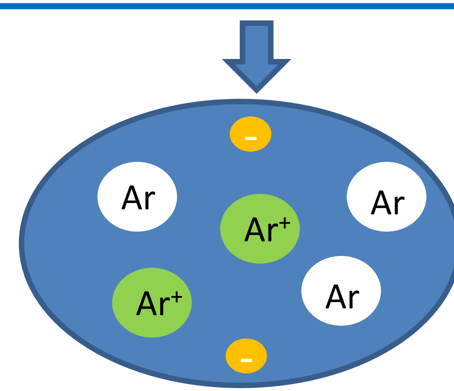








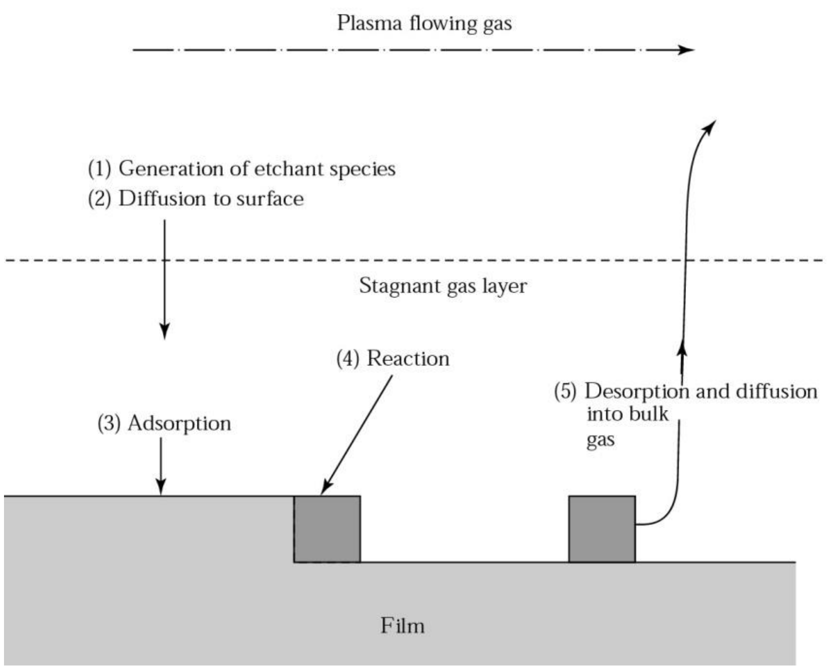
Plasma :
The ionized gas composed of equal numbers of positive ions and negative electrons and unionized molecules



Plasma :

1. Initiated by free electron (such like field emission from negative biased electrode)
2. The electron gain kinetic energy from electrical field
3. The electron collide with gas molecules → Ion + electron

Sequence: mechanism



Process

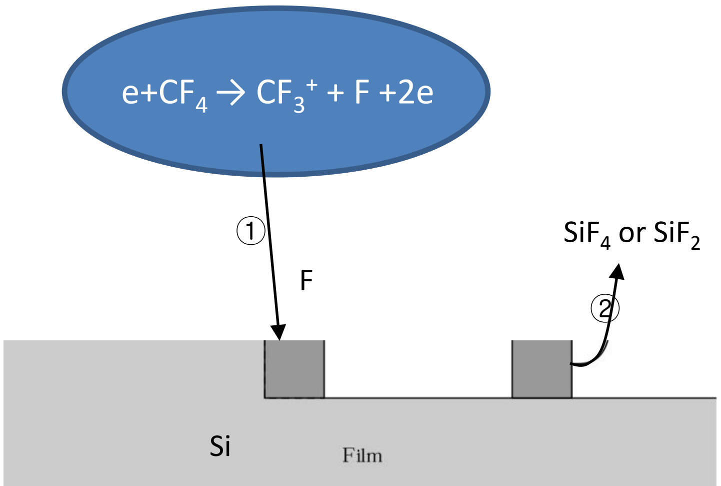
1. The etchant species is generated by plasma
2. The reactant moves to the surface of substrate
3. The reactant is absorbed on the surface
4. Chemical (Physical) reaction
5. The compounds are detached

<Etching gas for dry method>

SOLID	ETCH GAS	ETCH PROD.
Si, SiO_2, Si_3N_4	CF_4, SF_6, NF_3	SiF_4
Si	CCl_2 , CCl_2F_2	$SiCl_2$ $SiCl_4$
Al	BCl_3, CCl_4, $SiCl_4$, Cl_2	$AlCl_3$, Al_2Cl_6,
Organic solid	O_2,	CO, CO_2, H_2O
	O_2 + CF_4	CO, CO_2, HF
Refractory Metal (W, Ta, Mo)	CF_4	WF_6, ...

Dry Etching: Anisotropic (3)

Physical mode & Chemical mode



① Sputtering effect : Ion bombardment
→Physical mode
② Pure chemical reaction
→ Chemical mode

<100mTorr

~100mTorr

Higher Pressure

Physical Sputtering
(and Ion Beam Milling)

- Physical momentum transfer
- Directional etch (anisotropic) possible
- Poor selectivity
- Radiation damage possible

Reactive Ion Etching (RIE)

- Physical (ion) and Chemical
- Directional (~ anisotropic)
- More selective than sputtering

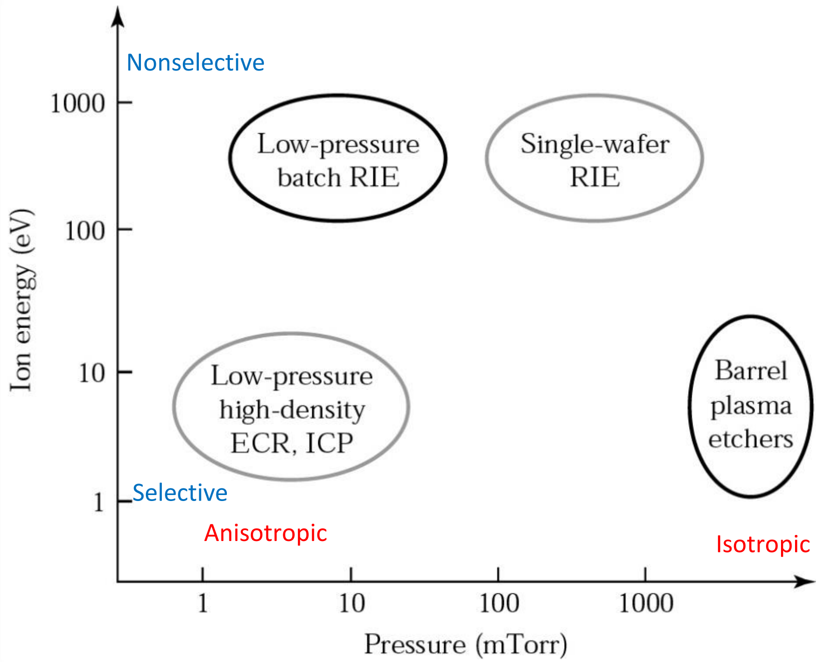
Plasma etching

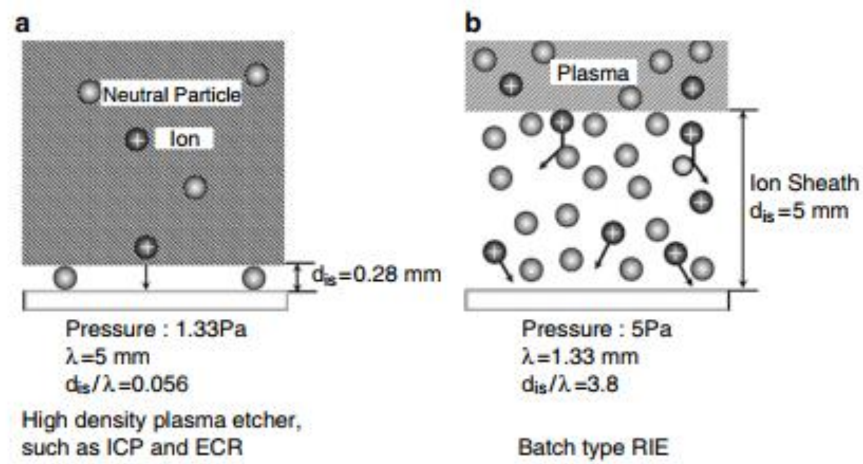
- Chemical, thus faster by 10-1000x
- Isotropic
- More selective
- Less prone to radiation damage

Higher Excitation Energy

Dry Etching: Anisotropic (4)

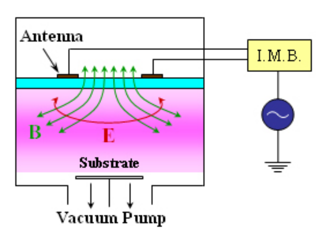
- **Comparison of ion energy and operating pressure ranges for different types of plasma reactors.**



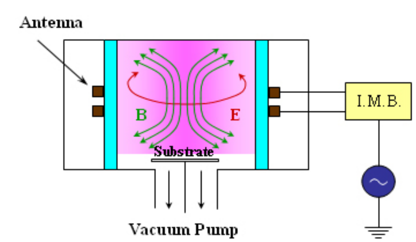


**ICP: inductively coupled plasma*
ECR: electron cyclotron resonance

Anisotropic etching & High selectivity : Ultimate target
→ - Low pressure
- High plasma density with low power



<TCP: transformer coupled plasma>

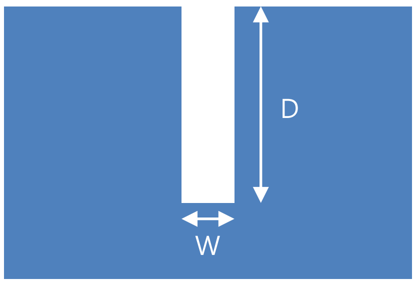


<ICP>

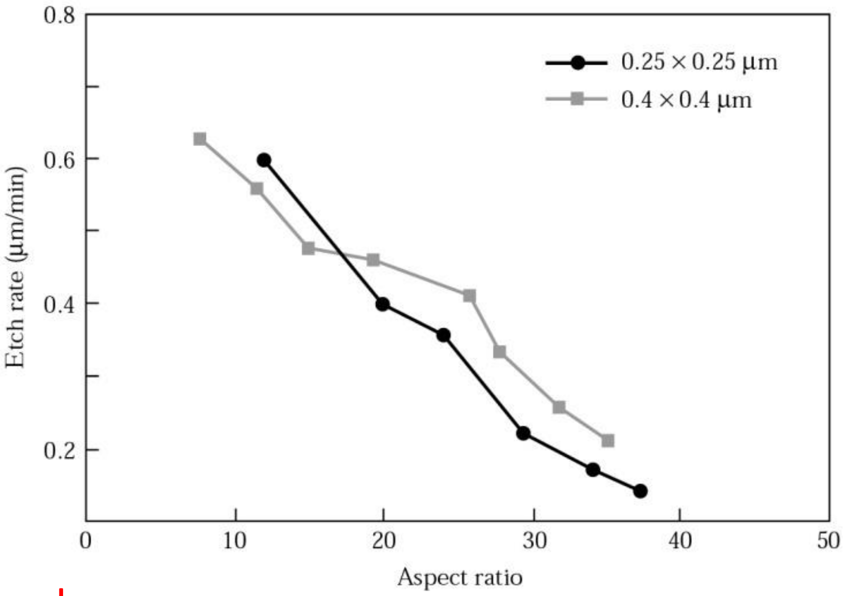
Dry Etching: Anisotropic (5)

Etching (1): Bulk Micromachining

- **Trench structure**



Aspect ratio $= \frac{D}{W}$



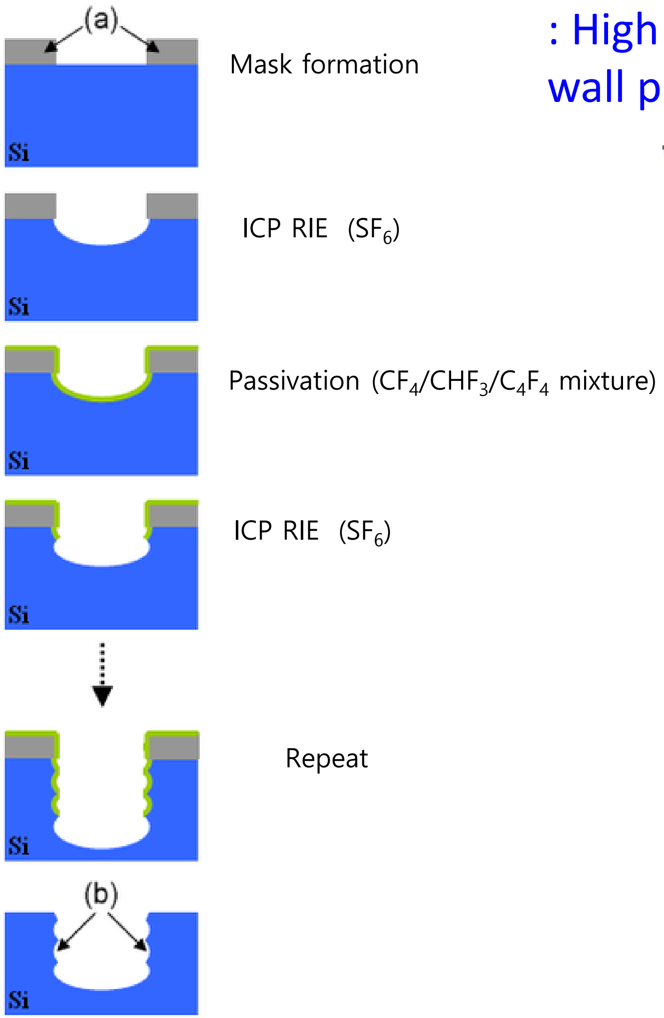
High aspect ratio & Small dimension
→ Low etching rate
:limitation of ion and neutral transport in trench

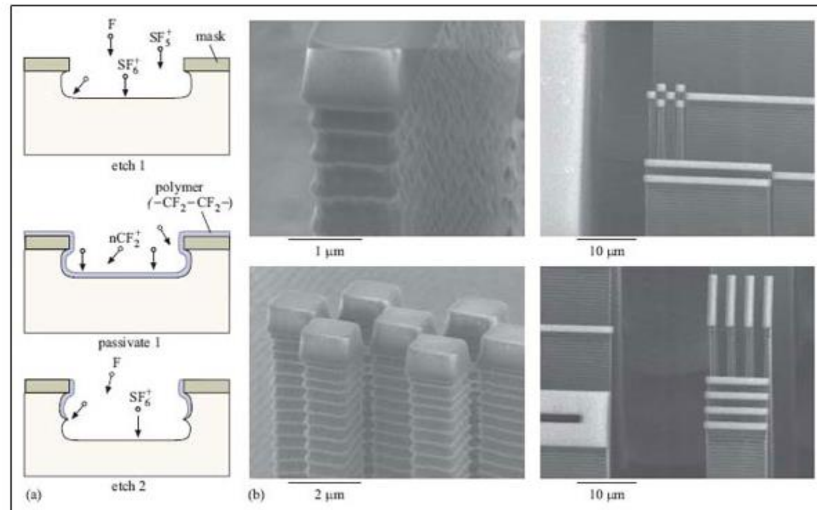
Dry Etching: Anisotropic (6)

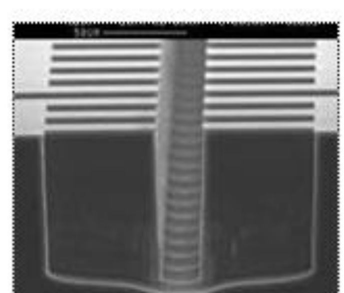
Etching (1): Bulk Micromachining

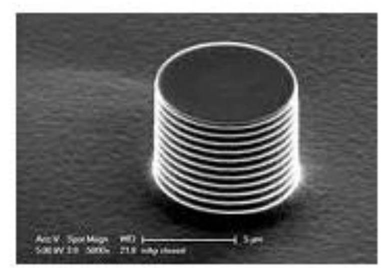
New method (1): Bosch Process (Deep RIE)

: High aspect ratio trench or pillar structure → Side wall passivation









Dry Etching: Anisotropic (7)

Etching (1): Bulk Micromachining

- **New method (2): Atomic Layered Etch (ALE)**

  : self-limiting chemical modification steps -> affect only the top atomic layers of the wafer -> etching steps which remove only the chemically-modified areas, allows the removal of individual atomic layers