

Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 2: MEMS fabrication I: bulk micromachining (1)

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Micromachining

Process Type	Examples
Lithography	photolithography, screen printing, electron-beam lithography, x-ray lithography
Thin-Film Deposition	chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), sputtering, evaporation, spin-on application, plasma spraying, etc.
Electroplating	blanket and template-delimited electroplating of metals
Directed Deposition	electroplating, stereolithography, laser-driven chemical vapor deposition, screen printing, transfer printing
Etching	plasma etching, reactive-ion enhanced (RIE) etching, deep reactive ion etching (DRIE), wet chemical etching, electrochemical etching, etc.
Directed Etching	laser-assisted chemical etching (LACE)
Machining	drilling, milling, electric discharge machining (EDM), diamond turning, sawing, sand blasting, etc.
Bonding	fusion bonding, anodic bonding, adhesives, etc.
Surface Modification	wet chemical modification, plasma modification
Annealing	thermal annealing, laser annealing

Etching Process

Silicon Etching

A simple movie in nano-format...

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Bulk Micromachining (1)

- The purpose of bulk micromachining
 - Selectively remove significant amounts of silicon from a substrate
 - Broadly applied in the fabrication of micromachined sensors, actuators, and structures
- Fabrication method: dry/wet etching
 - Undercut structures that are required to physically move
 - Form membranes on one side of a wafer
 - Make a variety of trenches, holes, or other structures

Bulk Micromachining (1)

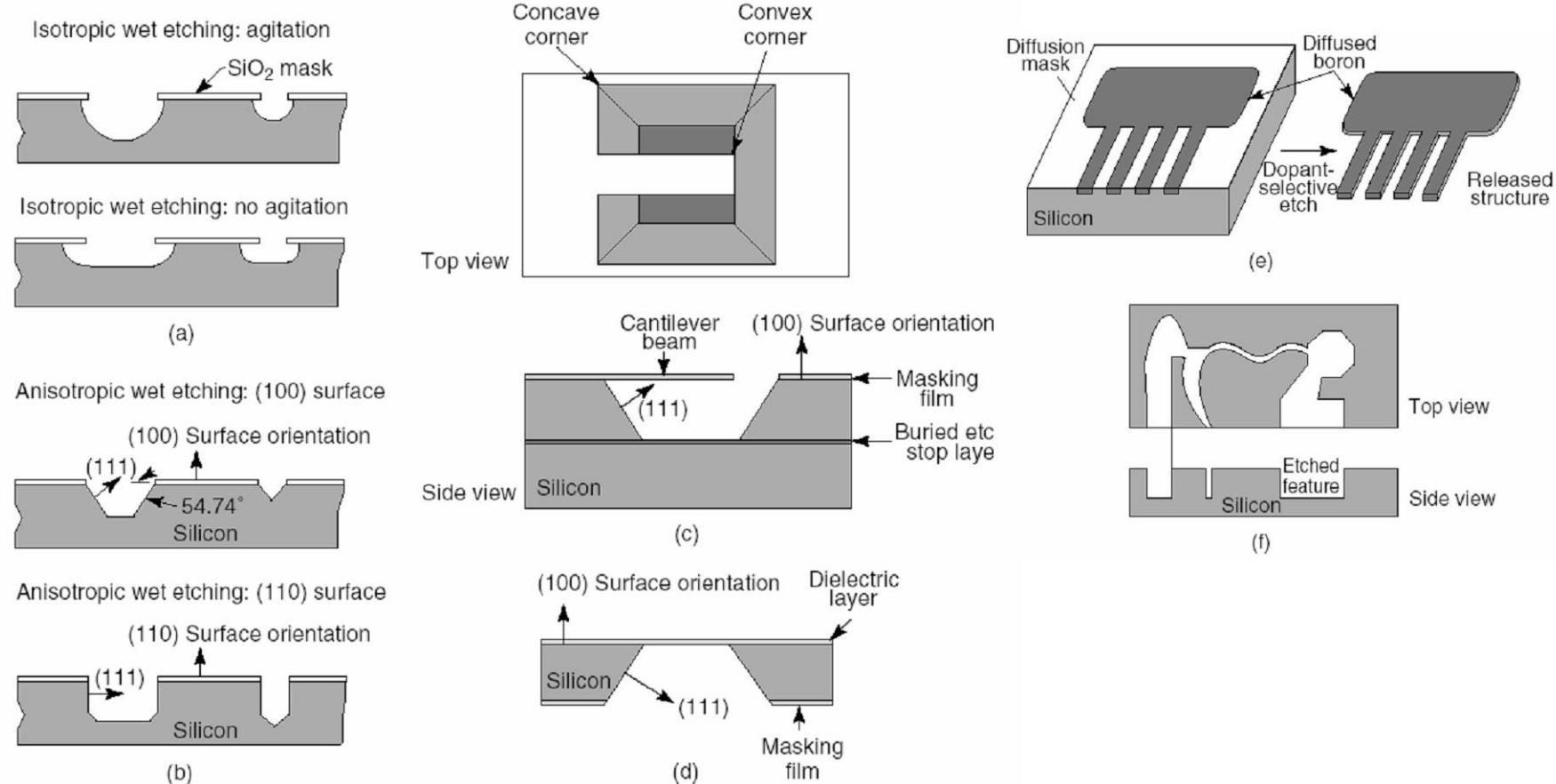


Figure 1. Bulk silicon micromachining: (a) isotropic etching; (b) anisotropic etching; (c) Anisotropic etching with buried etch-stop layer; (d) dielectric membrane released by back-side bulk etching; (e) dopant dependent wet etching; (f) anisotropic dry etching

Bulk Micromachining (1)

Terminology:

Etch Rate – How fast material is removed

Selectivity – Ratio of etch rates of materials exposed to etching

Anisotropy – Degree of lateral etch to vertical etch

Wet Etching – chemical bath

Dry Etching – chemical / physical material removal using gas / vapor

	Dry Etching	Wet Etching
Production-Line Automation	Good	Poor
Cost chemicals	Low	High
Selectivity	Poor	Can be very good
Sub-micron features	Applicable	Not Applicable
Etch Rate	Slow (0.1um/min)	Fast(1 um/min)

(Madou)

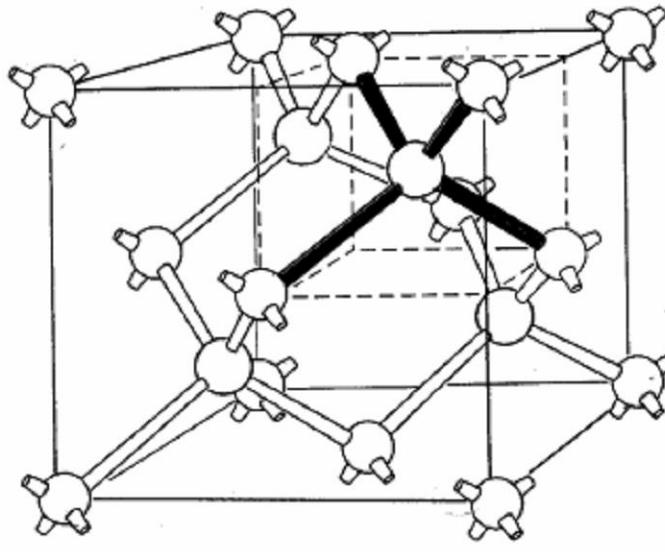
Bulk Micromachining (2)

- Comparison of bulk silicon etchants

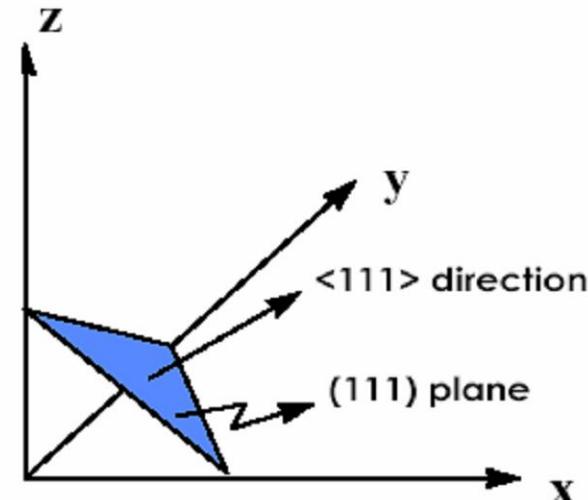
	HNA	Alkali-OH	EDP	TMAH	XeF ₂	SF ₆ plasma	DRIE
Etch type	wet	wet	wet	wet	dry	dry	dry
Anisotropy	no	yes	yes	yes	no	varies	yes
Si etch rate ($\mu\text{m}/\text{min}$)	1 to 3	1 to 2	0.02 to 1	≈ 1	1 to 3	≈ 1	>1
Si roughness	low	low	low	Variable	high	variable	low
Nitride etch	low	low	low	1 to 10 nm/min	-	low	low
Oxide etch (nm/min)	10 to 30	1 to 10	1 to 80	≈ 1	low	low	low
P++ etch stop	no	yes	yes	yes	no	no	no
CMOS Compatibility	no	no	yes	yes	yes	yes	yes

(Madou)

Silicon Crystallography (1)



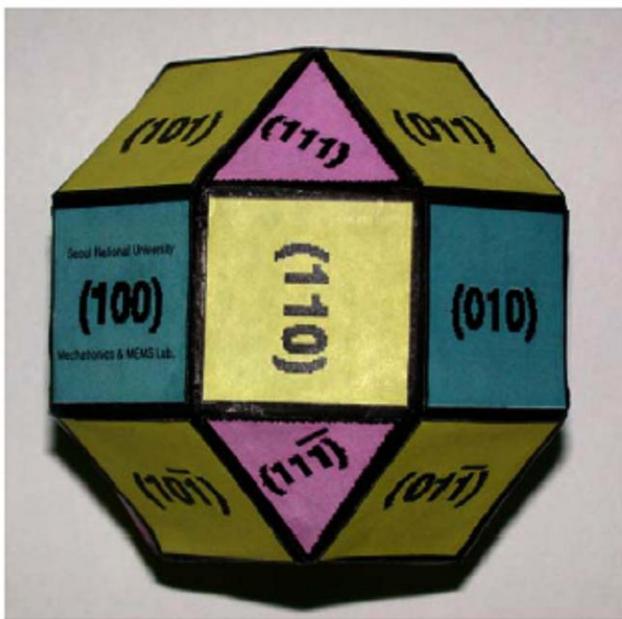
Si crystalline structure



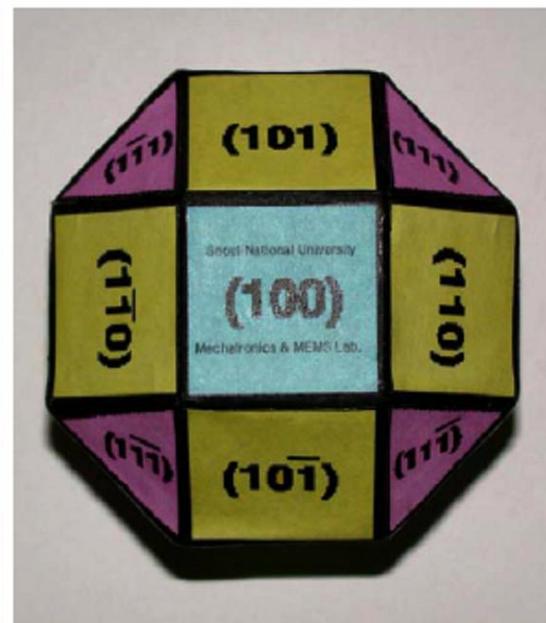
- Miller indices
 - $(i j k)$: a specific crystal plane or face
 - $\{i j k\}$: a family of equivalent planes
 - $[i j k]$: a specific direction of a unit vector
 - $\langle i j k \rangle$: a family of equivalent directions

Silicon Crystallography (2)

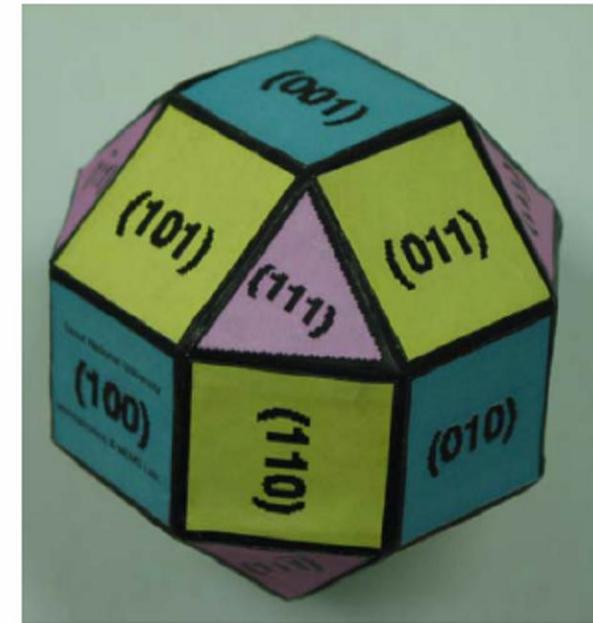
(110) silicon



(100) silicon

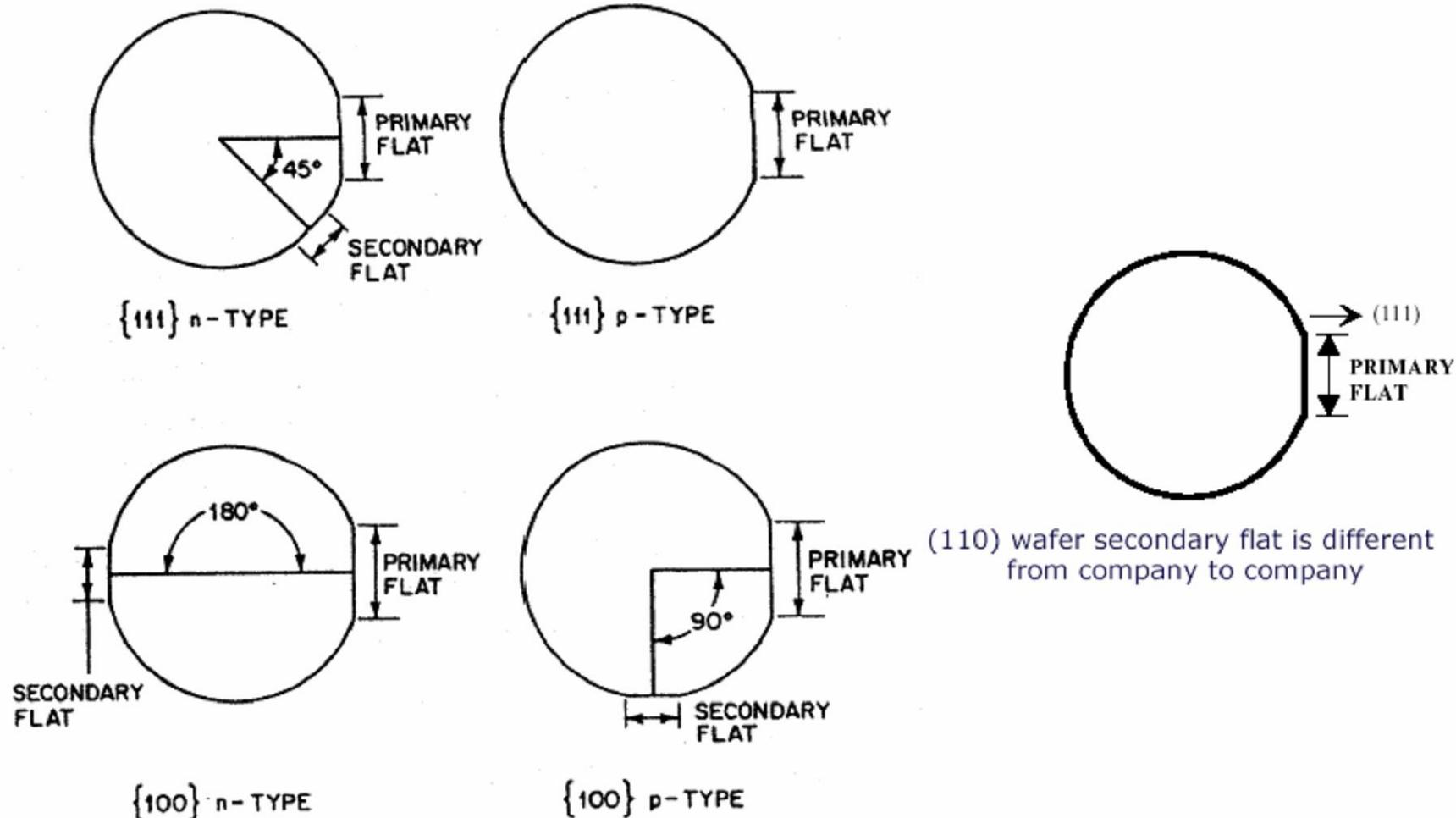


(111) silicon



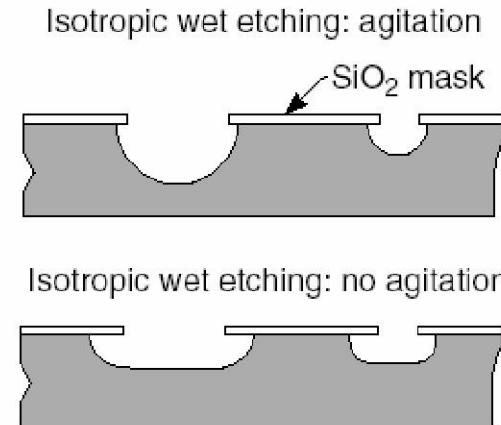
(Open Courseware: Readings_Etc)

Silicon Crystallography (3)



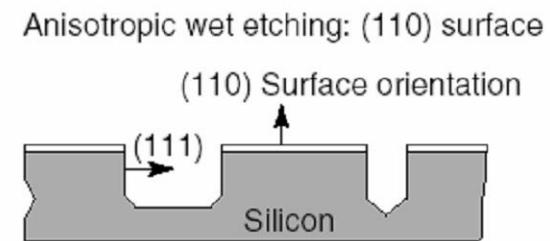
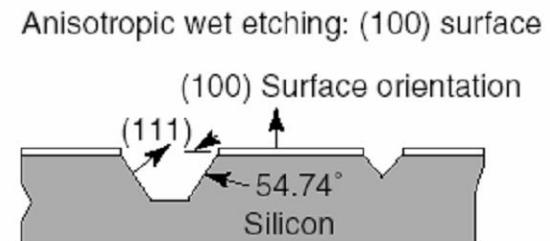
Isotropic Wet Etching

- **Isotropic wet etching**
 - Etching with chemical reaction
 - etching in all directions a substrate
 - Induces etch reaction with silicon through the opening region
 - agitation required: stirring, ultrasonic
 - Considering opening area to size of reaction bubble
 - Bubble disturbs exchange of etchant
 - Slow down etch rate
 - The most common isotropic wet silicon etchant: HNA
 - HNA = HF + HNO₃ + CH₃COOH
 - Reaction: 18HF + 4HNO₃ + 3Si → 2H₂SiF₆ + 4NO(g) + 8H₂O

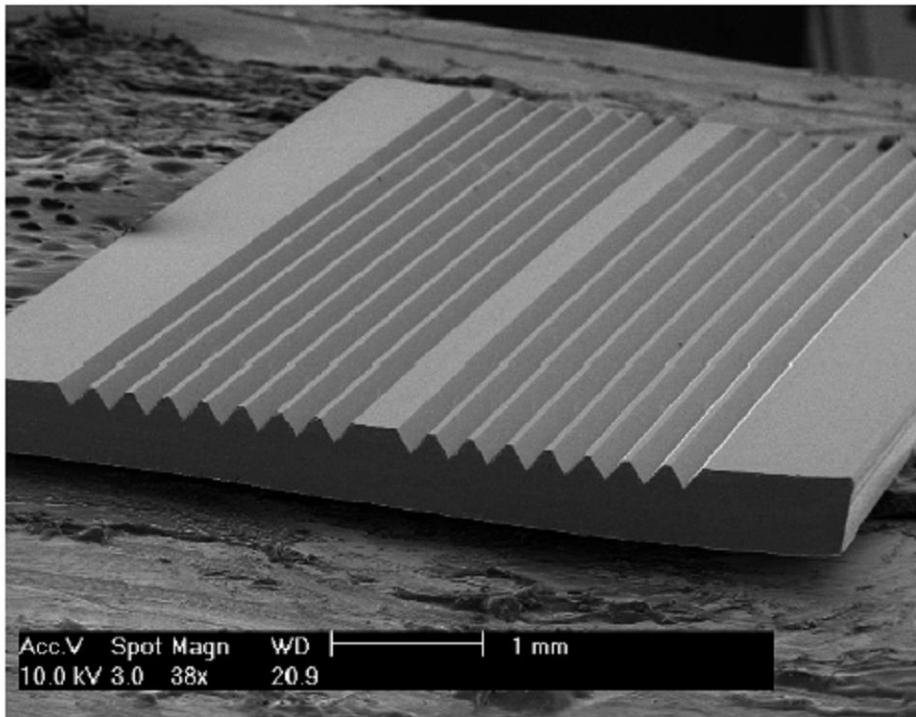


Anisotropic Wet Etching (1)

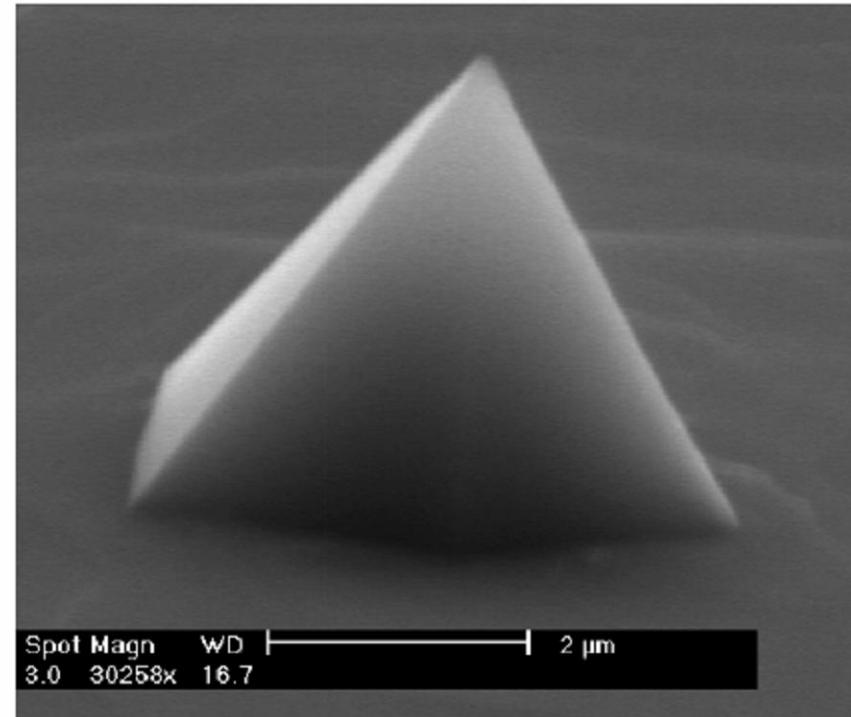
- **Anisotropic wet etching**
 - Anisotropic etchants etch much faster in one direction than in another
 - exposing the slowest etching crystal planes over time
 - (111) planes have the slowest etch rate
 - Several solutions:
 - Alkaline OH (KOH, NaOH)
 - Tetramethylammonium hydroxide (TMAH, $(\text{CH}_3)_4\text{NOH}$)
 - Ethylenediamine pyrocatechol (EDP, $\text{NH}_2(\text{CH}_2)_2\text{NH}_2 + \text{C}_6\text{H}_4(\text{OH})_2$)
 - Etching at concave corners on (100), stop at (111) intersections. Convex corners are undercut



Example of Anisotropic Wet Etching



Optical bench using (100) silicon



3 {111}-faceted tip

Anisotropic Wet Etching (2)

- **Alkali Hydroxide Etchants (KOH, NaOH, CeOH...)**
 - Reaction: $\text{Si} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2(\text{OH})_2^{2-} + 2\text{H}_2$
 - Etch rate: $1 \sim 2 \mu\text{m}/\text{min}$
 - (100)/(111) Etch ratio = 400:1 ~ extremely high
 - Etch mask: SiO_2 ($\sim 1 \text{ nm}/\text{min}$), Si_3N_4 (negligible)
 - Etch rate slows down in boron doped regions ($\geq 2 \times 10^{19} \text{ cm}^{-3}$)
→ rapid recombination of electrons generated by oxidation reactions
 - (100) etch → pyramidal pits with 54.74° (111) side wall angles
 - (110) etch → “perfectly” rectangular trenches. (110) etch is so high!
 - “Mirror-like” finish is possible. Cf) EDP & TMAH
 - Drawback: Use of alkali ions ~ detrimental to CMOS process

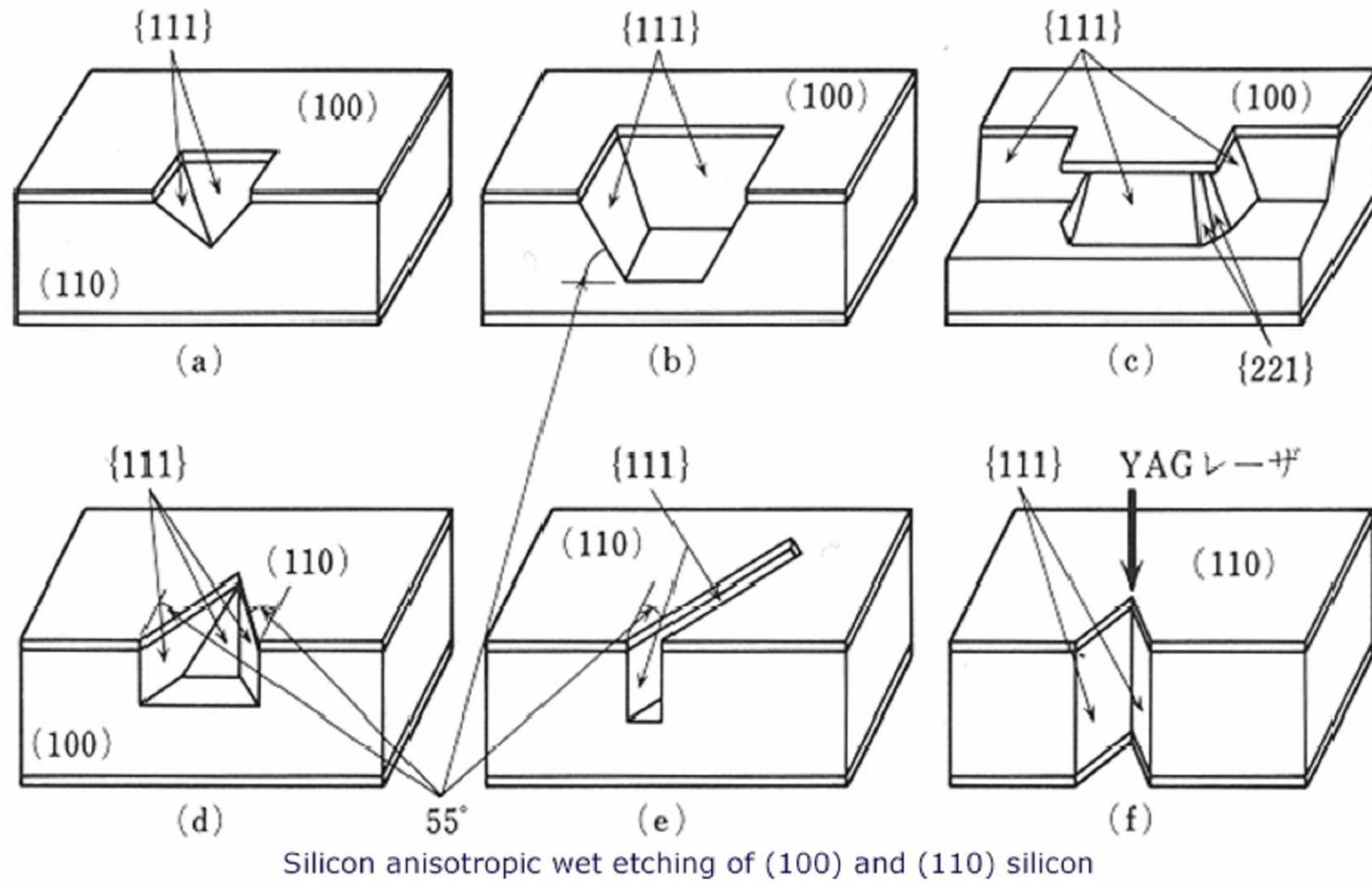
Anisotropic Wet Etching (3)

- **Ammonium Hydroxide (NH_4OH)**
 - Etch rate: $0.11 \mu\text{m/min}$ in (100) Si ($85 \sim 92^\circ\text{C}$, 9.7 wt% in water)
 - Drawback: hillock formation (roughness), slow etch rate, evaporation loss of ammonia gas (noxious) when heated
- **Tetramethyl Ammonium Hydroxide (TMAM)**
 - Relatively safer than EDP. Low cost.
 - Does not etch aluminum with additives.
 - Etch rate slows down in boron doped regions ($\geq 1 \times 10^{19} \text{ cm}^{-3}$) ~ boron etch stop up to 40:1 ($2 \times 10^{20} \text{ cm}^{-3}$) cf) solubility limit = $2.5 \times 10^{20} \text{ cm}^{-3}$
 - (100)/(111) Etch ratio = $10 \sim 35:1$ ~ relatively low
 - Etch rate: $0.5 \sim 1.5 \mu\text{m/min}$ at 90°C
 - Etch mask: SiO_2 ($0.05 \sim 0.25 \text{ nm/min}$), Si_3N_4 (similar to SiO_2)

Anisotropic Wet Etching (4)

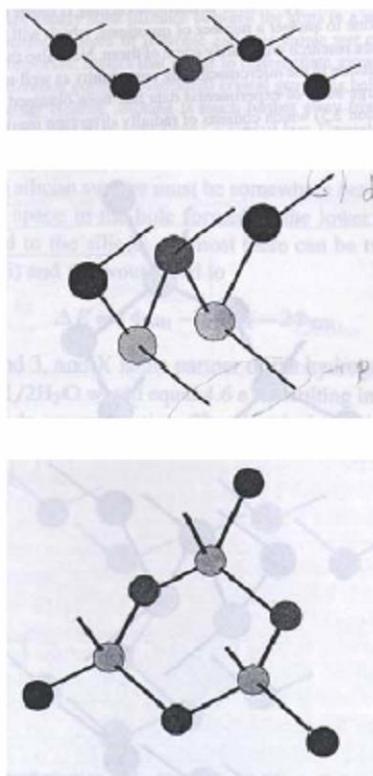
- **Ethylene Diamine Pyrochatechol (EDP)**
 - (100)/(111) Etch ratio = 35:1 ~ relatively low
 - Good selectivity for heavy P-type doping
 - ~ 50 times slowing of etch rate ($> 7 \times 10^{19} \text{ cm}^{-3}$)
 - Etch mask: SiO_2 , Si_3N_4 , Au, Cr, Ag, Cu, Ta...
 - Drawback: Attack Al quickly, not compatible to CMOS process
 - very corrosive and potentially carcinogenic
 - Etch rate: $0.02 \sim 1 \text{ } \mu\text{m/min}$ in (100) Si ($70 \sim 97 \text{ } ^\circ\text{C}$)
- **Hydrazine (H_4N_2) water mixtures**

Anisotropic Wet Etching (5)



Anisotropic Etching Mechanism

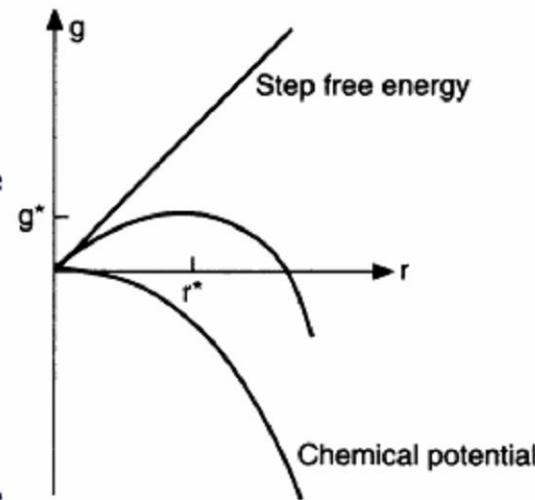
- M. Elwenspoek et al.
 - Explained the etching mechanism by the crystal growth theory
 - $\{111\}$ plane has slow etch rate $\leftarrow \{111\}$ plane is the smooth face



$\{100\}$ plane

$\{110\}$ plane

$\{111\}$ plane



$\Delta\mu$: the chemical potential difference

γ : step free energy

h : the height of the step

r : the radius of the hole or island

ρ : the density of the solid material

$$\Delta G = -\pi r^2 h \rho \Delta \mu + 2\pi r \gamma$$

$$r^* = \frac{\gamma}{h \rho \Delta \mu}$$

$$\Delta G^* = \Delta G(r^*) = \frac{\pi \gamma^2}{h \rho \Delta \mu}$$

Ref.) M. Elwenspoek, and H. V. Jansen, Silicon Micromachining, Cambridge University Press, 1998

Boron Etch Stop (1)

- Boron etch stop
 - 20 times slowing of etch rate for $> 10^{20} \text{ cm}^{-3}$ boron doping in KOH
 - 50 times slowing of etch rate for $> 7 \times 10^{19} \text{ cm}^{-3}$ boron doping in EDP
 - Tensile stress (Boron atoms are smaller than silicon)
 - The extremely high boron concentrations are not compatible with standard CMOS or bipolar techniques

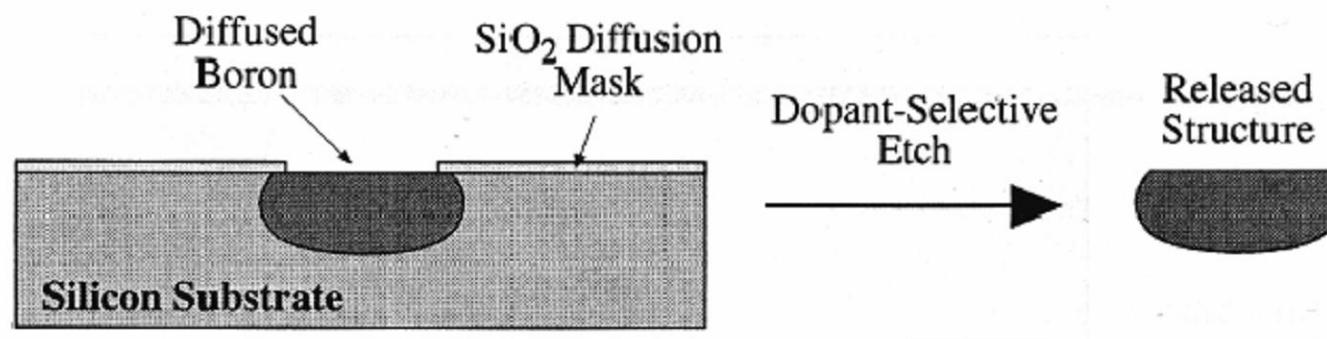
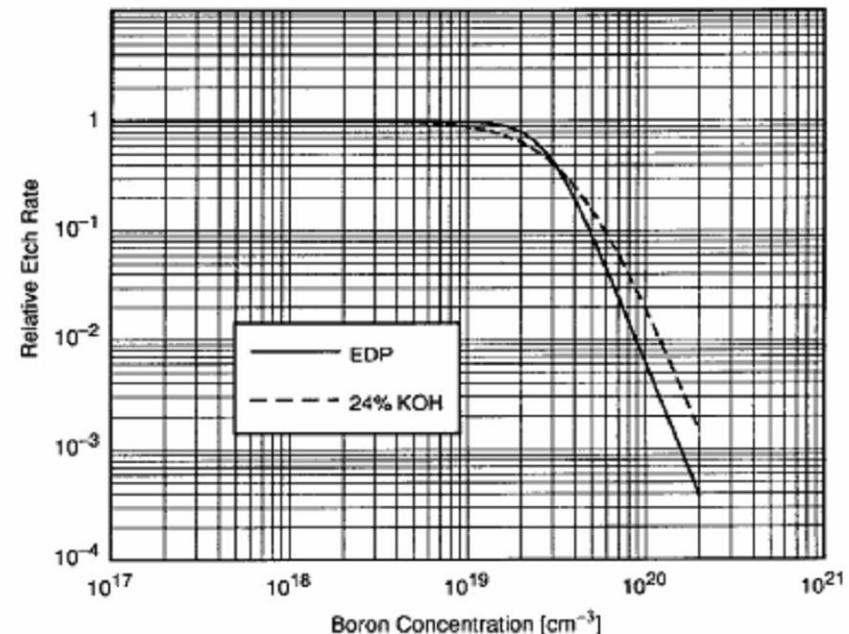


Illustration of the use of heavy boron doping with a dopant-selective etch to form free structures

Boron Etch Stop (2)

- Boron penetration
 - Excessive Boron doping affects IC.
 - Boron having high diffusion rate penetrates channel and gate oxide of IC.
 - In general IC MEMS, backside of substrate is wet-etched.
 - Extremely high boron doping of backside damages gate of IC, and then can be a representative cause of leak current.

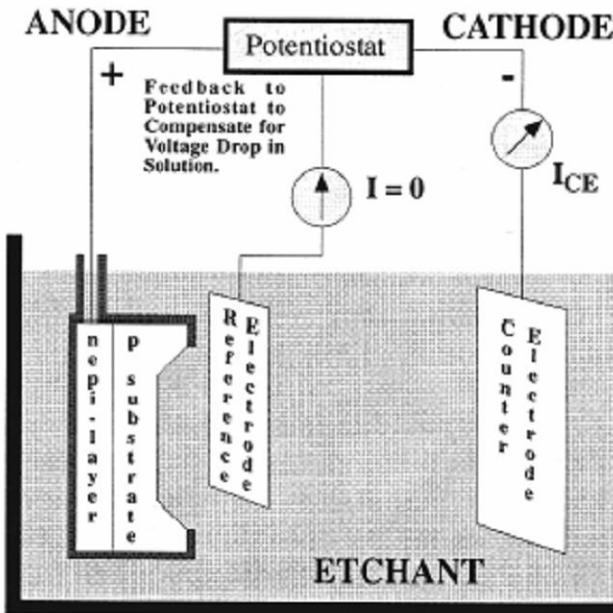


Electrochemical Etch Stop (1)

- Electrochemical wet etching
 - Appling external voltage → Implanting hole → Changing surface to hydroxide
 - Appling voltage through chemical
 - Cathode: Platinum electrode
 - Anode: Silicon
 - Hole is implanted to silicon positively charged → Silicon draws OH-of chemical → Oxidizing
 - HF added to chemical removes oxide of Si surface, then induces etching.
 - Etching effects electro polishing, because surface roughness is low.
 - Nitride or PR are used as etch mask.

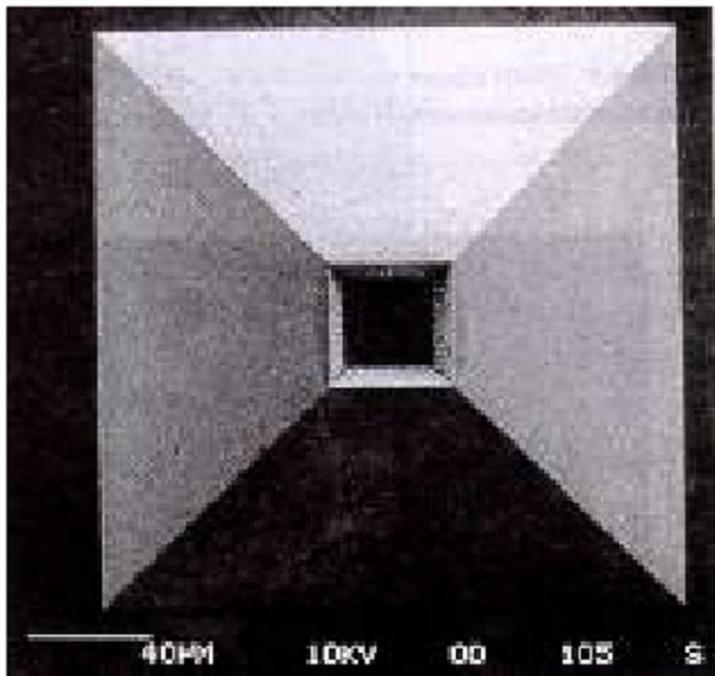
Electrochemical Etch Stop (2)

- Diode junction etch stop
 - P-type Si is etched away in echants (KOH, EDP, TMAH)
 - Formation of SiO_2 by anodic oxidation when the etchant reaches the junction
 - Etch-rate drop equivalent to the selectivity over SiO_2

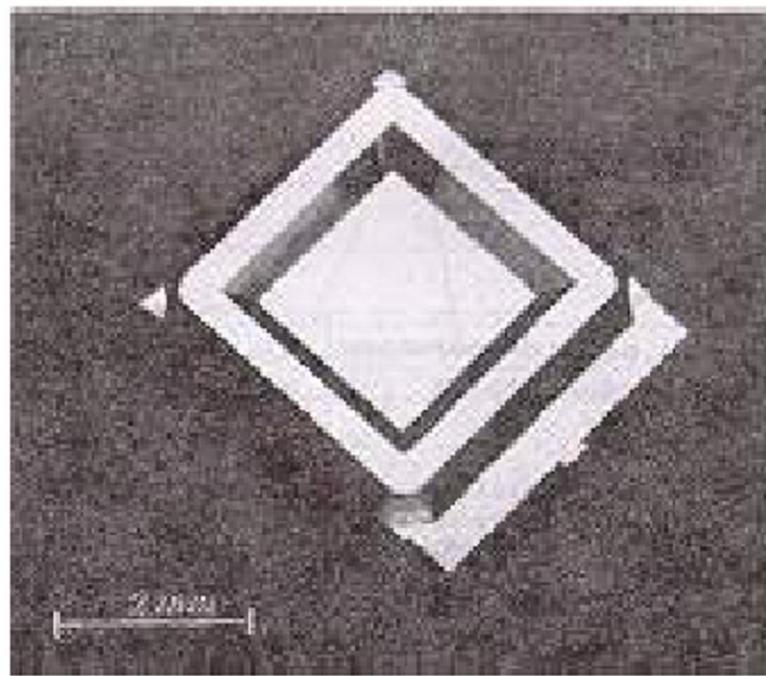


A standard three-electrode system for diode junction etch stop

(100) Si Wet Etch (1)



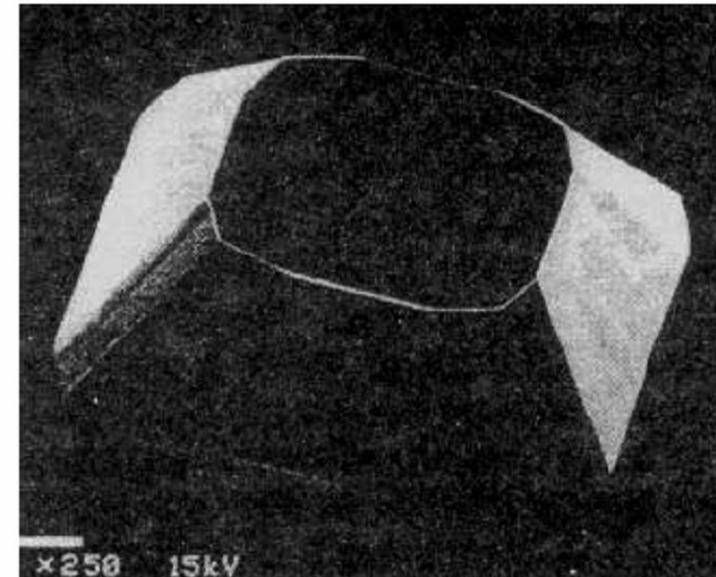
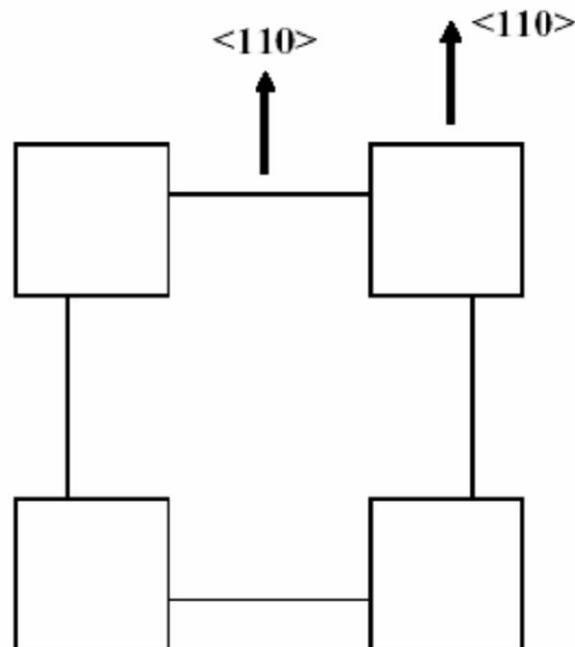
Nozzle



Diaphragm

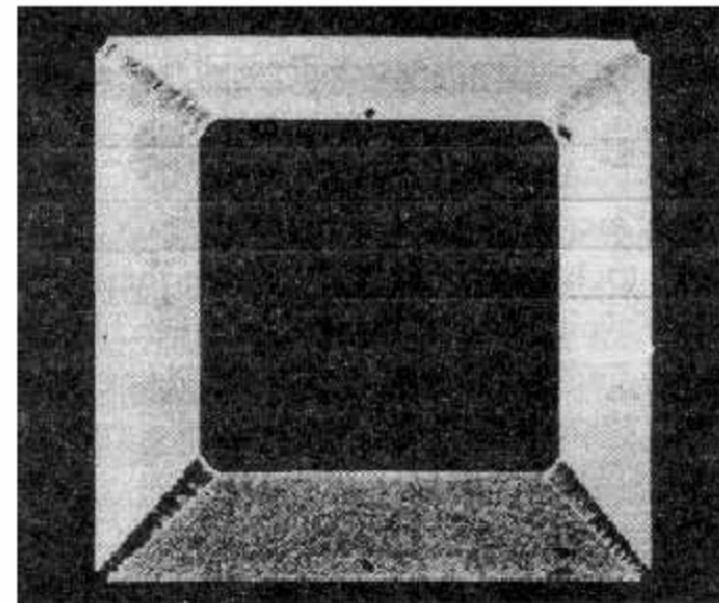
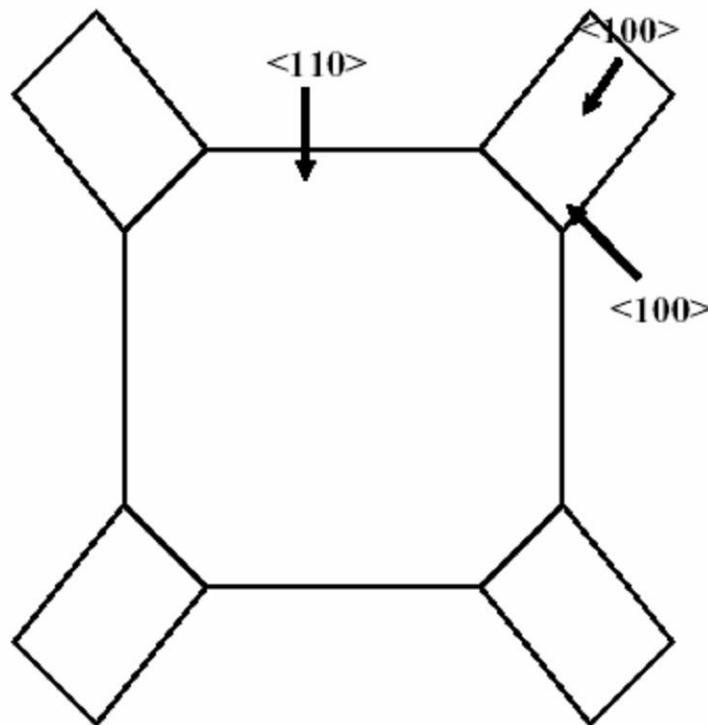
(100) Si Wet Etch (2)

- Rectangular corner compensation for mesa structure fabrication
 - Mask layout of compensation pattern for preventing undercut



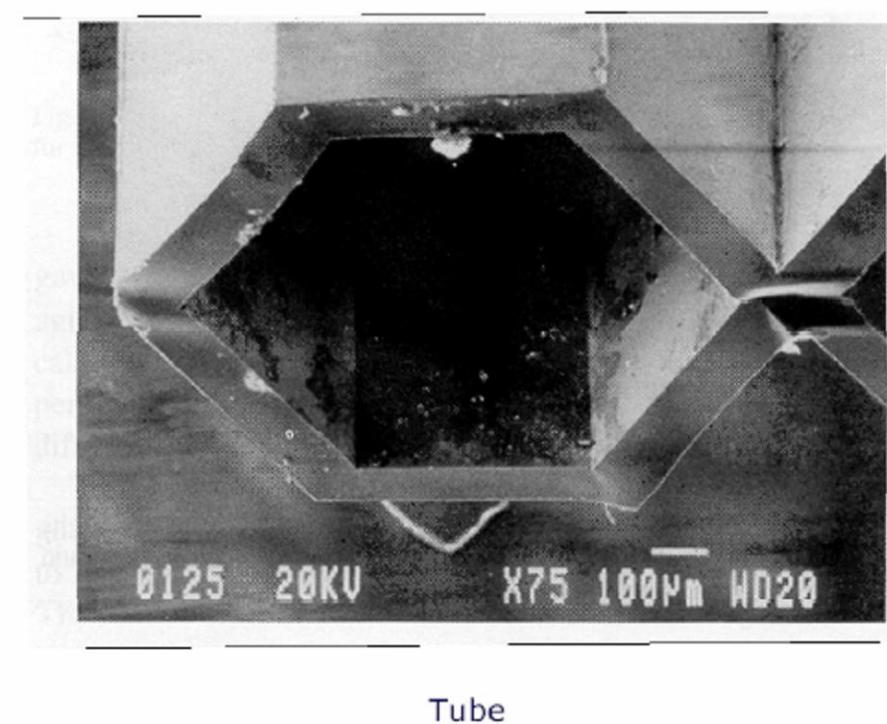
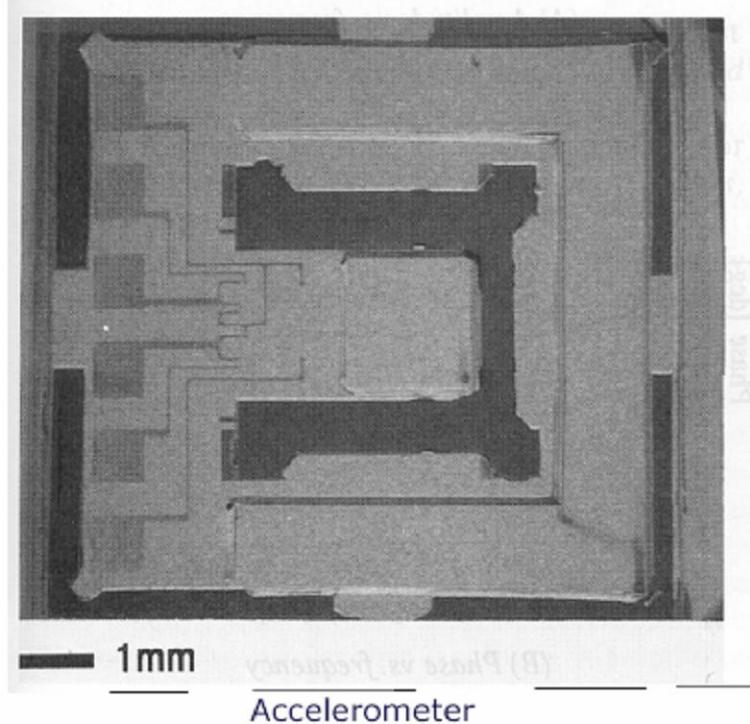
(100) Si Wet Etch (3)

- 45° rotated rectangular corner compensation for mesa structure fabrication



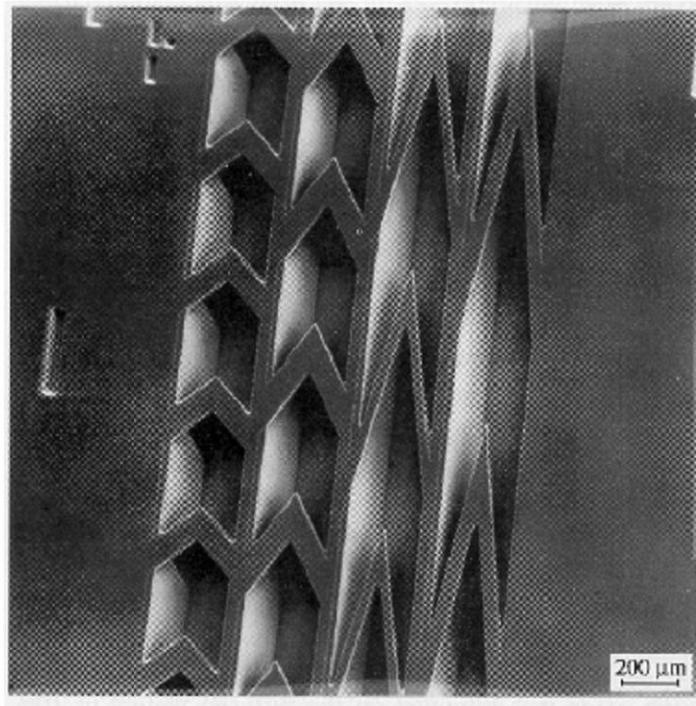
Examples of (100) Si Wet Etch (1)

- Application examples (1)

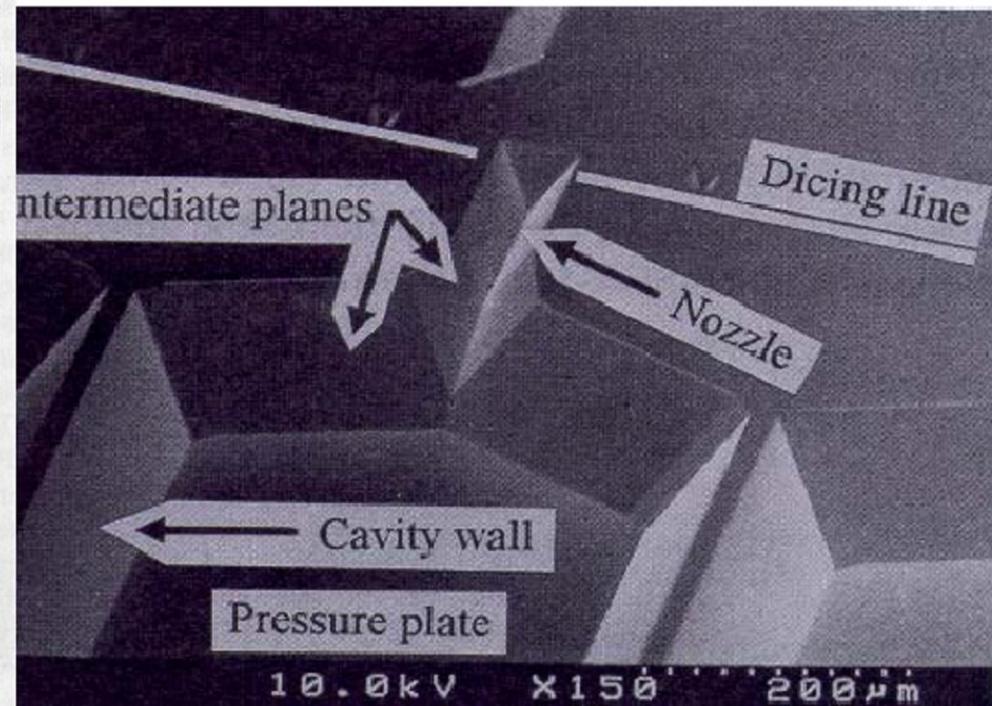


Examples of (100) Si Wet Etch (2)

- Application examples (2)



Holding structure over v-grooves



Ink jet printer nozzle

Wet Etch Mask (1)

- Mask materials
 - Silicon dioxide
 - Thermal film is the best.
 - CVD films etch 30 % faster
 - Sputter film is poor
 -
 - Silicon nitride
 - CVD films are the best
 - Sputter film is poor
 - Gold, chromium, platinum, silver, copper, tantalum
 - resist against KOH and EDP

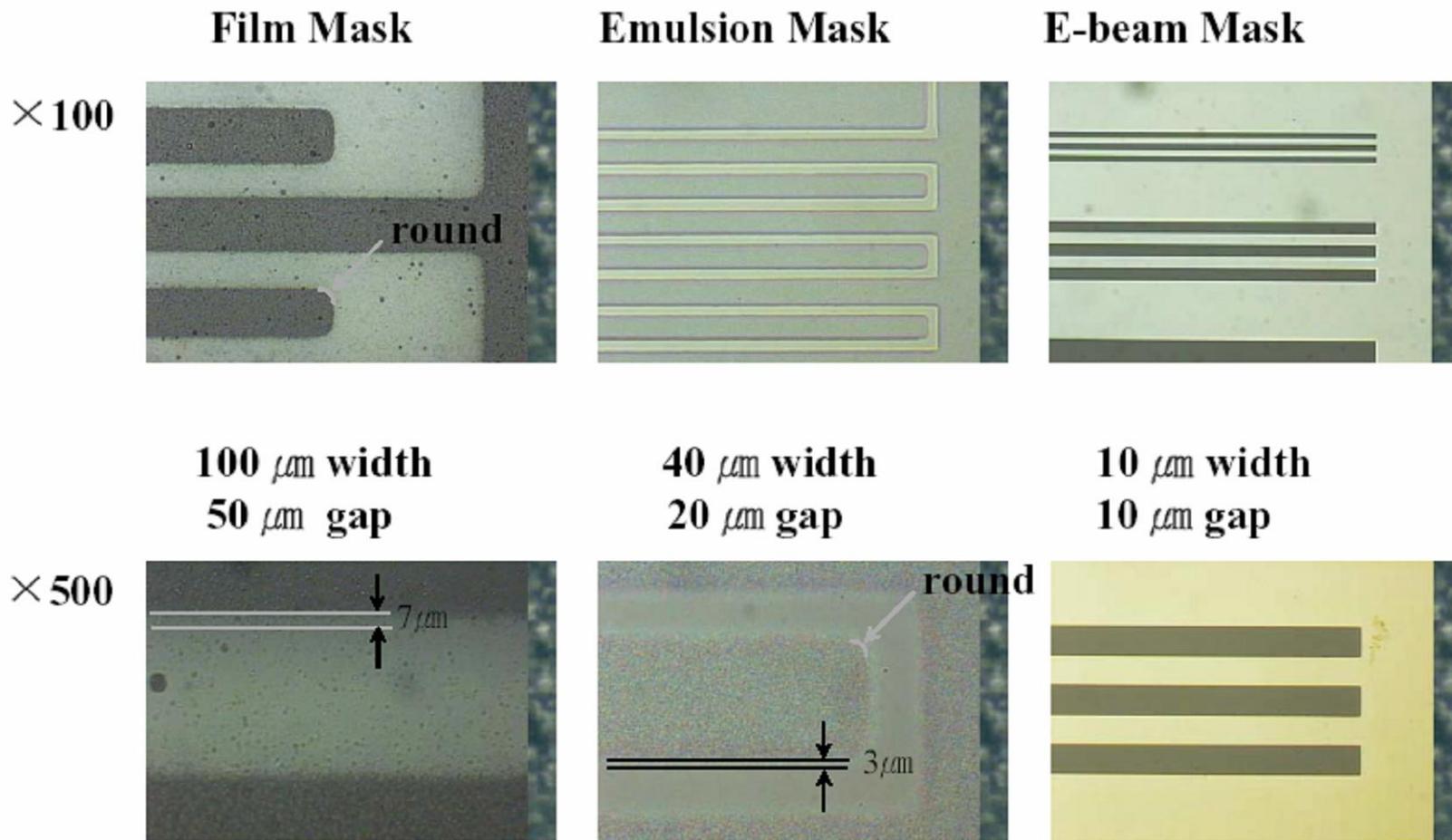
Wet Etch Mask (2)

- Etching Masks: Mask Qualities vs. Etching Properties
 - Mask qualities on etching properties
 - Resolution, CD tolerance, edge sharpness
 - Roughness on vertical sidewall profile
 - Result in selectivity

	<i>Film Mask</i>	<i>Emulsion mask</i>	<i>E-beam mask</i>
<i>resolution</i>	<i>50 μm</i>	<i>10 μm</i>	<i>1 μm</i>
<i>tolerance</i>	<i>7-8 μm</i>	<i>2-3 μm</i>	<i>0.2 μm</i>
<i>cost</i>	<i>25 \$</i>	<i>125 \$</i>	<i>1400 \$</i>
<i>contrast</i>	<i>bad</i>	<i>good</i>	<i>excellent</i>
<i>cleaning</i>	<i>No</i>	<i>No</i>	<i>Yes</i>
<i># of usage</i>	<i>several</i>	<i>less than 20</i>	<i>unlimited if cleaned</i>
<i>hardness</i>	<i>flexible</i>	<i>hard</i>	<i>hard</i>

Wet Etch Mask (3)

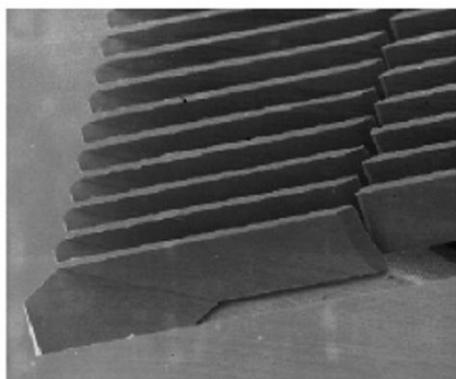
- Etching masks: comparison of mask properties



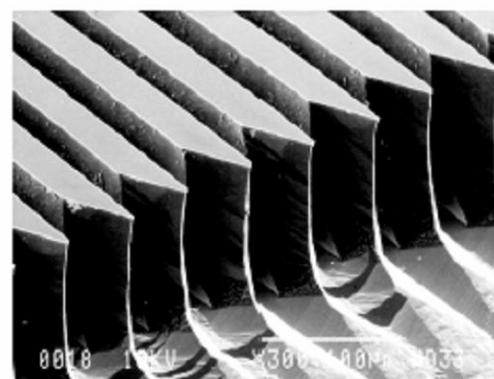
Wet Etch Mask (4)

- Etching masks: fabricated structures using different Mask

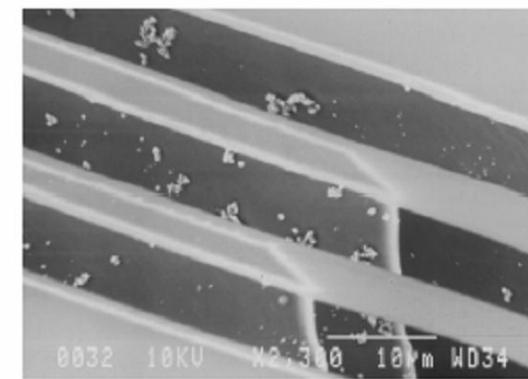
Film mask



Emulsion mask



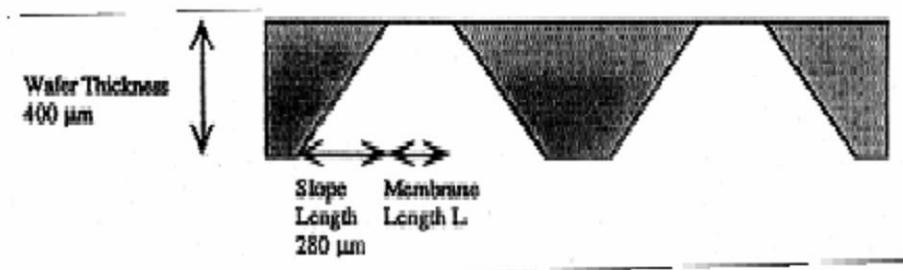
E-beam mask



Layout	100 μm width 50 μm gap	40 μm width 20 μm gap	10 μm width 10 μm gap
Fabrication	75 μm width 75 μm gap	35 μm width 25 μm gap	8 μm width 12 μm gap
Selectivity	45	55	90

Limitations of Wet Etch

- Processing yield: dependent with etch stop method
 - Time etch stop is simple but not reliable
 - Electrochemical etch stop is reliable but complex
- Limited Geometry Freedom (Crystal-direction Dependence)
- Extensive Real Estate Consumption & Large Dimension



- Corner Compensation
- However, for nozzles & grooves, proven mass production method (e.g. injector nozzles, ink jet printer nozzles, pressure sensors, ...)

Dry Etching (1)

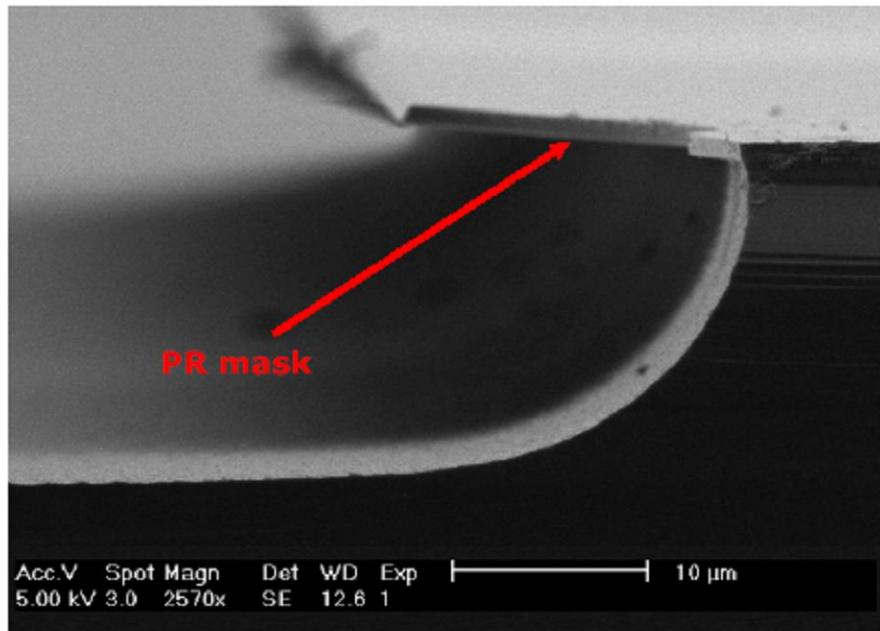
- **Xenon Difluoride Etching (XeF_2)**

- Non-plasma, isotropic dry etch process
- Very high selectivity for Al, SiO_2 , Si_3N_4 , PR
- Reaction: $2\text{XeF}_2 + \text{Si} \rightarrow 2\text{Xe} + \text{SiF}_4$
- Etch rate: $1 \sim 3 \mu\text{m/min}$
- Drawback: Rough surface
 - reaction with water (HF)
 - silicon fluoride polymer
- Use of BF_3 ~ much smooth surface

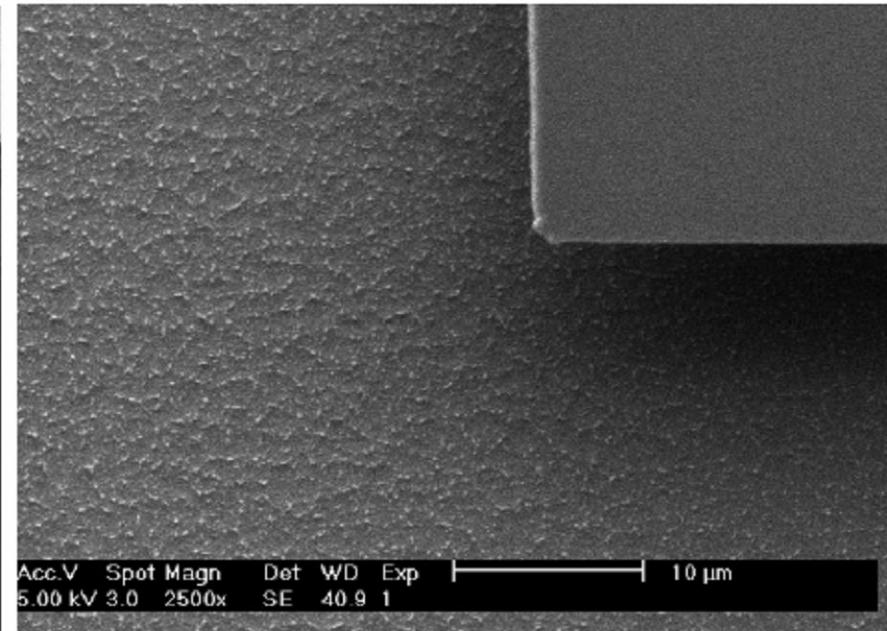


XeF_2 etcher at ISRC

Example of isotropic Dry Etching



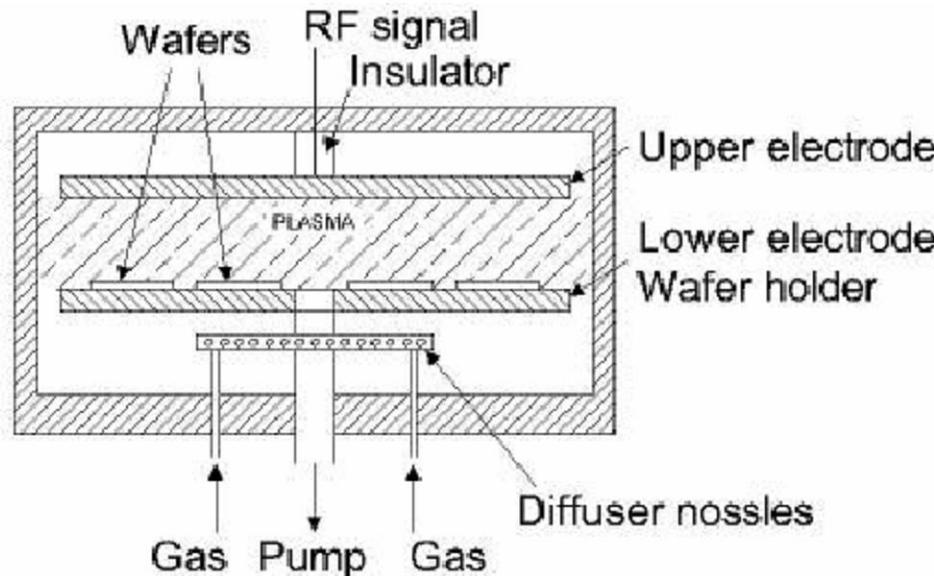
Undercut shape



Etched silicon surface

Dry Etching (2)

- **Plasma/Reactive Ion Etching (RIE)**
 - anisotropic dry etch process
 - Process in which chemical etching is accompanied by ion bombardment
 - Combination of physical and chemical etching



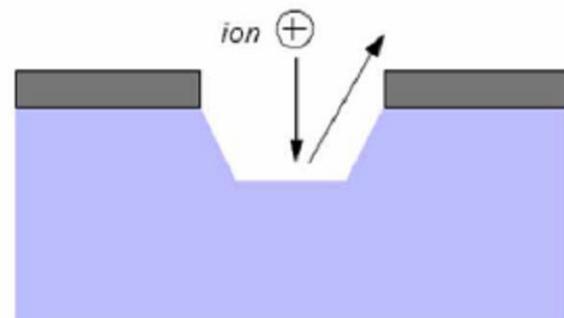
Typical parallel-plate reactive ion etching system

RIE principles (1)

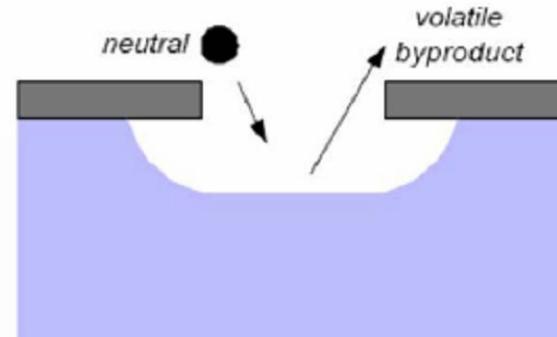
	Plasma Etching		Reactive Etching		Physical Etching	
	Barrel Reactor	Planar Reactor	Ion	Ion Beam	Sputtering	Ion Beam Milling
Substrate Location	Surrounded by plasma	On grounded electrode in Plasma	On powered electrode in plasma	In beam, remote from plasma	On powered electrode in plasma	In beam, remote from plasma
Pressure (torr)	$10^{-1} \sim 1$	$10^{-1} \sim 1$	$10^{-2} \sim 10^{-1}$	$10^{-4} \sim 10^{-3}$	$10^{-5} \sim 10^{-3}$	10^{-4}
Ion energy(eV)	0	1 ~ 100	100 ~ 1000	100 ~ 1000	100 ~ 1000	100 ~ 1000
Active Species	Atoms, Radicals	Atoms, radicals, reactive ions	Radicals, reactive ions	Reactive ions	Ar ⁺ ions	Ar ⁺ ions
Products	Volatile	Volatile	Volatile	Volatile	Nonvolatile	Nonvolatile
Mechanism	Chemical	Chemical/ Chemical-Physical	Chemical/ Physical	Chemical/ Physical	Physical	Physical
Etch Profile	Isotropic	Isotropic/ Anisotropic	Isotropic/ Anisotropic	Anisotropic	Anisotropic	Anisotropic
Selectivity	30 : 1 - 10 : 1	10 : 1 - 5 : 1	30 : 1 - 5 : 1	10 : 1 - 3 : 1	1 : 1	1 : 1
Resist Compatibility	Excellent	Excellent	Good	Good	Poor	Poor
Device Damage	Little	Little	Some possible	Some possible	Very possible	Very possible
Etch Rate (micrometer/min)	0.1 ~ 0.5	0.1 ~ 0.5	0.05 ~ 0.1	0.05 ~ 0.1	0.02 ~ 0.05	0.02 ~ 0.05
Resolution (micrometers)	3	2	1 ~ 2	1 ~ 2	0.5 ~ 1	0.5 ~ 1

RIE principles (2)

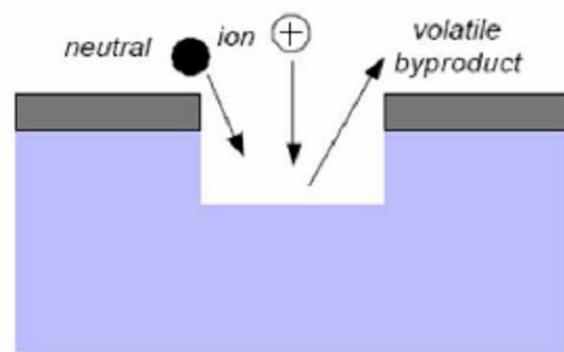
- Mechanism of RIE (Reactive Ion Etching)



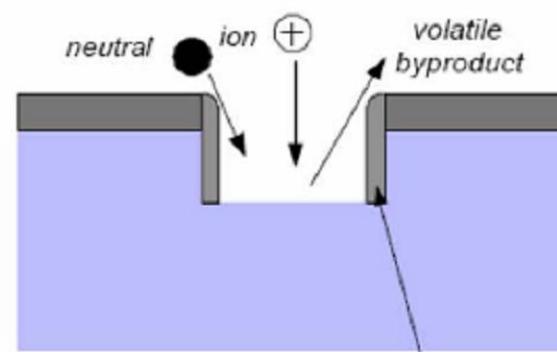
sputtering



chemical



ion-enhanced energetic



ion-enhanced inhibitor

- Gas Type, Chamber, Ion Generation in fluencies

Mask materials for RIE

- Etch mask: PR (Photo Resist), Hard mask (SiO_2 , Al)
- Selectivity
 - = etch rate of etching material / etch rate of mask
- Usually, standard PR (for CMOS) is not adequate for O_2 plasma etch, for which hard mask is required
- Selectivity of silicon: AZ1512
 - Cl based etch (physical etch): <2
 - F based etch (chemical etch): <10
(if O_2 gas is inserted into the chamber, the selectivity would be smaller than 10)

Reaction in RIE process (1)

- Reactants
 - Cl-based
 - Sputtering or ion-enhanced etch mechanism
 - High anisotropy
 - Low selectivity
 - Cl_2 , BCl_3
 - F-based
 - Chemical etch mechanism
 - High selectivity
 - High etch rate
 - Isotropic etching
 - SF_6

Reaction in RIE process (2)

- An example of RIE mechanisms (Cl based)

Ion and electron formation



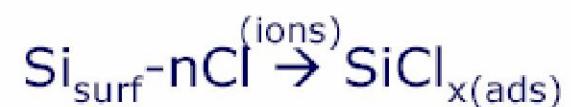
Etchant formation



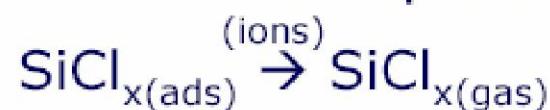
Adsorption of etchant on the substrate



Reaction on surface

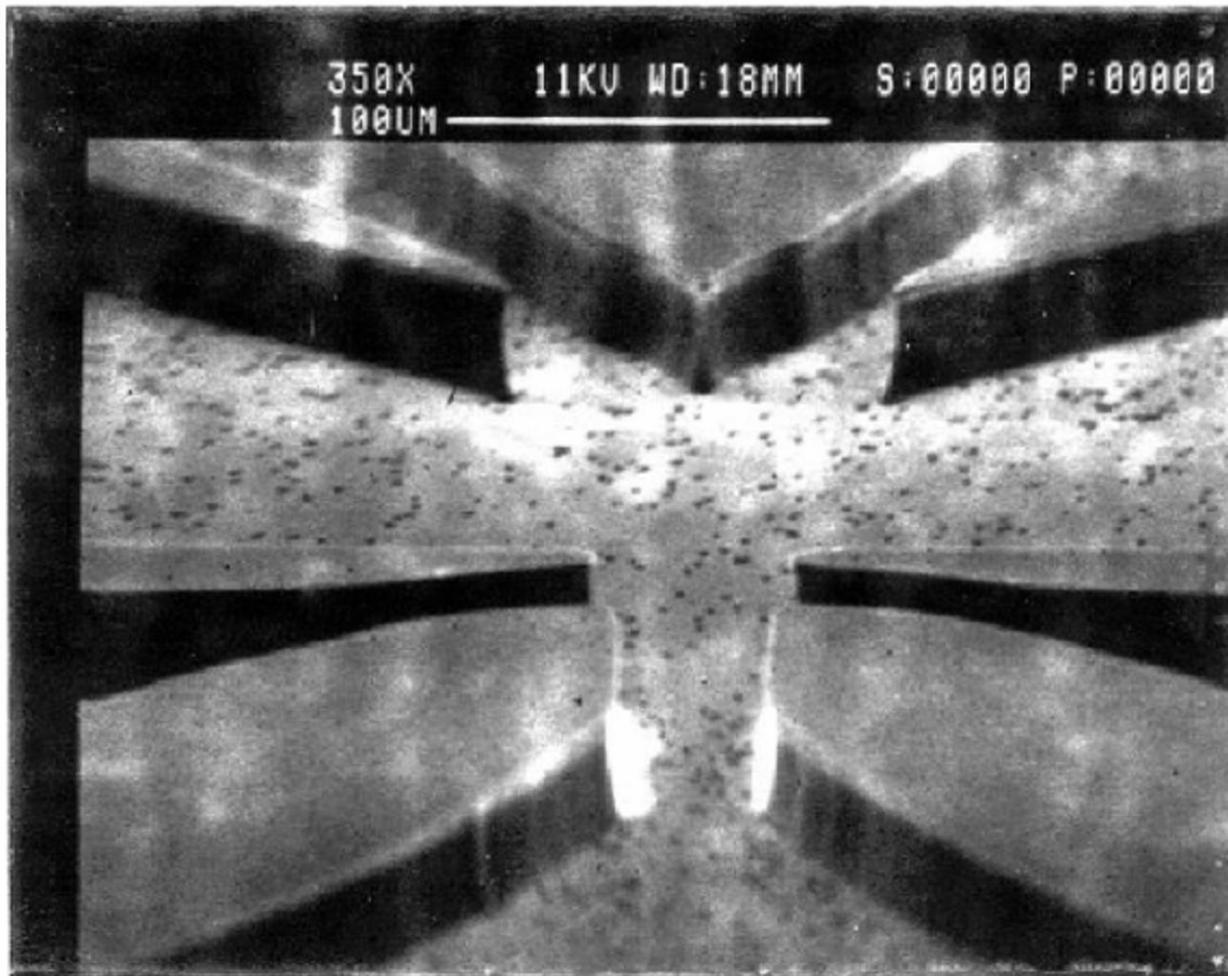


Product desorption



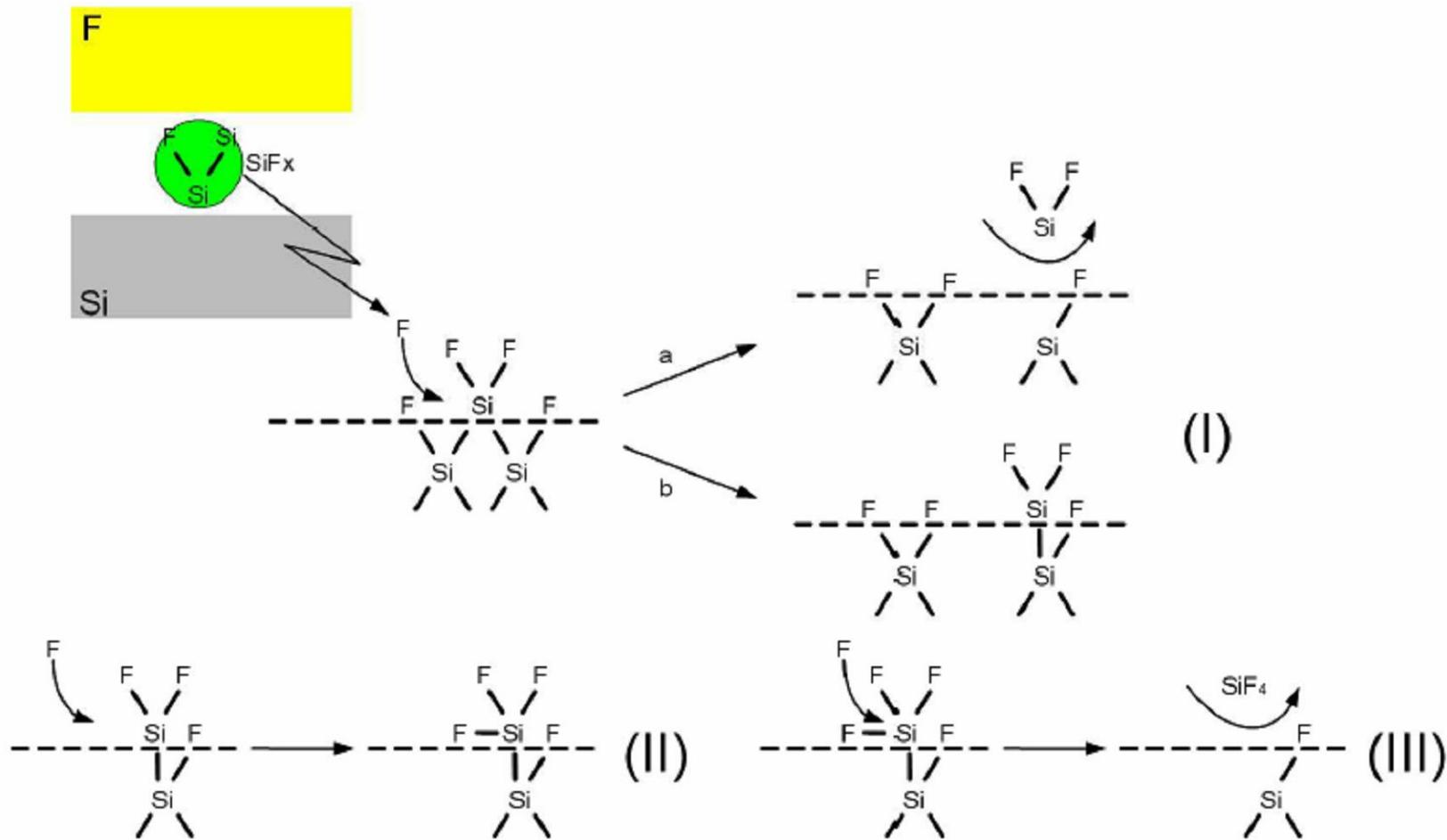
Example using BCl_3

- Fabrication example (proportional amplifier)



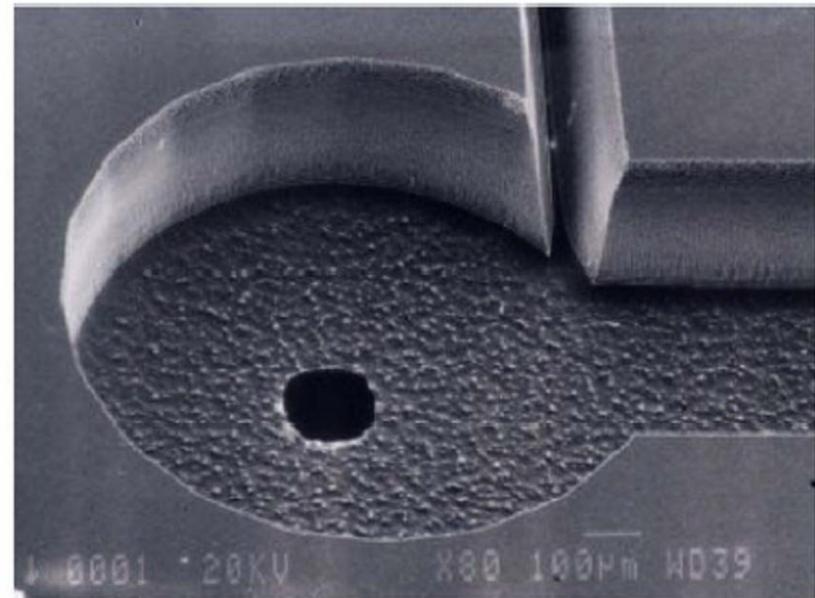
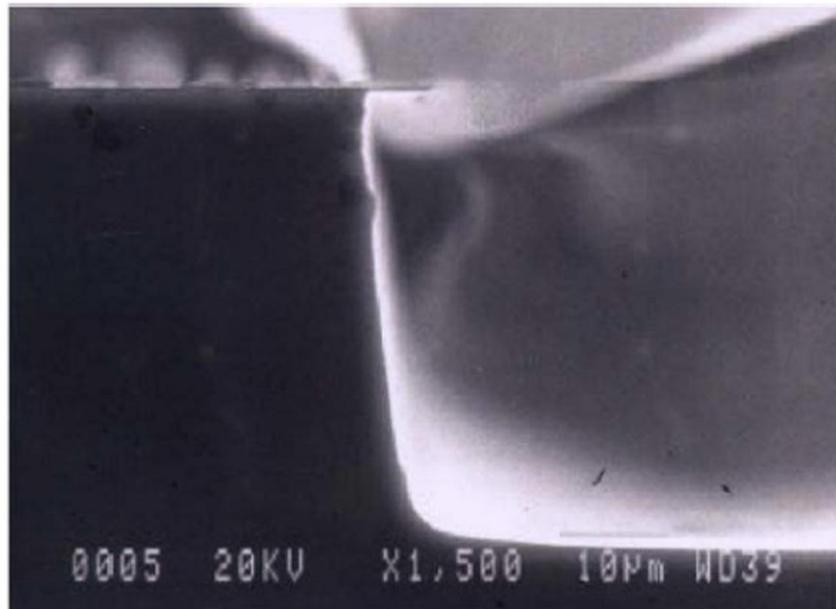
Reaction in RIE process (3)

- An example of RIE mechanisms (F based Si etch)



Example using SF₆

- Fabrication example (vortex amplifier)



Wet etching vs. Dry etching

- In wet etchants, the etch reactants come from a liquid source
- In dry etchants, the etch reactants come from a gas or vapor phase source and are typically ionized
 - Atom or ions from the gas are the reactive species that etch the exposed film
- Selectivity: in general, dry etching has less selectivity than wet etching
- Anisotropy: in general, dry etching has higher degree of anisotropy than wet etching
- Etch rate: in general, dry etching has lower etch rate than wet etching
- Etch control: dry etching is much easier to start and stop than wet etching