Lecture 21, 22:

Silicon Wet Etching

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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 (2)

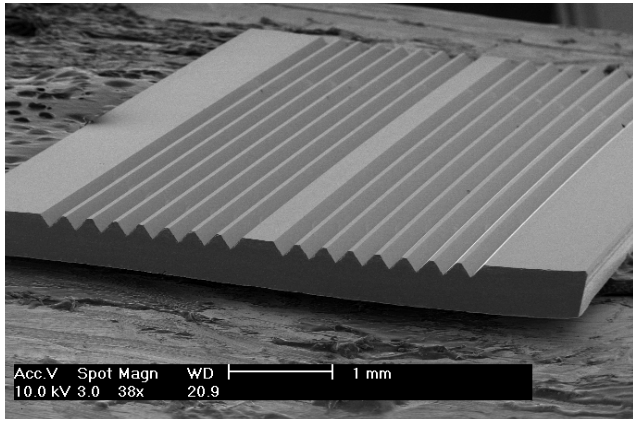
- Comparison of example bulk silicon etchant

	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 (μm /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

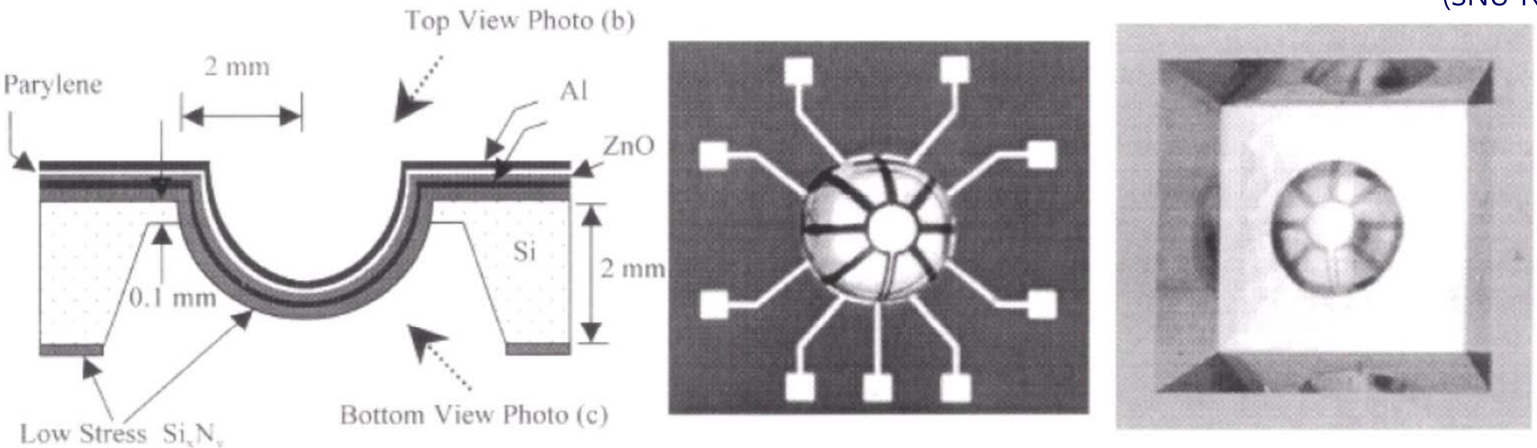
Ref.) K. R. Williams, and R. S. Muller, JMEMS, Vol. 5, No. 4, pp. 256-269, 1996
Marc J. Madou, "Fundamentals of MICROFABICATION," 2nd edition

Isotropic & Anisotropic Etch

- Isotropic wet etching
  - Etching with chemical reaction
    → etching in all directions
- Anisotropic wet etching
  - Anisotropic etchants etch much faster in one direction than in another
    → exposing the slowest etching crystal planes ((111) planes) over time

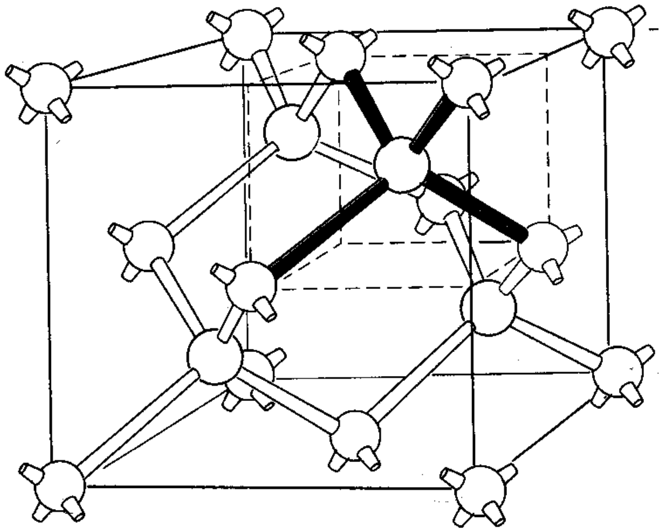


Example of anisotropic wet etching:
optical bench using (100) silicon
(SNU NML)

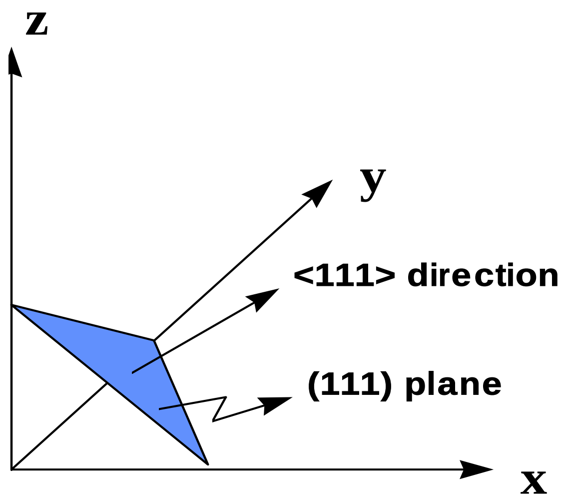


Example of isotropic wet etching: dome shaped diaphragm microphone
Ref) E. Kim, MEMS '99, pp. 505-510, 1999

Silicon Crystallography (1)



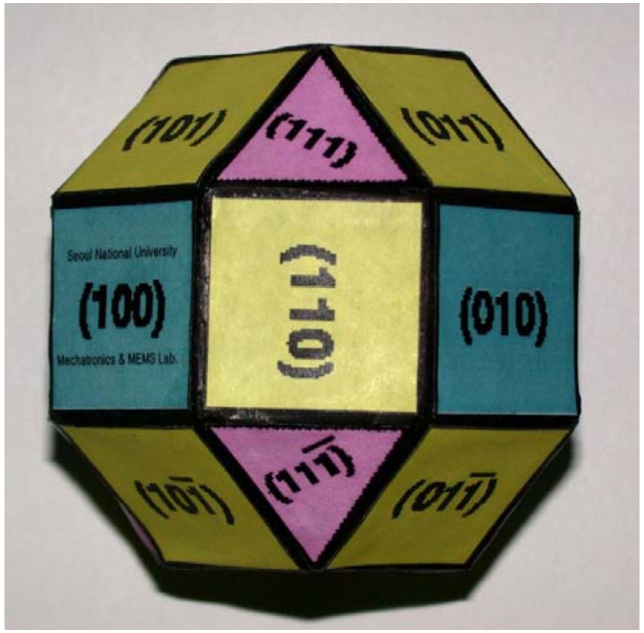
Si crystalline structure



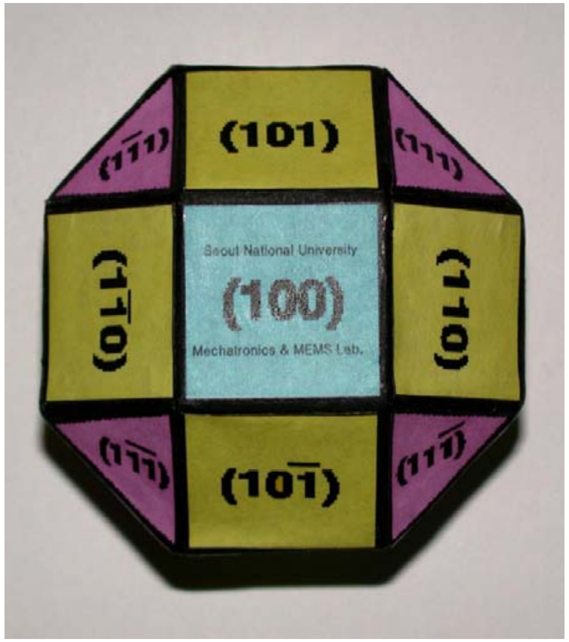
- Miller indices
  - (i j k) : a specific crystal plane or face
  - {i j k} : a family of equivalent planes
  - [i j k] : a specific direction of a unit vector
  - <i j k> : a family of equivalent directions

Silicon Crystallography (2)

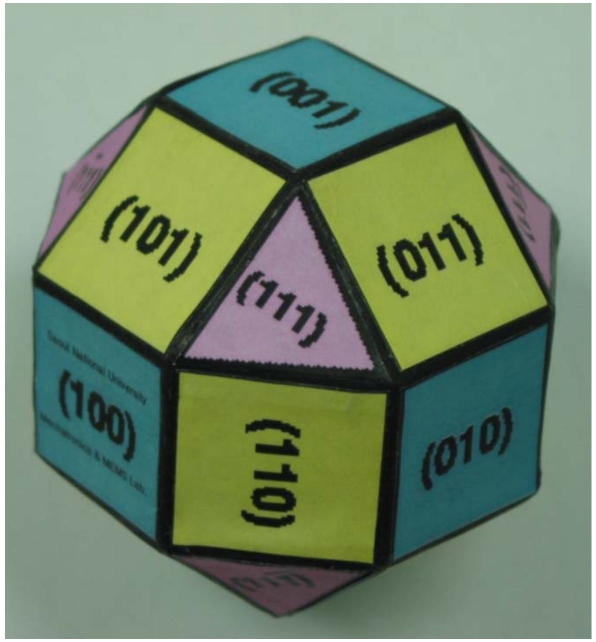
(110) silicon



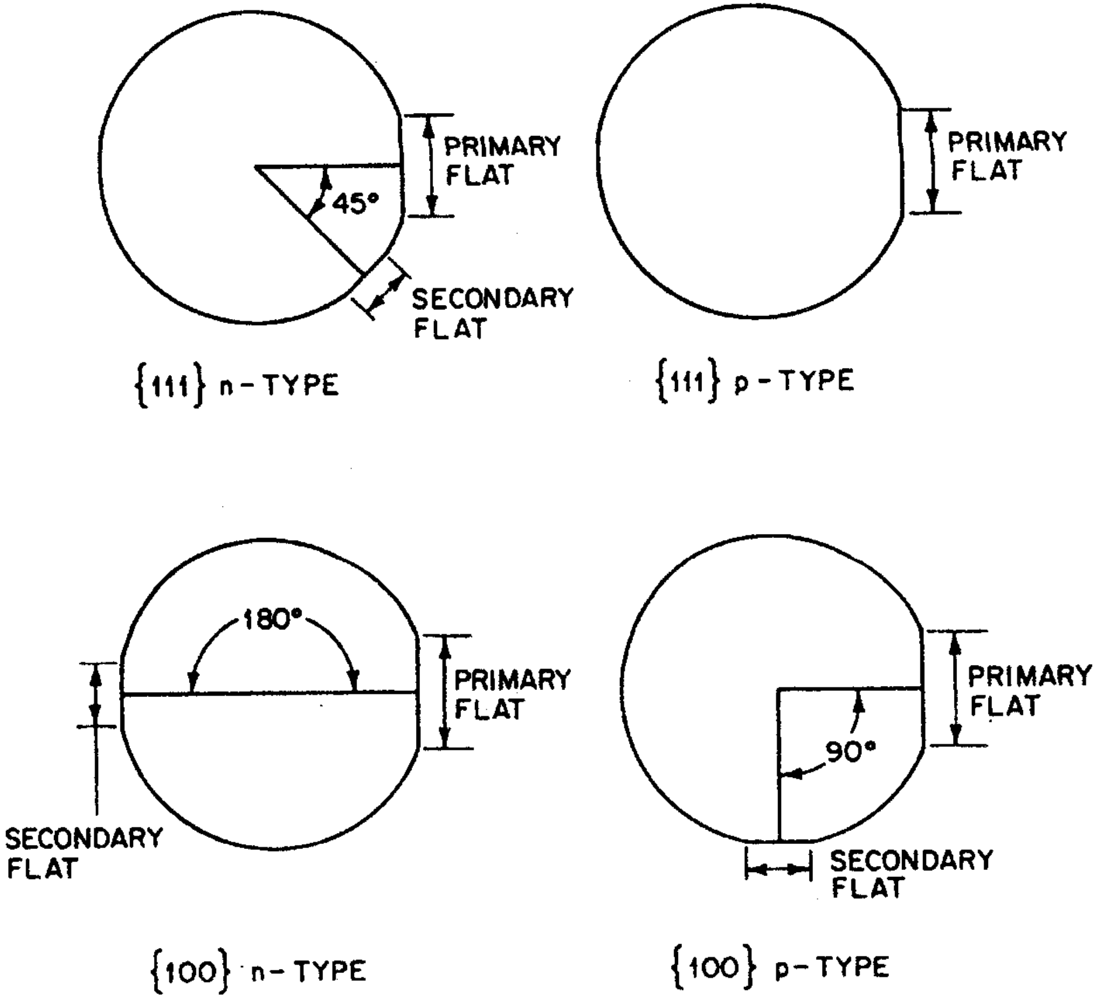
(100) silicon

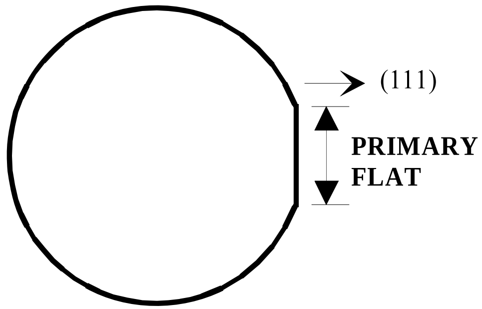


(111) silicon



Wafer Type

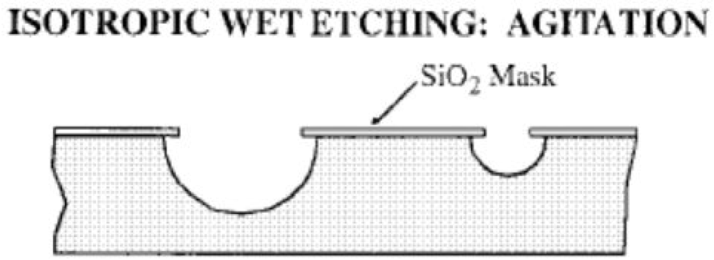


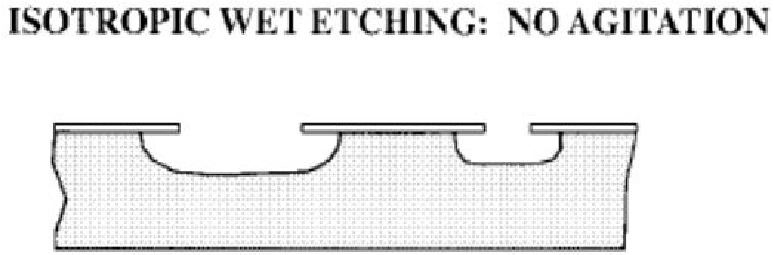


(110) wafer secondary flat is different from company to company

Isotropic Wet Etching (1)

- Si isotropic etching by HNA
  - HNA: **H**ydrofluoric acid + **N**itric acid + **A**cetic acid
  - Isotropic etchant
  - $Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2$
  - HNO_3: oxidize silicon
  - HF: F ion forms the soluble compound, H_2SiF_6
  - CH_3COOH: Prevent dissociation of HNO_3 into NO_3 or NO_2
    → thereby allowing formation of the species directly responsible for the oxidation of Si: $N_2O_4 \leftrightarrow 2NO_2$
  - Drawback: Poor selectivity over SiO_2





Isotropic Wet Etching (2)

- Electrochemical reaction in HNA etching
  - Injection of holes into Si to form Si2+

$$HNO_3 + H_2O + HNO_2 \rightarrow 2HNO_2 + 2OH^- + 2h^+$$

$$Si + 2h^+ \rightarrow Si^{2+}$$

  - Reaction of hydrated Si to form SiO_2

$$Si^{2+} + 2OH^- \rightarrow Si(OH)_2 \rightarrow SiO_2 + H_2O$$

  - Dissolution of SiO_2 and formation of water soluble product

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

Overall reaction is,

$$2e^- + HNO_2 + HNO_3 + H_2O \rightarrow 2HNO_2 + 2OH^-$$

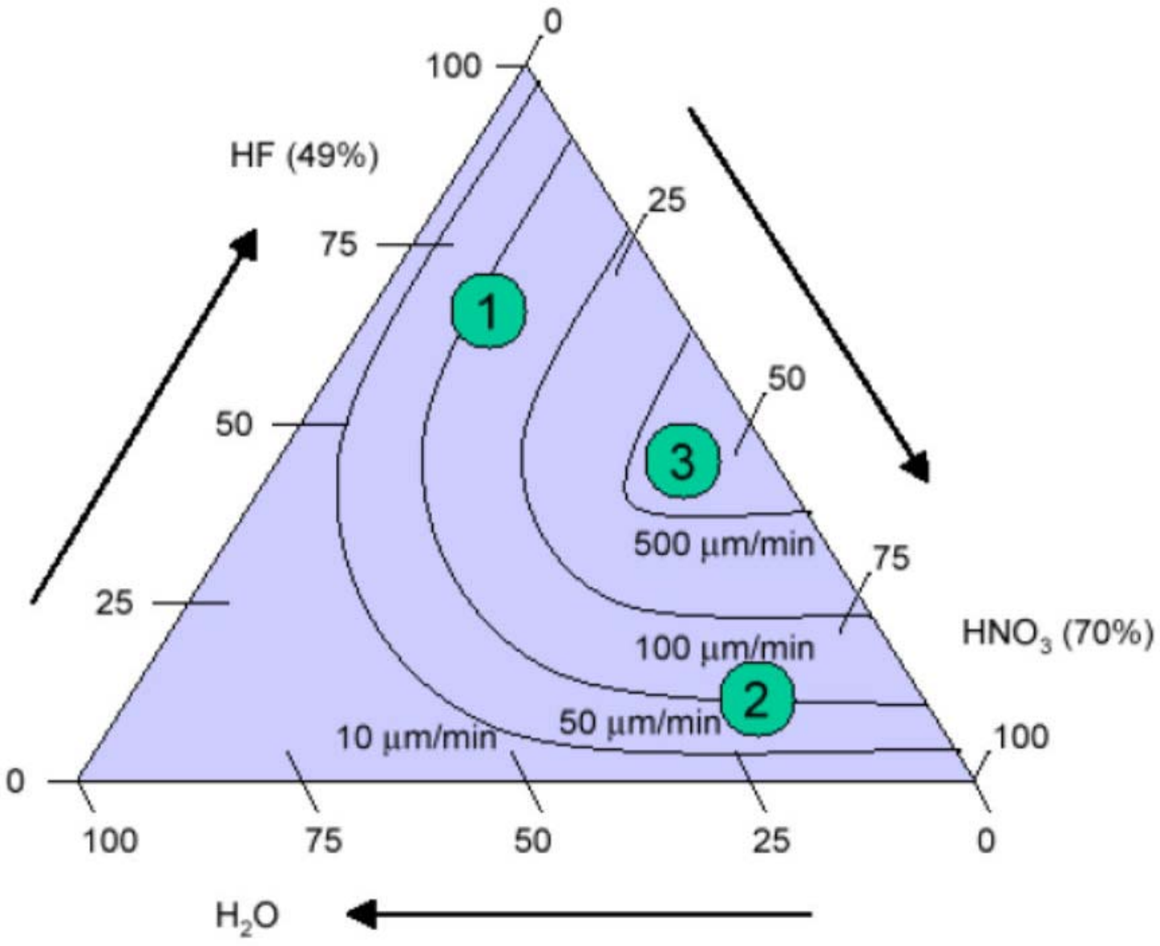
Which can be rewritten,

$$HNO_2 + HNO_3 + H_2O \rightarrow 2HNO_2 + 2OH^- + 2h^+$$

→ Etching is "Charge-transfer-driven process"

Isotropic Wet Etching (3)

- Isoetch contours



Isotropic Wet Etching (4)

- Region (1)
  - For high HF concentrations, contours are parallel to the lines of constant HNO_3, therefore the etch rate is controlled by HNO_3 in this region
  - Leaves little residual oxide
- Region (2)
  - For high HNO_3 concentrations contours are parallel to the lines of constant HF, therefore the etch rate is controlled by HF in this region
  - Leaves a residual 300~500 nm of oxide
- Region (3)
  - Initially not very sensitive to the amount of H_2O, then etch rate falls of sharply for 1:1 HF:HNO_3 ratio

Isotropic Wet Etching (5)

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					

Table of HNA etchant formulations

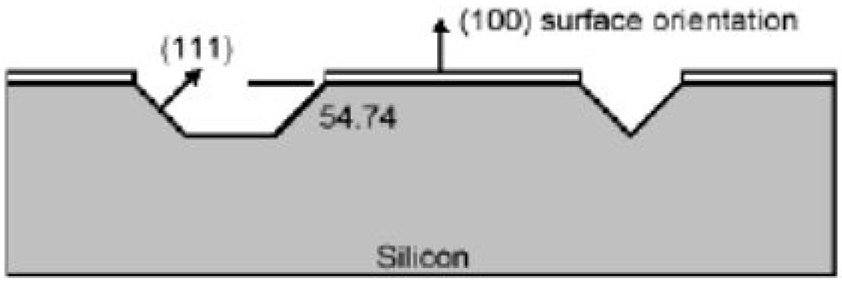
Ref.) Kurt E. Petersen, Proceedings of The IEEE, 70(5), pp. 420-457, 1982

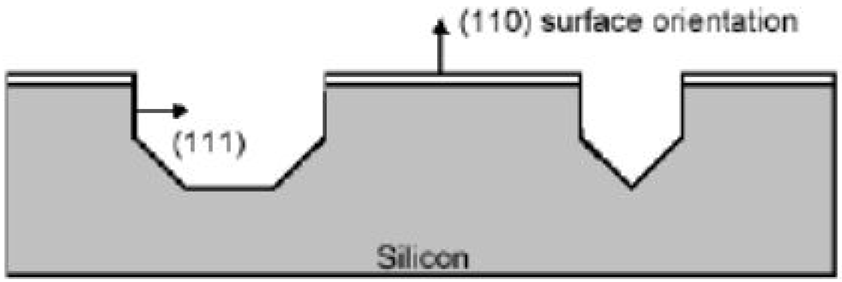
Anisotropic Wet Etching (1)

- Anisotropic wet etching
  - Anisotropic etchants etch much faster in one direction than in another

    → Exposing the slowest etching crystal planes over time

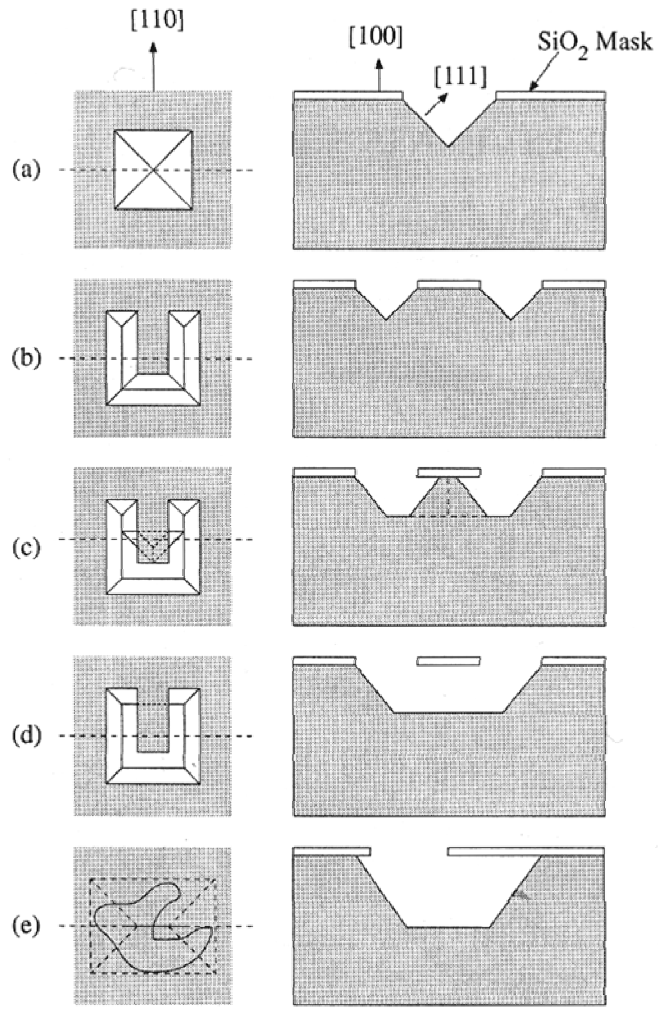
    → (111) planes have the slowest etch rate
  - Several solutions: Alkalic OH (KOH, NaOH), TMAH, EDP
  - Etching at concave corners on (100), stop at (111) intersections, convex corners are under cut



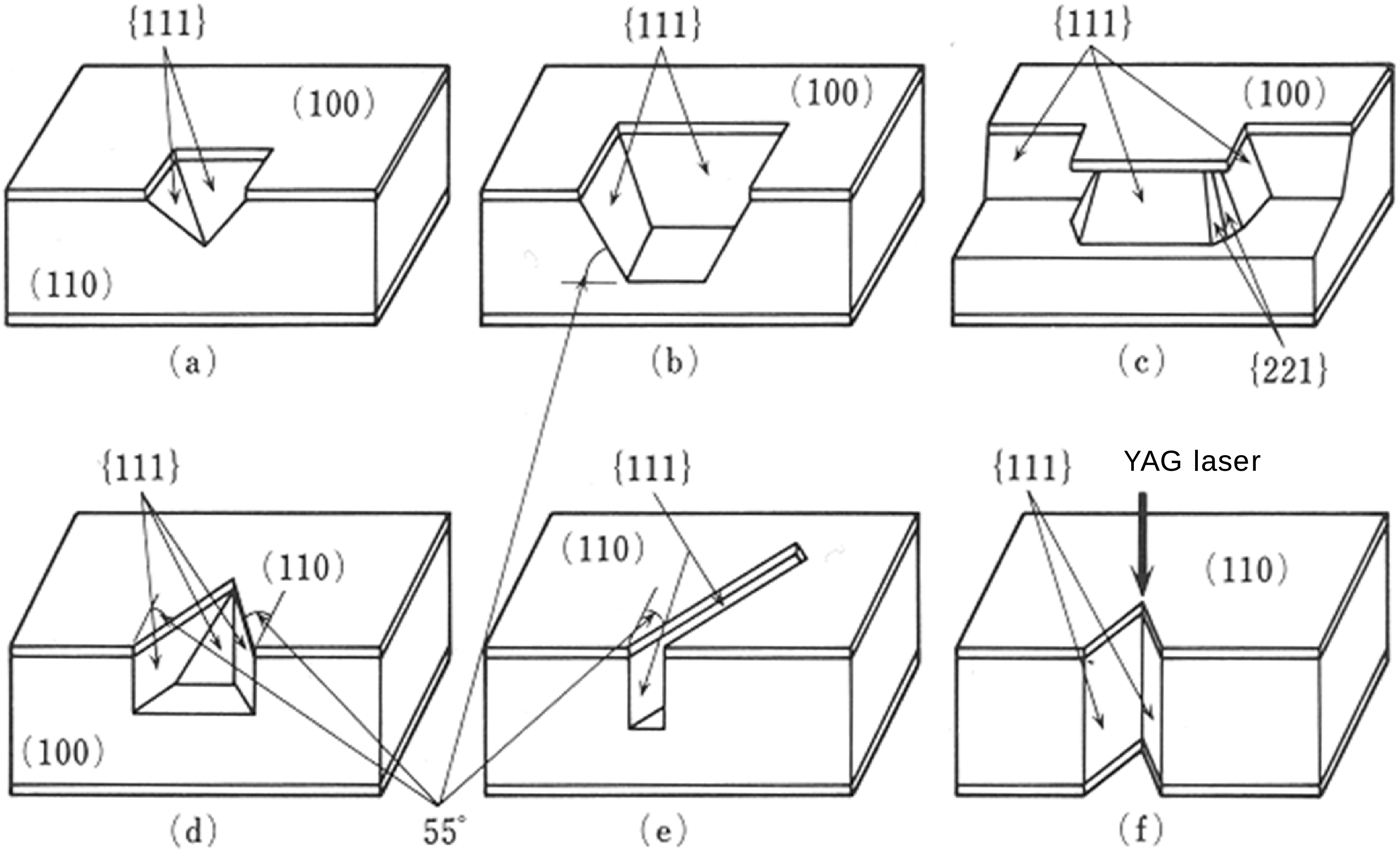


Anisotropic Wet Etching (2)

- Examples of anisotropic etching
  - (a) typical pyramidal pit bounded by (111) planes, etched into (100) silicon with an anisotropic etch through a square hole in an oxide mask
  - (b) cantilever mask pattern 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 such as EDP
  - (d) further etching of (c) produces a cantilever beam suspended over pit
  - (e) illustration of the fact that anisotropic etch undercutting converges to predictable shapes after a sufficiently long time



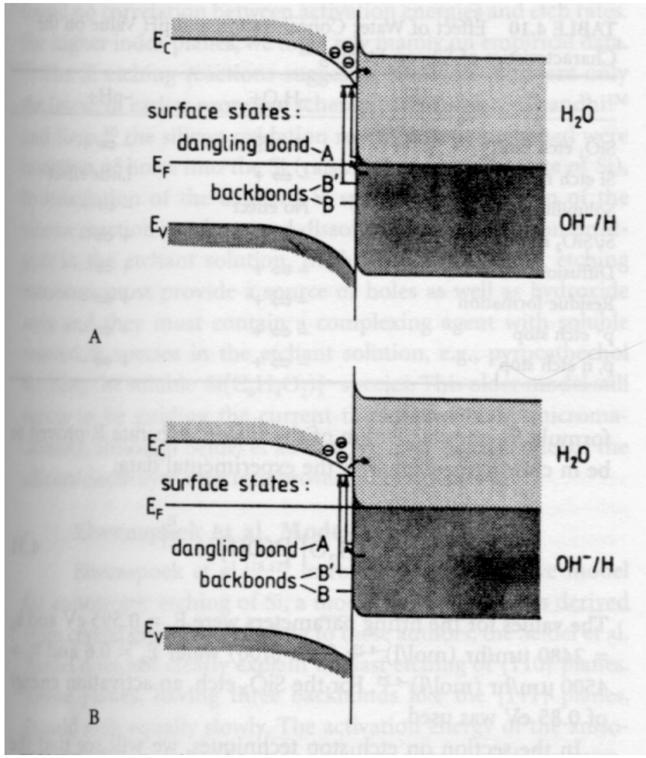
Anisotropic Wet Etching (3)



Silicon anisotropic wet etching of (100) and (110) silicon

Anisotropic Wet Etching Mechanism (1)

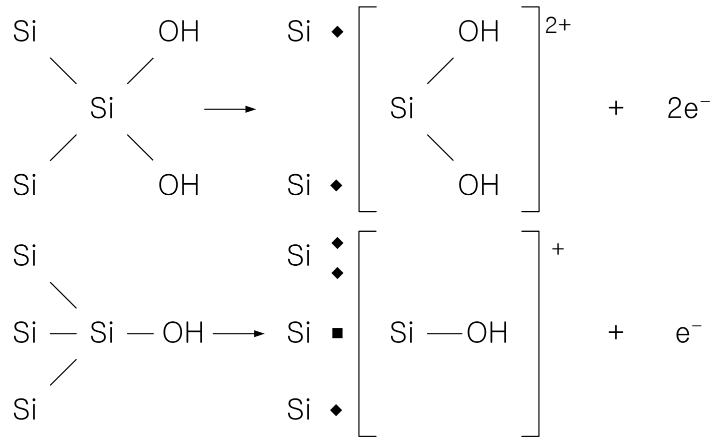
- H. Seidel et al.
  - Band model of the silicon/electrolyte interface for moderately doped Si



Band model of the Si/electrolyte interface
(A) p-type Si, (B) n-type Si

$$\begin{cases} 4H_2O + 4e^- \rightarrow 4H_2O^- \\ 4H_2O^- \rightarrow 4OH^- + 4H^+ + 4e^- \rightarrow 4OH^- + 2H_2 \end{cases}$$

$$\begin{cases} Si + 2OH^- \rightarrow Si(OH)_2^{2+} + 2e^- \\ Si(OH)_2^{2+} + 2OH^- \rightarrow Si(OH)_4 + 2e^- \\ Si(OH)_4 + 4e^- + 4H_2O \rightarrow Si(OH)_6^{2-} + 2H_2 \end{cases}$$



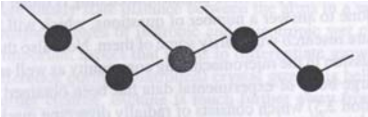
(100) Si

(111) Si

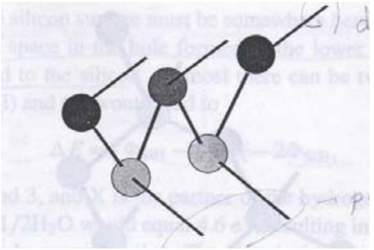
Ref.) H. Seidel, et al., J. Electrochem. Soc., vol. 137, no. 11, Nov. 1990

Anisotropic Wet Etching Mechanism (2)

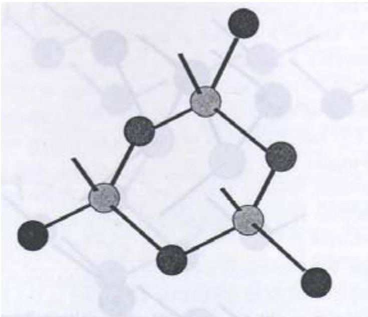
- M. Elwenspoek et al.
  - Explained the etching mechanism by the crystal growth theory
  - {111} plane has slow etch rate ← {111} plane is the smooth face



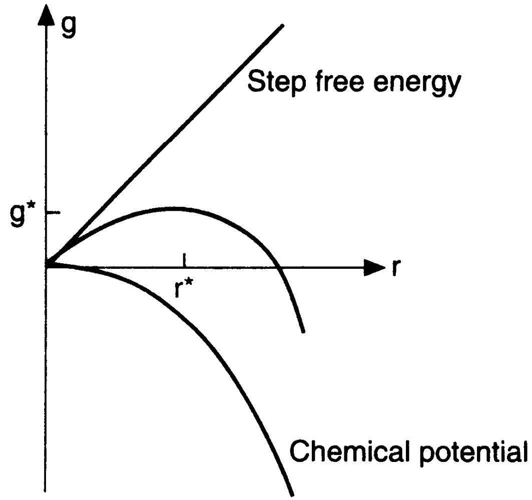
{100} plane



{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

Si Anisotropic Etchants

	Alkali-OH	EDP(ethylene diamine pyrocatechol)	TMAH (tetramethyl ammonium hydroxide)
Si etch rate ㎛/min	1 to 2	1 to 30	~1
Si roughness	Low	Low	variable[1]
Nitride etch	Low	Low	1 to 10 nm/min
Oxide etch	1 to 10 nm/min	1-80 nm/min	1 nm/min
Al selective	No	No[2]	Yes[3]
Au selective	Yes	Yes	Yes
P++ etch stop ?	Yes	Yes	Yes
Electrochemical stop ?	Yes	Yes	Yes
CMOS compatible ?[4]	No	Yes	Yes
Cost[5]	Low	Moderate	Moderate
Disposal	Easy	Difficult	Moderate
Safety	Moderate	Low	High

1 Varies with wt% TMAH, can be controlled to yield very low roughness.
2 Some formulations do not attack Al, but are not common.
3 With added Si, polysilicic acid or pH control.
4 Defined as 1) allowing wafer to be immersed directly with no special measures and 2) no alkali ions.
5 Includes cost of equipment.

Hydroxide Etching of Si

- Several hydroxides are useful
  - KOH, NaOH, CeOH, RbOH, NH_4OH, TMAH: $(CH_3)_4NOH$
- Oxidations of silicon by hydroxyls to form a silicate

$$Si + 2OH^- + 4h^+ \rightarrow Si(OH)_2^{++}$$

- Reduction of wafer

$$2H_2O \rightarrow 4OH^- + 2H_2 + 4h^+$$

- Silicate further reacts with hydroxyls to form a water soluble complex

$$Si(OH)_2^{++} + 4OH^- \rightarrow SiO_2(OH)_2^{2-} + 2H_2O$$

- Overall redox reaction

$$Si + 2OH^- + 4H_2O \rightarrow Si(OH)_2^{++} + 2H_2 + 4OH^-$$

KOH Etching of Si (1)

- Typical and most used of the hydroxide etches
- Etch rate
  - ~1 um/min for (100) Si planes
  - Slow down for boron-doping levels above 2 x 10^{19} cm^{-3}
  - ~ 140 nm/hr for silicon nitride
  - ~ 200 nm/min for oxide
- Anisotropy

$$(111):(110):(100) \approx 1:600:400$$

KOH Etching of Si (2)

- Simple hardware
  - Hot plate & stirrer
  - Keep cover or use reflux condenser to keep propanol from evaporating

- Presence of alkali metal (potassium, K) makes this completely incompatible with MOS or CMOS processing

- Comparatively safer and non-toxic

KOH Etching of Si (3)

- Typical recipe and etch rate of KOH Si etching

Formulation	Temp °C	Etch rate (㎛/min)	(100)/(111) Etch ratio	Masking films (etch rate)
KOH (44 g) Water, isopropanol (100 ml)	85	1.4	400:1	SiO_2 (1.4 nm/min) Si_3N_4 (negligible)
KOH (50 g) Water, isopropanol (100 ml)	50	1.0	400:1	SiO_2 (1.4 nm/min) Si_3N_4 (negligible)

TMAH Etching of Si (1)

- **T**etra **M**ethyl **A**mmonium **H**ydroxide: $(CH_3)_4$ NOH
- Etch rate: 0.5 ~ 1.5 um/min
- Etch rate falls off ten times at 10^{20} cm^{-3} boron concentration
  → B solid solubility in Si: 2.5 x 10^{20} cm^{-3}
- Al etch rate 1 um/min → 1 nm/min, when pH 13→ pH 12 (for 22 wt% TMAH)
- MOS/CMOS compatible
  - No alkali metals: Li, Na, K, …
  - Used in positive photoresist developers which do not use choline.
  - Does not significantly etch SiO_2 or Al! (Bond wire safe!)
- Anisotropy: (111):(100) ≈ 1:10 to 1:35

TMAH Etching of Si (2)

- Hydroxide etches are generally safe and predictable, but they usually involve an alkali metal which makes them incompatible with MOS or CMOS processing.

- Ammonium hydroxide (NH_4OH) is one hydroxide which is free of alkali metal, but it is really ammonia which is dissolved into water. Heating to 90°C for etching will rapidly evaporate the ammonia from solution.

- Ballasting the ammonium hydroxide with a less volatile organic solves the problem:
  - Tetramethyl ammonium hydroxide: $(CH_3)_4NOH$
  - Tetraethyl ammonium hydroxide: $(C_2H_5)_4NOH$

TMAH Etching of Si (3)

- Selectivity of TMAH etchants

Selectivity of TMAH Etchants for Various Dielectrics versus (100) Silicon			
Dielectric	Selectivity 4 wt% TMAH, 80°C	Selectivity (Si-doped, 13.5g/l), 4 wt% TMAH, 80°C	Selectivity 20 wt% TMAH, 95°C
Thermal Silicon Dioxide	5.3×10^3	34.7×10^3	5.2×10^3
Low-Temperature Oxide (LTO)	1.3×10^3	4.2×10^3	2.8×10^3
PECVD Oxide	1.4×10^3	4.3×10^3	No value given
LPCVD Silicon Nitride	24.4×10^3	49.3×10^3	38×10^3
PECVD Silicon Nitride	9.2×10^3	18.5×10^3	3.6×10^3

Ammonium Hydroxide Wet Etching

- NH_4OH (ammonium hydroxide)
- CMOS compatibility
- Several recipes
  - 9.7 wt% NH_4OH in H_2O
    - (110) silicon etch rate: 0.11um/min at 85 ~ 92 ℃
  - 1~18 wt% NH_4OH at 75 ℃
    - (100) max. etch rate: 30 um/h
    - Rough surface

- Disadvantage
  - Slow etch rate, hillock formation
  - Rapid evaporative losses of ammonia gas (noxious) when heated

EDP Etching of Si (1)

- **E**thylene **D**iamine **P**yrocatechol
- Also known as **E**thylene diamine-**P**yrocatechol–**W**ater (EPW)
- EDP etching is readily masked by SiO_2, Si_3N_4, Au, Cr, Ag, Cu, and Ta

  → But EDP can etch Al!

- Anisotropy: (111):(100) ≈ 1:35

- EDP is very corrosive, very carcinogenic, and never allowed near mainstream electronic microfabrication.

- 50 times slowing of etch rate for > 7 x 10^{19} cm^{-3} boron doping

EDP Etching of Si (2)

- Typical formulation
  - 1 L ethylene diamine, $NH_2\text{-}CH_2\text{-}CH_2\text{-}NH_2$
  - 160 g pyrocatechol, $C_6H_4(OH)_2$
  - 6 g pyrazine, $C_4H_4N_2$
  - 133 mL H_2O

- Ionization of ethylene diamine

$$NH_2(CH_2)_2NH_2 + H_2O \rightarrow NH_2(CH_2)_2NH_3+ + OH^-$$

- Oxidation of Si and reduction of water

$$Si + 2OH^- + 4H_2O \rightarrow Si(OH)_6^{2-} + 2H_2$$

- Chelation of hydrous silica

$$Si(OH)_6^{2-} + 3C_6H_4(OH)_2 \rightarrow Si(C_6H_4O_2)_3^{2-} + 6\ H_2O$$

EDP Etching of Si (3)

- Requires reflux condenser to keep volatile ingredients from evaporating.

- Completely incompatible with MOS or CMOS processing!
  - It must be used in a fume collecting bench by itself.
  - It will rust any metal in the nearby vicinity.
  - It leaves brown stains on surfaces that are difficult to remove.

- EDP has a faster etch rate on convex corners than other anisotropic etches
  - It is generally preferred for undercutting cantilevers.
  - It tends to leave a smoother finish than other etches, since faster etching of convex corners produces a polishing action.

EDP Etching of Si (4)

- Typical recipe and etch rate of KOH Si etching

Formulation	Temp °C	Etch Rate (μm/min)	(100)/(111) Etch Ratio	Masking Films (etch rate)
Ethylene diamine (759ml) Pyrocatechol (120g) Water (100ml)	115	0.75	35:1	SiO_2 (0.2 nm/min) Si_3N_4 (0.1 nm/min) Au, Cr, Ag, Cu, Ta (negligible)
Ethylene diamine (759ml) Pyrocatechol (120g) Water (240ml)	115	1.25	35:1	As above

Hydrazine Etching of Si

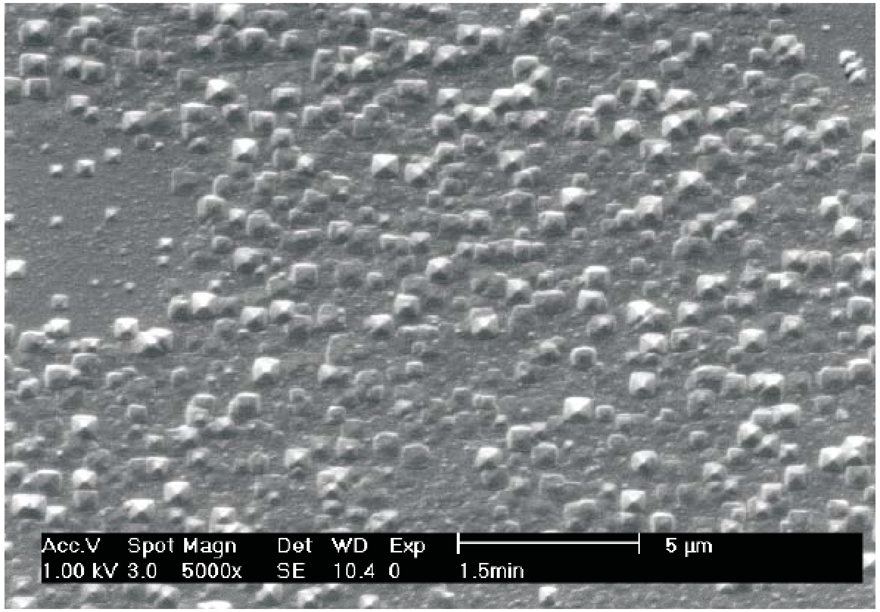
- Hydrazine (N_2H_4) + water mixtures
- Anisotropic silicon etchants
- 100 ml N_2H_4 in 100 ml water at 100 ℃: etch rate 2 um/min, no doping dependence, masked with silicon dioxide or aluminum
  - Heavily antimony doped wafer at 70 ~ 120 ℃: 0.8 ~ 2 um/min
  - Moderately doped samples at 70 ~ 120 ℃ : 1.5 ~ 3.3 um/min
- Hydrazine is very dangerous
  - A very powerful reducing agent (used for rocket fuel)
  - Flammable liquid
  - Hypergolic: $N_2H_4 + 2H_2O_2 \rightarrow N_2 + 4H_2O$ (explosively)
  - Pyrophoric: $N_2H_4 + O_2 \rightarrow N_2 + 4H_2O$ (explosively)
  - Flash point: 52°C in air.

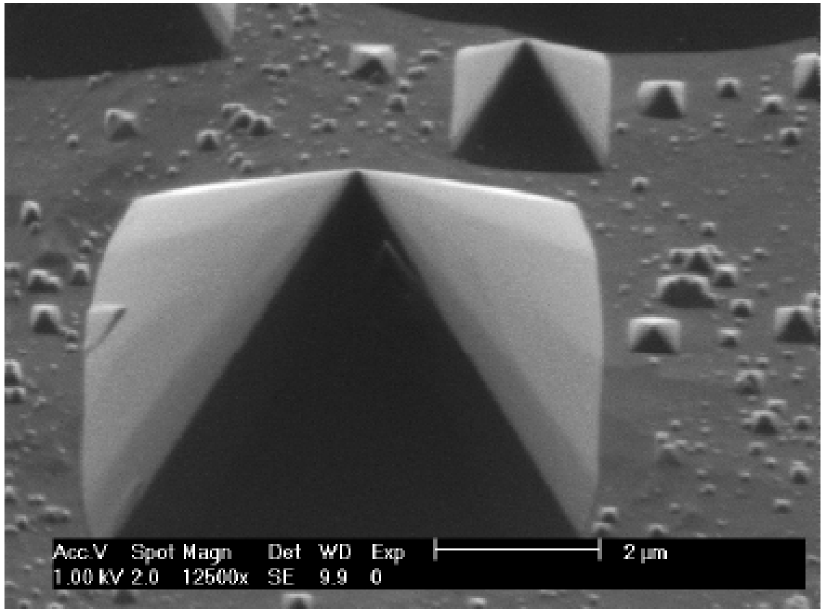
Amine Gallate Etching of Si

- Much safer than EDP
- Typical recipe
  - 100 g gallic acid
  - 305 mL ethanolamine
  - 140 mL H_2O
  - 1.3 g pyrazine
  - 0.26 mL FC-129 surfactant
- Anisotropy: (111):(100) ≈ 1:50 to 1:100
- Etch rate: ~1.7 um/min at 118°C

Evolution of Hillocks during Si Etching

- In the anisotropic etching of Si using alkaline solutions, hillock formation is an impediment to achieving smooth surfaces.
- Hillocks are generally reported as being pyramidal or near-pyramidal in shape, bounded by {111} or near-{111} planes, giving the appearance of a bowed square perimeter.





Examples of hillocks after Si wet etching using TMAH solution

Ref.) John T. L. Thong, IOP JMM, 11, pp. 61-69, 2001

Boron Etch Stop (1)

- Boron etch stop
  - 20 times slowing of etch rate for > 10^{20} cm^{-3} boron doping in KOH
  - 50 times slowing of etch rate for > 7 x 10^{19} 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

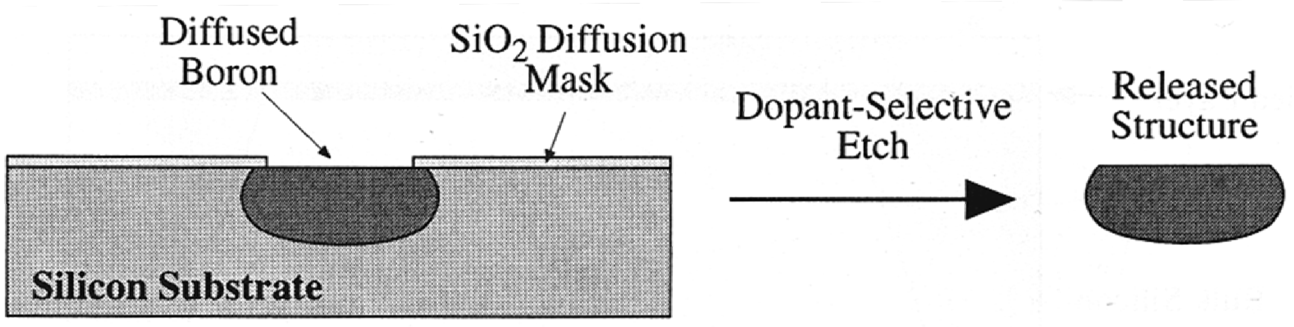
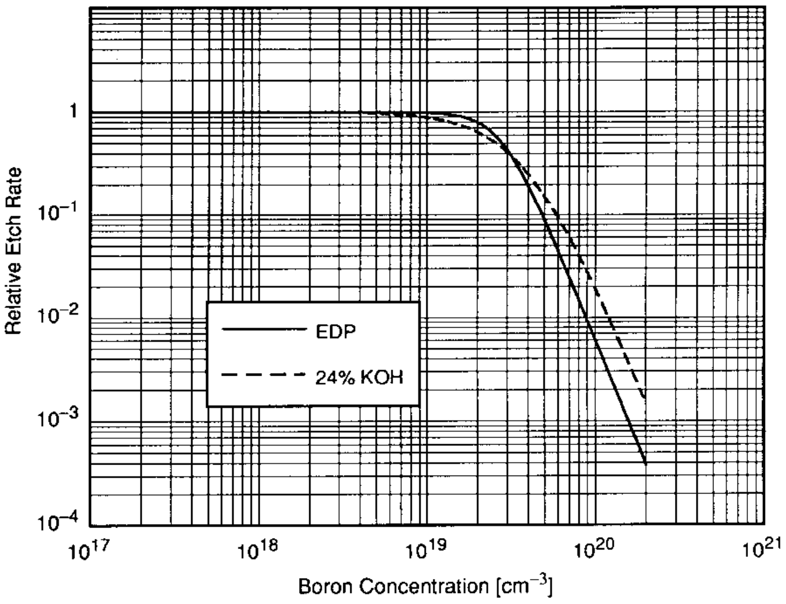


Illustration of the use of heavy boron doping with a dopant-selective etch to form free structures

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.

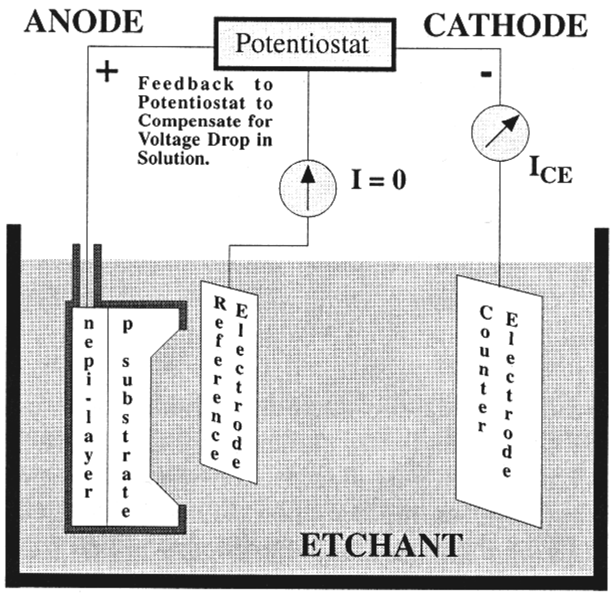


Electrochemical Etch Stop (1)

- 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

Electrochemical Etch Stop (3)

- Diode junction etch stop mechanism
  - Reverse voltage at Diode → No voltage at P-type silicon
  - Exposure to etchant → Etching
  - N-type is exposed → Making hydroxide →Stop etching
  - Possible to control thickness exactly

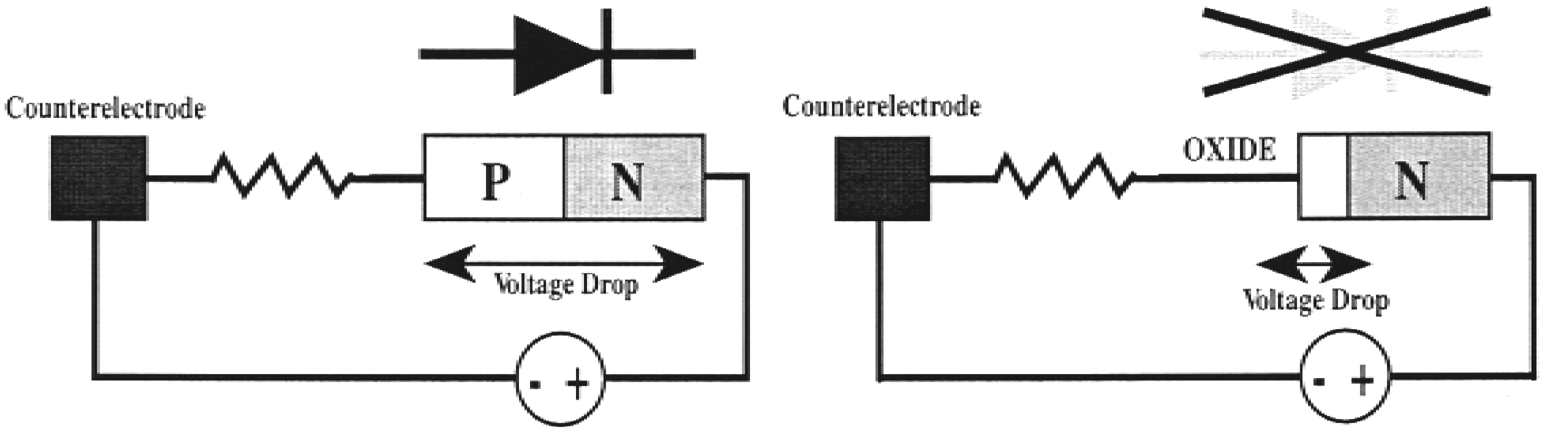
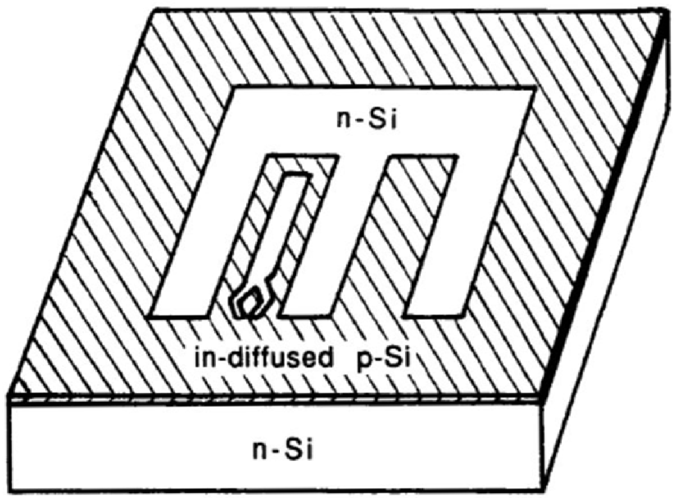


Illustration of diode junction etching

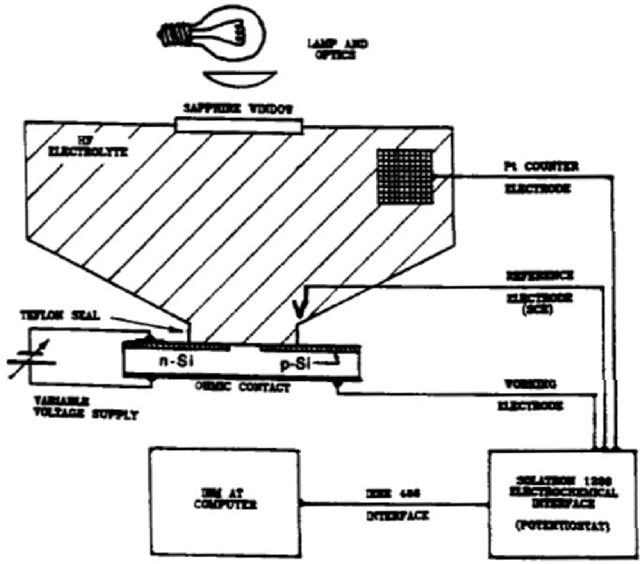
Electrochemical Etch Stop (4)

- Photo–assisted electrochemical etch stop
  - An n-type silicon region on a wafer may be selectively etched in an HF solution by illustrating and applying a reverse bias across a p-n junction

    → the p-type layer cathodic and the n-type layer anodic



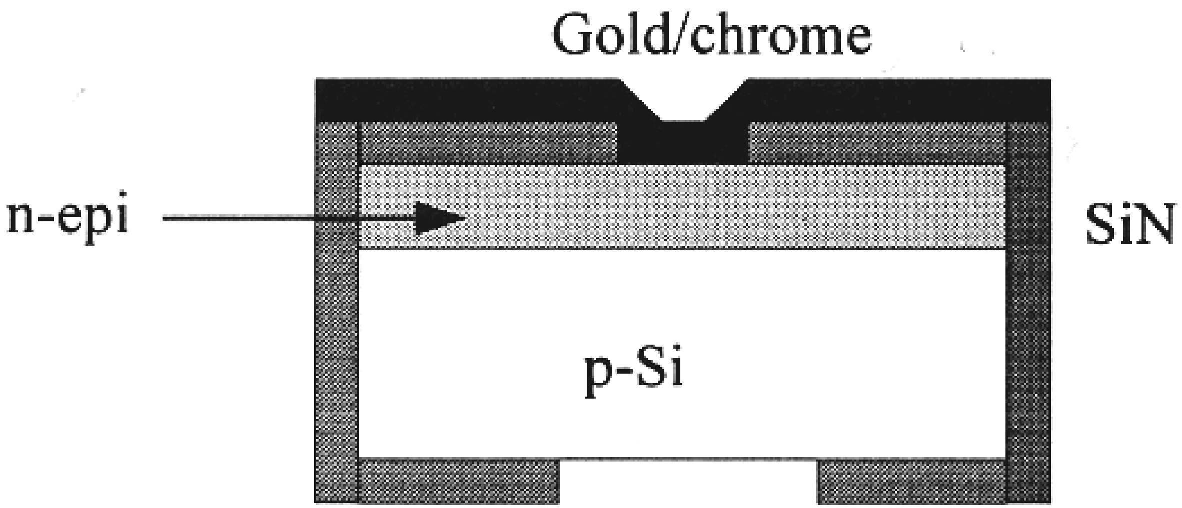
Schematic of the spatial geometry of the in-diffused p-Si layer in to n-Si used to form cantilever beam structures



Schematic of the photoelectrochemical etching experimental apparatus

Electrochemical Etch Stop (5)

- Electrodeless etch-stop
  - Dose not require external contacts or power source
  - The passivation voltage is generated internally in a Au/Cr/n-Si/TMAH cell.
  - The etch stop is effective for both p- and n- type silicon



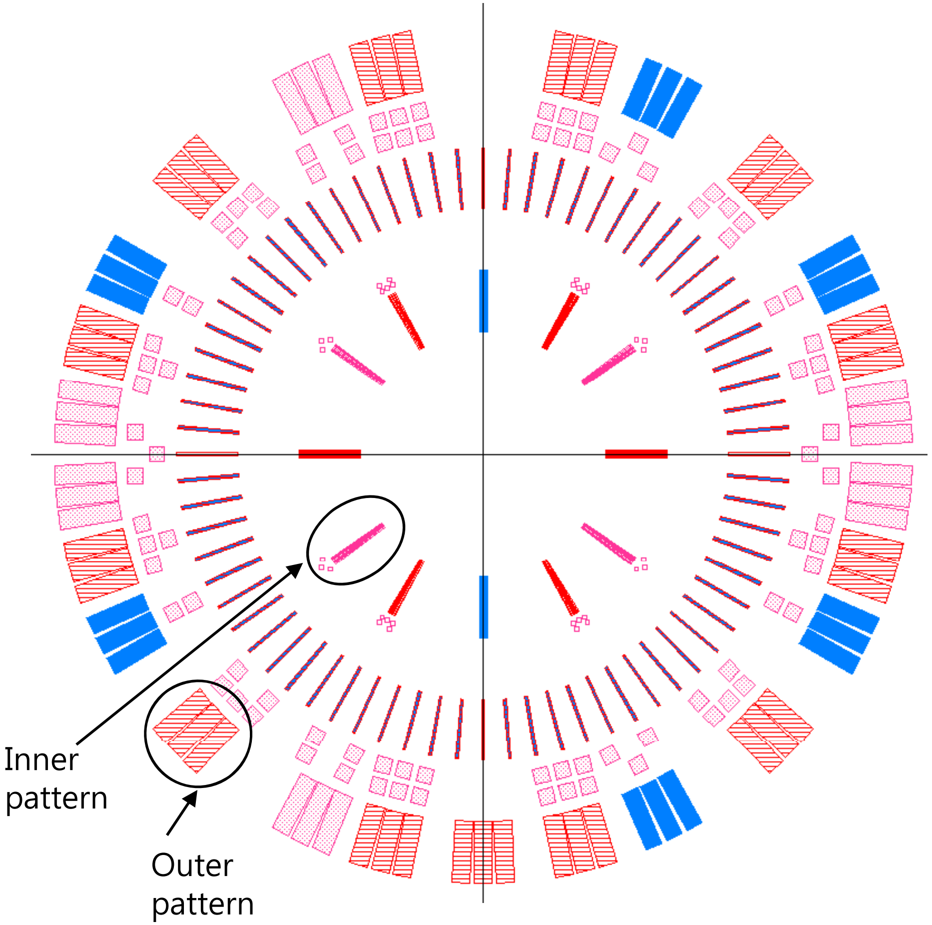
Test-wafers with SiN on the sides and gold/chrome on the front.

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 Test Pattern (1)

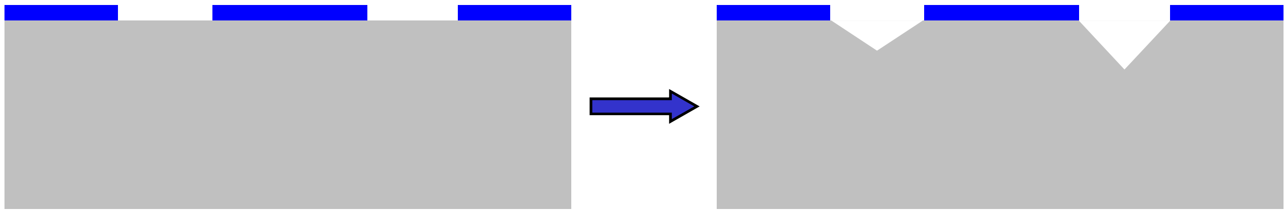
- Wagon wheel pattern mask



- Wagon wheel pattern
  - Size: 50 mm x 400 mm
  - Pattern repeated every 5 degree
  - Inner pattern
    : Pattern width 5 mm
    : Observation of slow etch rate
  - Outer pattern
    : Pattern width 300 mm
    : Observation of fast etch rate

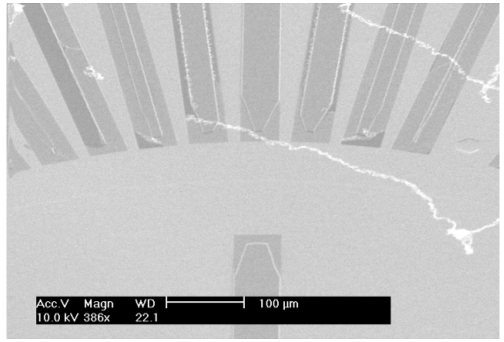
Wet Etch Test Pattern (2)

- Patterns defined by only photolithography



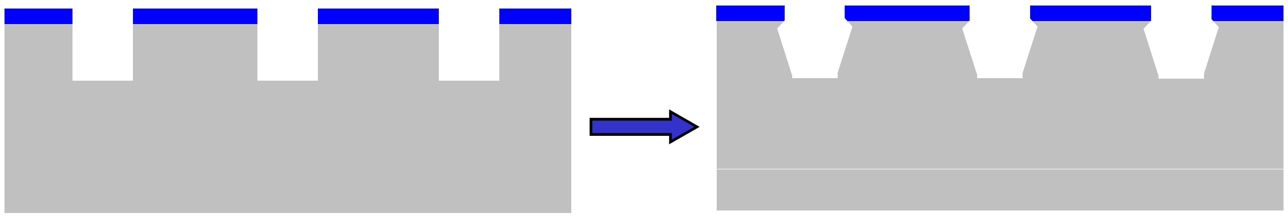
Pattern Wet etch

Oxide Silicon

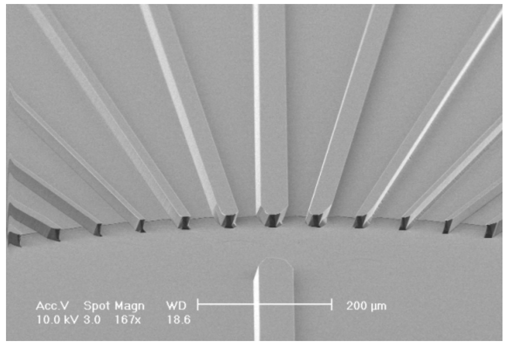


Wet etch result

- Patterns defined by deep Si etch



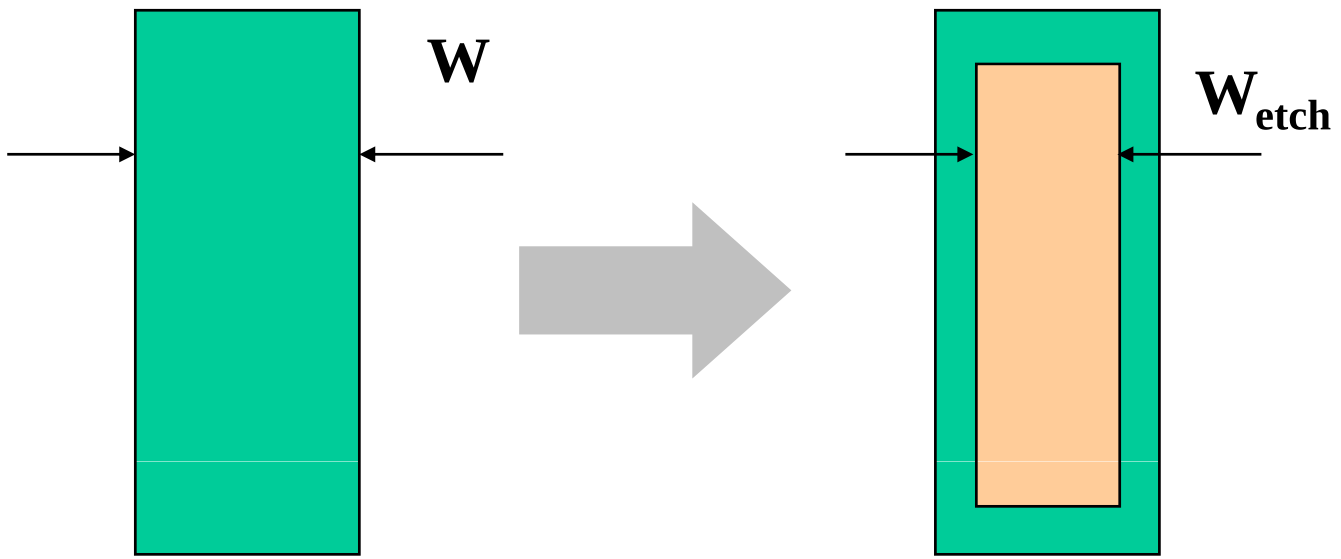
Pattern Wet etch



Wet etch result

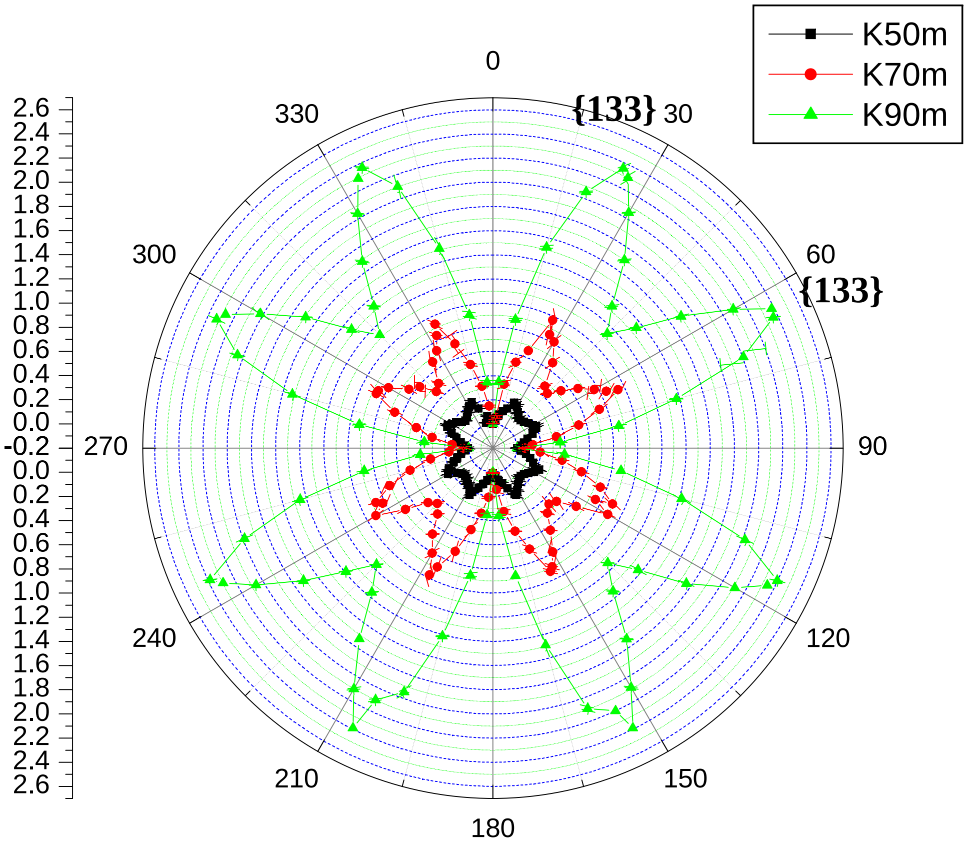
Wet Etch Test Pattern (3)

- Wet etch rate inspection



$$Etch\ rate = \frac{W - W_{etch}}{2}$$

(100) Si Wet Etch (1)



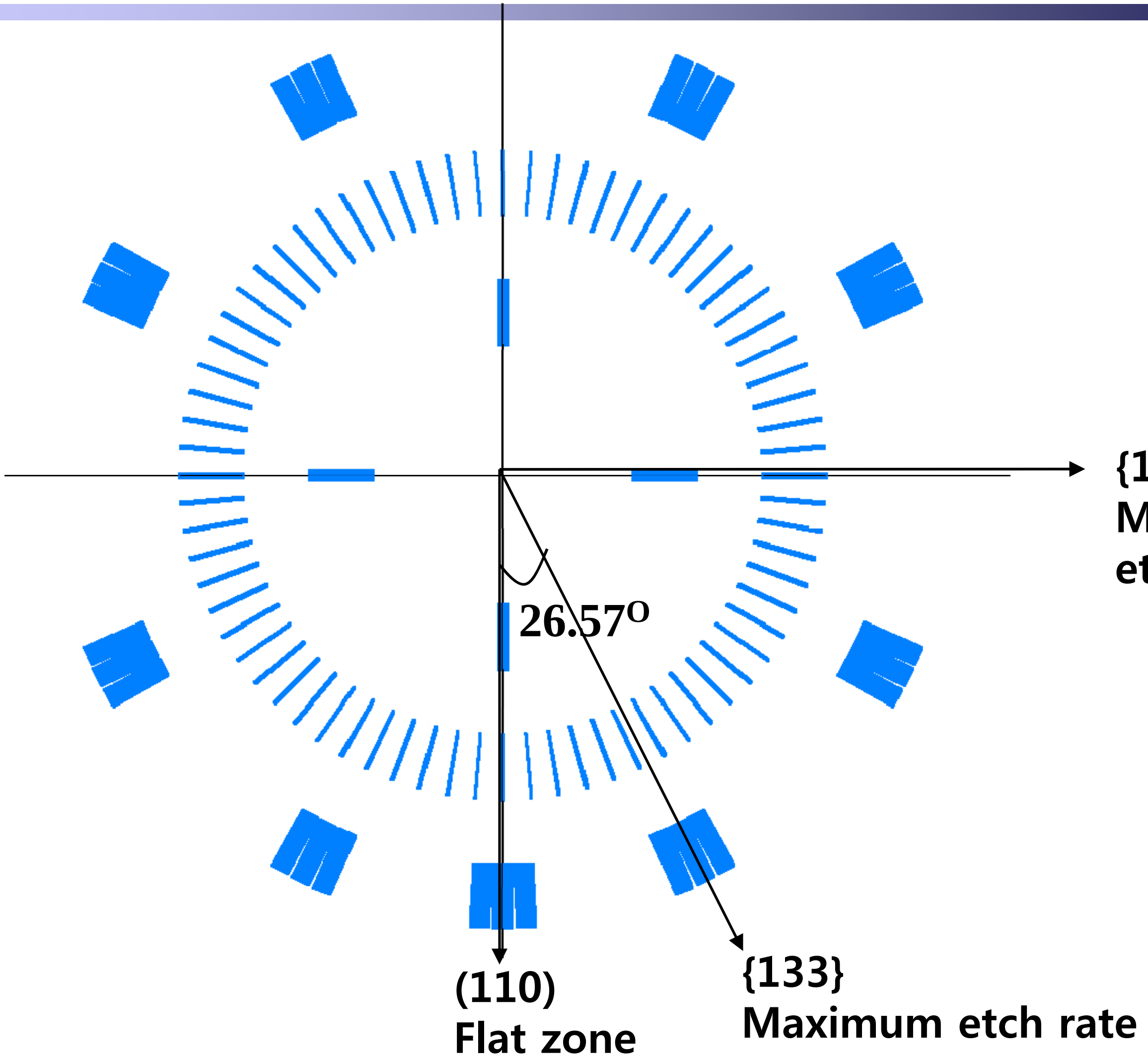
40wt % KOH

K50m: 50 ℃

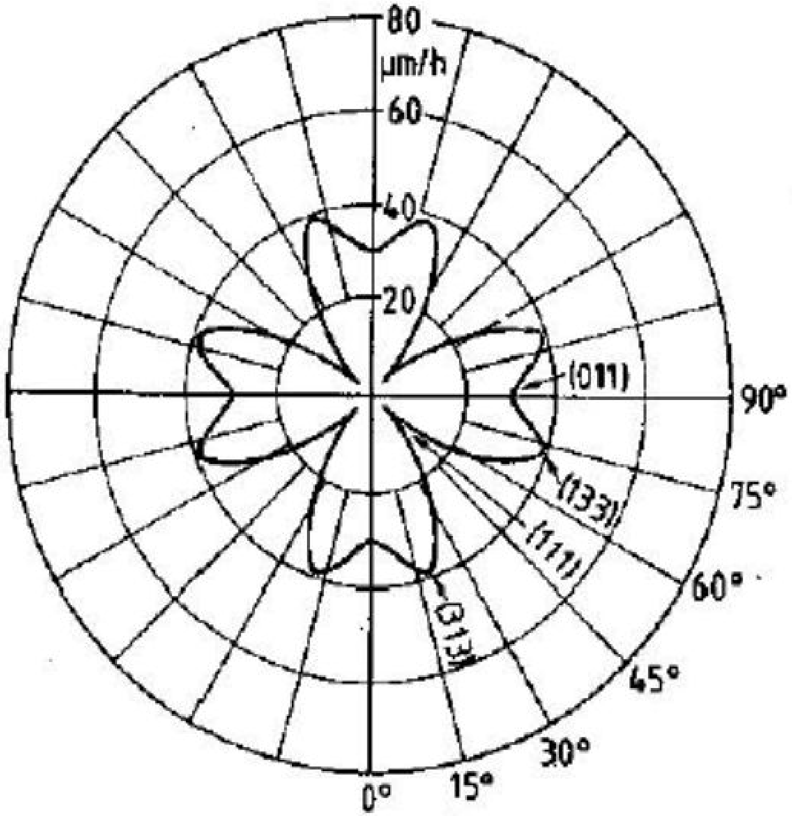
K70m: 70 ℃

K90m: 90 ℃

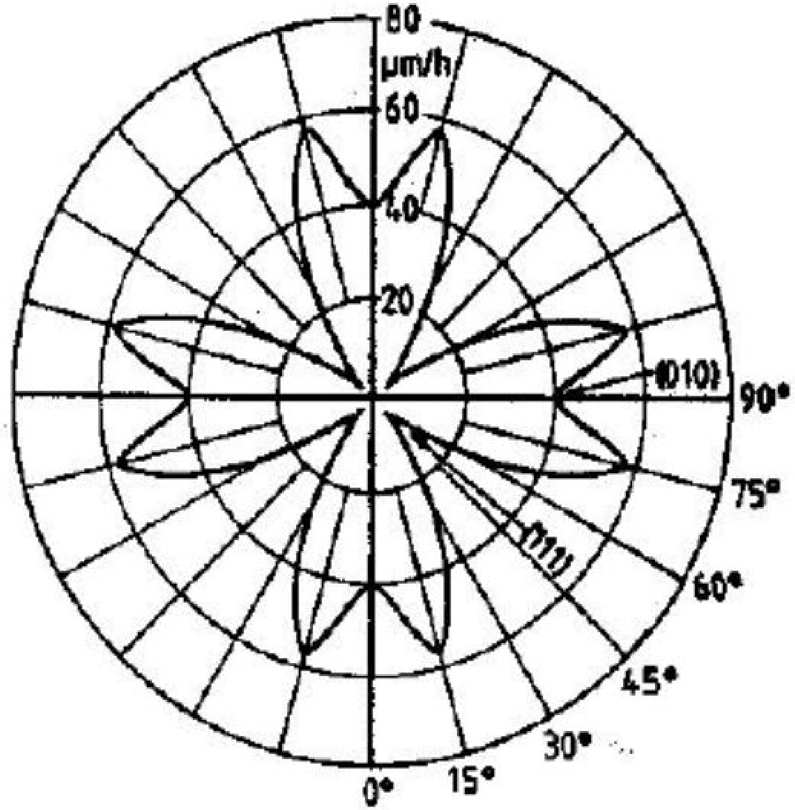
(100) Si Wet Etch (2)



(100) Si Wet Etch (3)



EDP solution at 95 ℃

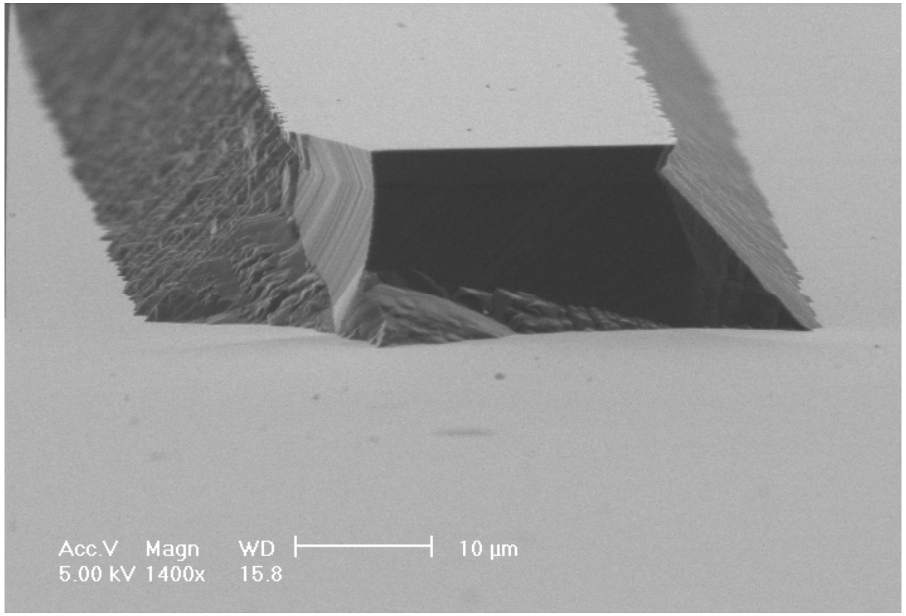


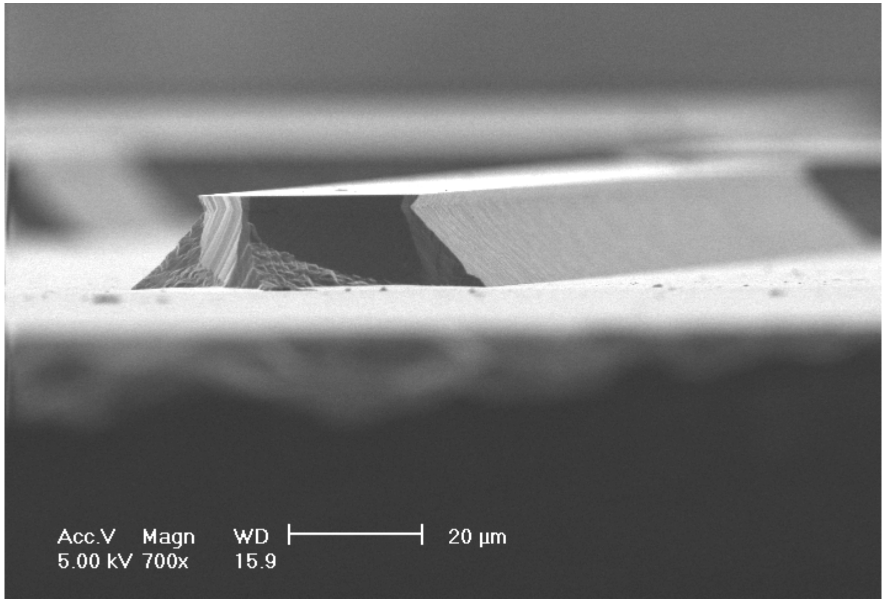
KOH solution at 78 ℃

Ref.) H. Seidel, *J. of Electrochemical Society*, 137(11), pp. 3613-3632, 1990

(100) Si Wet Etch (4)

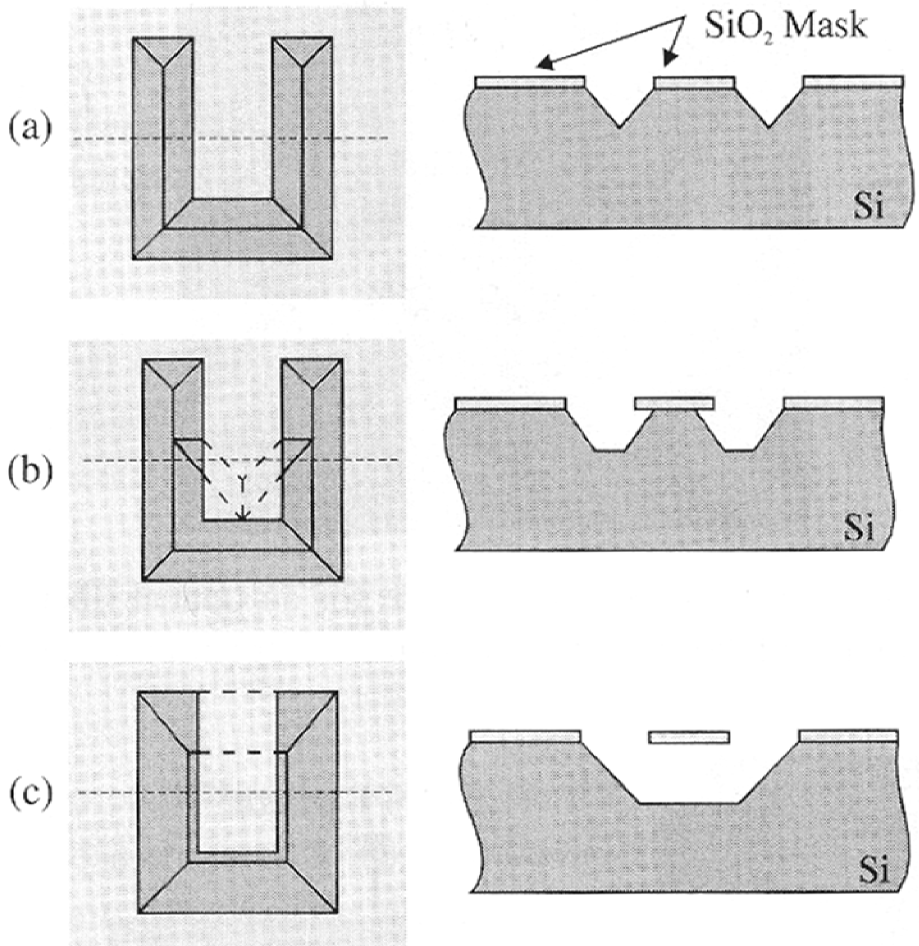
- SEM view: (100) wafer, KOH 40%, 50℃





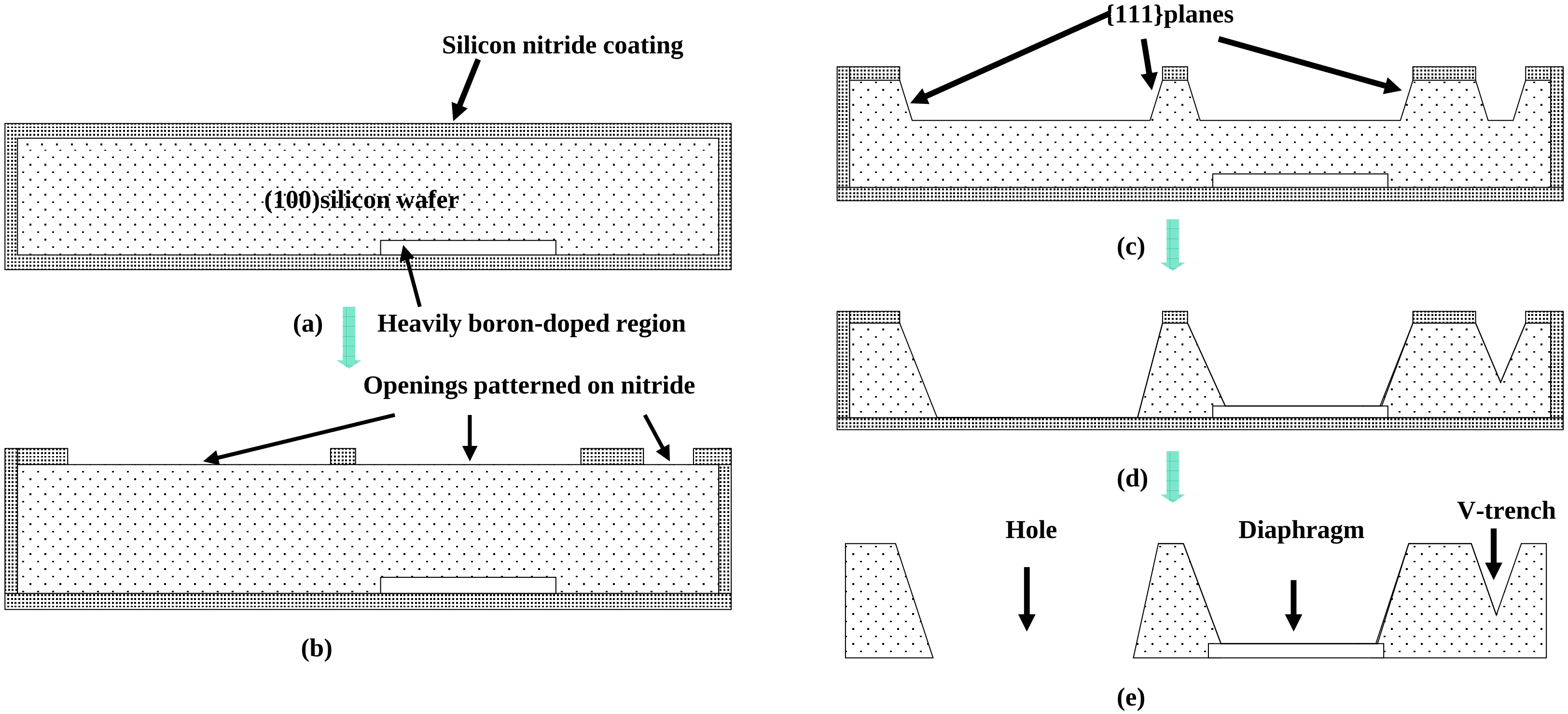
(100) Si Wet Etch (5)

- Micromachining of (100) wafer

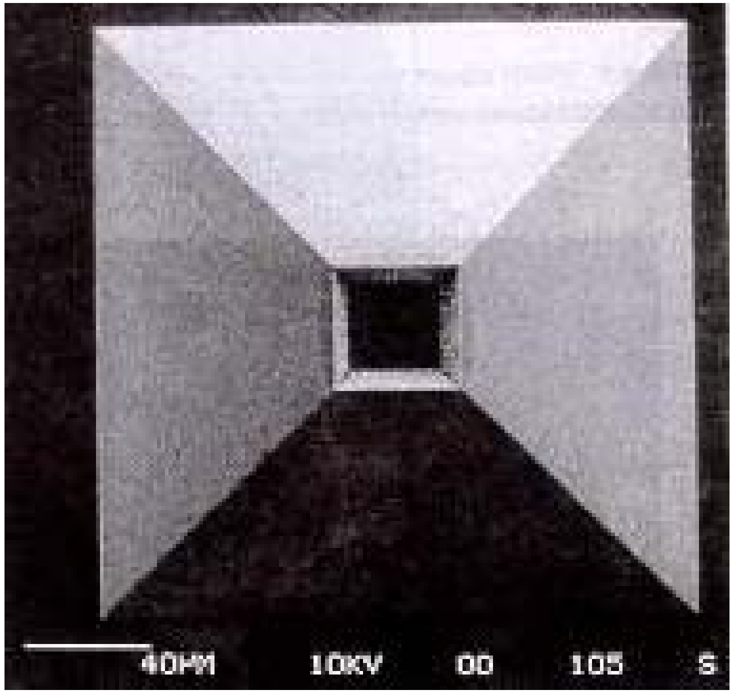


(100) Si Wet Etch (6)

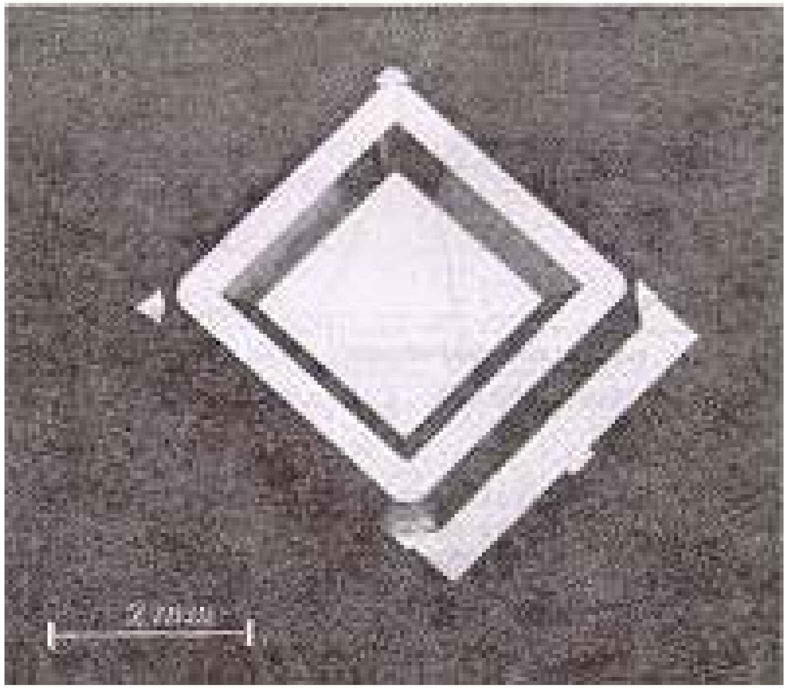
- Anisotropic Silicon Etching



(100) Si Wet Etch (7)



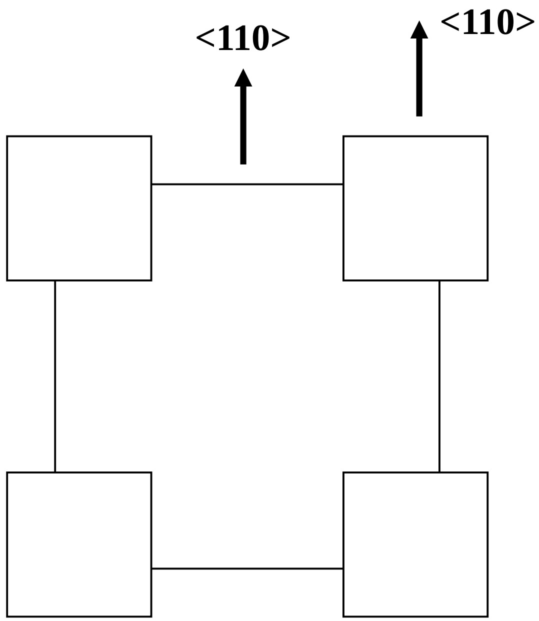
Nozzle

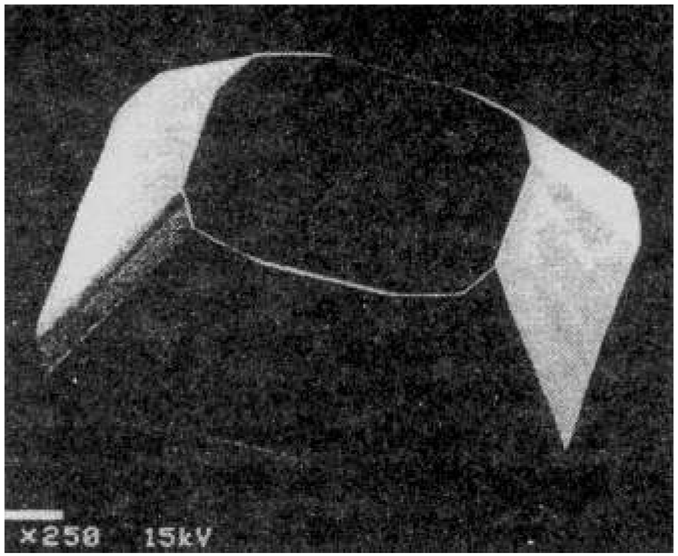


Diaphragm

(100) Si Wet Etch (8)

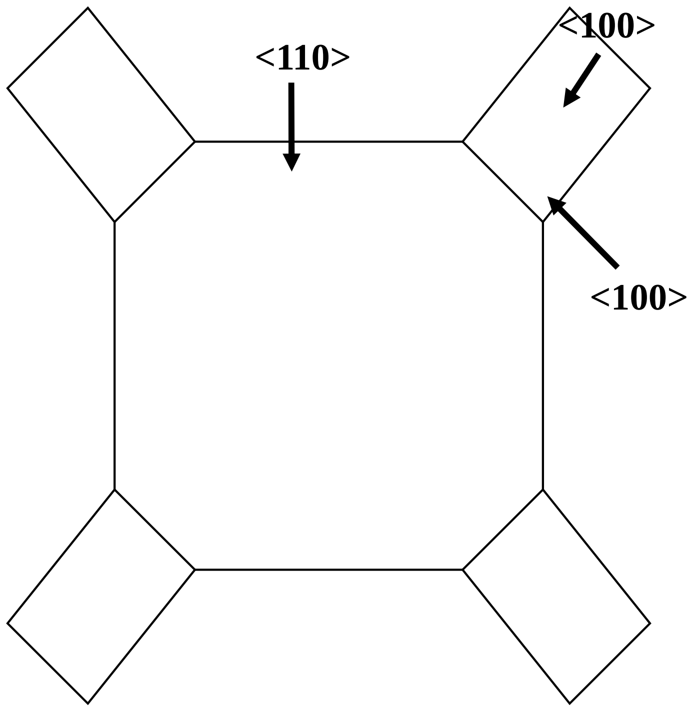
- Rectangular corner compensation for mesa structure fabrication
  - Mask layout of compensation pattern for preventing undercut

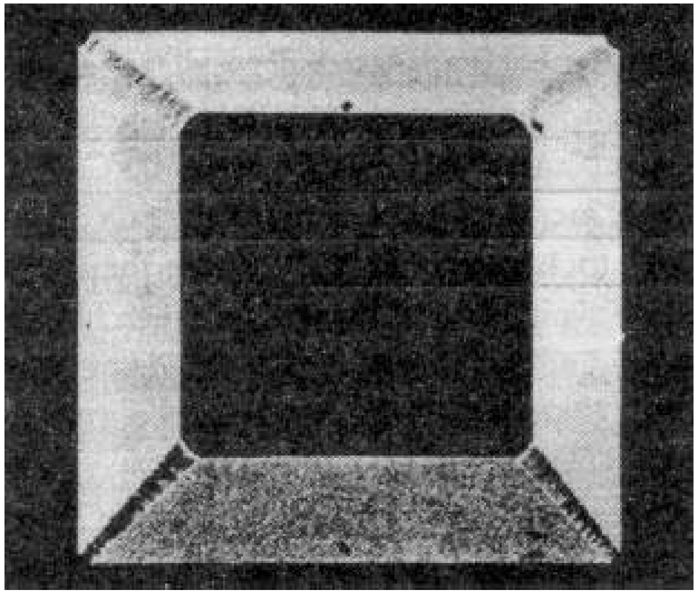




(100) Si Wet Etch (9)

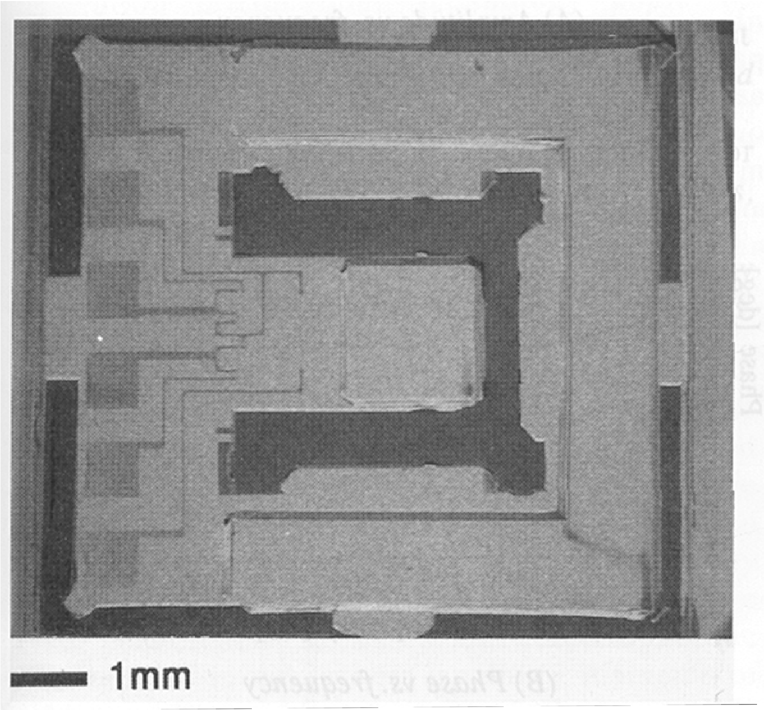
- 45° rotated rectangular corner compensation for mesa structure fabrication



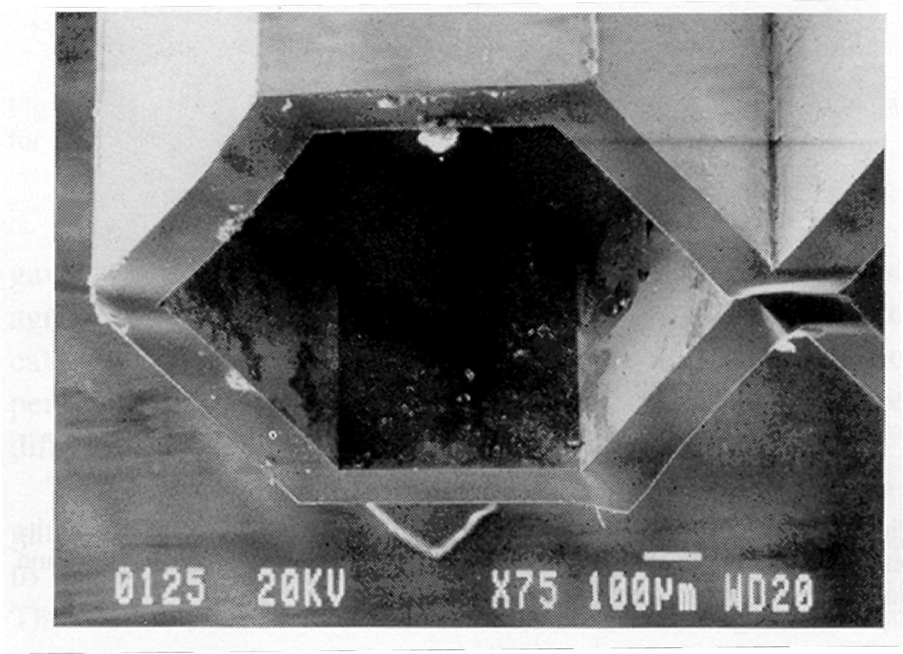


(100) Si Wet Etch (10)

- Application examples (1)



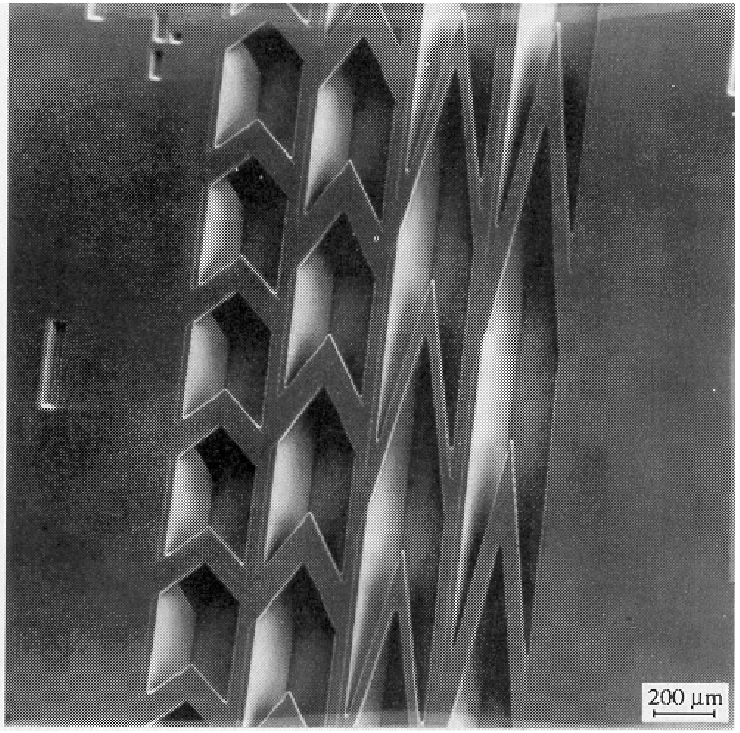
Accelerometer



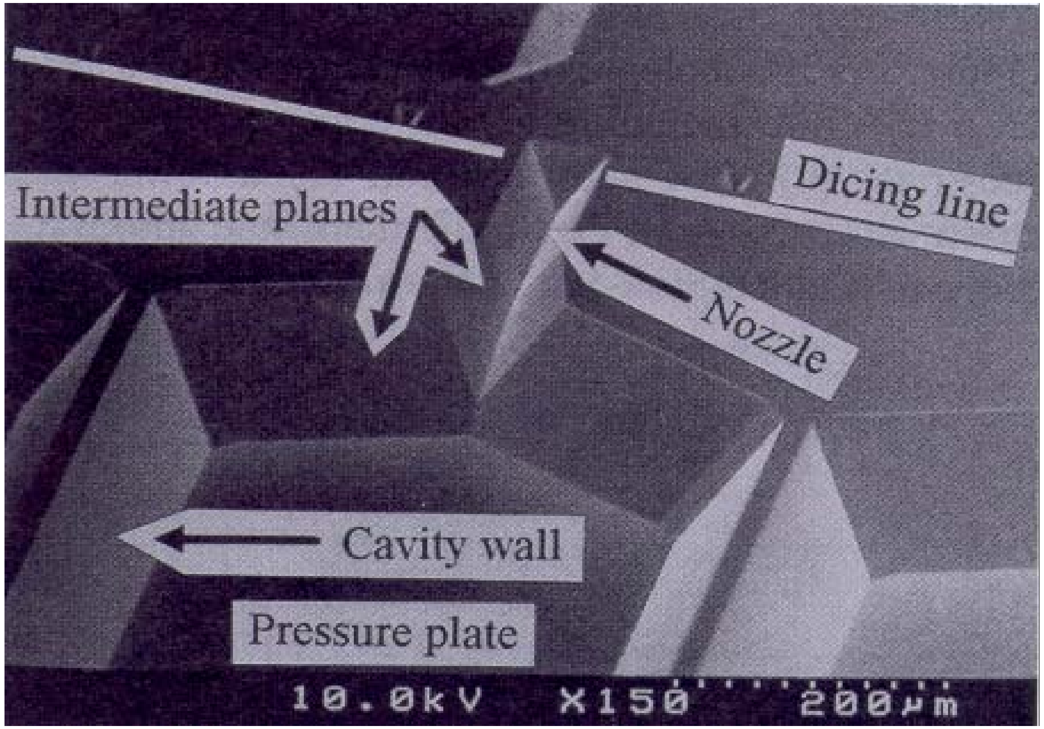
Tube

(100) Si Wet Etch (11)

- Application examples (2)

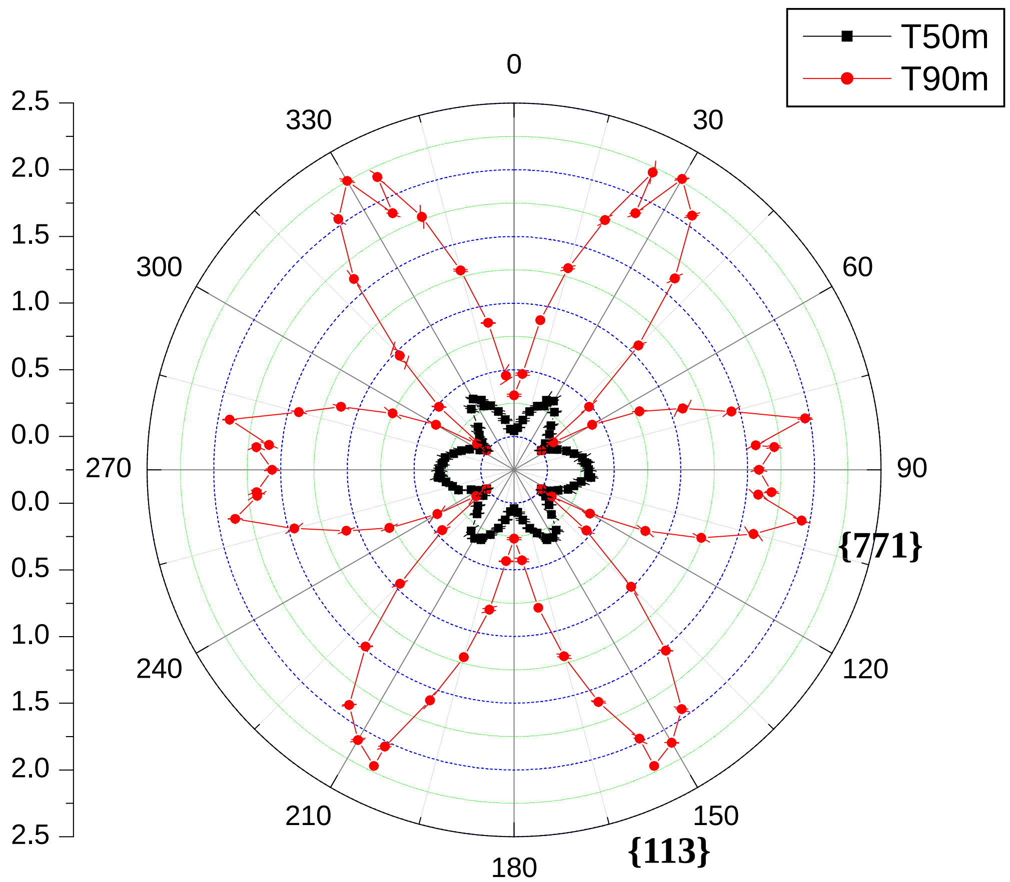


Holding structure over v-grooves



Ink jet printer nozzle

(110) Si Wet Etch (1)

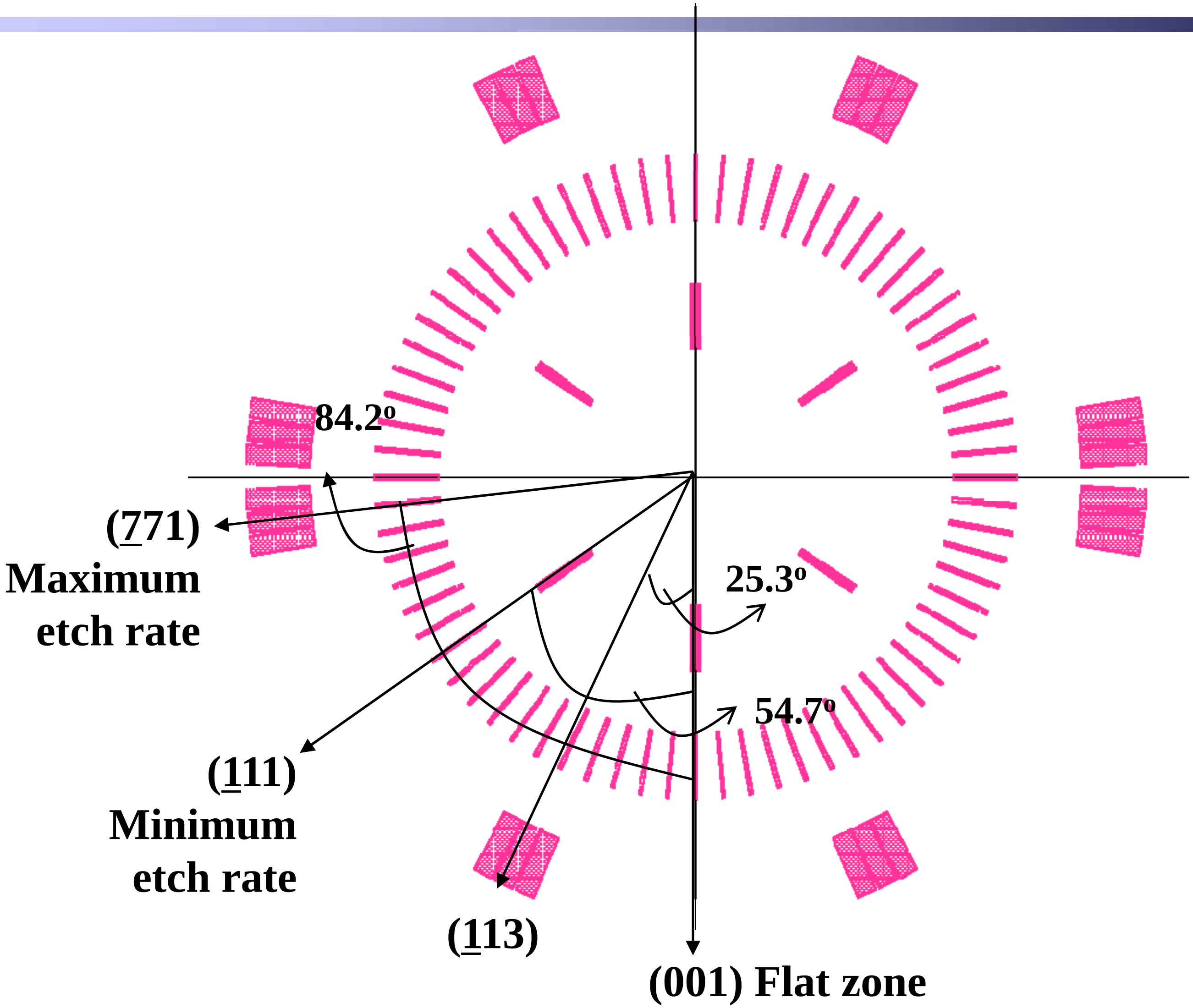


40wt % TMAH

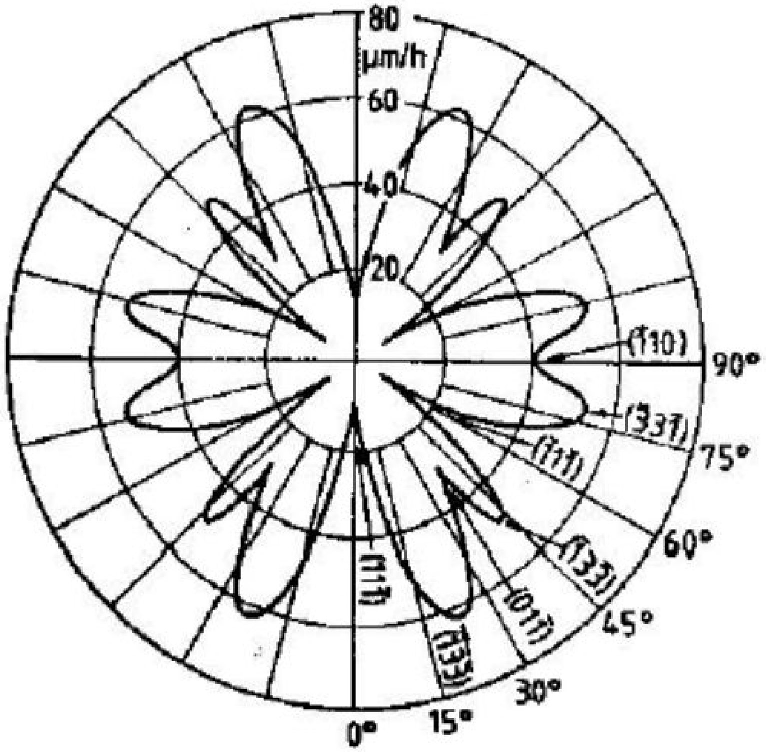
T50m: 50 ℃

T90m: 90 ℃

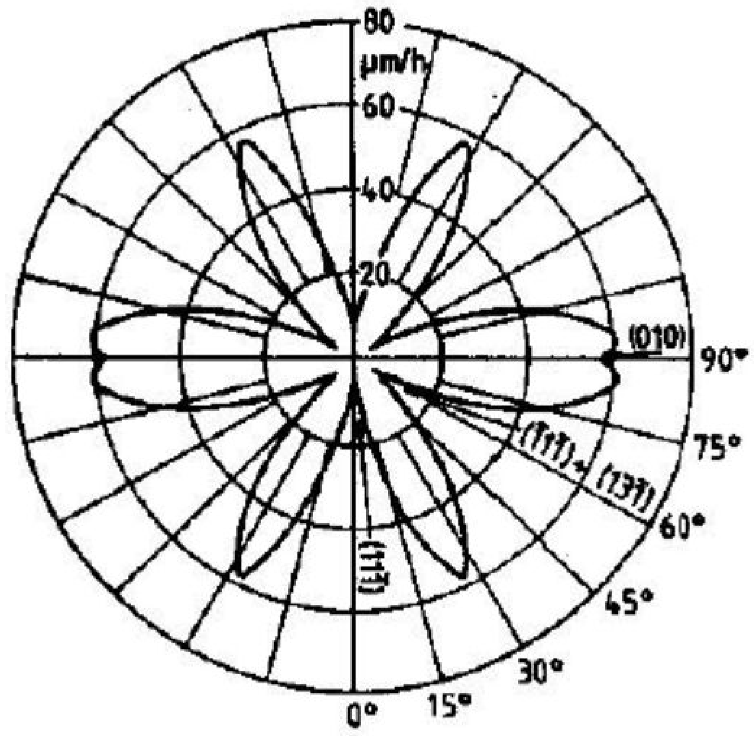
(110) Si Wet Etch (2)



(110) Si Wet Etch (3)



EDP solution at 95 ℃

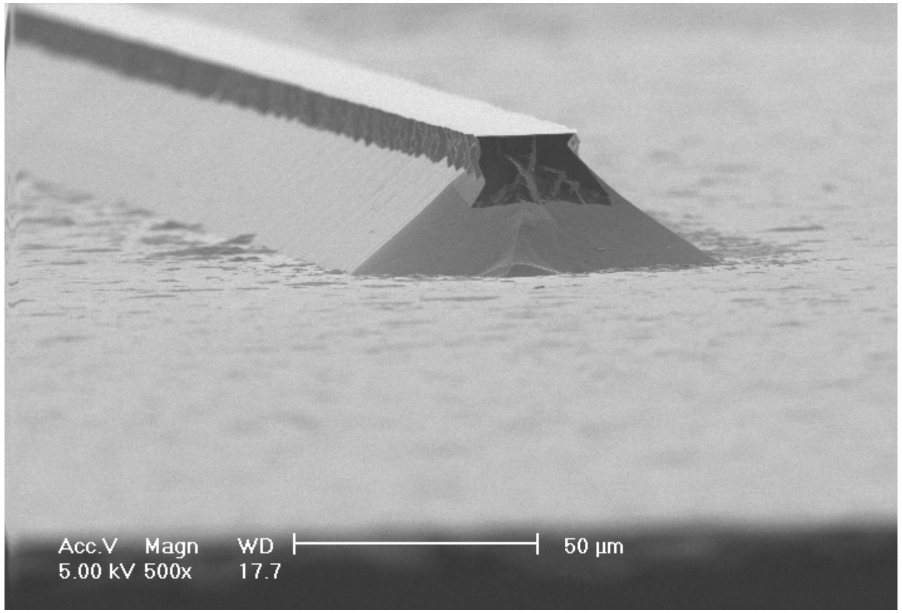


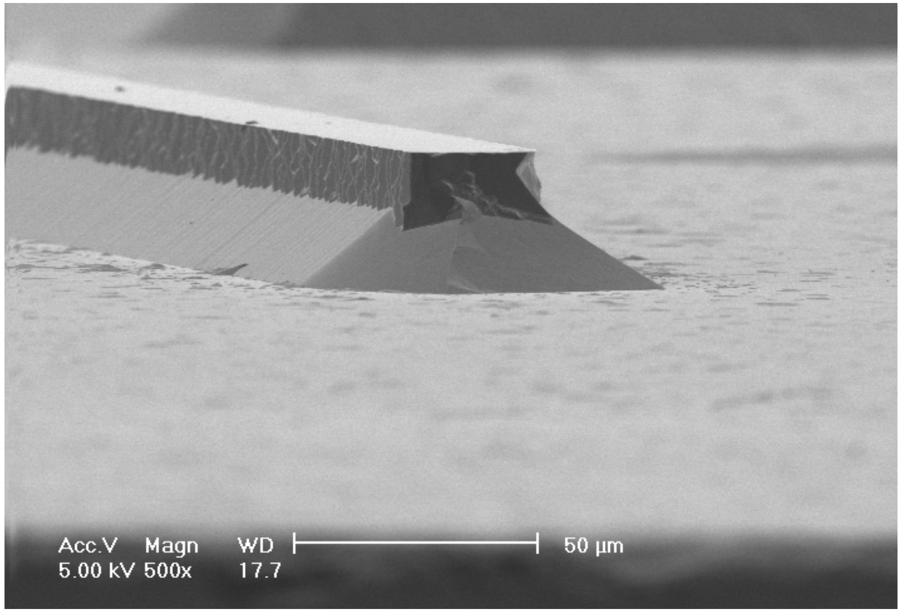
KOH solution at 78 ℃

Ref.) H. Seidel, *J. of Electrochemical Society*, 137(11), pp. 3613-3632, 1990

(110) Si Wet Etch (4)

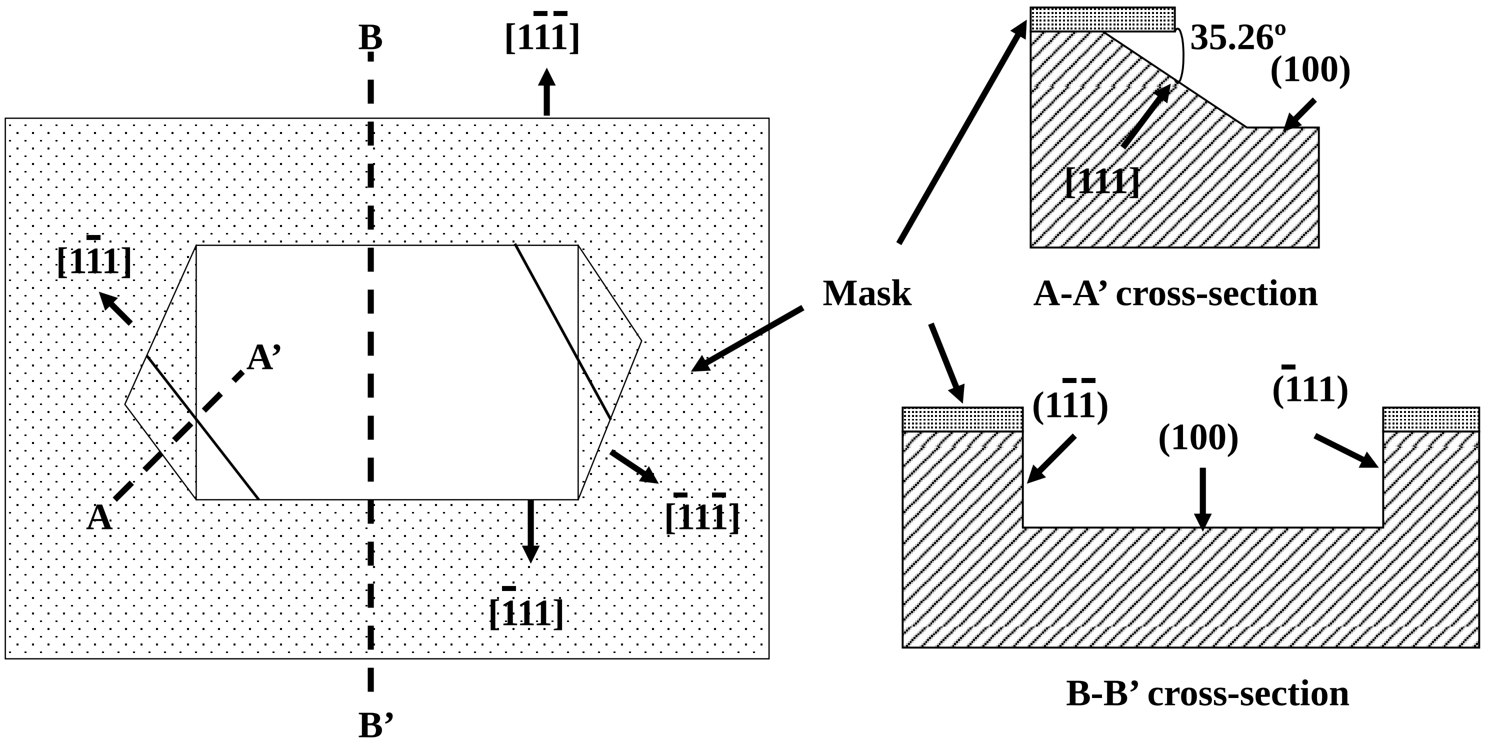
- SEM view: (110) wafer, KOH 40%, 50℃





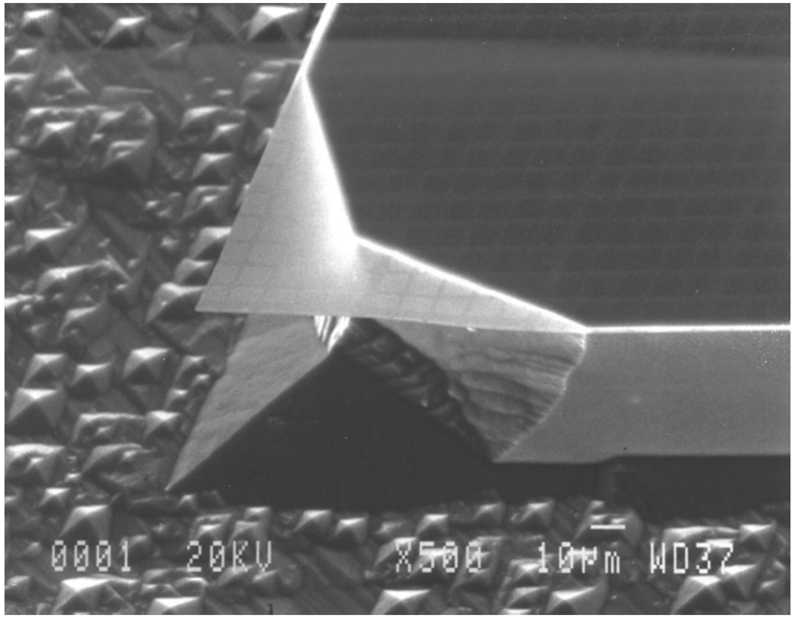
(110) Si Wet Etch (5)

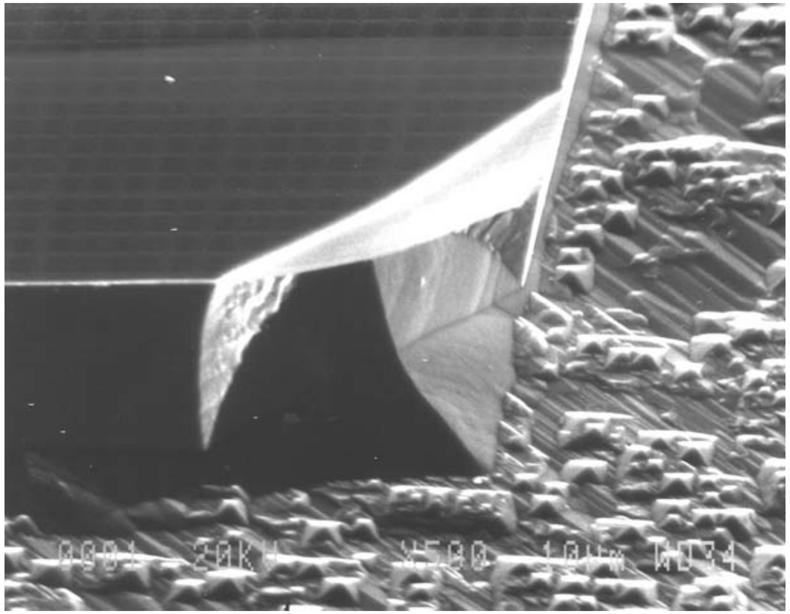
- Top and cross-sectional view of wet etched (110) silicon wafer



(110) Si Wet Etch (6)

- Convex corners
  - The planes that emerge under convex corners are not compatible with the planes that we find in the etch rate minima.
- Acute and obtuse convex corners of parallelogram
  - Need compensation pattern for undercut and residues

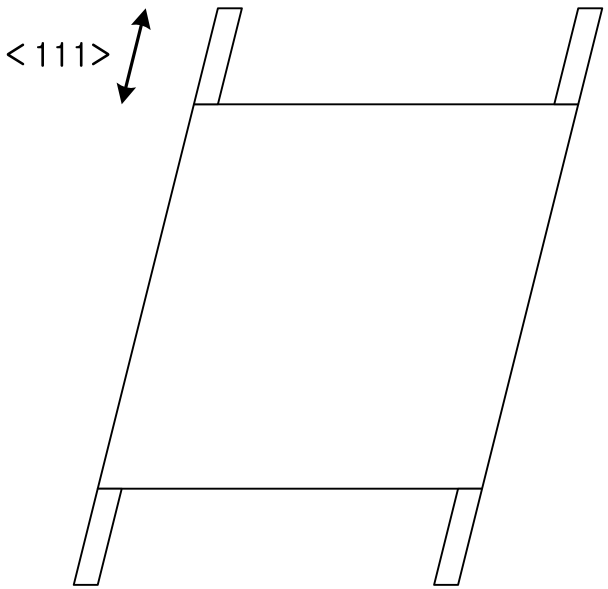




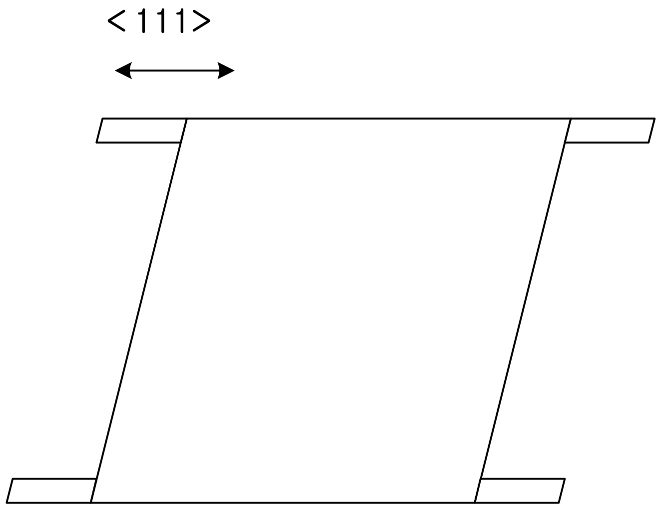
(SNU NML)

(110) Si Wet Etch (7)

- Compensation pattern design using <111> beam



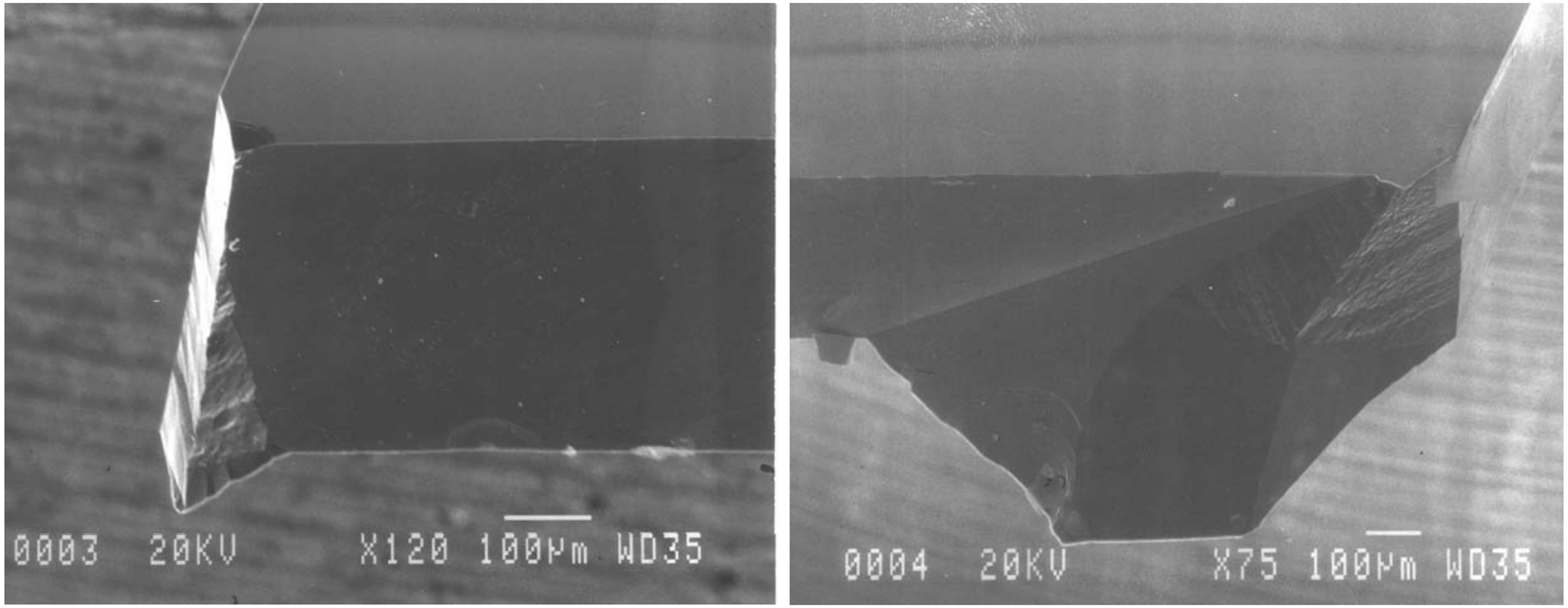
<111>direction compensation
beams oblique to the wafer flat



<111>direction compensation
beams oblique to the wafer flat

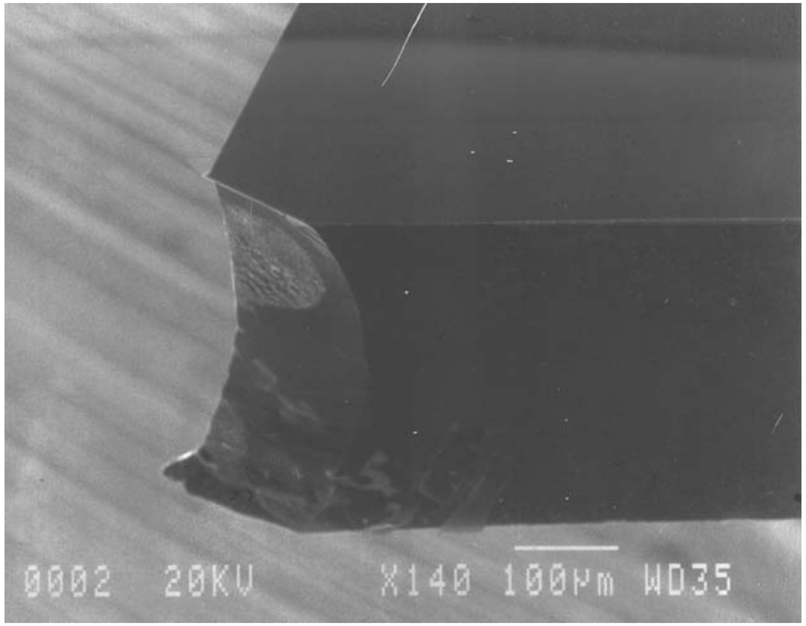
(110) Si Wet Etch (8)

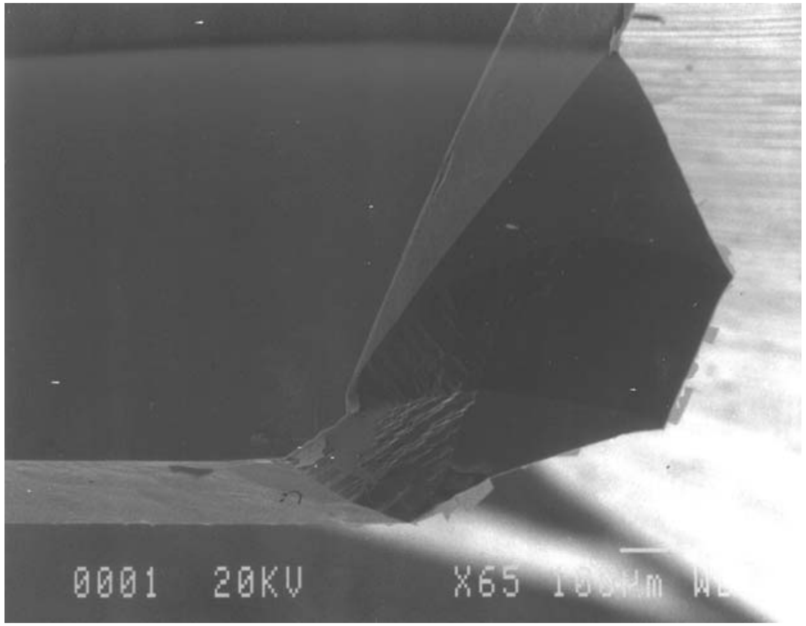
- Compensation results
  - Good compensation effects on acute corners
  - Need other compensation pattern on convex corners



(110) Si Wet Etch (9)

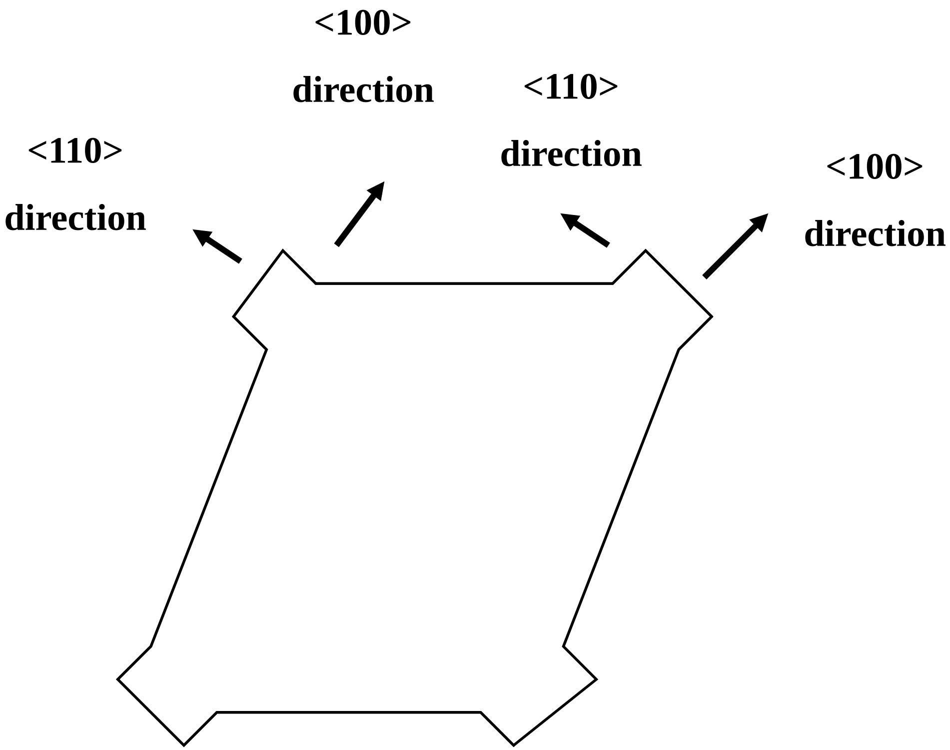
- Compensation results
  - Good compensation effects on acute corners
  - Need other compensation pattern on convex corners





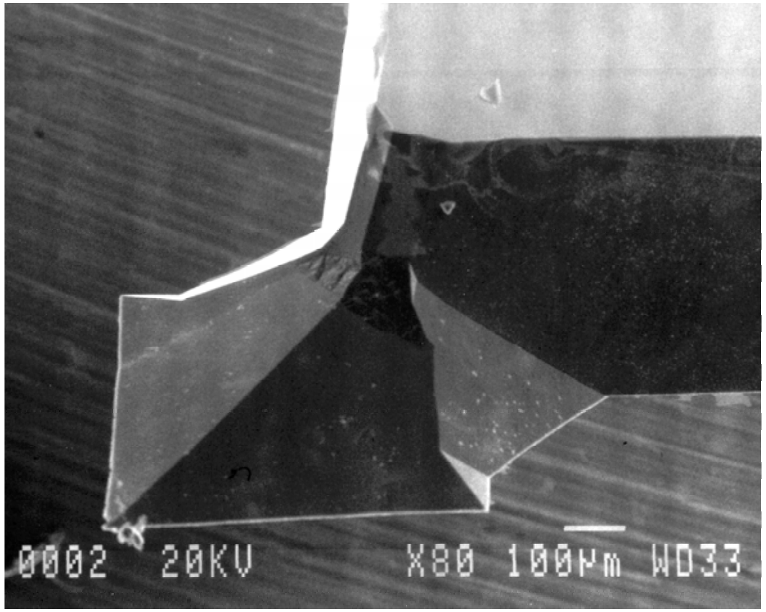
(110) Si Wet Etch (10)

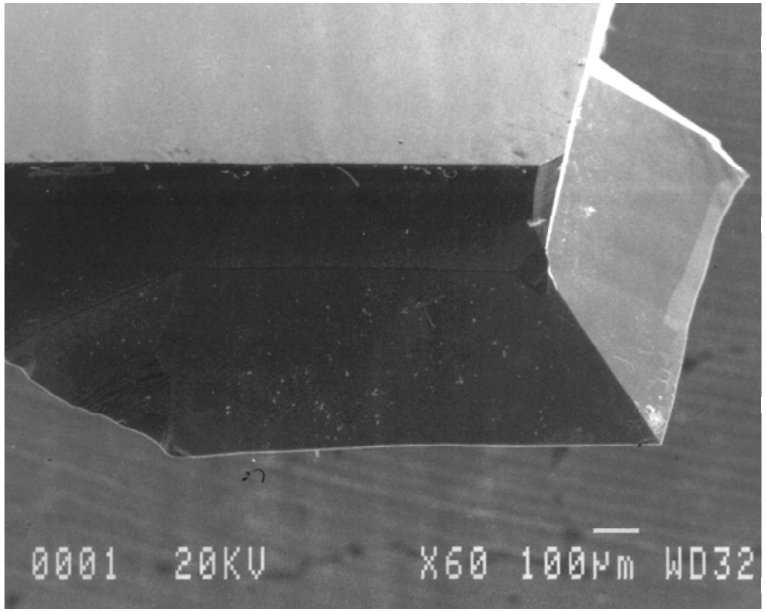
- Rectangular compensation pattern design



(110) Si Wet Etch (11)

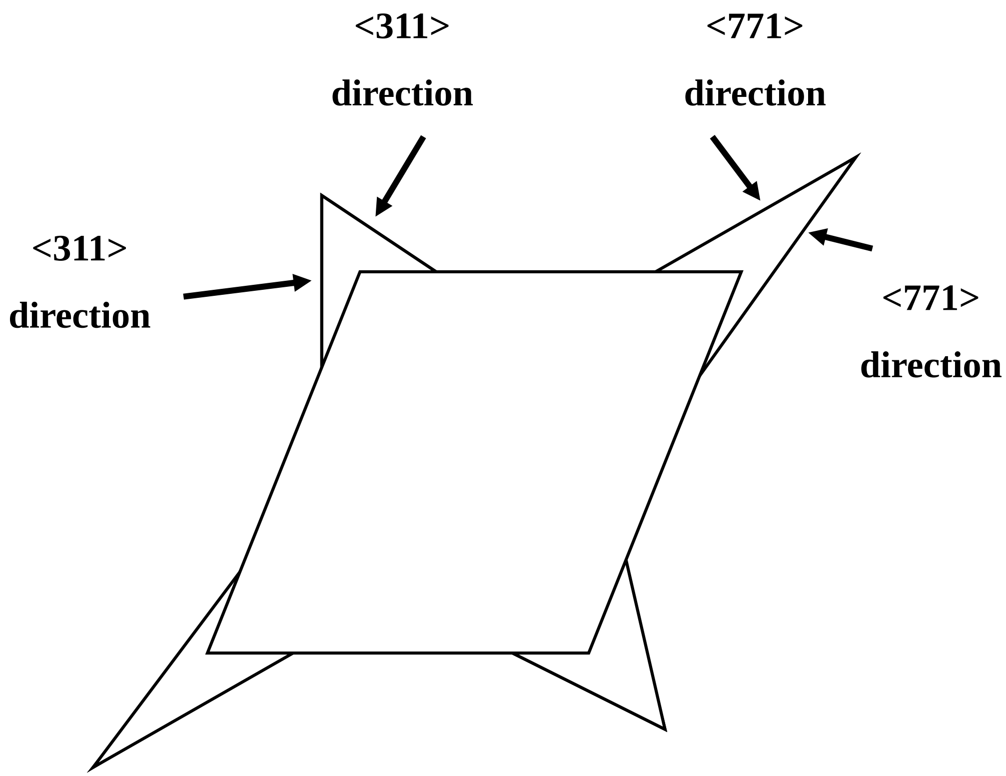
- Compensation results
  - Large residues remain





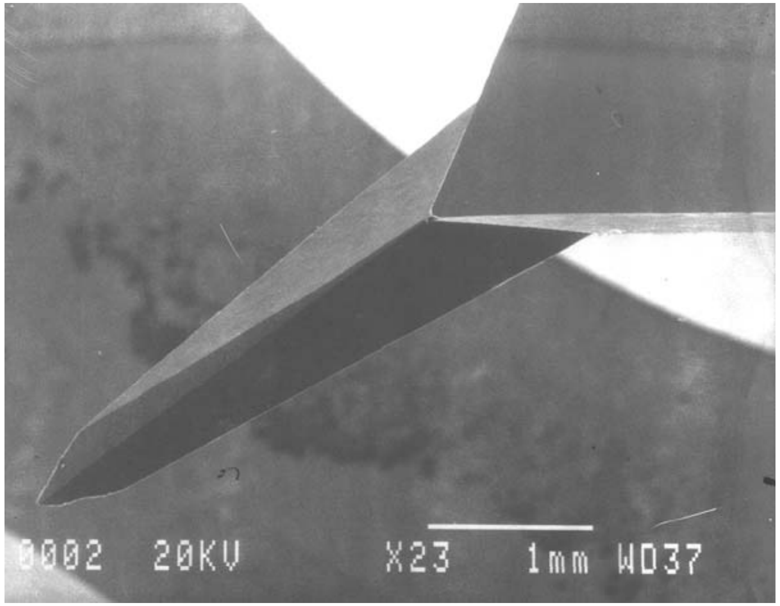
(110) Si Wet Etch (12)

- Triangular compensation pattern design

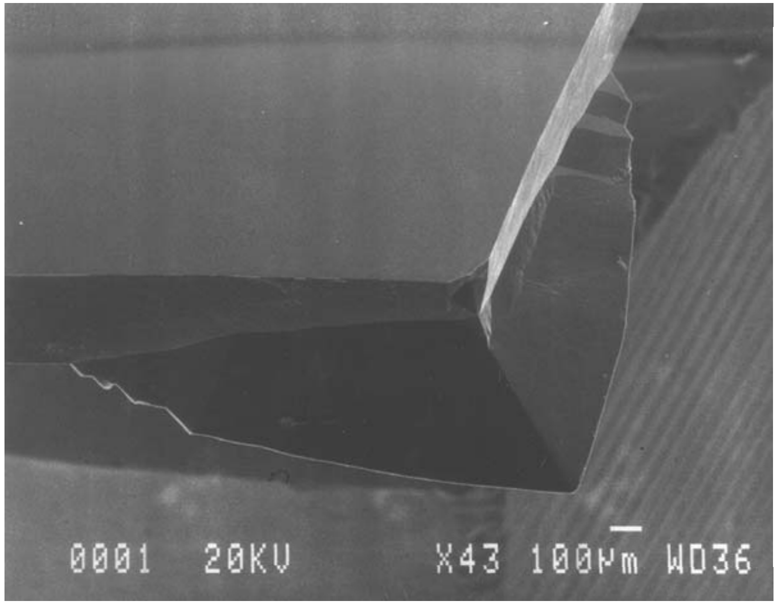


(110) Si Wet Etch (13)

- Compensation results
  - Very large unwanted residues at the bottom
  - Features sharp corners at the top of the structures



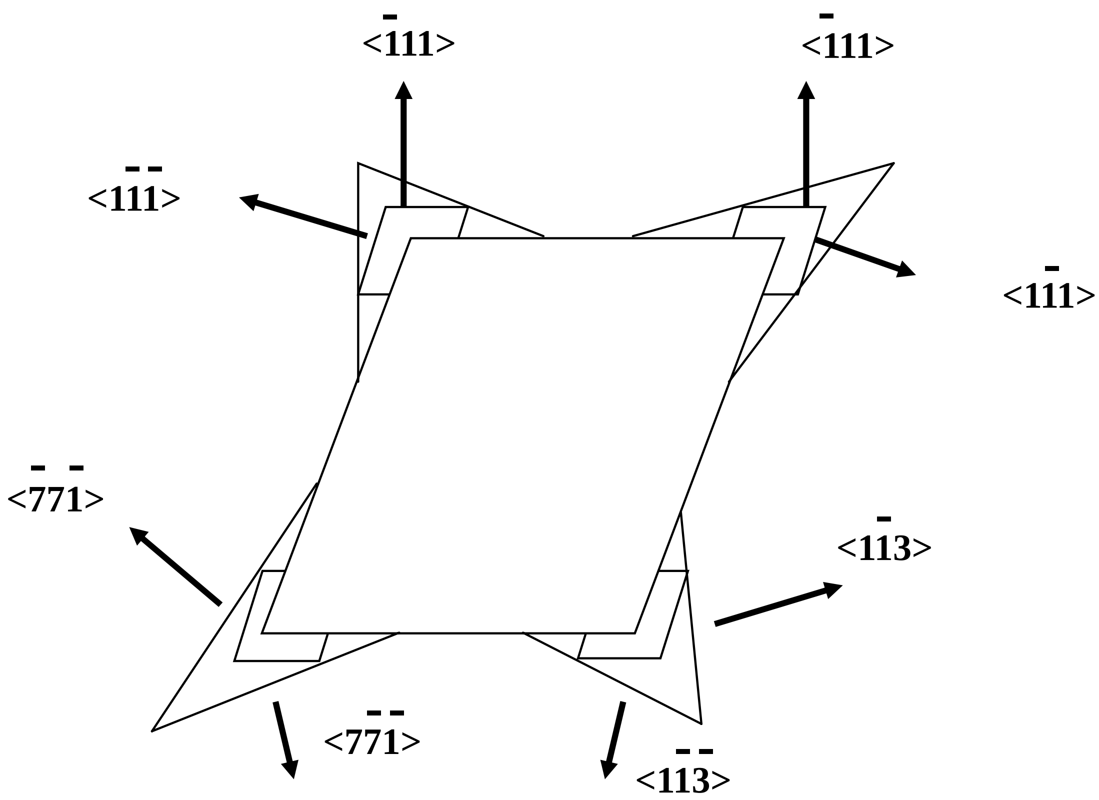
Etch front place : 311



Etch front place : 771

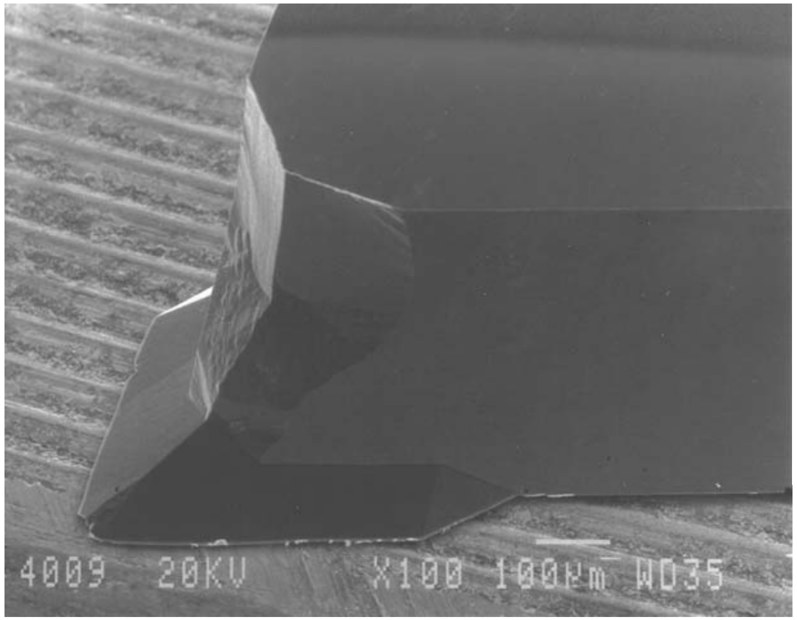
(110) Si Wet Etch (14)

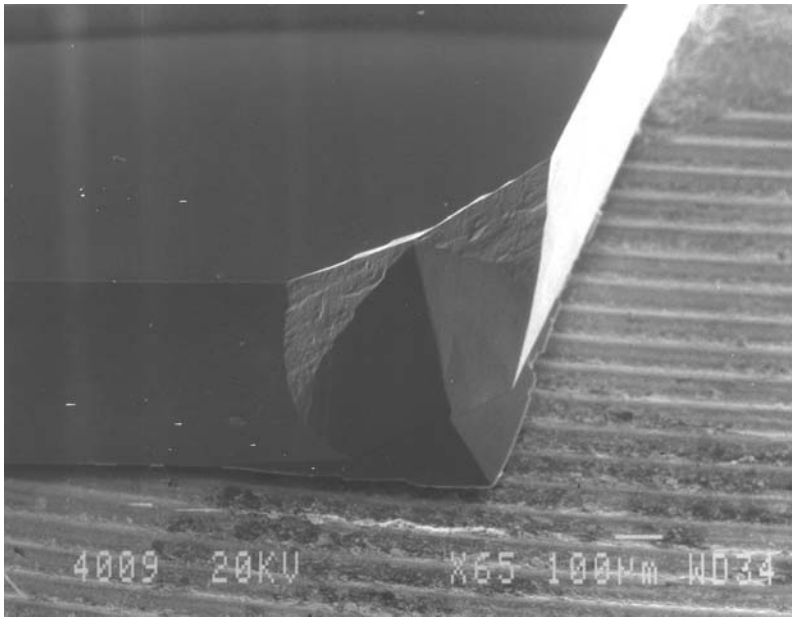
- Rhombic compensation pattern design



(110) Si Wet Etch (15)

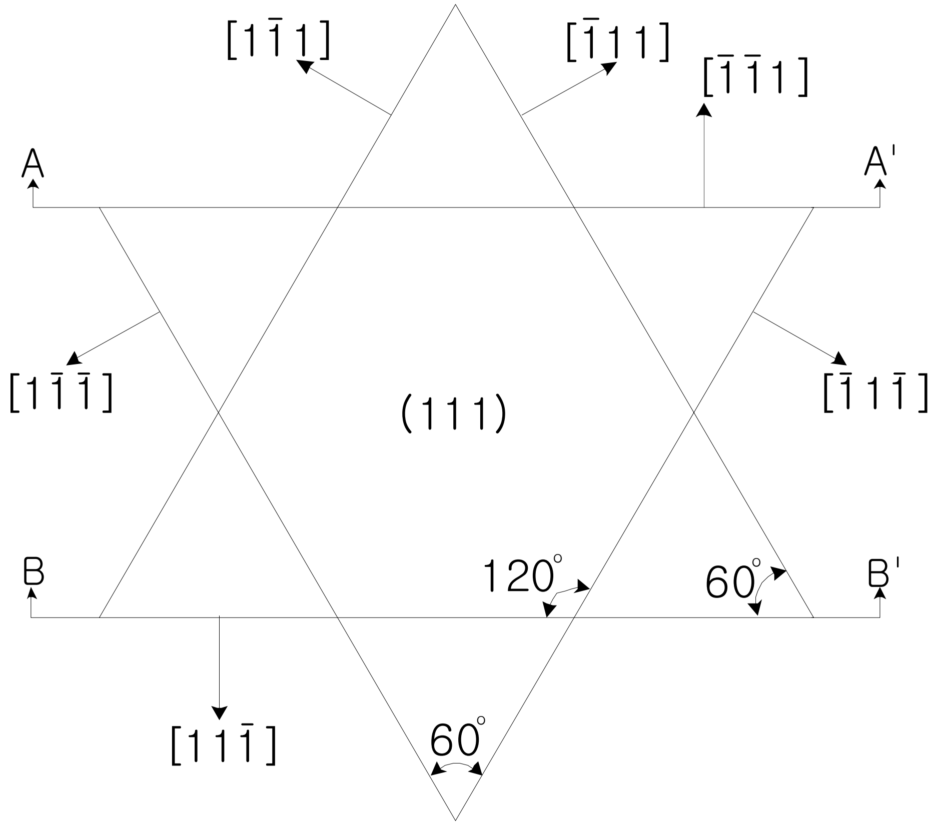
- Compensation results
  - Good compensation effects on both corners
  - Very small unwanted residues at the bottom
  - Features relatively sharp corners at the top

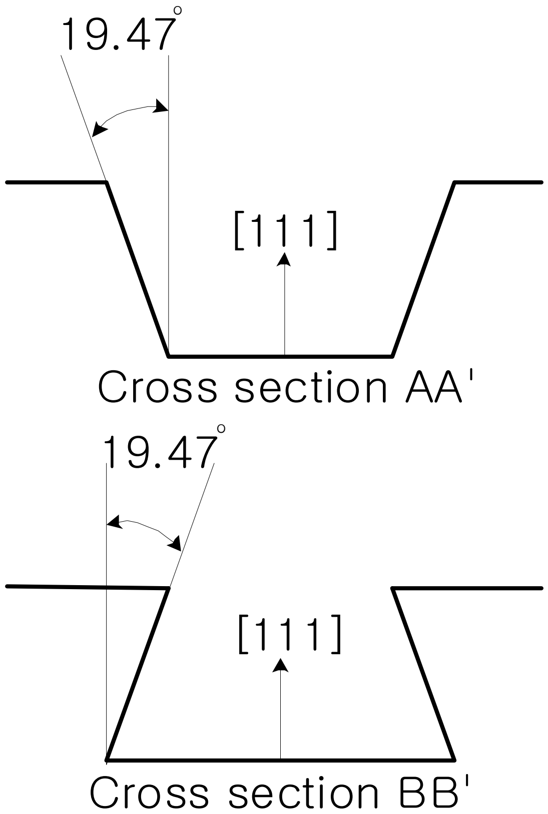




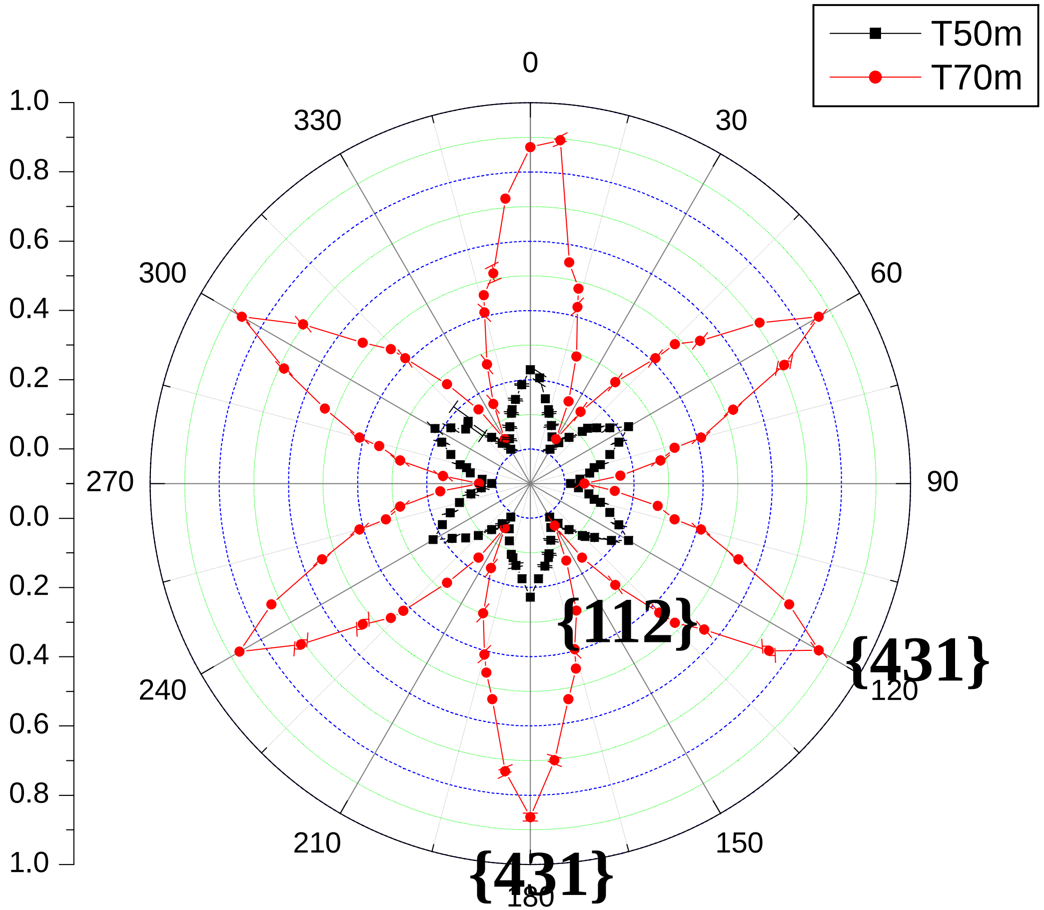
(111) Si Wet Etch (1)

- Crystallography of Si (111)





(111) Si Wet Etch (2)

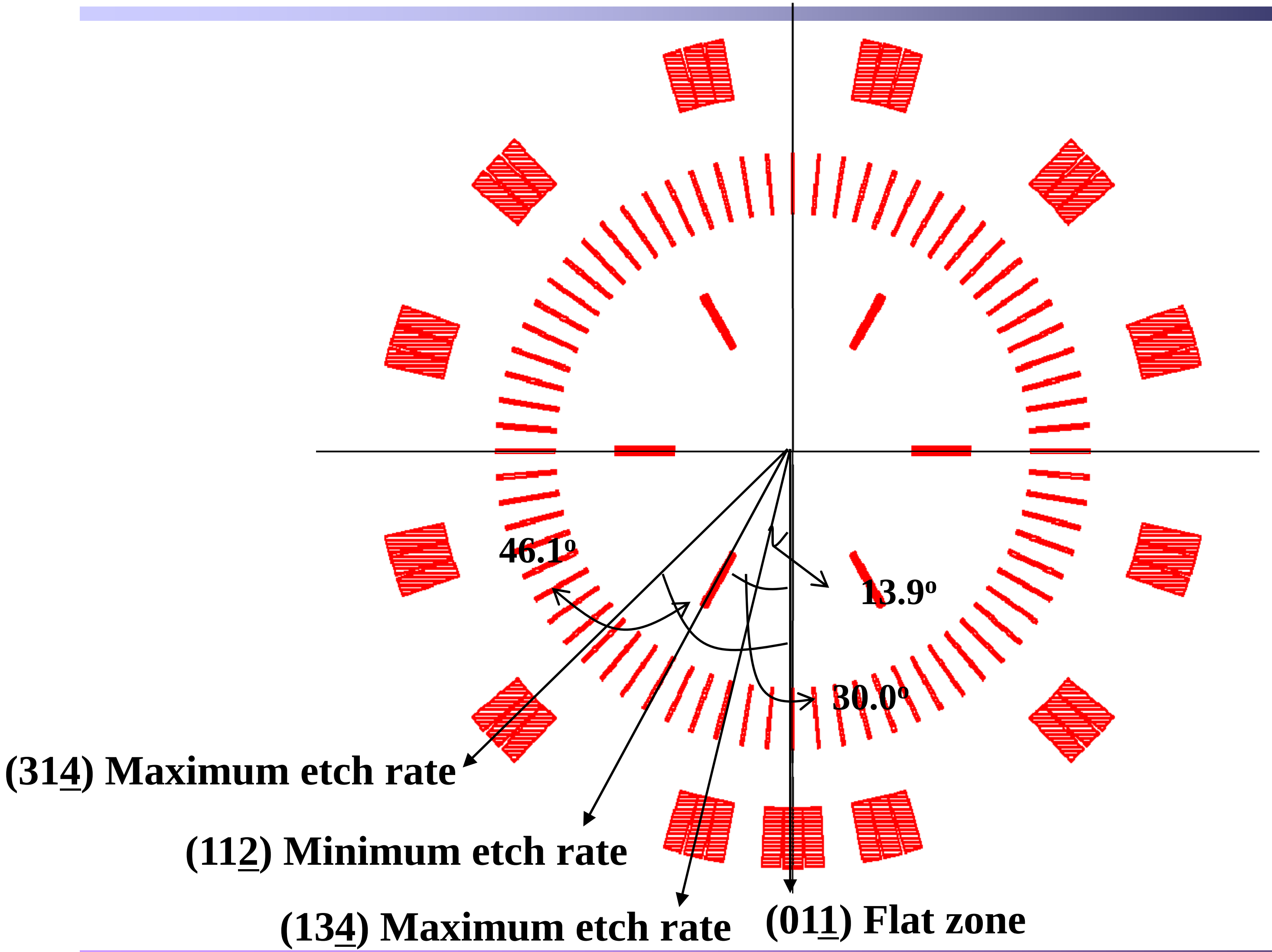


40wt % KOH

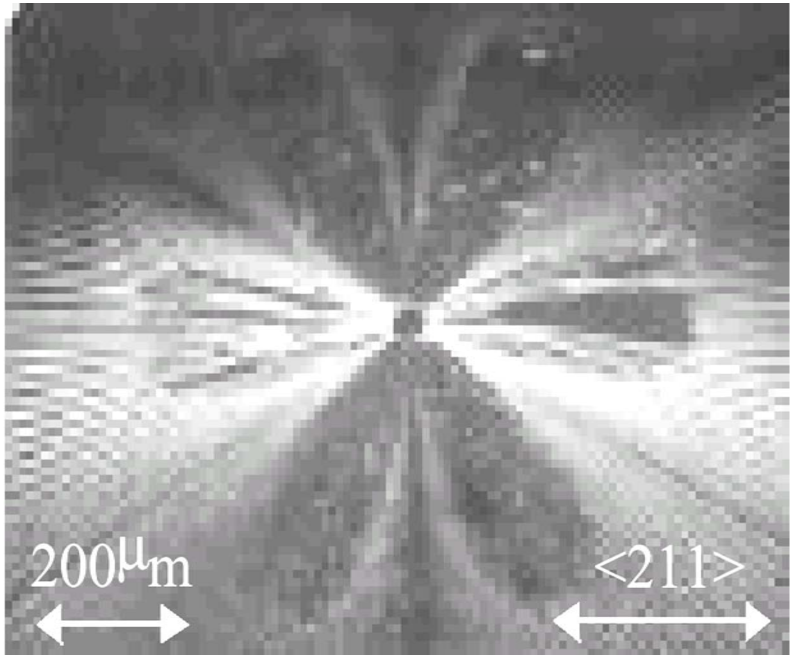
T50m: 50 ℃

T70m: 70 ℃

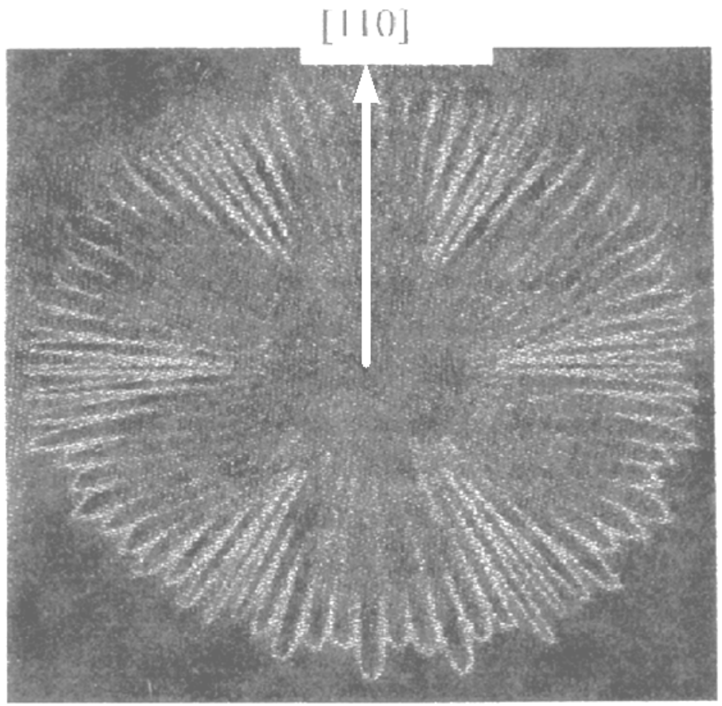
(111) Si Wet Etch (3)



(111) Si Wet Etch (4)



22 wt% TMAH at 80℃



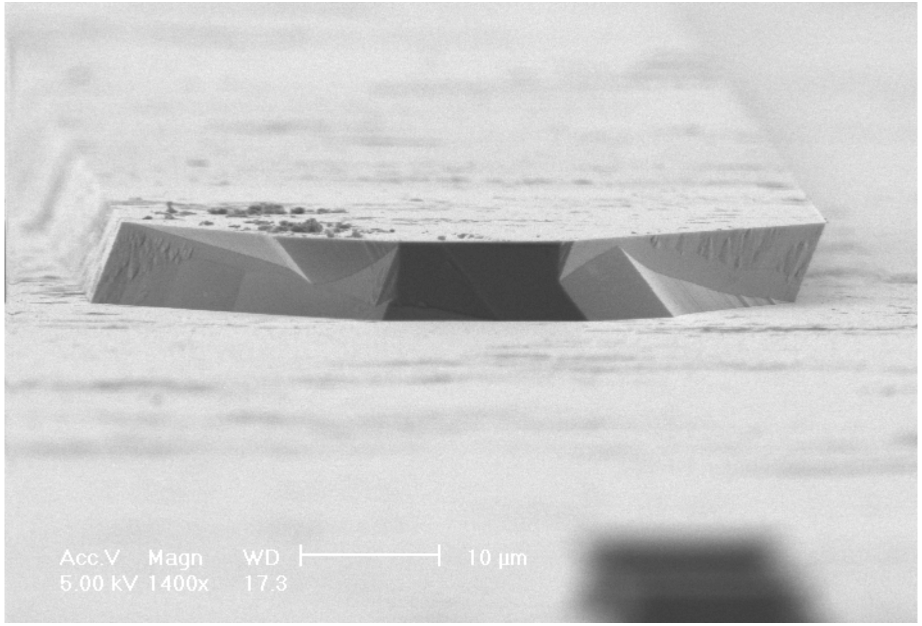
KOH at 80℃

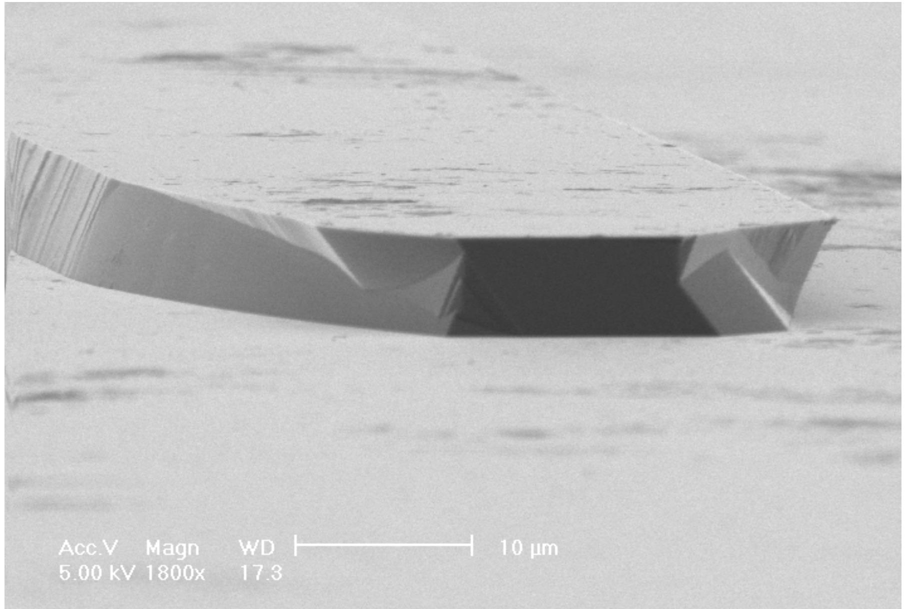
Ref) M. Sekimura, MEMS99, 1999

Ref) B.C.S. Chou, C-N. Chen, and J-S. Shie, Sensors and Actuators A, vol. 75, 1999

(111) Si Wet Etch (5)

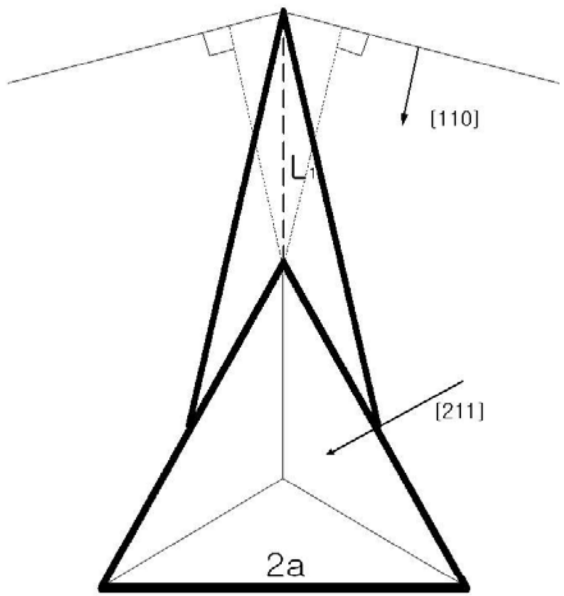
- SEM view: (111) wafer, TMAH 10%, 50℃



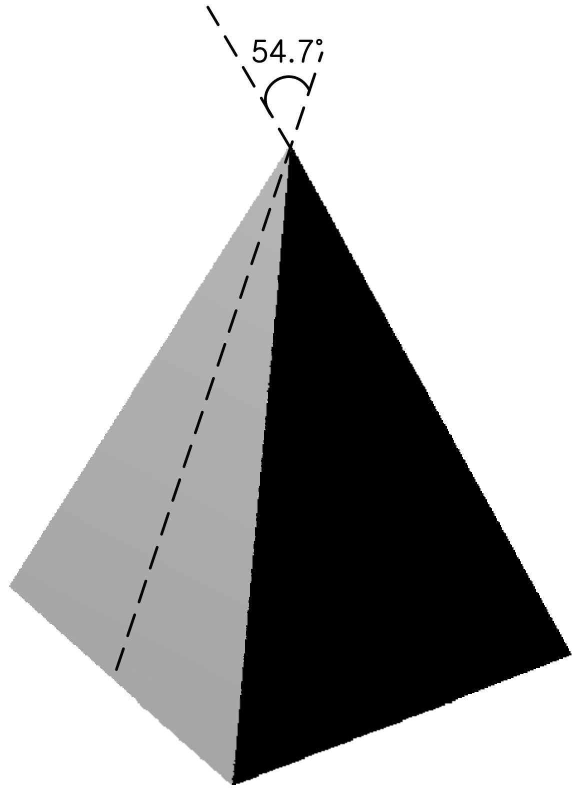


(111) Si Wet Etch Application (1)

- 3 {111}-faceted tip
  - Very sharp tip with 54.7°
  - Convex compensation design



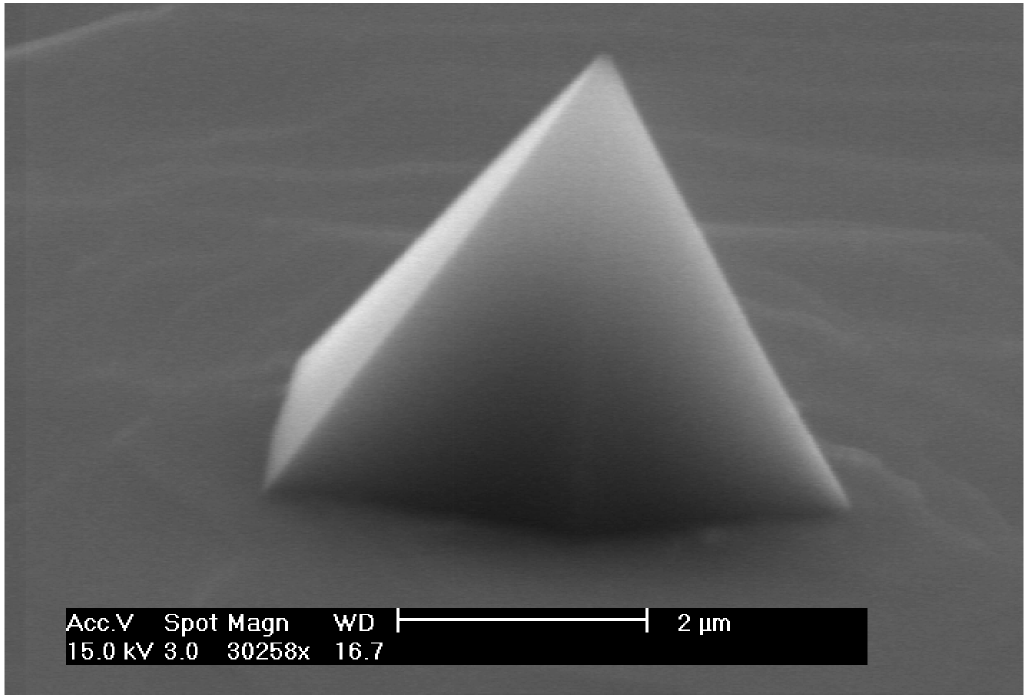
$$L_1 = \frac{2}{3} a \sin 70.53^\circ \frac{R_{110}}{R_{211}}$$



Dong-il "Dan" Cho **Nano/Micro Systems & Controls Lab.**

(111) Si Wet Etch Application (2)

- 3 {111}-faceted tip (composed of $(\bar{1}11)$, $(1\bar{1}1)$, $(11\bar{1})$)
  - Wet etch time: 3 min
  - Tip height: 5 μm

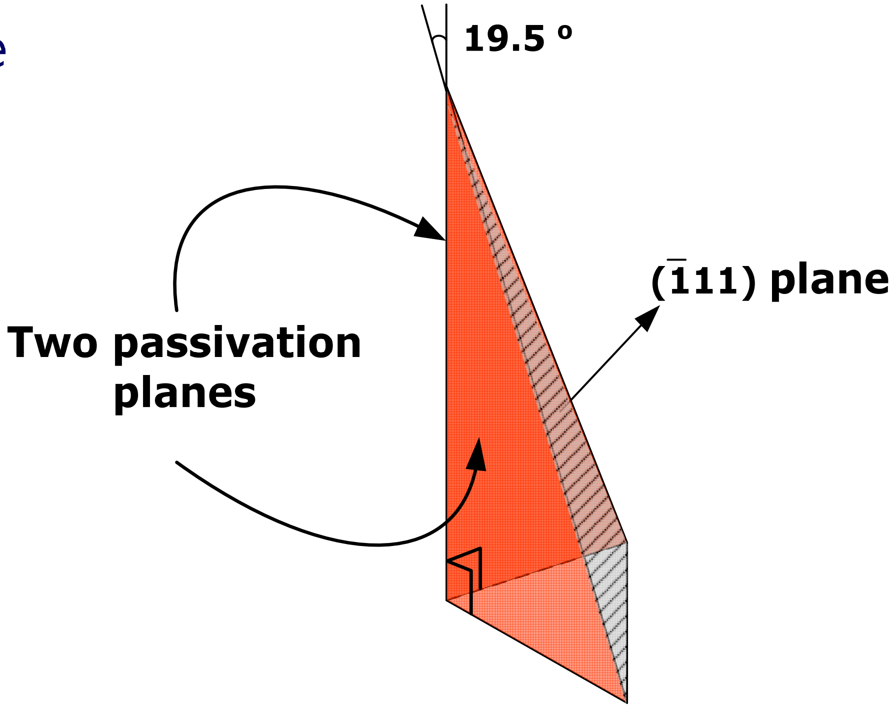


3 {111}-faceted tip

(111) Si Wet Etch Application (3)

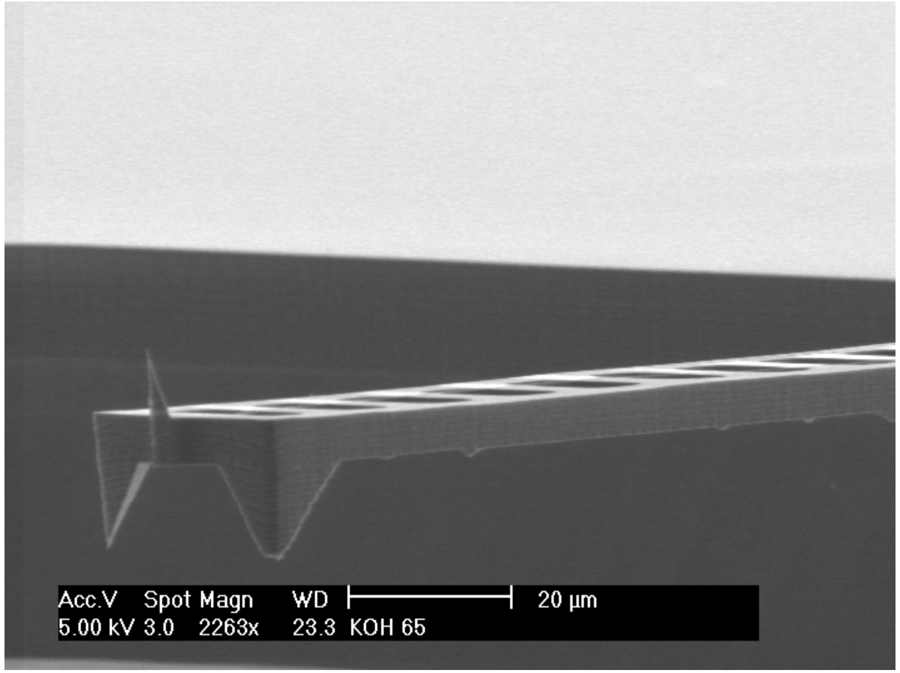
- (111) nano tip
  → Consist of single (111) plane and two passivation planes

- Advantages
  - Tip sharpness
    - Ultra-sharp cone angle
    - High-aspect ratio nano tip
  - Stable wet etch properties
    - Wet etch time
    - Wet etch conditions

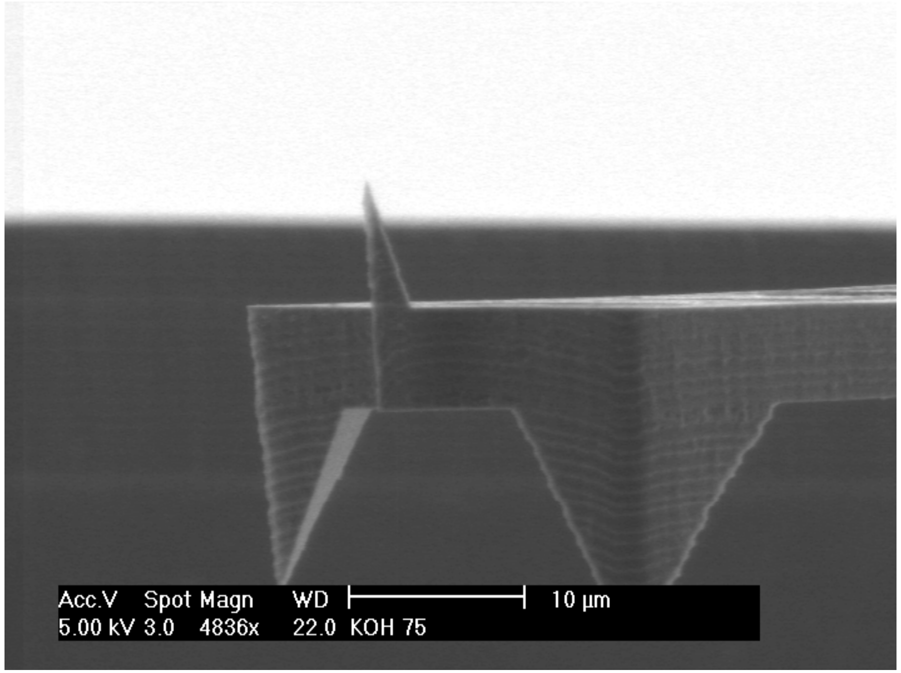


(111) nano tip

(111) Si Wet Etch Application (4)

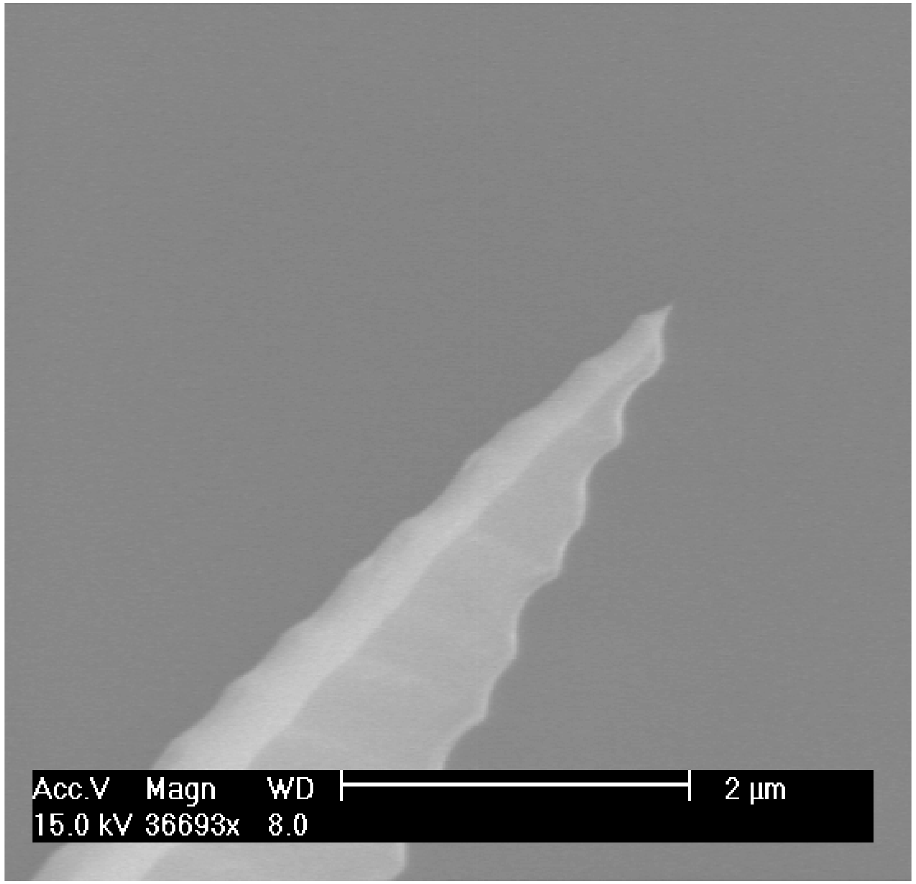


Single nano tip



Tip height: 10 µm

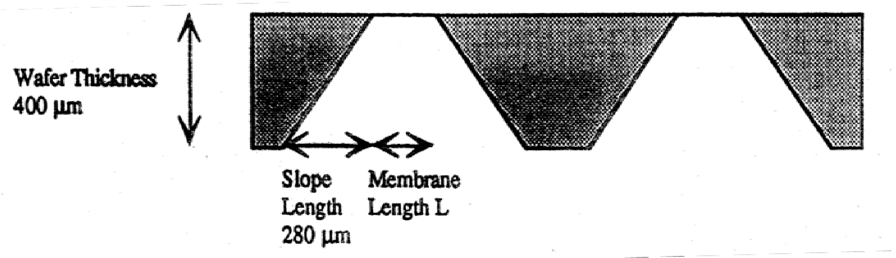
(111) Si Wet Etch Application (5)



- Specification of nano tip
  - Cantilever
    - Thickness: 8 µm
    - Length: 250 µm
    - Width: 30 µm
    - Pitch: 200 µm
  - Nano tip
    - Height: 10 µm
    - Aspect ratio: 3:1
    - Tip radius: 10 nm
    - Total cone angle: 19.5°

Limitation 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, …)

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