Lecture 19, 20:

Silicon Wet Etching

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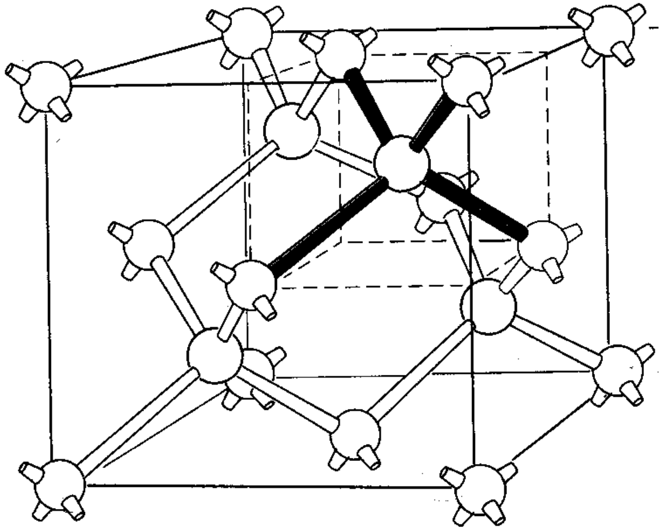
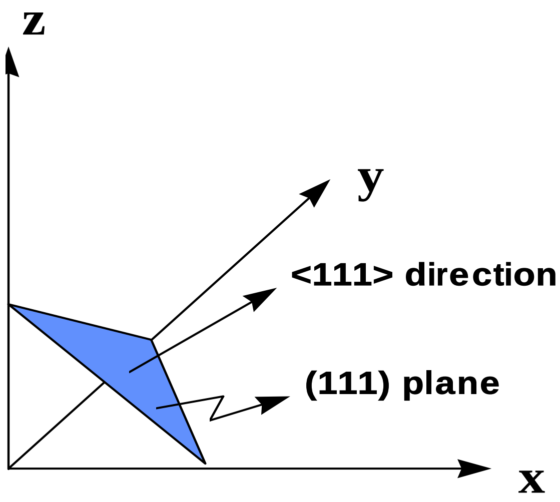
Silicon Crystallography (1)

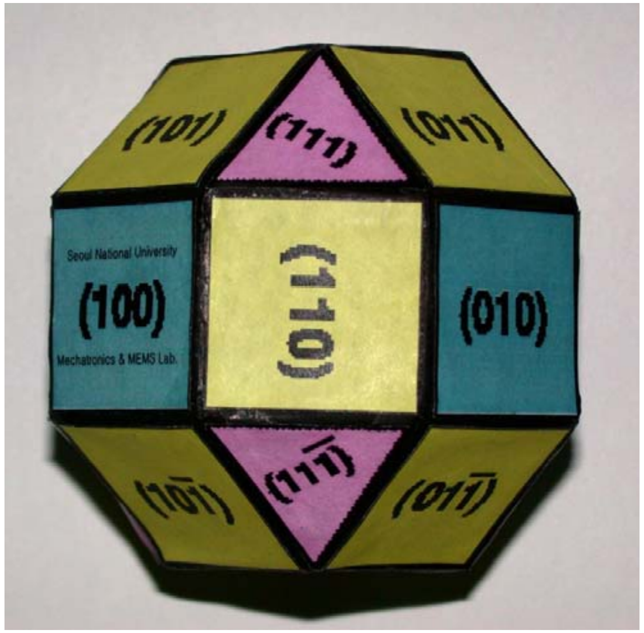

Si crystalline structure



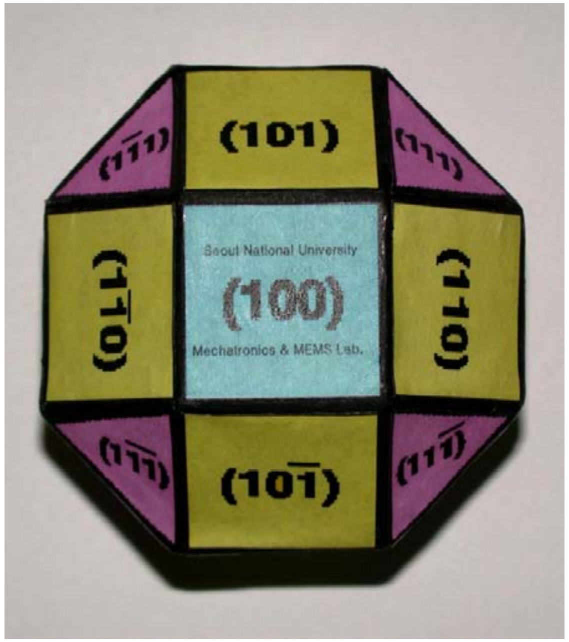
- Miller indices
  - (i j k) : a specific crystal plane or face
  - {i j k} : a family of equivalent planes
  - [i j k] : a specific direction of a unit vector
  - <i j k> : a family of equivalent directions

Silicon Crystallography (2)

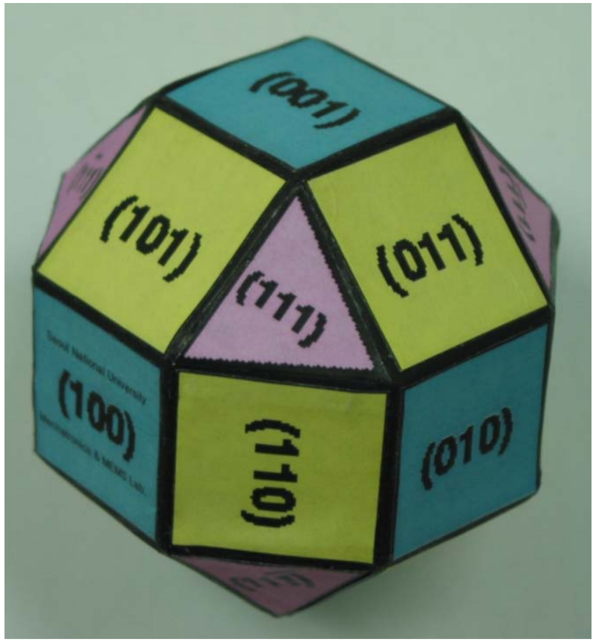
(110) silicon



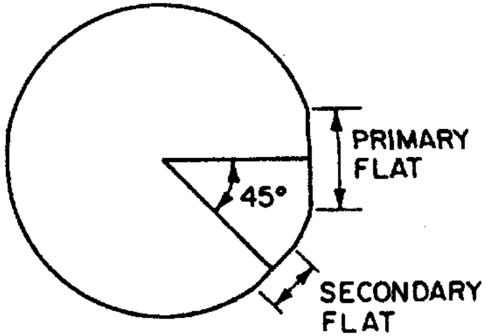
(100) silicon



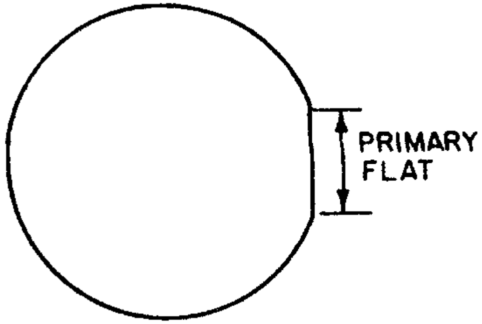
(111) silicon



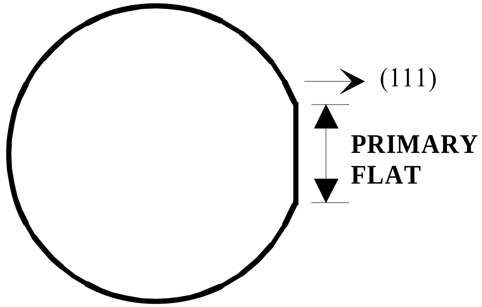
Wafer Type



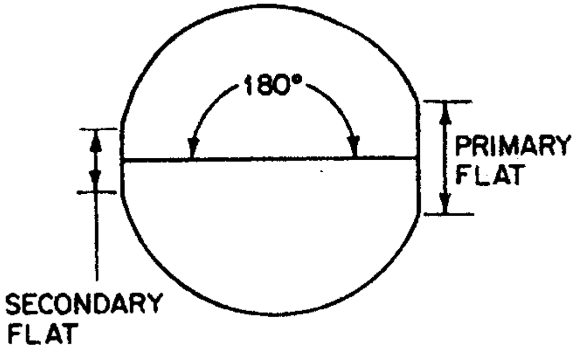
{111} n-TYPE



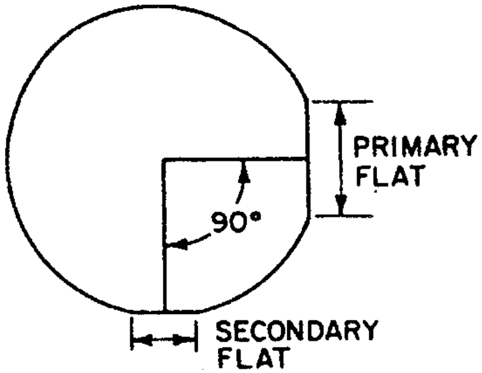
{111} p-TYPE



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



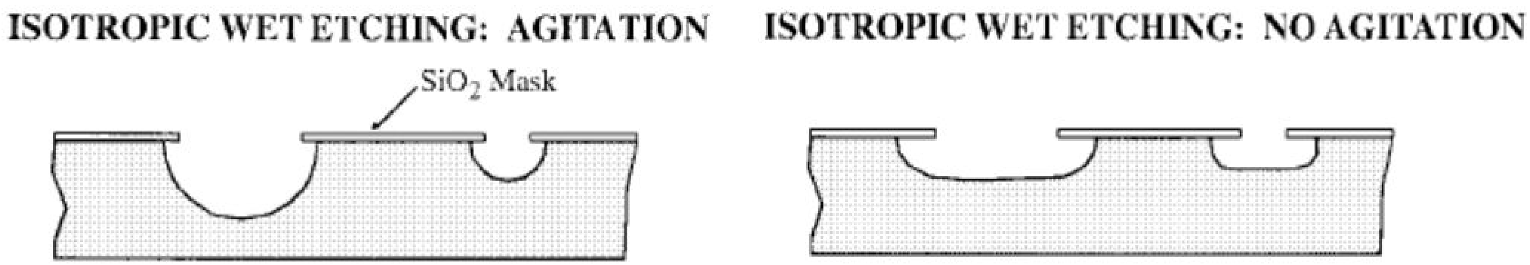
{100} n-TYPE



{100} p-TYPE

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 Si^{2+}

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

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

  - 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,

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

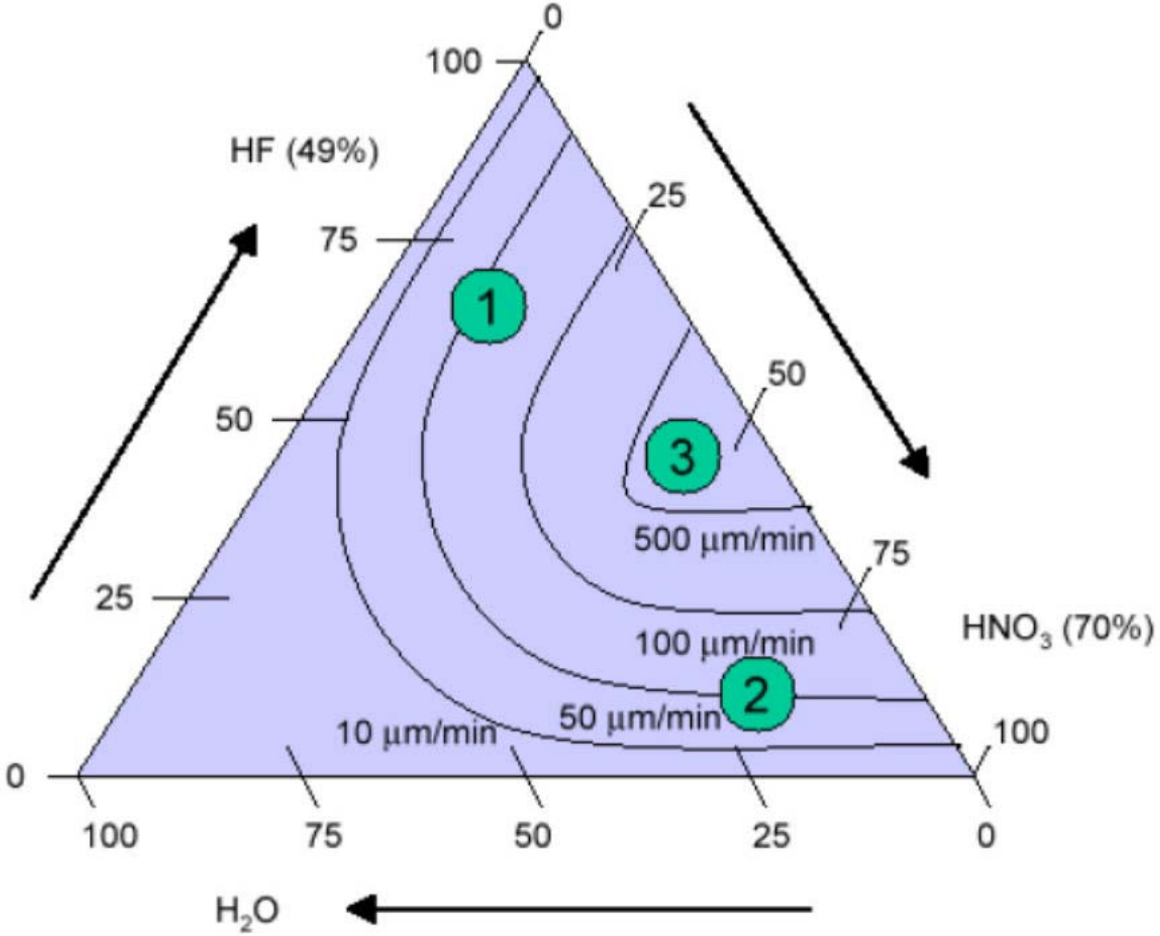
  Which can be rewritten,

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

→ 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)

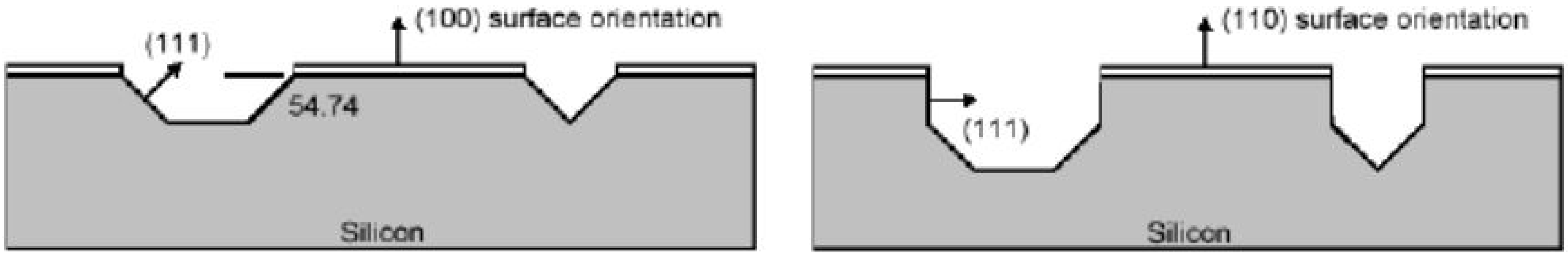
Etchant (Diluent)	Reagent Quantities	Temp. °C	Etch Rate (μm/min)	(100)/(111) Etch Ratio	Dopant Dependence	Masking Films (etch rate)
HF	10 ml				$\leq 10^{17}$ cm^{-3} n or p reduces etch rate ≈150 ×	
HNO_3	30 ml	22	0.7 to 3.0	1:1		SiO_2 (30 nm/min)
(water, CH_3COOH)	80 ml					
HF	25 ml					
HNO_3	50 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 o f HNA etchant formulations

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

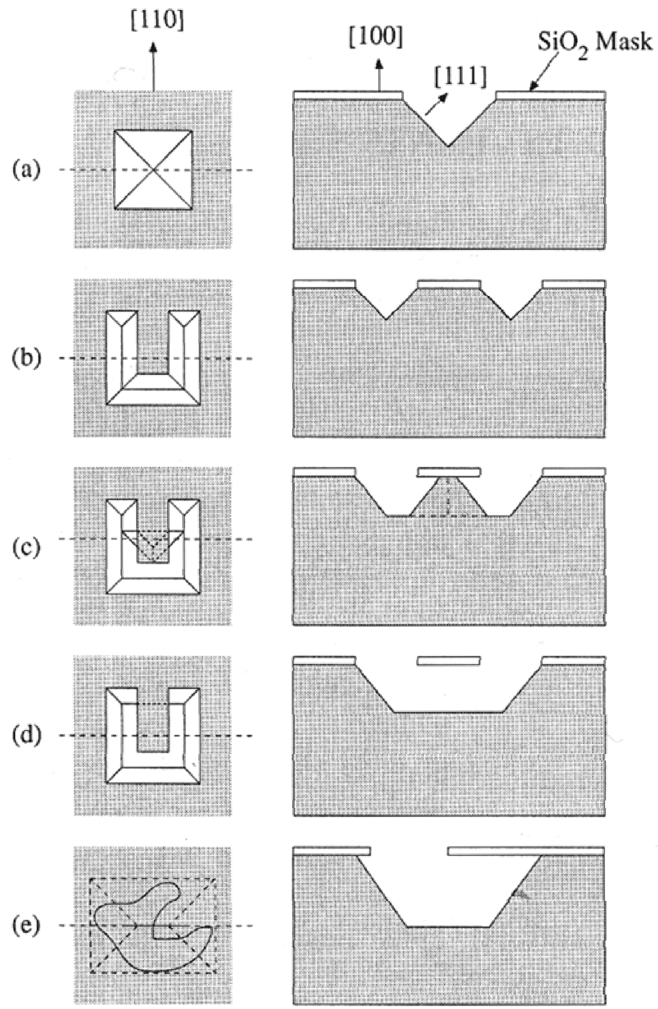
Anisotropic Wet Etching (1)

- 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

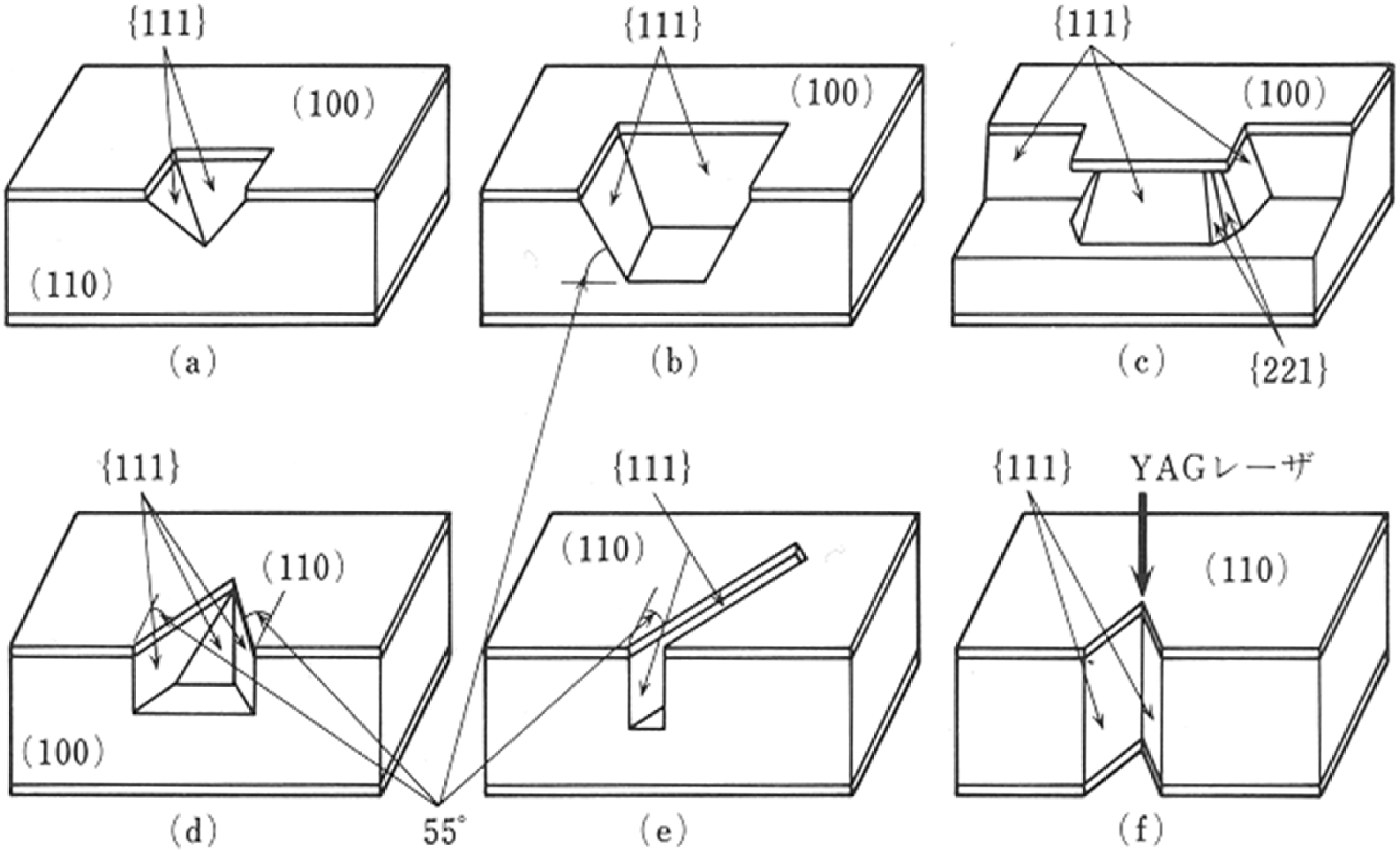


Anisotropic Wet Etching (2)

- 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



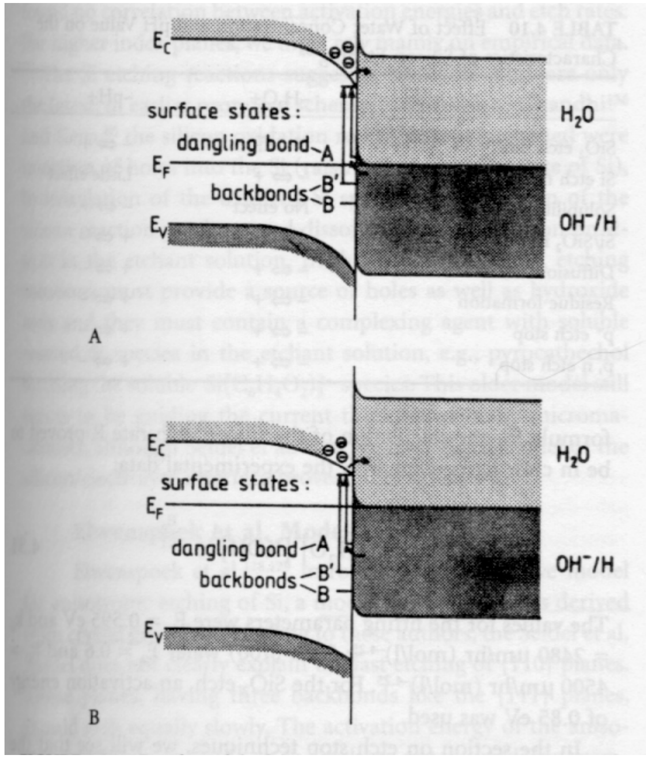
Anisotropic Wet Etching (3)



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

Anisotropic Wet Etching Mechanism (1)

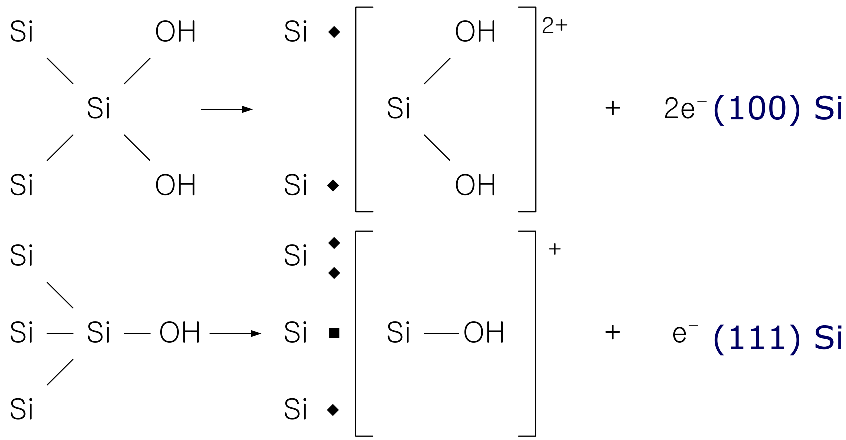
- H. Seidel et al.
  - Band model of the silicon/electrolyte interface for moderately doped Si



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

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

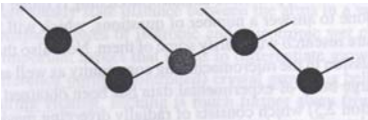
$$\begin{cases} Si + 2OH^- \rightarrow Si(OH)_2^{2+} + 2e^- \\ Si(OH)_2^{2+} + 2OH^- \rightarrow Si(OH)_4 + 2e^- \\ Si(OH)_4 + 4e^- + 4H_2O \rightarrow Si(OH)_6^{2-} + 2H_2 \end{cases}$$



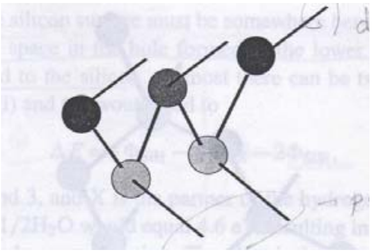
Ref.) H. Seidel, et al., J. Electrochem. Soc., vol. 137, no. 11, Nov. 1990

Anisotropic Wet Etching Mechanism (2)

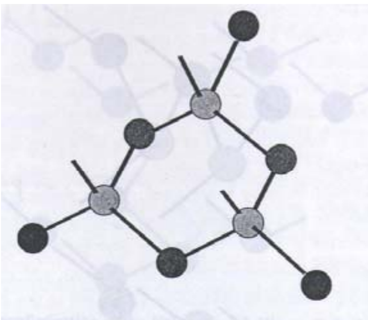
- M. Elwenspoek et al.
  - Explained the etching mechanism by the crystal growth theory
  - {111} plane has slow etch rate ← {111} plane is the smooth face



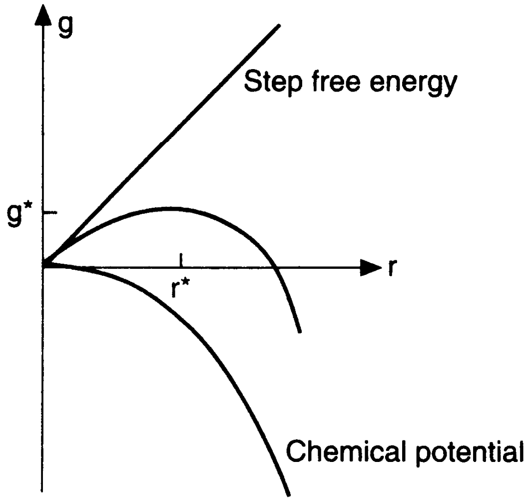
{100} plane



{110} plane



{111} plane



Δμ : 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 μm/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 > 7×10^{19} cm^{-3} boron doping

EDP Etching of Si (2)

- Typical formulation
  - 1 L ethylene diamine, NH_2-CH_2-CH_2-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 (㎛/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

Silicon Wet Etchants (1)

Comparison of Example Silicon Etchants

	HNA ($HF+HNO_3$ +Acetic Acid)	Alkali-OH	EDP (ethylene diamine pyrochat-echol)	TMAH (tetramethyl-ammonium hydroxide)	XeF_2	SF_6 Plasma	DRIE (Deep Reactive Ion Etch)
Etch Type	wet	wet	wet	wet	dry [1]	dry	dry
Anisotropic?	no	yes	yes	yes	no	varies	yes
Availability	common	common	moderate	moderate	limited	common	limited
Si Etch Rate μm/min	1 to 3	1 to 2	1 to 30	≈ 1	1 to 3	≈ 1	> 1
Si Roughness	low	low	low	variable [2]	high [3]	variable	low
Nitride Etch	low	low	low	1 to 10 nm/min	?	low	low
Oxide Etch	10 to 30 nm/min	1 to 10 nm/min	1 to 80 nm/min	≈ 1 nm/min	low	low	low
Al Selective	no	no	no [4]	yes [5]	yes	yes	yes
Au Selective	likely	yes	yes	yes	yes	yes	yes
p++ Etch Stop?	no (n slows)	yes	yes	yes	no	no (some dopant effects)	no

Silicon Wet Etchants (2)

Comparison of Example Silicon Etchants

	HNA ($HF+HNO_3$ +Acetic Acid)	Alkali-OH	EDP (ethylene diamine pyrochat-echol)	TMAH (tetramethyl-ammonium hydroxide)	XeF_2	SF_6 Plasma	DRIE (Deep Reactive Ion Etch)
Electrochemical Stop?	?	yes	yes	yes	no	no	no
CMOS Compatible?[6]	no	no	yes	yes	yes	yes	yes
Cost[7]	low	low	moderate	moderate	moderate	high	high
Disposal	low	easy	difficult	moderate	N/A	N/A	N/A
Safety	moderate	moderate	low	high	moderate?	high	high

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

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

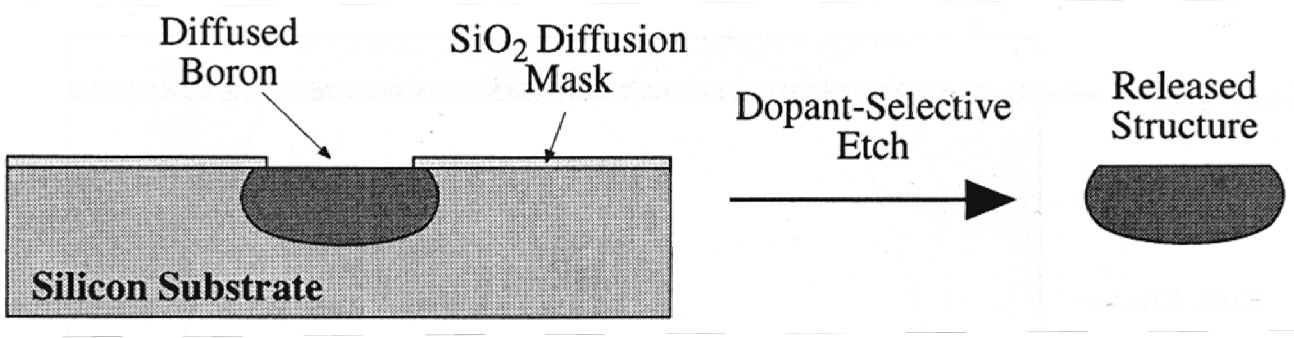
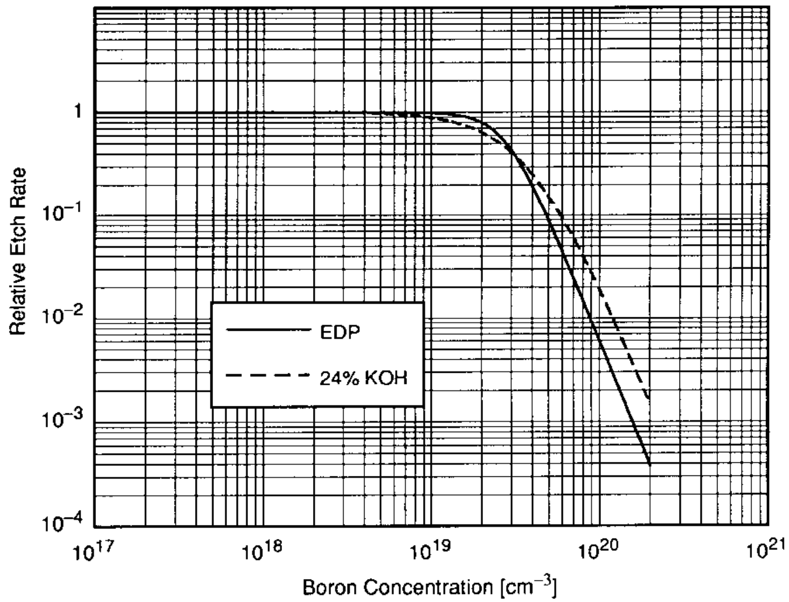


Illustration of the use of heavy boron doping with a dopant-selective etch to form free structures

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.

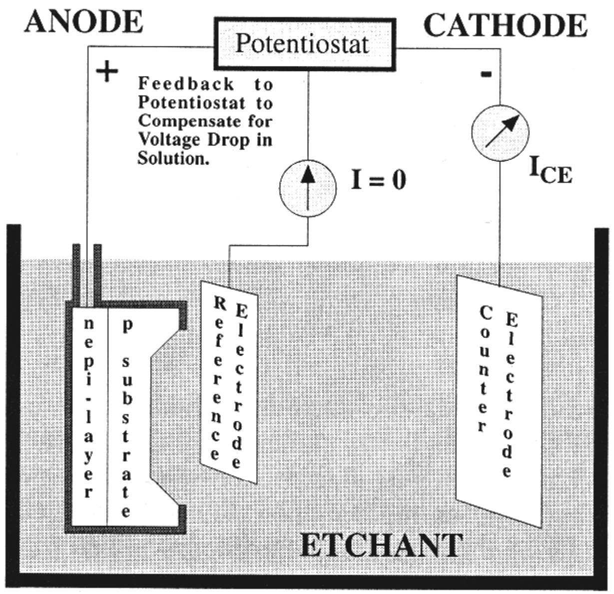


Electrochemical Etch Stop (1)

- 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

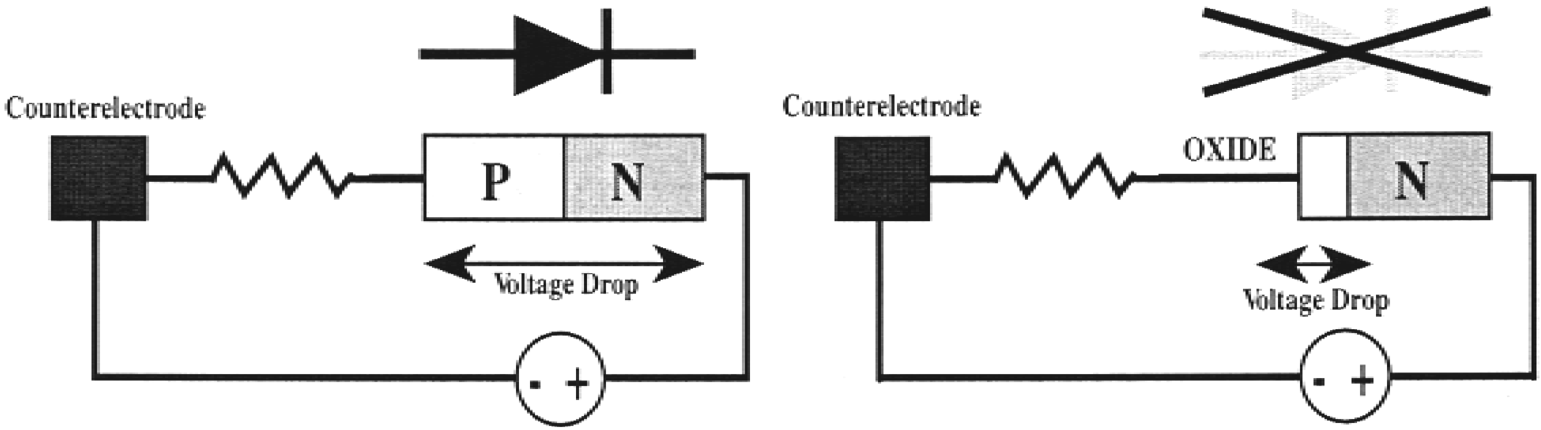
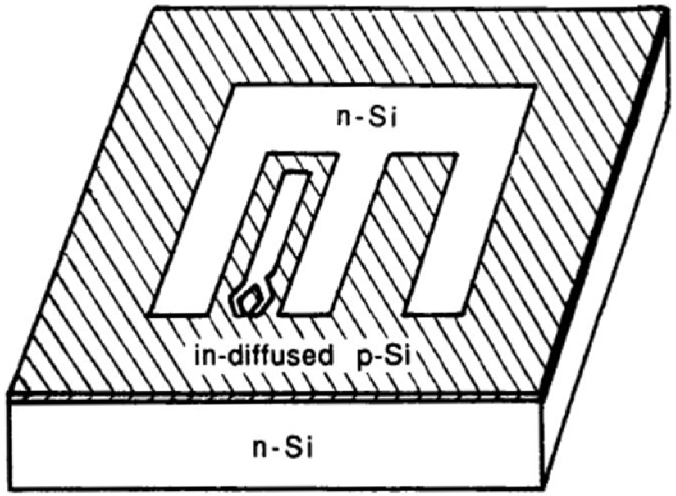


Illustration of diode junction etching

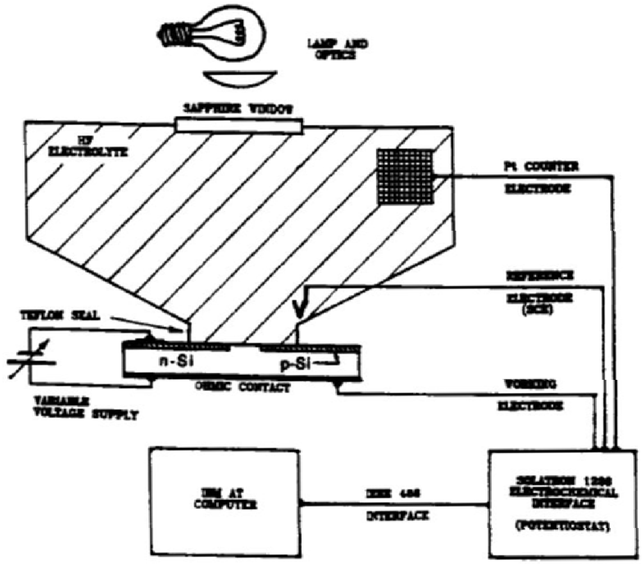
Electrochemical Etch Stop (4)

- 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



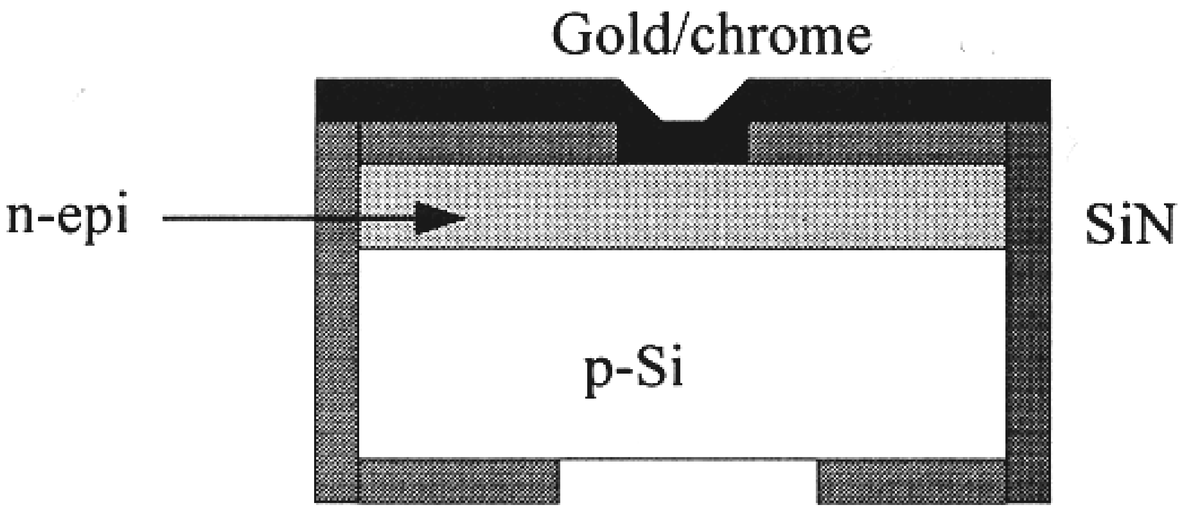
Schematic of the spatial geometry of the indiffused p-Si layer in to n-Si used to form cantilever beam structures



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 Mask (2)

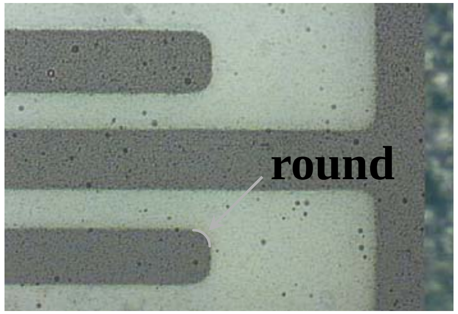
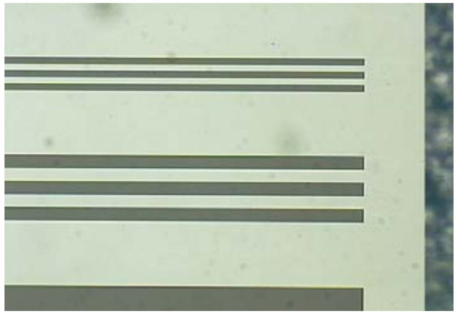
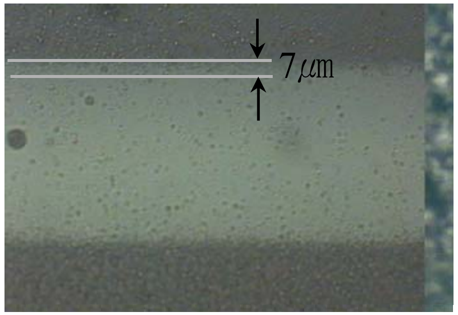
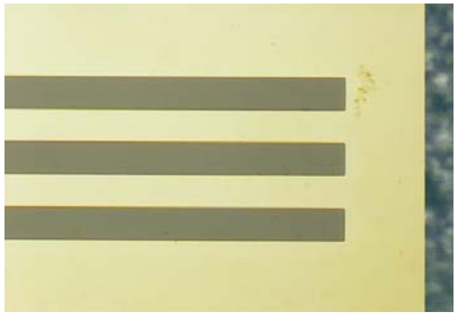
- Etching Masks: Mask Qualities vs. Etching Properties
  - Mask qualities on etching properties
    - Resolution, CD tolerance, edge sharpness
    - Roughness on vertical sidewall profile

  - Result in selectivity

	Film Mask	*E-beam mask*
resolution	*50 ㎛*	*1 ㎛*
tolerance	*7-8 ㎛*	*0.2 ㎛*
cost	*25 $*	*1400 $*
contrast	*bad*	*excellent*
cleaning	*No*	*Yes*
# of usage	*saveral*	*unlimited if cleaned*
hardness	*flexible*	*hard*

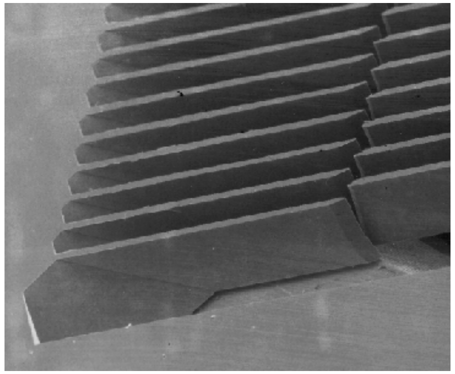
Wet Etch Mask (3)

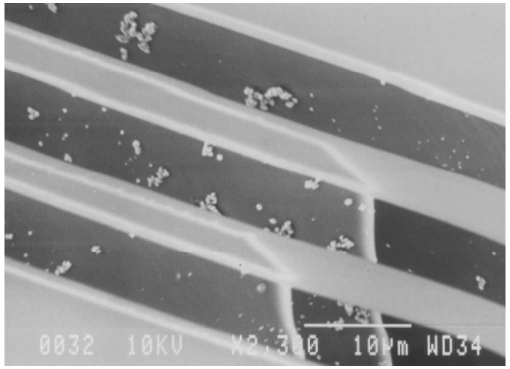
- Etching masks: comparison of mask properties

	Film Mask	**E-beam Mask**
×100		
	100 ㎛ width **50 ㎛ gap**	**10 ㎛ width** **10 ㎛ gap**
×500		

Wet Etch Mask (4)

- Etching masks: fabricated structures using different Mask

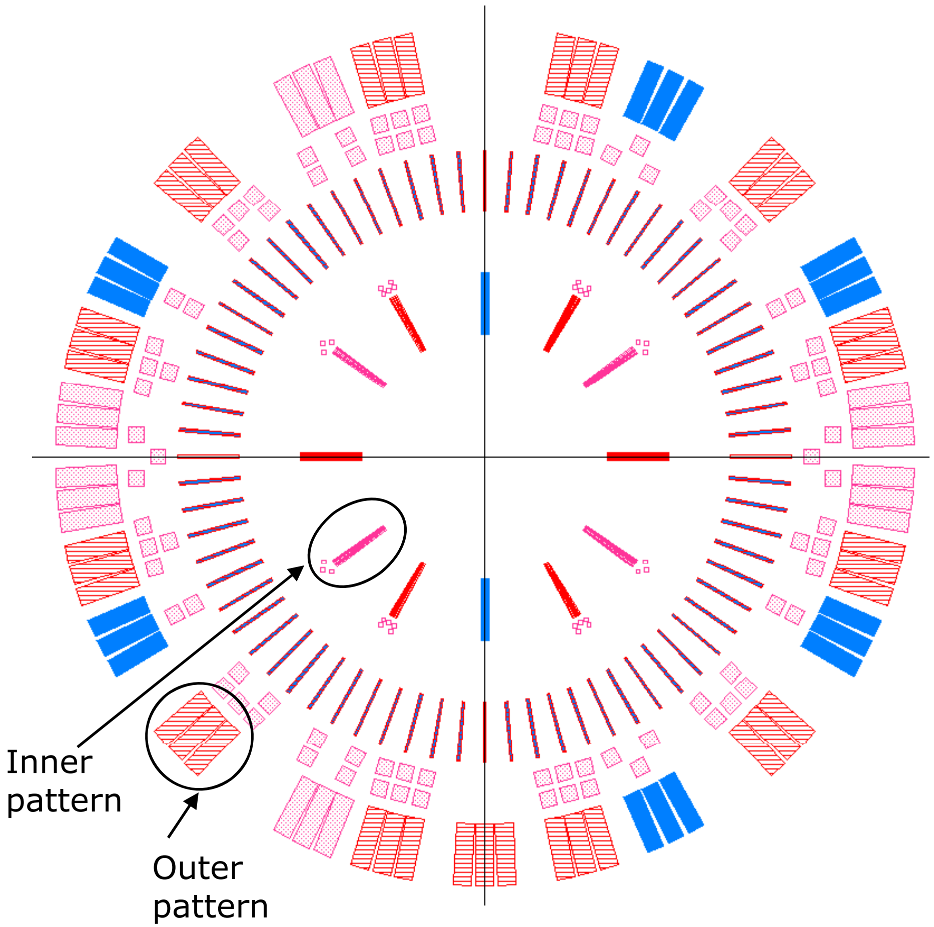




	Film mask	E-beam mask
Layout	100 ㎛ width 50 ㎛ gap	10 ㎛ width 10 ㎛ gap
Fabrication	75 ㎛ width 75 ㎛ gap	8 ㎛ width 12 ㎛ gap
Selectivity	45	90

Wet Etch Test Pattern (1)

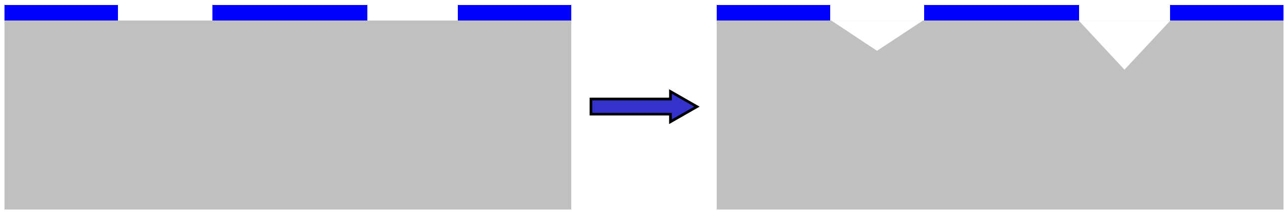
- Wagon wheel pattern mask



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

Wet Etch Test Pattern (2)

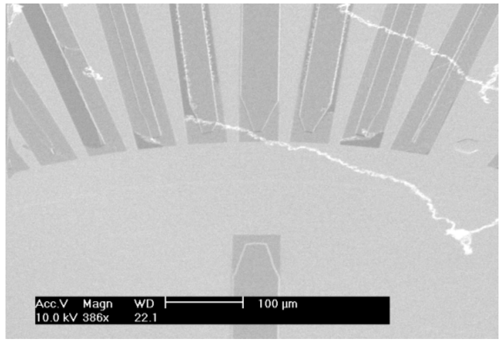
- Patterns defined by only photolithography



Pattern

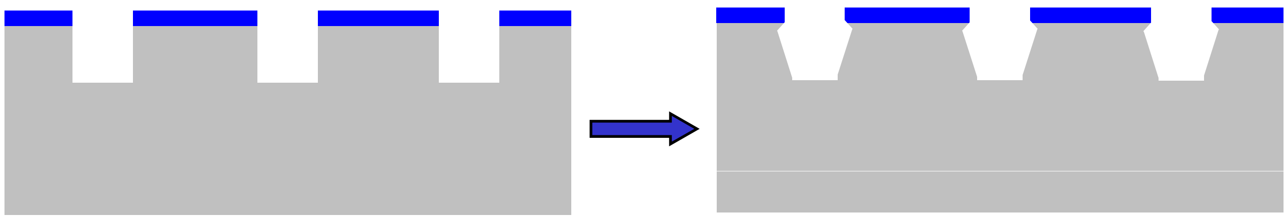
Wet etch

Oxide Silicon



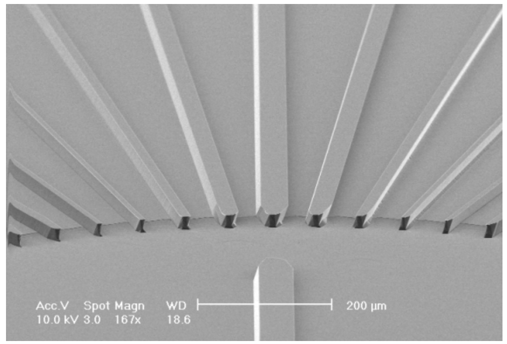
Wet etch result

- Patterns defined by deep Si etch



Pattern

Wet etch

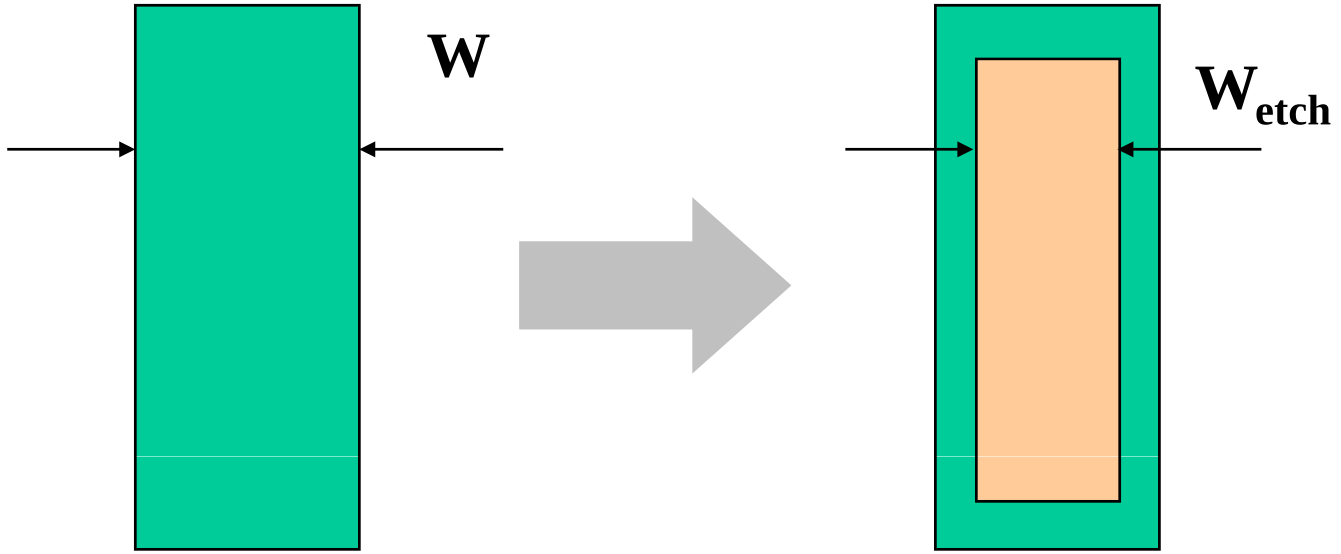


Wet etch result

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

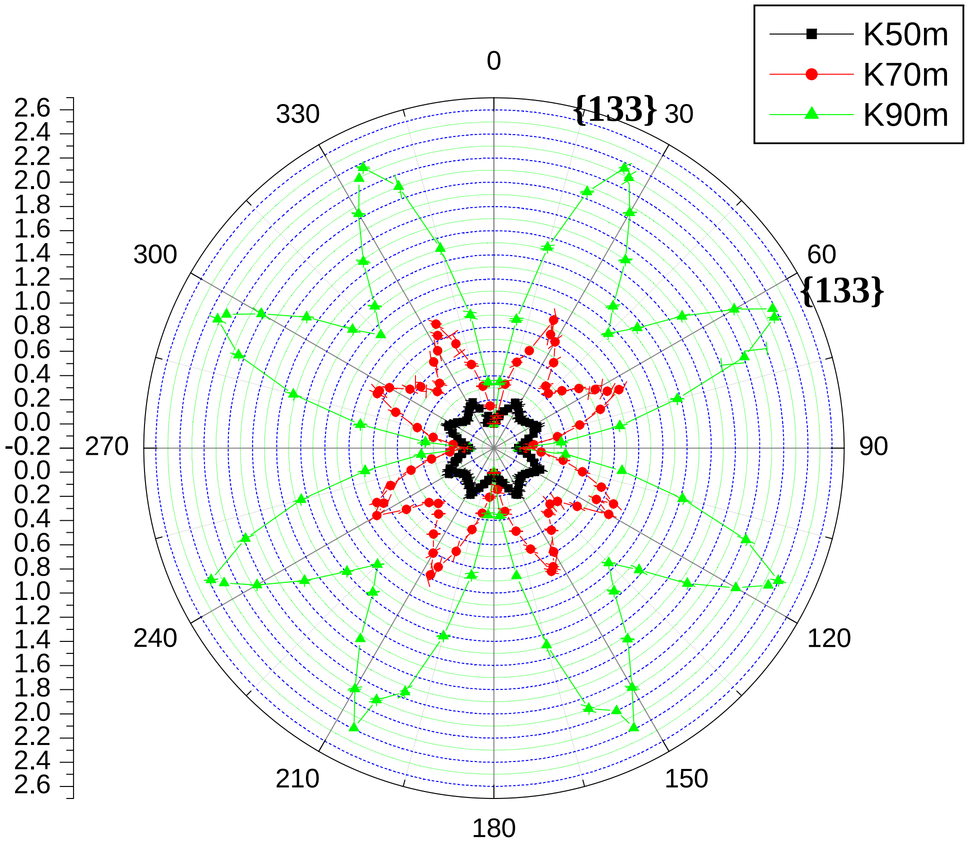
Wet Etch Test Pattern (3)

- Wet etch rate inspection



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

(100) Si Wet Etch (1)



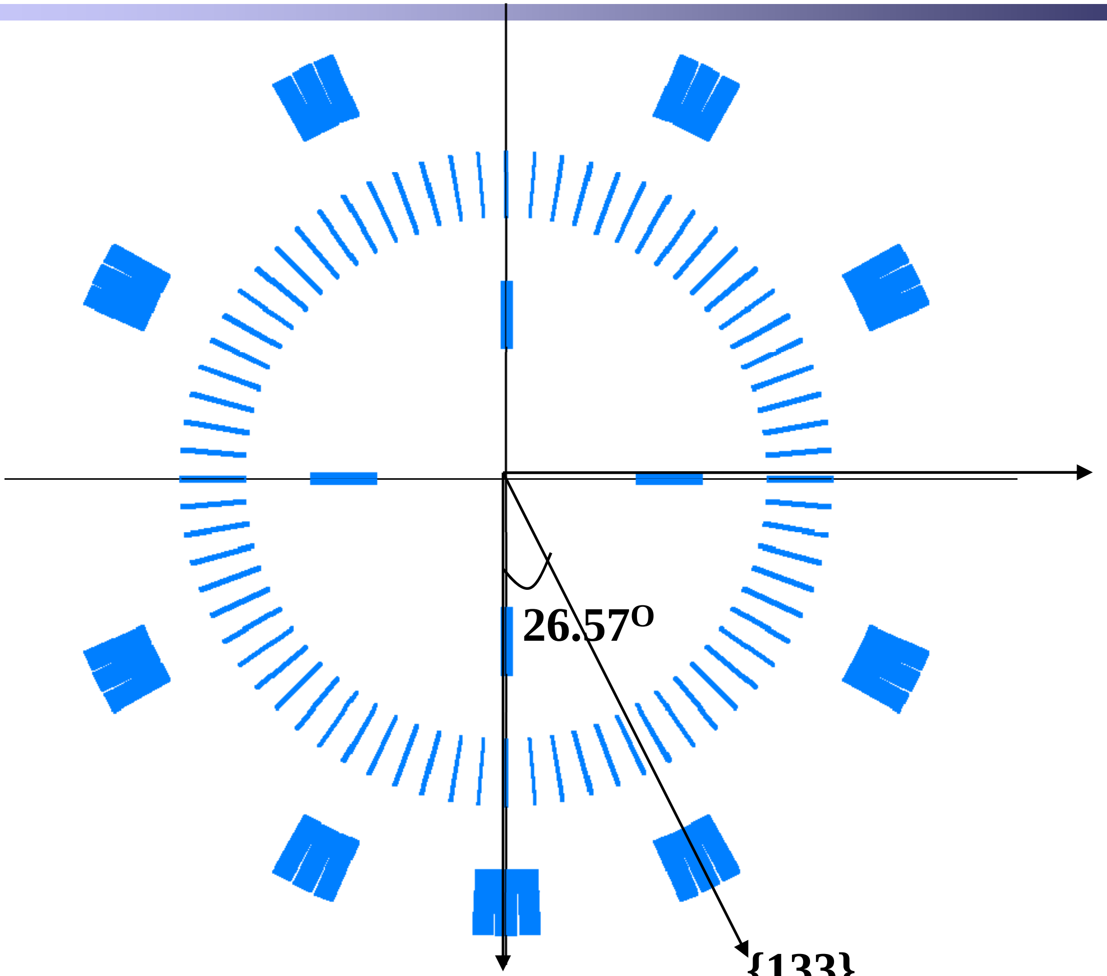
40wt % KOH

K50m: 50 ℃

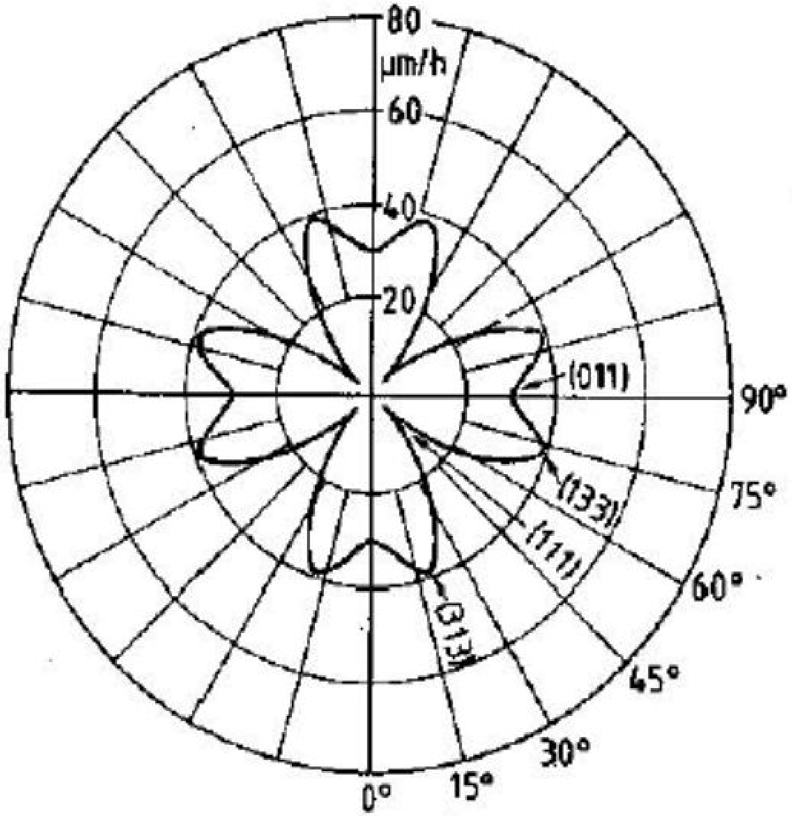
K70m: 70 ℃

K90m: 90 ℃

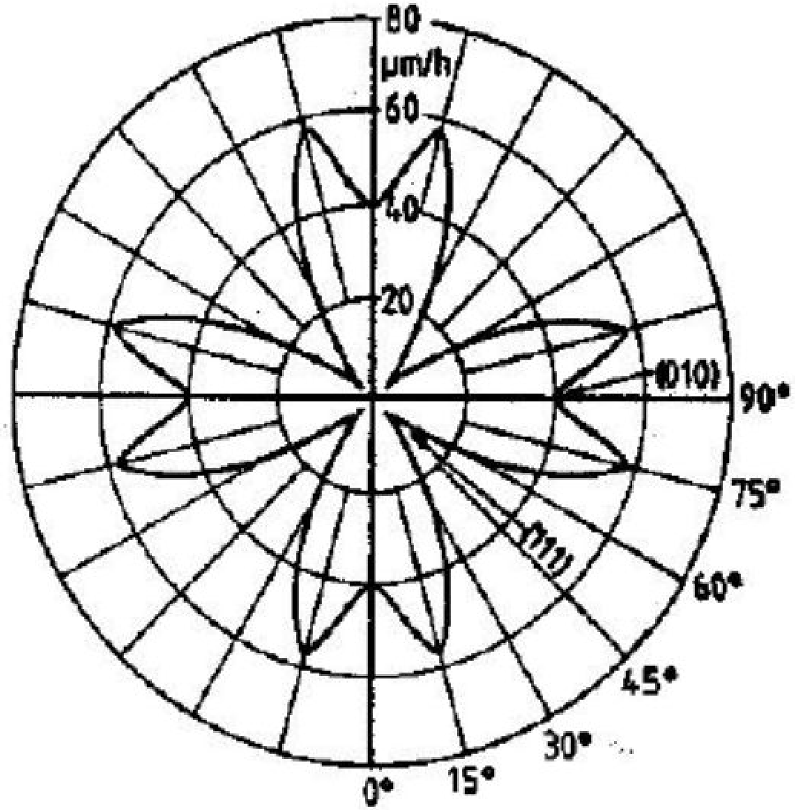
(100) Si Wet Etch (2)



(100) Si Wet Etch (3)



EDP solution at 95 ℃

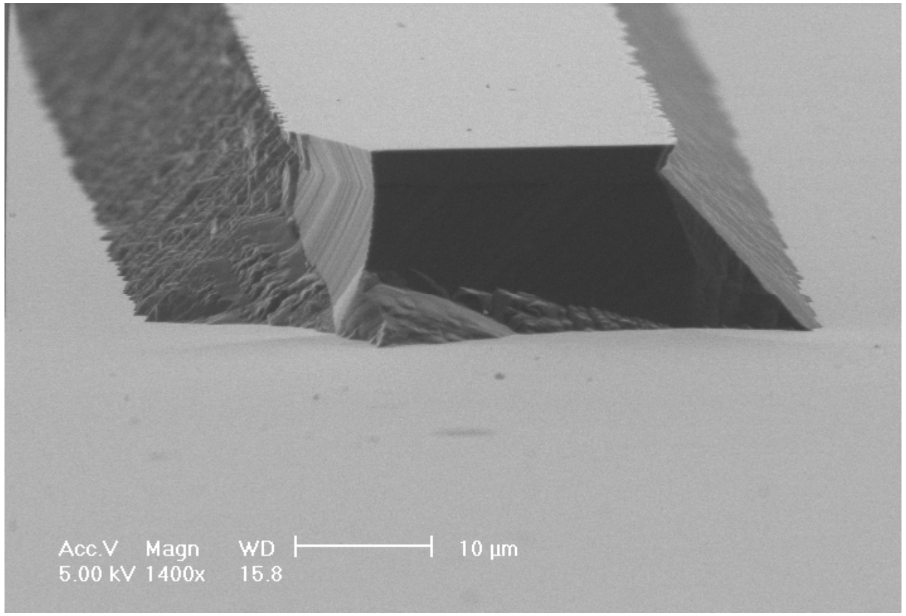


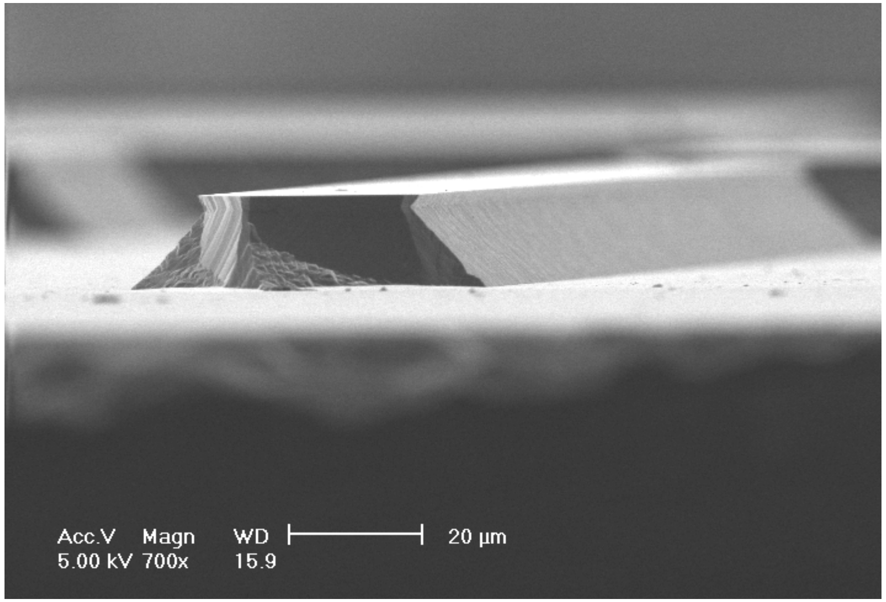
KOH solution at 78 ℃

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℃





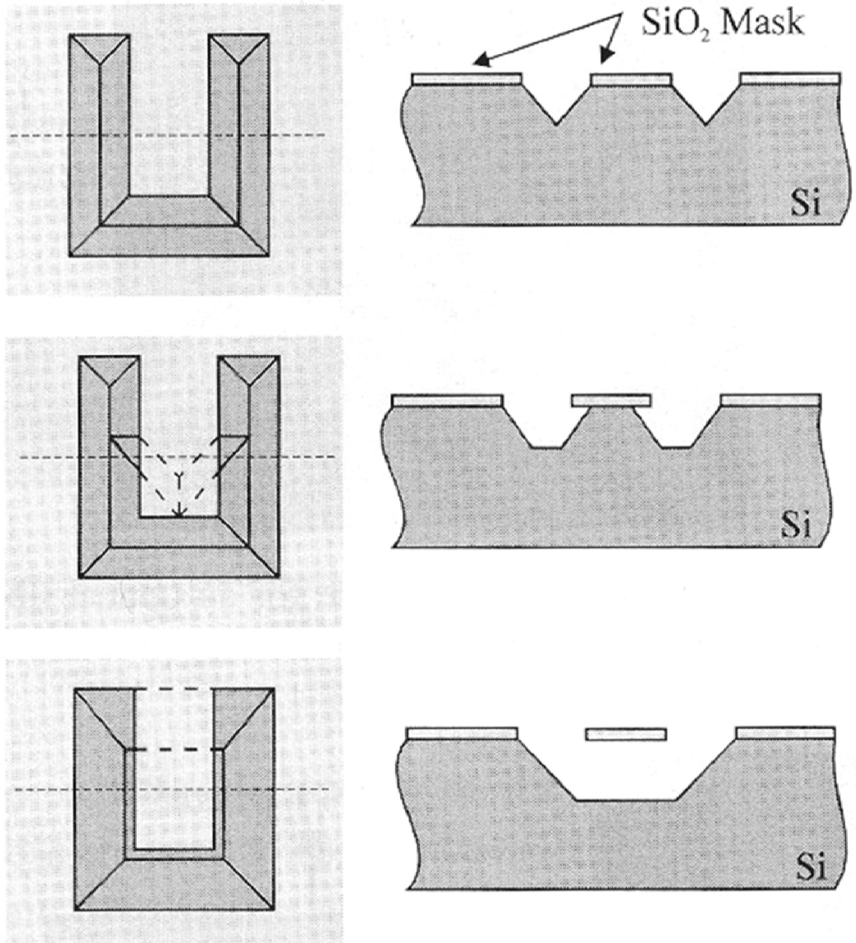
(100) Si Wet Etch (5)

- Micromachining of (100) wafer

(a)

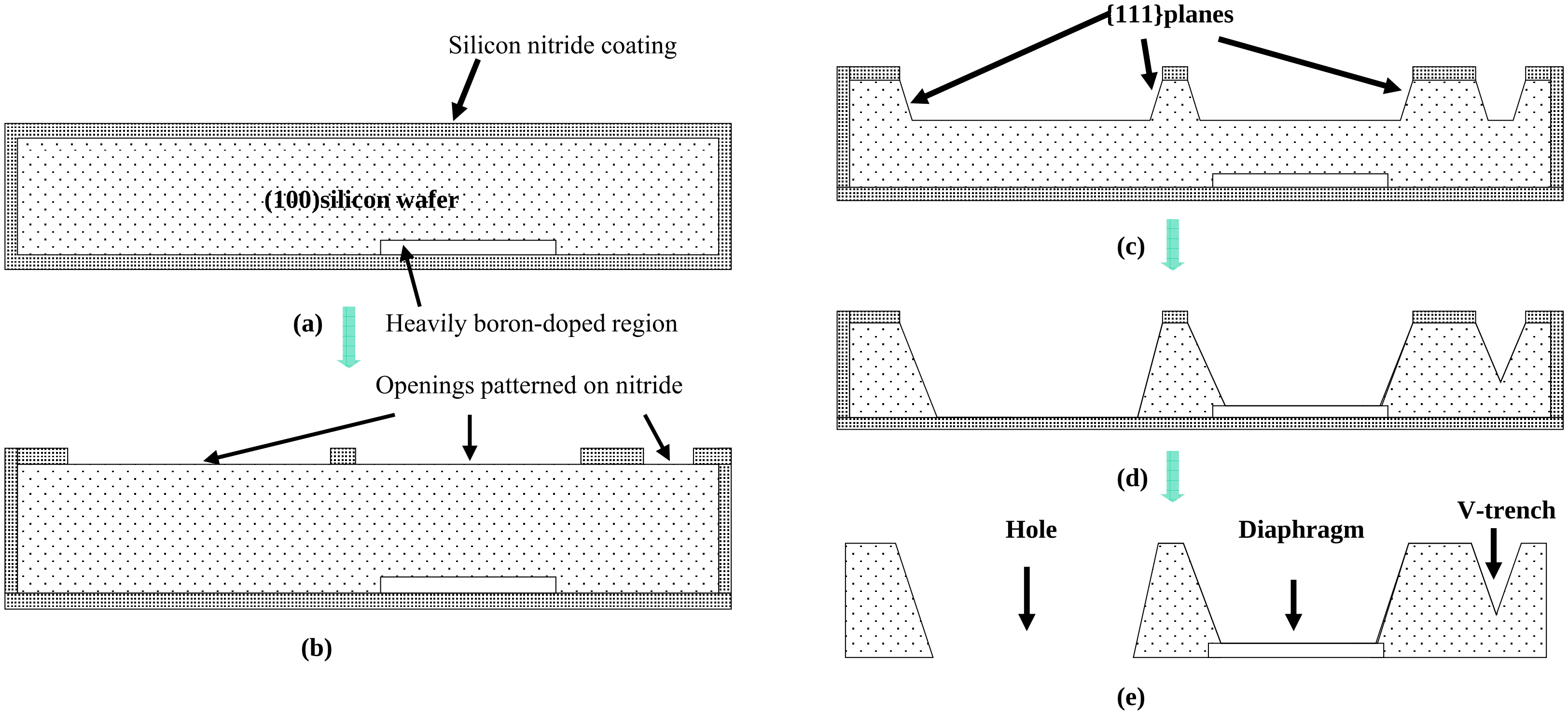
(b)

(c)

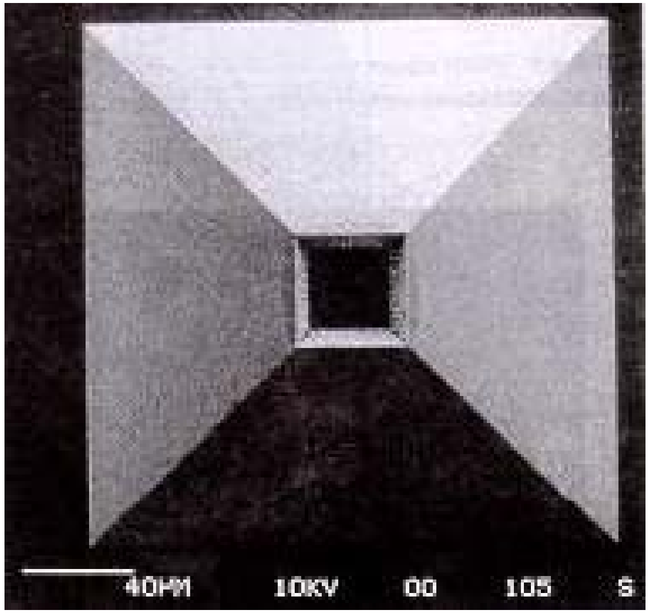


(100) Si Wet Etch (6)

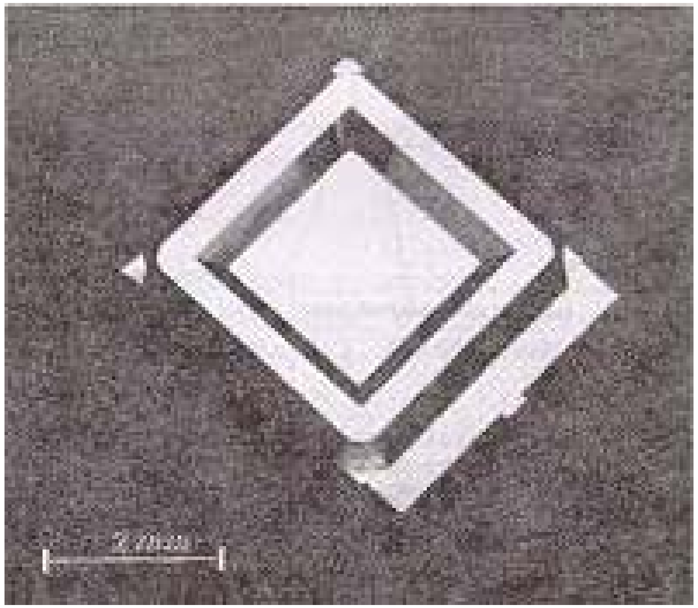
- Anisotropic Silicon Etching



(100) Si Wet Etch (7)



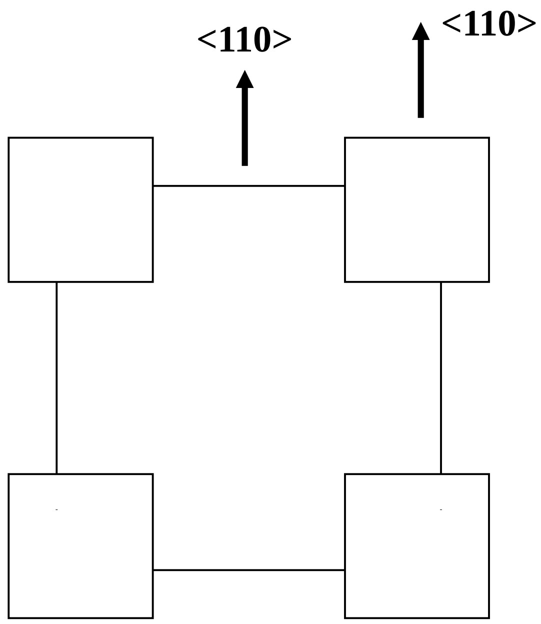
Nozzle

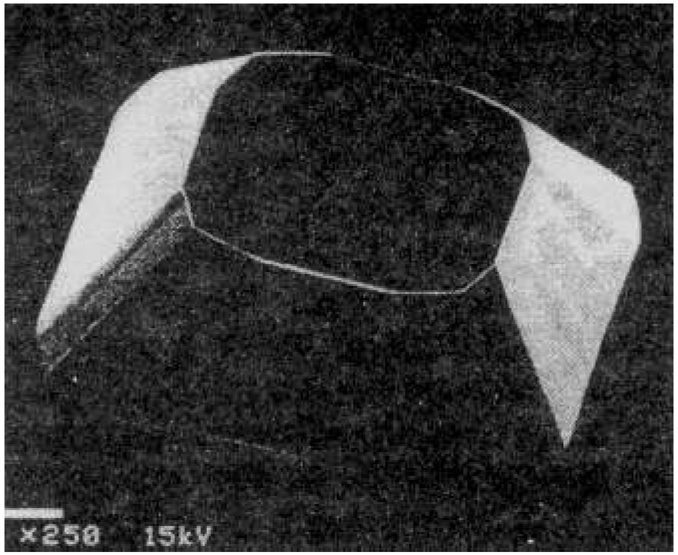


Diaphragm

(100) Si Wet Etch (8)

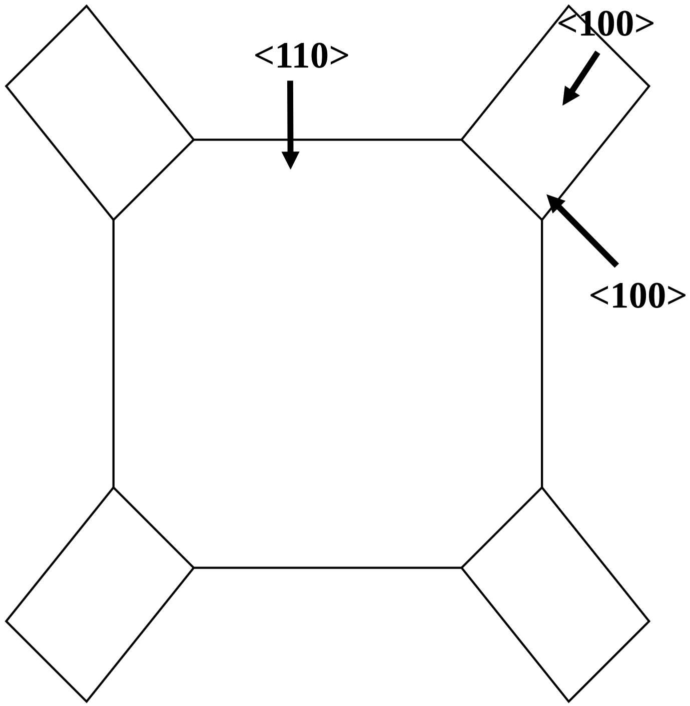
- Rectangular corner compensation for mesa structure fabrication
  - Mask layout of compensation pattern for preventing undercut

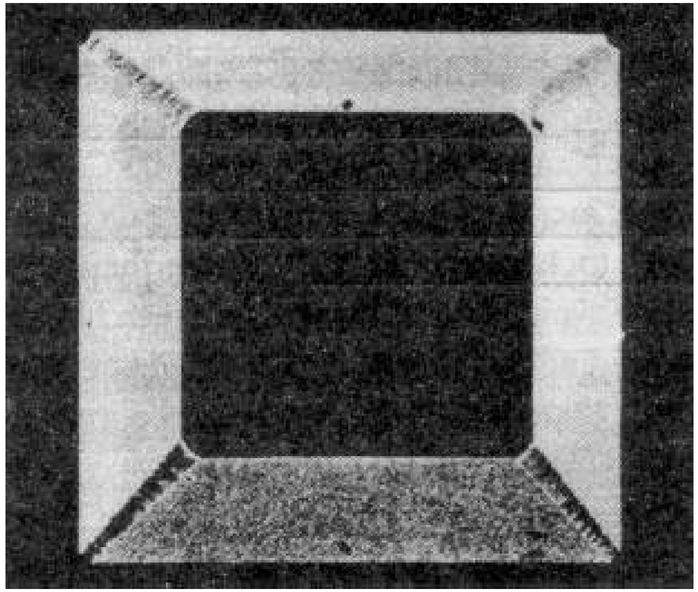




(100) Si Wet Etch (9)

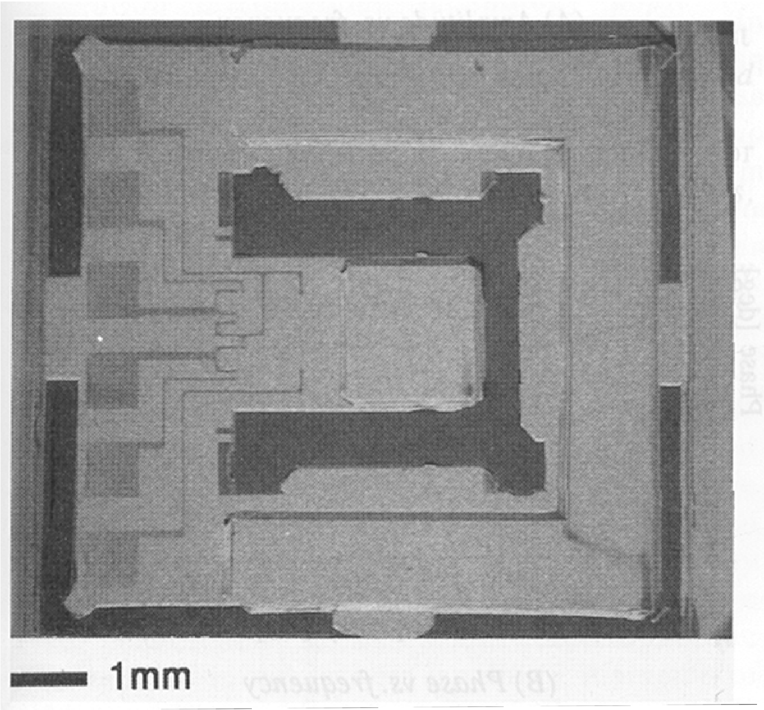
- 45º rotated rectangular corner compensation for mesa structure fabrication



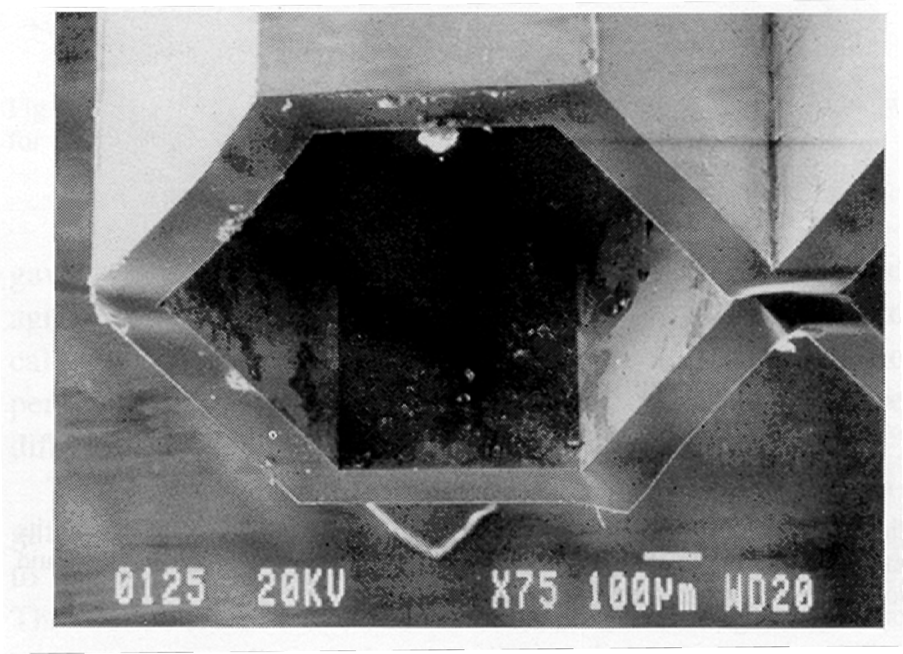


(100) Si Wet Etch (10)

- Application examples (1)



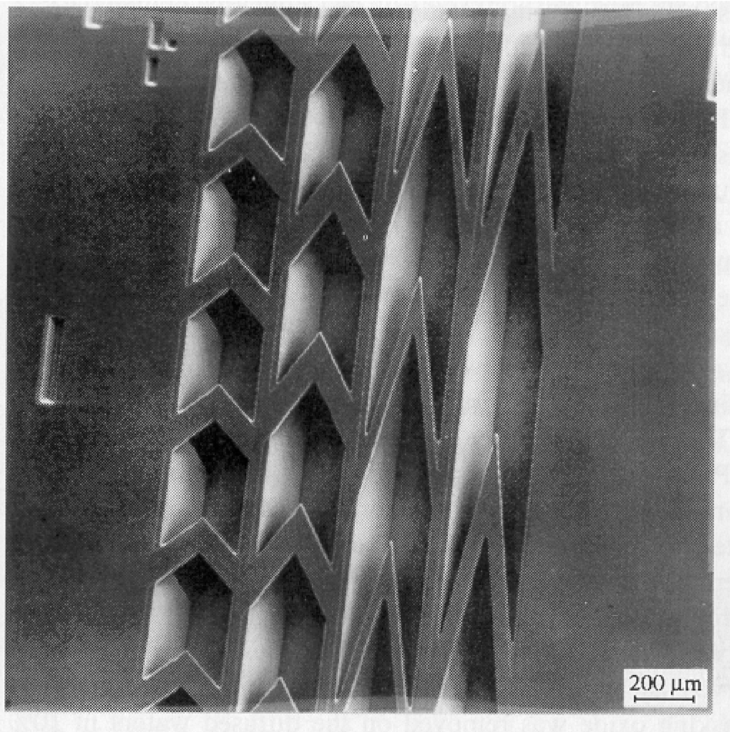
Accelerometer



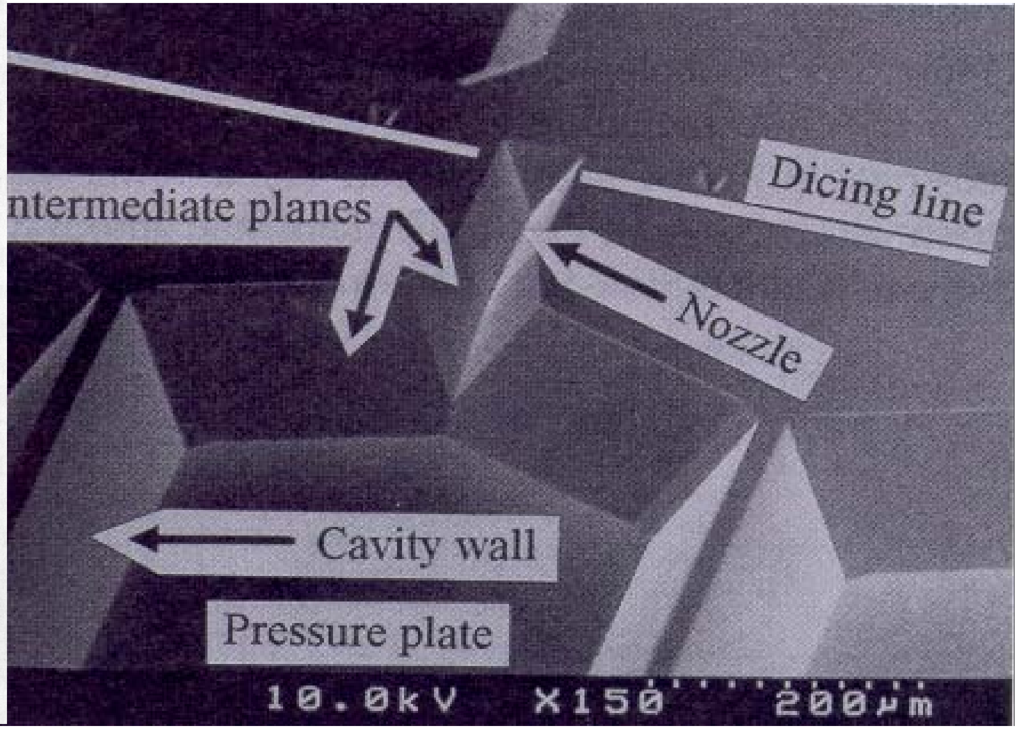
Tube

(100) Si Wet Etch (11)

- Application examples (2)

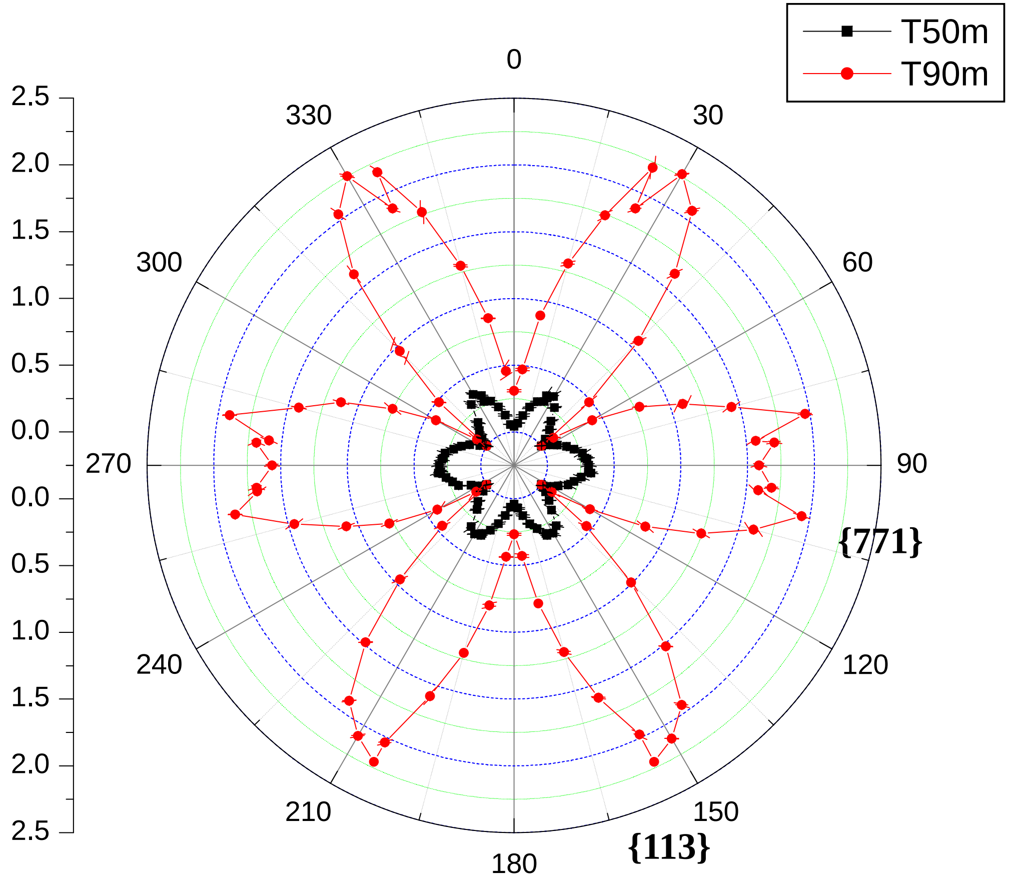


Holding structure over v-grooves



Ink jet printer nozzle

(110) Si Wet Etch (1)

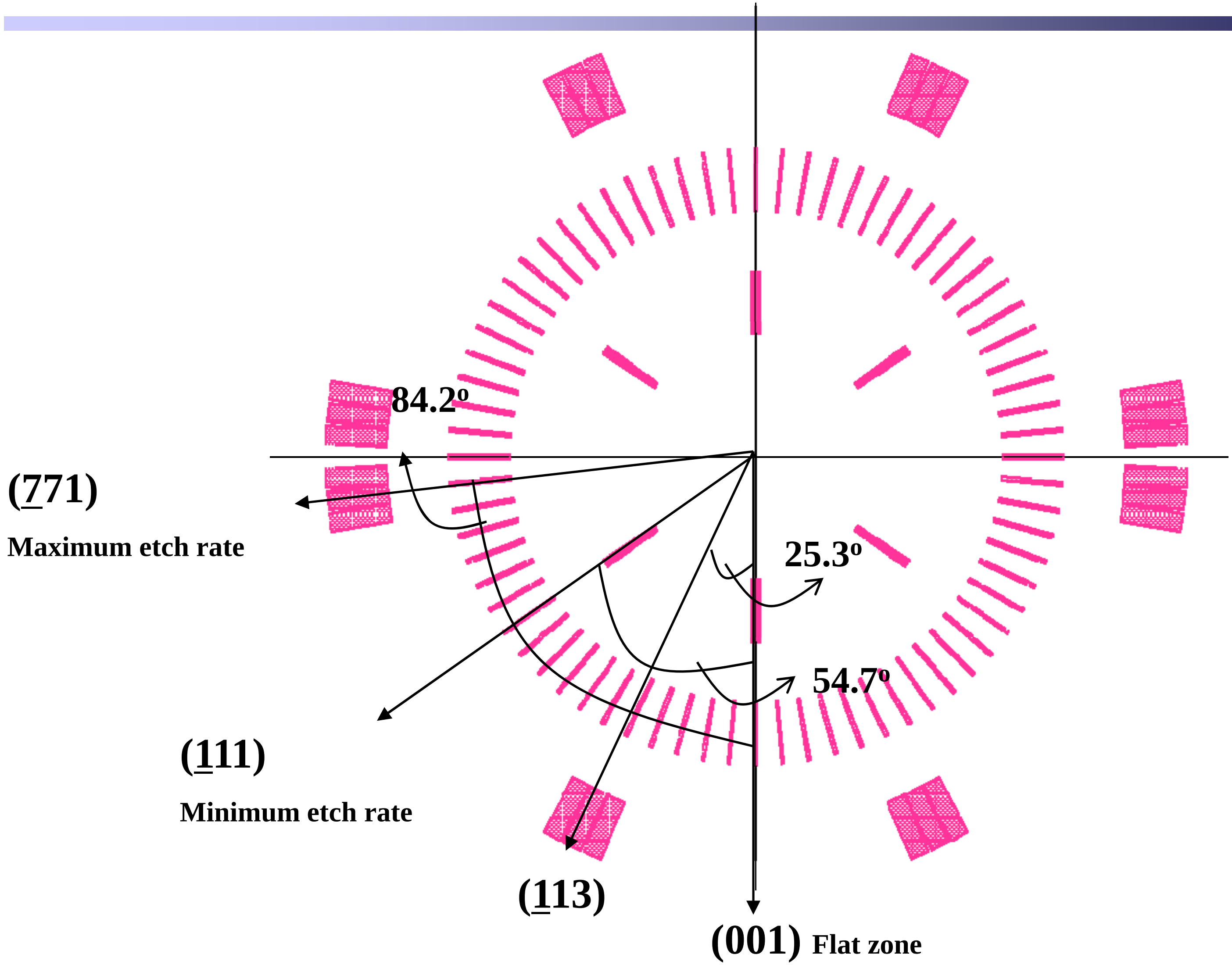


40wt % TMAH

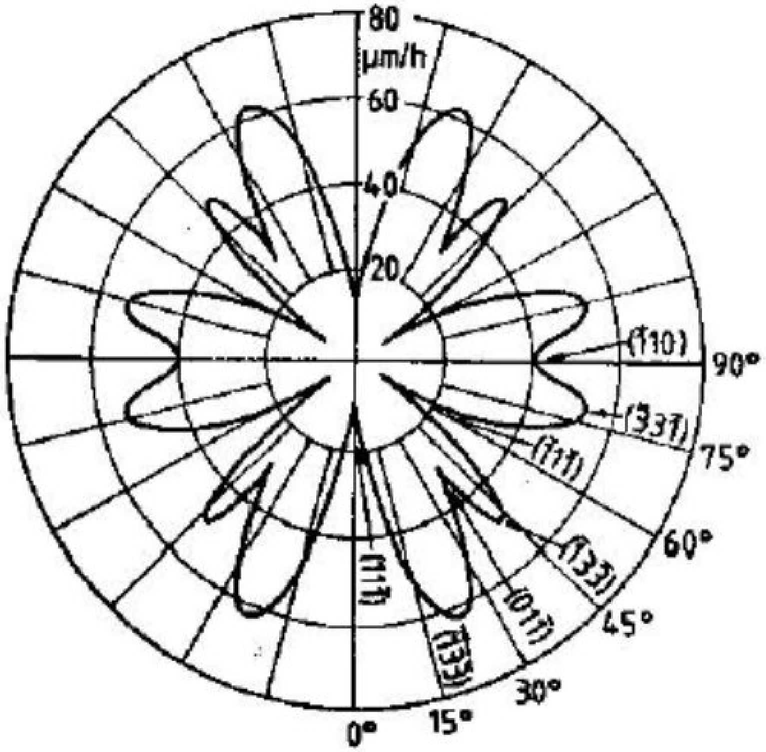
T50m: 50 ℃

T90m: 90 ℃

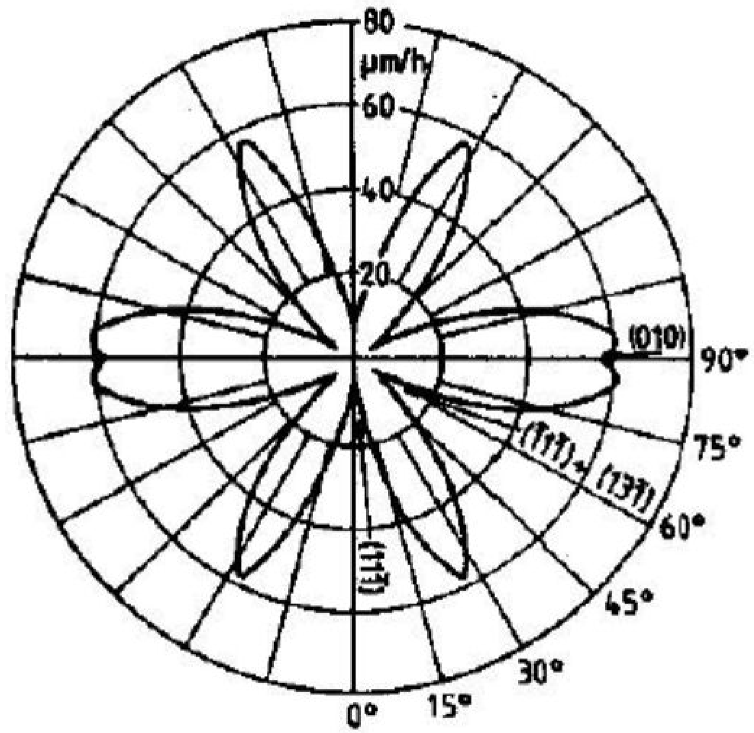
(110) Si Wet Etch (2)



(110) Si Wet Etch (3)



EDP solution at 95 ℃

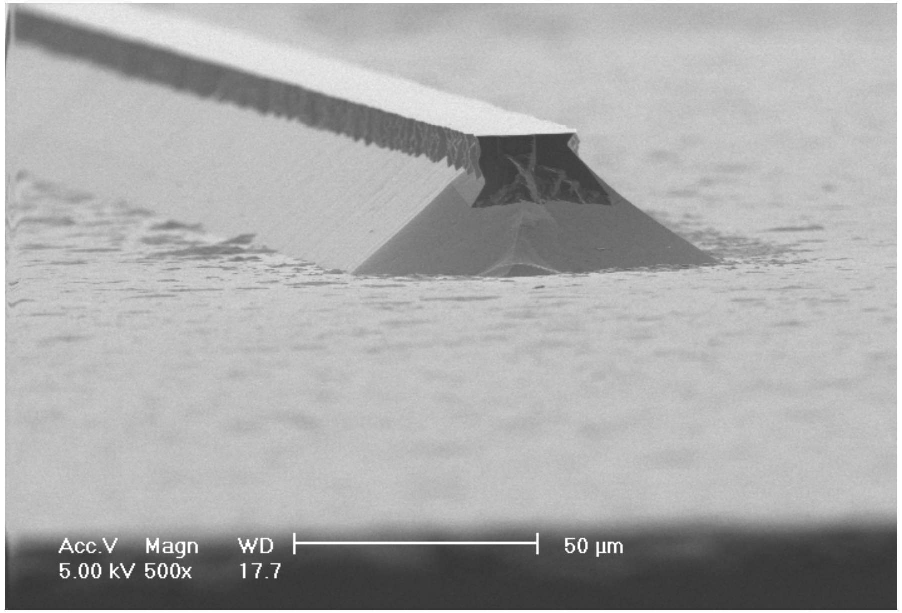


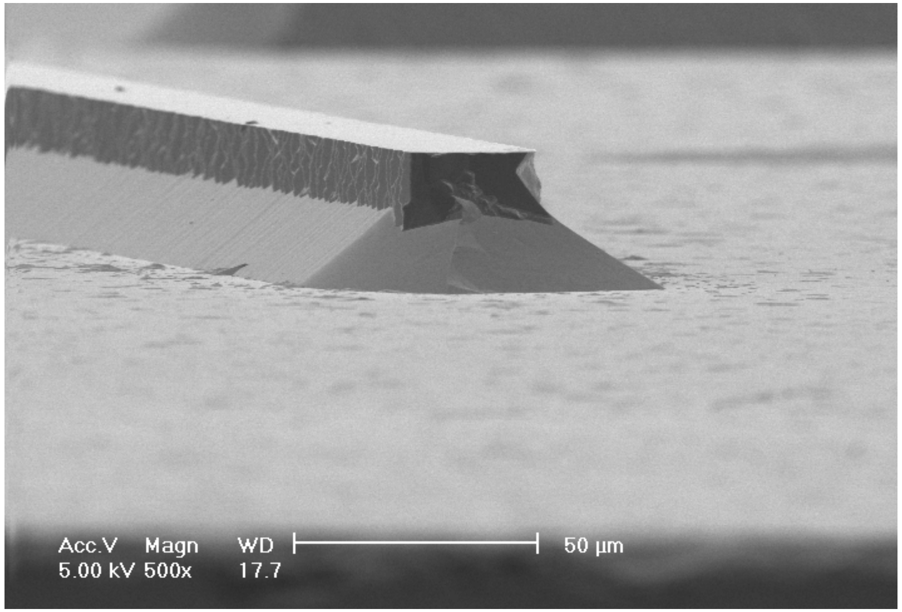
KOH solution at 78 ℃

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

(110) Si Wet Etch (4)

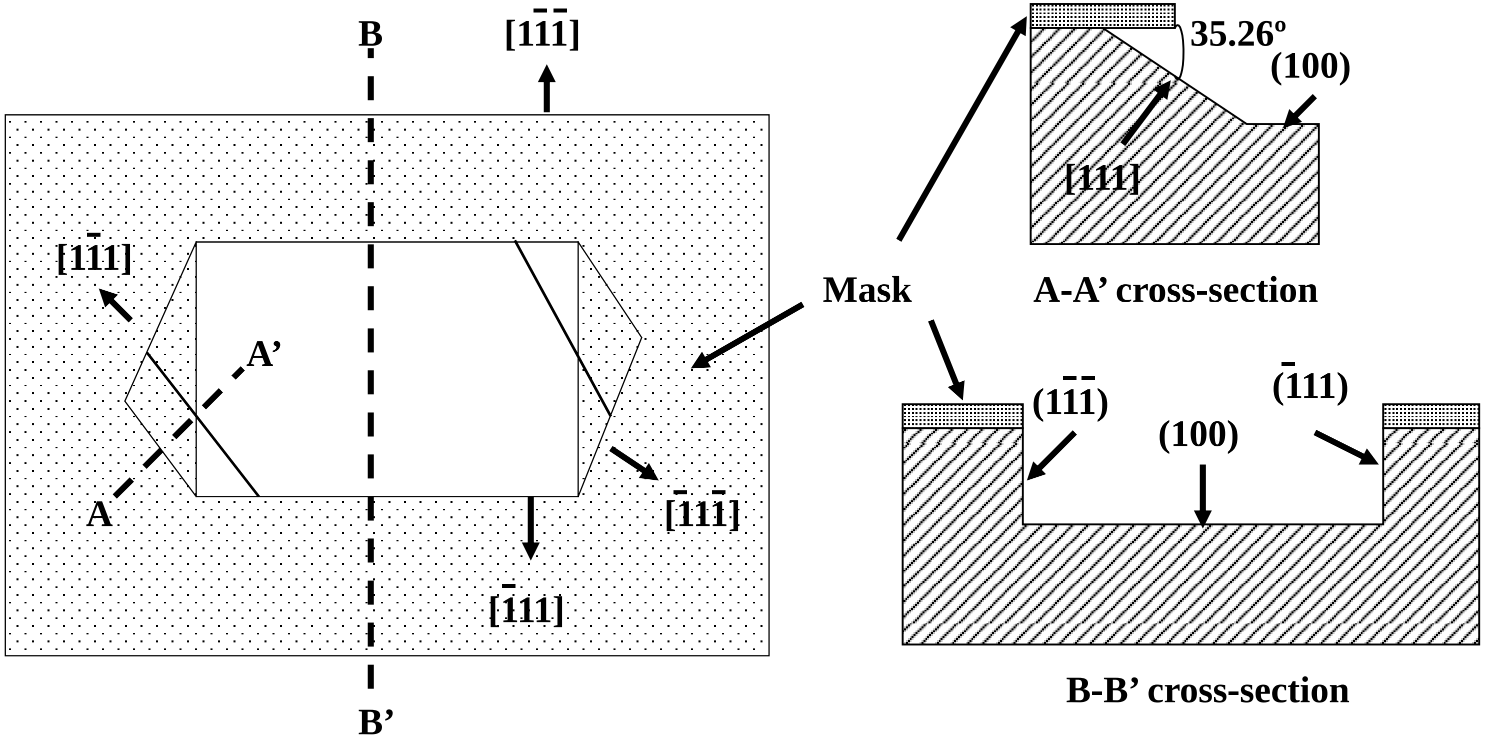
- SEM view: (110) wafer, KOH 40%, 50℃





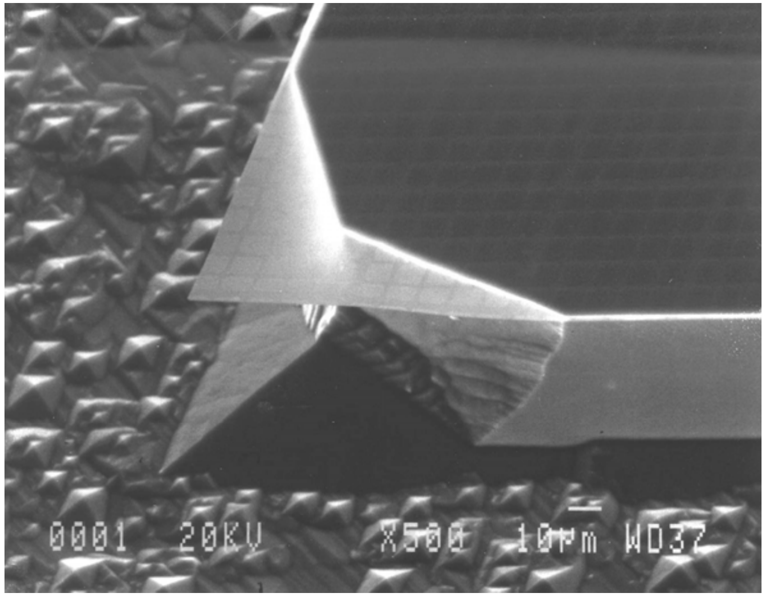
(110) Si Wet Etch (5)

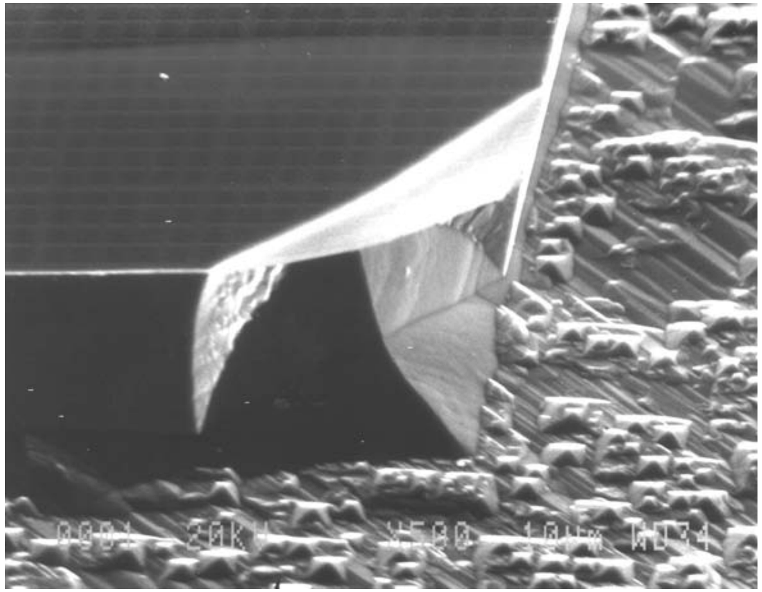
- Top and cross-sectional view of wet etched (110) silicon wafer



(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

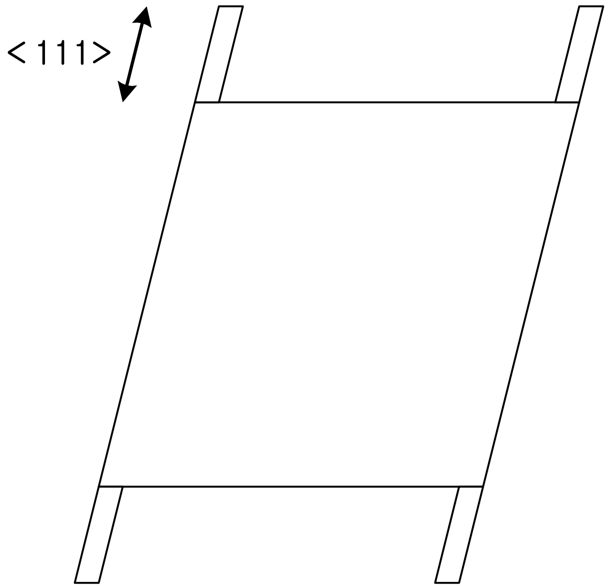




(SNU NML)

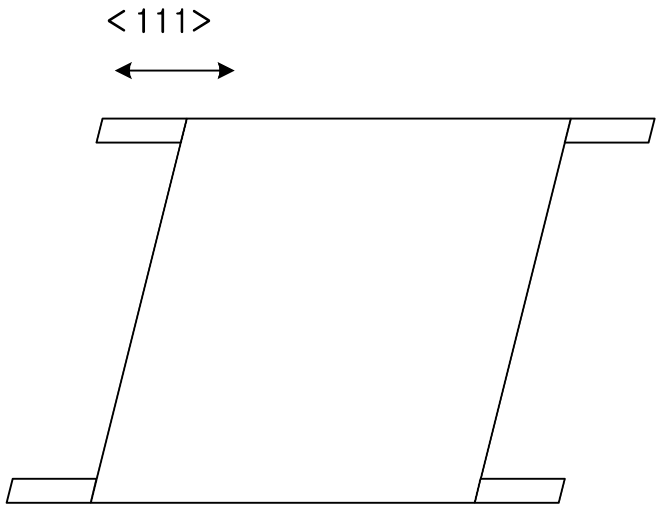
(110) Si Wet Etch (7)

- Compensation pattern design using <111> beam



<111>direction compensation

beams oblique to the wafer flat

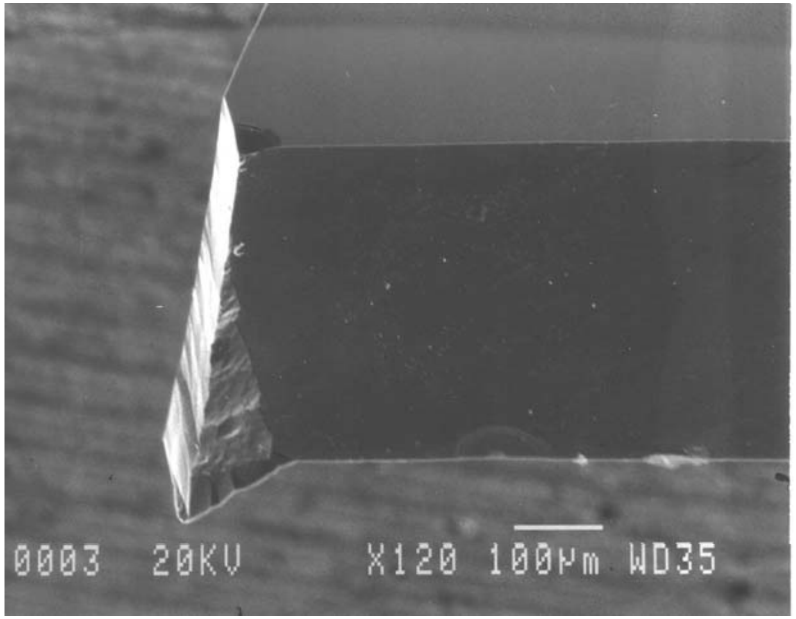


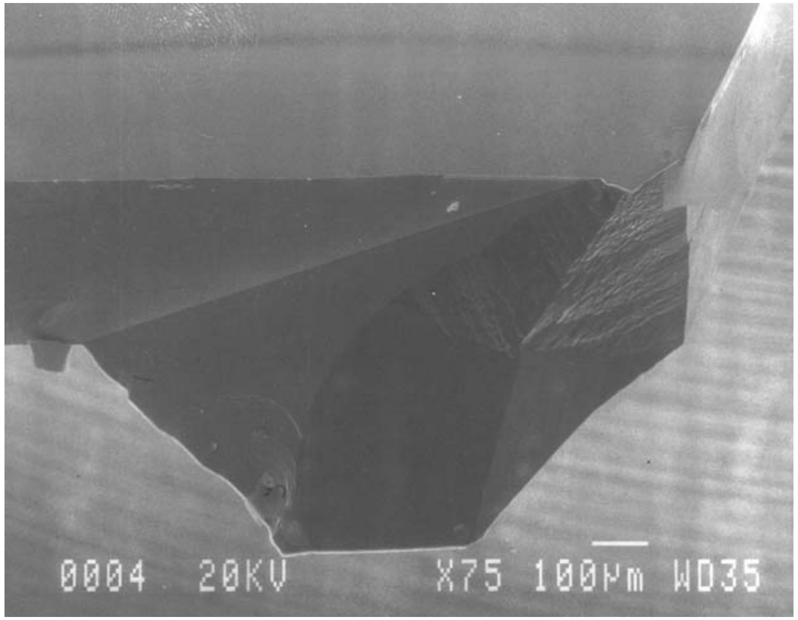
<111>direction compensation

beams oblique to the wafer flat

(110) Si Wet Etch (8)

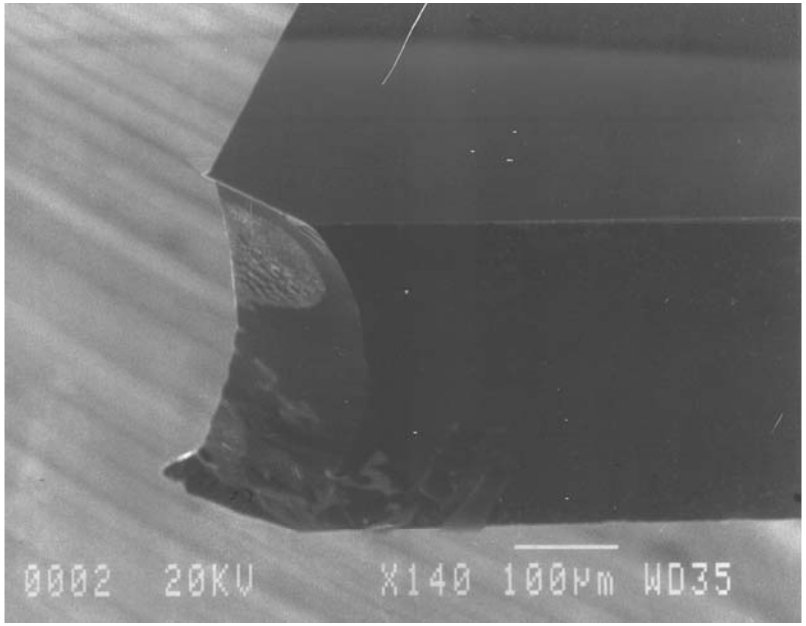
- Compensation results
  - Good compensation effects on acute corners
  - Need other compensation pattern on convex corners

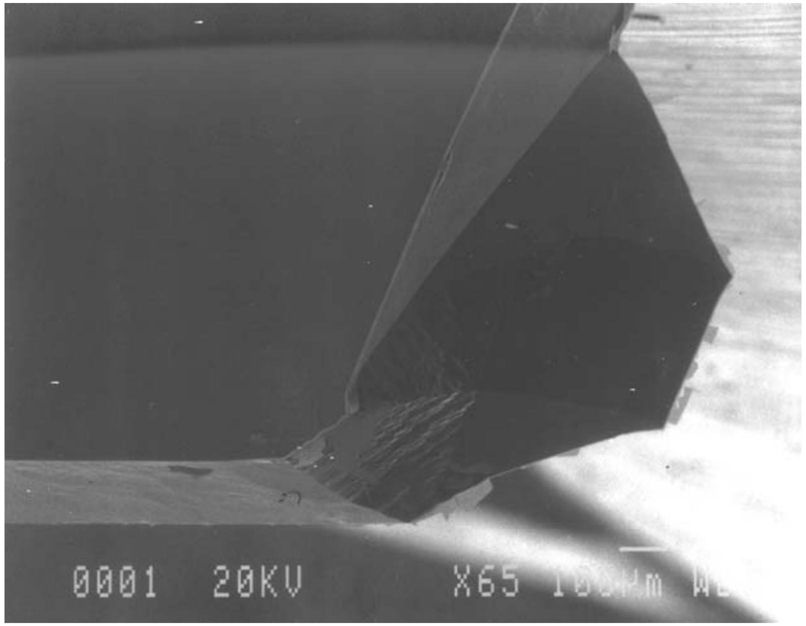




(110) Si Wet Etch (9)

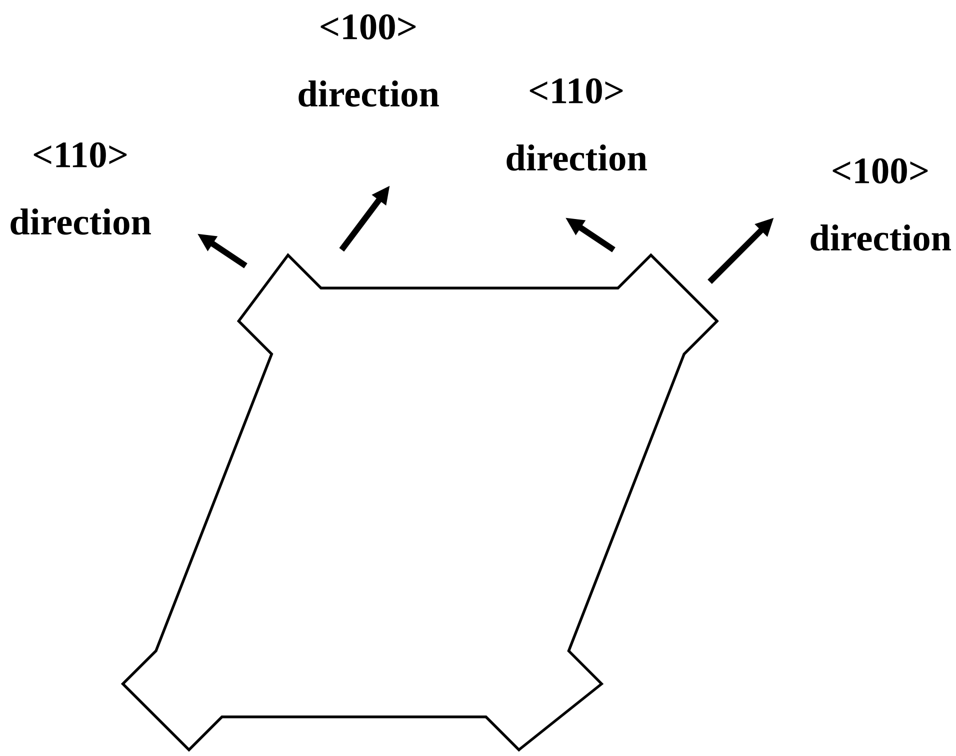
- Compensation results
  - Good compensation effects on acute corners
  - Need other compensation pattern on convex corners





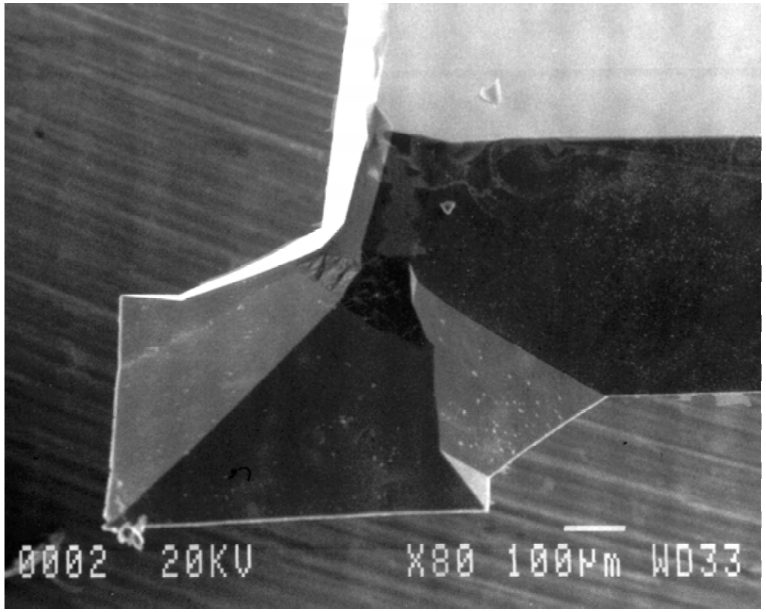
(110) Si Wet Etch (10)

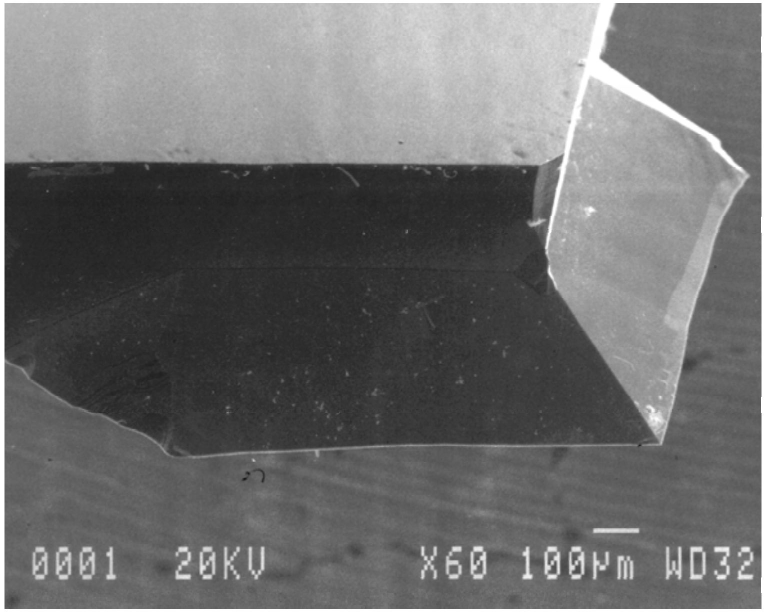
- Rectangular compensation pattern design



(110) Si Wet Etch (11)

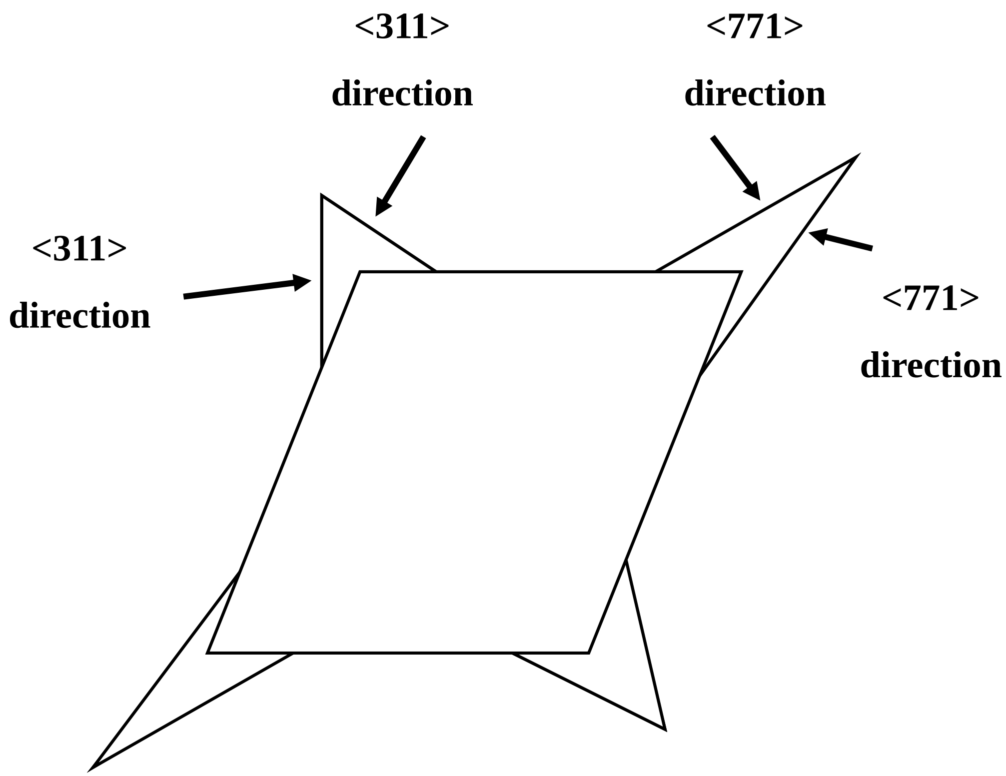
- Compensation results
  - Large residues remain





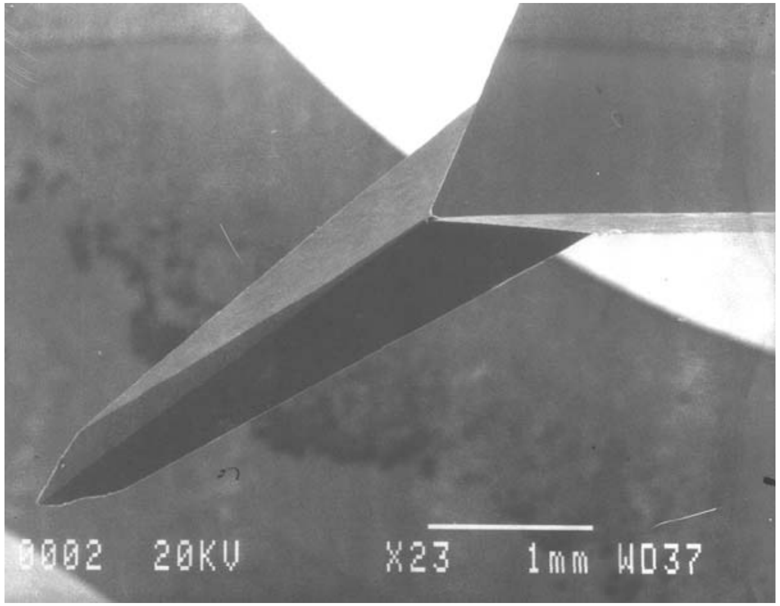
(110) Si Wet Etch (12)

- Triangular compensation pattern design

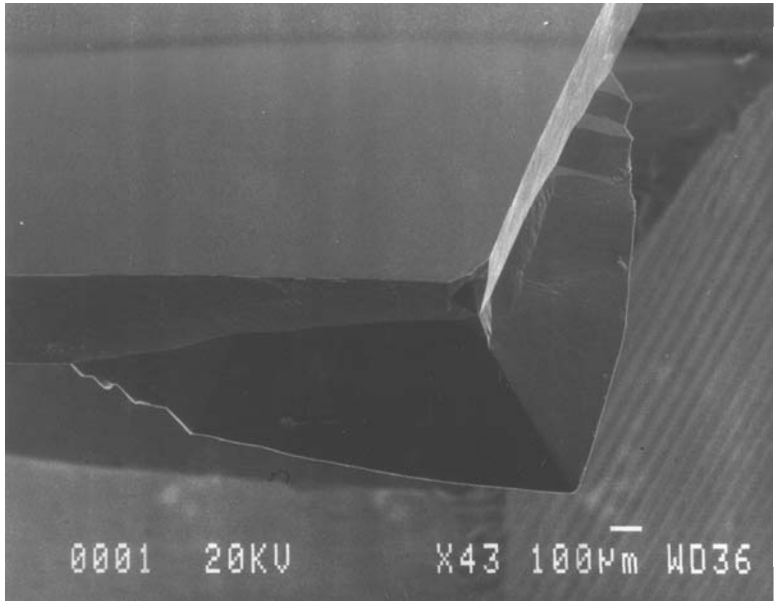


(110) Si Wet Etch (13)

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



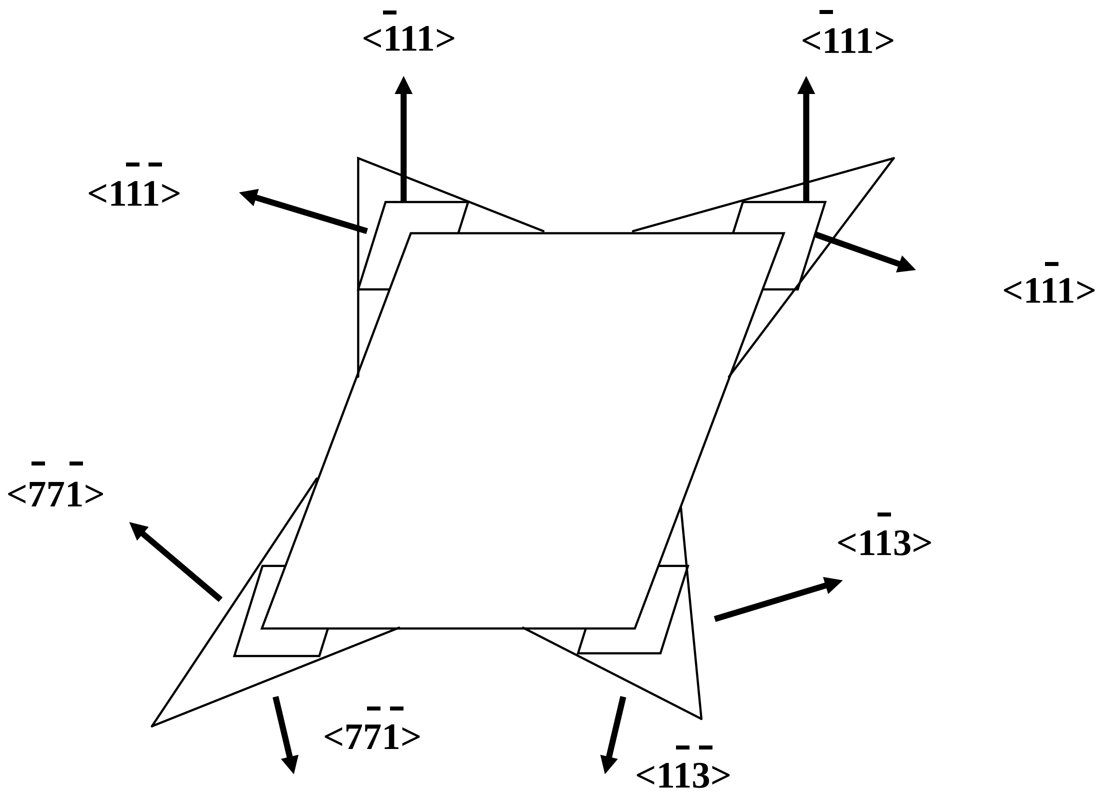
Etch front place : 311



Etch front place : 771

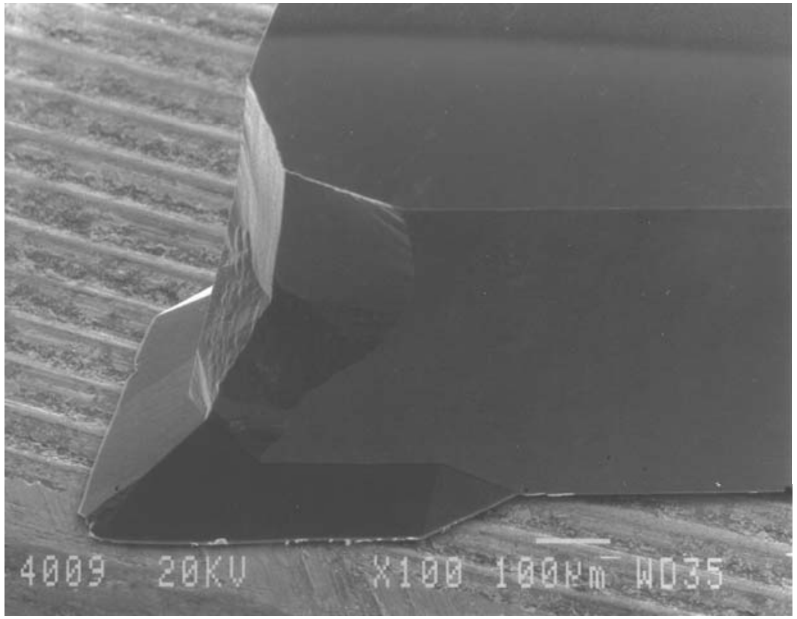
(110) Si Wet Etch (14)

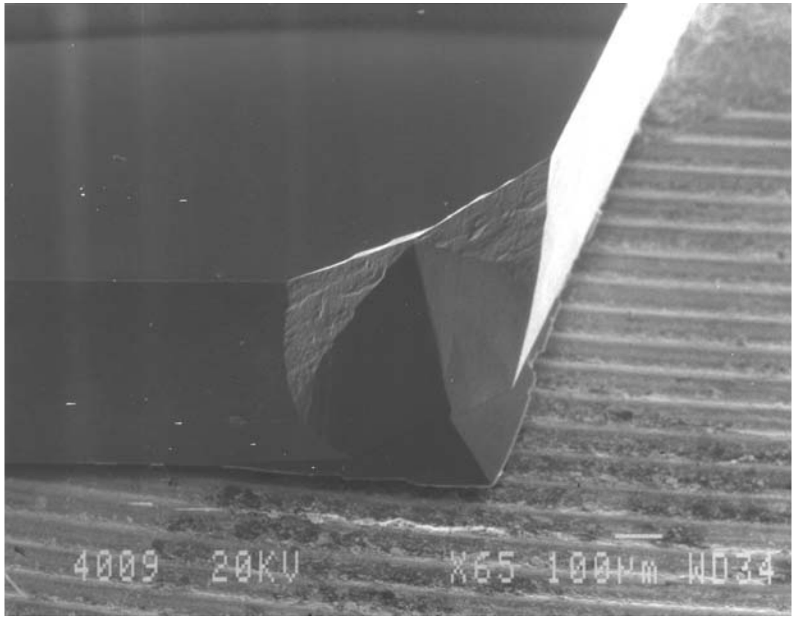
- Rhombic compensation pattern design



(110) Si Wet Etch (15)

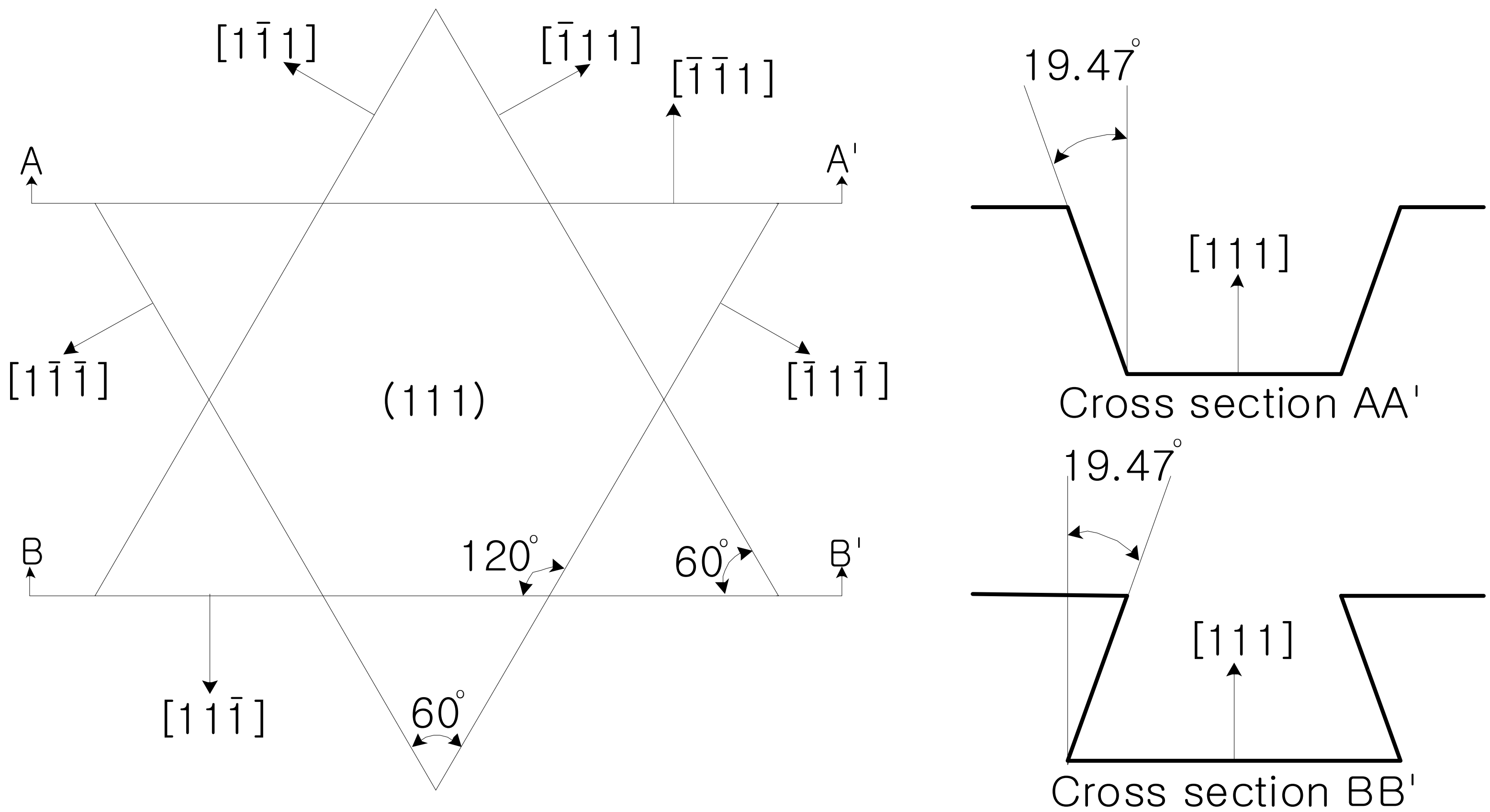
- Compensation results
  - Good compensation effects on both corners
  - Very small unwanted residues at the bottom
  - Features relatively sharp corners at the top



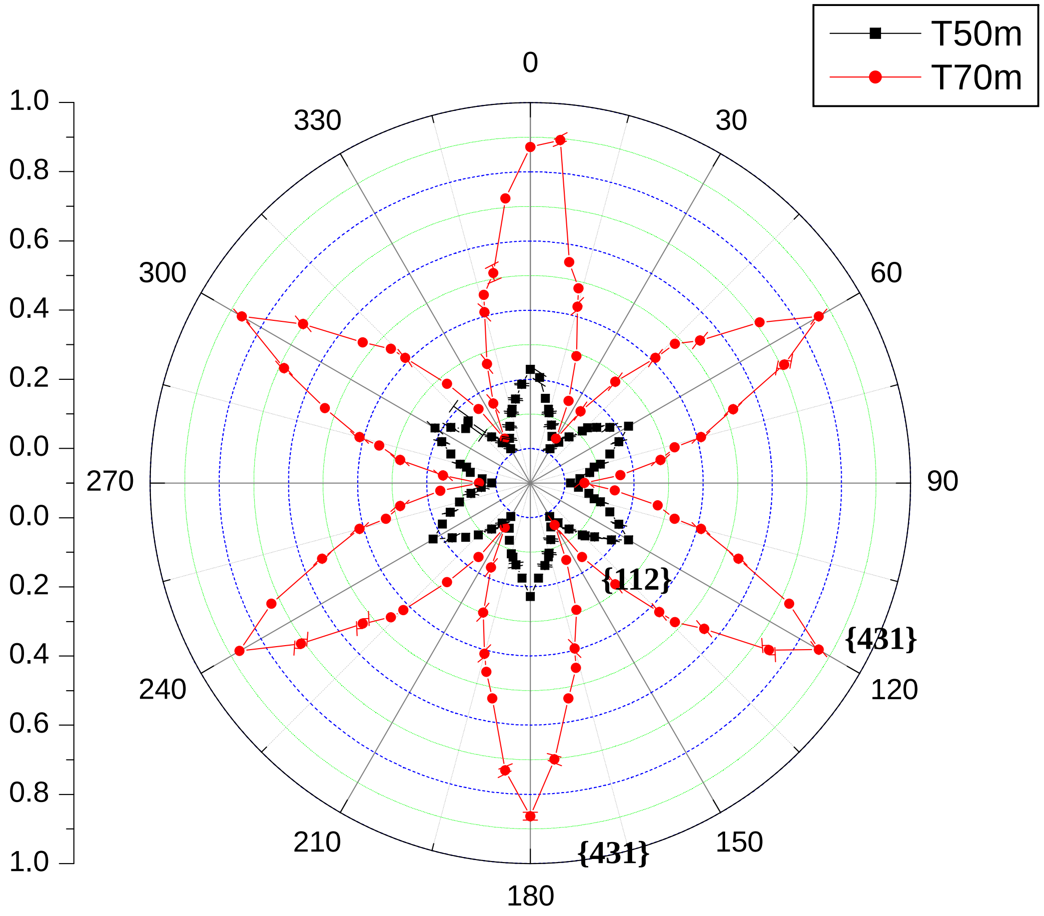


(111) Si Wet Etch (1)

- Crystallography of Si (111)



(111) Si Wet Etch (2)

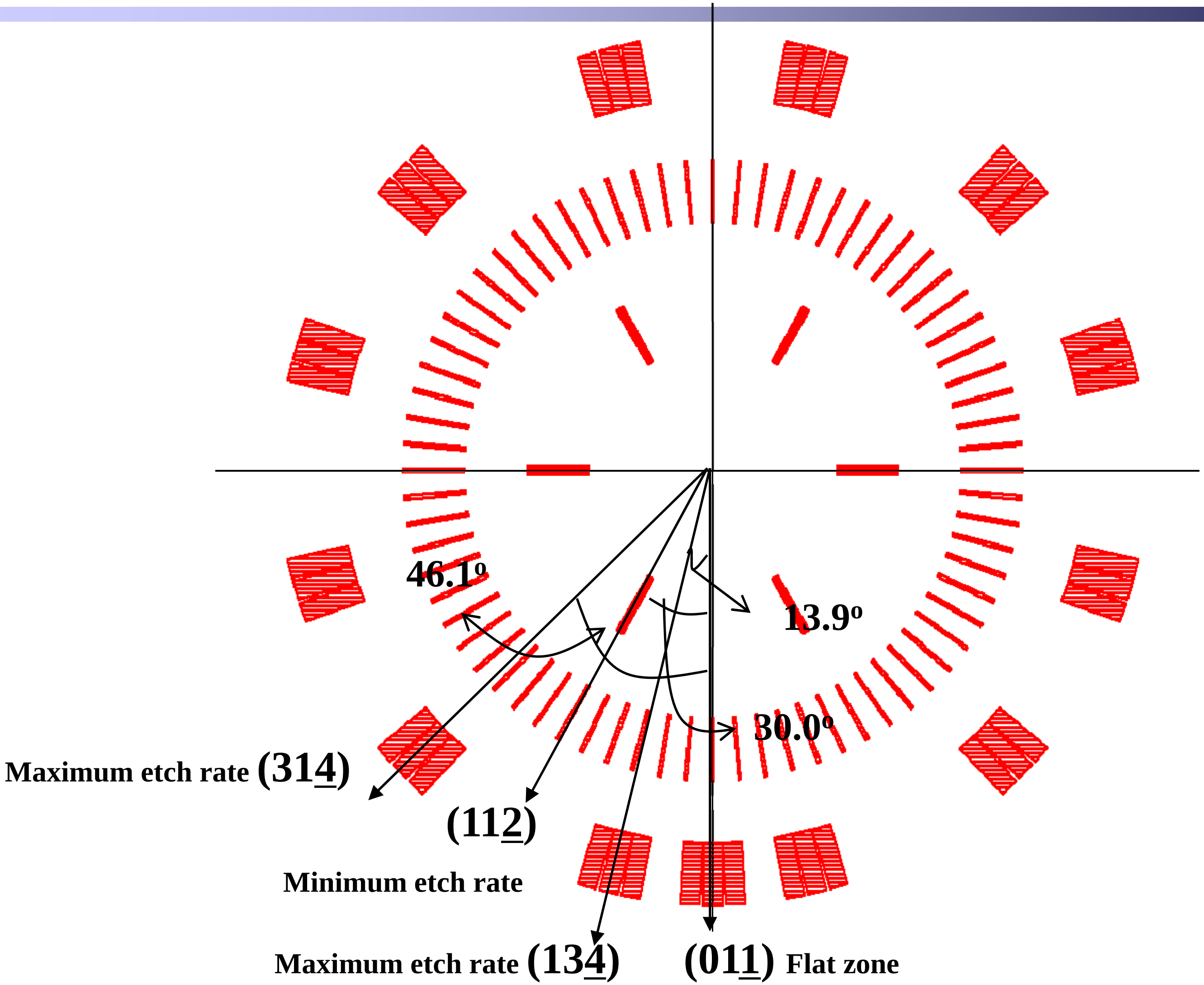


40wt % KOH

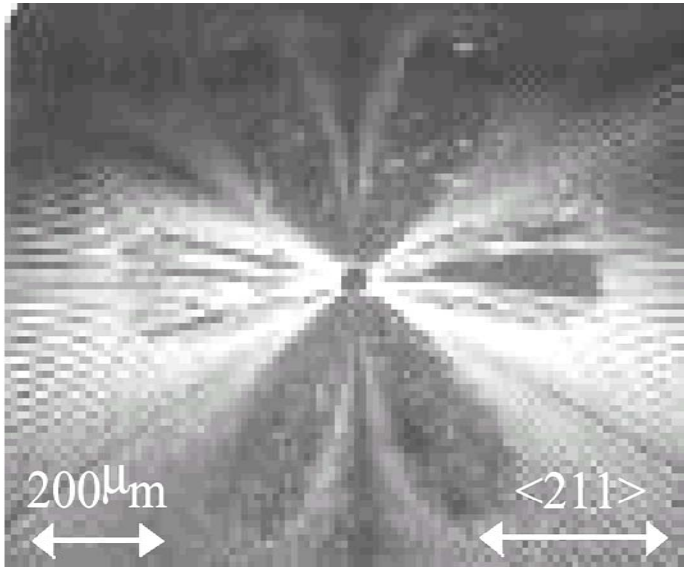
T50m: 50 ℃

T70m: 70 ℃

(111) Si Wet Etch (3)

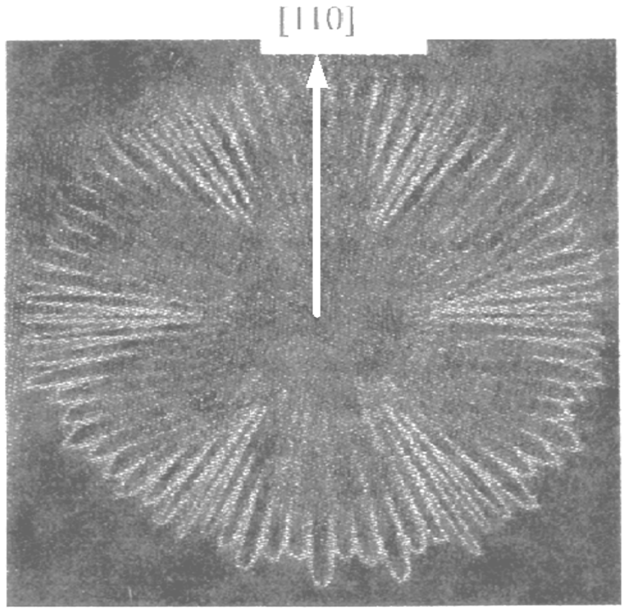


(111) Si Wet Etch (4)



22 wt% TMAH at 80℃

Ref) M. Sekimura, MEMS99, 1999

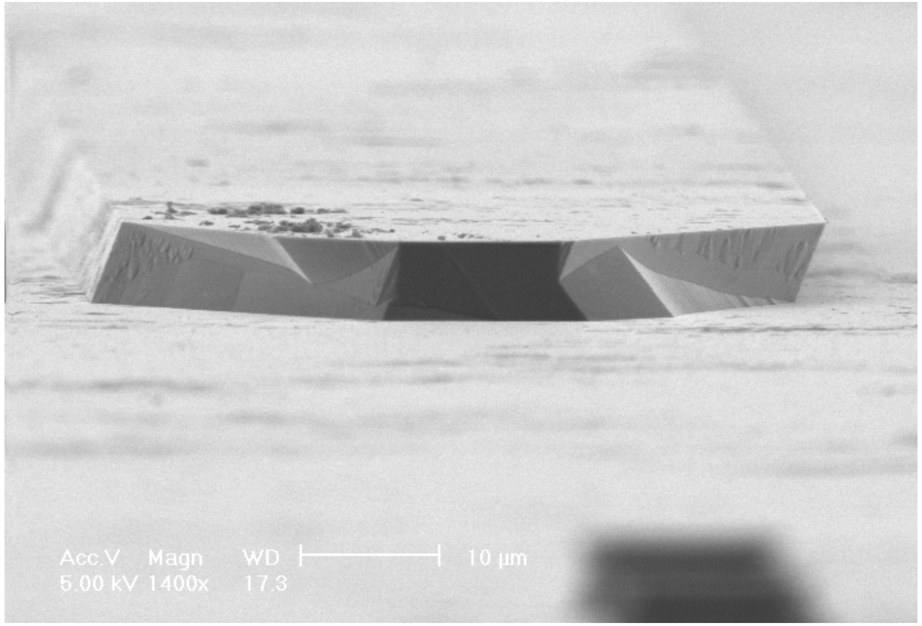


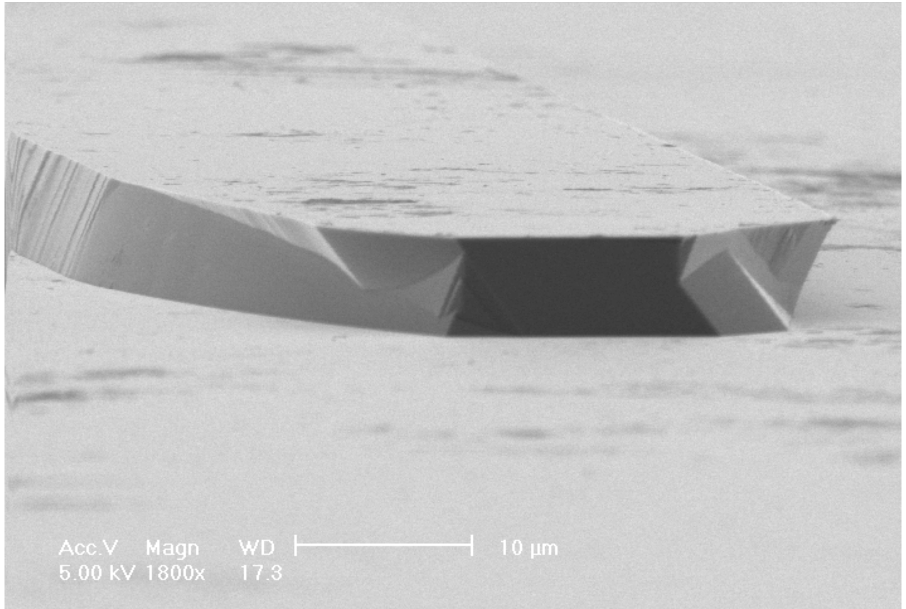
KOH at 80℃

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

(111) Si Wet Etch (5)

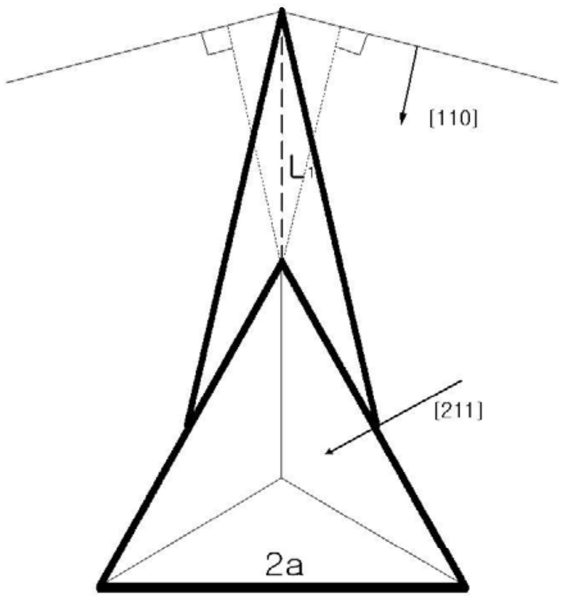
- SEM view: (111) wafer, TMAH 10%, 50℃



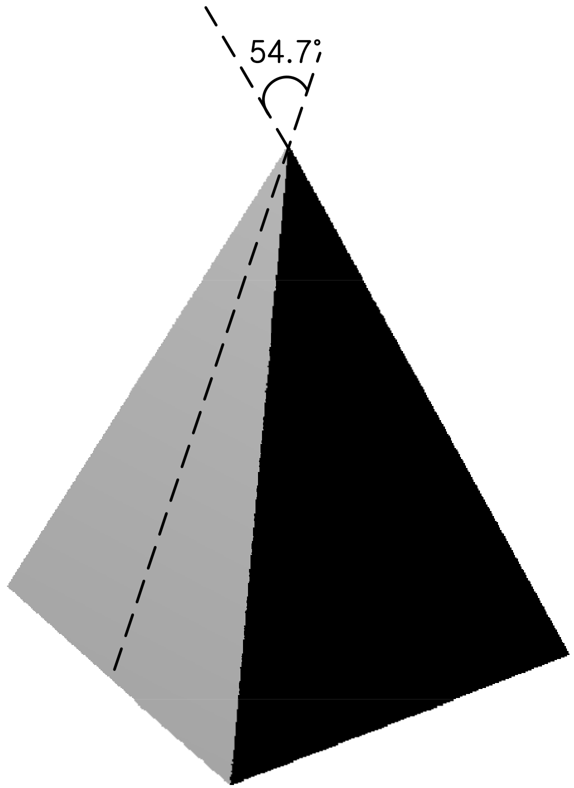


(111) Si Wet Etch Application (1)

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

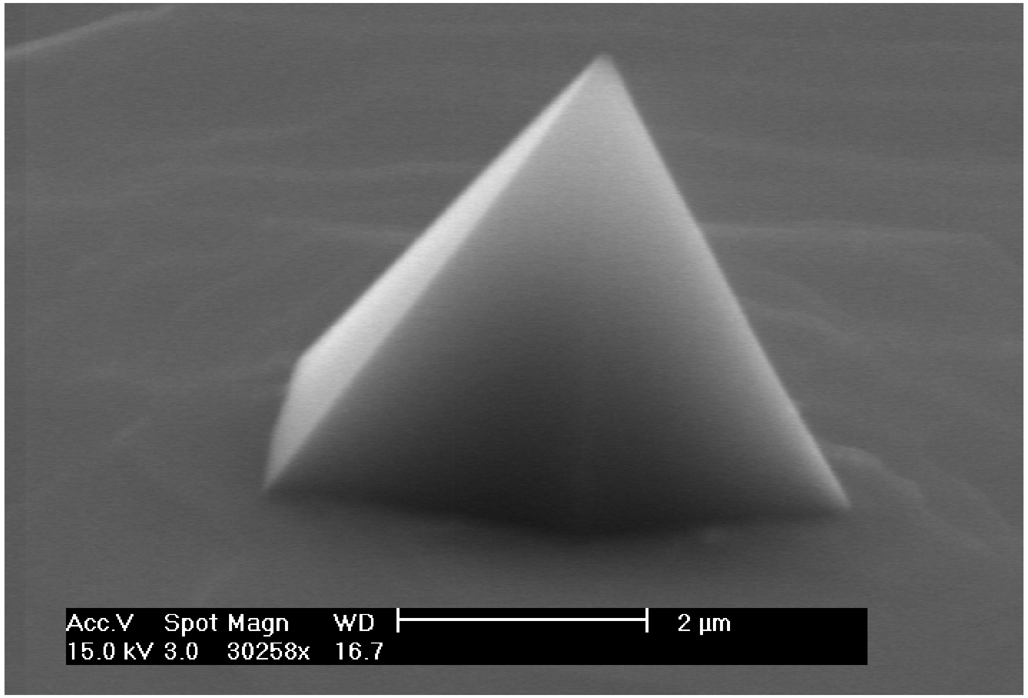


$$L_1 = \frac{2}{3} a \sin 70.53^\circ \frac{R_{110}}{R_{211}}$$



(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

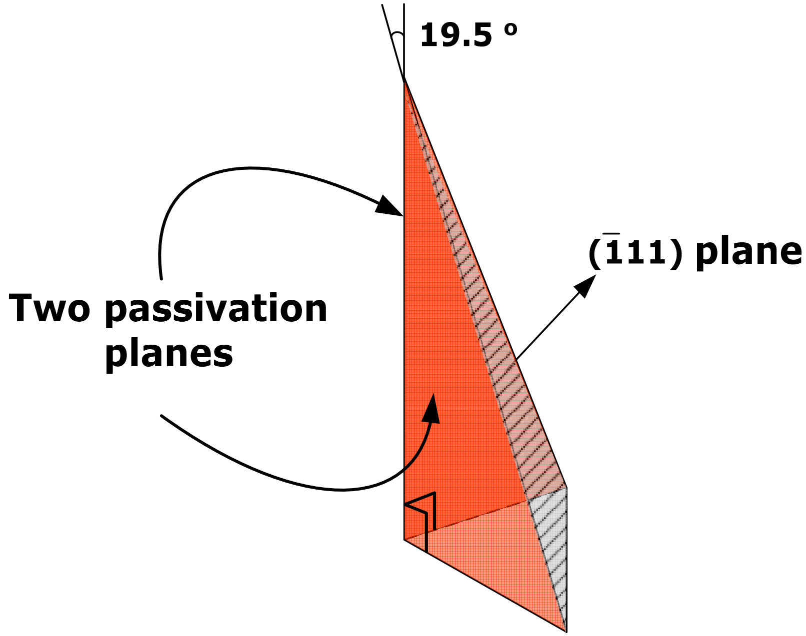


3 {111}-faceted tip

(111) Si Wet Etch Application (3)

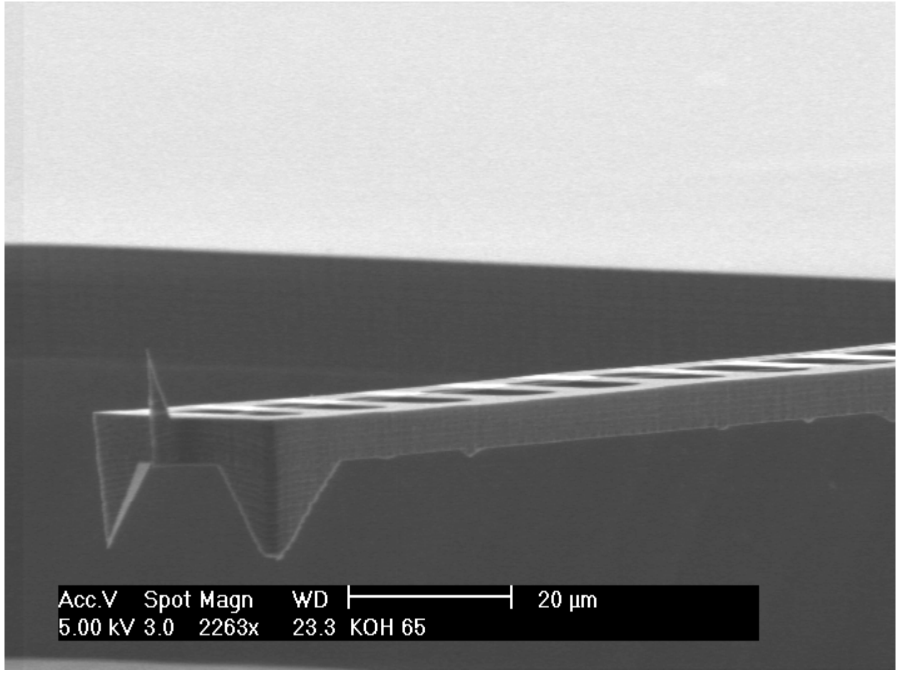
- (111) Nano tip
  → Consist of single (111) plane and two passivation planes

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

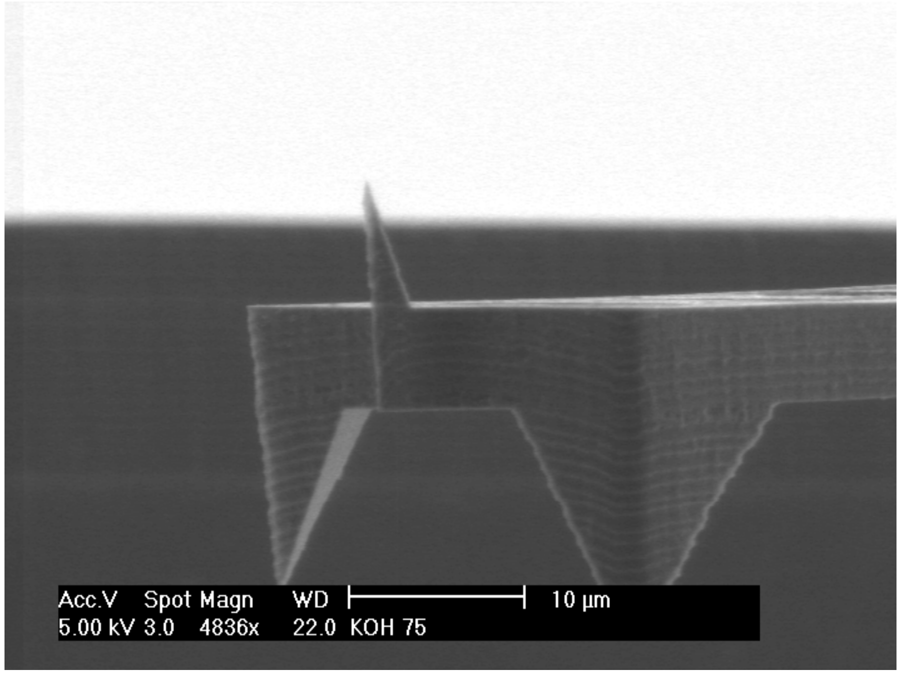


(111) Nano tip

(111) Si Wet Etch Application (4)

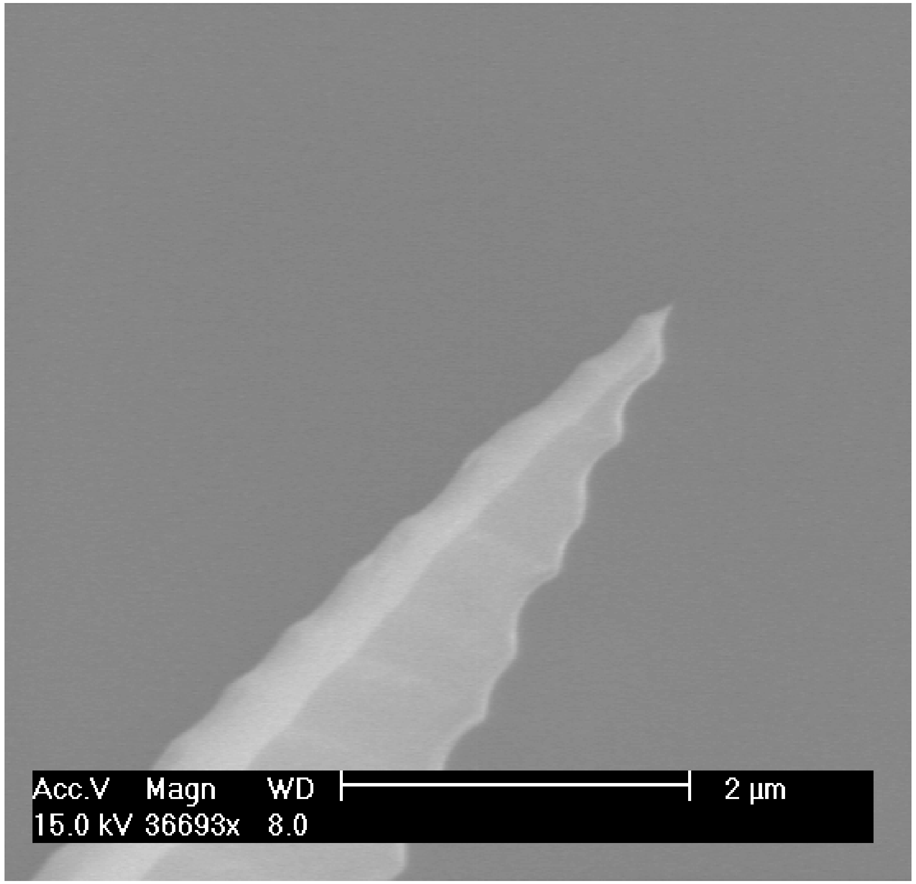


Single nano tip



Tip height: 10 µm

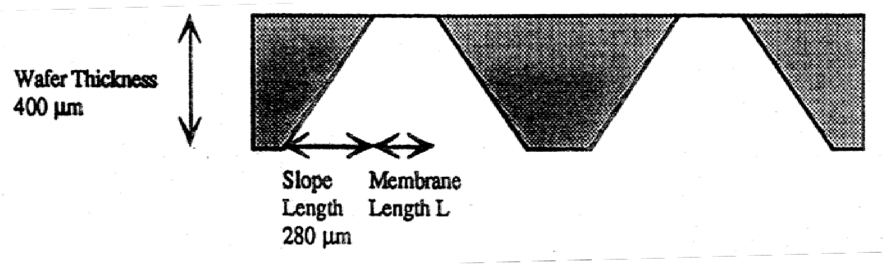
(111) Si Wet Etch Application (5)



- 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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