MSN 551 notes

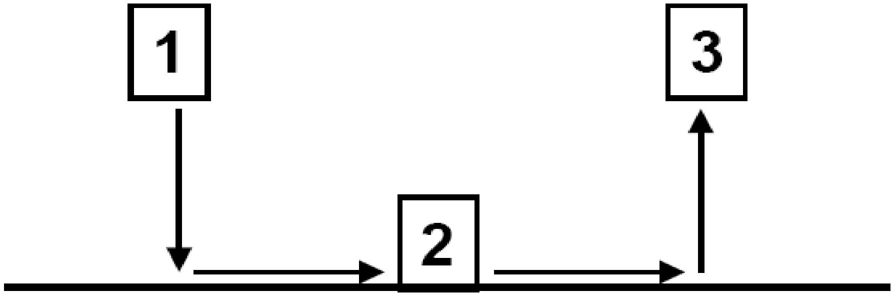
Wet Etching

Overview

- Wet etching : description and applications
- Silicon wet etching
  - Materials
  - Mechanisms
  - Simulation
  - Practical issues

- Wet etching other materials
  - Available Data

Wet Etching



1 Reactant transport to surface

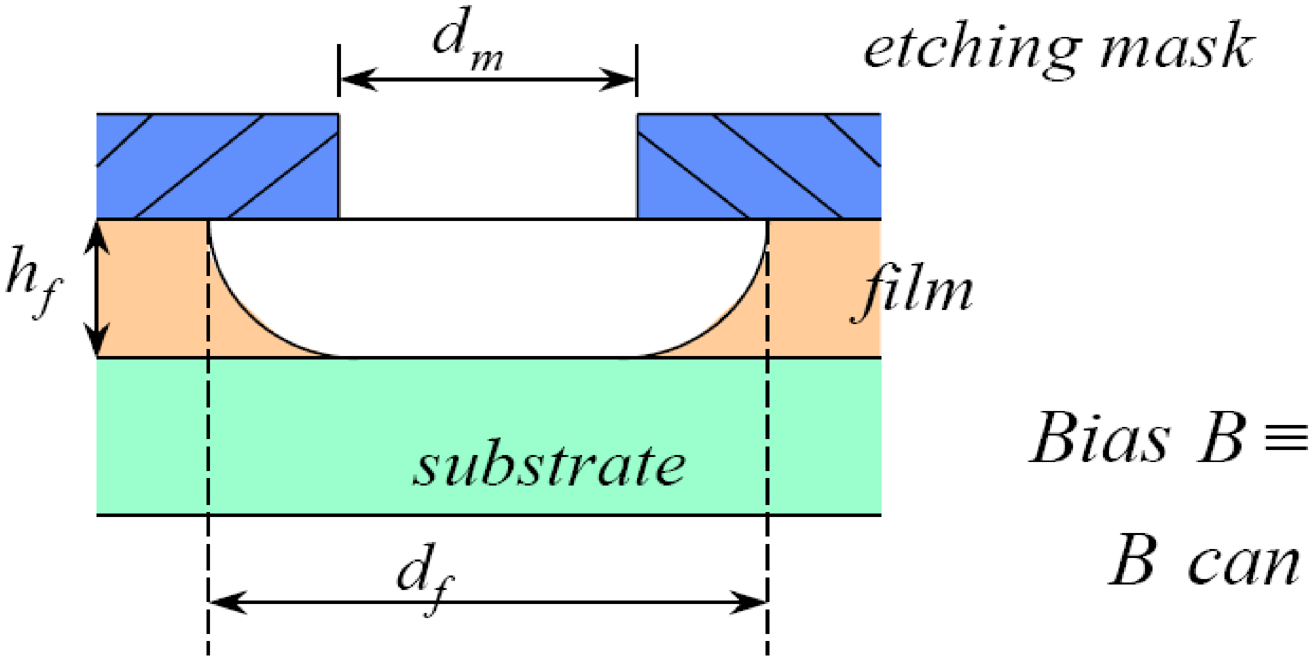
2 Selective and controlled reaction of etchant with the film to be etched

3 Transport of by-products away from surface

Etch Process - Figures of Merit

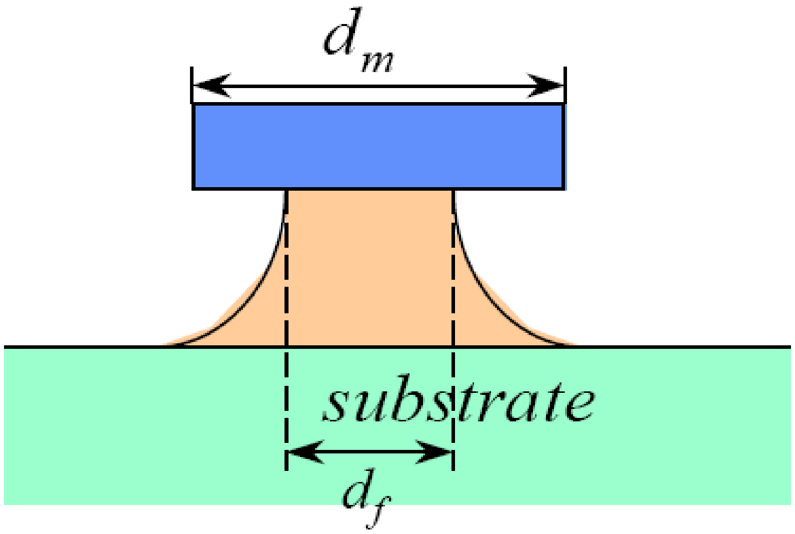
- Etch rate
- Etch rate uniformity
- Selectivity
- Anisotropy

(1) Bias



$$Bias\ B \equiv d_f - d_m$$

$$B\ can\ be > 0\ or < 0.$$



Complete Isotropic Etching

Vertical Etching = Lateral Etching Rate

$B = 2 \times h_f$

Complete Anisotropic Etching

Lateral Etching rate = 0

$B = 0$

(2) Degree of Anisotropy

$$A_f \equiv 1 - \frac{|B|}{2h_f}$$

$$\underset{\substack{\uparrow \\ \mathit{isotropic}}}{0} \le A_f \le \underset{\substack{\uparrow \\ \mathit{anisotropic}}}{1}$$

$$\therefore \ |B| = 2h_f \qquad\qquad |B| = 0$$

UNIFORMITY

$$\text{Etch rate uniformity (\%)} = \frac{\text{(Maximum etch rate-Minimum etch rate)}}{\text{(Maximum etch rate+Minimum etch rate)}} \text{ x100\%}$$

Example: Calculate the average etch rate, etch rate uniformity given the etch rates at center, top left, top right, bottom right, bottom left are 750, 812, 765, 743, 798 nm

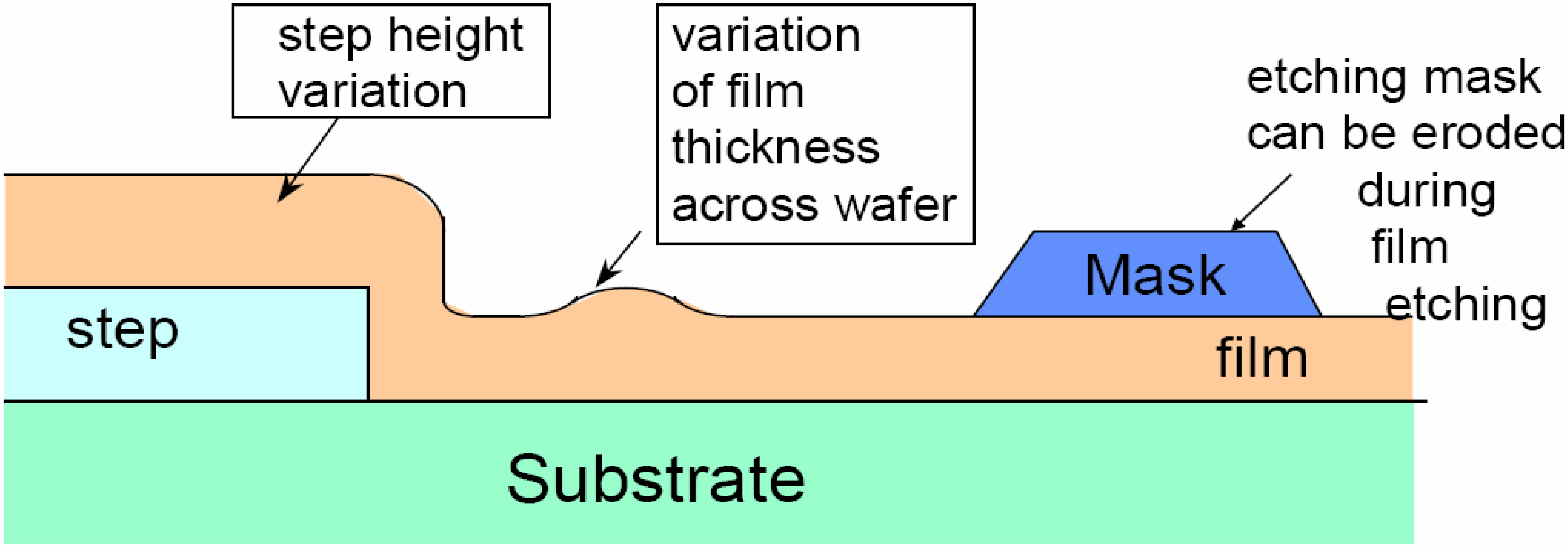
What factors may affect etch rate uniformity?

Drawbacks of Wet Etching

- Lack of anisotropy
- Poor process control
- Excessive particulate contamination

=> Wet etching used for **noncritical** feature sizes

Worst-Case Design Considerations for Etching



a) Film thickness variation:

target thickness value

$$h_{f(\max)} = h_f \cdot \left(1+\delta\right)$$

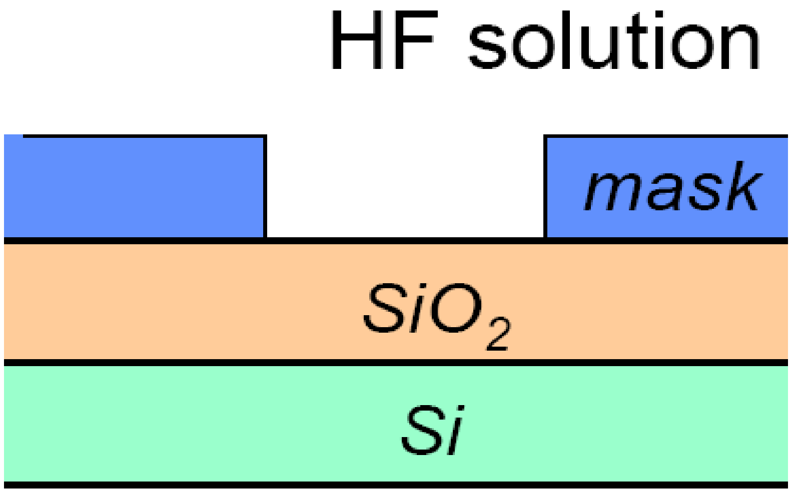
variation factor

WET ETCH BASICS

Concentration: Often expressed as a weight percentage. That is the ratio of the weight of solute in a given weight solution. For example a solution containing 5 gms of solute in 95 grams of solvent is a 5 % solution.

Molarity: concentration expressed as moles of solute in 1 liter of solution. A solution containing one mole of solute in 1 liter of solution is termed a molar (1M) solution. A mole is the molecular weight in grams. Example: 10 gms of sulfuric acid in 500 ml of solution. H2SO4 has molecular weight of 1x2+32+16x4=98 so 10gms/98gm/M = 0.102M and 500ml is 1/2 liter, so this solution is 0.204 Molar

Examples



SiO_2/Si etched by HF solution

$\mathbf{S}_{\mathbf{SiO2,\ Si}}$ Selectivity is very large (~ infinity)

SiO_2/Si etched by RIE (e.g. CF_4)

$\mathbf{S}_{\mathbf{SiO2,\ Si}}$ Selectivity is finite (~ 10)

ETCH RATES FOR VARIOUS TYPES OF SiO2

Thermal SiO2 * RIT data, Dr. Fuller, et.al. # from Madou Text ** from Journal of MEMs, Dec.'96, Muller, et.al.	BOE (7:1) 1:1 HF:HCl 49% HF KOH@ 72 °C KOH @ 90 °C	1,000 Å/min * 23,000 Å/min** 18,000 Å/min # 900 Å/min* 2500 Å/min*
CVD SiO2 (LTO)	BOE (7:1) 1:1 HF:HCl 49% HF	3,300 Å/min # 6,170 Å/min #
P doped SiO2 (spin-on dopant) (Photoresist adhesion problems)	BOE (7:1) 1:1 HF:HCl 49% HF	2000 Å/min 25,000 Å/min
Boron doped SiO2 (spin-on dopant)	BOE (7:1) 1:1 HF:HCl 49% HF	200 Å/min*
Phosphosilicate Glass (PSG) * RIT data, Dr. Fuller, et.al.	BOE (7:1) 1:1 HF:HCl 49% HF	10,000 Å/min # 11,330 Å/min # 28,000 Å/min

from Madou Text

** from Journal of MEMs, Dec.'96, Muller, et.al.

Wet Etching (cont.)

- Wet etch processes are generally isotropic
- Wet etch processes can be highly selective
- Acids are commonly used for etching:

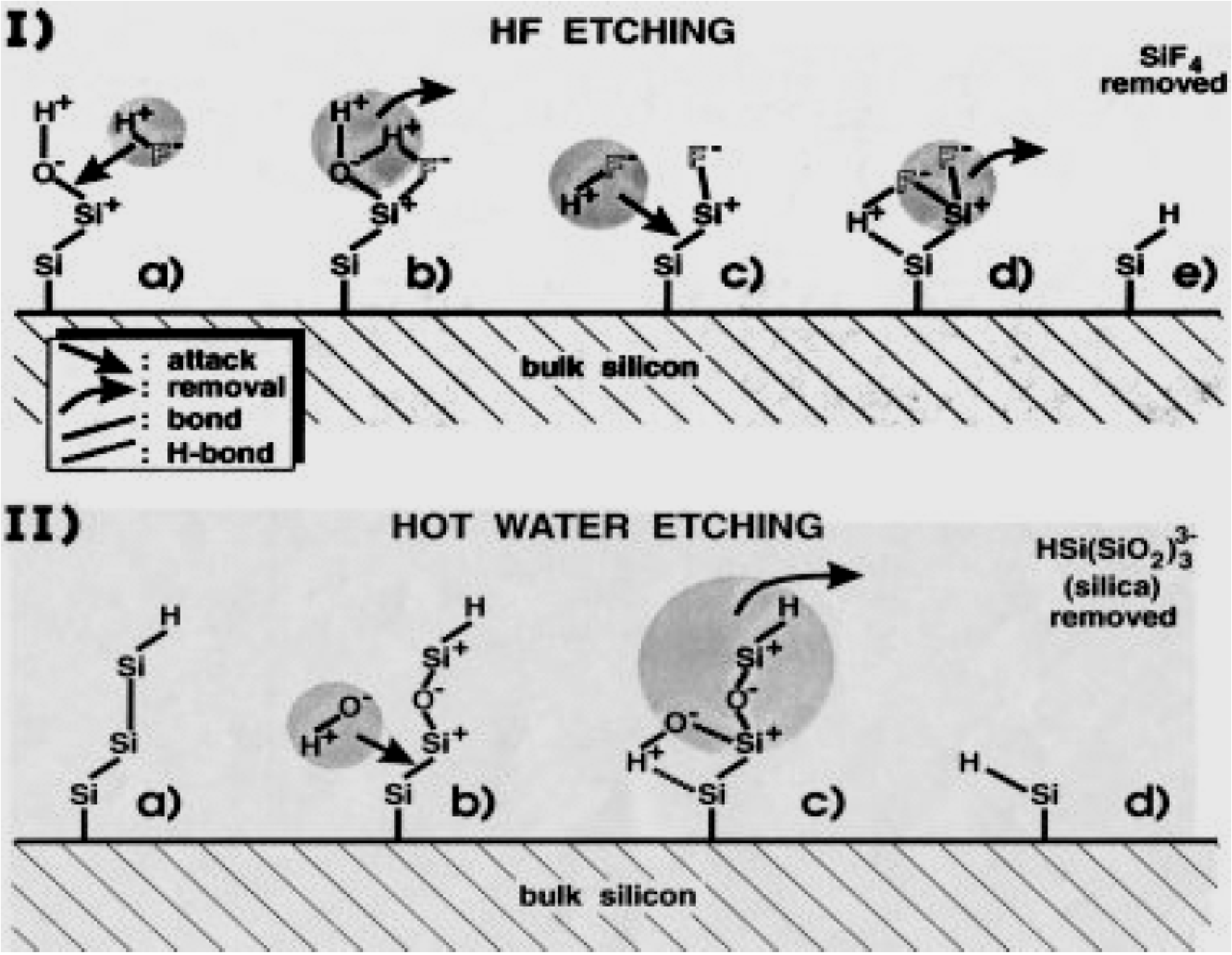
HNO_3 <=> $H^+ + NO_3^-$

HF <=> $H^+ + F^-$

H^+ is a strong oxidizing agent

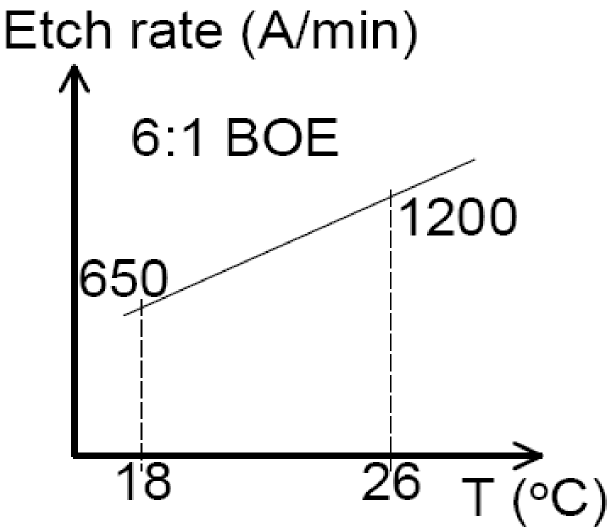
=> high reactivity of acids

Si wet etching mechanisms



Wet Etch Processes

(1) Silicon Dioxide



To etch SiO_2 film on Si, use

$HF + H_2O$

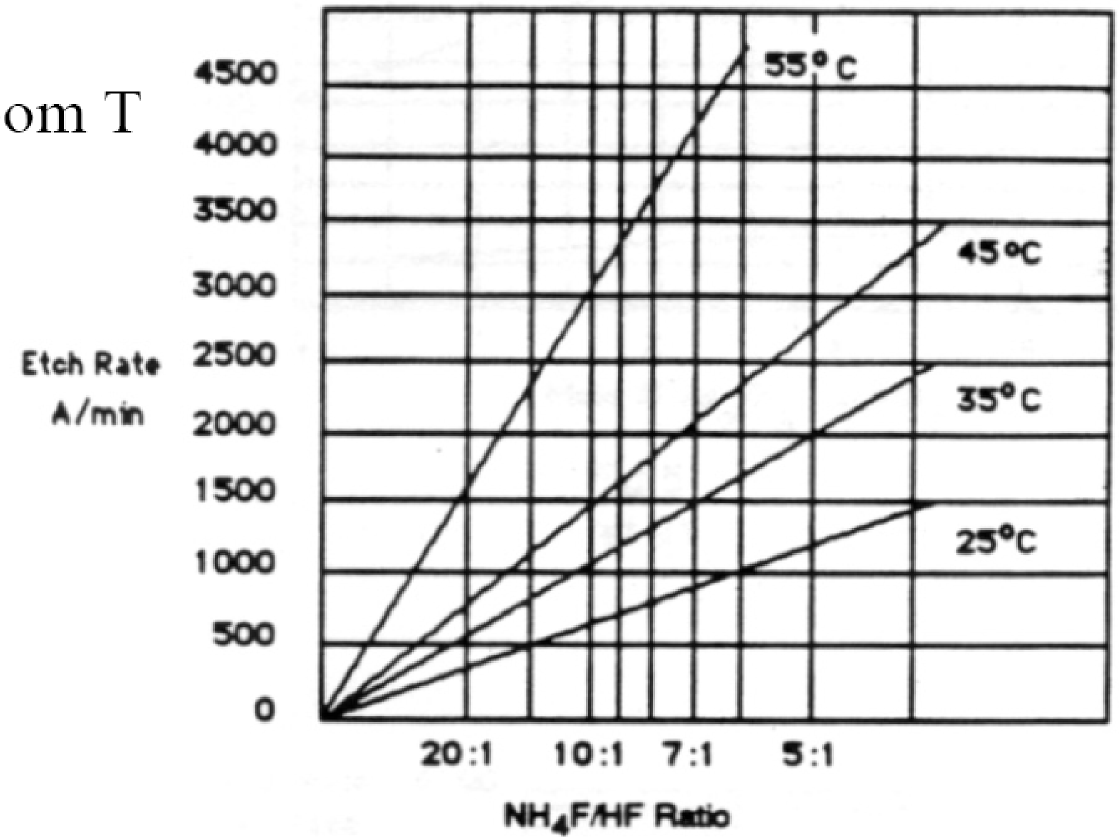
$$SiO_2 + 6HF \rightarrow H_2 + SiF_6 + 2H_2O$$

<u>Note</u>: HF is usually buffered with NH_4F to maintain $[H^+]$ at a constant level (for constant etch rate)

$$NH_4F \rightarrow NH_3 + HF$$

TYPES OF BHF

7:1 NH_4F/HF gives about 1000 Å/min etch rate at room T



Wet Etch Processes (cont.)

(2) Silicon Nitride

To etch Si_3N_4 film on SiO_2, use

H_3PO_4

(phosphoric acid)

(180^{o}C: ~100 A/min etch rate)

Typical selectivities:

- 10:1 for nitride over oxide
- 30:1 for nitride over Si

Wet Etch Processes (cont.)

(3) Aluminum

To etch Al film on Si or SiO_2, use

H_3PO_4 + CH_3COOH + HNO_3 + H_2O

(phosphoric acid) *(acetic acid)* *(nitric acid)*

(~30°C)

$$6H^+ + 2Al \rightarrow 3H_2 + 2Al^{3+}$$

(Al^{3+} is water-soluble)

Wet Etch Processes (cont.)

(4) Silicon

(i) Isotropic etching

Use HF + HNO_3 + H_2O

$$3Si + 4HNO_3 \rightarrow 3SiO_2 + 4NO + 2H_2O$$

$$3SiO_2 + 18HF \rightarrow 3H_2SiF_6 + 6H_2O$$

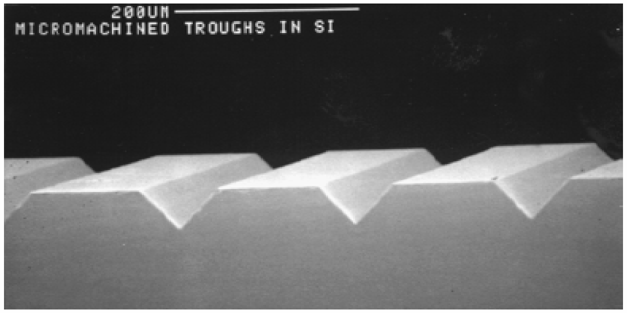
(ii) **Anisotropic etching (e.g. KOH, EDP)**

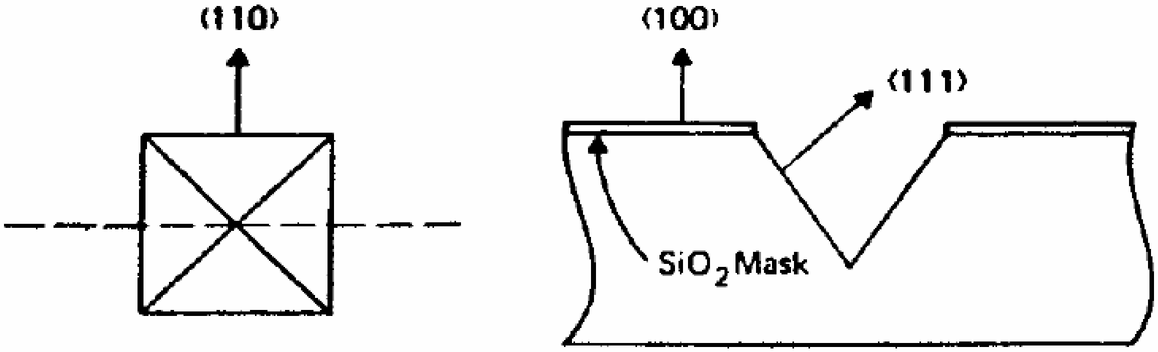
Anisotropic Etching of Silicon - 1

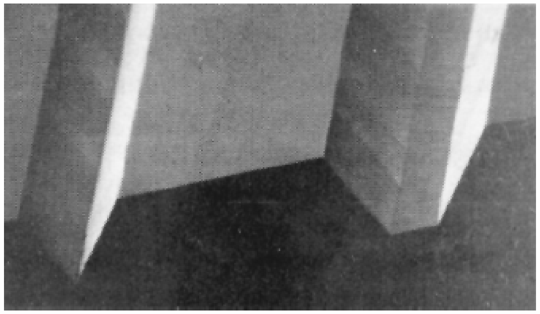
- Differing hybridized (sp^3) orbital orientation on different crystal planes causes drastic differences in etch rate.
- Typically, etch rates are: (100) > (110) > (111).
- The (111) family of crystallographic planes are normally the "stop" planes for anisotropic etching.
- There are 8 (111) planes along the $\pm x \pm y \pm z$ unit vectors.
- Intersections of these planes with planar bottoms produce the standard anisotropic etching structures for (100) Si wafers:
  - V-grooves
  - pyramidal pits
  - pyramidal cavities

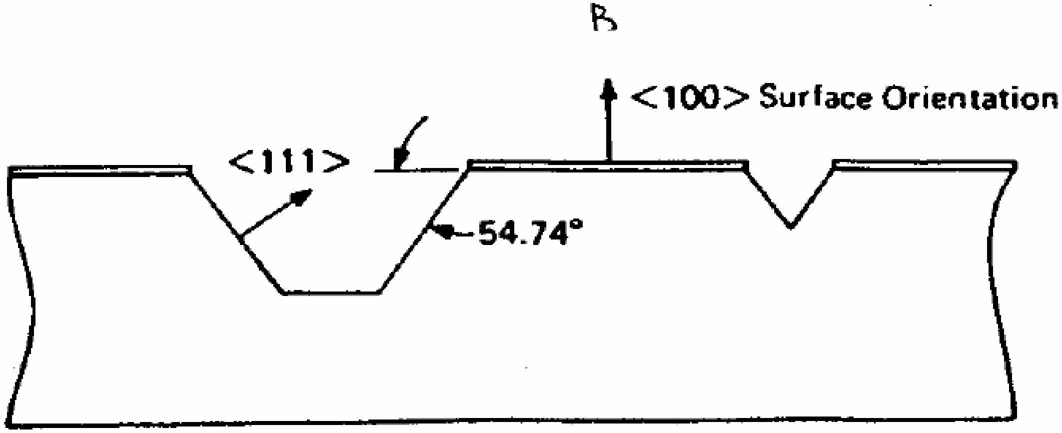
Effect of Slow {111} Etching with KOH or EDP

Mask opening aligned in <110> direction => {111} sidewalls





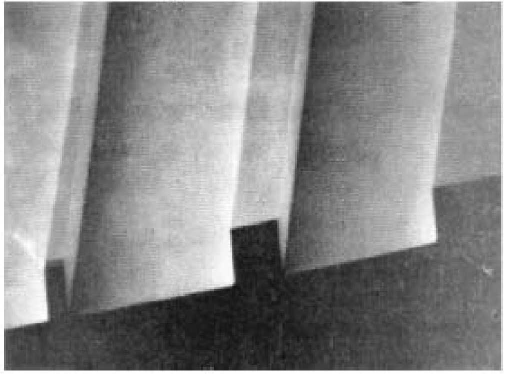


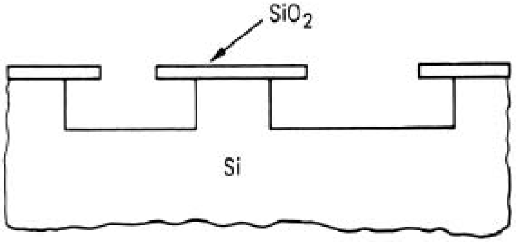


[110]-Oriented Silicon

{111} planes oriented perpendicular to the (110) surface

=> possible to etch pits with vertical sidewalls!





Bottom of pits are

- flat ({110} plane) if KOH is used
  {100} etches slower than {110}
- V-shaped ({100} planes) if EDP is used
  {110} etches slower than {100}

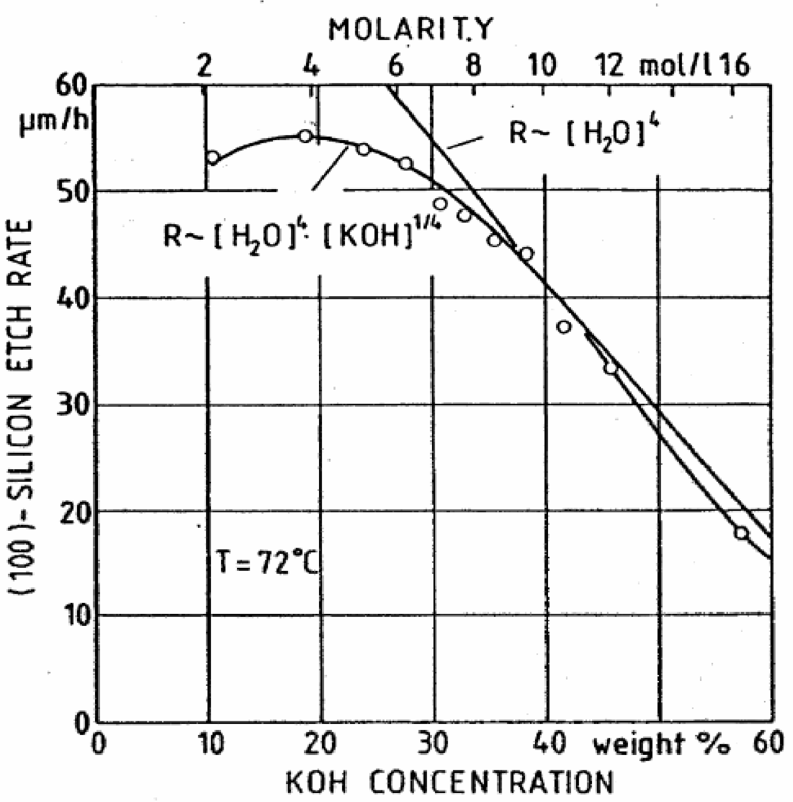
Hydroxide Etching of Silicon

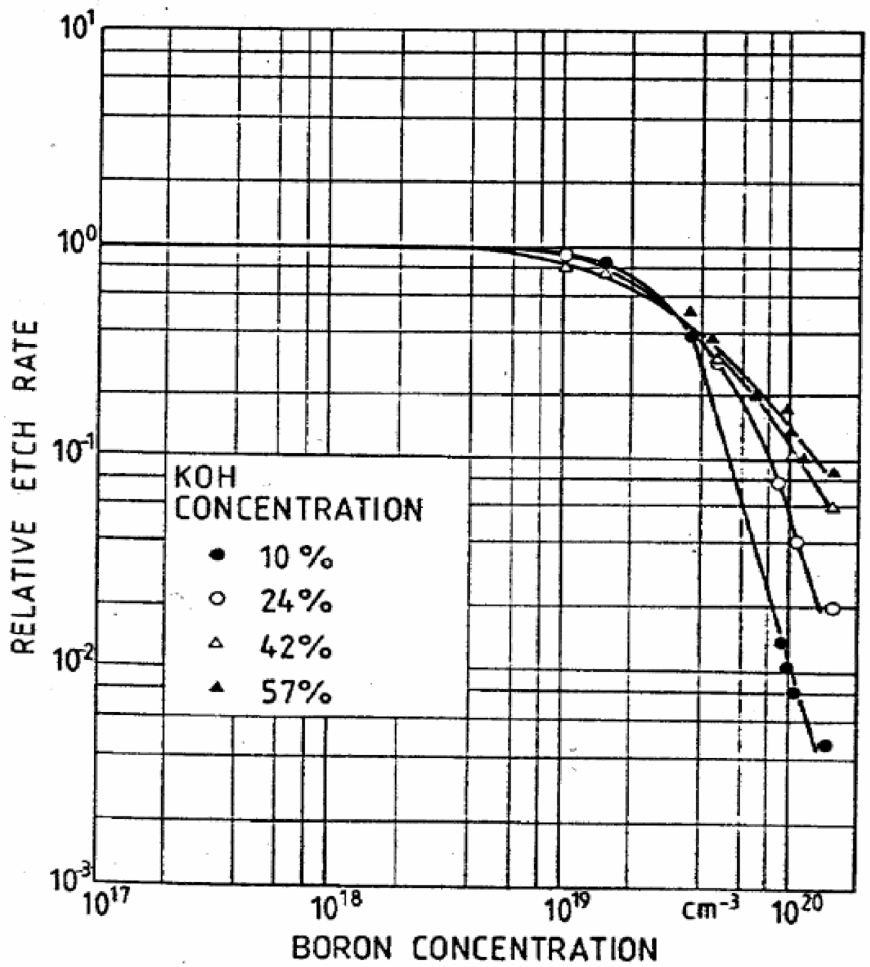
- Several hydroxides are useful:
  - KOH, NaOH, CeOH, RbOH, NH_4OH, TMAH: $(CH_3)_4NOH$
- Oxidation of silicon by hydroxyls to form a silicate:
  - $Si + 2OH^- + 4h^+ \rightarrow Si(OH)_2^{++}$
- Reduction of water:
  - $4H_2O \rightarrow 4OH^- + 2H_2 + 4h^+$
- Silicate further reacts with hydroxyls to form a water-soluble complex:
  - $Si(OH)_2^{++} + 4OH^- \rightarrow SiO_2(OH)_2^{2-} + 2H_2O$
- Overall redox reaction is:
  - $Si + 2OH^- + 4H_2O \rightarrow Si(OH)_2^{++} + 2H_2 + 4OH^-$

KOH Etching of Silicon - 1

- Typical and most used of the hydroxide etches.
- A typical recipe is:
  - 250 g KOH
  - 200 g normal propanol
  - 800 g H_2O
  - Use at 80°C with agitation
- Etch rates:
  - ~1 µm/min for (100) Si planes; stops at p^{++} layers
  - ~14 Angstroms/hr for Si_3N_4
  - ~20 Angstroms/min for SiO_2
- Anisotropy: (111):(110):(100) ~ 1:600:400

KOH ETCHING OF SILICON





Rochester Institute of Technology
Microelectronic Engineering

KOH Etching of Silicon - 2

- Simple hardware:
  - Hot plate & stirrer.
  - Keep covered 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 safe and non-toxic.

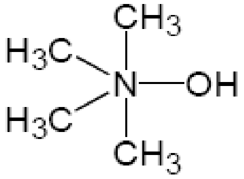
EDP Etching of Silicon - 1

- Ethylene Diamine Pyrocatechol
- Also known as Ethylene diamine - Pyrocatechol - Water (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.
- Typical etch rates for (100) silicon:

70°C	14 μm/hr
80°C	20 μm/hr
90°C	30 μm/hr = 0.5 μm/min
97°C	36 μm/hr

TMAH Etching of Silicon - 1

- Tetra Methyl Ammonium Hydroxide
- 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
- Typical recipe:
  - 250 mL TMAH (25% from Aldrich)
  - 375 mL H_2O
  - 22 g Si dust dissolved into solution
  - Use at 90°C
  - Gives about 1 μm/min etch rate

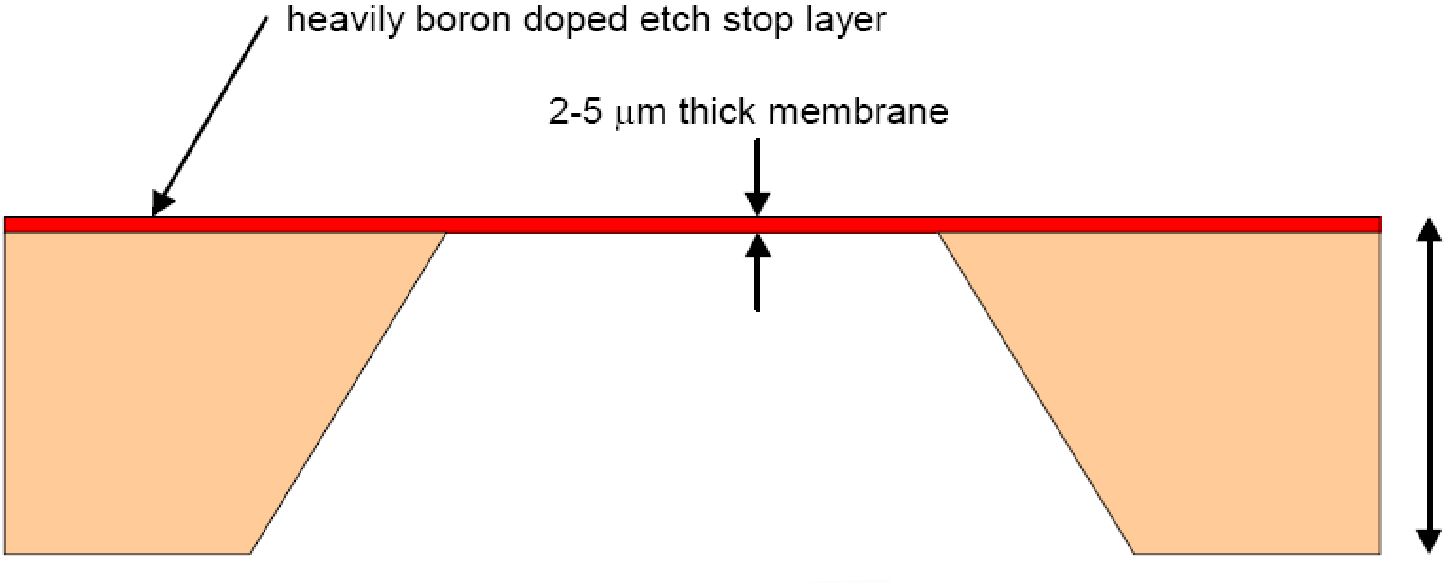


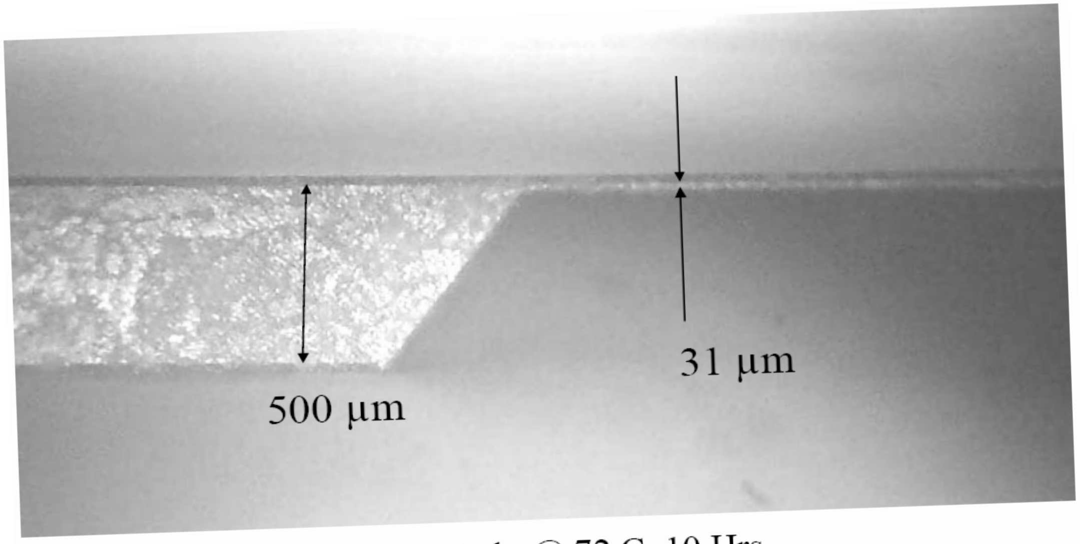
tetramethyl ammonium hydroxide
(TMAH)

Anisotropic Etch Stop Layers - 1

- Controlling the absolute depth of an etch is often difficult, particularly if the etch is going most of the way through a wafer.
- Etch stop layers can be used to drastically slow the etch rate, providing a stopping point of high absolute accuracy.
- Boron doping is most commonly used for silicon etching.
- Requirements for specific etches:
  - HNA etch actually speeds up for heavier doping
  - KOH etch rate reduces by 20× for boron doping $> 10^{20}$ cm^{-3}
  - NaOH etch rate reduces by 10× for boron doping $> 3 \times 10^{20}$ cm^{-3}
  - EDP etch rate reduces by 50× for boron doping $> 7 \times 10^{19}$ cm^{-3}
  - TMAH etch rate reduces by 10× for boron doping $> 10^{20}$ cm^{-3}

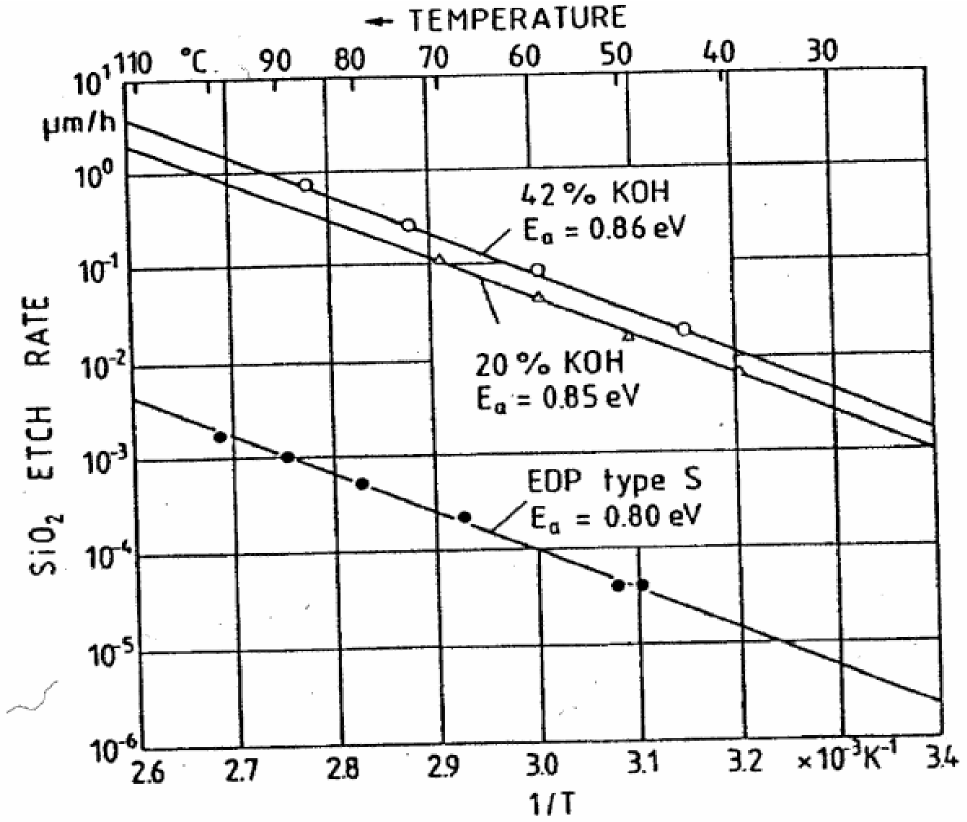
Anisotropic Etch Stop Layers - 2

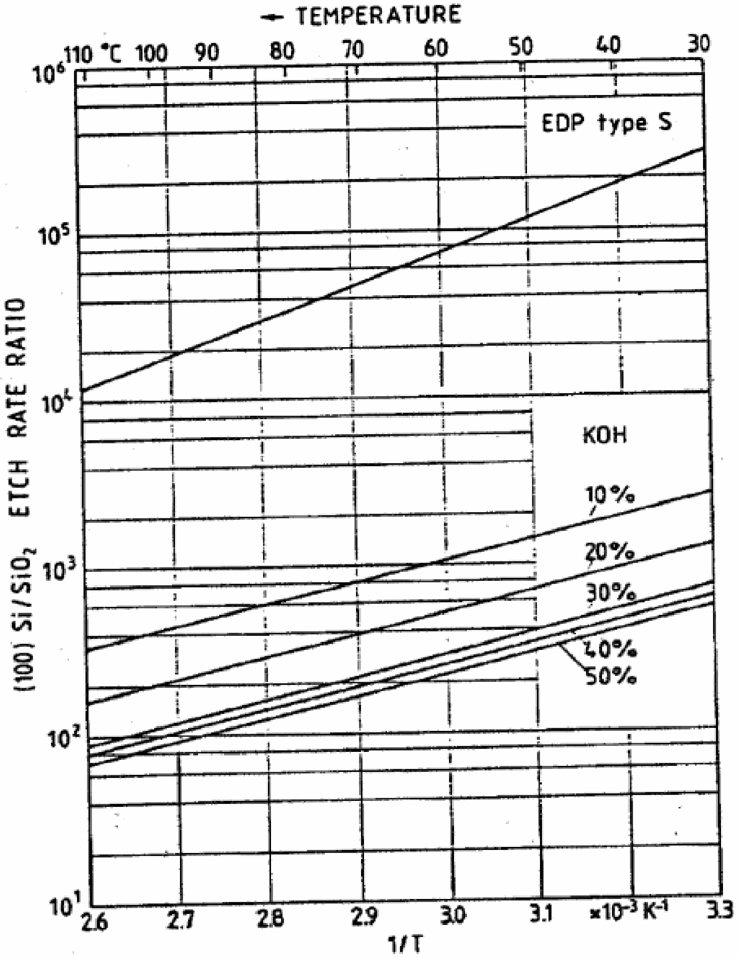




20% KOH Etch, @ 72 C, 10 Hrs.

KOH ETCHING OF SILICON OXIDE





HNA Etching of Silicon - 1

- Hydrofluoric acid + Nitric acid + Acetic acid
- Produces nearly isotropic etching of Si
- Overall reaction is:
  - $Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2$
  - Etching occurs via a redox reaction followed by dissolution of the oxide by an acid (HF) that acts as a complexing agent.
  - Points on the Si surface randomly become oxidation or reduction sites. These act like localized electrochemical cells, sustaining corrosion currents of ~100 A/cm^2 (relatively large).
  - Each point on the surface becomes both an anode and cathode site over time. If the time spent on each is the same, the etching will be uniform; otherwise selective etching will occur.

HNA Etching of Silicon - 2

- Silicon is promoted to a higher oxidation state at an anodic site which supplies positive charge in the form of holes:
  - $Si^0 + 2h^+ \rightarrow Si^{2+}$
- NO_2 from the nitric acid is simultaneously reduced at a cathode site which produces free holes:
  - $2NO_2 \rightarrow 2NO_2^- + 2h^+$
- The Si^{2+} combines with OH^- to form SiO_2:
  - $Si^{2+} + 2OH^- \rightarrow Si(OH)_2 \rightarrow SiO_2 + H_2O$
- The SiO_2 is then dissolved by HF to form a water soluble complex of H_2SiF_6:
  - $SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$

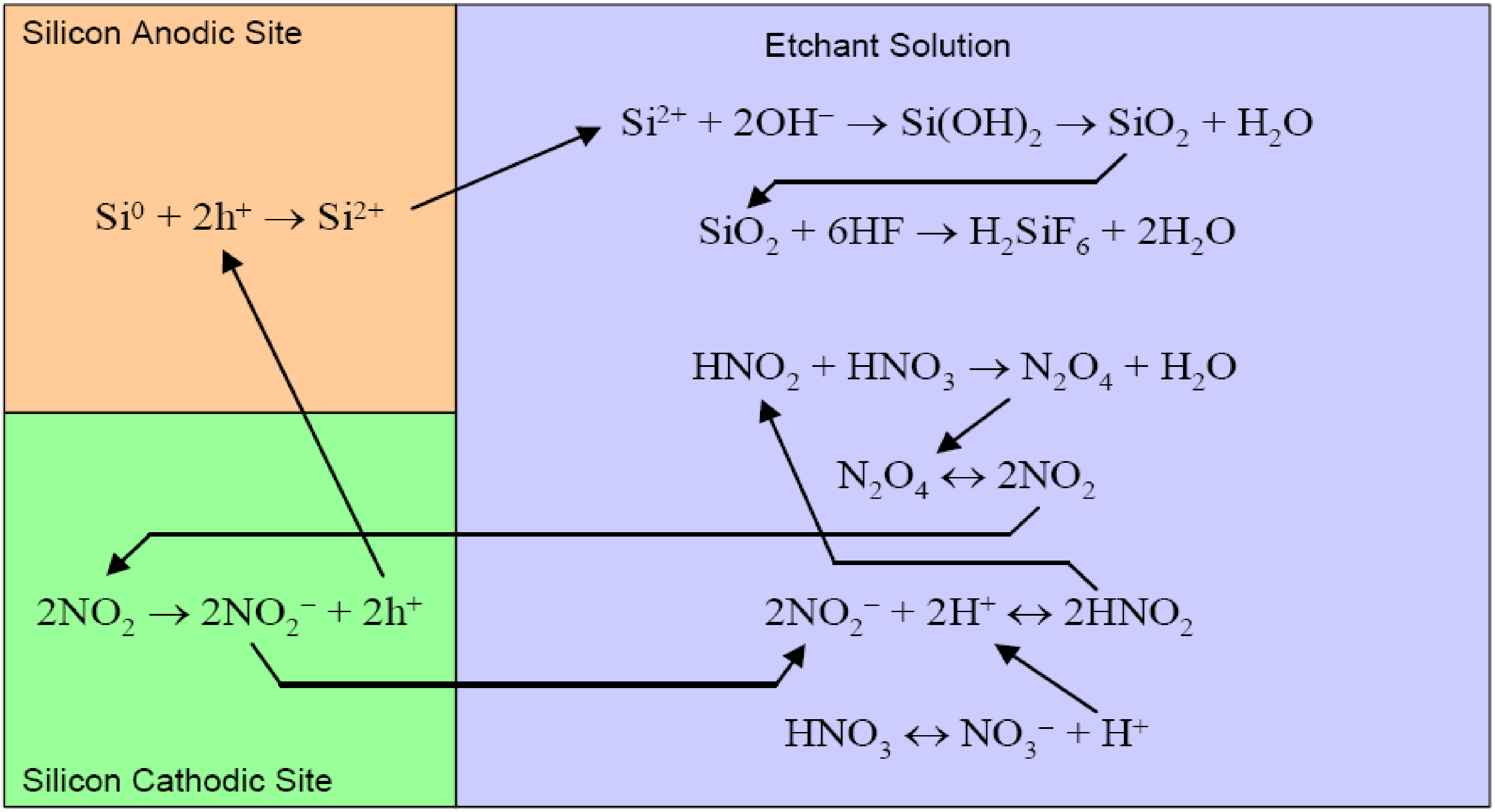
HNA Etching of Silicon - 3

- Nitric acid has a complex behavior:
  - Normal dissociation in water (deprotonation):
    - $HNO_3 \leftrightarrow NO_3^- + H^+$
  - Autocatalytic cycle for production of holes and HNO_2:
    - $HNO_2 + HNO_3 \rightarrow N_2O_4 + H_2O$
    - $N_2O_4 \leftrightarrow 2NO_2 \leftrightarrow 2NO_2^- + 2h^+$
    - $2NO_2^- + 2H^+ \leftrightarrow 2HNO_2$
  - NO_2 is effectively the oxidizer of Si
    - Its reduction supplies holes for the oxidation of the Si.
  - HNO_2 is regenerated by the reaction (autocatalytic)
  - Oxidizing power of the etch is set by the amount of undissociated HNO_3.

HNA Etching of Silicon - 4

- Role of acetic acid (CH_3COOH):
  - Acetic acid is frequently substituted for water as the dilutent.
  - Acetic acid has a lower dielectric constant than water
    - 6.15 for CH_3COOH versus 81 for H_2O
    - This produces less dissociation of the HNO_3 and yields a higher oxidation power for the etch.
  - Acetic acid is less polar than water and can help in achieving proper wetting of slightly hydrophobic Si wafers.

HNA Etching of Silicon - 5



Silicon Anodic Site

$Si^0 + 2h^+ \rightarrow Si^{2+}$

Etchant Solution

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

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

$HNO_2 + HNO_3 \rightarrow N_2O_4 + H_2O$

$N_2O_4 \leftrightarrow 2NO_2$

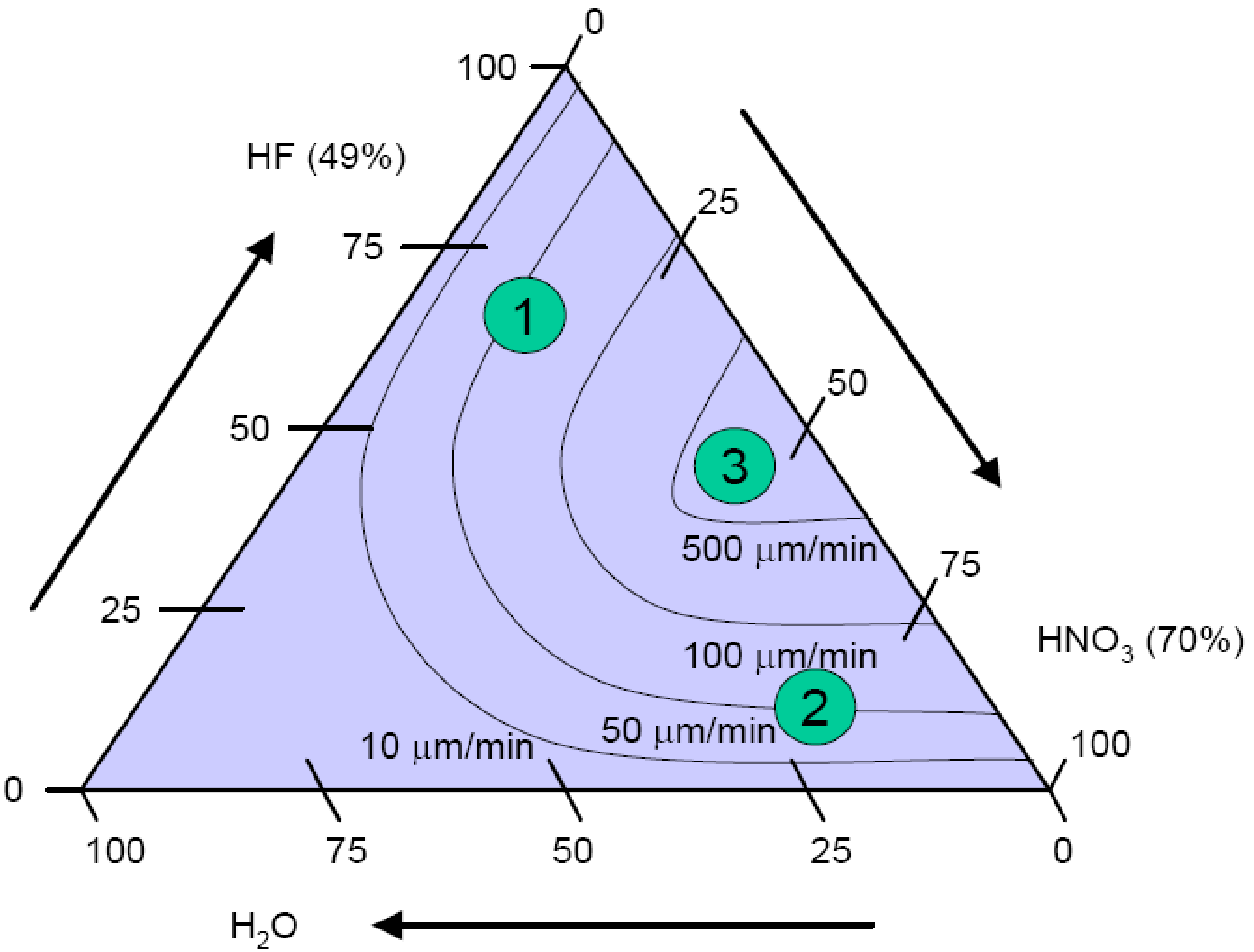
$2NO_2^- + 2H^+ \leftrightarrow 2HNO_2$

$HNO_3 \leftrightarrow NO_3^- + H^+$

$2NO_2 \rightarrow 2NO_2^- + 2h^+$

Silicon Cathodic Site

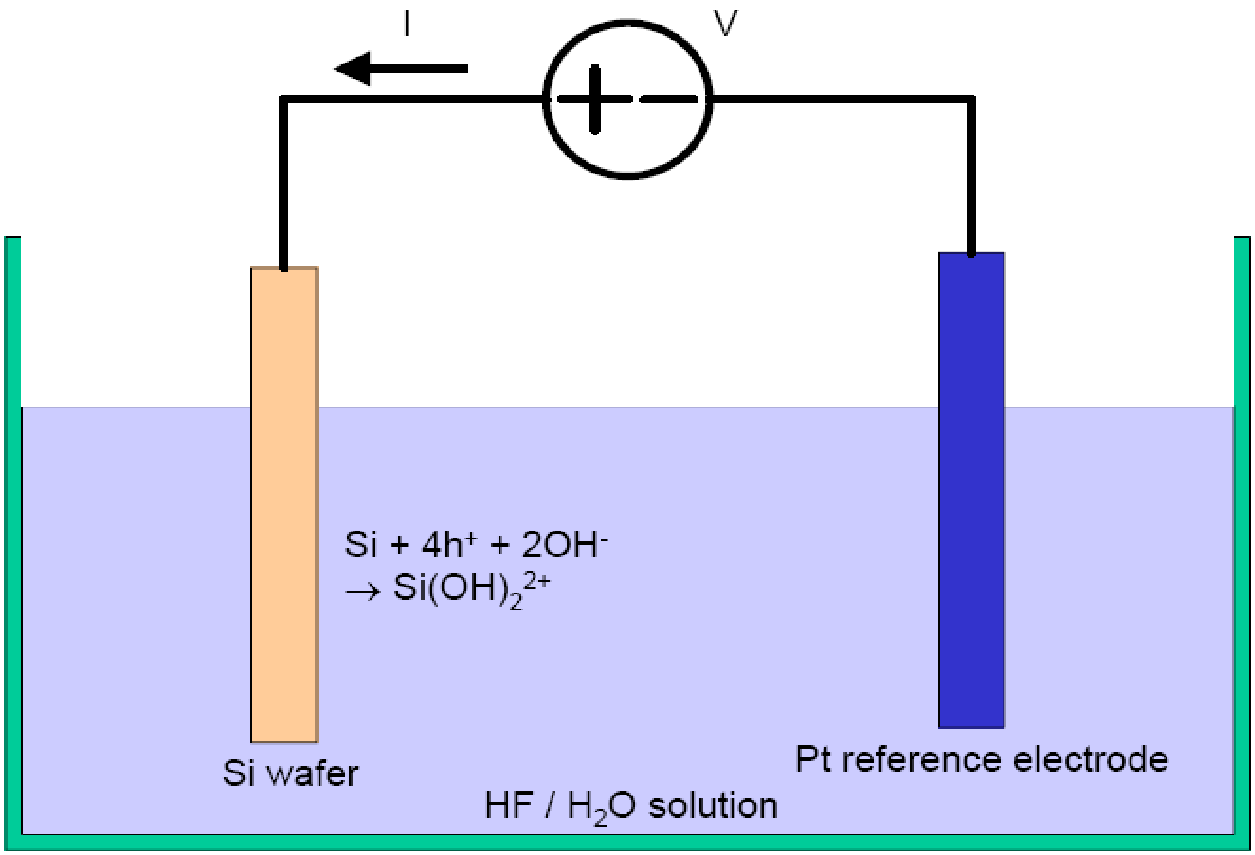
HNA Etching of Silicon - 6



HNA Etching of Silicon - 7

- 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; limited by oxidation process.
- 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 30-50 Angstroms of SiO_2; self-passivating; limited by oxide dissolution; area for polishing.
- Region ③
  - Initially not very sensitive to the amount of H_2O, then etch rate falls of sharply for 1:1 HF:HNO_3 ratios.

Electrochemical Etch Effects - 1

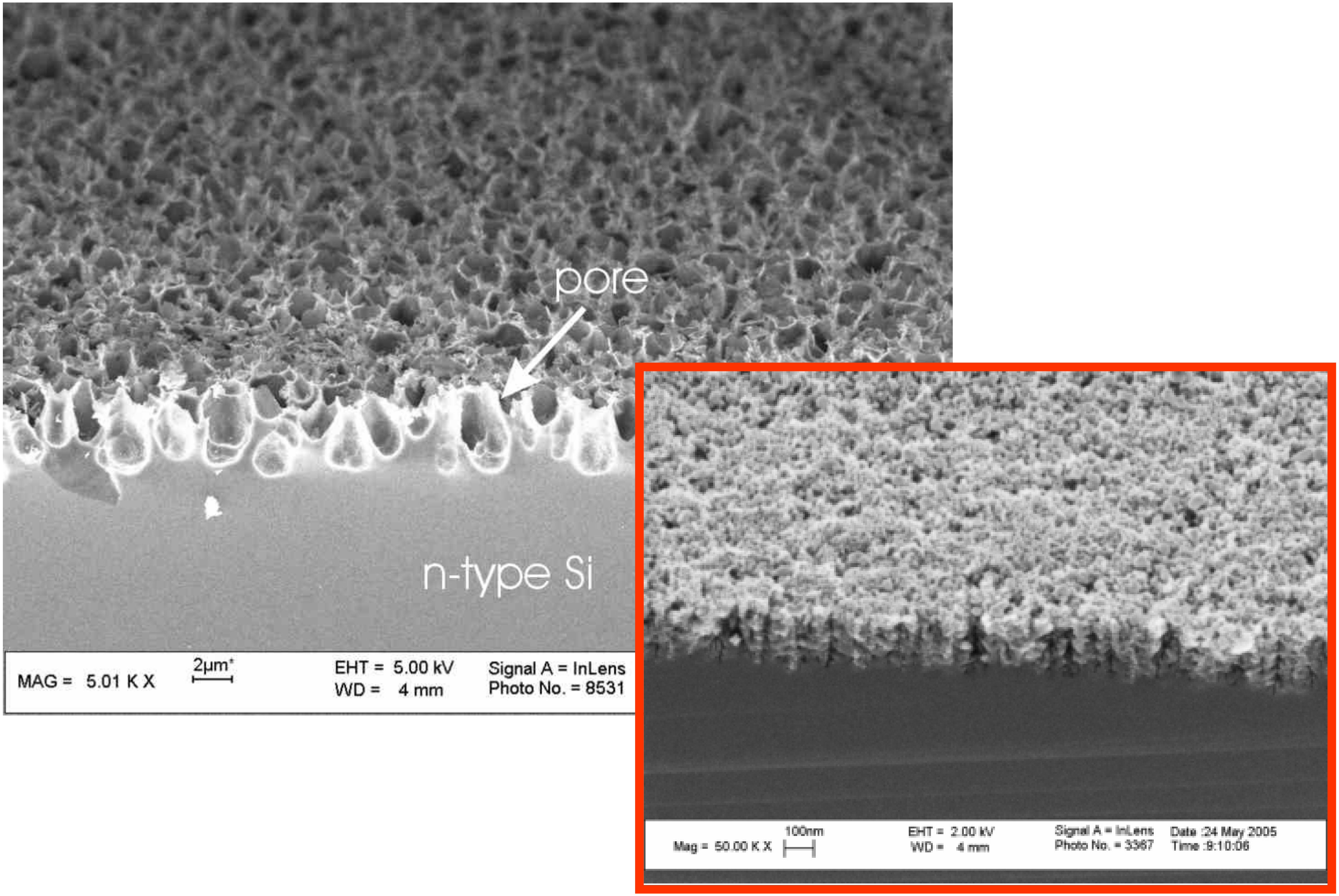


Porous Silicon

Electrochemical Etch Effects - 2

- HF normally etches SiO_2 and terminates on Si.
- By biasing the Si positively, holes can be injected by an external circuit which will oxidize the Si and form hydroxides which the HF can then dissolve.
- This produces an excellent polishing etch that can be very well masked by LPCVD films of Si_3N_4.
- If the etching is performed in very concentrated HF (48% HF, 98% EtOH), then the Si does not fully oxidize when etched, and porous silicon is formed, which appears brownish.

Porous Silicon



Observing Defects

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 22 27 NOVEMBER 2000

Dislocation density in GaN determined by photoelectrochemical and hot-wet etching

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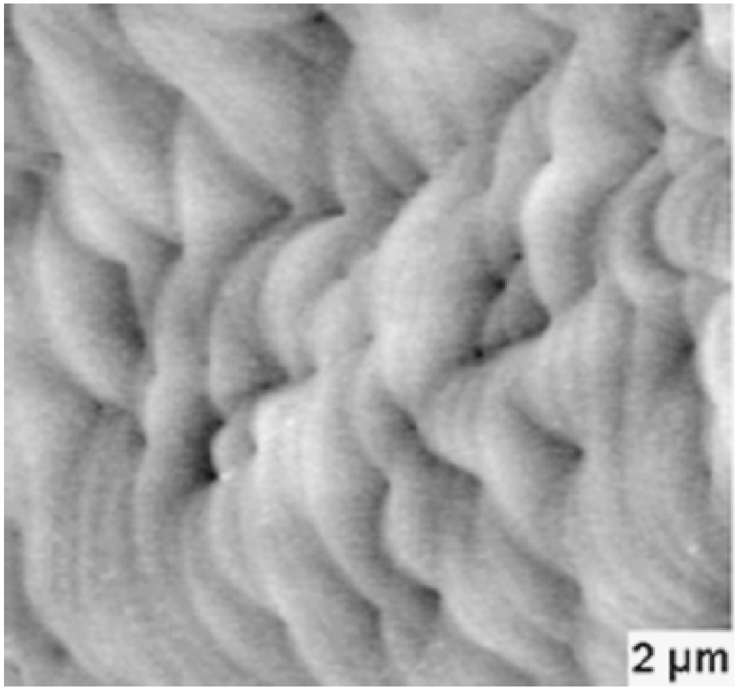

FIG. 1. AFM image ($2\times2\ \mu m^2$) of as-grown GaN. Some point defects (pits) positioned at surface step terminations are visible. The average step height is 0.8 nm and the root-mean-square (rms) roughness is 0.4 nm. The vertical scale ranges from 0 to 10 nm.

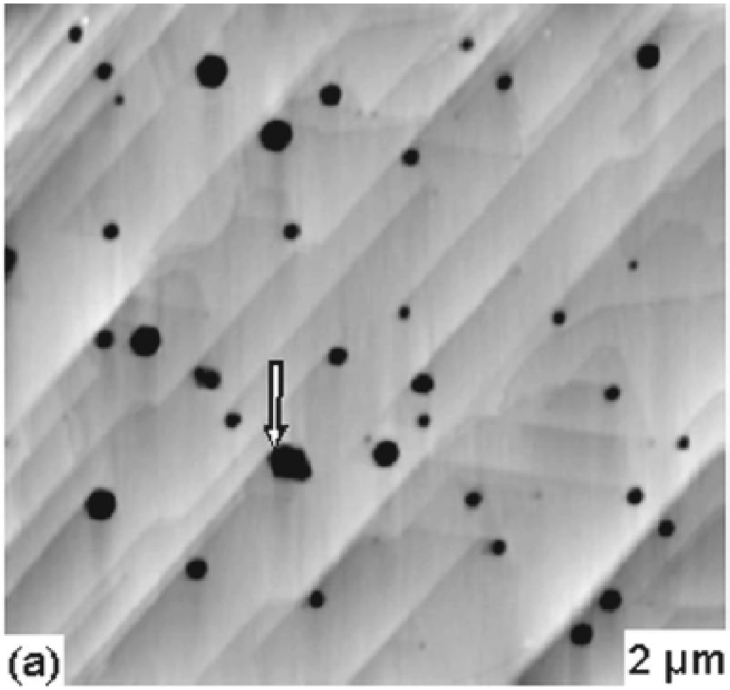

FIG. 3. AFM images ($2\times2\ \mu m^2$) of the GaN samples etched by wet etching. (a) Surface morphology of the GaN sample after etching by molten KOH for 2 min at 210 °C. Etch pits are revealed on the surface with a density of 1×10^9 cm^{-2}. (b) Surface morphology of the GaN sample after etching by H_3PO_4 for 6 min at 160 °C. The EPD is the same found for the KOH-etched sample. The vertical scale ranges from 0 to 10 nm.

ETCH FOR SILICON DEFECT DELINEATION

Sirtl Etchant: 1 part 49%HF, 1 part CrO3 (5M) (ie 500 g/liter) Etch rate ~3.5um/min. good on (111), poor on (100) faceted pits.

Secco Etchant: 2 parts 49%HF, 1 part K2Cr2O7 (0.15M) (ie 44 g/liter). Etch rate ~1.5 um/mon. Best with ultrasonic agitation. Good on all orientations. Non-crystallographic pits.

Wright Jenkins Etchant: 2 parts 49%HF, 2 parts conc. Acetic acid, 1 part con. Nitric acid, 1 part CRO3 (4M) (ie 400 g/liter), 2 part Cu(NO3)2 +3H2O (0.14M) (ie 33 g/liter). Etch rate ~1.7 um/min. Faceted pits, good shelf life.

Observing Crystal orientations

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Dislocation density in GaN determined by photoelectrochemical and hot-wet etching

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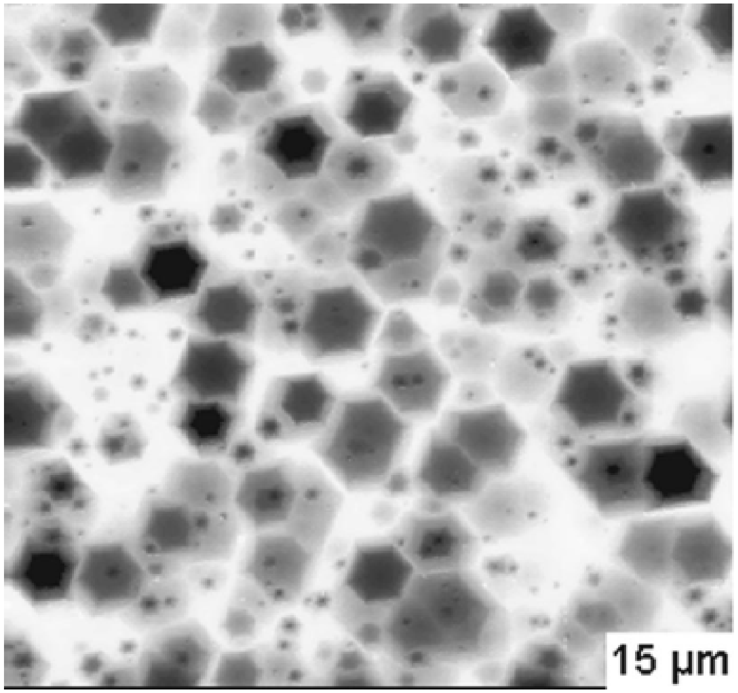

FIG. 4. AFM image ($15\times15\ \mu m^2$) of the GaN sample etched for 10 min at 200 °C using H_3PO_4. Two different types of etch pits with different sizes are revealed on the etched surface. Altogether, we estimated the EPD to be $1\times10^8\ cm^{-2}$. The vertical scale ranges from 0 to 450 nm.

Optically assisted etch rate Enhancement

Mechanisms:

Thermal
And E-H generation

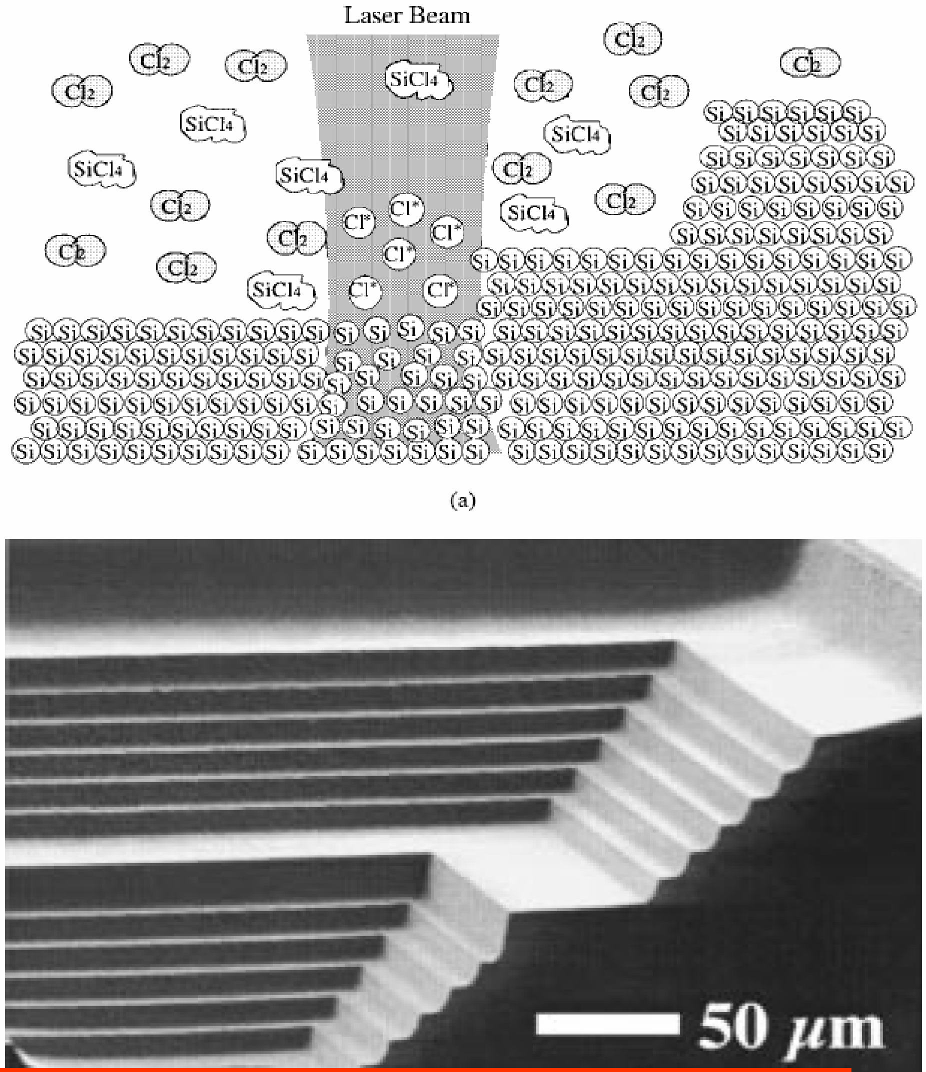

Fig. 5. Example of the use of LACE for the bulk micromachining of silicon. (a) Illustration of the process by which optical energy leads to local heating, which in turn drives the etching reaction, after Bloomstein and Ehrlich [71] (the Cl* symbols represent the highly reactive chlorine radicals formed locally by the laser beam). (b) SEM of an example structure showing step sizes of 10 and 30 μm etched into a silicon substrate. The overall size of the structure is 500 $\times 500 \mu$m $\times \approx 180 \mu$m deep, and the etching required ≈8 min. (SEM courtesy R. Aucoin, Revise, Inc., Burlington, MA.)

Simulation: ACES (free tool)

- Simulates Anisotropic Wet etching of Silicon

http://galaxy.micro.uiuc.edu/research/completed/aces/pages/download.html

You will have a simulation homework using this piece of software.
Please download and learn how to use it.

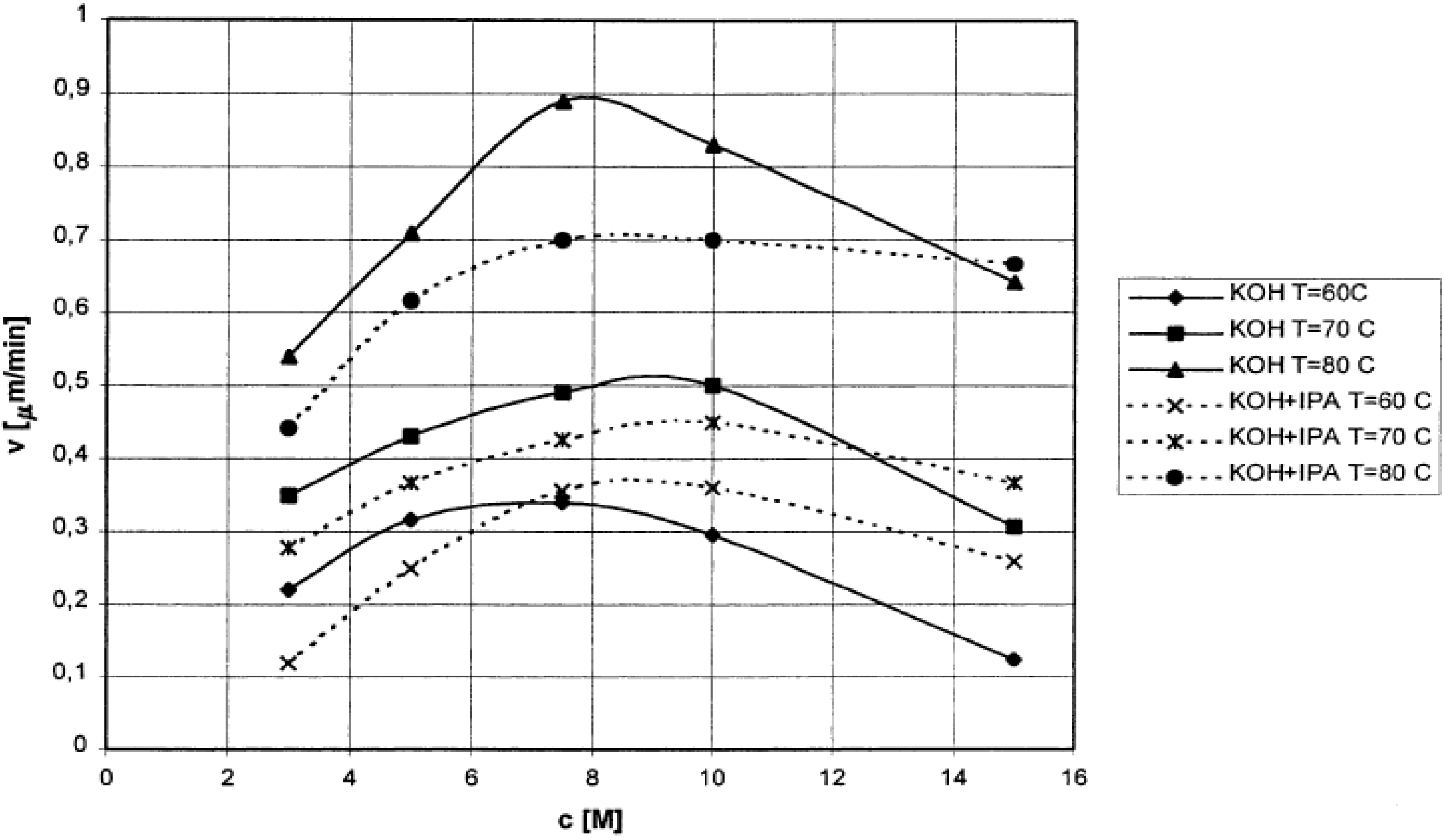

Fig. 1. Etching rates of Si(1 0 0) plane in KOH (solid lines) and KOH + IPA (dashed lines) solutions vs. KOH concentration.

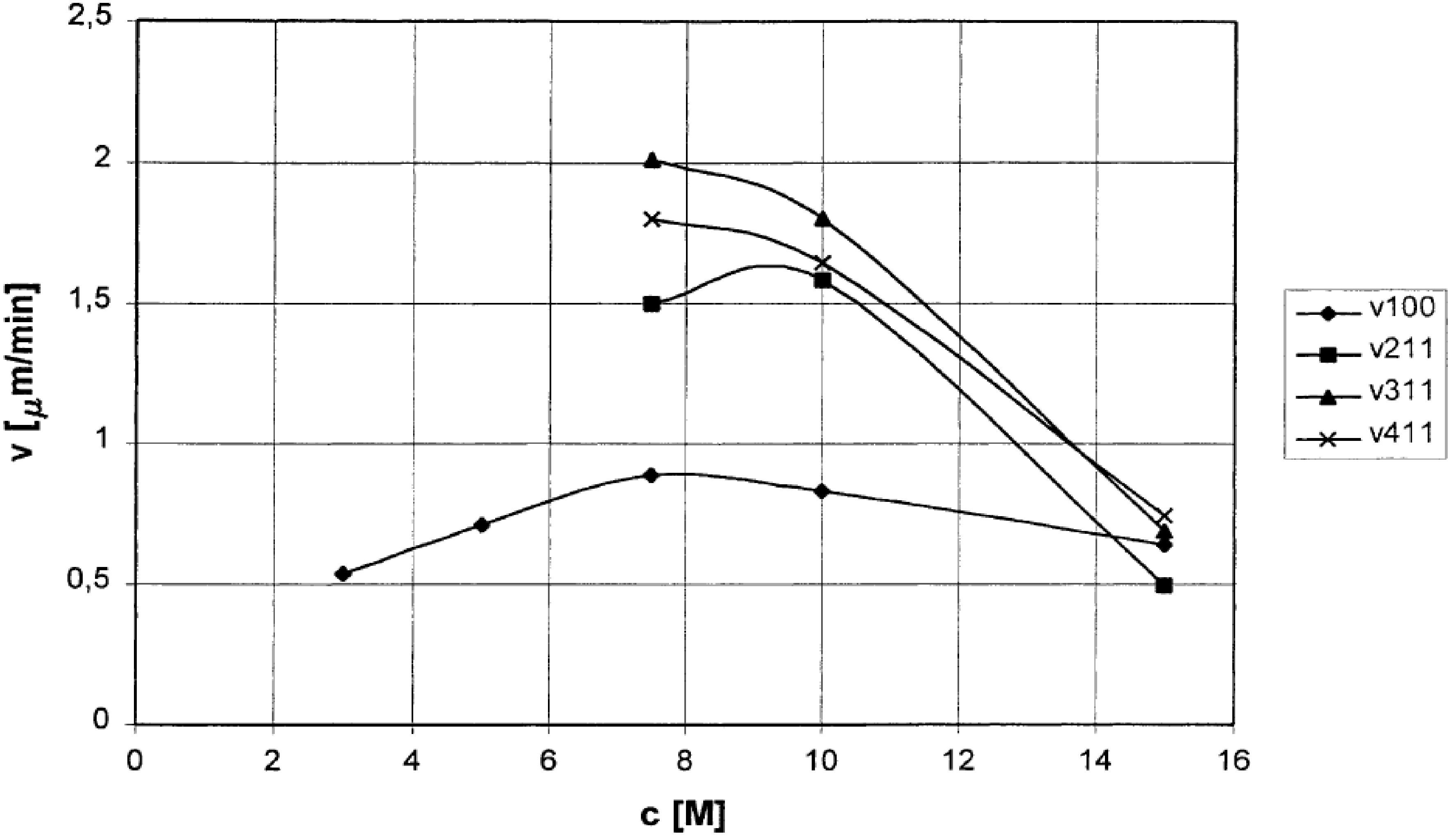

Fig. 2. Etching rates of Si(h k l) planes in KOH solution vs. KOH concentration at $T = 80°C$.

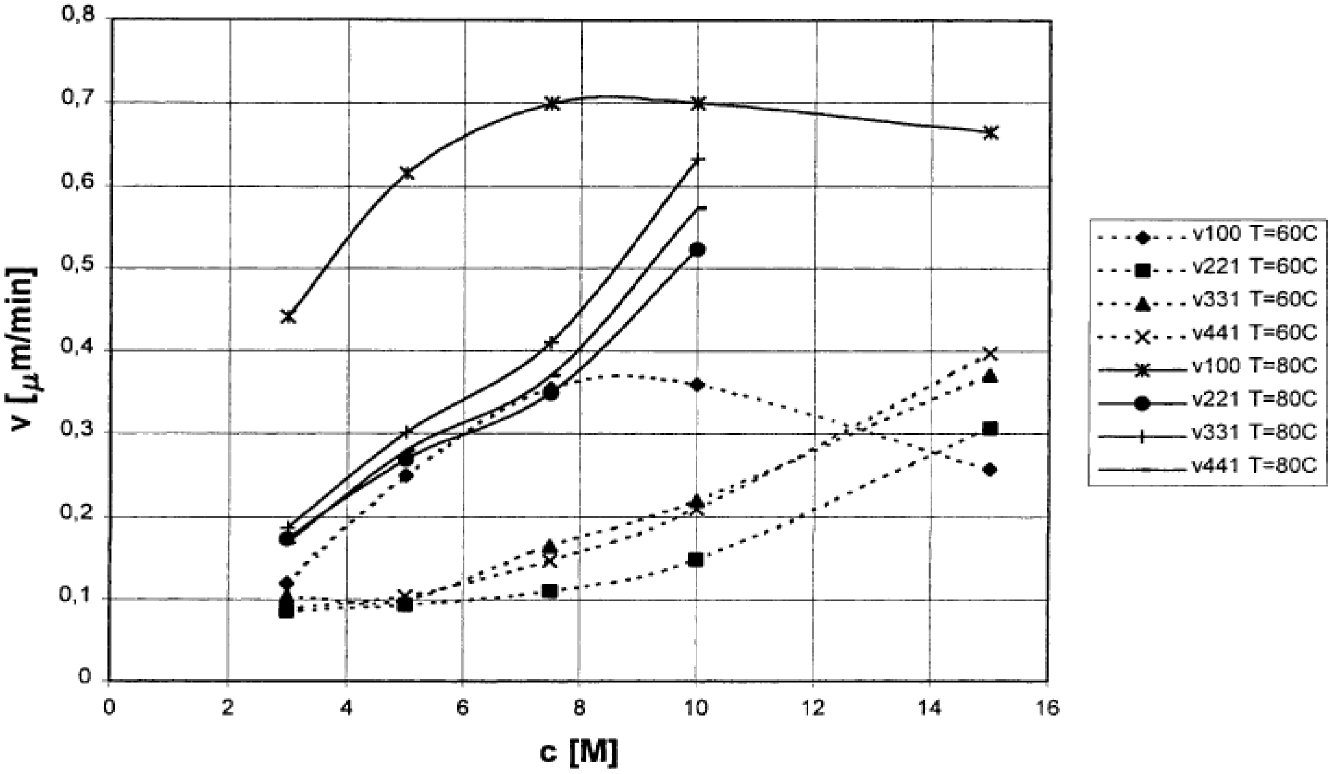

Fig. 3. Etching rates of (h k l) planes in KOH + IPA solution vs. KOH concentration, $T = 80°C$: solid lines, $T = 60°C$: dashed lines.

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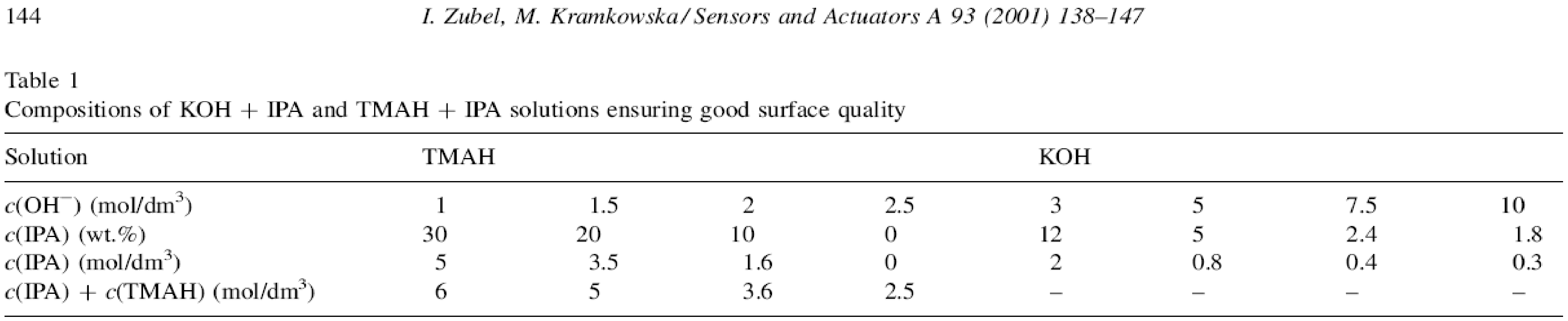

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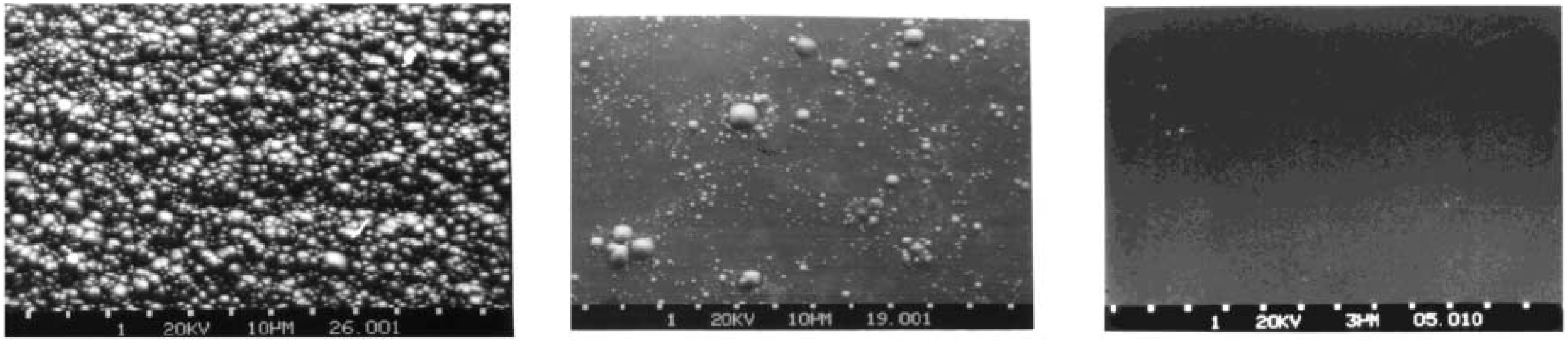
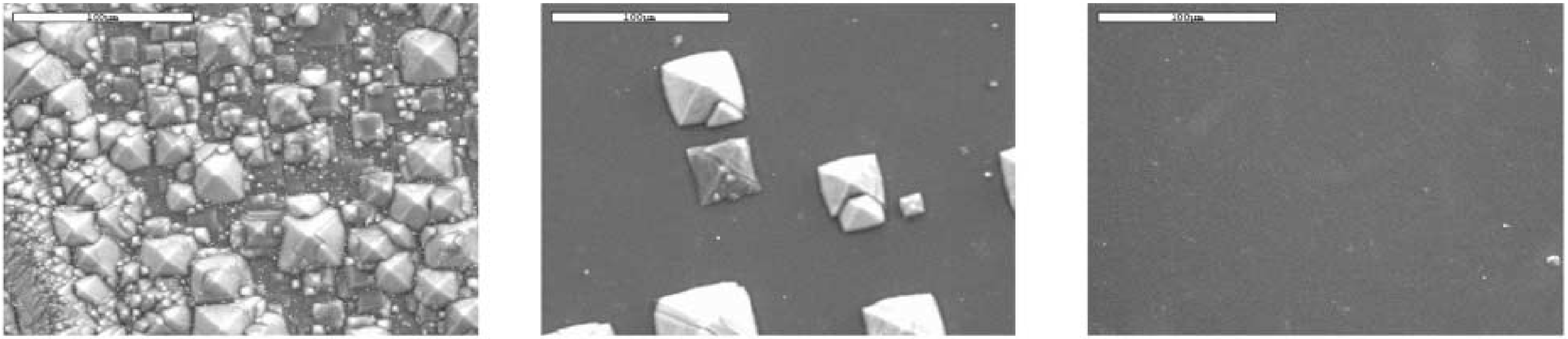
Table 1
Compositions of KOH + IPA and TMAH + IPA solutions ensuring good surface quality

Solution	TMAH				KOH			
$c(\mathrm{OH}^-)$ (mol/dm^3)	1	1.5	2	2.5	3	5	7.5	10
c(IPA) (wt.%)	30	20	10	0	12	5	2.4	1.8
c(IPA) (mol/dm^3)	5	3.5	1.6	0	2	0.8	0.4	0.3
c(IPA) + c(TMAH) (mol/dm^3)	6	5	3.6	2.5	–	–	–	–

If the wafer is not a good quality crystal, then you might not be able to
Reproduce these results.



3M KOH 7M KOH 10 M KOH



3M KOH + 5% IPA 3M KOH + 9% IPA 3M KOH + 12%IPA

Fig. 7. Surface morphologies of silicon wafers etched in KOH and KOH + IPA solution.

Bubbles!

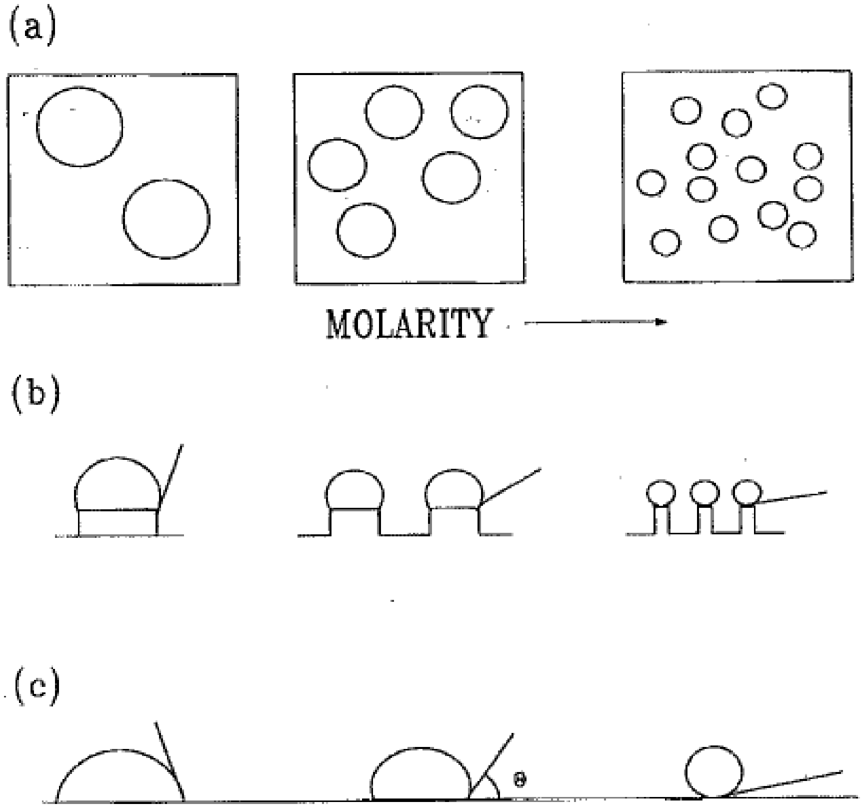
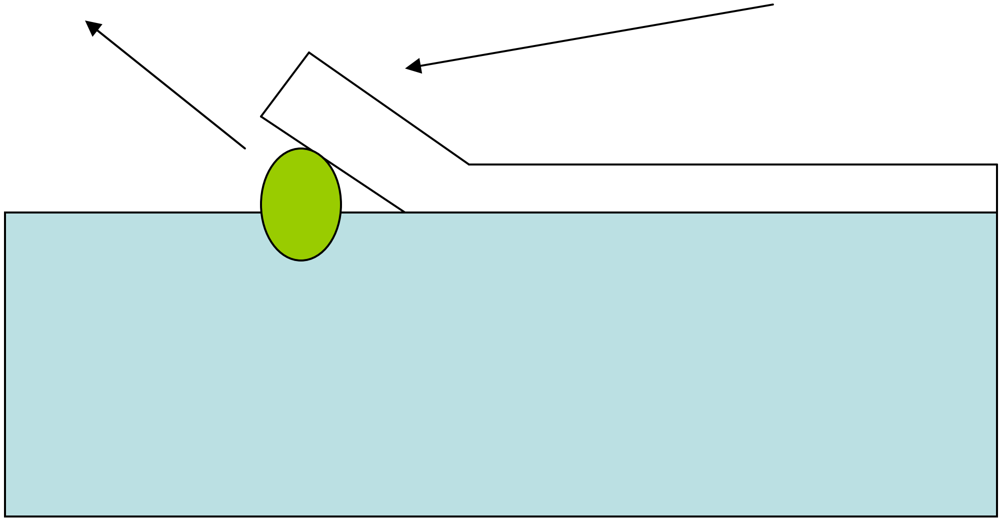


FIG. 7. (a) Schematic description of bubble size and density as a function of molarity. (b) Schematic description of etch roughness caused by masking during bubble growth. The etch rate is assumed constant as a function of molarity. The depth of the etch has no direct correlation to the size of the bubble. Typically, bubbles at detachment are many tens of micrometers in diameter. Since dwell times are of the order of seconds, the depth of etching around the pseudomasked area would be tens of angstroms for an etch rate of a few hundred Å/min. (c). Growing bubble size and shape as a function of contact angle θ. The area of contact of the bubble during growth would be masked from etching.

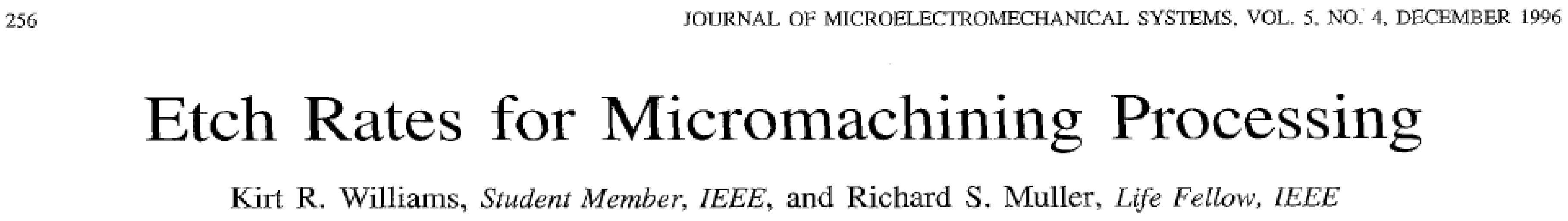
Bubbles



Bubble will push mask away before escaping

Detached mask is no longer
Able to protect the layer under it

Other Materials



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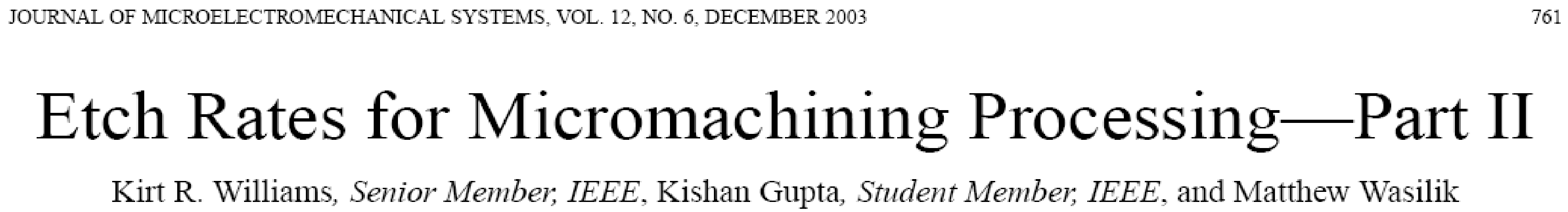
Etch Rates for Micromachining Processing

Kirt R. Williams, *Student Member, IEEE*, and Richard S. Muller, *Life Fellow, IEEE*



JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 12, NO. 6, DECEMBER 2003 761

Etch Rates for Micromachining Processing—Part II

Kirt R. Williams, *Senior Member, IEEE*, Kishan Gupta, *Student Member, IEEE*, and Matthew Wasilik

Good survey of etching , especially wet etching

TABLE I
ETCH DESCRIPTIONS, ABBREVIATIONS, AND TARGET MATERIALS

Etchant	Etchant Abbrev.	Target Material
Isotropic Silicon Etchant "Trilogy Etch" (126 HNO_3 : 60 H_2O : 5 NH_4F), ~20°C	Si Iso Etch	Silicon
KOH (30% by weight), 80°C	KOH	Silicon ODE
10:1 HF (10 H_2O : 1 49% HF), ~20°C	10:1 HF	Silicon Dioxide
5:1 BHF (5 40% NH_4F : 1 49% HF), ~20°C	5:1 BHF	Silicon Dioxide
Pad Etch 4 from Ashland (13% NH_4F + 32% HAc + 49% H_2O + 6% propylene glycol + surfactant), ~20°C	Pad Etch 4	SiO_2, not Al
Phosphoric Acid (85% by weight), 160°C	Phosphoric	Silicon nitride
Al Etchant Type A from Transene (80% H_3PO_4 + 5% HNO_3 + 5% HAc +10%H_2O), 50°C	Al Etch A	Aluminum
Titanium wet etchant (20 H_2O : 1 H_2O_2 : 1 HF), ~20°C	Ti Etch	Titanium
Chromium etchant CR-7 from Cyantek (9% $(NH_4)_2Ce(NO_3)_6$) + 6% $HClO_4$ + H_2O), ~20°C	CR-7	Chromium
Chromium etchant CR-14 from Cyantek (22% $(NH4)_2Ce(NO3)_6$) + 8% HAc+ H2O), ~20°C	CR-14	Chromium
Molybdenum etchant (180 H_3PO_4 : 11 HAc : 11 HNO_3 : 150 H_2O), ~20°C	Moly Etch	Molybdenum
Hydrogen peroxide (30wt% H_2O_2, 70wt% H_2O), 50°C	H_2O_2 50°C	Tungsten
Copper etchant type CE-200 from Transene (30% $FeCl_3$ + 3-4% HCl + H_2O), ~20°C	Cu $FeCl_3$ 200	Copper
Copper etchant APS 100 from Transene (15-20% $(NH_4)_2S_2O_8$ + H_2O), 30°C	Cu APS 100	Copper
Dilute aqua regia (3 HCl : 1 HNO_3 : 2 H_2O), ~30°C	Dil. Aqua regia	Noble metals
Gold etchant AU-5 from Cyantek (5% I_2 +10% KI + 85% H_2O), ~20°C	AU-5	Gold
Nichrome etchant TFN from Transene (10-20% $(NH_4)_2Ce(NO_3)_6$) + 5-6% HNO_3 + H_2O), ~20°C	NiCr TFN	NiCr
1 H_2SO_4 : 1 H_3PO_4, 160°C	Phos+Sulf	Sapphire
Piranha (~50 H_2SO4 : 1 H_2O_2), 120°C	Piranha	Cleaning
Microstrip 2001 photoresist stripper, 85°C	Microstrip	Photoresist
Acetone, ~20°C	Acetone	Photoresist
Methanol, ~20°C	Methanol	Cleaning
Isopropanol, ~20°C	IPA	Cleaning
XeF_2, 2.6 mTorr, homemade chamber	XeF_2	Silicon
HF + H_2O vapor, 1 cm over dish with 49% HF	HF vapor	Silicon dioxide
Technics plasma, O_2, 400 W @ 30 kHz, 300 mTorr	Technics O_2	Photoresist
STS ASE DRIE, mechanical chuck, high frequency, typical recipe	DRIE HF mech.	Silicon
STS ASE DRIE, electrostatic chuck, high frequency, typical recipe	DRIE HF ES	Silicon
STS ASE DRIE, mechanical chuck, stop-on-oxide (low-frequency platen), typical recipe	DRIE LF mech.	Silicon
STS ASE DRIE, electrostatic chuck, stop-on-oxide (low-frequency platen), typical recipe	DRIE LF ES	Silicon
STS 320 RIE, SF_6, 100 W @13.56 MHz, 20 mTorr	STS 320 SF_6	Si, SiN, metals
STS 320 RIE, SF_6 + O_2, 100 W @13.56 MHz, 20 mTorr	STS SF_6+O_2	Si, SiN, metals
STS 320 RIE, CF_4, 100 W @13.56 MHz, 60 mTorr	STS 320 CF_4	Si, SiO, SiN
STS 320 RIE, CF_4 + O_2, 100 W @13.56 MHz, 60 mTorr	STS CF_4+O_2	Si, SiO, SiN
Ion milling with argon ions at 500 V, ~1 mA/cm^2, normal incidence (Commonwealth data)	Ion Mill	Everything

Notation:
BHF = buffered hydrofluoric acid
DRIE = deep reactive ion etch
RIE = reactive ion etch
STS ASE = Surface Technology Systems Advanced Silicon Etch

TABLE V
ETCH RATES OF AL, Ti, V, Nb, Ta, AND Cr (nm/min)

Etch	Aluminum Evap	Al + 2% Si Sputtered	Titanium Sputtered	Vanadium Evap	Niobium Ion-Mill	Tantalum Evap	Tantalum Ion-Mill	Chromium Evap	Chromium Ion-Mill	Patterned Cr on Au Evap
Si Iso Etch	60	400	300	9600	79	5.8	5.3	R 8.8	-	< 2.3
KOH	12,900	F	soft	< 12	3.2	S	2.8	4.2	-	0
10:1 HF	W	250	1100	S	S	S	S	S	S	-
5:1 BHF	11	140	W	< 2	0	S	R 0	0	< 0.3	P
Pad Etch 4	1.9	R < 15	< 2	S	S	S	S	S	S	-
Phosphoric	> 500	980	-	-	0	-	0	100	-	-
Al Etch A	530	660	0	-	-	-	-	T 0	-	1.0
Ti Etch	150	240	1100	-	-	-	-	0	S	-
CR-7	3.8	S	< 2	60	R 0	S	< 0.7	170	150	110
CR-14	0	0.8	< 2	15	-	-	-	93	W	120
Moly Etch	> 20	-	-	-	-	-	-	R 0	-	-
H_2O_2 50ºC	T 0	0.25	-	-	-	-	-	110	W	-
Cu $FeCl_3$ 200	35	W	-	-	-	-	-	0.053	S	-
Cu APS 100	< 0.3	-	-	-	-	-	-	0	S	-
Dil. Aqua regia	600	W	< 0.5	-	0	S	< 2	0	S	-
AU-5	-	-	-	-	-	-	-	0	S	-
NiCr TFN	> 46	-	-	-	-	-		> 170	W	W
Phos+Sulf	W	W	-	-	-	-		I > 500		
Piranha	> 5200	W	240	-	6.3	S	T 0	> 16	5.7	R 0
Microstrip	-	-	-	-	-	-	-	-	-	-
Acetone	S	0	0	S	S	S	S	S	S	S
Methanol	S	S	S	S	S	S	S	S	S	S
IPA	S	S	S	S	S	S	S	S	S	S
XeF_2	S	0	29	W	W	W	W	-	-	-
HF vapor	R	R	R	-	-	-	-	S	S	-
Technics O_2	S	0	0	S	S	S	S	S	S	S
DRIE HF mech.	-	-	4.9	-	-	-	-	-	-	-
DRIE HF ES	-	-	-	-	-	-	-	-	-	-
DRIE LF mech.	-	-	-	-	-	-	-	-	-	-
DRIE LF ES	-	-	-	-	-	-	-	-	-	-
STS 320 SF_6	-	-	-	-	W	W	W	< 1	< 0.7	S
STS SF_6+O_2	< 2.8	-	-	-	26	W	37	< 1	< 0.9	S
STS 320 CF_4	S	S	-	-	-	-	-	< 1	< 3	-
STS CF_4+O_2	0.87	1.5	-	-	14	-	21	< 1.3	< 1.2	-
Ion Mill	73	W	38	W	W	42	42	58	58	W