ME 141B: The MEMS Class Introduction to MEMS and MEMS Design

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Outline

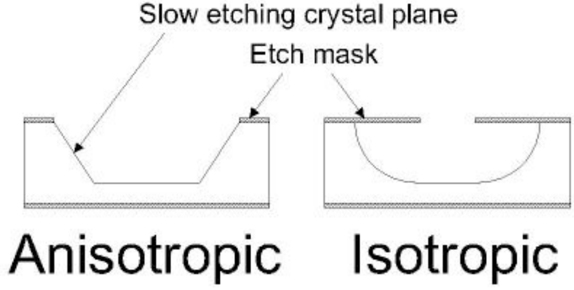
- Etching
  - Wet Etching
    - Isotropic
    - Electrochemical Enhanced
    - Anisotropic
    - Chemical Model for Silicon
    - Etch Stops
  - Dry Etching – next class

Etching

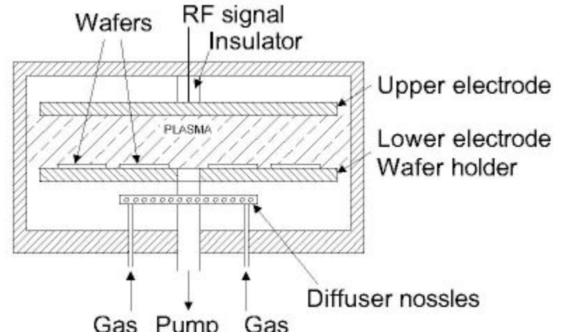
- Wet Etching
  - Isotropic
  - Anisotropic (for crystals only)
- Dry etching using plasma reactors
  - Isotropic “plasma” etching at relatively high gas pressures
  - Anisotrpoic “reaction-ion” etching at relatively lower gas pressures
- Sputter etching or ion-beam milling
  - Not very selective

Etching Processes

- Wet Etching:
  - Material is dissolved when immersed in a chemical solution



- Dry etching
  - Where material is sputtered or dissolved using reactive ions or a vapor phase etchant



Wet Etching

- Simplest etching technology
- All you need is a container of liquid chemicals!
- There are complications
  - Selectivity
    - Must find mask that will not dissolve
    - Other materials can't dissolve
  - Silicon can be both isotropic and anisotropic
- Why use wet etching?
  - Simple technology
  - Good for thin films
- Why not use it?
  - Undercutting!
  - Anisotropic etch corners, etc…

Considerations for etching

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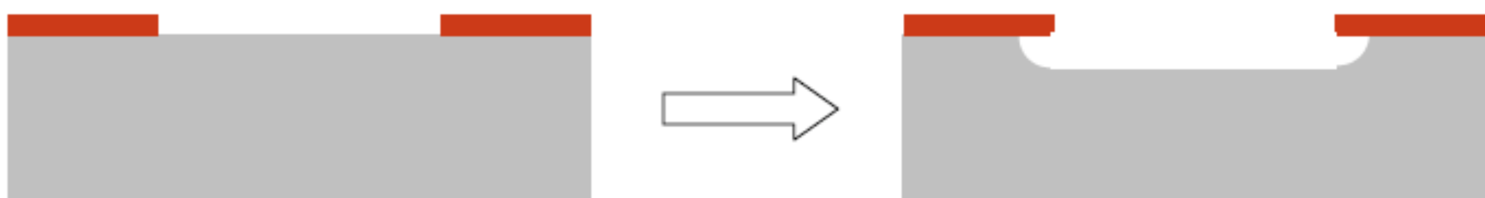
- Isotropic
  - Etch rate the same in all crystal directions
- Anisotrpoic
  - For wet etches, rate depends on crystal plane
  - For dry etches, directionality determined by process
- Selectivity
  - Etch rate of substrate vs. etch rate of mask
- Mask Adhesion (for wet etching)
  - Increased etching along mask/substrate interface
- Temperature
  - Reaction rate limited?
- Stirring
  - Mass transfer limited?

Isotropic Etching

- Etch rate is independent of orientation
- Isotropic etch profile
  - Assume a well-adhered mask with infinite selectivity
  - Mask undercut, rounded etch profile



- Applications
  - Flow channels
  - Removal of sacrificial layers in surface micromachining

Isotropic etching

- Some wet etches:
  - Si mixture of nitric, acetic, and HF
  - SiO_2 buffered HF (BOE), also HF vapor
  - SiN hot phosphoric acid
  - PolySi KOH
  - Al PAN etch (phosphoric, acetic, nitric acids)
- Some dry etches:
  - Si XeF_2 vapor
  - Organics O_2 plasma
- Mostly clean enough for front enf, with the exception of KOH, which is a contamination risk for very high T processes. XeF_2 vapor is often used as a final release etch

Isotropic etching

- Provides a high degree of selectivity and etch rate. Can be controlled by composition, temperature, dopant concentration
- Etching proceeds by
  - 1. Reactant transport to surface
  - 2. Surface reaction
  - 3. Reaction product transport from the surface
- If 1 or 3 is rate determining step – it’s diffusion limited
  - Can improve by stirring, gas evolution
- If 2, the reaction rate limited and ca be controlled by temperature, etchant composition
  - Prefer to be reaction rate limited – higher etch rates, better controlled

Isotropic Silicon Etching

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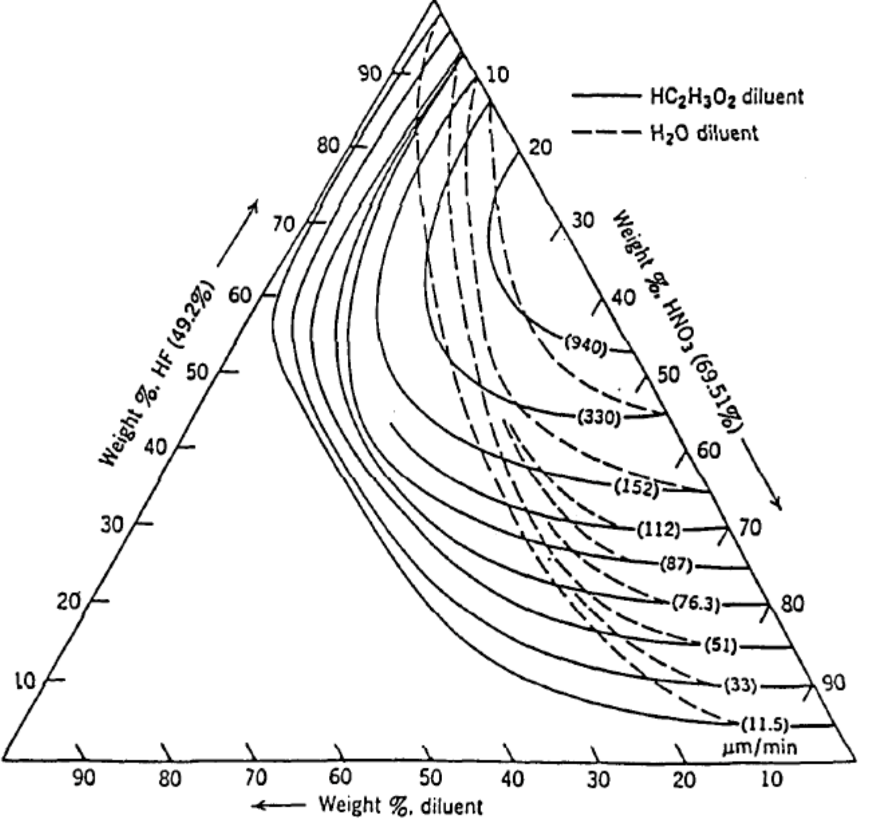
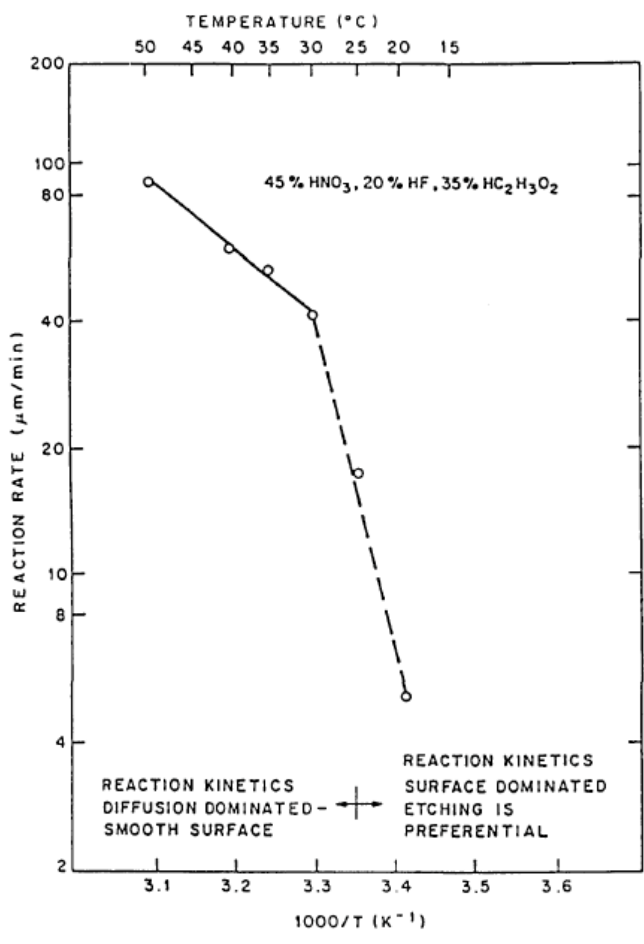
- No spatial orientation dependence
- Most common isotropic etchants are mixtures of nitric and hydrofluoric acids diluted in water and/or acetic acid
- Holes and hydroxide ion supplied by nitric acid when it combines with water and trace impurities of nitrous acid:
  - $HNO_2 + HNO_3 + H_2O \rightarrow HNO_2 + 2h^+ + 2(OH)^-$
- Regeneration of HNO_2 makes the reaction autocatalytic

Etch Concentration Iso-Etch Curves (Experimental)

- Increasing HNO_3 concentration move reaction toward diffusion limited case
- Increase T of HF concentration increases reaction rate
- Note High Rates!

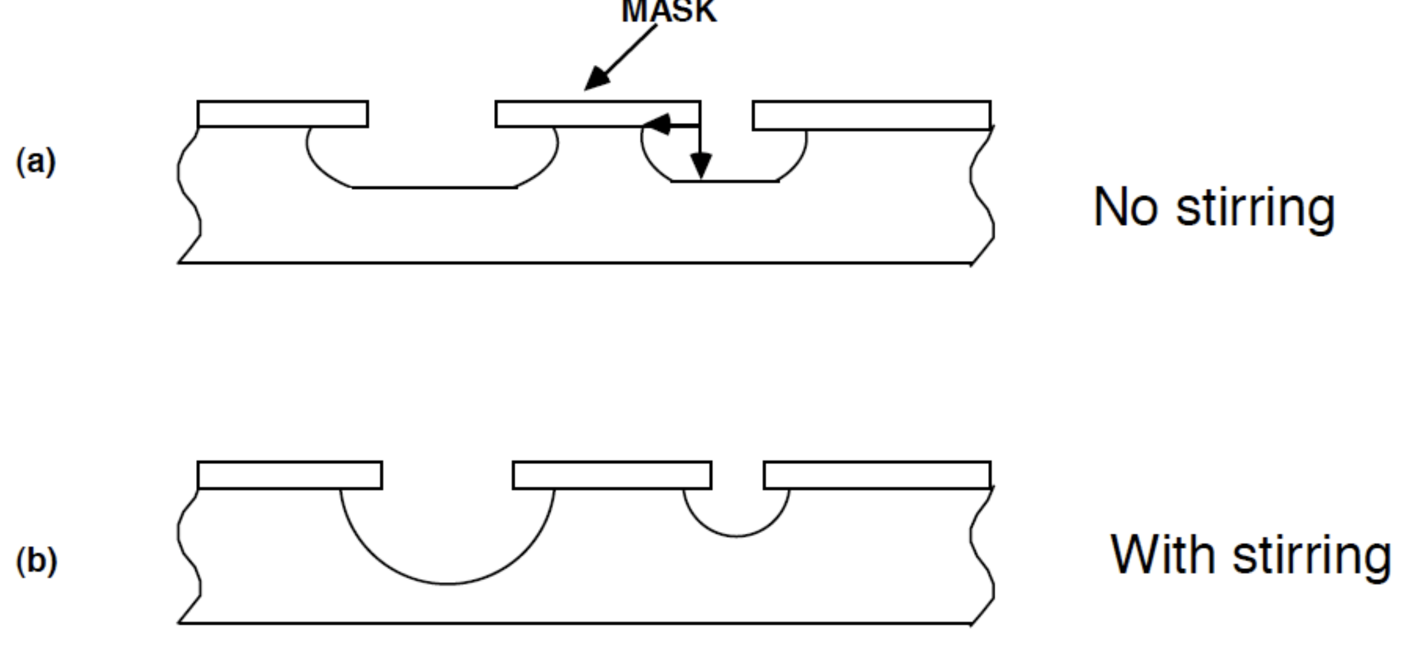


Temperature Dependence



- $HF:HNO_3:CH_3COOH$
- Increasing temperature increases reaction rate
- Note transition from diffusion dominated to surface dominated

Selectivity



Lateral etching under a mask layer proceeds at the same rate as vertically for isotropic etchants

However, stirring can alter relative rates

Masking

- Thermally grown SiO_2 etches at 30-80 nm/min in the HF:HNO_3 system, limiting the etch time, however thick layers are often used due to ease of patterning
- Photoresists do not stand up to the strong oxidizing agent (HNO_3) and are therefore not used
- Black wax can be used to mask the etchant at room temperature
- Silicon nitride is the preferred masking material. Etch rate is on the order of 1-10 nm/min. Chromium can also be used
- Dopant concentration $<10^{17}$ cm^{-3} (n or p) result in an etch rate reduction of ~150 X, presumably due to the lower mobile carrier concentrations available to contribute to charge transfer mechanisms of silicon oxidation

Electrochemical etching

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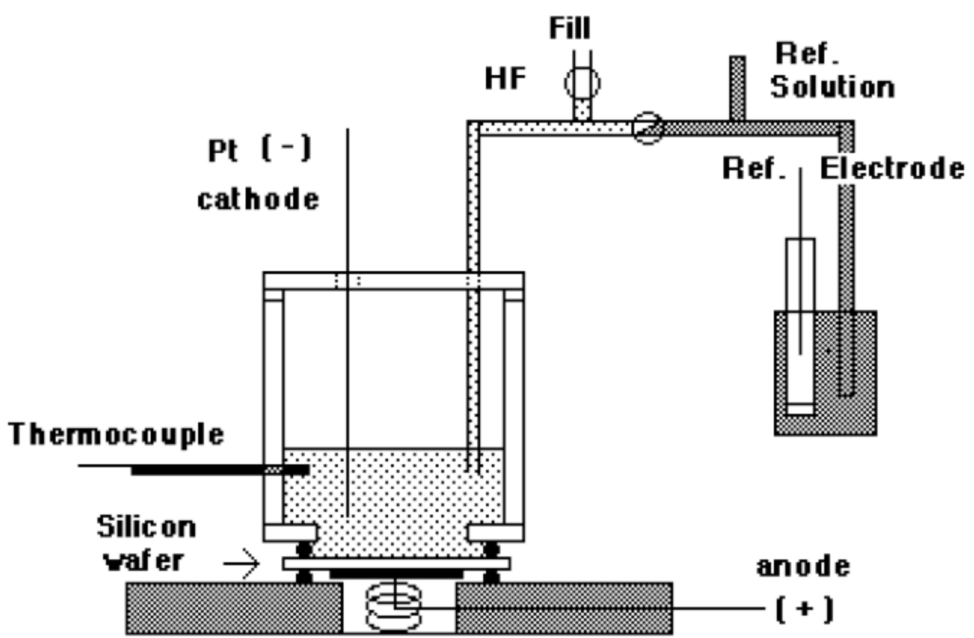
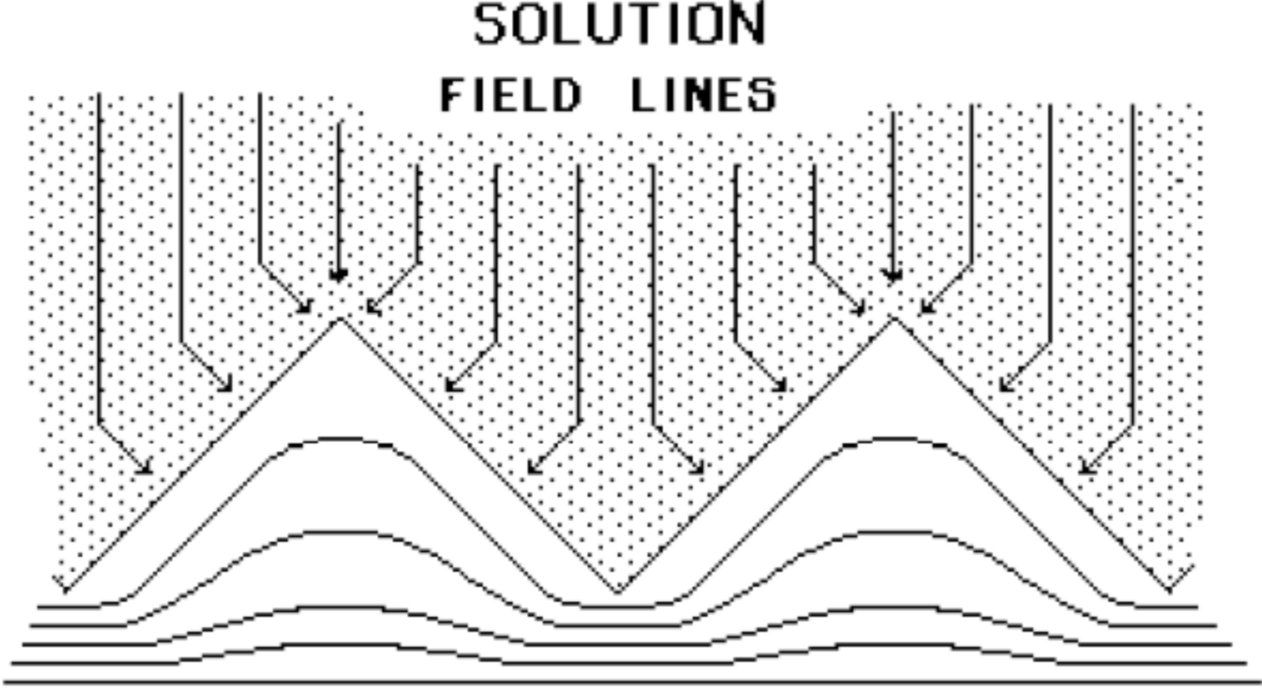
- External electrical source is employed to drive the chemical reaction by supplying holes (H+) to the silicon surface. Etchants are HF/H_2O



Electrochemical Etching

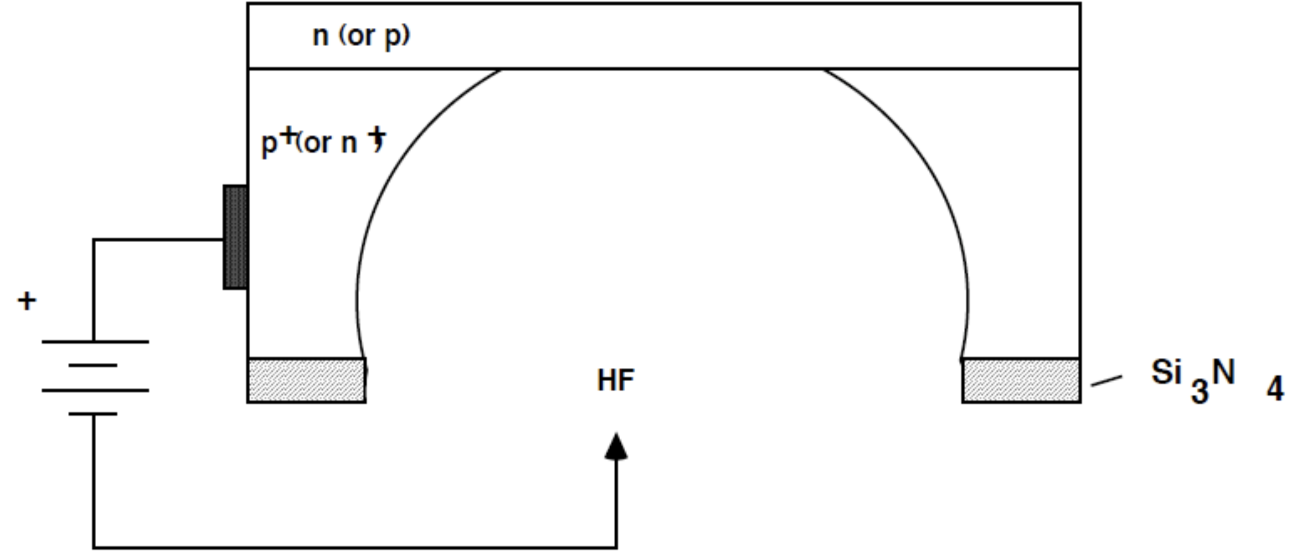
- Primarily used to polish surfaces. Etch rate increases with current density, preferentially etches high spots



Typical current densities ~ 100 mA/cm^2

Electrochemical Etch Stops

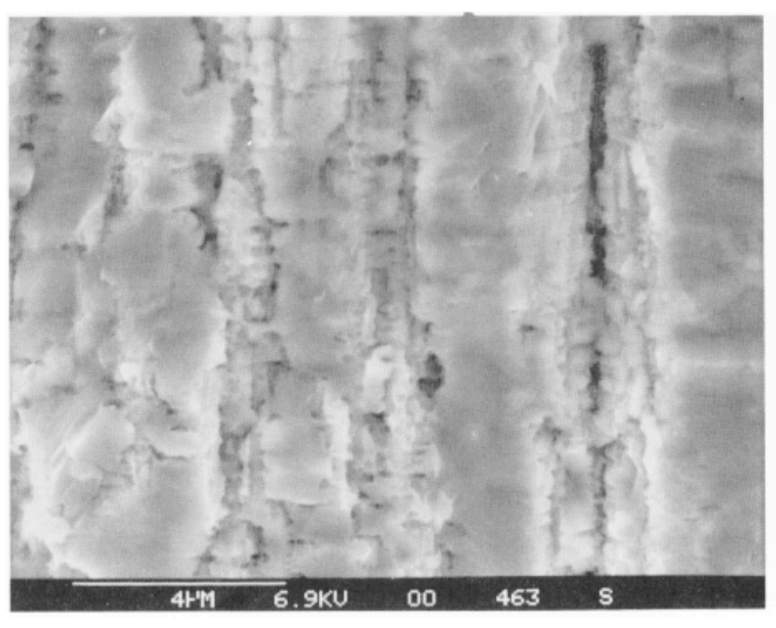
- Heavily doped (low resistivity) substrates can be selectively removed leaving behind thin, lightly doped layers. (HF or NH_4F)

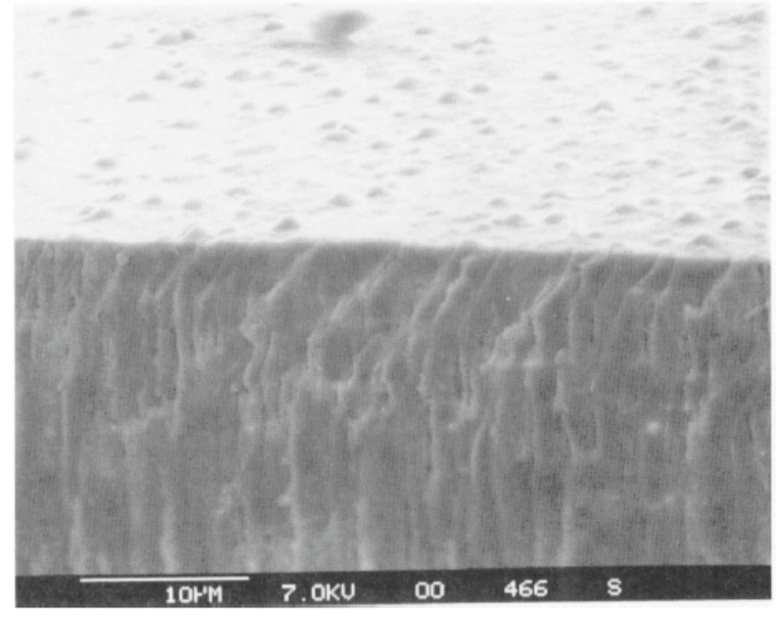


Porous Silicon

- Electrochemical etching at high HF concentrations + low etch current leads to high aspect ratio pores
  - Diameters in range 2 nm to several microns
  - Oriented in <100> direction
  - Aspect ratio maintained over distance of mm
  - High surface area to volume ratio – oxidizes rapidly
  - Porosity varies with current density
  - Pore formation in n-type Si requires illumination
    - Operation in the dark provides preferential etching of p-type regions
  - Used to produce permeable membranes, thermal isolation, thick films of SiO_2, Si_3N_4

Micrographs of Porous Silicon



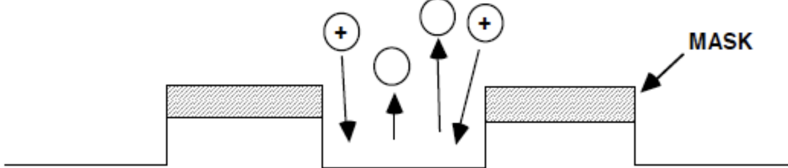


Anisotropic etching

- Wet
  - Crystallographic effects
  - Commonly used etchants
  - Etchant characteristics
  - Model of Silicon Etching
  - Etch Stops
- Dry
  - SCREAM
  - Deep Reactive Ion Etching

Bulk Anisotropic Etching

- All physical etching techniques are to some extent anisotropic-impinging ions arrive perpendicular to the etching surface



- Certain chemical etchants are anisotropic according to crystallographic orientation (KOH most common)
- The mechanism for preferential etching of silicon is not well understood, but is clearly attributable to the different bond configurations and densities exposed on crystallographic planes
- Basic principal exploited in metallography for many years

Anisotrpoic wet etching

- Depends on having a singe-crystal substrate
- The effect depends on the different etch rates of different exposed crystal planes
- Silicon etchants for which <111> planes etch slowly
  - Strong bases (KOH, NaOH, NH_4OH)
  - TMAH
  - Ethylene diamine pyrochatechol
  - Hydrazine

Wet Anisotropic Etching

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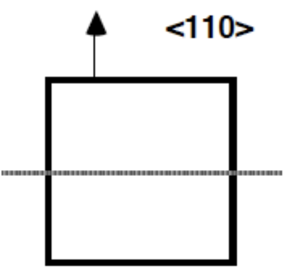

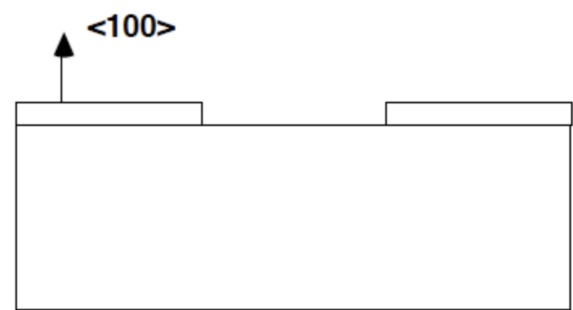

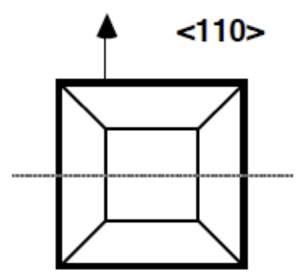

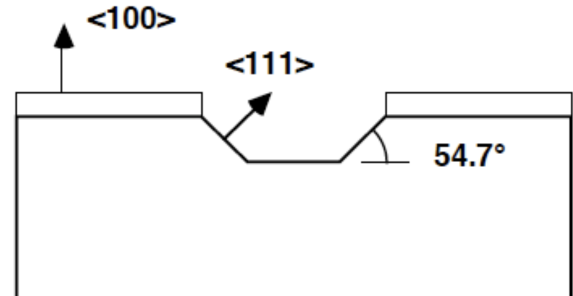

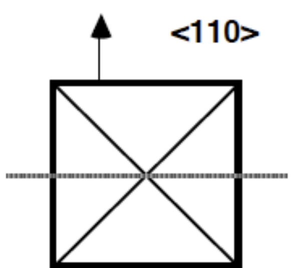

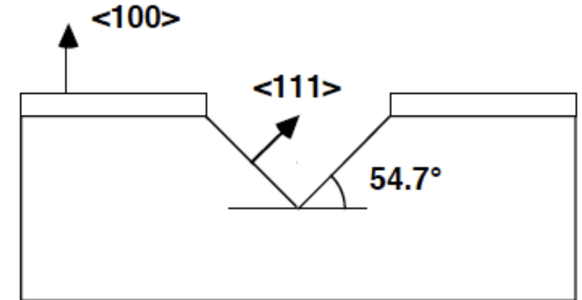

Wet Anisotropic Etching

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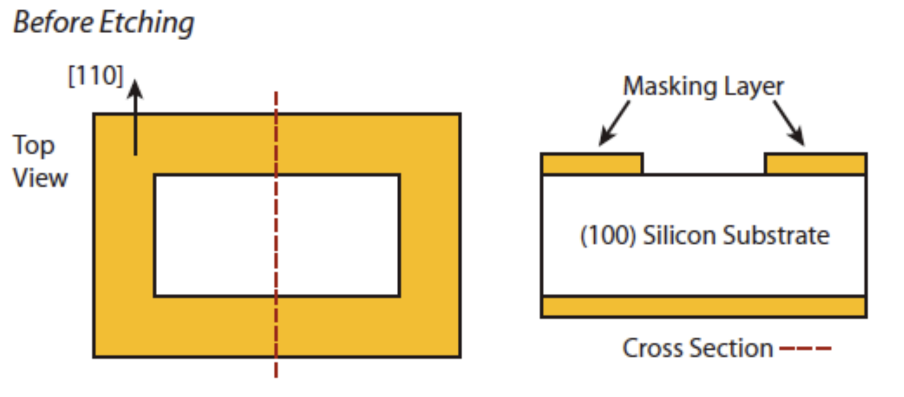
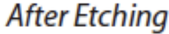
- {111} planes are close-packed – highest density of atoms, bonds in plane, lowest density perpendicular to plane
- Possible that the perpendicular bonds become shielded by surface bonded (OH) thereby slowing etch rate?
- Results in highly anisotropic etching along the planes at angles defined by the surface plane intersection with the (111) surface

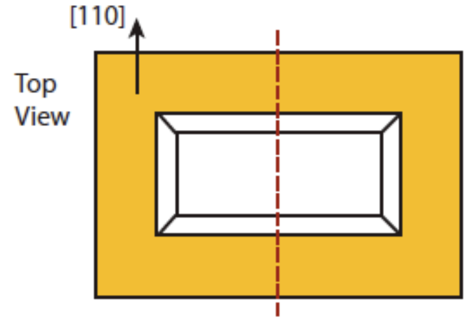
Selectivity and etch masks for KOH etches

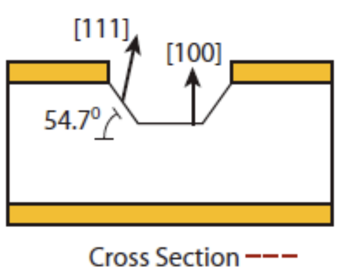
- Deep etches are long – selectivity matters
- Mask must last long enough to bring the etch to completion
- Sidewall erosion must be at an acceptably slow rate
- Etch rate of {111} planes is finite but small
  - Condition-dependent, of order 400:1 for {100} rate/{111} rate
- Etch rate of mask
  - Si:SiO_2 selectivity about 100:1
  - Si:LPCVD SiN selectivity at least 1000:1
  - PECVD SiN not effective (low quality)
  - Do NOT use photoresist!

Making a Trench with KOH





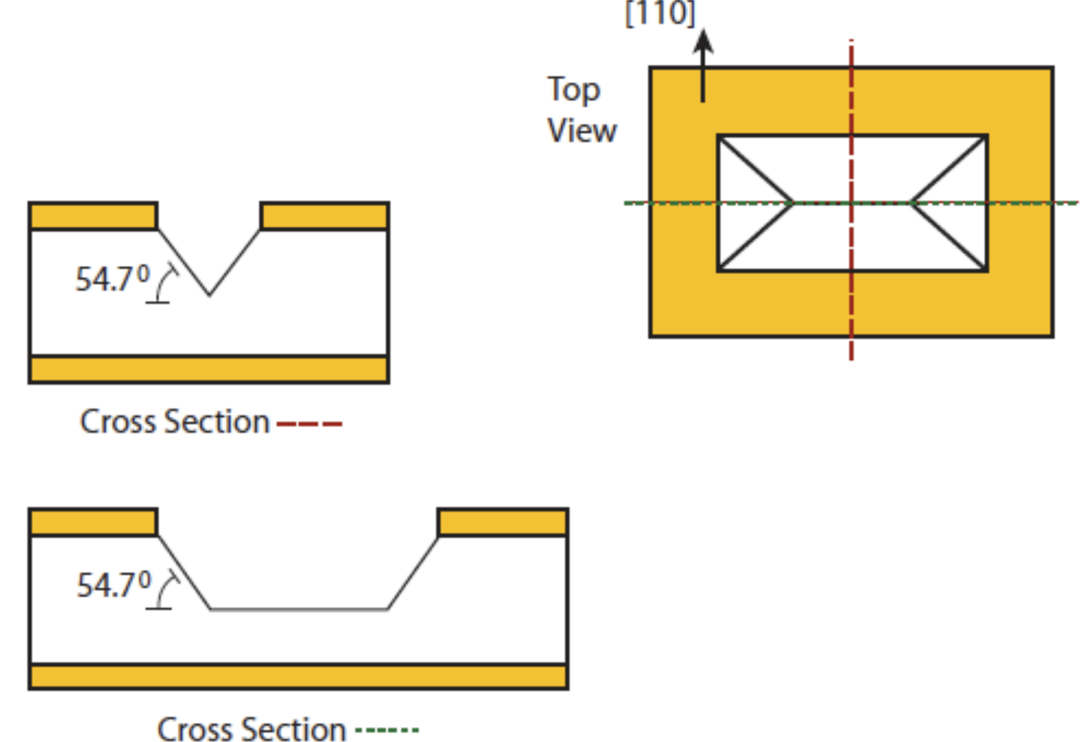




- A rectangular patter is aligned to a [110] direction on a <100> silicon wafer

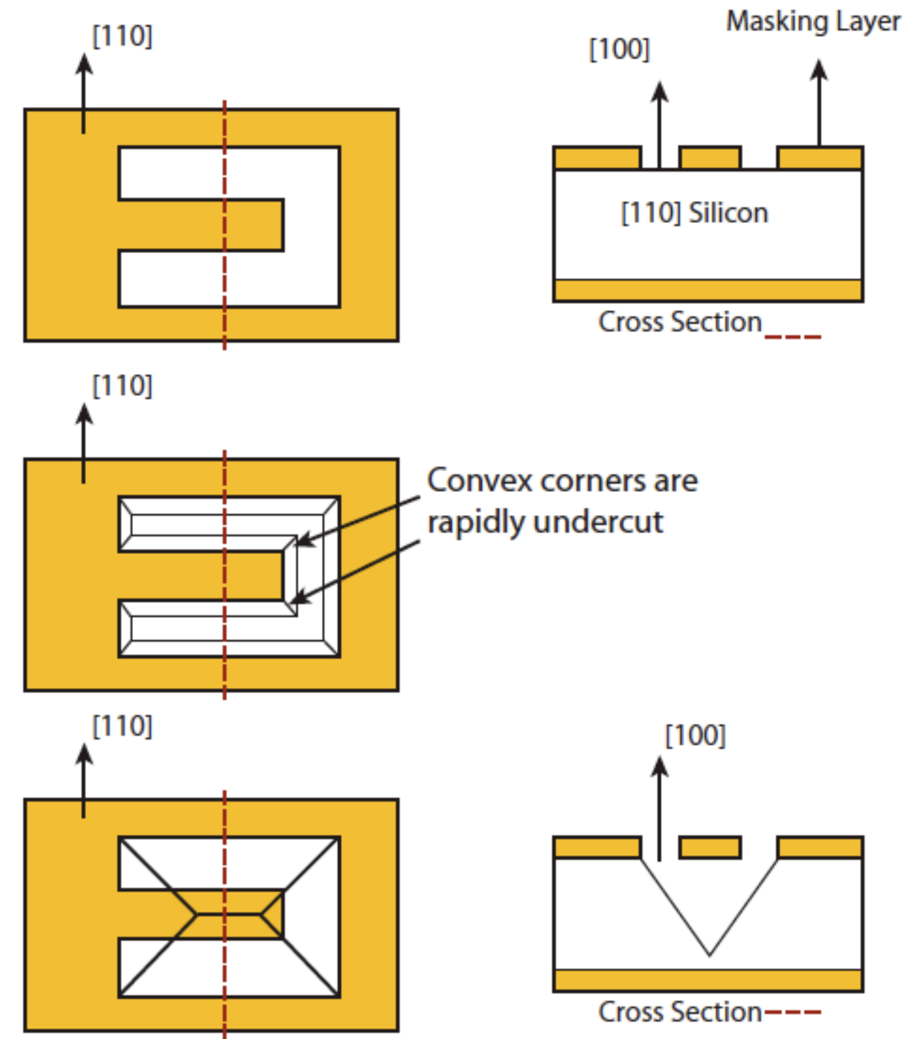
Making a V-groove

- The previous etch is allowed to go to “termination”, i.e. the slowing of etch rate with only {111} planes are exposed (can also make square, pyramidal)

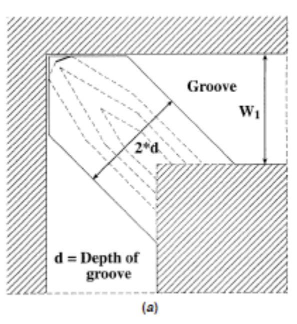


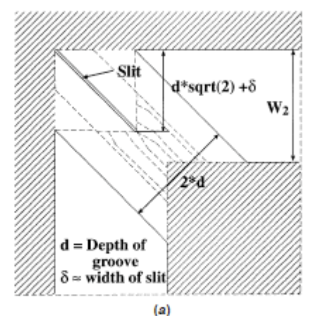
Convex Corners

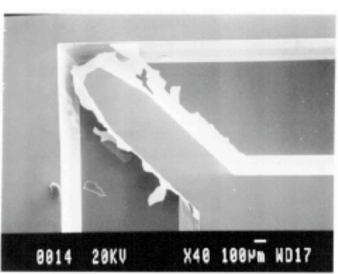
- Convex corners become undercut, as there is no single slow-etching (111) plane to stop on

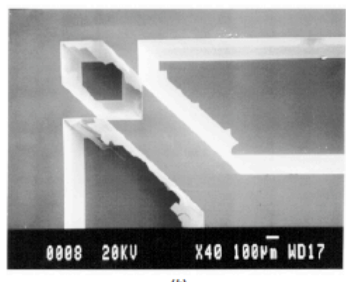


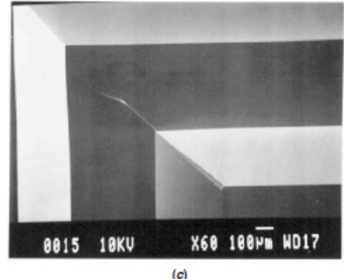
Corner Compensation

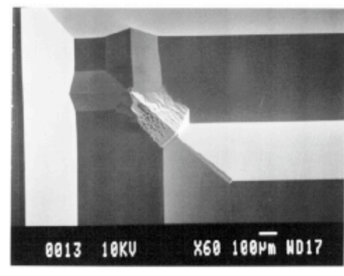








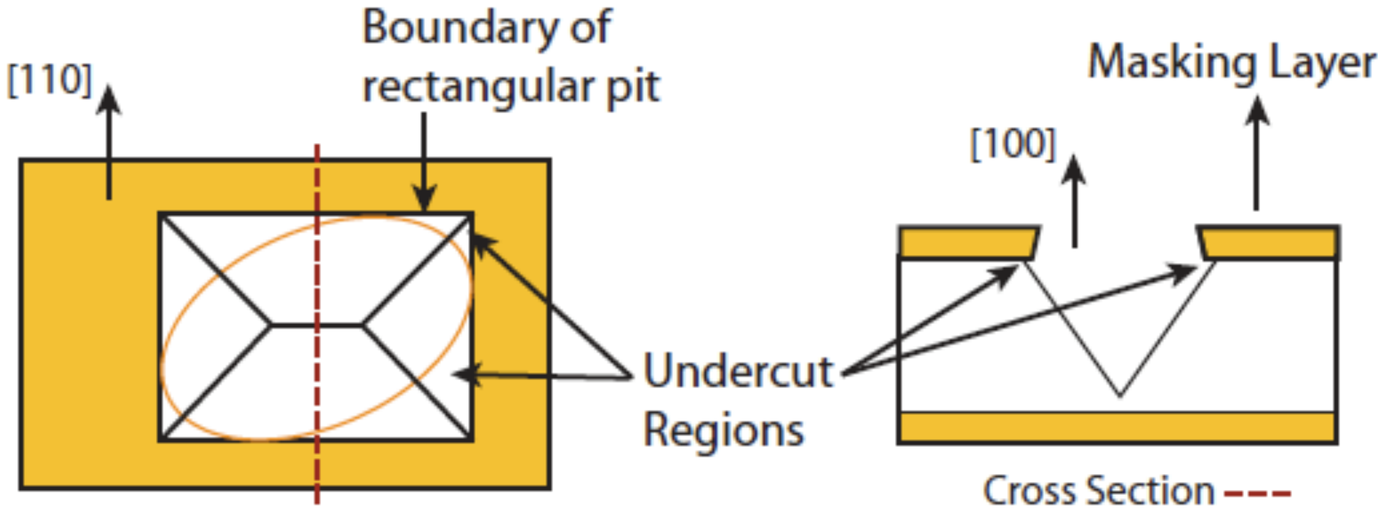




- To etch a convex corner with KOH, add extra material at corner
- Amount of material is chosen so that it will etch away just when the overall etch reaches the desired depth
- Extra material protect convex corner from attack

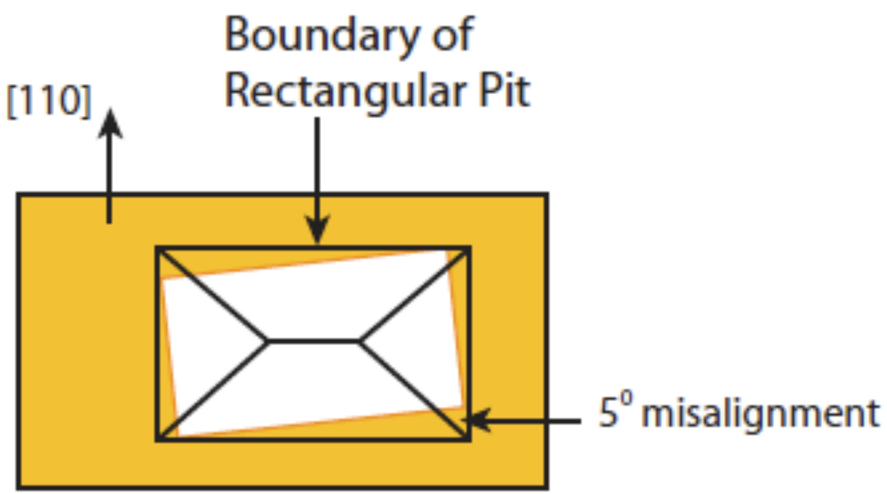
Arbitrary Shapes

- Any mask feature, if etched long enough, will result in a V-groove tangent to the mask along <110> directions



Misalignment

- Misalignment of the mask relative to the [110] direction always results in a larger etched region

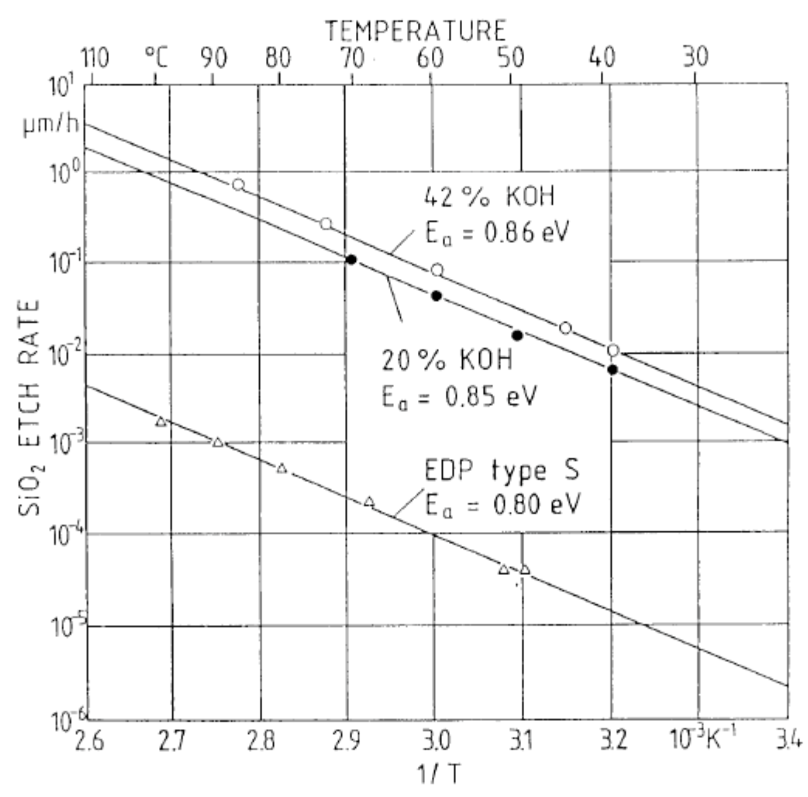


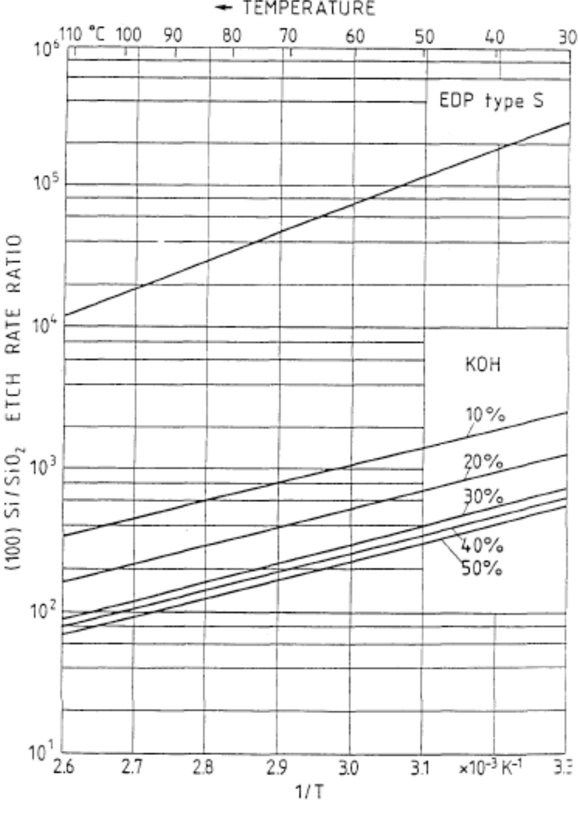
Common anisotropic etchants

- There are three etchant systems which are commonly used for anisotropic etching of silicon
- Alkaline-hydroxide and water – KOH, NaOH
  - (+) High etch rate ratio (100)/(111)
  - (-) Relatively high SiO_2 etch rate, alkali contamination
- Ethylene-diamine/pyrocatechol in water (EDP)
  - (+) High selectivity, allows variety of etch mask material
  - (-) Optically dense, carcinogenic
- Hydrazine-water (N_2H_4:H_2O)
  - (+) Low SiO_2 etch rate
  - (-) Low etch rate ration (100)/(111), gas is explosive!
- Others: CsOH, NH_4OH, $(CH_3)_4NOH$

Etch Masks

- Oxide or nitride layer masks usually used:
  - Si_3N_4 virtually unetched by all anisotropic wet etches
  - SiO_2 etch rate is dependent on etch conditions



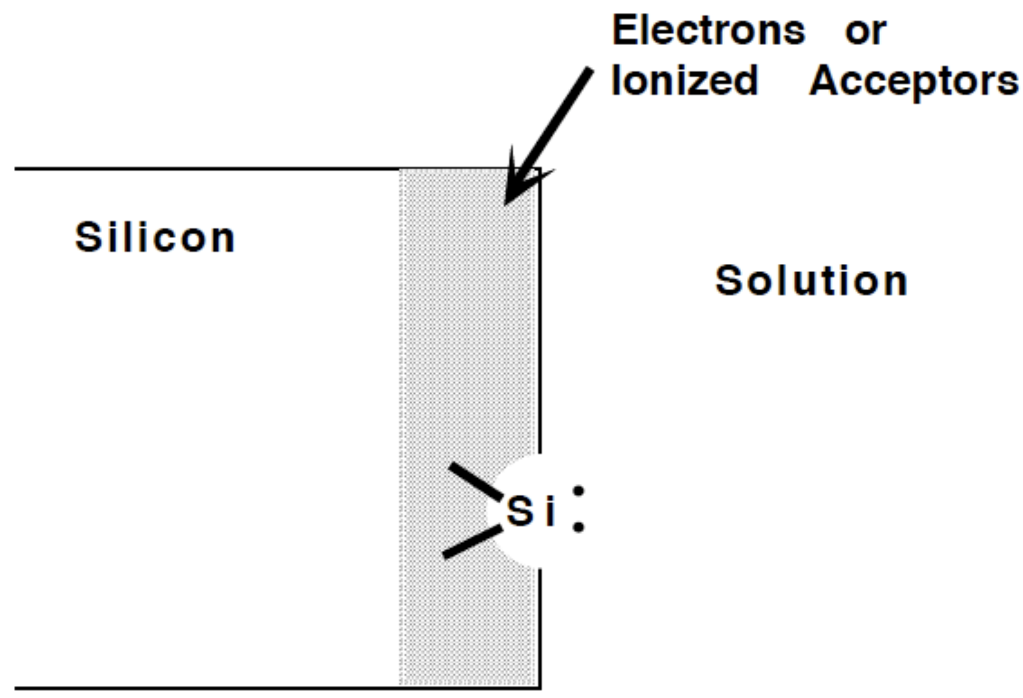


Chemistry of wet silicon etching

- Oxidation by Si electron:
  - $Si + 2h^+ \rightarrow Si^{2+}$
- Attachment of hydroxyl groups (OH)-
  - $Si^{2+} + 2(OH)^- \rightarrow Si(OH)_2$
- Reaction of $Si(OH)_2$ with a complexing agent in solution, e.g. HF
  - $Si(OH)_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O + H_2$
  - Forms species which are soluble into etchant solution

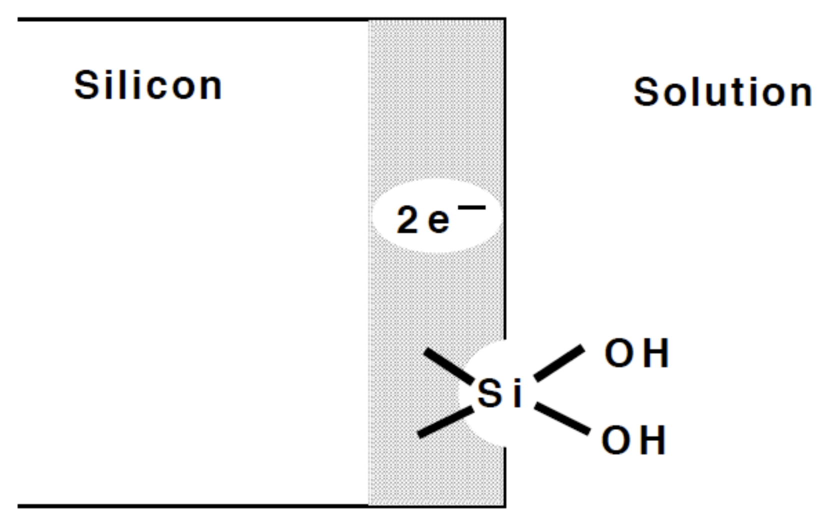
Qualitative model for silicon etching

- Negative charge collects at the surface of silicon when it is brought into contact with the ionized etchant solution



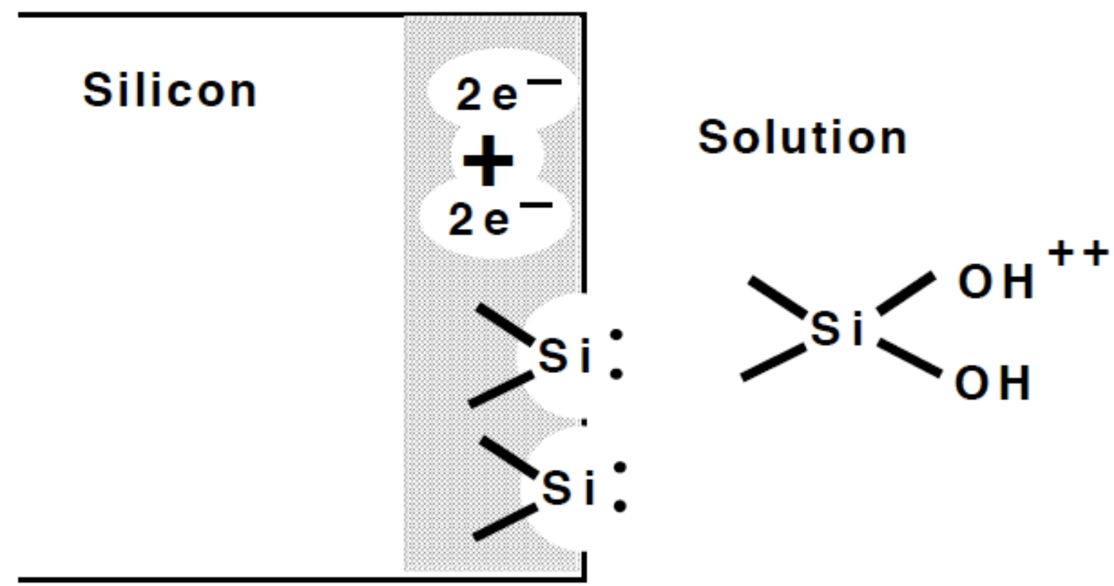
Reaction

- OH- groups attach to the dangling bonds at the surface
- For (100) and (110) surfaces there will be two dangling bonds, for (111) there will only be one
- Releases one electron per bond into silicon – remains localized near the silicon surface (for lower doping)



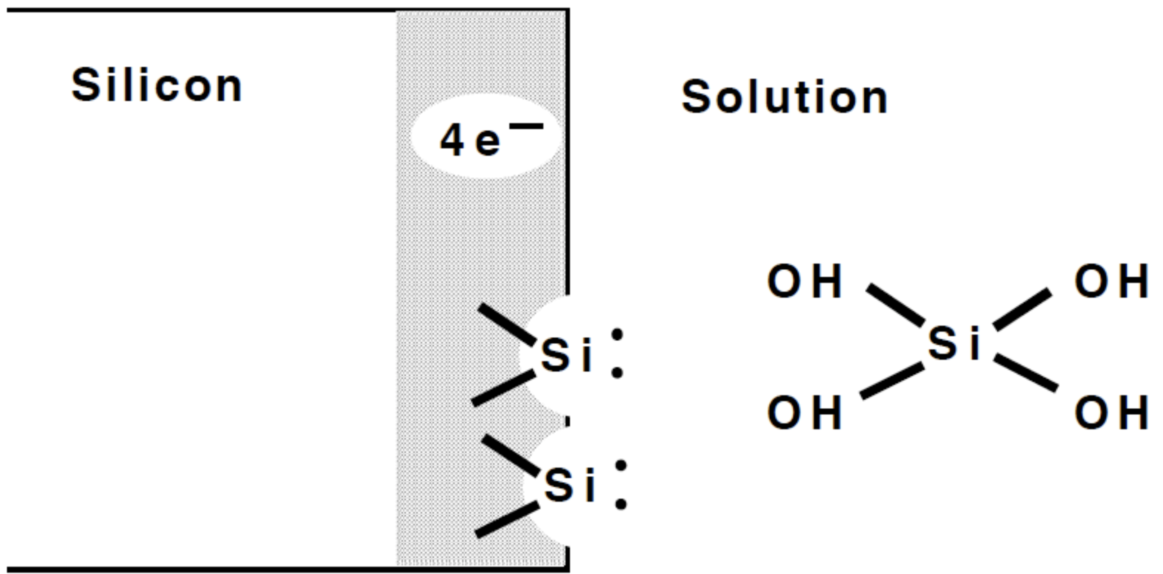
Dissolution

- If sufficient energy available (thermal) Si-Si bonds break (i.e. lift electrons from valence to conduction band)
- This will be the rate limiting step
- The (111) surface requires 3 bonds to be broken – lower etch rate



Complexing

- Silicon hydroxide complex will react with two more OH- ions to form orthosilic acid



Diffusion and Ionization

- Removal of $Si(OH)_4$ occurs by diffusion. In solution of pH>12, bulk reaction:

$$Si(OH)_4 \rightarrow 2SiO_2(OH)_2^{-} + 2H^{+}$$

- The excess electrons near the surface will react with water molecules near the surface to produce hydroxide ions (OH)- and hydrogen gas (H_2)
- These hydroxide ions will attach to dangling bonds
- If the production of $Si(OH)_4$ is too fast the $Si(OH)_4$ will not diffuse away. Instead a polymerization by the separation of water will occur, which leads to the formation of an SiO_2- like complex
- This appears as a white residue on the wafer surface

Diffusion and Ionization

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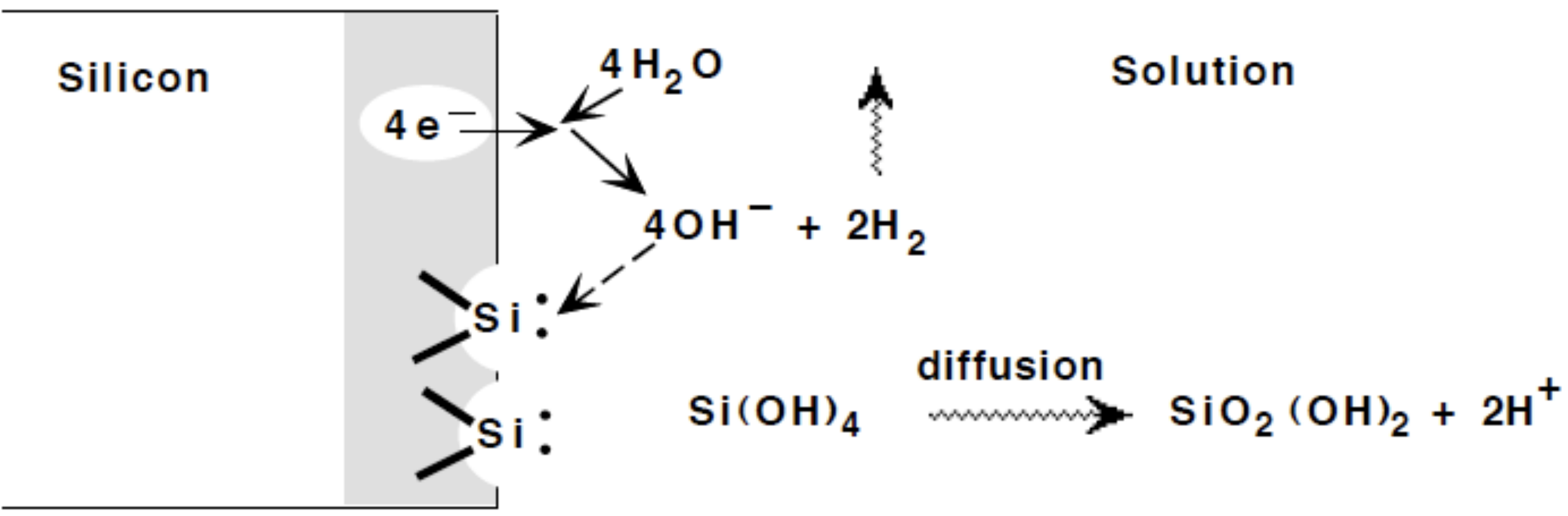


Key Points of Model

- The hydroxide ions required for oxidation of silicon are generated through a reduction of water at the silicon surface
  - Hydroxide ions in the bulk electrolye do not contribute to the etching – repelled by negative charge on surface
  - Etch rate depends on molar concentrations of *water*
  - Cation will have little effect on the etch rate (K, Na, NH_4)
- The dissolution of silicon dioxide is assumed to be purely a chemical reaction
  - SiO_2 etch rate will depend on pH of bulk electrolyte solution
- For B concentrations > 3x 10^{19}, the silicon becomes degenerate and the electrons are no longer confined to the surface. This prevents the formation of hydroxide ions at the surface, and thus causes the etching to stop

Key points of the model

- Anodic biases will prevent the confinement of electrons near the surface and lead to etch stop as in the case of p + material
- Model still needs to be confirmed by careful experiment, but following trends are captures
- Effect of water concentration and pH

	- H_2O +	- pH +
SiO_2 etch rate	no effect	- → +
Si etch rate	- → +	little effect
Solubility	no effect	- → +
Si/SiO_2 ratio	- → +	+ → -
Diffusion effects	- → +	+ → -
Residue formation	- → +	+ → -
p^+ etch stop	- → +	+ → -
pn etch stop	- → +	+ → -

Etch Stops

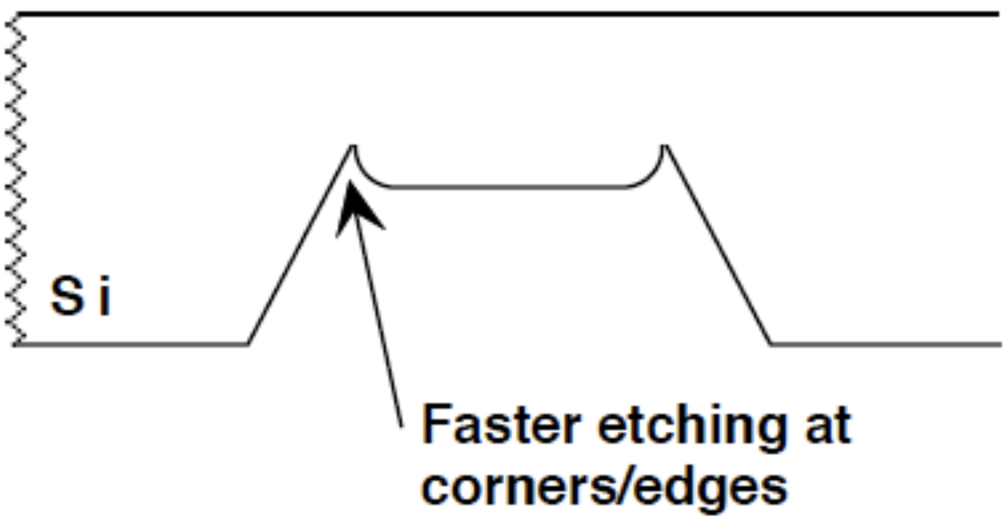
- When etching into a wafer to leave a specific thickness of material, it is necessary to have some kind of etch stop
- Example – diaphragm creation for pressure sensors
- Generally the methods fall into three categories
  - Timed
  - Chemical
  - Electrochemical

Timed Etching

- Successful timed etching requires precise control of
  - Sample thickness
  - Etch rate
- Etch rate control requires monitoring and stabilization of:
  - Etchant composition
  - Etchant aging
    - Stabilization of N_2
    - Total amount of material etched (loading)
  - Etchant temperature
  - Diffusion effects (stirring)
  - Light
  - Surface preparation of sample (roughness, native oxide)

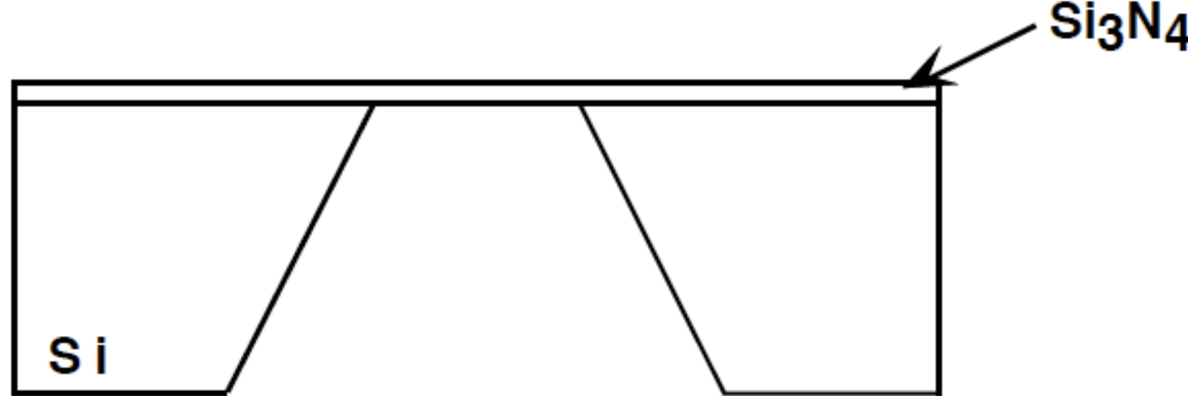
Timed Etching

- Some additional practical matters include
  - Sample removal – prefer not to open reaction
  - Surface smoothness – highly dependant on chemistry
  - Pillowing (similar to a corrosion phenomena)



Chemical Etch Stop

- By changing the composition of the material, it is possible to modify etch rates
- In extreme example use an entirely different material (although beware of undercutting/footing effects)



- Use of dopants in Si used to achieve required selectivity

Chemical Etch Stop

- n (or p) on n+ or (p+) isotropic
  - The HF:HNO_3:CH_3COOH system will etch heavily doped (10^{17} cm^{-3}) silicon ~150 x faster than lightly doped silicon
- p++ on p (or n) anisotropic
  - Any of the anisotropic etchants will exhibit etch-stop on silicon with boron concentrations > 5 x 10^{19} cm^{-3}
  - But such high B levels compromise the quality of the crystal
    - Slip planes
    - Tensile stress
    - Too heavily doped to fabricate IC devices
- Can solve some of these problems using epitaxial silicon as the electrical device layer

Wet Etching Summary

- Wet Etching has been the key to bulk micromachined MEMS
- Key elements:
  - Anisotropy
  - Economic Rates (1-10um/hr) while maintaining control
  - Etch Selectivity
    - Masking
    - Etch Stops
  - Ability to integrate with electrical devices
- Key mechanisms required for process control are well understood
  - Some models, much empiricism

Dry Etching Motivation

- General Trend in IC processing to move away from “wet chemistry” for on chip processes
- For MEMS ability to bulk micromachine with gas or plasma phase etchants, at comparable rates while achieving high anisotropy, is increasing in importance
- Deep Reactive Ion Etching (DRIE) has become the standard bulk micromachining process
- Opportunity to examine approaches to process development control

Dry Etching Outline

- Overview of dry etching techniques
  - Gaseous etching, plasma etching, ion etching, reactive ion etching laser assisted etching, deep reactive ion etching
- Empirical characterization of deep reactive ion etching
  - Application of design of experiments to create response surfaces for process
- Comparison of wet and dry etching capabilities

Dry (Plasma) Etching

- At reduced pressure, a glow discharge is set up in a reactive gas environment
- This produces
  - Ions that can be accelerated by the electric fields at the bounding edges of the plasma so that they strike the surface
    - These can be quite directional in their impact
  - Free radicals (uncharged) that can diffuse to the surface and undergo reaction
- Etching depends on reaction followed by creation of a gaseous byproduct which is pumped away

Applicability

- Most materials can be plasma etched
  - Oxide
  - Nitride
  - Silicon
  - Most Metals (not the noble metals)
  - Polymers
- The art is in achieving suitable selectivity both for masking layers and to layers that ie beneath the layer being etched
  - Known recipes (gas mixtures, plasma conditions) with desired selectivity
  - End-point detection is an important part of “best practice” when using plasma etching

Dry Etching Categories

Dry Etching

Glow discharge methods-Diode Set-up

Ion beam methods -Triode Set-ups

Physical etching only

Plasma etching	Reactive ion etching sputtering	Sputter etching	Ion milling	Ion beam assisted chem.etch	Reactive ion beam etching
Reactive gas plasma	Reactive gas plasma	Inert gas plasma	Inert gas ion beam	Inert gas ion beam	Reactive gas ion beam
Low energy bombard.	High energy bombard.	High energy bombard.	No reactive neutrals	Reactive neutrals added	Some reactive neutrals

0.2 - 2 Torr → 0.01 - 0.2 Torr → 10^{-3} to 10^{-4} Torr

FIGURE 2.1 Relationship between the various dry etching techniques. (Adapted from Lehmann, H. W., in *Thin Film Processes II*, Vossen, J. L. and Kern, W., Eds. Academic Press, Boston, 1991.)

Dry Etching Process

- Plasma-assisted etching: Various technologies
- Physical bombardment (sputtering)
  - Ion million
  - Sputter etching
- Chemical reaction
  - Plasma etching: little or no ion bombardment
  - Dry equivalent of wet chemistry (e.g. SF_6 etching of Si)
- Combination of physical and chemical mechanisms
  - Plasma etching: with bombardment
  - Reactive ion etching
  - Reactive ion beam etching

Non-Plasma Gaseous Etching

- Some fluorine-based gases are sufficiently reactive to etch silicon without plasma (dissociates at Si surface)
- E.g. XeF_2 etching of silicon (oxide or resist mask)

$$2XeF_2 + Si \rightarrow 2Xe + SiF_4$$

  - Room temperature etch
  - Isotropic
  - Highly exothermic
  - High etch rates (10um/min)
  - Excellent selectivity: oxides and resists
  - Rough surfaces after etching (add BrF_3 to smooth)

Plasma Etching

- Glow discharge used to create a chemically-reactive species from a non-reactive gas
- E.G. SF_6 plasma etching of silicon (oxide or resist ask)

$$2SF_6 + E\ \text{field} \rightarrow 2SF_5^{+} + 2F^{-}\ (+\ \text{other ionic species})$$

$$Si + 4F^{-} \rightarrow SiF_4\ (\text{gas}) + 4e^{-}$$

- Etch rates as high as 8um/min observed for SF_6:Si

Plasma Etching Schematic

Dry Etching

Glow discharge methods-Diode Set-up

Ion beam methods -Triode Set-ups

Physical etching only

Plasma etching

Reactive ion etching sputtering

Sputter etching

Ion milling

Ion beam assisted chem.etch

Reactive ion beam etching

Reactive gas plasma

Reactive gas plasma

Inert gas plasma

Inert gas ion beam

Inert gas ion beam

Reactive gas ion beam

0.2 - 2 Torr

0.01 - 0.2 Torr

10^{-3} to 10^{-4} Torr

Low energy bombard.

High energy bombard.

High energy bombard.

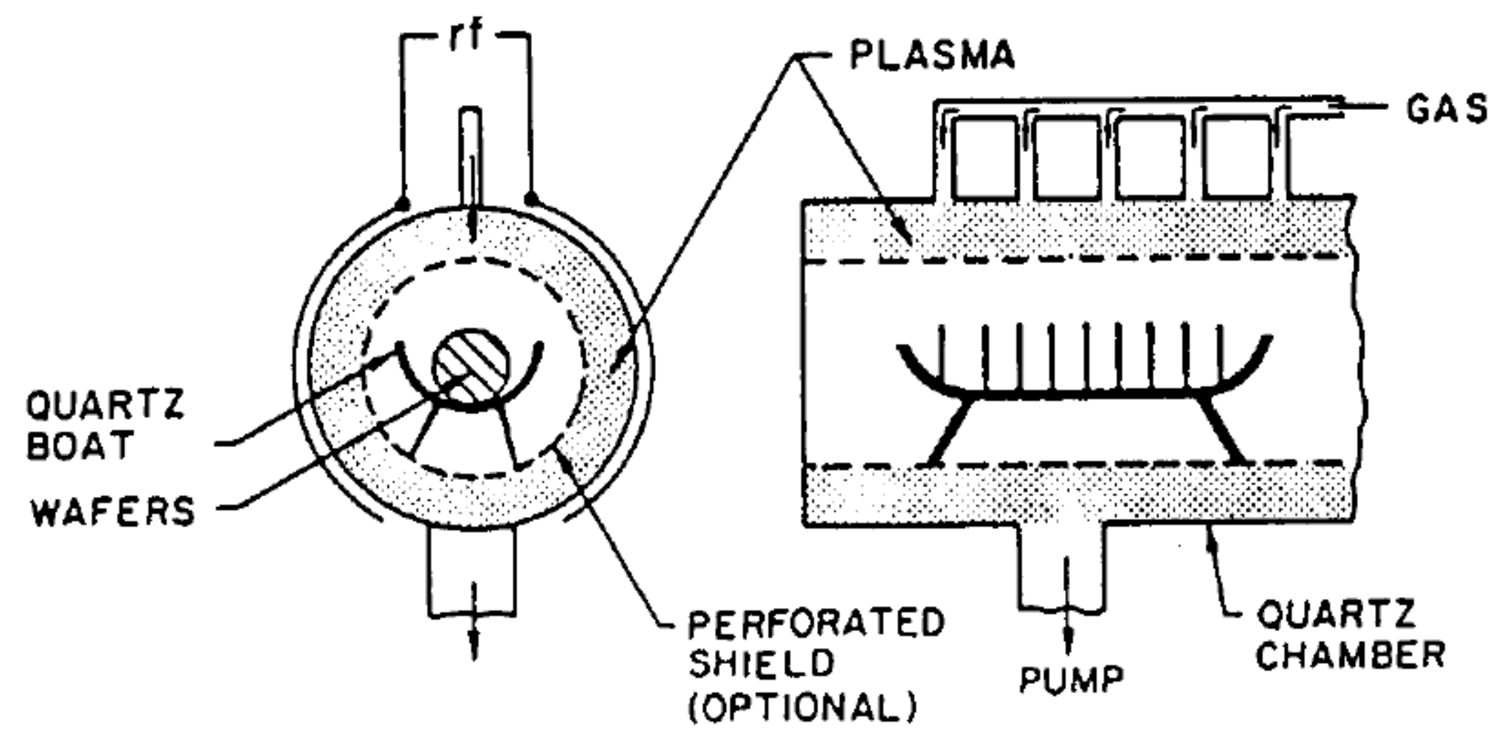
No reactive neutrals

Reactive neutrals added

Some reactive neutrals

FIGURE 2.1 Relationship between the various dry etching techniques. (Adapted from Lehmann, H. W., in *Thin Film Processes II*, Vossen, J. L. and Kern, W., Eds. Academic Press, Boston, 1991.)

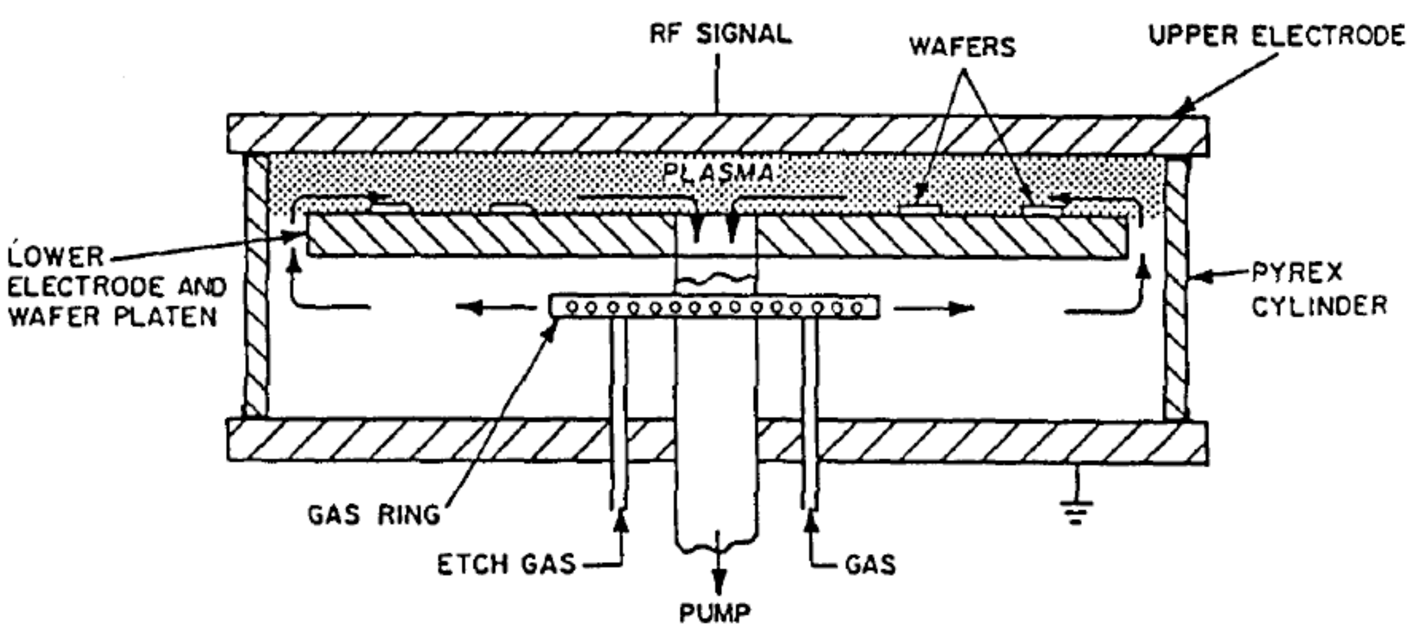
Plasma Etching (Barrel Reactor)



- Selective, isotropic, poor uniformity
- Application: O_2 plasma for photoresist stripping (ashing)

Schmidt (Flamm et al)

Parallel Plate Plasma Etching



- More anisotropic, less selective
- Typical RIE configuration
- Multiple wafer capability

Schmidt (Flamm et al)

Plasma Etchant

TABLE 2.7 Plasma Etchants for Microelectronic Materials

Material	Common Etch Gases[a]	Dominant Reactive Species	Product	Comment	Vapor Pressure (Torr at 25°C)
Aluminum	Chlorine-based	Cl, Cl_2	$AlCl_3$	Toxic gas and corrosive gases	7×10^{-5}
Copper	Forms low pressure compounds	Cl, Cl_2	$CuCl_2$	Toxic gas and corrosive gases	5×10^{-2}
Molybdenum	Fluorine-based	F	MoF_6	—	530
Polymers of carbon and photoresists (PMMA and polystyrene)	Oxygen	O	H_2O, CO, CO_2	Explosive hazard	H_2O = 26, CO, CO_2 > 1 atm
III-V and II-VI compounds	Alkanes	—	—	Flammable gas	—
Silicon	Fluorine- or chlorine-based	F, Cl, Cl_2	SiF_4, $SiCl_4$	Toxic gas	SiF_4 > 1 atm, $SiCl_4$ = 240
SiO_2	CF_4, CHF_3, C_2F_6, and C_3F_6	CF_X	SiF_4, CO, CO_2	—	SiF_4 > 1 atm, CO, CO_2 > 1 atm
Tantalum	Fluorine-based	F	TaF_3	—	3
Titanium	Fluorine- or chlorine-based	F, Cl, Cl_2	TiF_4, TiF_3, $TiCl_4$	—	TiF_4 = 2.10^-4, $TiCl_4$ = 16
Tungsten	Fluorine-containing	F	WF_6	—	1000

[a] Common chlorine containing gases: BCl_3, CCl_4, Cl_2, and $SiCl_4$. Common fluorine containing gases: CF_4, SF_4, and SF_6. (After References 6, 26, 38, and 39.)

Reactive Plasma Gas Etchants

TABLE 2.5 Frequently Used Reactive Plasma Gases

Etchant: Purpose	Composition (Additive-Etchant): Application
Oxide etchant: Etches through oxide to initiate etching	C_2F_6-Cl_2: SiO_2 BCl_3-Cl_2: Al_2O_3 CCl_4-Cl_2: Al_2O_3
Oxidant: Increases etchant concentration and suppresses polymerization	O_2-CF_4: Si N_2O-CHF_3: SiO_2 O_2-CCl_4: GaAs, InP
Inert gas: Stabilizes plasma, dilutes etchant, improves heat transfer	Ar-O_2: organic material removal He-CF_3Br: Ti, Nb
Inhibitor former: improves selectivity, induces anisotropy	C_2F_6-Cl_2: Si BCl_3-Cl_2: GaAs, Al H_2-CF_4: SiO_2 CHF_3-SF_6: Si O_2(50%)-SF_6: Si
Water and oxygen scavenger: prevents inhibition, improves selectivity	BCl_3-Cl_2: Al H_2-CF_4: SiO_2
Radical scavenger: increases film formation and improves selectivity	H_2-CF_4: SiO_2 CHF_3-SF_6: Si CF_3Br-SF_6: Si CF_2Cl_2-SF_6: Si

(Most data from Flamm, D. L., *Solid State Tech.*, 49–54, 1993. With permission.)

Development of dry etchants

TABLE 2.6 The Evolution in Gas Mixtures for Dry Etching

Material being etched	Conventional chemistry	New chemistry	Benefits
PolySi	Cl_2 or BCl_3 / CCl_4 / CF_4 / $CHCl_3$ / CHF_3 } sidewall passivating gases	$SiCl_4/Cl_2$	No carbon contamination
		BCl_3/Cl_2	
		$HBr/Cl_2/O_2$	Increased selectivity to SiO_2 and resist
		HBr/O_2	No carbon contamination
		Br_2/SF_6	
		SF_6	Higher etch rate
		CF_4	
Al	Cl_2, BCl_3, $SiCl_4$ + sidewall passivating gases	$SiCl_4/Cl_2$	Better profile control
		BCl_3/Cl_2	No carbon contamination
		HBr/Cl_2	
Al-Si (1%)-Cu (0.5%)	Same as Al	$BCl_3/Cl_2 + N_2$	N_2 accelerates Cu etch rate
Al-Cu (2%)	$BCl_3/Cl_2/CHF_3$	$BCl_3/Cl_2 + N_2 + Al$	Additional aluminum helps etch copper
W	$SF_6/Cl_2/CCl_4$	SF_6 only	No carbon contamination
		NF_3/Cl_2	Etch stop over TiW and TiN No carbon contamination
TiW	$SF_6/Cl_2/O_2$	SF_6 only	
WSi_2, $TiSi_2$, $CoSi_2$	CCl_2F_2	CCl_2F_2/NF_3	Controlled etch profile
		CF_4/Cl_2	No carbon contamination
Single crystal Si	Cl_2 or BCl_3 + sidewall passivating gases	CF_3Br	Higher selectivity trench etch
		HBr/NF_3	
SiO_2 (BPSG)	CCl_2F_2	CCl_2F_2	CFC alternatives
	CF_4	CHF_3/CF_4	
	C_2F_6	CHF_3/O_2	
	C_3F_8	CH_3CHF_2	
Si_3N_4	CCl_2F_2	CF_4/O_2	CFC alternatives
	CHF_3	CF_4/H_2	
		CHF_3	
		CH_3CHF_2	
GaAs	CCl_2F_2	$SiCl_4/SF_6$	Florine provides etch stop on AlGaAs
		$/NF_3$	
		$/CF_4$	
InP	None	CH_4/H_2	Clean etch
		HI	Higher etch rate than with CH_4/H_2

(From Peters, L., *Semicon. Intl.*, 66–70, 1992. With permission.)

Mask Materials

TABLE 2.9 Mask Materials in Dry Etching

Mask Material	SF_6	CHF_3	CF_4	O_2	N_2
Si	–	+/–	–	+	+
SiO_2	+/–	–	+/–	+	+
Si_3N_4	+/–	–	+/–	+	+
Al/Al_2O_3	+	+	+	+	+
W	–	–	–	+	+
Au	+	+	+	+	+
Ti	–	–	–	+	+
Resist	+/–	+/–	+/–	–	+
CFs	+	+	+	+	–

Source: After Elwenspoek et al., Universiteit Twente, *Micromechanics*, (1994).

Ion Beam Etching

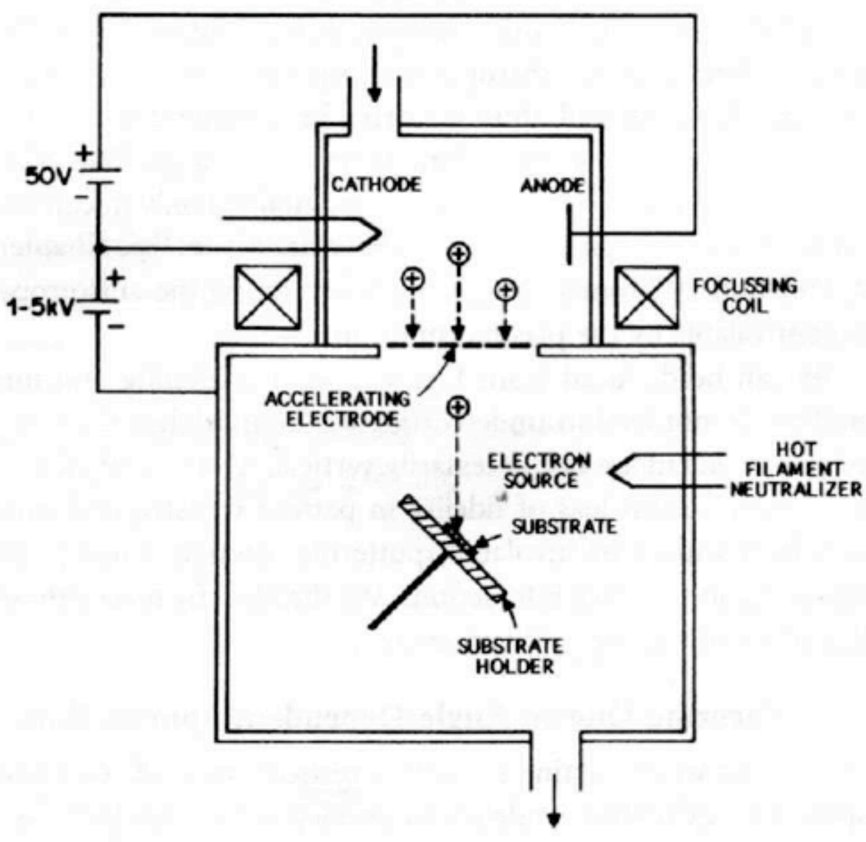
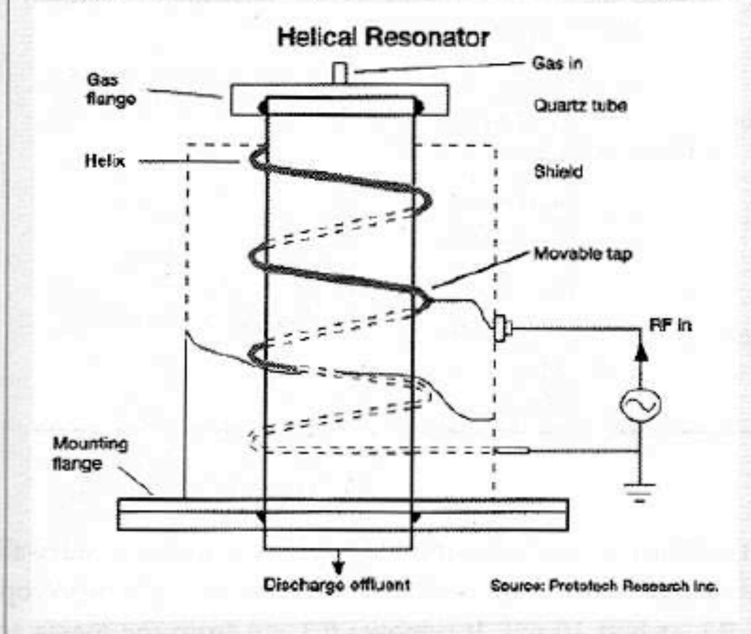


FIGURE 2.10 Ion-beam etching (IBE) apparatus (triode). In an ion beam apparatus, the beam diameter is approximately 8 cm. The substrates are mounted on a moveable holder allowing etching of large substrates. The coils focus the ion beam and densify the ion flux in magnetically enhanced confined ion etching (MIE).

Particles accelerated toward substrate

Inductively coupled plasma

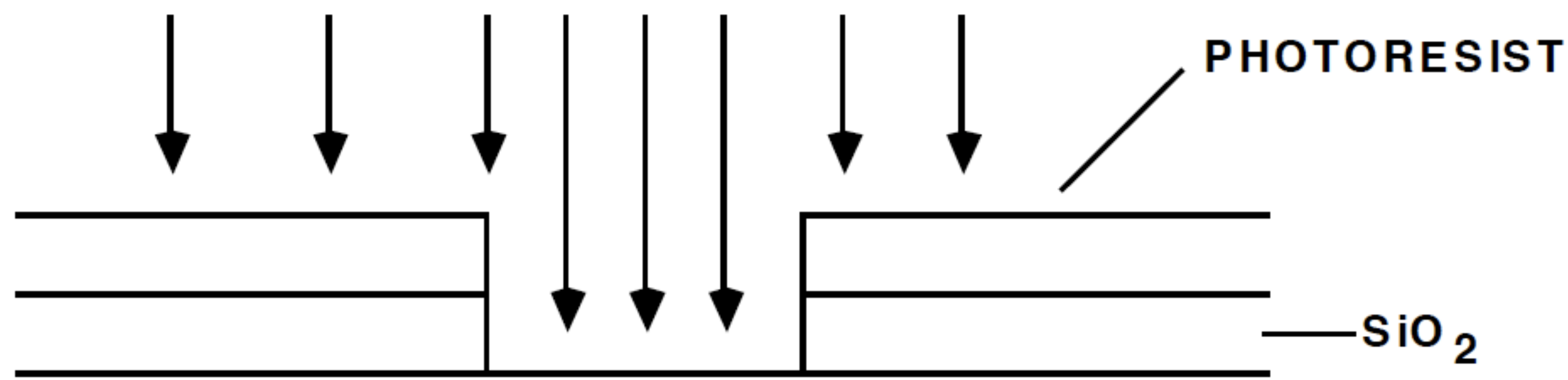
- Combines electrical and magnetic fields to form plasma and accelerate ions
- But, useful (i.e. uniform) etching area, only a fraction of chamber (c.f. purely plasma reactors)
- Currently single wafer tools



Inductively-coupled plasma

This electrostatic, shielded, inductive-coupled plasma source produces electric field lines from helical resonator combined with an electrostatic shield to produce electric field lines that are circumferential in response to the axial RF magnetic field.

Reactive ion Etching SiO_2/Si (CF_4/H_2)



- Anisotropic (directional) –ions accelerated – kinetic bombardment
- Selectivity relatively low – photoresist/SiO_2 consumed

Dry Etching Types

TABLE 2.2 Some Popular Dry Etching Systems[a]

	CAIBE	RIBE	IBE	MIE	MERIE	RIE	Barrel Etching	PE
Pressure (Torr)	$\sim 10^{-4}$	$\sim 10^{-4}$	$\sim 10^{-4}$	10^{-3}–10^{-2}	10^{-3}–10^{-2}	10^{-3}–10^{-1}	10^{-1}–10^{0}	10^{-1}–10^{1}
Etch mechanism	Chem./phys.	Chem./phys.	Phys.	Phys.	Chem./phys.	Chem./phys.	Chem.	Chem.
Selectivity	Good	Good	Poor	Poor	Good	Good	*Excellent*	*Good*
Profile	Anis. or iso.	Anis.	Anis.	Anis.	Anis.	Iso. or anis.	Iso.	Iso. or anis.

Note: CAIBE = Chemically assisted ion beam etching; MERIE = Magnetically enhanced reactive ion etching; MIE = Magnetically enhanced ion etching; PE = Plasma etching; RIBE = Reactive ion beam etching; RIE = Reactive ion etching.[15,16]

[a] Many of the more recent dry etching techniques are not listed here. For more information on inductively coupled plasmas (ICP), electron cyclotron plasmas (ECR), microwave multipolar plasmas (MMP), and introductory material on helicon plasma sources, helical resonators, rotating field magnetrons, hollow cathode reactors, etc., refer to References 16–22.

Shape

- The higher the pressure, the more isotropic the etch because reactants are scattered many times before reaching the surface (this is called “plasma etching)
- To achieve directional anisotropy, one must go to low pressure to achieve long mean-free paths for the ions (this is called “reactive-ion etching” or RIE)
- Deep reactive ion etching is another thing altogether

Etch Stops

- Less flexibility than for wet etches
- No equivalent to electrochemical etch stops
- Chemical etch stops limited to use a different materials
  - Buried oxide in silicon on insulator (SOI) wafers
  - Risk of footing effects (see later)
- Timed etches are more common
  - Very careful process control required to define membranes
- Use leak detection to monitor through thickness etches

Laser Assisted Etching

UCSB nanolab

Laser photon energy creates chlorine ions, etch Si

(Also SiC, Al_2O_3?)

Allows $1 \mu m^3$ “pixel” to be addressed - etch pixel by pixel

Not a mass production process, but potential use for trimming

Release (also Focused Ion Beam, Laser Ablation (damage))

DRIE - Background

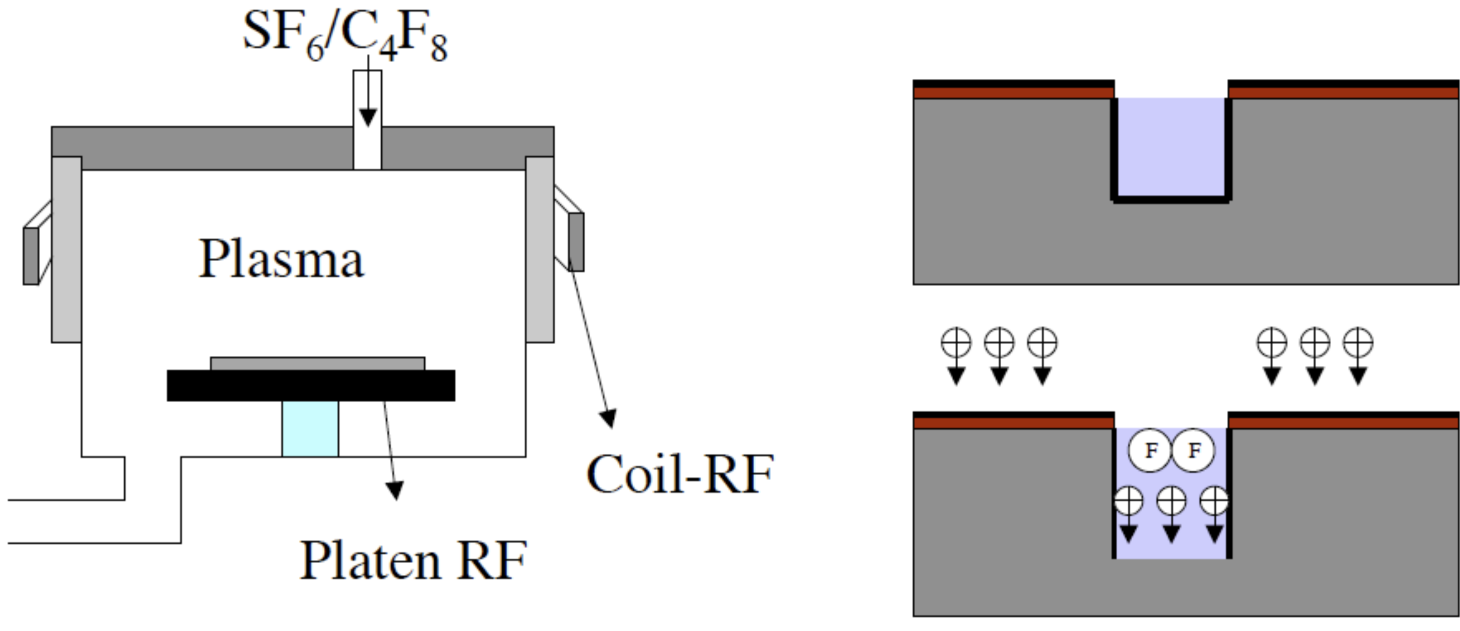
- High aspect ratio etching of silicon is emerging as a critical MEMS technology
- DRIE requires sidewall passivation during etching, two approached:
  - Co-mix passivating and etching gases
  - Time multiplexed passivating and etching processes : Bosch Process

TMDE = Time **M**ultiplexed **D**eep **E**tching

TMDE greatly expands design space for processes

Need to map parameter space in order to use process effectively

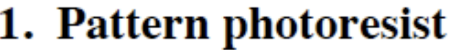
DRIE Schematic

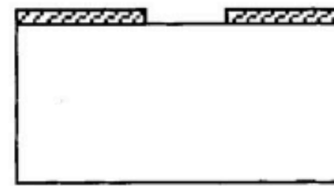


- Alternative passivation/etch cycles
- Passivation cycle: CF_n polymer from C_4F_8 deposited on all surface
- Etch cycle: polymer removed from base at higher rate due to ion directionality, then exposed Si etched by fluorine species

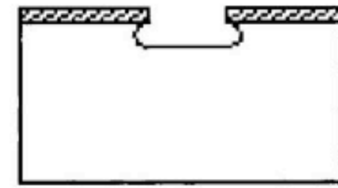
Deep reactive Ion Etching (The Bosch Process)

- Photoresist mask: selectivity about 50:1
- Oxide Mask: selectivity > 100:1
-

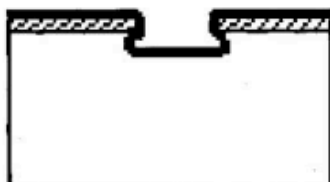




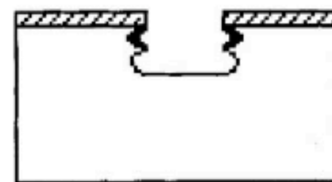
2. Reactive ion etch in SF_6



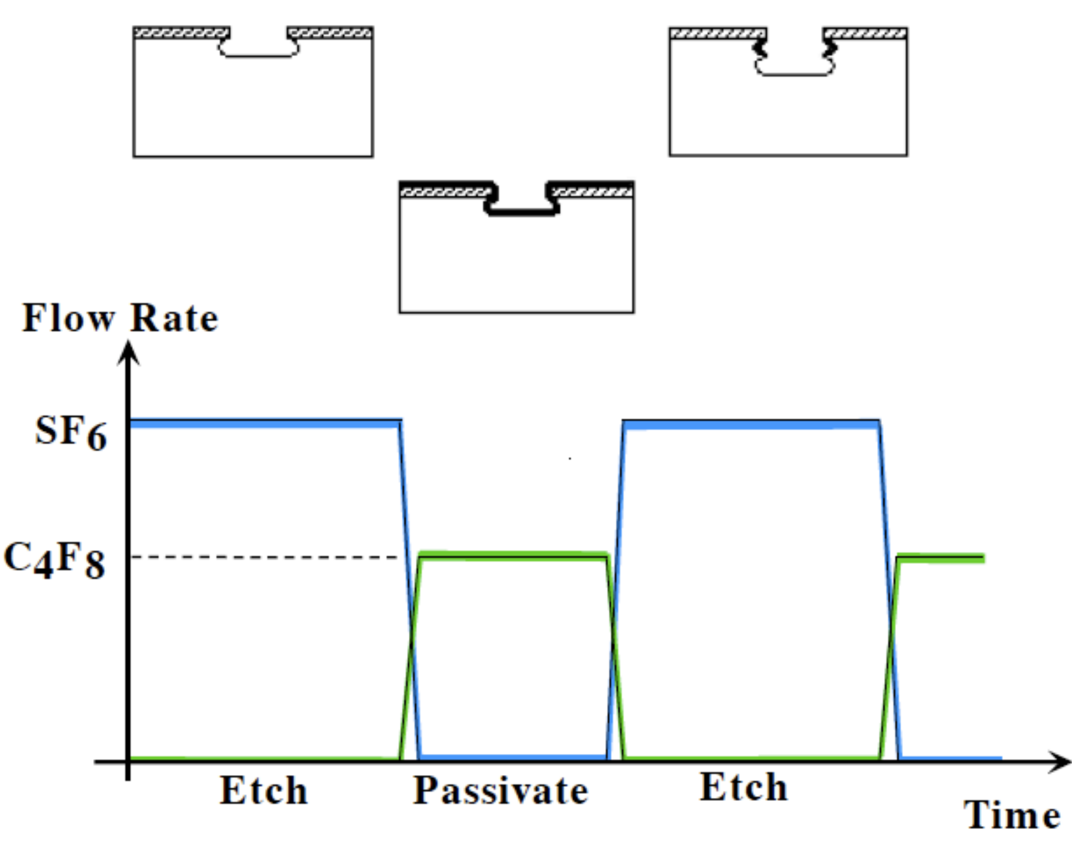
3. Deposit passivation (C_4F_8) (produces a teflon-like polymer)



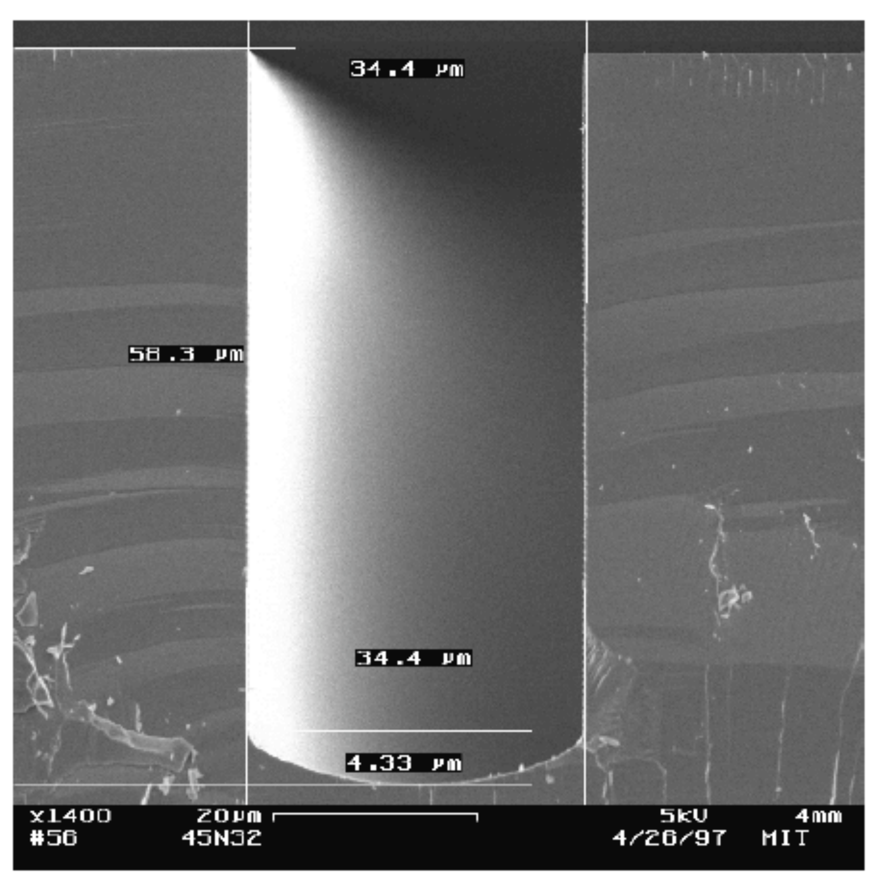
4. Etch and repeat cycle (directional ions clear passivation from bottom only)

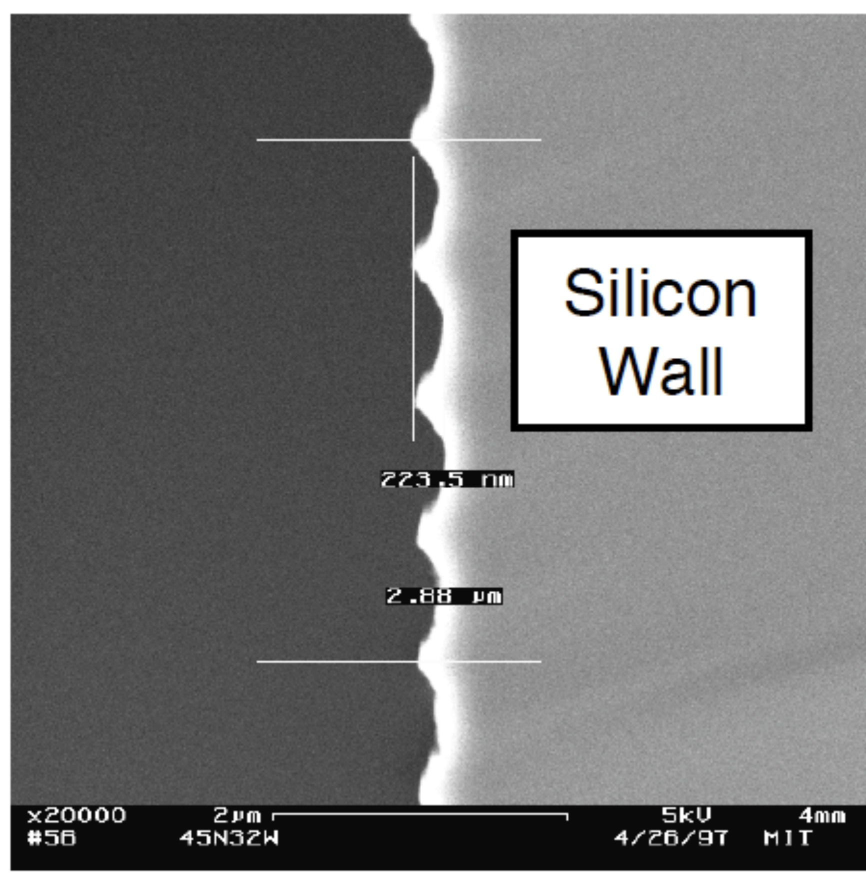


TMDE Gas Flow Scheme



TMDE





Microengine Fabrication Details

Fuel Manifold

3 mm

Flame Holders

340 μm

Fuel Manifold
Fuel Injectors
Inlet
Compressor Blades
Flame Holders
Combustion Chamber
Exhaust Nozzle
Centerline of Rotation
Turbine

400 μm
12 μm

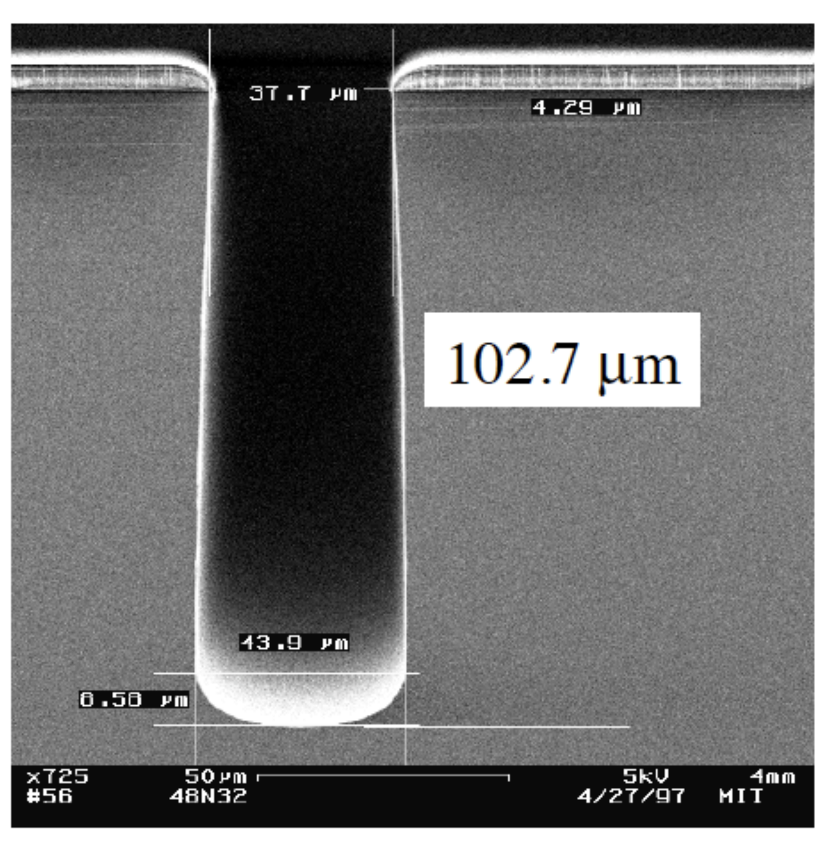
Journal Bearing

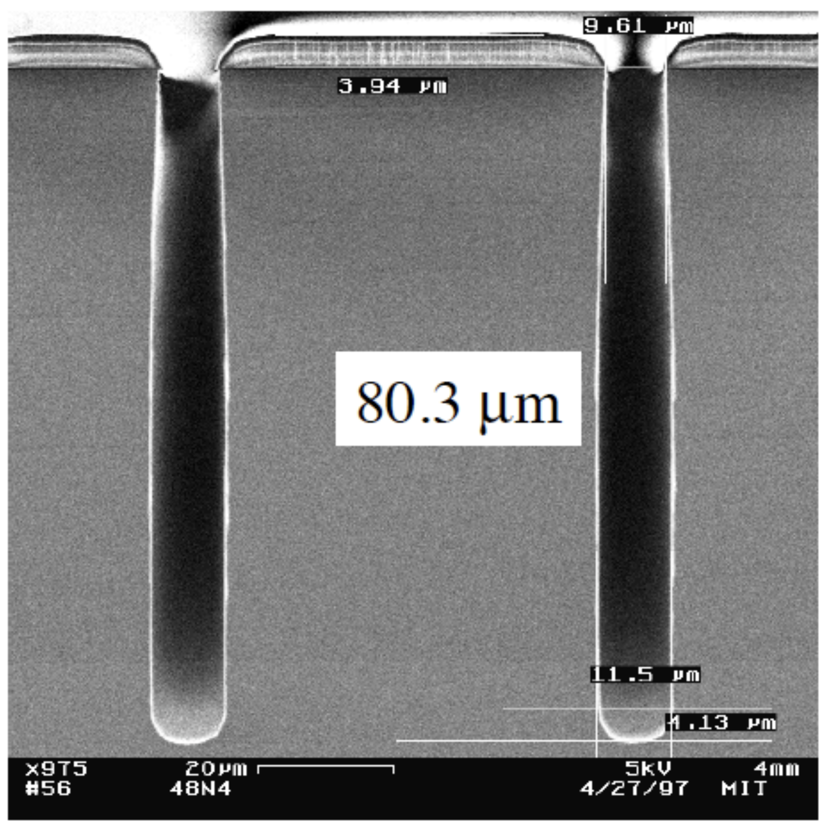
30 μm

Fuel Injector

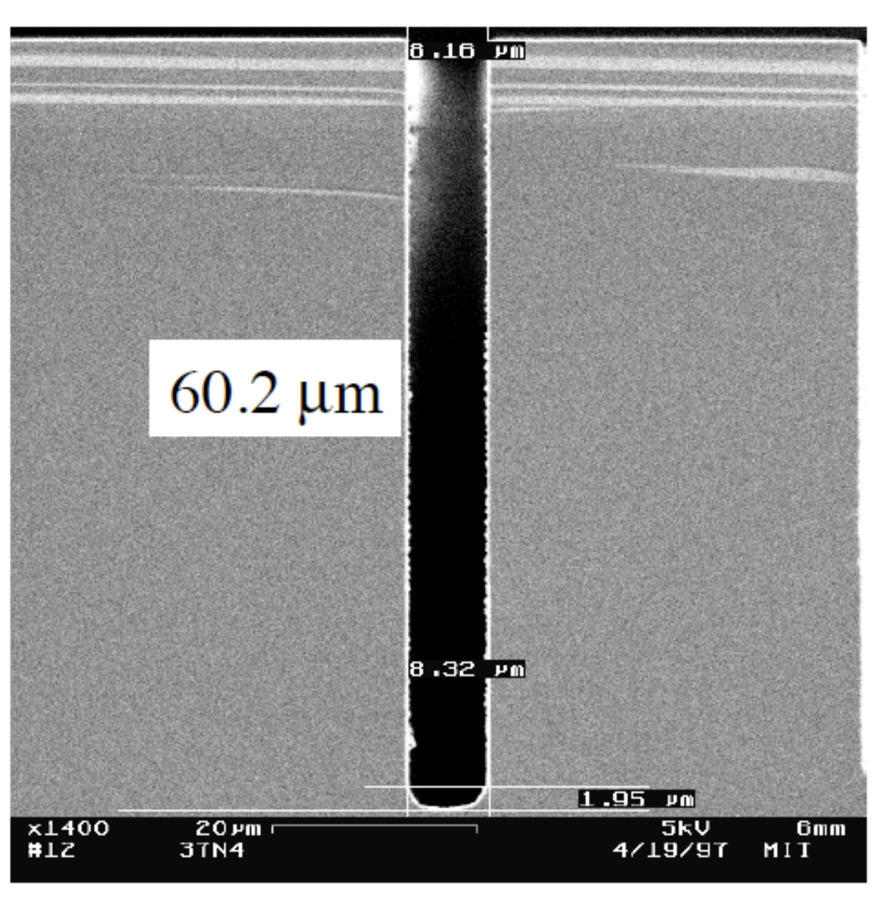
Turbine

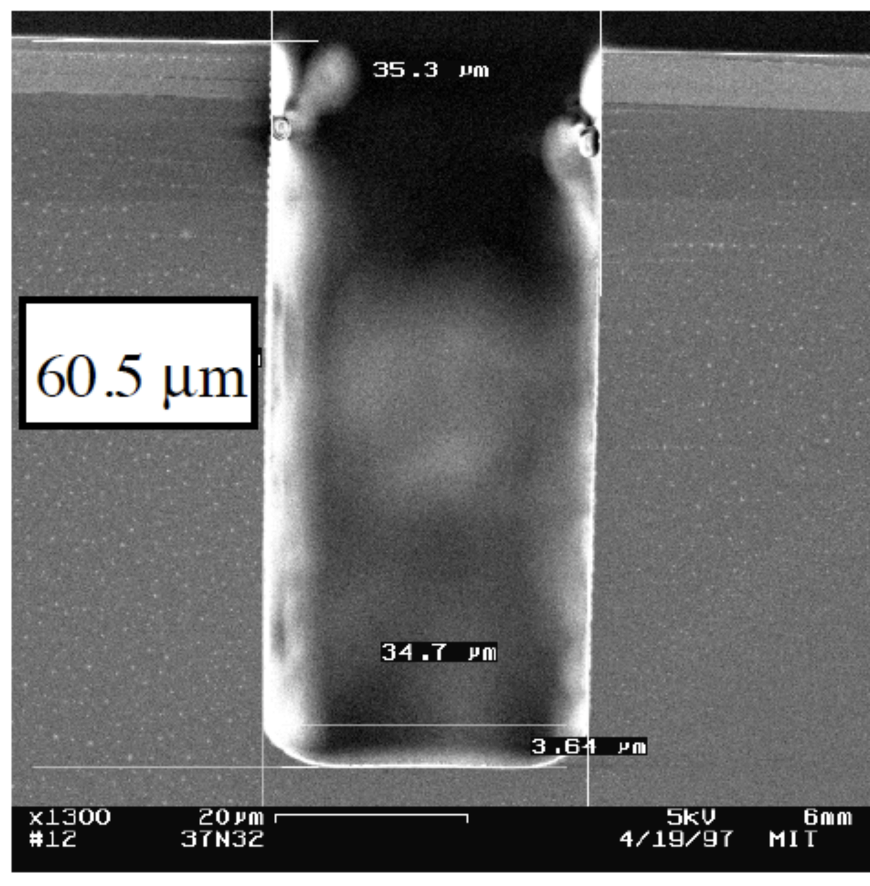
Aspect Ratio Dependant Etching





Control of AR





Research

Anisotropy

$\alpha = 18.4$ → Increase Coil Power → $\alpha = 62.8$

$\alpha = 18.4$ ↓ Increase SF_6 Flow ↓ $\alpha = 6.5$

$\alpha = 6.5$ → Increase Coil Power → $\alpha = 32.3$

$\alpha = 32.3$ ↑ Decrease SF_6 Flow ↑ $\alpha = 62.8$

Anisotropy

Anisotropy

$\alpha = 18.4$

Decrease Coil Power

$\alpha = 4.8$

Increase SF_6 Flow

$\alpha = 3.0$

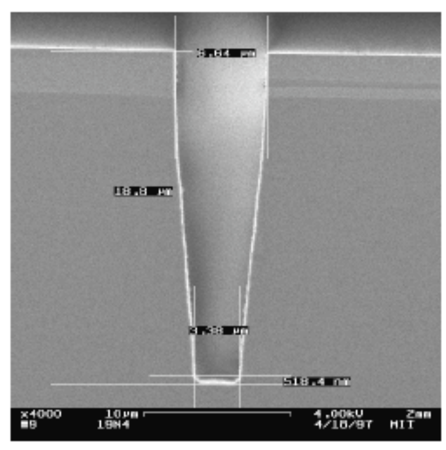
Increase Coil Power

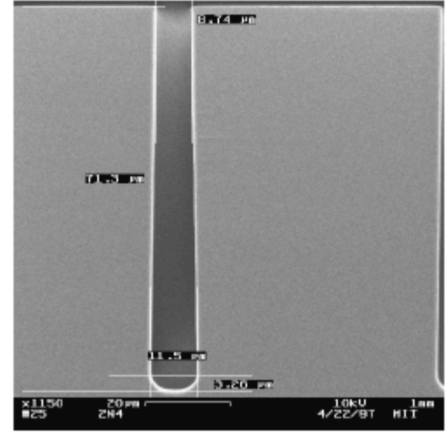
$\alpha = 12.5$

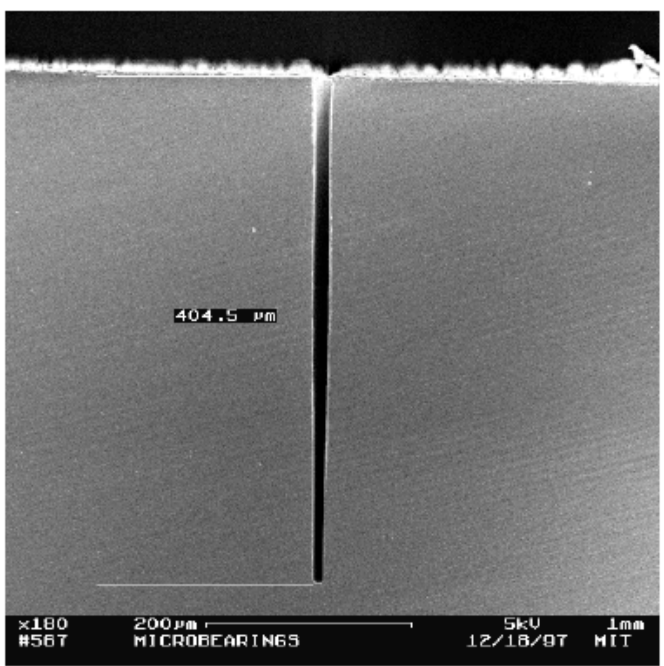
Decrease SF_6 Flow

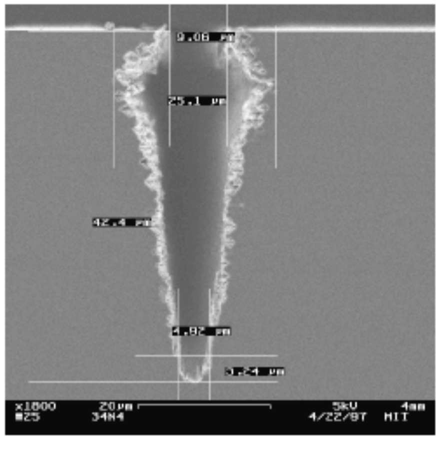
$\alpha = 19.5$

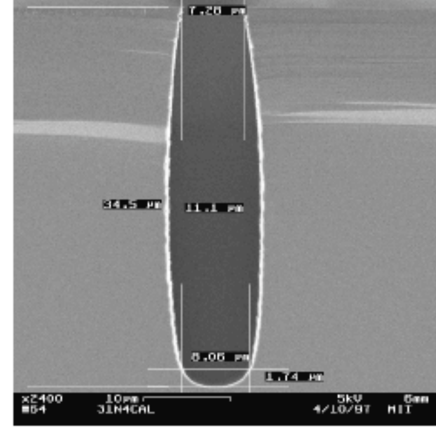
Profile Control and Anistropy





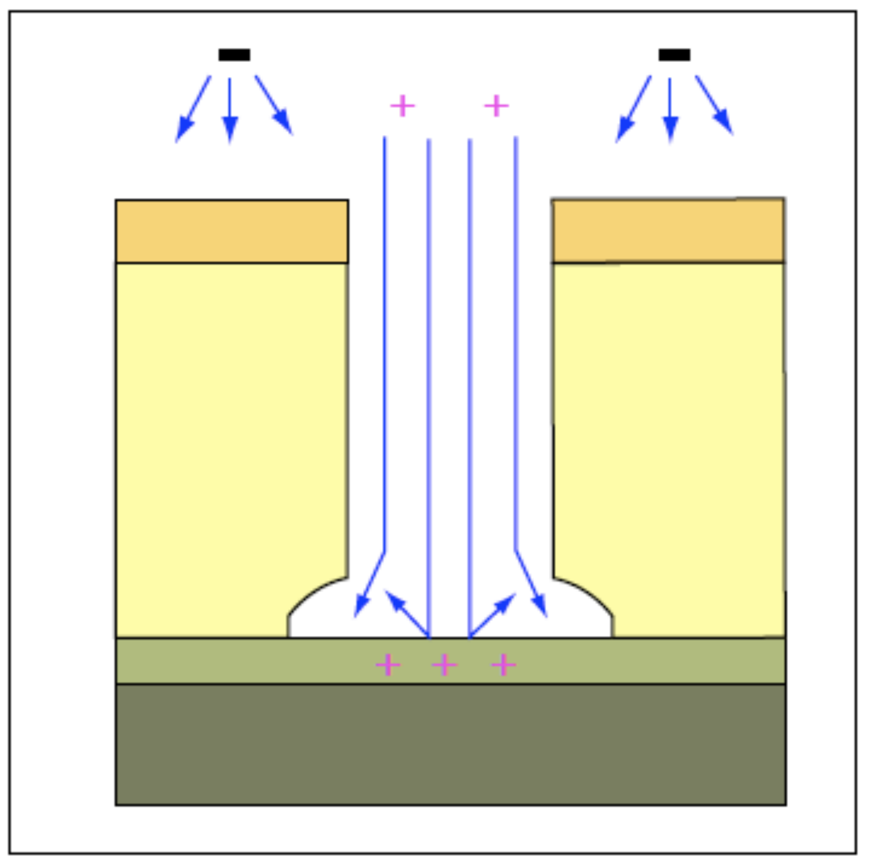




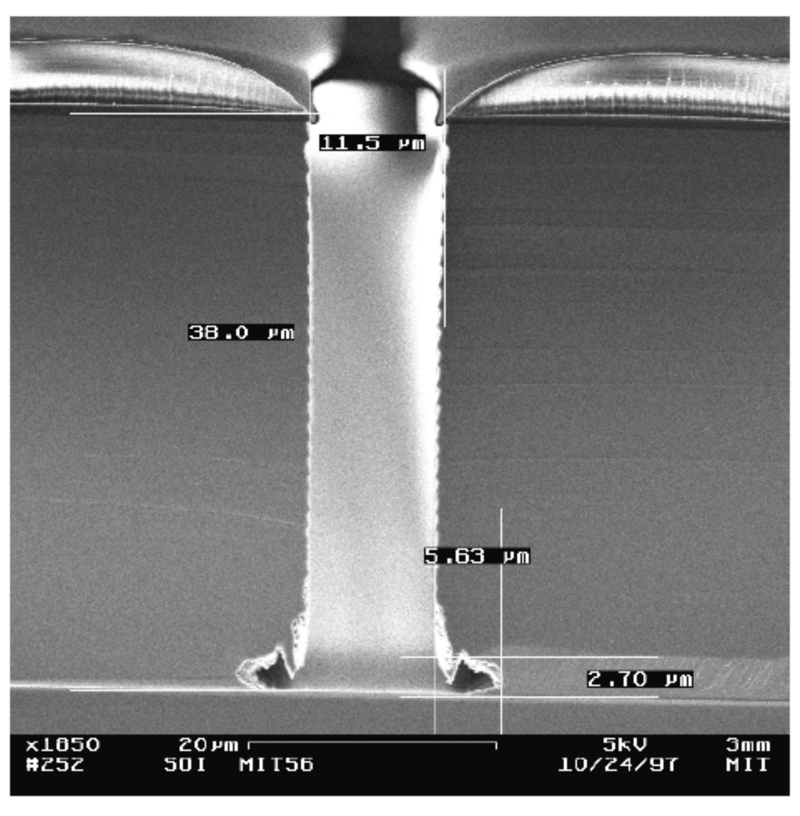


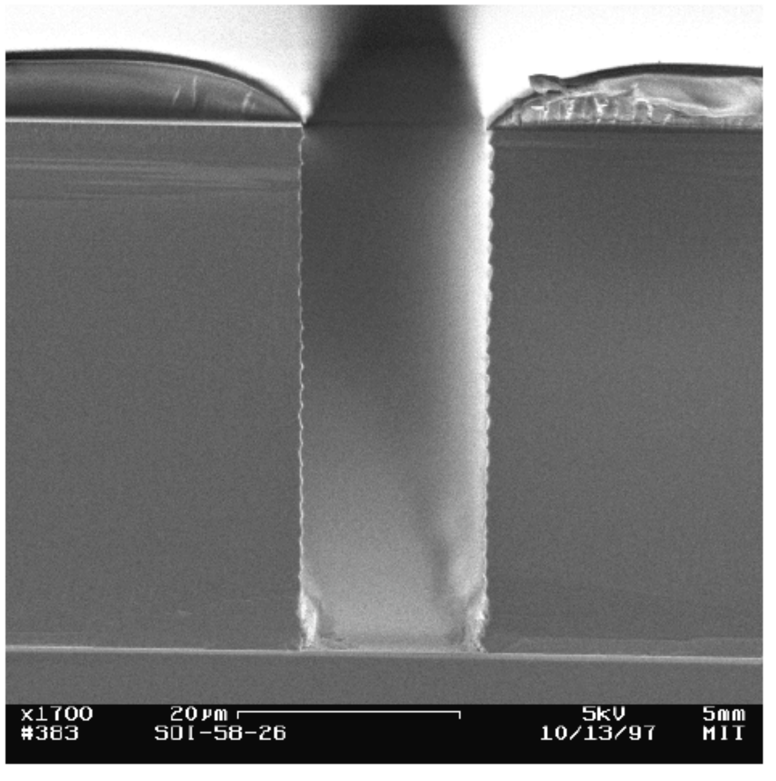
DRIE with Etch Stop

- SOI substrate
- Buried oxide acts as an etch stop
- Charging can led to "footing"



Footing effect





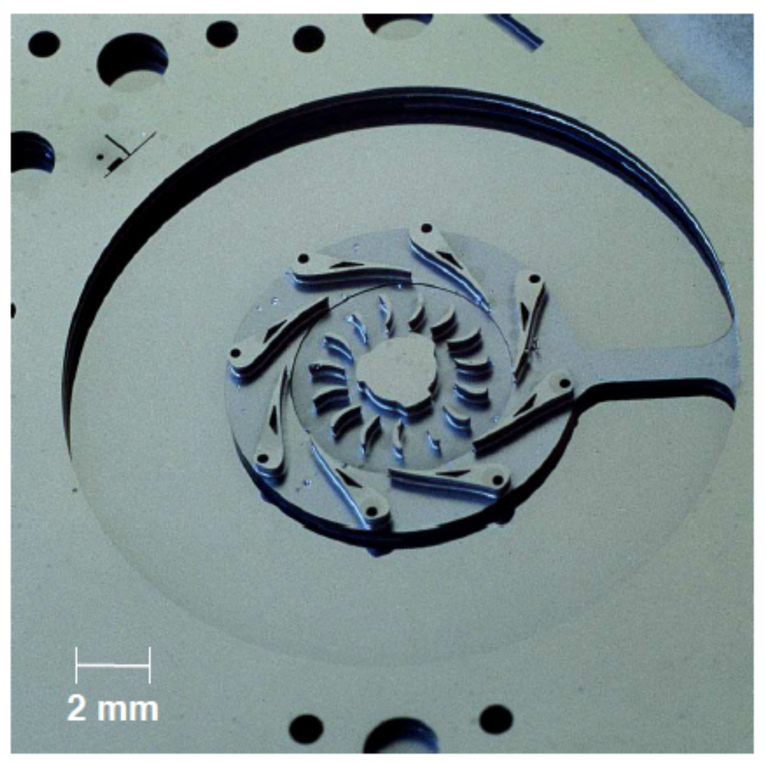
- Decrease C_4F_8 flow
- IncreaseSF_6 flow
- Increase passivating time

Observations and Compromises

Increases in:	Positive effect:	Deleterious effect:
SF_6 Flow Rate	ARDE Si Etching Rate	Grass Formation Uniformity Anisotropy Scalloping
APC Position	Selectivity Fillet Radius	Anisotropy Uniformity Surface Roughness
Electrode Power	Anisotropy Surface Roughness	Selectivity Fillet Radius
Coil Power	Si Etching Rate	Uniformity

Microengine

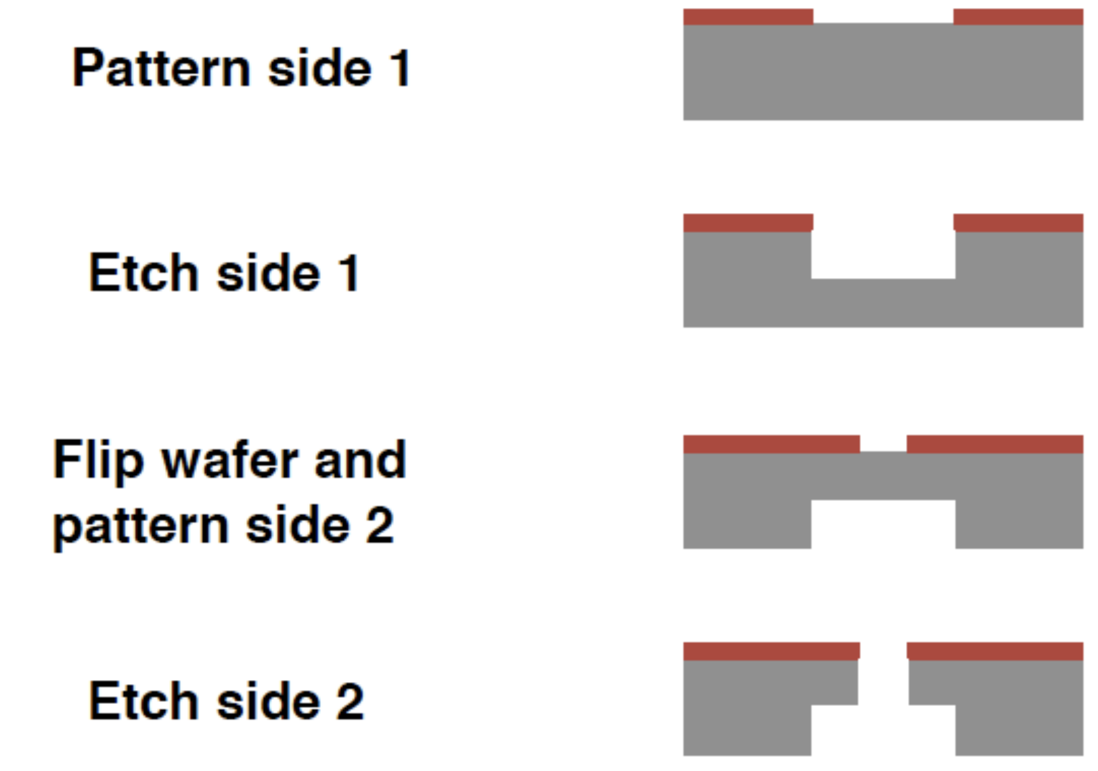
Compressor



Combustor & Turbine

Multi-level Etching

- Making multi-level etches can be challenging
- For through etches with two different depths, simply etch from both sides of wafer, with double-sided alignment



Multi-level etching with nested masks

- Etching two sets of deep (> about 10 um) features on the same side of the wafer requires a nested mask

1. Grow oxide mask

2. Define resist mask

3. Etch oxide to form mask

4. Strip resist; pattern with new resist mask

5. Etch to first depth

6. Strip resist mask

7. Using oxide as a mask, etch to second depth

8. Strip oxide mask

Dry Etching Pros/Cons

- Potential for highly anisotrpoic (parallel plate/RIE/DRIE)
  - Parallel sided, deep trenches
- Less selective than wet etches, absence of good etch stops
- Complex physics/chemistry: sensitive to pressure, gas flows, temperature, loadings
  - Need to characterize, empirically model
  - Need to maintain control
- Uniformity, achieved via single wafer reactors
- Throughput of single wafer systems can be low
- Capital cost of operating cost intrinsically high

Wet etching pros/cons

- Selectivity can be high
  - Masking
  - Etch anisotrpoy
  - Etch stops
- Reproducible (if solutions, electrochemistry controlled)
- Inexpensive batch process
- Potential for loss of resolution through undercut (isotropic)
- Temperature/agitation sensitivity (needs to be controlled)
- Surface tension, bubble formation, wetting, solution degradation
- Waste disposal

Concluding remarks

- Variety of dry etching technologies are available for bulk micromachining
- Deep reactive ion etching via time multiplexed etching/ deposition cycles is probably the most promising technology
- Advantages and disadvantages vs. wet etching
- Process control and modeling in early stages, but design of experiments approach, using response surfaces is probably the best approach available