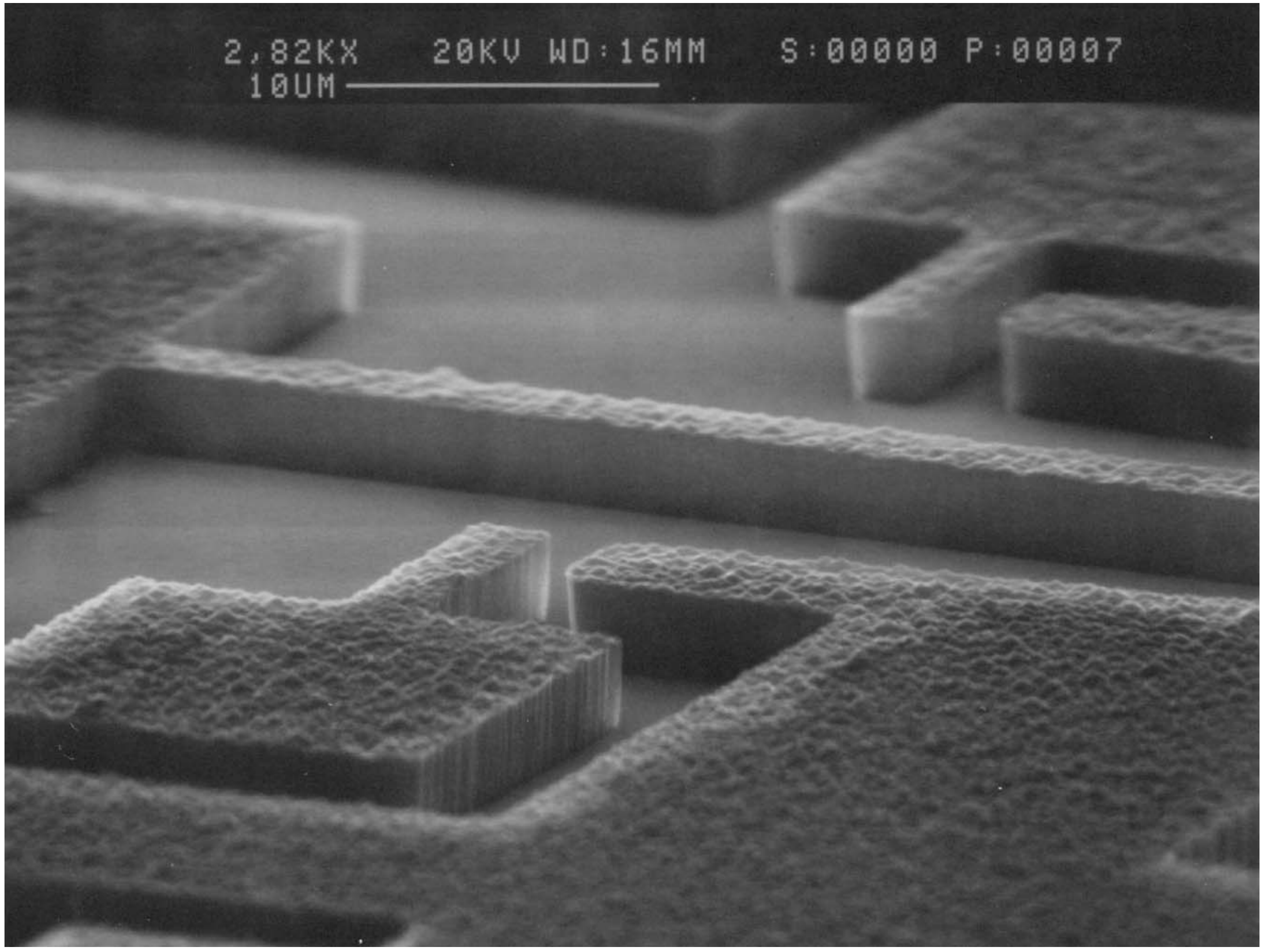
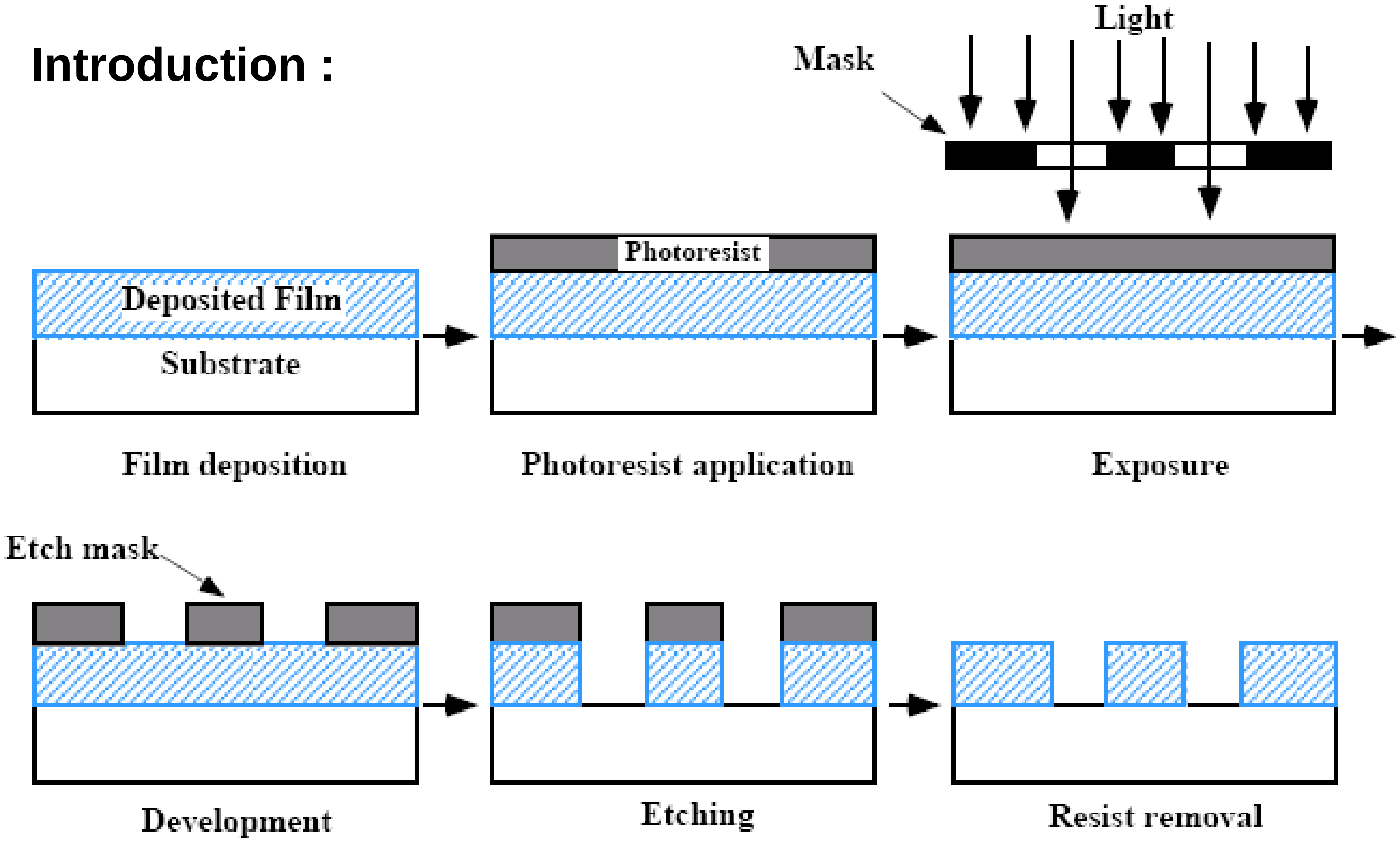
Lecture 7

Etching



Etching: Basic Terminology

Introduction :



- Etching of thin films and sometimes the silicon substrate are very common process steps.
- Usually selectivity, and directionality are the first order issues.

Etching - Overview

- Basic Terminology
- Wet Etching
- Dry / Plasma Etching
    - Mechanisms
    - Example
    - Reactor Designs
- Summary and Appendix

Etching: Basic Terminology

1. ***Etch rate***
2. ***Selectivity***
3. ***Anisotropy***
4. ***Uniformity / Homogeneity***

Etching: Basic Terminology

Etch rate: r

- Speed at which ethcing occurs
- Typical unit: r [nm/min]

Selectivity : S

- Ratio of two etch rates

$$S = \frac{r_1}{r_2}$$

Example 1:

SiO_2 etching with hydrofluoric acid (HF): $SiO_2 + 6\,HF \rightarrow H_2SiF_6 + 2\,H_2O$

A. Determine the etch time for a 1,2 µm thick SiO_2 film
with r_{SiO2} = 400 nm/min → 3 min.

B. How thick should the resist mask be if the selectivity is $S_{SiO2/resist}$ = 4?

➡ **Etch rate and selectivity are crucial for defining masks!**
(Photo- or “Hard”masks)

BOE：buffered oxide etching
BHF: buffered HF

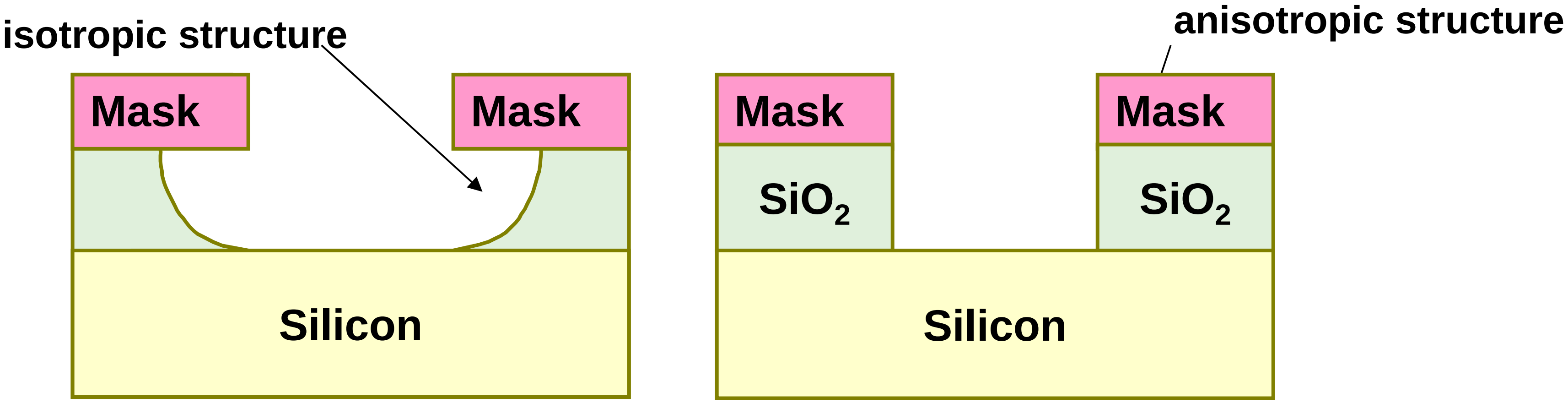
→

NH_4F buffer: Help to prevent depletion of
F- → decrease etch rate of photoresist

Etching: Basic Terminology

Anisotropy A

- ***Isotropic*** etching removes material equally in all directions
  → Undercut of the mask



- ***Anisotropic*** etching removes material only perpendicular to the surface
  → accurate transfer of the mask pattern

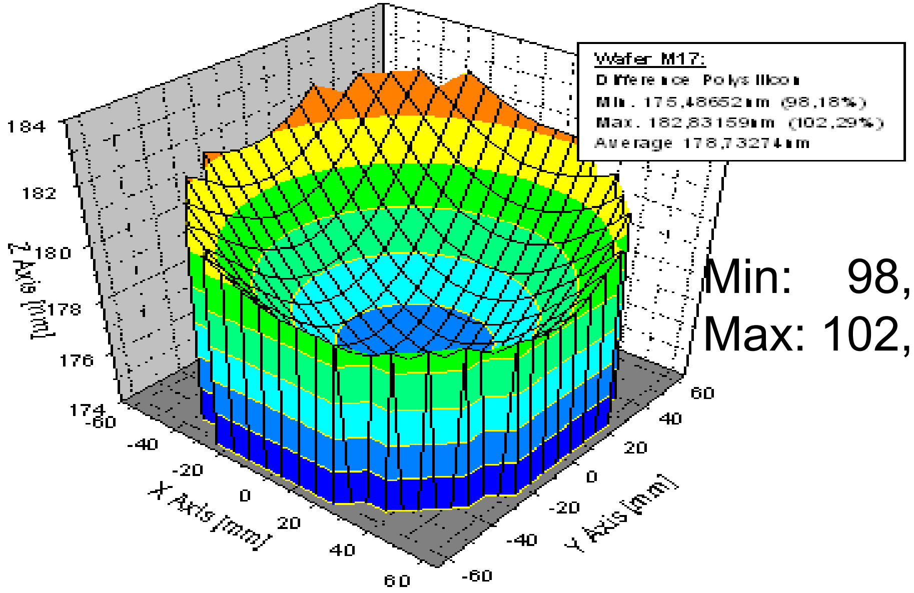
$$\text{Anisotropy}: \frac{\text{vertical etch rate - horizontal etch rate}}{\text{vertical etch rate}} \qquad A = 1 - \frac{r_{hor}}{r_{vert}}$$

Etching: Basic Terminology
Uniformity / Homogeneity

- Measures the distribution of the etch rate
  - Wafer to wafer, esp. for multi-wafer processing
  - Across one wafer (e.g. center vs. edge)
- Has to be considered when determining etching time (e.g. overetching)
- Production: Matching production tools (esp. litho and etching)

$$U = \frac{R_{high} - R_{low}}{R_{high} + R_{low}}$$

R_{high}: Max etch rate
R_{low}: Min etch rate



Min: 98,18%
Max: 102,29%

Etching Performance Parameters

Etch Rate *R*	**The film thickness being etched per unit time. *R* has significant effects on throughput.**
Etch Uniformity	**Variation of etch rate throughout one wafer, multiple wafers or multiple batches of wafers**
Selectivity *S*	**The ratio of the etch rates between two different materials**
Anisotropy *A*	**Etching directionality** **A=0, isotropic; A=1, anisotropic**
Undercut	**Unilateral overetching**

Pattern Transfer =Lithography + Etching

Two Critical Issues:

- **Selectivity**

$$S = \frac{r_1}{r_2}$$

r_1: **Etching rate of material being etched**

r_2: **Etching rate of masking material or the material below the film**

- **Directionality: isotropic/anisotropic**

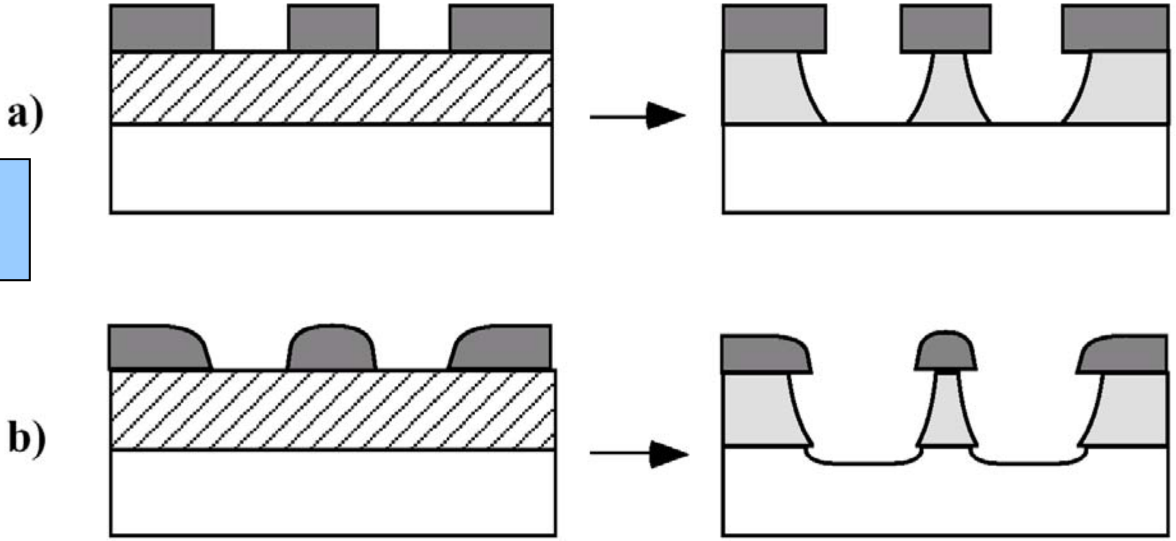
$$A = 1 - \frac{r_{lat}}{r_{vert}}$$

r_{lat}: **Lateral etch rate**

r_{vert}: **Vertical etch rate**

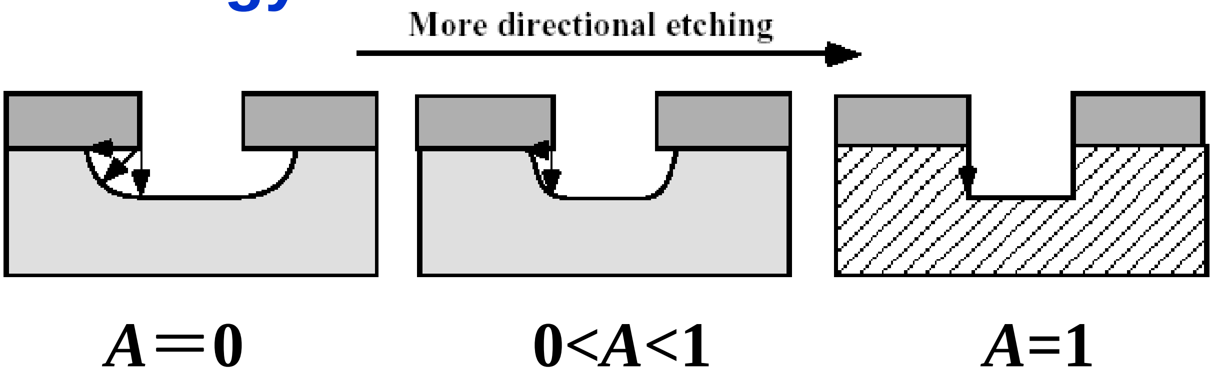
Silicon Etching

Pattern Transfer Demo



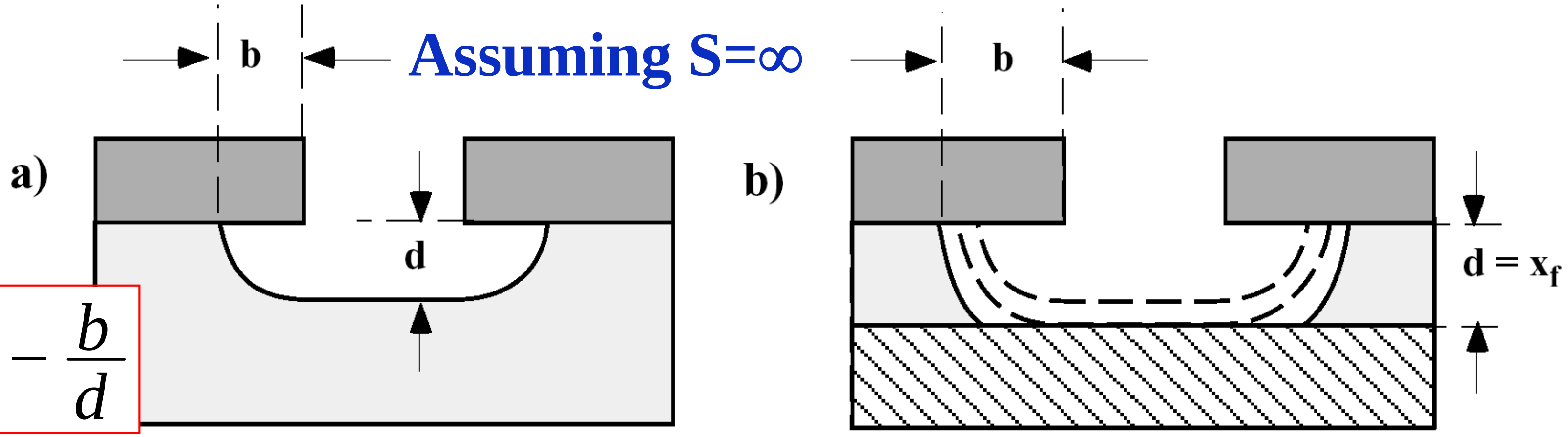
Etching: Basic Terminology

Directionality



Overetching

Assuming S=∞



$$A = 1 - \frac{b}{d}$$

Uniformity/non-uniformity

$$U = \frac{R_{high} - R_{low}}{R_{high} + R_{low}}$$

R_{high}: Max etch rate
R_{low}: Min etch rate

Etching - Overview

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Wet Etching: Examples

Example 2: Etch Si using HNO_3 and HF (HNA)

$$\mathrm{Si} + \mathrm{HNO_3} + 6\mathrm{HF} \rightarrow \mathrm{H_2SiF_6} + \mathrm{HNO_2} + \mathrm{H_2O} + \mathrm{H_2}$$

Isotropic

Example 3: Etch Si_3N_4 using hot phosphoric acid

$$Si_3N_4 + H_3PO_4 + H_2O \rightarrow NO\uparrow + NO_3^- + H_2PO_4^- + H_2SiO_3$$

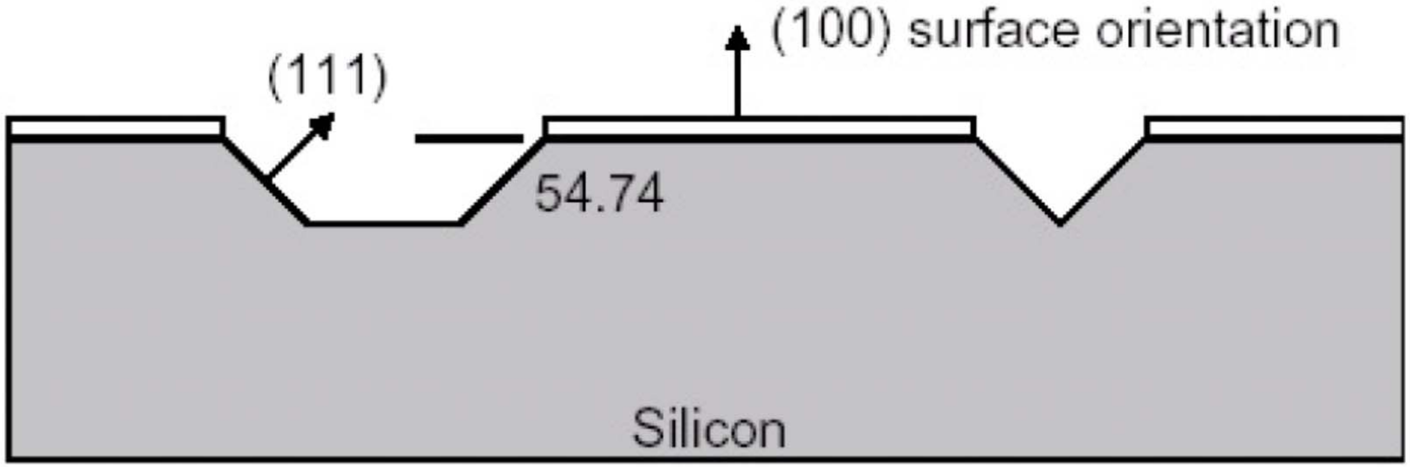
Wet Etching: Examples

Anisotropic

Example 4: Etch Si using KOH

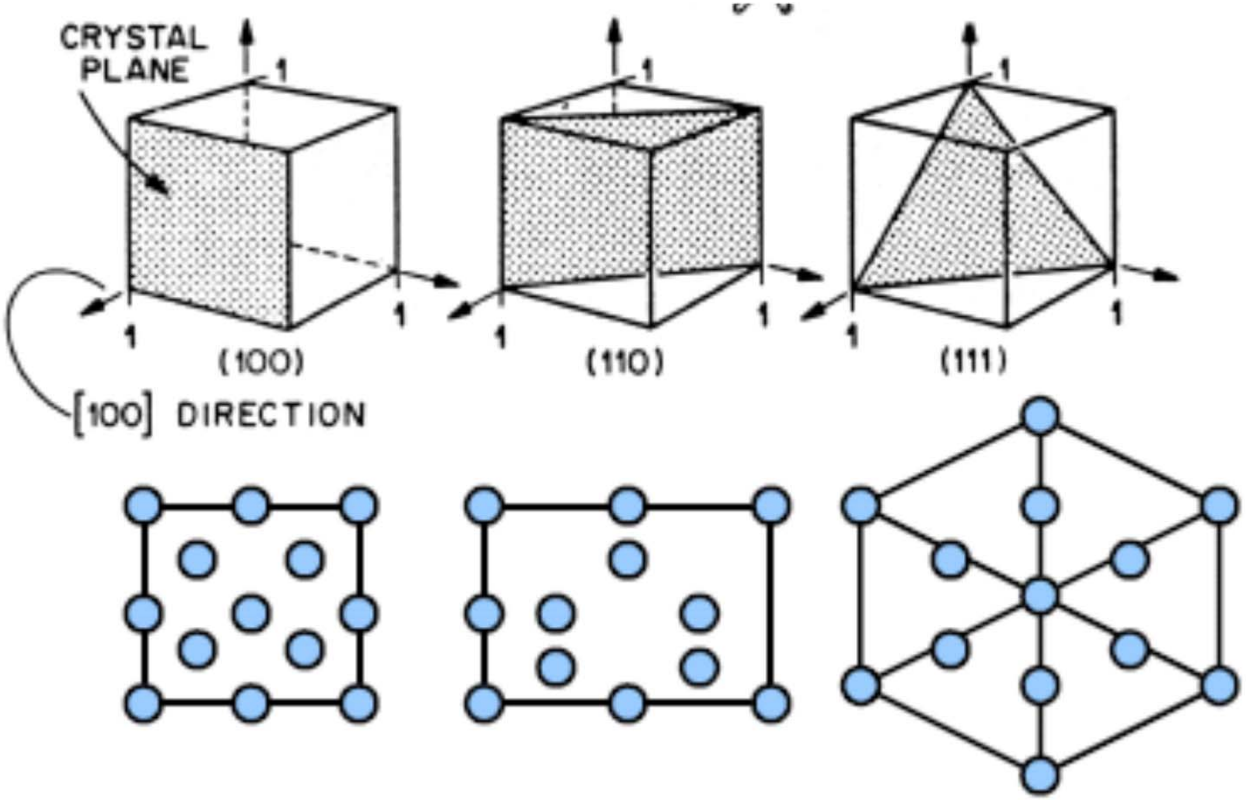
$$\mathrm{Si + 2OH^- + 4H_2O \Rightarrow Si(OH)_2^{++} + 2H_2 + 4OH^-}$$

Anisotropic wet etching results from surface orientation



Wet Etching: Examples

Example 3: Etch Si using KOH

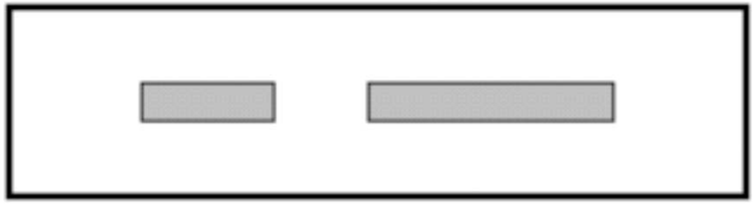


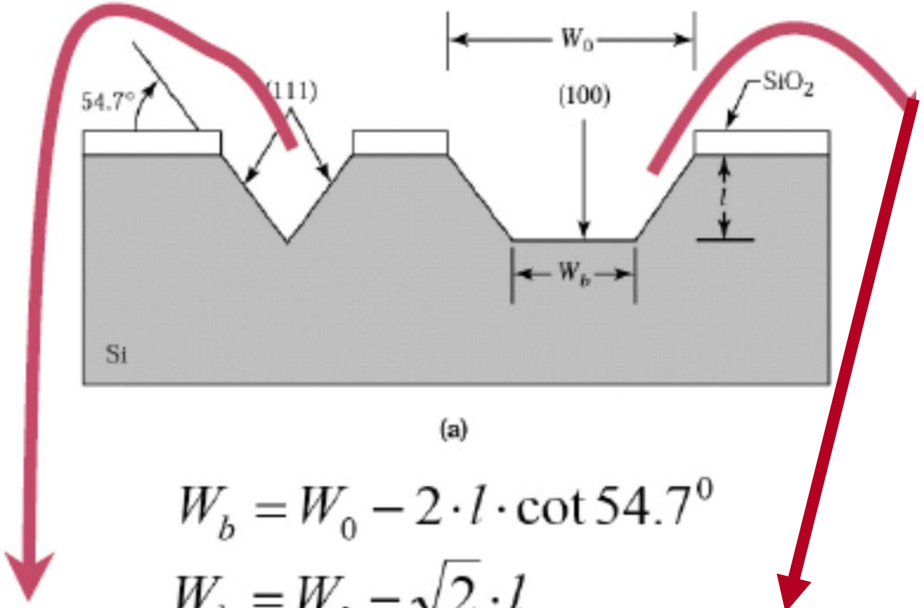
Atomic density: <111> > <110> > <100>

Etch rate: $R_{(100)} \cong 100\ R_{(111)}$

Wet Etching: Examples

Example 3: Etch Si using KOH



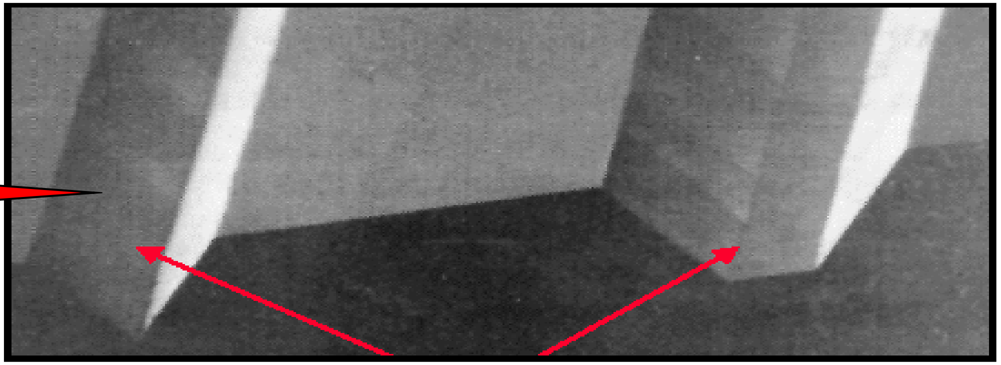


(a)

$$W_b = W_0 - 2\cdot l\cdot\cot 54.7^0$$

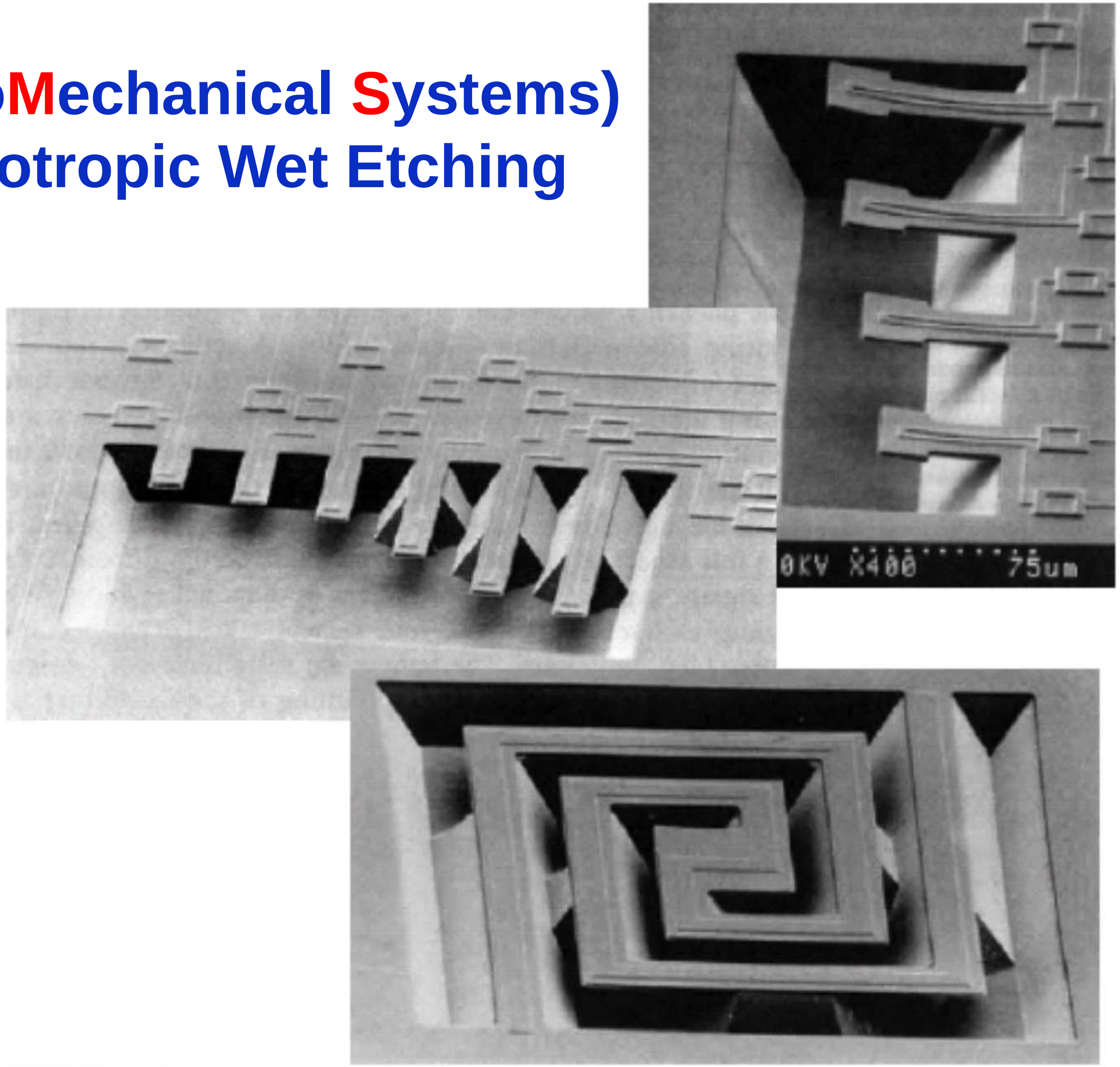
$$W_b = W_0 - \sqrt{2}\cdot l$$

Self-Limited



Wet Etching: Applications

MEMS (MicroElectroMechanical Systems) Made from Si Anisotropic Wet Etching



Wet Etching: Drawbacks

In the manufacture of large-scale electronic ICs, wet etching is being replaced by dry etching.

(1) Wet etching is mostly isotropic.

(2) Wet etching has poor resolution.

(3) Wet etching depends on a lot of corrosive chemicals, which are harmful to human bodies and environments.

(4) Wet etching needs a large number of chemical reagents to wash away the residues. Non-economical!!

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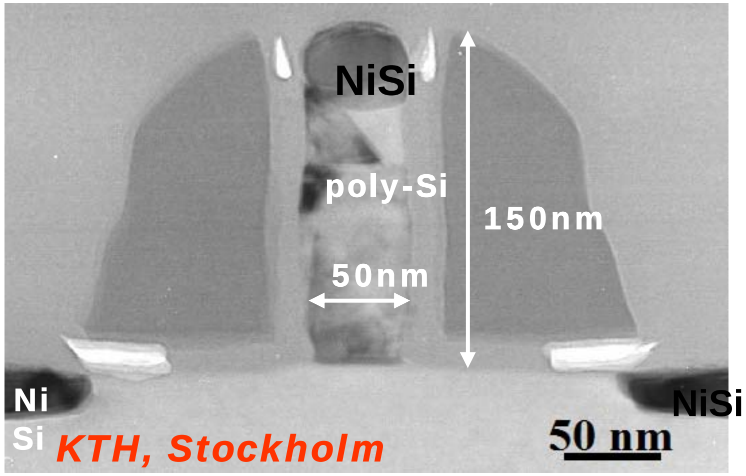
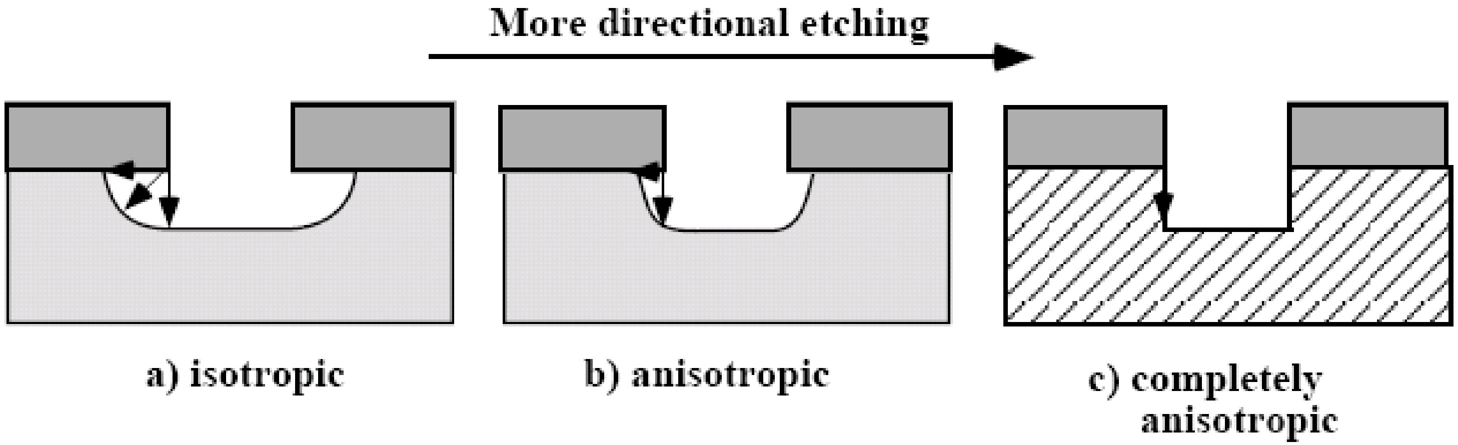
Etching: Requirements at the Nanoscale

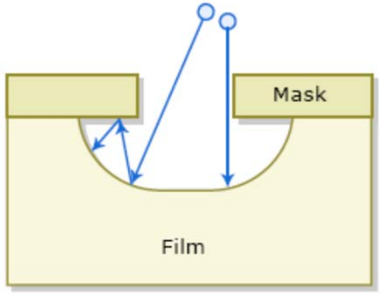
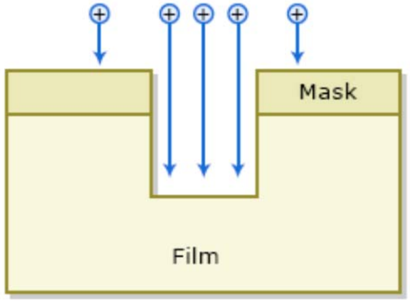


Etch Requirements at the Nanoscale:

1. ***Obtain desired profile*** (sloped or vertical)
2. ***Minimal undercutting*** or bias
3. ***Selectivity*** to other exposed films and resist
4. Uniform and reproducible
5. Minimal damage to surface and circuit
6. Clean, economical, and safe



Etching: Requirements at the Nanoscale

	Reactive neutral molecules 	Ions (z.B. Ar^+) 
	chemical	**physical**
Selectivity	++	--
Anisotropy	-- (<<1)	++ (~1)
Examples	liquid, steam or plasma	Ion bombardment (“sputter”)

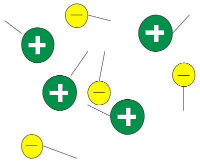
How can we combine chemical and physical components?

Plasma contains neutral radicals AND positive Ions!

Plasma

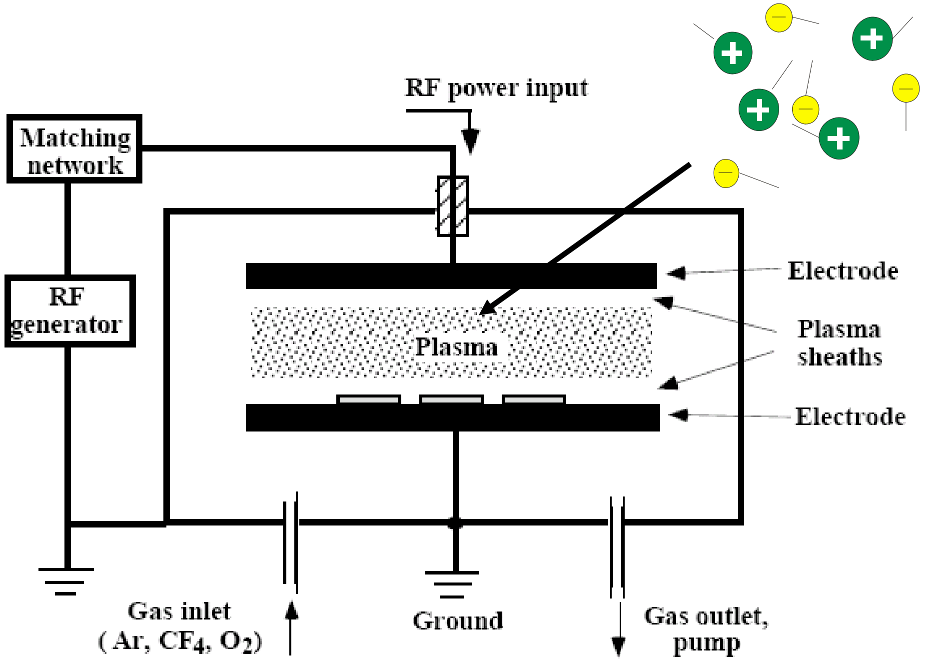
Plasma

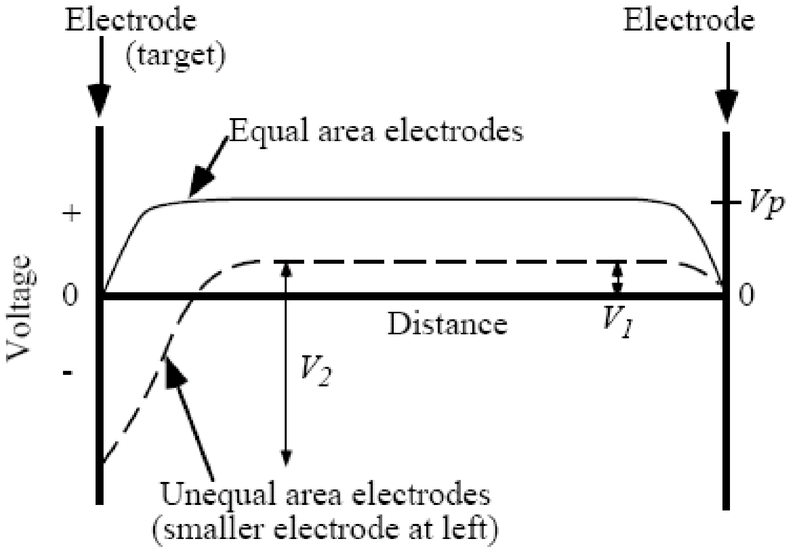
The ***4th aggregate state*** (in increasing excitation)

solid	**liquid**	**gaseous**	**PLASMA**
Ice H_2O	**Water** H_2O	**Steam** H_2O	**Ionized Gas** $H_2 \rightarrow 2H^+ + 2e^-$
T < 0°C	**0°C < T < 100°C**	**T > 100°C**	**T > 100000°C**
			
atoms / molecules are fixed in the crystal lattice	atoms / molecules can move freely as a network	atoms / molecules can move freely, large distances	Ions and electrons noy bound, very large distances

Plasma Generation

Application relevant generation of plasma in a parallel plate reactor





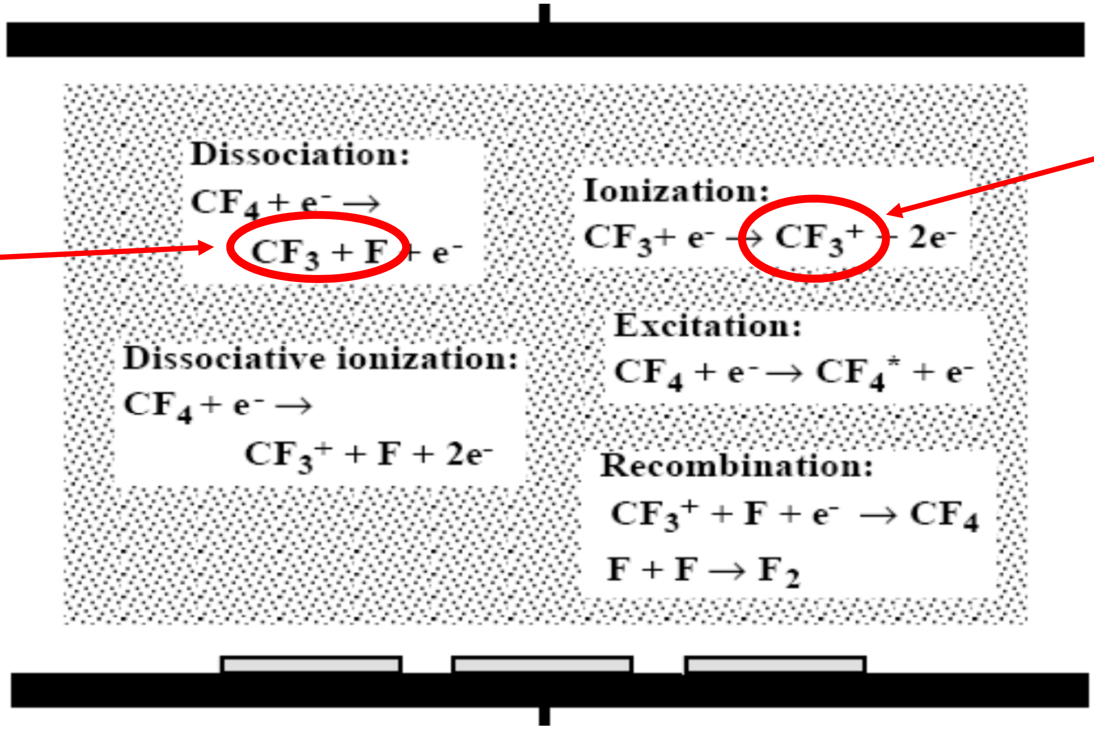
- Anode grounded
- Cathode connected to RF generator via impedance matching network
- High electric field ionizes gas molecules → Plasma!
- „Fast“ electrons follow RF field → positive ions determin plasma potential
- A smaller electrode leads to a higher voltage difference compared to plasma

Plasma Generation

High energy electrons in a plasma lead to further reactions

Free radicals,
Highly reactive

chemical etching!



Ionized molecules,
positivly charged

physical etching!

- Dissociation: Partitioning a molecule into components, e.g. free radicals
- Ionization: Further generation of free electrons and charged molecules
- Excitation: excited molecules relax and emit Photons (“glow”)
- Recombination: Radicals and molecules recombine

Plasma Etching Mechanisms

- Typically there are about 10^{15} cm^{-3} neutral species (1 to 10% of which may be free radicals) and 10^{8}-10^{12} cm^{-3} ions and electrons
- In standard plasma systems, the plasma density is closely coupled to the ion energy. Increasing the power increases both

- There are three principal mechanisms
  - chemical etching (isotropic, selective)
  - physical etching (anisotropic, less selective)
  - ion-enhanced etching (anisotropic, selective)
- Most applications today try to use the ion-enhanced mechanism (which provides in fact more than the sum of its components).

Plasma Etching Mechanisms

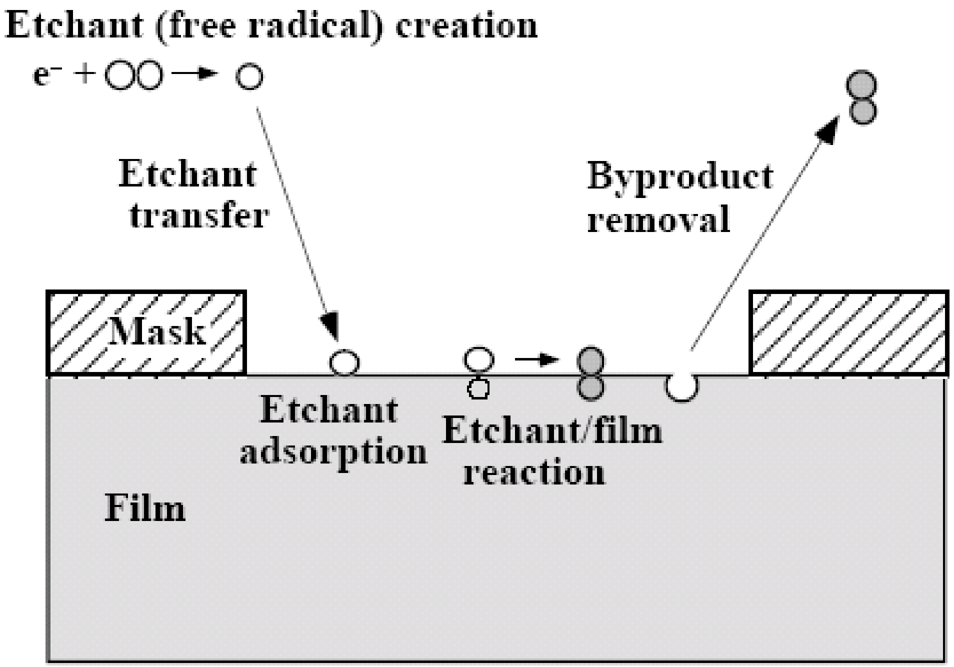
1. Chemical Etching

- Etching by reactive neutral species, such as “free radicals” (e.g. F, CF_3)
- Additives like O_2 can be used which react with CF_3 and reduce CF_3 + F recombination → higher etch rate

Example Chemical Etching:

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

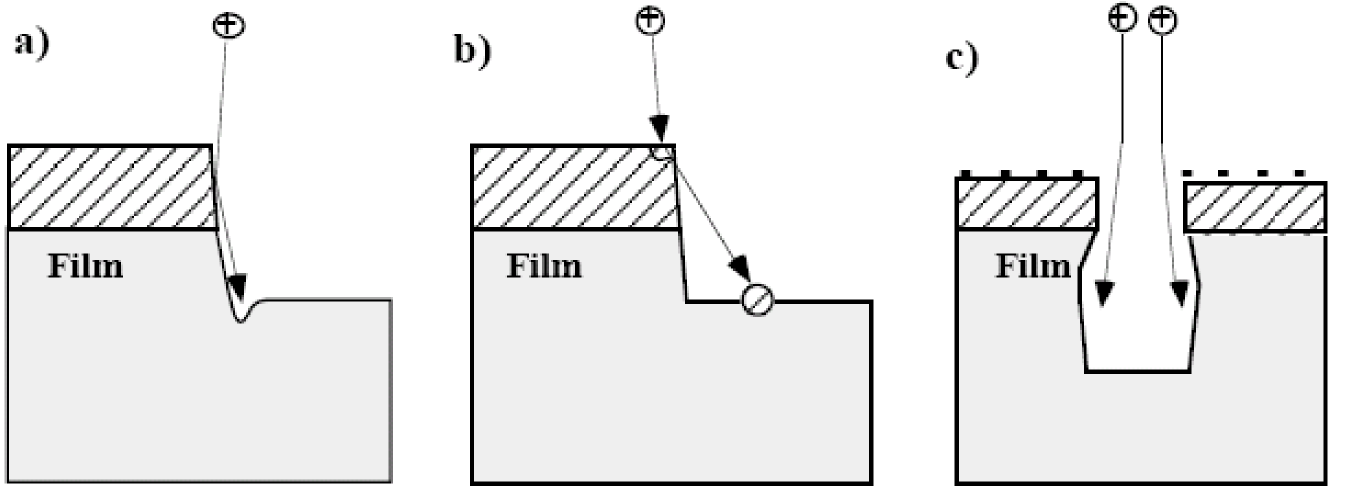
$$4F + Si \rightarrow SiF_4$$



Plasma Etching Mechanisms

2. Physical Etching or ”Sputter Etching”

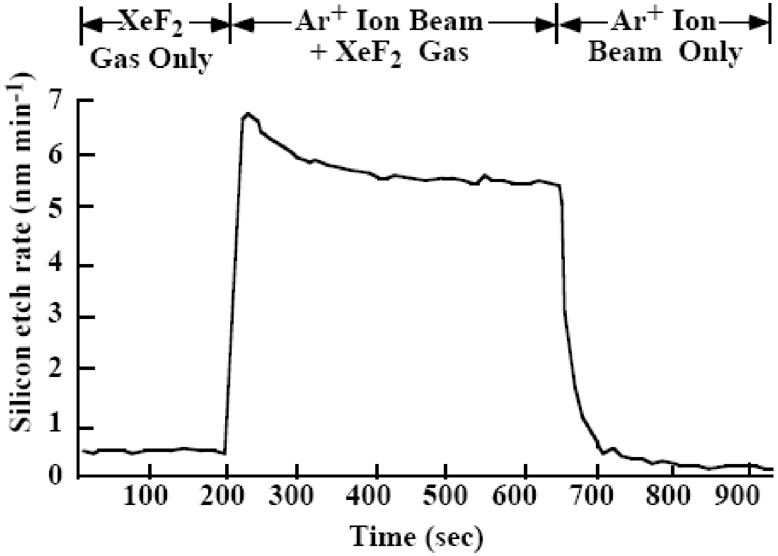
- Purely physical etching
- Highly directional (ε field across plasma sheath)
- Etches almost anything
- Poor selectivity: all materials sputter at about the same rate
- Pure sputter etching uses Ar+ →Damage to wafer surface and devices can occur:
  - (a) trenching ion
  - (b) bombardment damage, radiation damage, redeposition of photoresist
  - (c) charging
- These damages can occur in any etch system with a dominant physical etching component



Plasma Etching Mechanisms

3. Ion Enhanced Etching or Reactive Ion Etching (RIE)

- It has been observed that chemical and physical components of plasma etching do not always act independently - both in terms of net etch rate and in resulting etch profile.

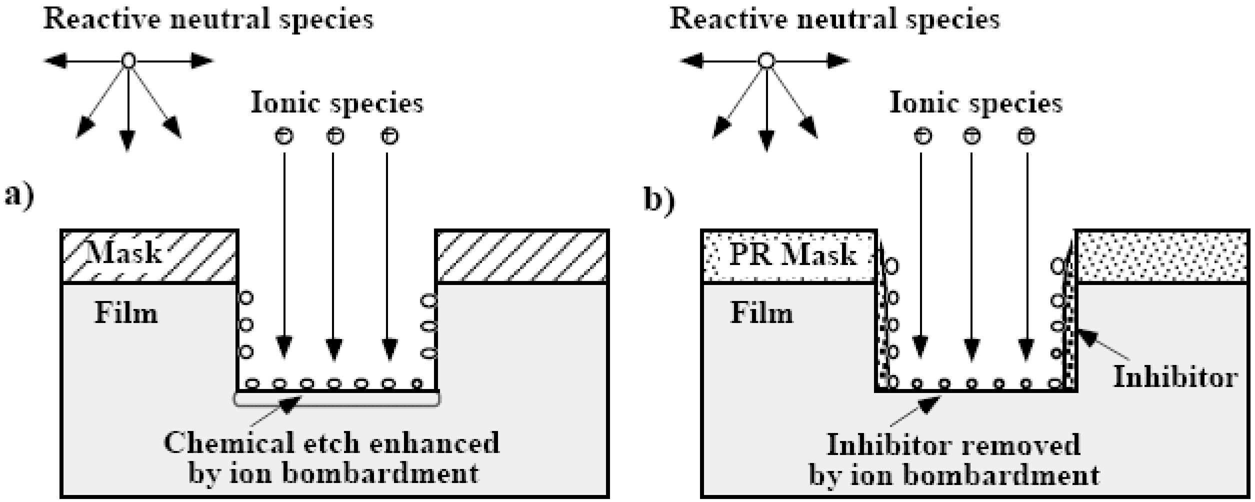


Example:

- Etch rate of silicon as XeF_2 gas (not plasma) and Ar^+ ions are introduced to silicon surface. Only when both are present does appreciable etching occur
- Etch profiles can be very anisotopic, and selectivity can be good
- Many different mechanisms proposed for this synergistic etching between physical and chemical components. Two mechanisms are shown below:

Plasma Etching Mechanisms

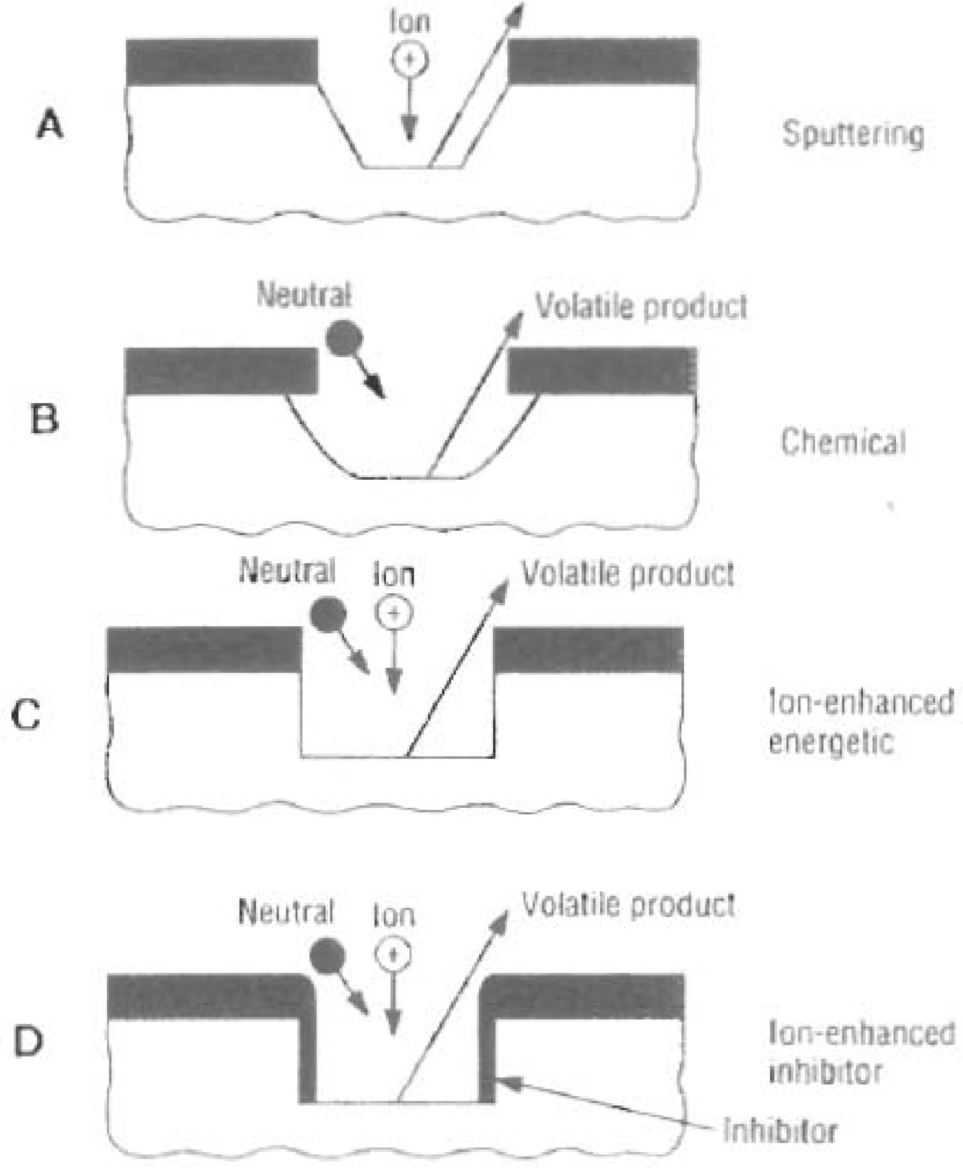
Ion Enhanced Etching



- Ion bombardment can enhance etch process (such as by damaging the surface to increase reaction, or by removing etch byproducts)
- Ion bombardment can remove inhibitor that is an indirect byproduct of etch process (such as polymer formation from carbon in gas or from photoresist)
- Whatever the exact mechanism (multiple mechanisms may occur at same time):
  - need both components for etching to occur.
  - get anisotropic etching and little undercutting because of directed ion flux.
  - get selectivity due to chemical component and chemical reactions.

→ many applications in etching today

Summary: Plasma Etching Mechanisms



SE (sputter etching)

PE (plasma etching)

RIE (reactive ion etching)

DRIE (deep reactive ion etching)

Concept Test 7.1

7.1: A plasma etch process can be described with the following terms:

Etch Rate – Selectivity - Anisotropy – Uniformity

A plasma etch tool has the following process parameters: **Pressure, Temperature, Gas composition, Gas flow, Substrate bias, RF power.**

Which of the following statements are true:

A. Pressure affects anisotropy and rate.

B. Temperature affects mainly the ion driven component.

C. The gas composition affects mainly the etch rate.

D. Gas flow affects mainly the chemical component.

E. Substrate bias affects mainly the chemical component.

F. RF power affects mainly the etch rate.

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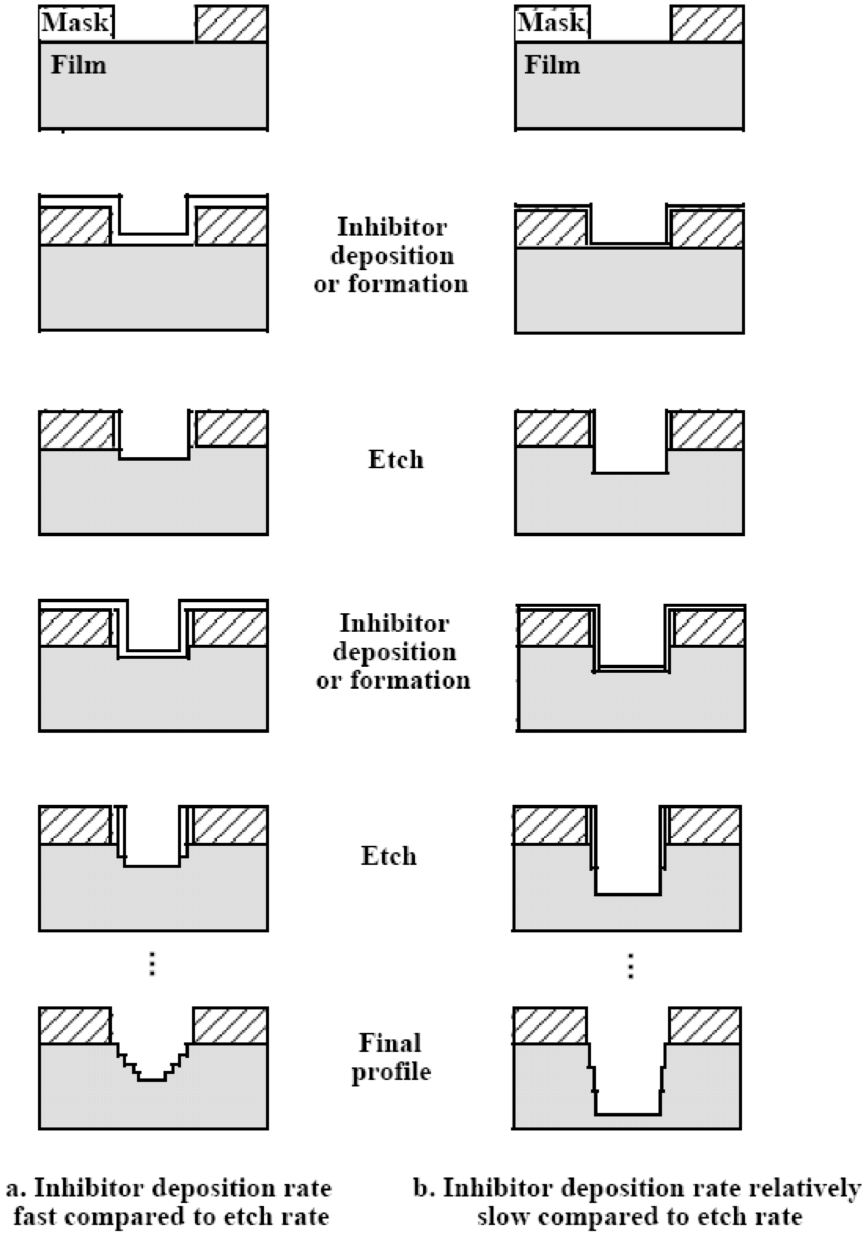
Reactive Ion Etching

Example:

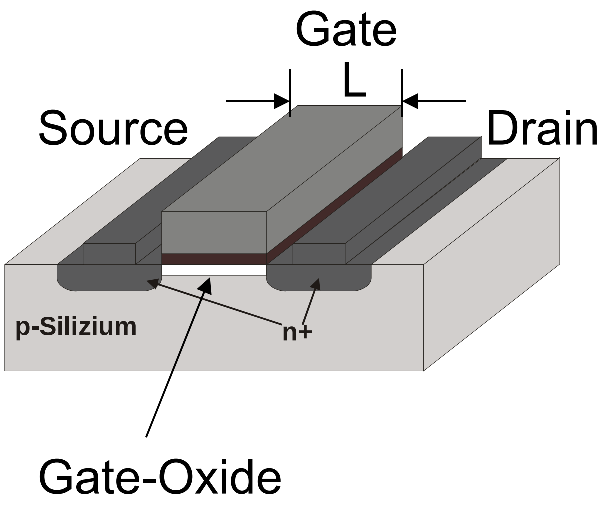
- RIE can achieve sloped sidewalls without undercutting
- Depends on ratio of inhibitor formation (“deposition”) to etching



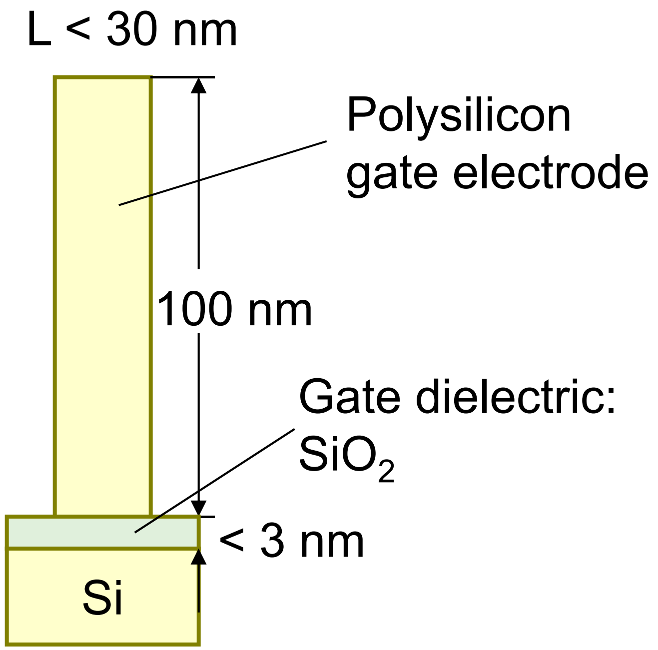
RIE Example: Highly Selective Silicon Etch Process

Goal:

Gate electrode etch process for silicon MOSFET



Requirements:



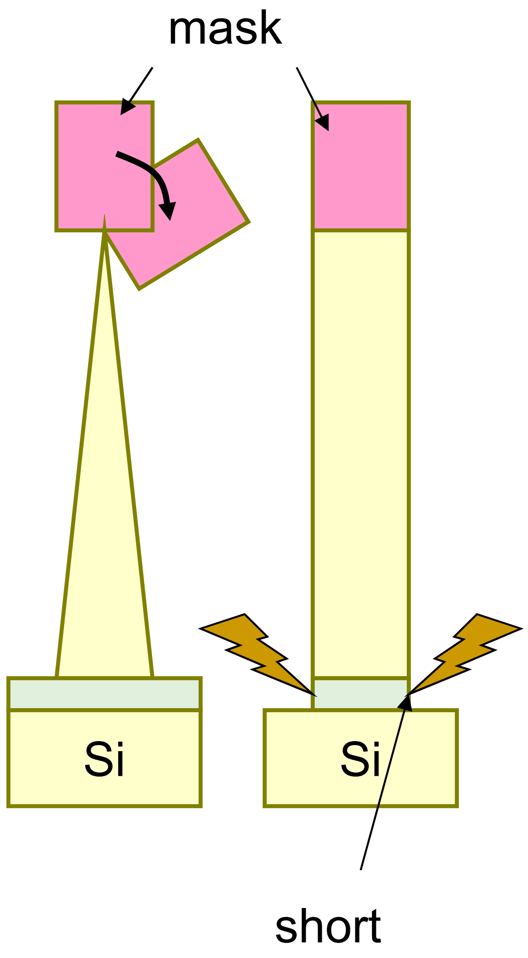
→ high anisotropy A

→ high selektivity S

→ 1 minute overetch:

r_{SiO2} << 3 nm/min

Issues:



RIE Example: Highly Selective Silicon Etch Process

Solution: Gate electrode etch process for silicon MOSFET

HBr + O_2 based plasma process in Oxford RIE Etcher

+ Etch product: Si + Br = SiBr (volatile)
+ O_2- addition to increase selektivity
+ Sidewall passivation with SiOBr (anistropy!)
- HBr is corrosive and highly poisonous

Process development: Optimizing process parameters

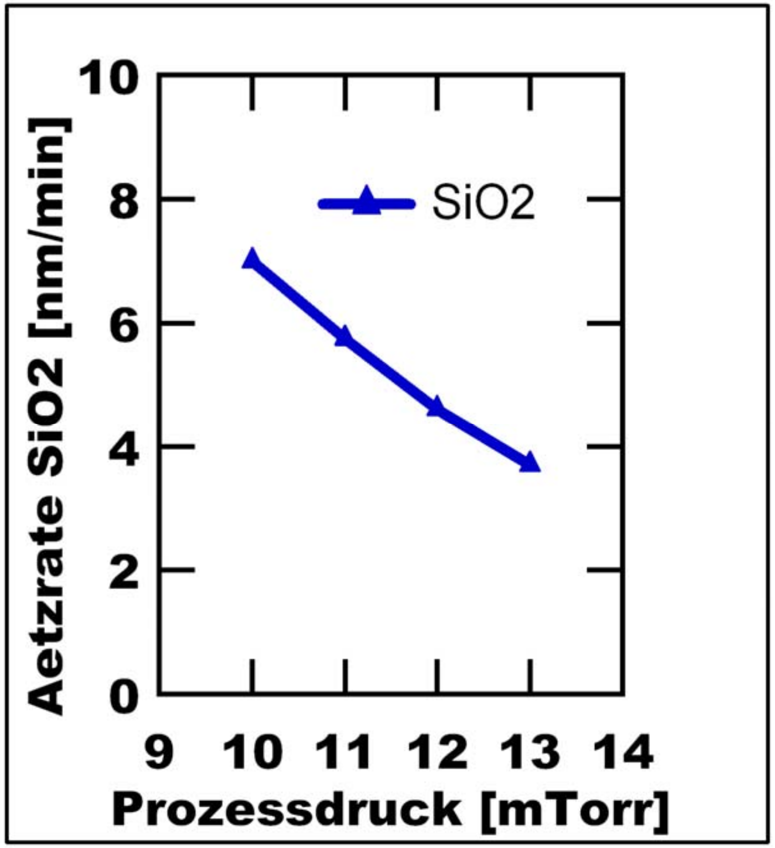
e.g. Pressure [mTorr]
    O_2-Admixture
    RF power
    Plasma power
    Gas flow

RIE Example: Highly Selective Silicon Etch Process

Process development: Optimizing process parameters

e.g. Variation of chamber pressur [mTorr]

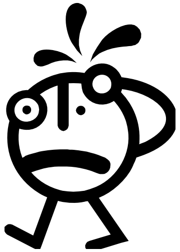
Fixed parameter: gas mixture: 2% O_2 in HBr



Preliminary result:

Rate too high ($r_{SiO2min}$ = 3.7 nm/min)

Further increase of pressure not feasible → loss of anisotropy



New optimization approach:

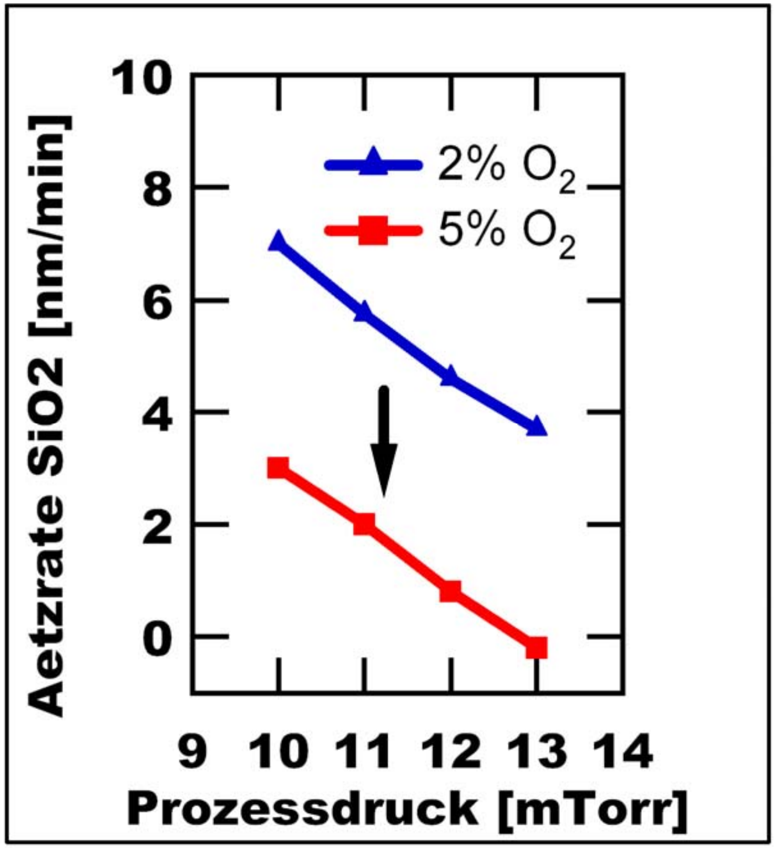
Increase of O_2 admixture

RIE Example: Highly Selective Silicon Etch Process

Process development: Optimizing process parameters

e.g. Variation of chamber pressur [mTorr]

NEW parameter: gas mixture: increase from 2% O_2 in HBr to **5%**



Result:

Rate optimized ($r_{SiO2min}$ ~ 0 nm/min)

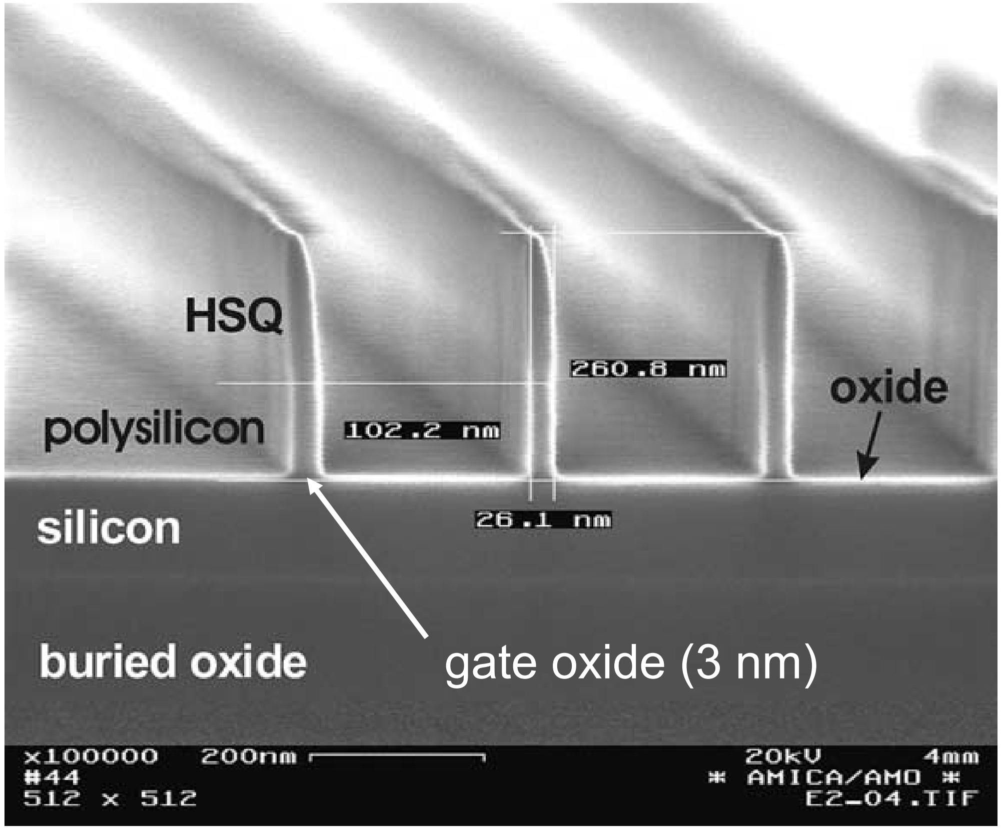
Next steps:

- Check polysilicon etch rate r_{Si}
- Check anisotropy

- If needed: further optimization:
  - RF power
  - Plasma power
  - Gas flow…

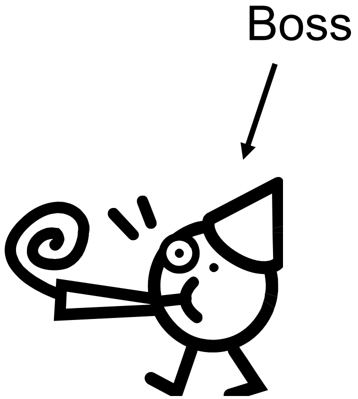
RIE Example: Highly Selective Silicon Etch Process

Result: highly selective, anisotropic HBr/O_2 RIE process



Scanning Electron Microscope (SEM) Image:

- 26 nm Poly-Si Gates
- Etch stop on 3 nm SiO_2



Optimized HBr/O_2 Process fulfils all requirements

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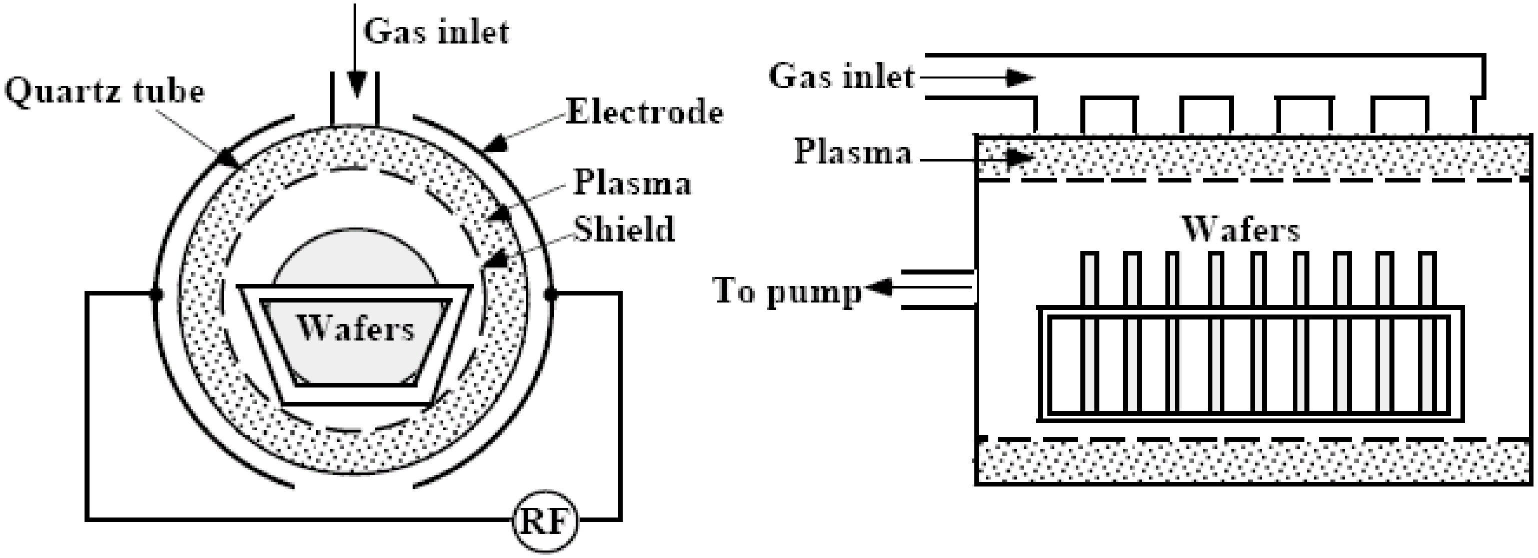
Plasma Etching: Reactor Designs

Different configurations have been developed to make use of chemical, physical or ion assisted etching mechanisms.

Barrel Etchers

- Purely chemical etching
- Used for non-critical steps, such as photoresist removal (”ashing”)



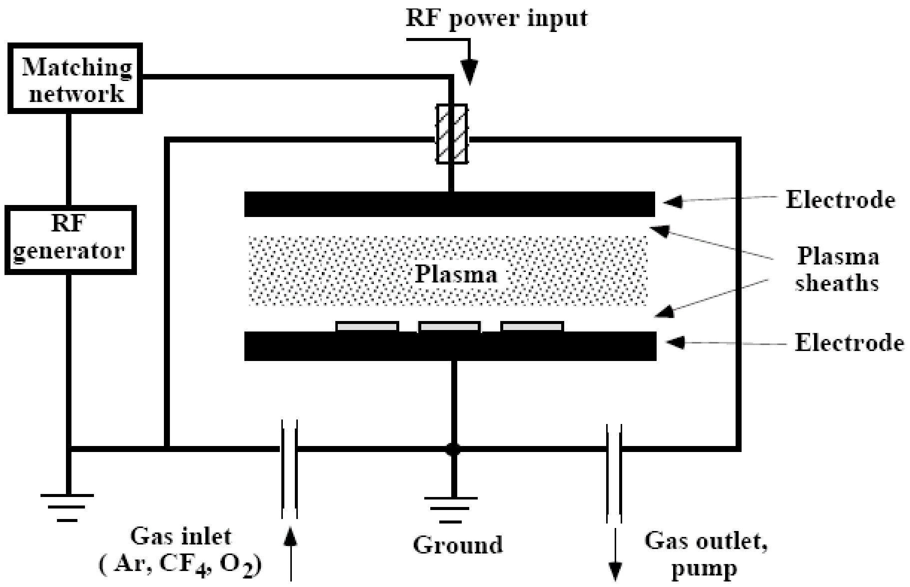
End view

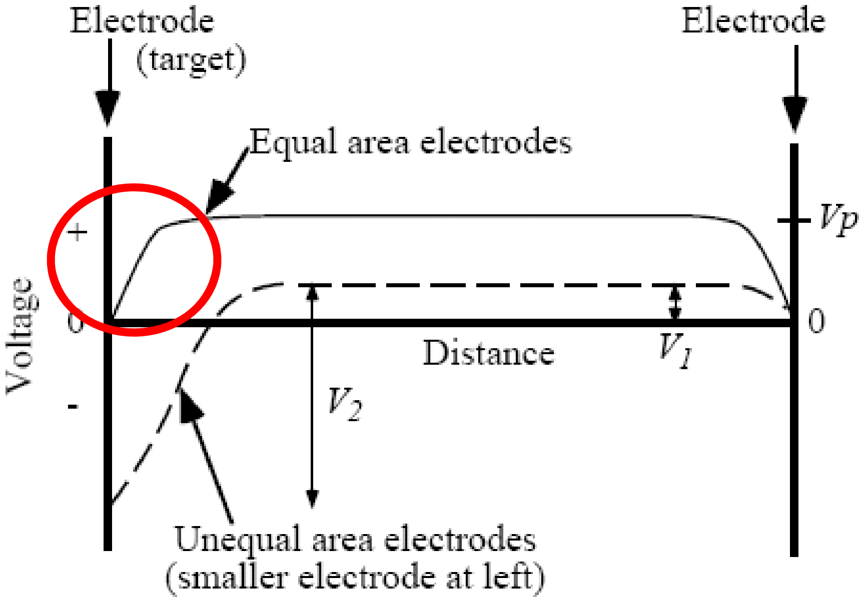
Side view

Plasma Etching: Reactor Designs

Parallel Plate Systems - Plasma Mode

- Electrodes have equal areas (or wafer electrode is grounded with chamber and larger)
- Only moderate sheath voltage (10-100 eV), so only moderate ionic component
- Strong chemical component
- Etching can be fairly isotropic and selective

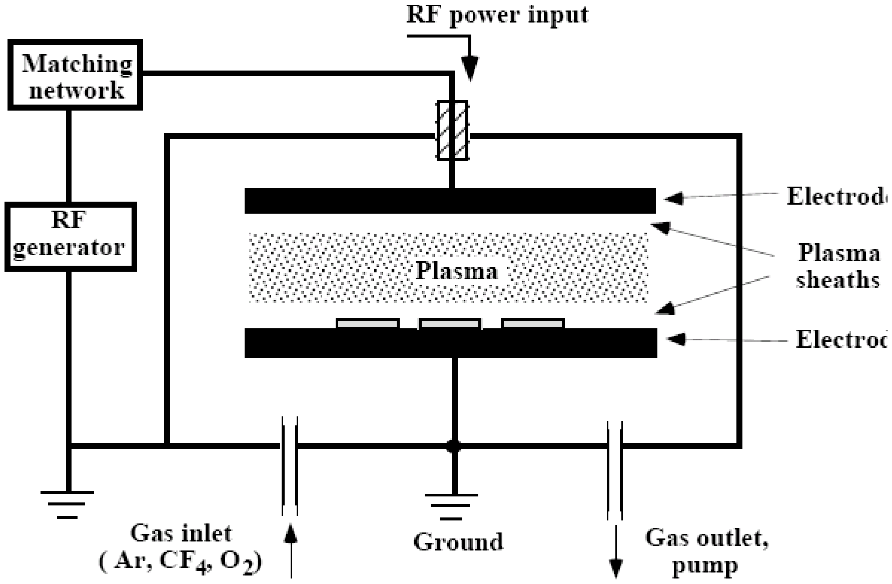


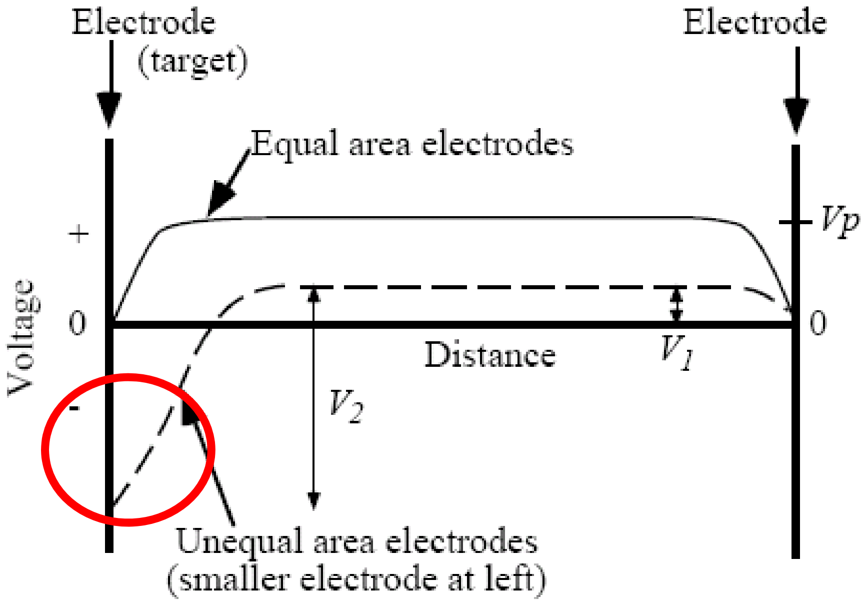


Plasma Etching: Reactor Designs

Parallel Plate Systems - Reactive Ion Etching (RIE) Mode

- For more directed etching, need stronger ion bombardment
- Wafers sit on smaller electrode (RF power there)
- Higher voltage drop across sheath at wafers.(100-700 eV)
- Lower pressures are used to attain even more directional etching (10-100 mtorr)
- More physical component than plasma mode for more directionality but less selectivity

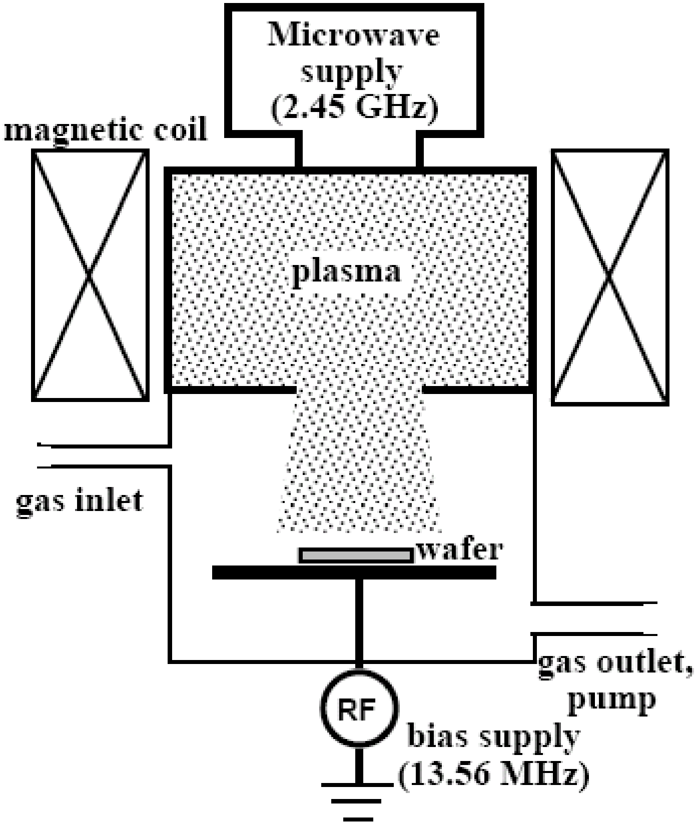




Plasma Etching: Reactor Designs

High Density Plasma (HDP) Etch Systems

- Uses remote, non-capacitively coupled plasma source (Electron cyclotron resonance - ECR, or inductively coupled plasma source - ICP)
- Uses separate RF source as wafer bias. ***This separates the plasma power (density) from the wafer bias (ion accelerating field)***



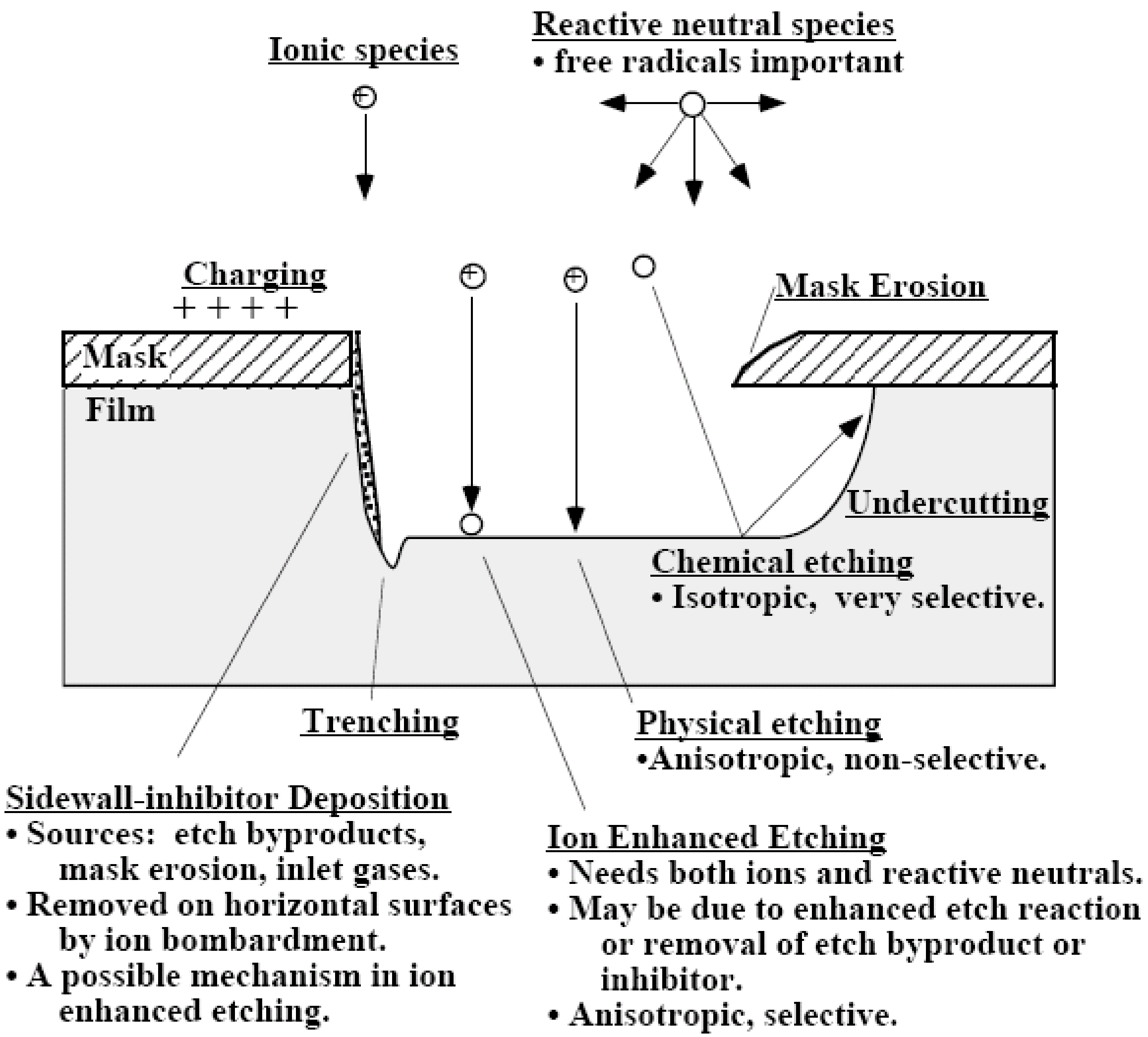
- Very high density plasmas (10^{11}-10^{12} ion cm^{-3}) can be achieved (faster etching)
- Lower pressures (1-10 mtorr range) can be utilized due to higher ionization efficiency (→ longer mean free path and → more anisotropic etching)
- These systems produce high etch rates, decent selectivity, and good directionality, while keeping ion energy and damage low

Widely used today!

Etching - Overview

- Basic Terminology
- Wet Etching
- Dry / Plasma Etching
  - Mechanisms
  - Example
  - Reactor Designs
- Summary and Appendix

Summary: Plasma Etching

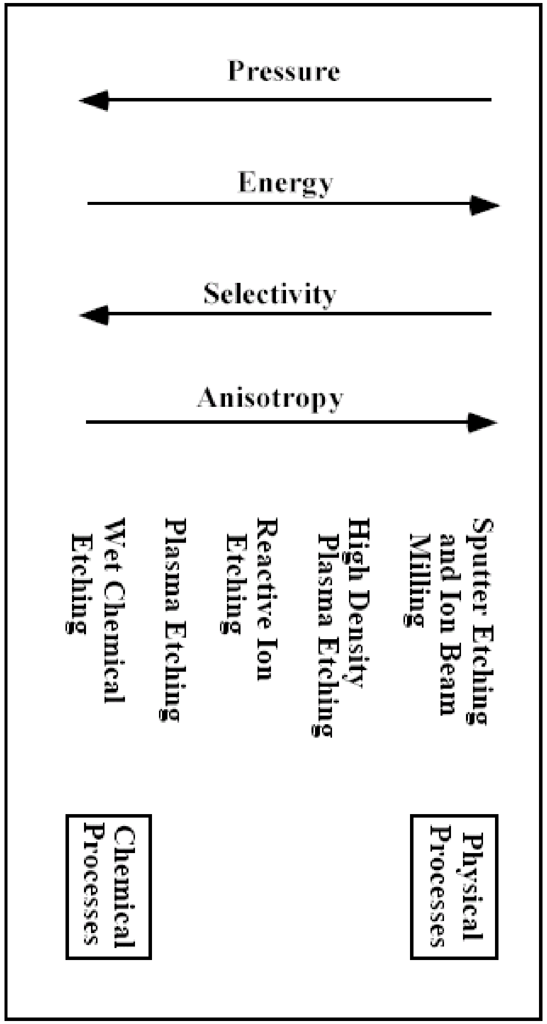


Chemical etching
- Isotropic, very selective.

Physical etching
- Anisotropic, non-selective.

Sidewall-inhibitor Deposition
- Sources: etch byproducts, mask erosion, inlet gases.
- Removed on horizontal surfaces by ion bombardment.
- A possible mechanism in ion enhanced etching.

Ion Enhanced Etching
- Needs both ions and reactive neutrals.
- May be due to enhanced etch reaction or removal of etch byproduct or inhibitor.
- Anisotropic, selective.



Summary: Etching

What's pattern transfer?

Lithography + Etching

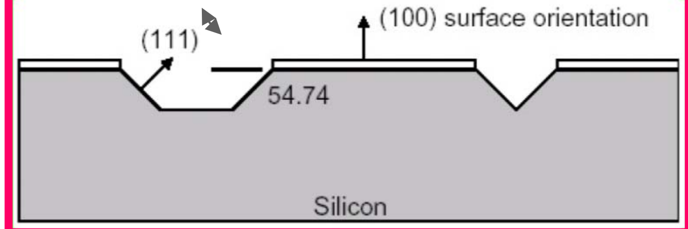
Tow critical issues?

Selectivity $S = \frac{r_1}{r_2}$ **Directionality** $A = 1 - \frac{r_{lat}}{r_{vert}}$

Wet Etching

Si——HNA, isotropic

——KOH, anisotropic



SiO_2——HF

MEMS

Dry Etching

Only Physical Etching (Sputter)

Reaction Ion Etching (RIE)

Directionality and Selectivity Improvement CF_4/O_2

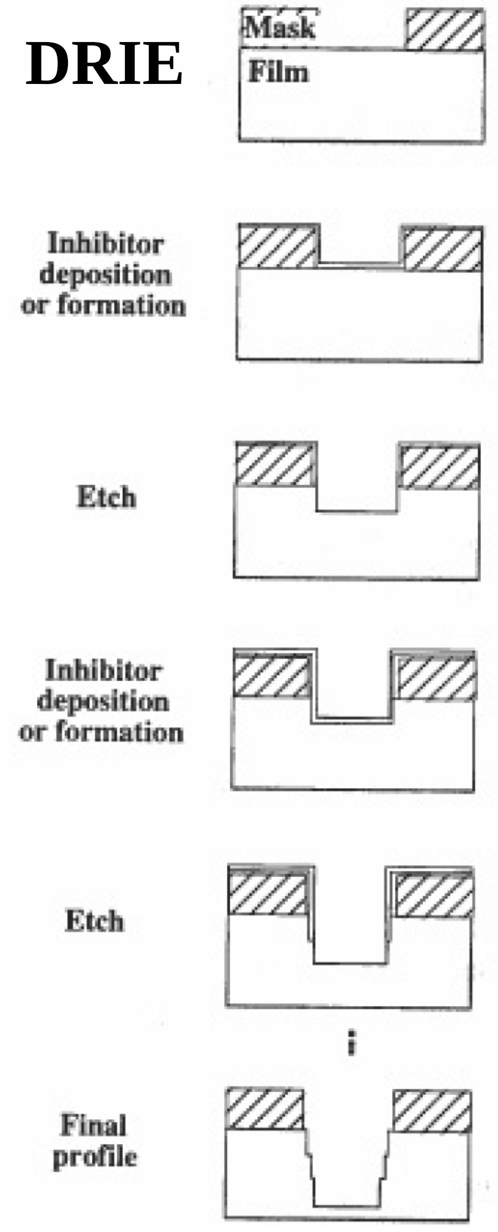
Only Chemical Etching PE

Summary of Key Ideas

- Etching of thin films is a key technology in modern IC manufacturing.
- Photoresist is generally used as a mask, but sometimes other thin films also act as masks.
- Selectivity and directionality (anisotropy) are the two most important issues. Usually good selectivity and vertical profiles (highly anisotropic) are desirable.
- Other related issues include mask erosion, etch bias (undercutting), etch uniformity, residue removal and damage to underlying structures.
- Dry etching is used almost exclusively today because of the control, flexibility, reproducibility and anisotropy that it provides.
- Reactive neutral species (e.g. free radicals) and ionic species play roles in etching.
- Generally neutral species produce isotropic etching and ionic species produce anisotropic etching.

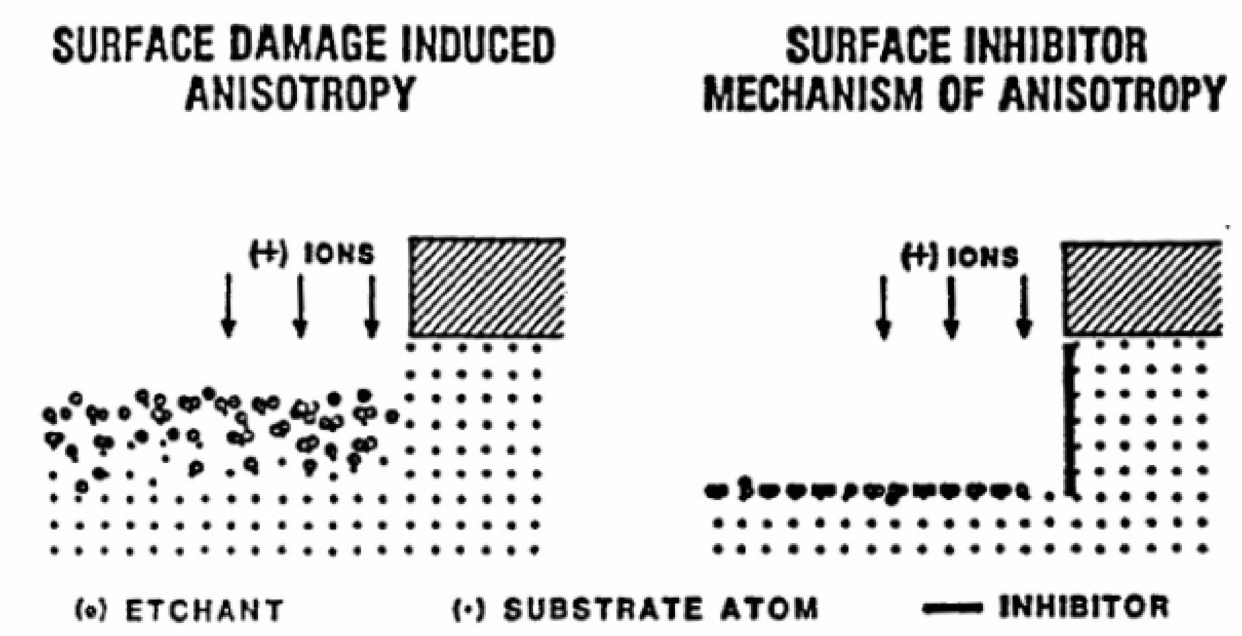
- Physical mechanisms:
    - Chemical etching involving the neutral species.
    - Physical etching involving the ionic species.
    - Ion-enhanced etching involving both species acting synergistically.

Appendix: Improving Etching Directionality



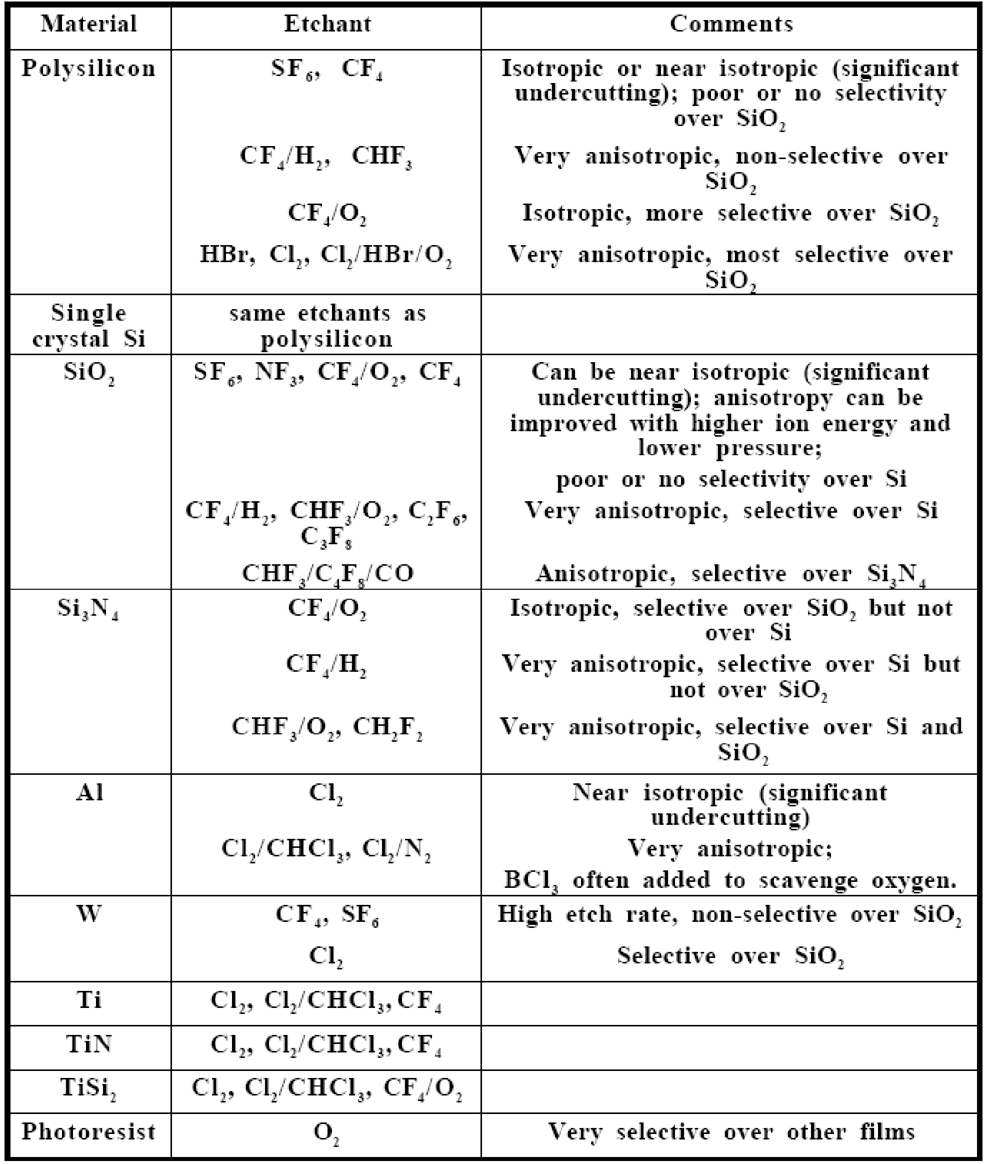
✓Increase ion bombardment (physical component)

✓Increase sidewall inhibitor



Appendix: Plasma Etching in Silicon Technology

Common etchants used for various films in silicon technology.



Material	Etchant	Comments
Polysilicon	SF_6, CF_4	Isotropic or near isotropic (significant undercutting); poor or no selectivity over SiO_2
	CF_4/H_2, CHF_3	Very anisotropic, non-selective over SiO_2
	CF_4/O_2	Isotropic, more selective over SiO_2
	HBr, Cl_2, $Cl_2/HBr/O_2$	Very anisotropic, most selective over SiO_2
Single crystal Si	same etchants as polysilicon	
SiO_2	SF_6, NF_3, CF_4/O_2, CF_4	Can be near isotropic (significant undercutting); anisotropy can be improved with higher ion energy and lower pressure; poor or no selectivity over Si
	CF_4/H_2, CHF_3/O_2, C_2F_6, C_3F_8	Very anisotropic, selective over Si
	$CHF_3/C_4F_8/CO$	Anisotropic, selective over Si_3N_4
Si_3N_4	CF_4/O_2	Isotropic, selective over SiO_2 but not over Si
	CF_4/H_2	Very anisotropic, selective over Si but not over SiO_2
	CHF_3/O_2, CH_2F_2	Very anisotropic, selective over Si and SiO_2
Al	Cl_2	Near isotropic (significant undercutting)
	$Cl_2/CHCl_3$, Cl_2/N_2	Very anisotropic; BCl_3 often added to scavenge oxygen.
W	CF_4, SF_6	High etch rate, non-selective over SiO_2
	Cl_2	Selective over SiO_2
Ti	Cl_2, $Cl_2/CHCl_3$, CF_4	
TiN	Cl_2, $Cl_2/CHCl_3$, CF_4	
$TiSi_2$	Cl_2, $Cl_2/CHCl_3$, CF_4/O_2	
Photoresist	O_2	Very selective over other films