ECE 416/516
IC Technologies
Lecture 12: Etching

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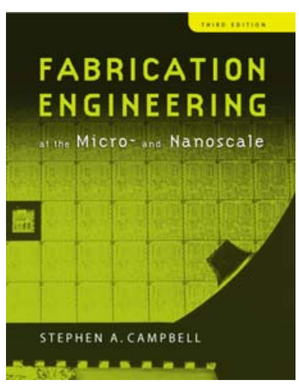
Spring 2012

Chapter 11

Etching



Lecture Topics & Objectives

- <u>Topics</u>

•Wet Etching
  - •Anisotropy
  - •Chemistry

•Dry Etching
  - •Bond chemistry
  - •Physical effects

•Reactive Ion Etching

•Ion Milling

- <u>Objectives</u>

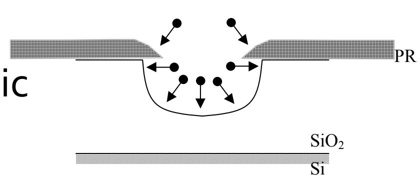
•Can explain the principles of wet and dry etch chemistries

•Can quantify anisotropies, etch rates, selectivity, loading,etc.

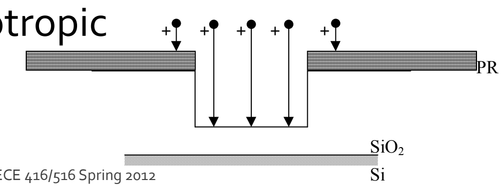
•Can explain RIE tradeoffs.

Wet and Dry Etching

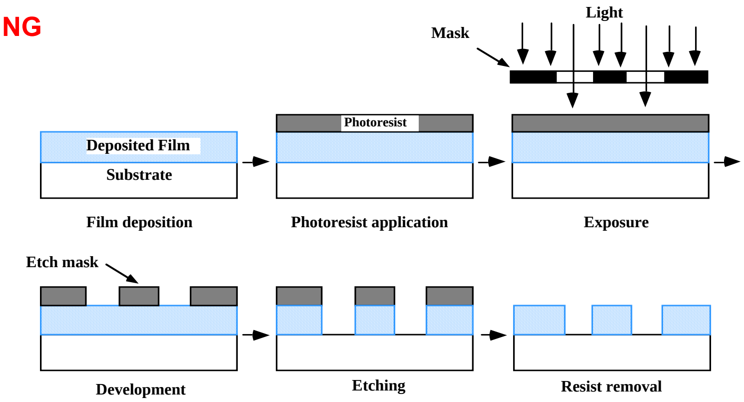
- Wet/isotropic



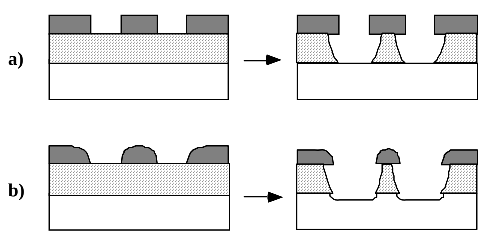
- Dry/anisotropic



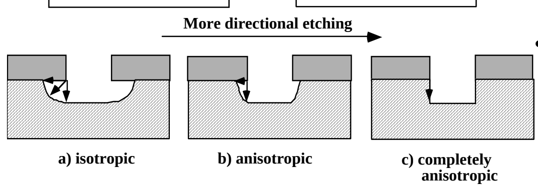
ETCHING



- Etching of thin films and sometimes the silicon substrate are very common process steps.
- Usually selectivity, and directionality are the first order issues.
- Selectivity comes from chemistry; directionality usually comes from physical processes. Modern etching techniques try to optimize both.
- Simulation tools are beginning to play an important role in etching just as they are in deposition. Topography simulators often do both, based on the same physical principles.



- Illustration of undercutting (directionality) and selectivity issues.



- Usually highly anisotropic (almost vertical profiles) and highly selective etching (ratios of 25-50) are desired, but these can be difficult to achieve simultaneously.

General etch requirements:

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

<u>Lift-off</u> (GaAs, MEMS)

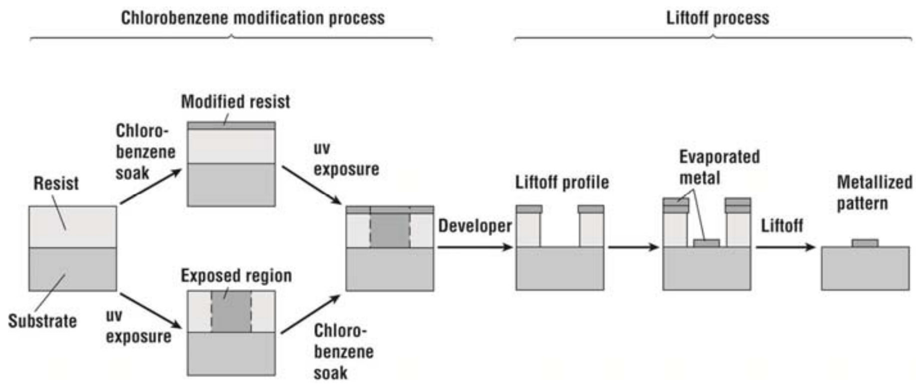


Figure 11.24 Process sequence for a liftoff operation *(after Hatzakis et al., © 1980 International Business Machines Corporation).*

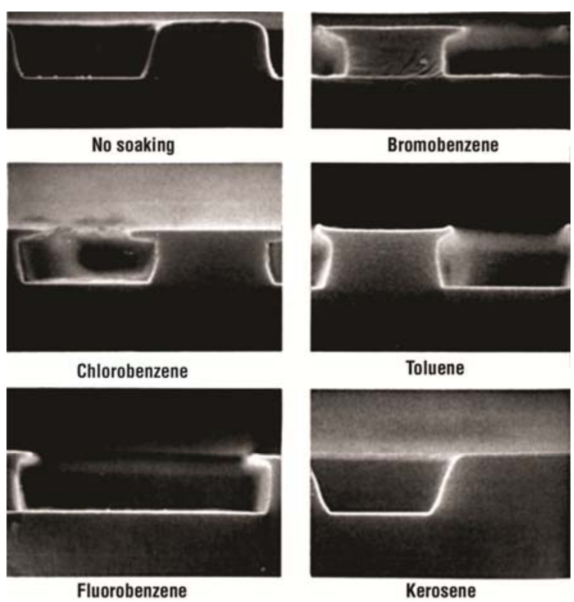


Figure 11.25 Liftoff profiles after various resist treatments *(after Hatzakis et al., © 1980 International Business Machines Corporation).*

Historical Development and Basic Concepts

- There are two main types of etching used in IC fabrication: wet etching and dry or plasma etching. Plasma etching dominates today.

Wet Etching and General Etching Ideas

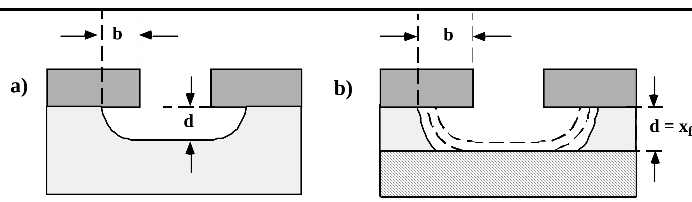
- Processes tend to be highly selective but isotropic (except for crystallographically dependent etches).

Examples:

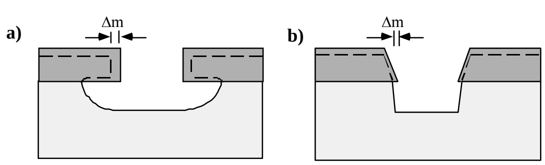
Etching of SiO_2 by aqueous HF: $SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$ (1)

Etching of Si by nitric acid (HNO_3) and HF: $Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2$ (2)

- Wafers typically submerged in specific chemical baths and rinsed in DI H_2O.



- Isotropic etching implies undercutting. This is often expressed in terms of the etch bias b.
- Etch anisotropy is defined as: $A_f = 1 - \frac{r_{lateral}}{r_{vertical}} = 1 - \frac{b}{d}$ (3)
- A_f = 0 for isotropic etching since $r_{lateral} = r_{vertical}$.
- Some overetching, shown above at right, is usually done to ensure complete etching (due to variations in film thickness and etch rate, r).
- Selectivity is usually excellent in wet etching ($S = r_1 / r_2$) since chemical reactions are very selective.



- Mask erosion can be an issue for both isotropic and anisotropic etching profiles.
- Because of their isotropic nature, wet chemical etches are rarely used in mainstream IC manufacturing today.

And Etch/Lithography Bias

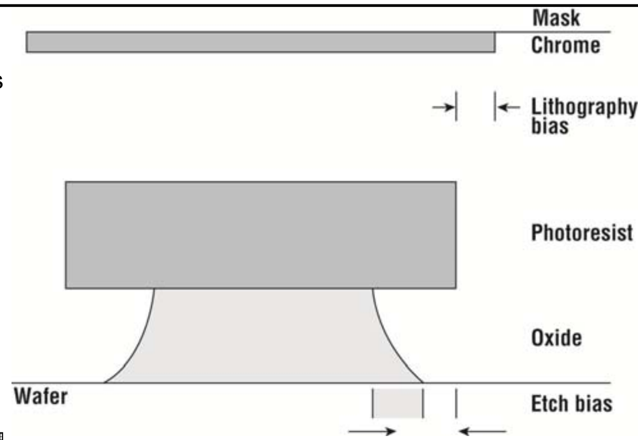
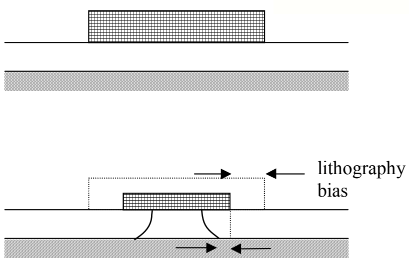


Figure 11.1 Typical isotropic etch process showing the etch bias.



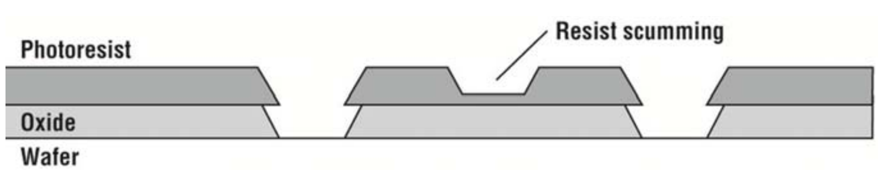


Figure 11.3 Resist scumming occurs when the photoresist is incompletely developed. The residual resist may serve as an etch mask to prevent a complete etch process.

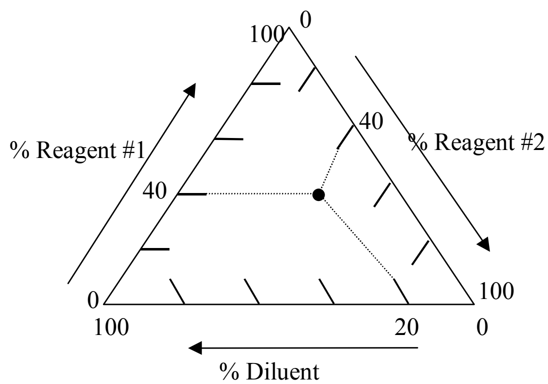
Wet Etching

*SiO_2: $Si + 6HF \rightarrow H_2 + SiF_6 + 2H_2O$
Reaction rate decreases as HF depleted
$\therefore$ Buffer: $NH_4F \leftrightarrow NH_3\uparrow + HF$

*Si: Typically oxidize Si and etch SiO_2, or
$Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2 + H_2O$

*Al: Strong acids or bases
$2\,Al + 6NaOH \rightarrow 2Na_3AlO_3 + 3H_2$
$2\,Al + 6HCl \rightarrow 2AlCl_3 + 3H_2$
But must first remove passivation oxide
$20\ CH_3COOH : 3\ HNO_3 : 77\ H_3PO_4$

Etch rates



Note clockwise sequence

Wet Etch

Si: (Typically oxidize Si and etch SiO_2)

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

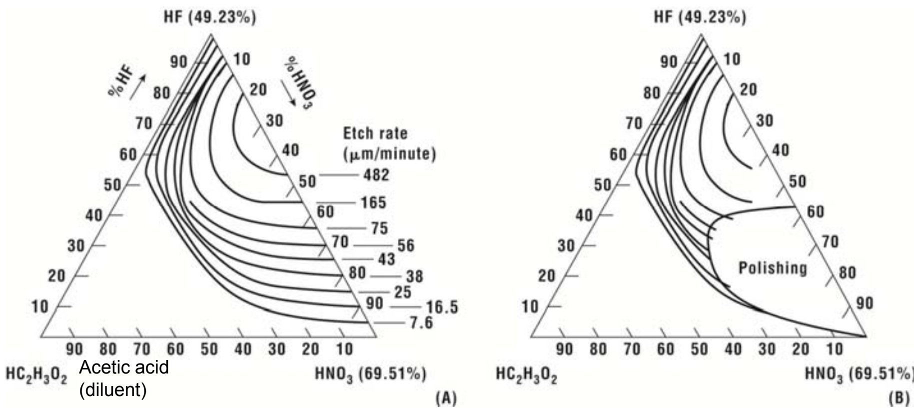


Figure 11.4 The etch rate of silicon in HF and HNO_3 *(after Schwarz and Robbins, reprinted by permission of the publisher, The Electrochemical Society Inc.)*.

Note clockwise sequence

Ex 11.1: 70% HNO3 : 49% HF : acetic acid = 2:6:2 = 20% + 60% + 20% → ~165μm/min

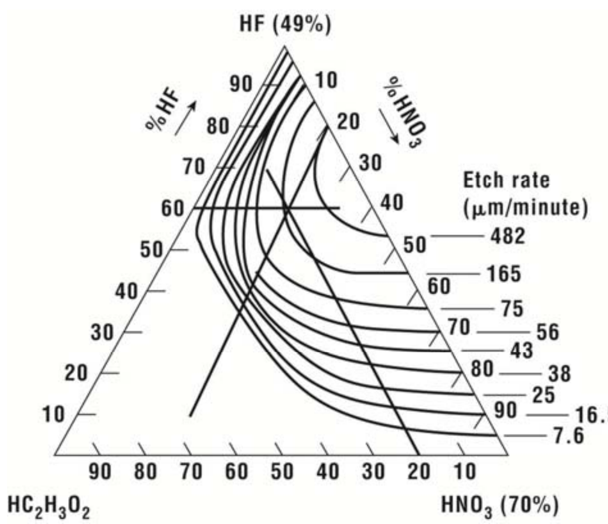
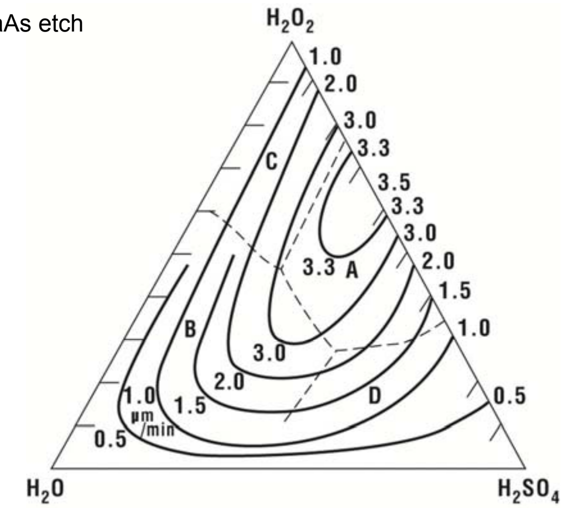


Figure 11.5 Intersection lines imposed on Figure 11.4A to show etch rate.

(Usually find possible concentrations for required etch rate)

GaAs etch



Note:
Scales increase clockwise

Figure 11.6 The etch rate of GaAs in H_2SO_4,H_2O_2, and H_2O. The right leg is the concentration of H_2SO_4, the bottom leg is H_2O, and the left leg is H_2O_2. All scales increase in the clockwise direction *(after Iida and Ito, reprinted by permission of the publisher, The Electrochemical Society Inc.).*

Anisotropic wet etching:

Solution etches (100)
100x faster than (111)

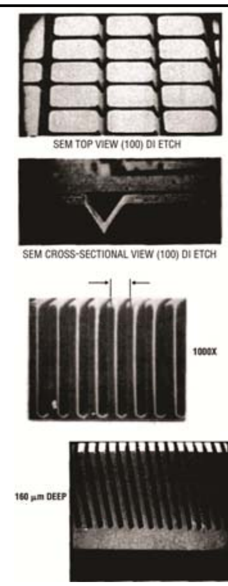


Figure 11.7 (100) silicon wafers after directional etching in KOH, isopropyl alcohol, and water. The upper photo shows a 50-µm-deep etch. The lower photographs are of 80-µm-deep trenches etched at 10-µm pitch on (110) and 10° off (110) *(after Bean [21], ©1978 IEEE).*

HF Sio$_2$ Etching #1

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

#1 $HF \leftrightarrow H^+ + F^-$

#2 $HF_2^- \leftrightarrow HF + F^-$

Dissociation constants ([ ] moles/litre):-

$K_1 = [H^+][F^-]/[HF] = 1.3\text{x}10^{-3}$

$K_2 = [HF][F^-]/[HF^-_2] = 0.104$

Etch rate R(nm/s) =

$0.25\ [HF] + 0.966[HF^-_2] - 0.014$

Eliminate $[F^-]$ from K_1, $K_2 \rightarrow$

$$K_1[HF]/[H^+] = K_2\ [HF^-_2]\ /\ [HF]$$

$$[HF^-_2] = (K_1/K_2)[HF]^2/[H^+]$$

Also $[HF] + [F^-] + 2[HF^-_2] = 1$, for 1litre 1M solution

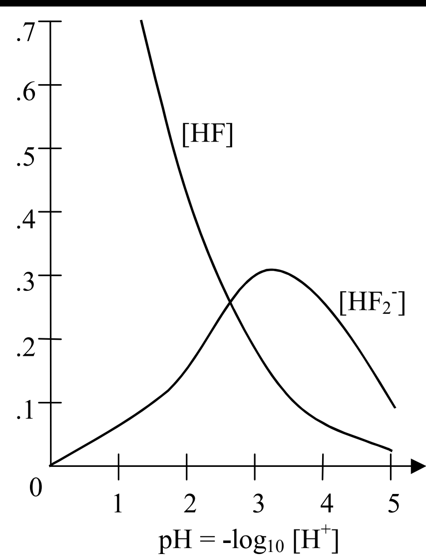
i.e. $\rightarrow [HF] + K_1[HF]/[H^+] + 2(K_1|K_2)\ [HF]^2/[H^+] = 1$

$\therefore\ [HF]^2 + [HF]([H^+] + K_1)(K_2/2K_1) = [H^+](K_2/2K_1)$

$$\&\ [HF] = \frac{K_2}{2}\left(1+\frac{[H^+]}{K_1}\right)\left[1+\frac{8\backslash K_2}{1+[H^+]\backslash K_1}\right]^{1/2} - 1$$

HF Sio$_2$ Etching #2

- As HF used up, reaction slows. Hence use buffer to replenish
- $NH_4F \leftrightarrow NH_3 + HF$
- $NH_4F \leftrightarrow NH_4^+ + F^-$
- $NH_4^+ \leftrightarrow NH_3 + H^+$
- $NH_4F \leftrightarrow NH_3 + HF$
- Optimum pH=2.8



Selective Etching

- Resistivity Sensitive or Concentration Dependent

- Can use low rate material as etch stop
  - e.g. if etch attacks heavily doped Si, but not low doped
  - Grow thin epi n-layer on substrate surface
  - Etch right through heavy doped substrate
  - Leave thin epi-layer diaphragm

- Also preferential etching (defects), staining, etc.

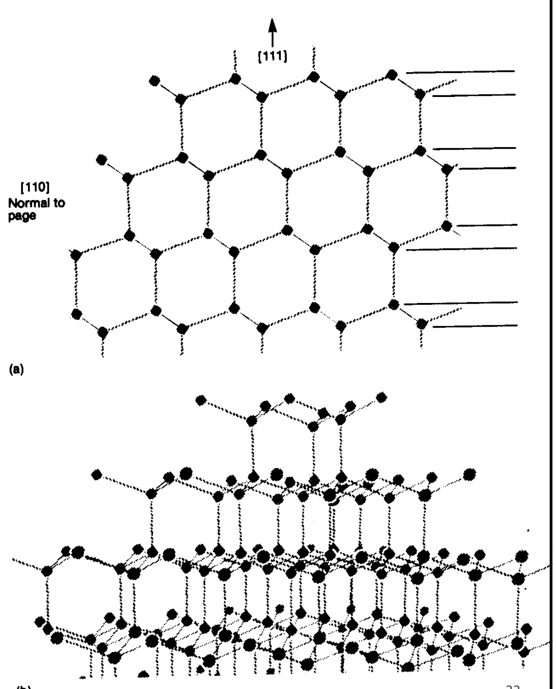
Anisotropic Etch #1

[111] ↑

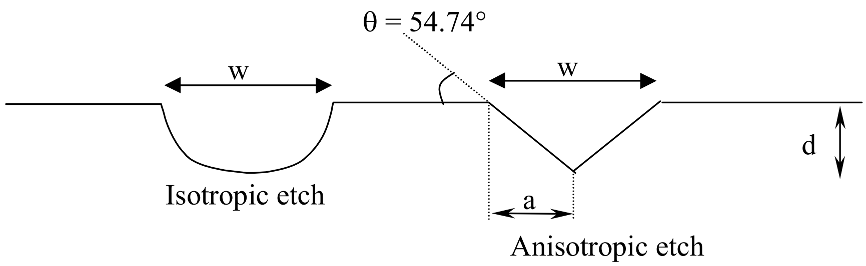
[110]
normal to screen

[111] direction:
double atom layers
(double bonding)

Some etches
work very slowly
in [111] direction.



Anisotropic Etch #2



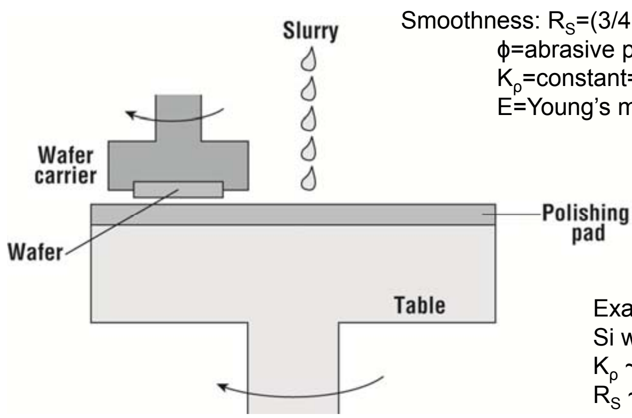
$w = 2a = 2d/\tan\theta = 2d/\tan 54.74^{\circ} = 2d/1.4$

Applications: MEMS.
eg. $Si + H_20 + 2K0H \rightarrow K_2Si0_3 + 2H_2$

CMP

Removal rate: $RR = k_P.P.v$
- k_P=Preston's coefficient
- P=pressure applied
- v=relative velocity (pad & wafer)

Smoothness: $R_S=(3/4)\phi P/(2K_\rho E)$
- ϕ=abrasive particle diameter
- K_ρ=constant=f(particle density)
- E=Young's modulus



Example:
Si with 100nm SiO_2
K_ρ ~ 0.5, P=1.5MPa
R_S ~ 0.3nm

Figure 11.8 Chemical mechanical polishing of the surface of a partially processed wafer done to achieve a high degree of global planarization.

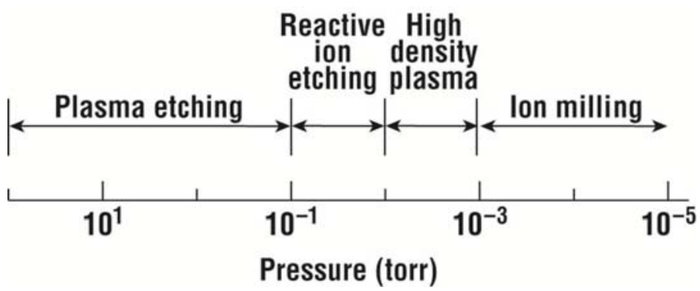
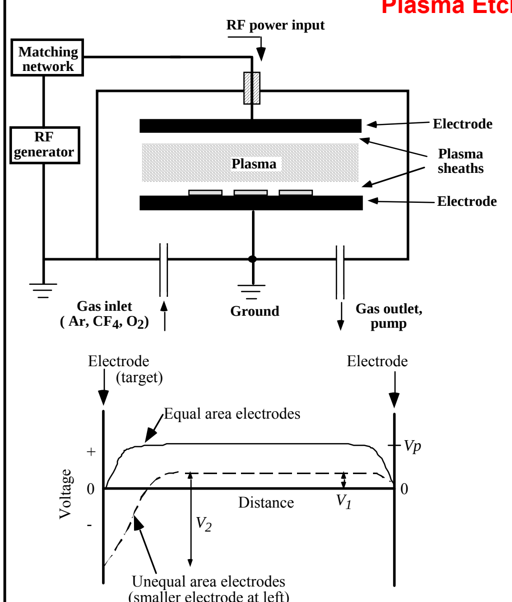


Figure 11.2 Types of etch processes on a chamber pressure scale.

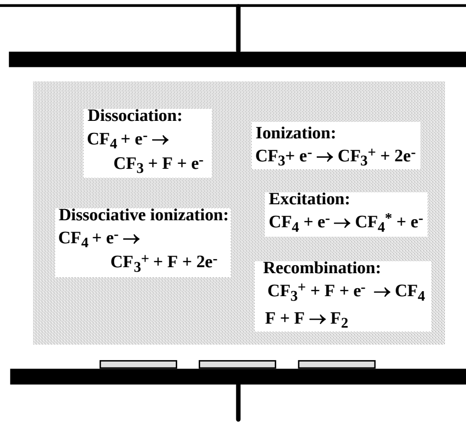
Plasma Etching



Developed and used for:
1. Faster and simpler etching in a few cases.
2. More directional (anisotropic) etching!!

- **Typical RF-powered plasma etch system look just like PECVD or sputtering systems. (See lectures 11 & 13)**
- **Both chemical (highly reactive) species and ionic (very directional) species typically play a role.**

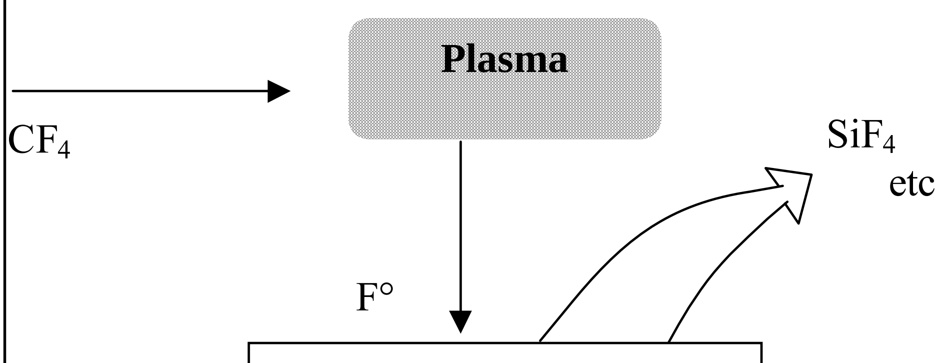
- **V_P is positive to equalize electron and ion fluxes.**
- **Smaller electrode has higher fields to maintain current continuity (higher RF current density).**



- Etching gases include halide-containing species such as CF_4, SiF_6, Cl_2, and HBr, plus additives such as O_2, H_2 and Ar. O_2 by itself is used to etch photoresist. Pressure = 1 mtorr to 1 torr.
- Typical reactions and species present in a plasma used are shown above.
- 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 (as determined by the sheath voltage). Increasing the power increases both.

Plasma Etch Principles

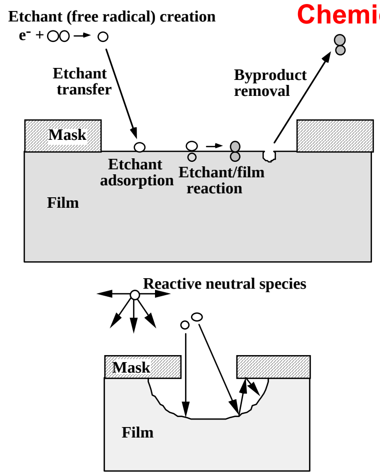
- Etch Si with CF_4:



- $Si + F^* \rightarrow SiF_4\uparrow$

Plasma Etching Mechanisms

- There are three principal mechanisms:
  - chemical etching (isotropic, selective)
  - physical etching (anisotropic, less selective)
  - ion-enhanced etching (anisotropic, selective)



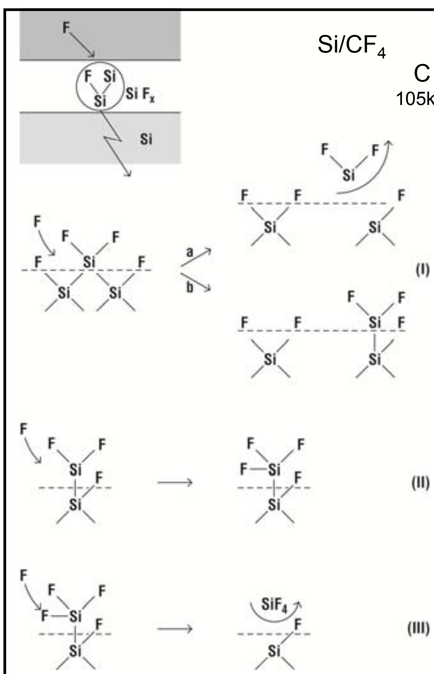
Chemical Etching

- Etching done by reactive neutral species, such as "free radicals" (e.g. F, CF_3)

$$e^- + CF_4 \rightarrow CF_3 + F + e^- \quad (4)$$

$$4F + Si \rightarrow SiF_4 \quad (5)$$

- Additives like O_2 can be used which react with CF_3 and reduce CF_3 + F recombination. ∴ higher etch rate.
- These processes are purely chemical and are therefore isotropic and selective, like wet etching.
- Generally characterized by $\cos^n \theta$ (n=1) arrival angle and low sticking coefficient ($S_c \approx 0.01$).



Si/CF_4

C — F + Si — Si = Si — F + 17 kcal/mole

105kcal/mole & 42.2kcal/mole

147kcal>130kcal, so no direct etch

Plasma → high E electrons crack CF_4 → free F^- (&CF_3^+)

← SiF_2 bonded to surface → released with extra F

Figure 11.9 Proposed mechanism of plasma etching of silicon in CF_4. A 1- to 5-atom-thick SiF_x layer forms on the surface. A silicon atom on the upper level is bonded to two fluorine atoms. An additional fluorine atom may remove the silicon as SiF_2. It is much more likely, however, that additional fluorine atoms bond to the silicon atom until SiF_4 forms and desorbs *(after Manos and Flamm, reprinted by permission, Academic Press).*

Plasma Etch Chemistry

Bond strengths:

C-*-F	+	Si-*-Si	=	Si-F	+ 17 kcal/mole
105 kcal/mole		42.2 kcal/mole		230 kcal/mole	

Energy added by plasma collisions to break C - F bonds

Etch SiO_2 with CF_x radicals

$$3SiO_2 + 4CF^+_3 \rightarrow 2CO + 2CO_2 + 3SiF_4$$
$$SiO_2 + 2CHF^+_2 \rightarrow 2CO + H_2 + SiF_4$$

(F-*-F + Si-*-0 = Si-F - 5 kcal/mole,
so F/SiO_2 etch very slow)

SiO_2/F F ⌣ F + Si ⌣ O = Si—F - 5kcal/mole, so energy needed
CF_3 more aggressive

Add O_2 to feed gas

Increases etch rates of Si and SiO_2

(O removes C?)

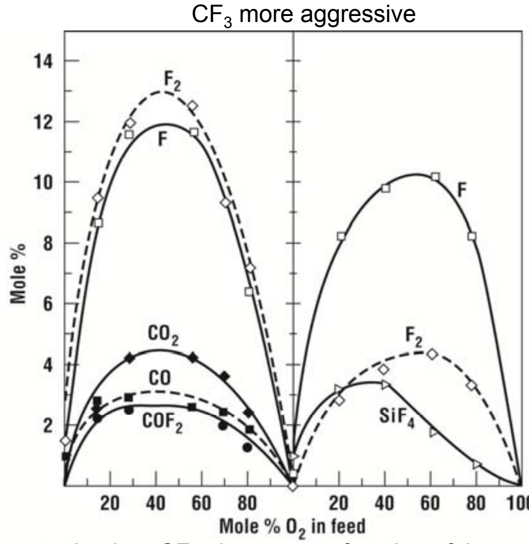


Figure 11.10 Species concentration in a CF_4 plasma as a function of the amount of oxygen in the feed gas *(after Smolinsky and Flamm, reprinted by permission, AIP).*

Feed Gas

F toxic

$\therefore$ CF_4, C_2F_6, SF_6 preferred

All produce high F^* concentrations

- Addition of 0_2 removes C

  Pushes CF_4 breakup to right

  Increases F^* concentration

  + 12% $0_2 \rightarrow$ order increase in $[F^*]$

- Conversely, add $H_2 \rightarrow$ removes F

  C rich plasma $\rightarrow$

  non-volatile polymerization" products

  (on side-walls)

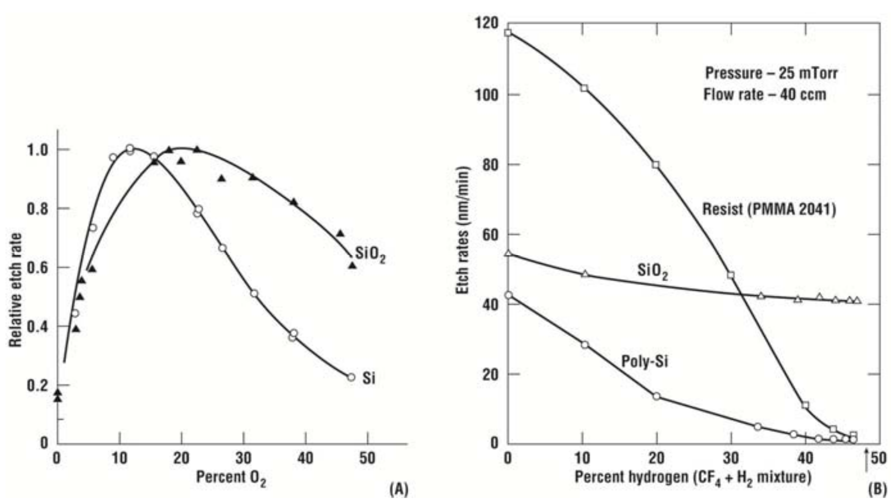


Figure 11.12 Etch rate of Si and SiO_2 in (A) CF_4/O_2 plasma *(after Mogab et al. [59], reprinted by permission, AIP)*, and (B) CF_4/H_2 plasma *(after Ephrath and Petrillo [100], reprinted by permission of the publisher, The Electrochemical Society Inc.)*

Selectivity #1

Example: Etch SiO_2 film on Si.

Etch rate $E_f = E_0 \pm e$

SiO_2 thickness $D_f = D_0 \pm d$

Nominal etch time $t_0 = D_0/E_0$

Thin areas etch in $t_1 = (D_0 - d)/(E_0 + e)$, and

Worst case final time $t_2 = (D_0 + d)/(E_0 - e)$

$\therefore$ Underlying Si may be etched for time

$\Delta t' = t_2 - t_1 = 2(E_0 d + D_0 e)/(E_0^2 - e^2)$

in some areas, plus design margin $\Delta t''$

If max. thickness Si which can be removed is D_s at etch rate E_s, then $E_s < D_s/(\Delta t' + \Delta t'')$

Selectivity #2

Material	Etch	Selectivity wrt:
Thermal SiO_2	$C_2F_6 + CHF_3$	Si – 5:1 PR – 5:1
Doped CVD SiO_2	$C_2F_6 + CHF_3$	Si – 30:1 PR – 10:1
Poly-Si	Cl_2	SiO_2 – 15:1 PR – 5:1
Al	$BCl_3 + Cl_2$	SiO_2 – 5:1 PR – 5:1 poly-Si – 3:1
Si_3N_4	$CF_4 + O_2$	CVD SiO_2–1:1 PR–3:1 polySi–1:8
Photo-resist (PR)	O_2	SiO_2 - 10^3:1 Si - 10^3:1

Loading Effects/End Point

- Etch rate R = $R_0/(1 + kA)$

for total etching area A

$1/R = 1/R_0 + kA/R_0$

Linear 1/R vs A fails for multi-etch

- End point:

Optical interference

End of reaction products in plasma

-mass spectrometry of effluent

-plasma optical emission spectrum

Increase in active reagent.

Loading effect (Example 11.2)

Plasma etch process at 30nm/min for single wafer. With 2 wafers, etch rate drops to 24nm/min. Predict etch rates for 3 and 4 wafers.

Loading effect: Etch rate decreases with area being etched.

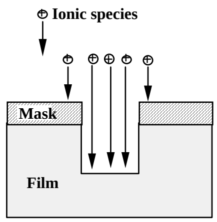
Eq'n 11.8: Rate $R = \frac{R_0}{1+kA}$ where R_0=empty chamber rate, A=etch area, and k=constant

So: $\frac{R_1}{R_2} = \frac{30}{24} = 1.25 = \frac{1+2kA_1}{1+kA_1}$

$$\text{giving } kA_1 = \frac{1}{3}, \text{ and } R_0 = R_1(1+kA_1) = 40nm/\min$$

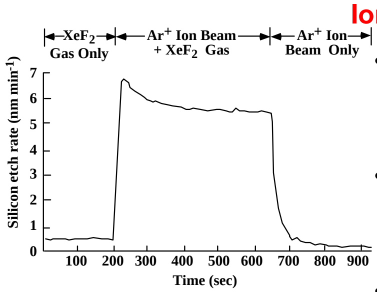
$$\text{so } R_3 = \frac{40nm/\min}{1+3(1/3)} = 20nm/\min, \text{ and } R_4 = \frac{40nm/\min}{1+4(1/3)} = \frac{120}{7} \approx 17nm/\min$$

Physical Etching

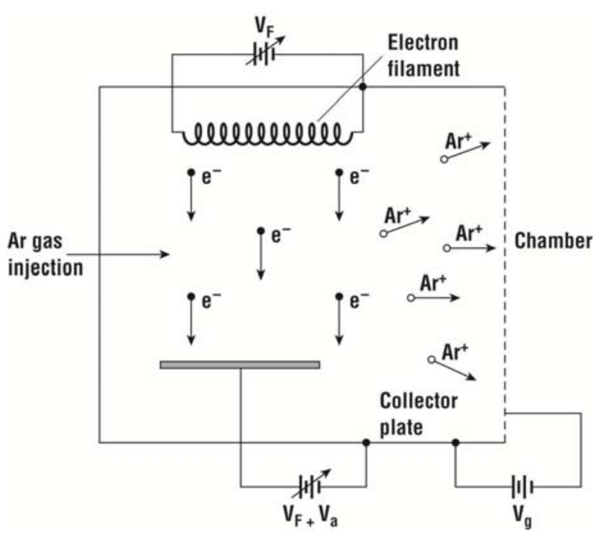


- Ion etching is much more directional (ε field across plasma sheath) and $S_c \approx 1$, i.e. ions don't bounce around (or if they do, they lose their energy.)
- Etching species are ions like CF_3^+ or Ar^+ which remove material by sputtering.
- Not very selective since all materials sputter at about the same rate.
- Physical sputtering can cause damage to surface, with extent and amount of damage a direct function of ion energy (not ion density).

Ion Enhanced Etching



- The chemical and physical components of plasma etching do not always act independently - both in terms of net etch rate and in resulting etch profile.
- Figure shows etch rate of silicon as XeF_2 gas (not plasma) and Ar^+ ions are introduced to the silicon surface. Only when both are present does appreciable etching occur.
- Etch profiles can be very anisotropic, and selectivity can be good.



Ion current

$$j_{\max} \approx K\sqrt{\frac{q}{m}}\frac{V_t^{3/2}}{l_g^2}$$

K=constant (chamber)
q/m=ionic charge/mass
V_t= grid potential difference (screen to accelerator)
l_g=grid separation (1-2mm)

Figure 11.15 Cross section schematic of a Kaufman ion source.

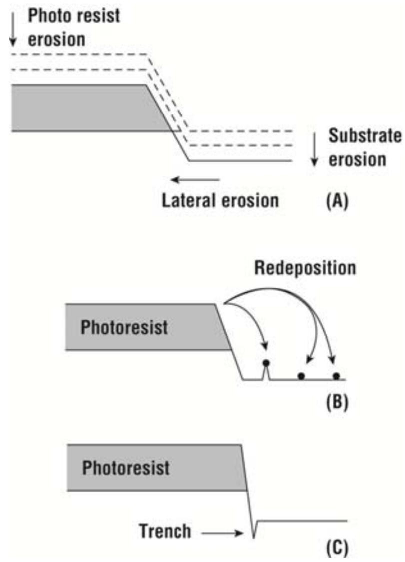


Figure 11.16 Problems that may occur during ion milling: (A) mask taper transfer, (B) redeposition from the mask, and (C) trenching.

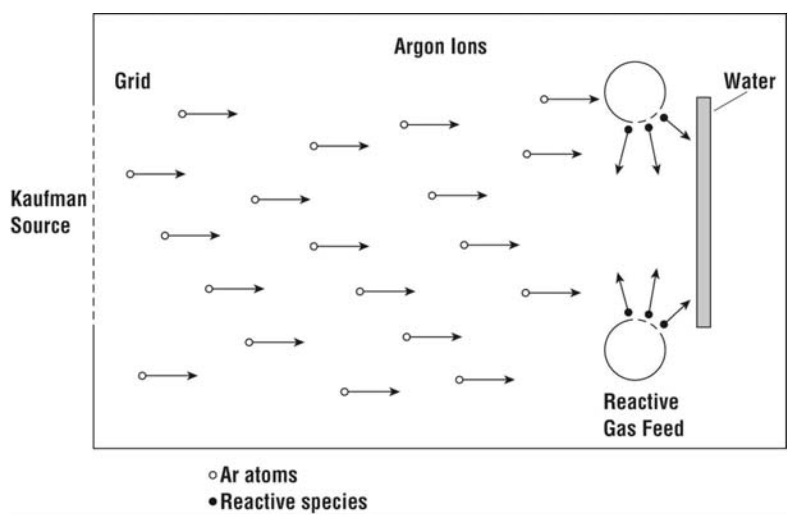
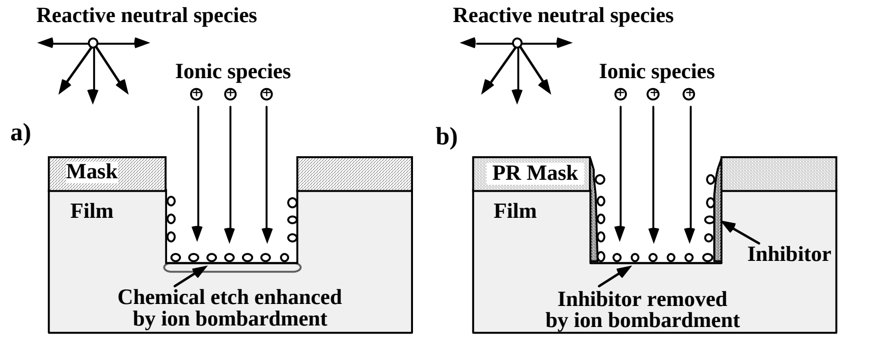


Figure 11.17 The use of a reactive bleed near the wafer surface in a conventional ion mill to introduce a chemical component to the etch process.



- Many different mechanisms proposed for this synergistic etching between physical and chemical components. Two mechanisms are shown above.
- Ion bombardment can enhance etch process (such as by damaging the surface to increase reaction, or by removing etch byproducts), or 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.

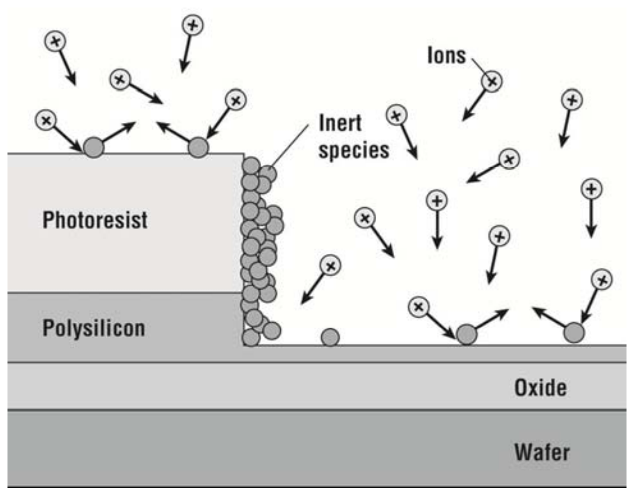
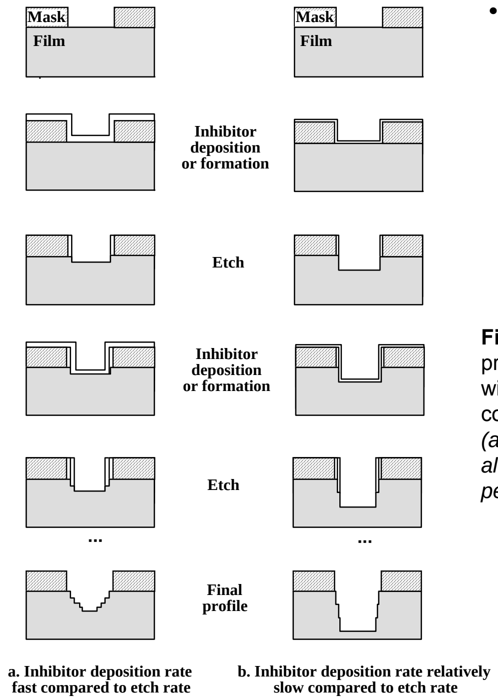


Figure 11.11 Schematic diagram of a high pressure anisotropic etch showing the formation of sidewall passivating films.



- **Can actually get sloped sidewalls without undercutting. Depends on ratio of inhibitor formation ("deposition") to etching, as shown.**

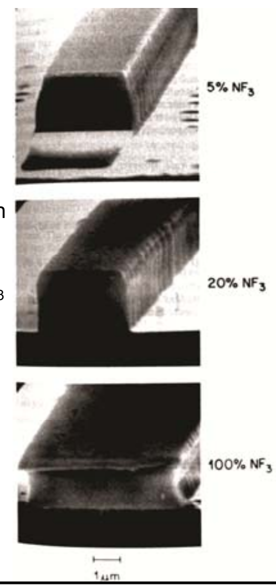
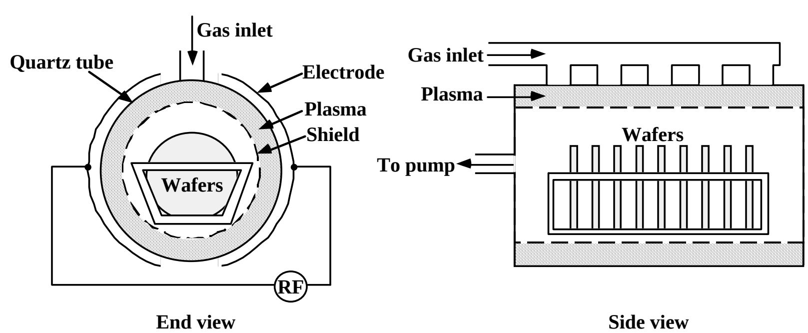


Figure 11.13 Etch profiles of SiO_2 with increasing concentration NF_3 *(after Donnelly et al., reprinted by permission, AIP).*

Types of Plasma Etching Systems

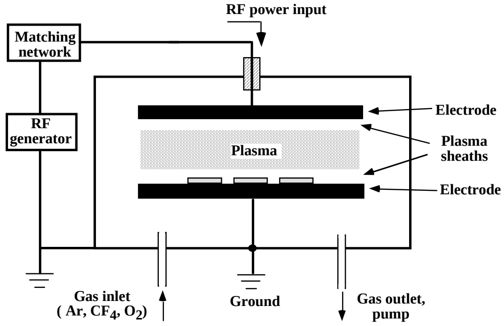
- **Different configurations have been developed to make use of chemical, physical or ion assisted etching mechanisms.**

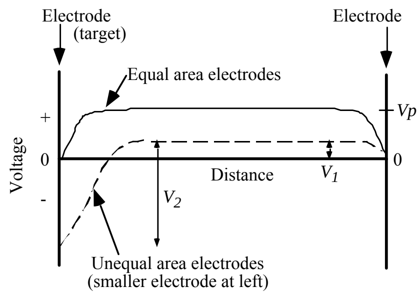
Barrel Etchers



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

Parallel Plate Systems - Plasma Mode



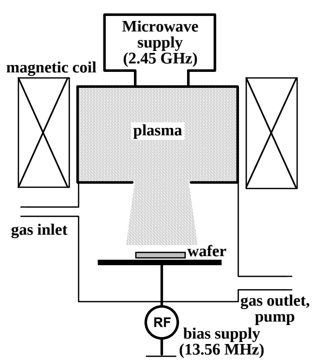


- Electrodes have equal areas (or wafer electrode is grounded with chamber and ∴ larger)
- Only moderate sheath voltage (10-100 eV), so only moderate ionic component. Strong chemical component.
- Etching can be fairly isotropic and selective.

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 ∴ directionality but less selectivity.

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.

RIE Systems

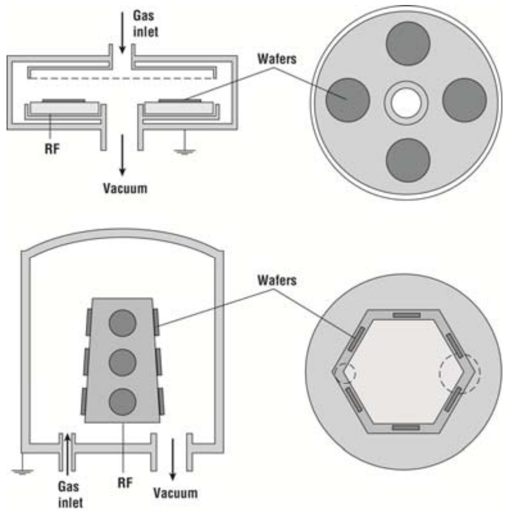


Figure 11.18 Top and side views of parallel-plate and hexode batch RIE systems. Typical conditions for either are 50 mtorr and 5 kW/m^2. For larger wafers the exhaust in the upper figure is drawn from the periphery rather than the center.

Cl can adhere to surface, block reaction
Hence accelerate reaction by ion bombardment

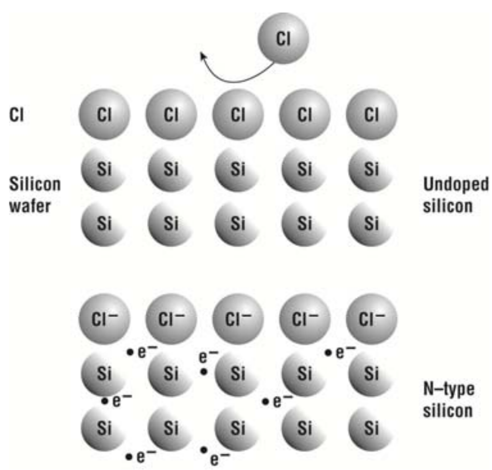


Figure 11.19 Once a monolayer of chlorine atoms has built on the surface, it impedes any chlorine addition.

Reactive Ion Etching (RIE)

Ion assisted etching

Wafers on cathode: ion bombardment

Electron transfer from substrate.

Examples:

RIE: Si/F_2 RIE: Si/Cl_2

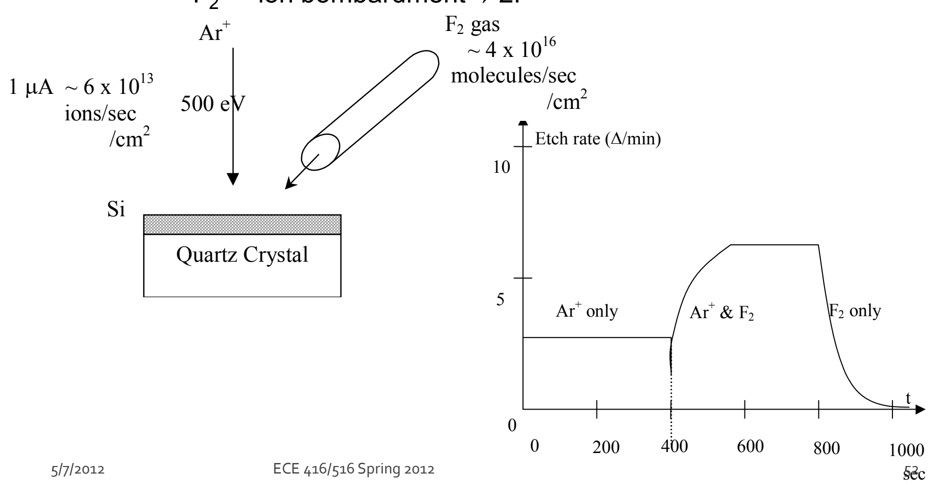
RIE: Si/XeF_2 RIE: Al/F_2

Electron stimulated etching

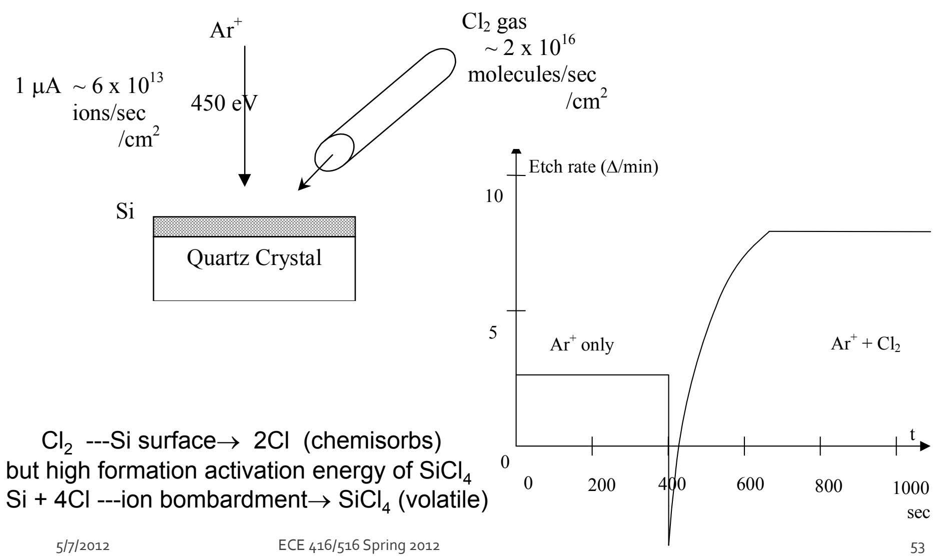
RIE: Si/F_2

$Si + 4F \rightarrow SiF_4$ (volatile) but low dissociation of F_2 on Si

F_2 ---ion bombardment$\rightarrow$ 2F

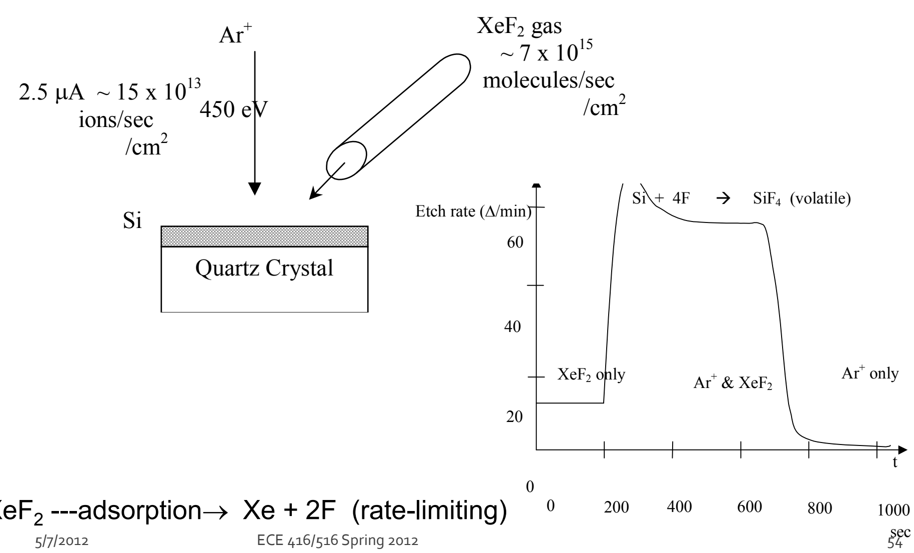


RIE: Si/Cl_2



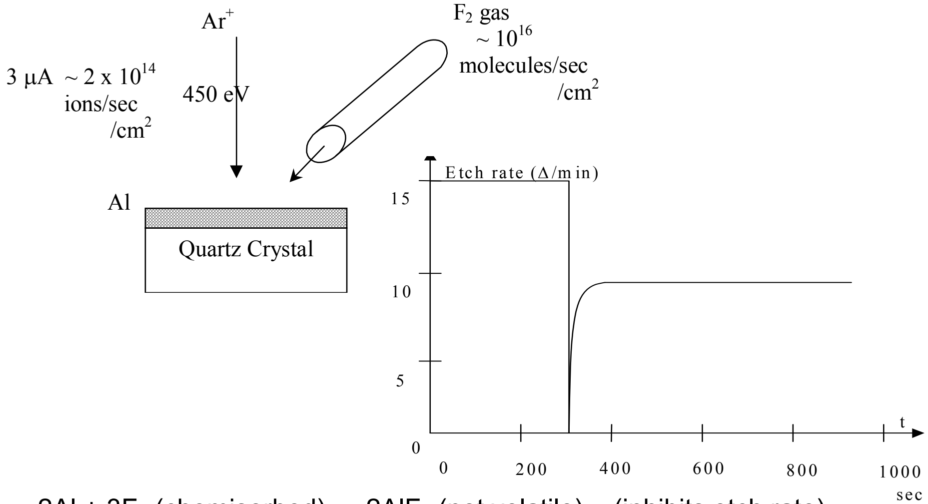
Cl_2 ---Si surface→ 2Cl (chemisorbs)
but high formation activation energy of $SiCl_4$
Si + 4Cl ---ion bombardment→ $SiCl_4$ (volatile)

RIE: Si/XeF_2



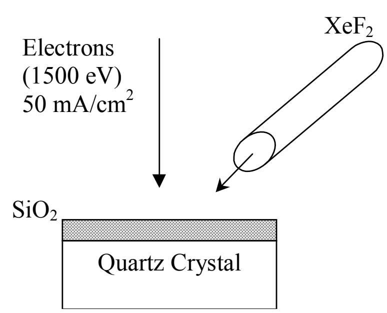
XeF_2 ---adsorption→ Xe + 2F (rate-limiting)

RIE: Al/F_2



2Al + $3F_2$ (chemisorbed) → $2AlF_3$ (not volatile) (inhibits etch rate)

Electron Stimulated Etching: SiO_2



Etch rate 20nm/min

No etching with just XeF_2 ($6x10^{-4}\tau$)

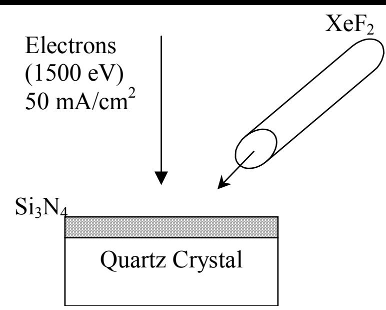
No etching with just electron beam ($4x10^{-4}\tau$)

XeF_2 → Xe + 2F (dissociative chemisorption on SiO_2)

SiO_2 ---electron beam→ Si + O_2

Si + 4F → SiF_4 (volatile)

Electron Stimulated Etching: Si_3N_4



Etch rate 60nm/min

No etching with just XeF_2 ($6x10^{-4}\tau$)

No etching with just electron beam ($4x10^{-4}\tau$)

$XeF_2 \rightarrow Xe + 2F$ (dissociative chemisorption on Si_3N_4)

$Si + 4F \rightarrow SiF_4$ (volatile)

RIE damage

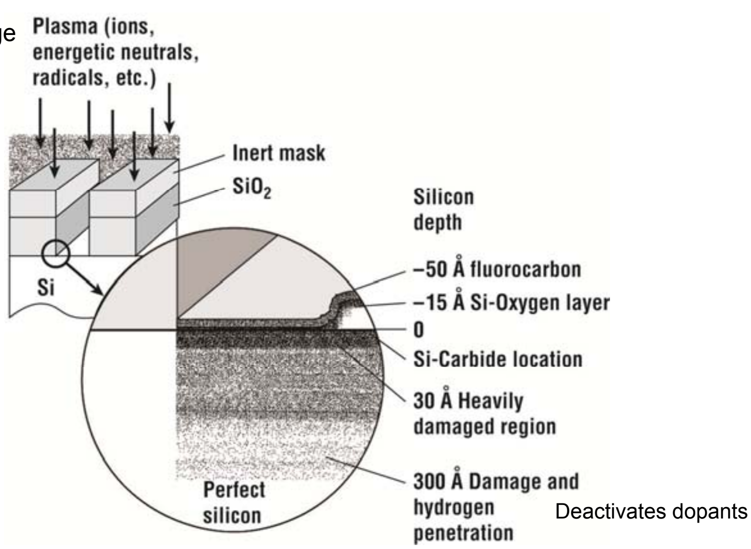
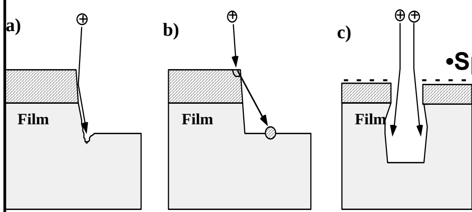


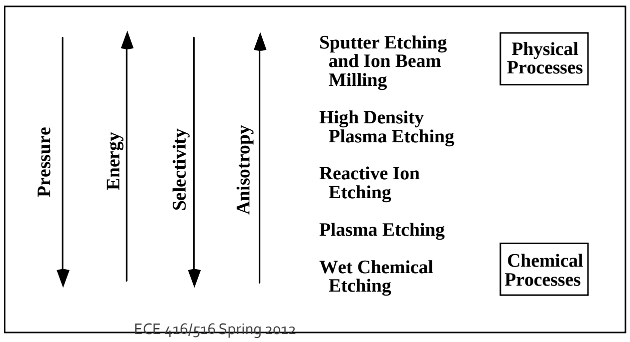
Figure 11.21 A cross section schematic of the results of a typical etch of SiO_2 down to Si using CF_4/H_2 *(after Oehrlein, Rembetski, and Payne, reprinted by permission, AIP).*

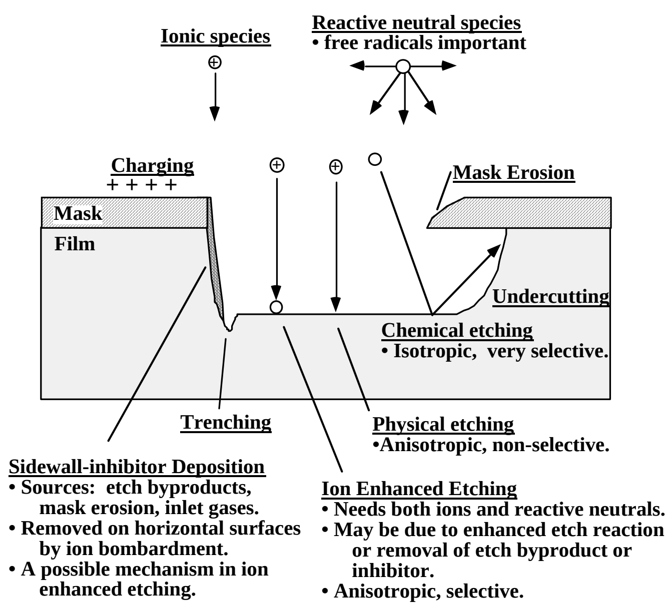
Sputter Etching



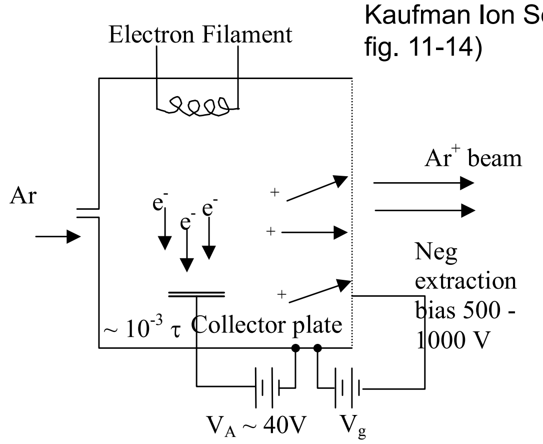
- Purely physical etching:
  - Highly directional, with poor selectivity
  - Can etch almost anything
- Sputter etching, uses Ar^+.
  - Damage to wafer surface and devices can occur: trenching (a), ion bombardment damage, radiation damage, redeposition of photoresist (b) and charging (c).
  - These can occur in any etch system where the physical component is strong.

Summary





Ion Milling #1



Kaufman Ion Source (Campbell fig. 11-14)

V_A sufficient that electron impact ionizes Ar
Directional ion beam etching by impact/sputter
Chamber press < 10^{-3}torr /(10 to 100)

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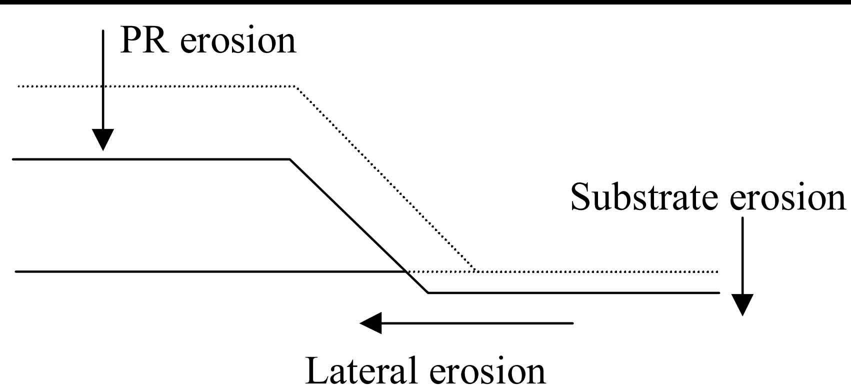
Ion Milling #2



- Electron flood gun → avoids substrate charging
- Reactive gas feed to increase selectivity

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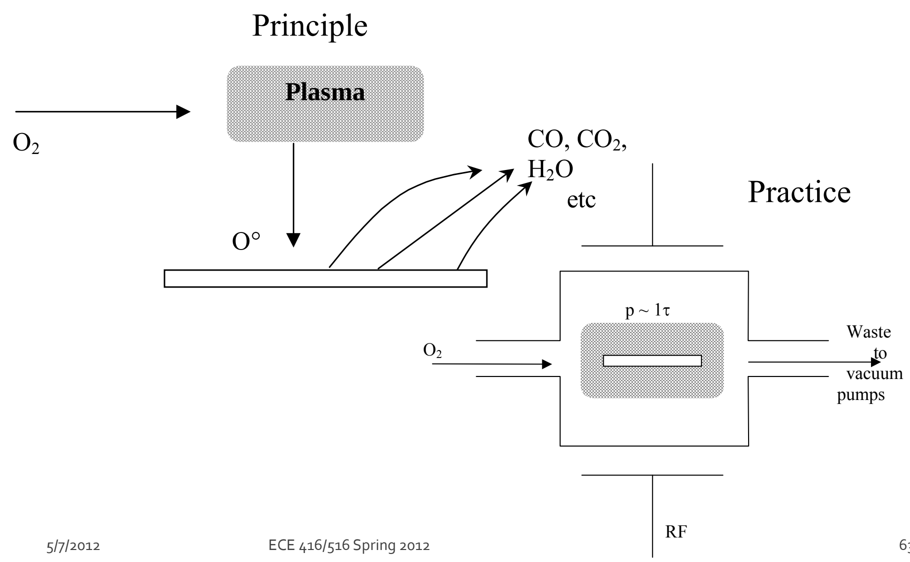
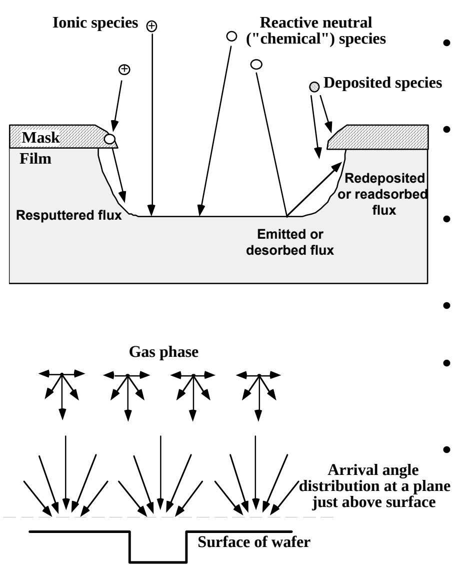
Photoresist removal: Plasma Ashing/Stripping



Models and Simulation



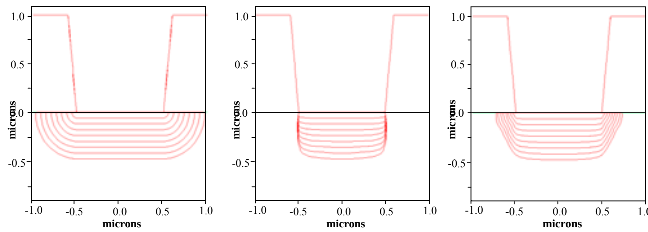
- There is a great deal of similarity between the deposition models described in lecture 13 and etching models.
- Both use incoming "chemical" (neutral) and ion fluxes and many other similar physical processes.
- As in deposition, the etch rate is proportional to the net flux arriving at each point.
- Chemical etching species are assumed to arrive isotropically (n = 1 in $\cos^n \theta$).
- Ionic species are assumed to arrive anisotropically (vertically) (n ≈ 10 - 80 in $\cos^n \theta$).
- The "sticking coefficient" concept is used as in the deposition case. Ionic species usually "stick" (S_c = 1), while reactive neutral species have low S_c values (bounce around).
- Sputtering yield has same angle dependence used in the deposition case.

Linear Etch Model

- While machine specific models have been developed, we will consider here general purpose etch models which can be broadly applied.
- Linear etch model assumes chemical and physical components act independently of each other (or appear to act independently for a range of conditions).

$$\text{Etch rate} = \frac{(S_c K_f F_c + K_i F_i)}{N} \qquad (7)$$

- F_c and F_i are the chemical flux and ionic flux respectively, which will have different incoming angular distributions and vary from point to point. K_i and K_f are relative rate constants for two components.
- Physical component (2nd term) can be purely physical sputtering, or can be ion-enhanced mechanism in regime where chemical flux not limiting ion etching.

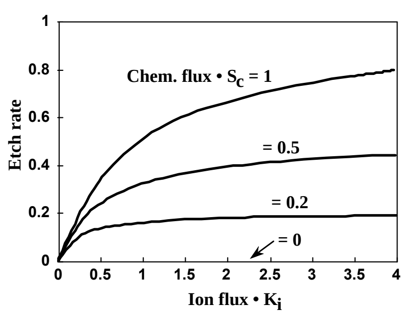


a). all chemical etching (ion flux=0); b). all physical or ionic etching (chem flux=0); c). half chemical, half physical.

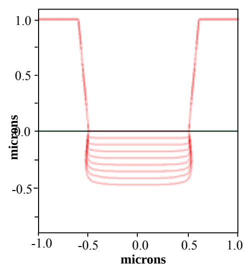
Saturation - Adsorption Etch Model

- Used for ion-enhanced etching, when chemical (neutral) and physical (ion) etch components are coupled.
- Examples - the ion flux is needed to remove a byproduct layer formed by the chemical etching, or ion bombardment damage induces chemical etching.

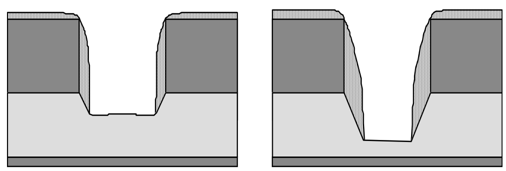
$$\text{Etch Rate} = \frac{1}{N}\frac{1}{\left(\frac{1}{K_i F_i} + \frac{1}{S_c F_c}\right)} \qquad (8)$$



- If either flux is zero, the overall etch rate is zero since both are required to etch the material.
- Etch rate saturates when one component gets too large relative to the other (limited by slower of two series processes).
- General approach with broad applicability. (But does not account for independently formed inhibitor layer mechanism, and does not model excess inhibitor formation.)



- SPEEDIE simulation (equal chemical and ion components): Note the anisotropic etching. Ion flux is required and it arrives with a vertical direction (n is large in $\cos^n \theta$).



(a) (b)

- Avant!'s TAURUS-TOPOGRAPHY simulation using their dry etch model with simultaneous polymer deposition.
- a). Etching SiO_2 (over Si, with a photoresist mask) after 0.9 minutes b). after 1.8 minutes.
- This explicitly models inhibitor deposition and sputtering.
- One can see the sloped etch profile, without etch bias, due to the excess polymer deposition.

Wet Etching Models

Diffusion limited (stagnant):

Diffusion depth $\delta(t) = 2\gamma\sqrt{D_A t}$

where

$2\gamma\, .\exp \gamma^2 \int_{-\gamma}^{\infty} \exp{-s^2}.ds = M_s\, \chi_{A0} C_A / n_s\, \rho_s$

& reaction rate:

$R_e = kC_A.\ \exp(k^2 t/D_A).[1 - \text{erf}\ (k^2\ t/D_A)^{1/2}]$

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.
- Simulation tools are fairly advanced today and include models for chemical, physical and ion-enhanced etching processes.
- Incoming angular distributions of etching species and parameters like sticking coefficients are used to model etching (similar to deposition modeling).

Summary

- Etch principles
- Etch chemistries
- Anisotropy, bias, etch rates, selectivity, plasma etch, reactive ion etch, feed gas effects, ion milling.