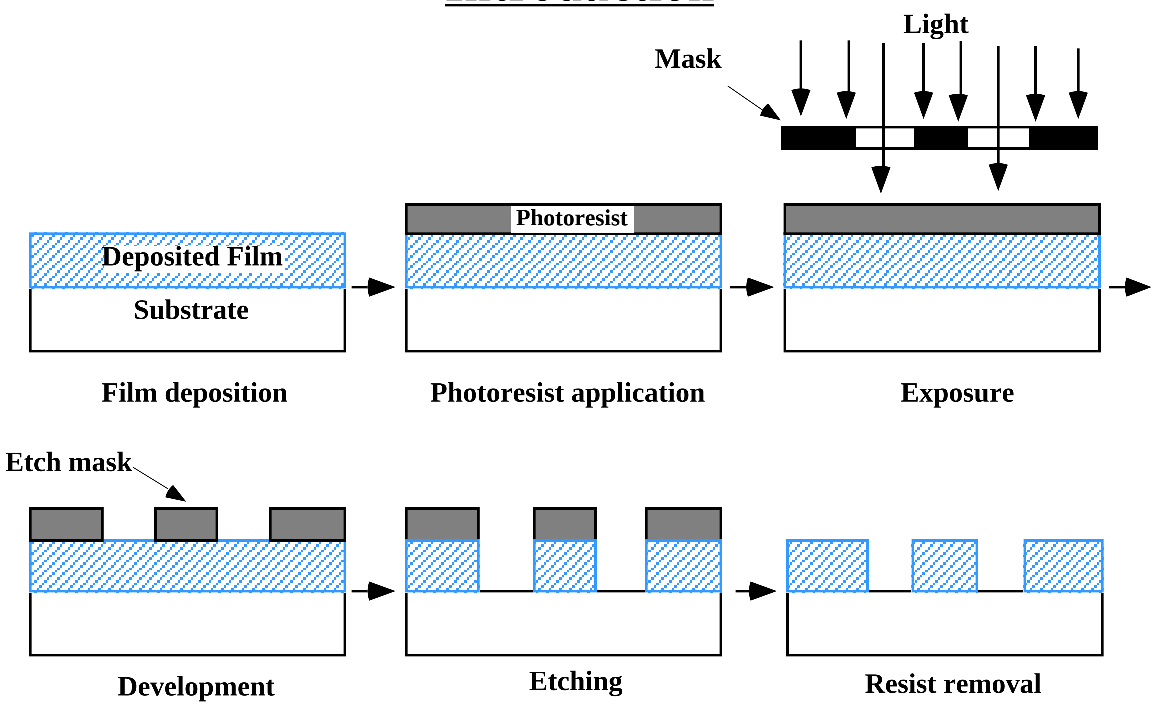
# EE 212 FALL 1999-00

# ETCHING - Chapter 10

## Introduction

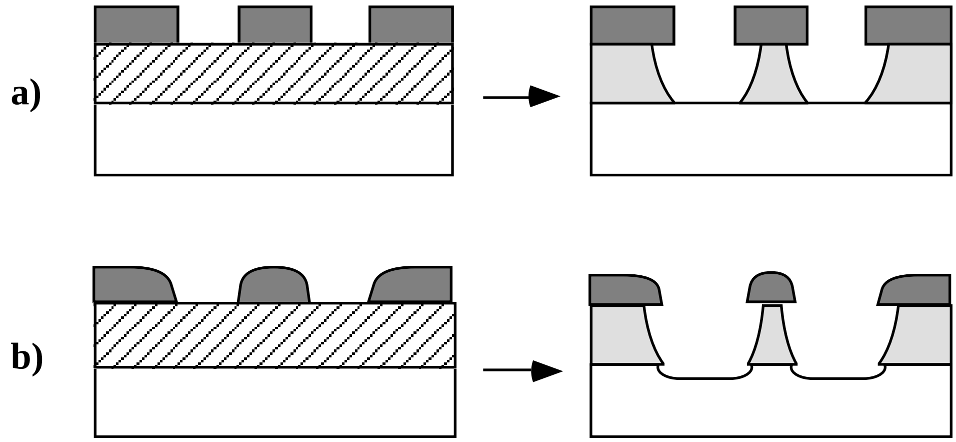



- **Etching of thin films and sometimes the silicon substrate are very common process steps.**

- **Usually selectivity, and directionality are the first order issues.**

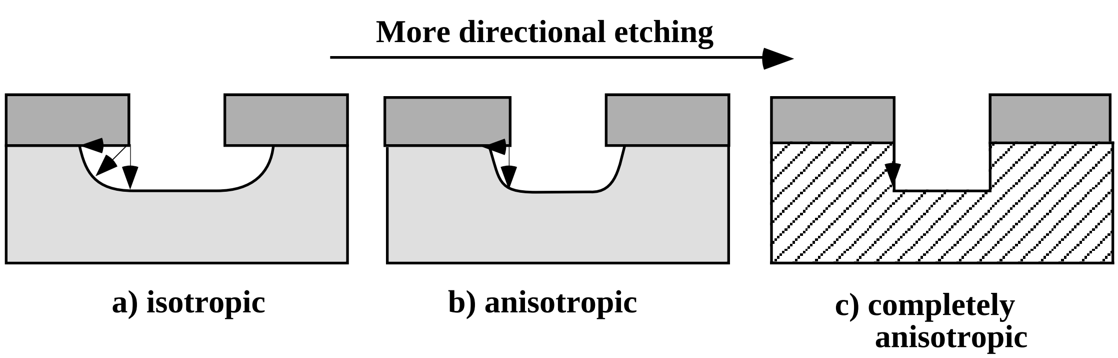
- **Selectivity comes from chemistry; directionality usually comes from physical processes. Modern etching techniques try to optimize both.**

- **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**

## 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

- **Wafers typically submerged in specific chemical baths.**

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

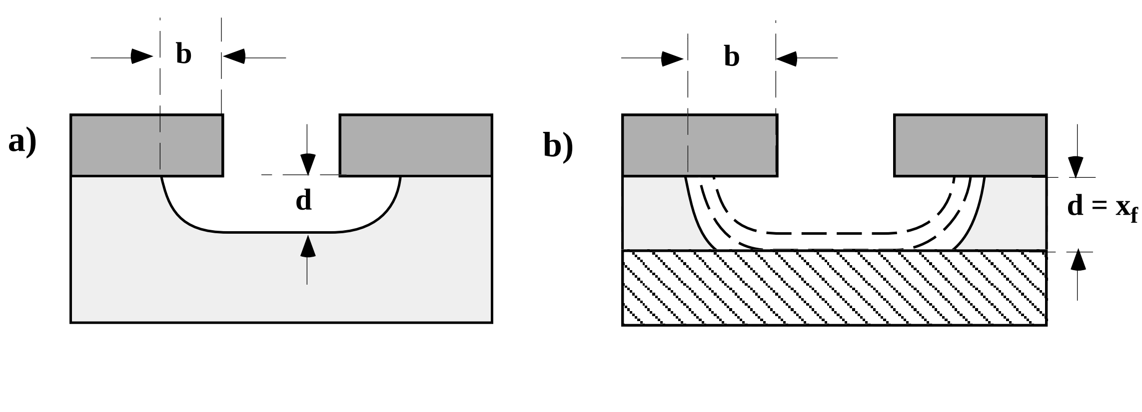
- **Examples:**

**Etching of $SiO_2$ by aqueous HF:**

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O \qquad (1)$$

**Etching of Si by nitric acid ($HNO_3$) and HF:**

$$Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2 \qquad (2)$$



- Isotropic etching implies undercutting. This is often expressed in terms of the etch bias b.

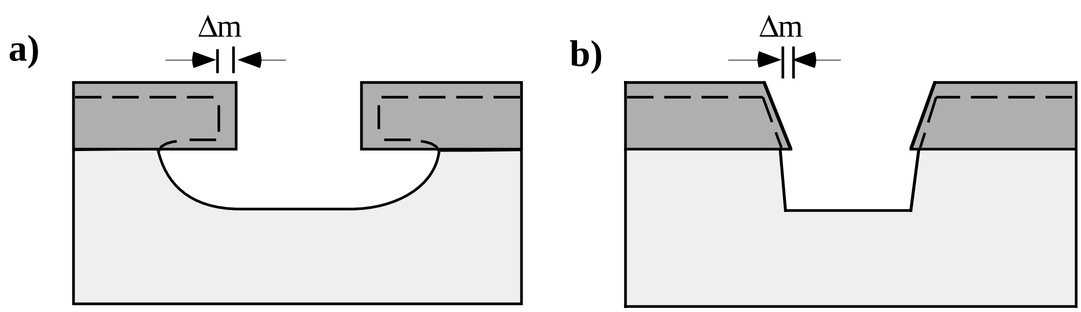
- Etch anisotropy is defined as:

$$A_f = 1 - \frac{r_{lat}}{r_{ver}} = 1 - \frac{b}{d} \qquad (3)$$

- $A_f = 0$ for isotropic etching since $r_{lat} = r_{ver}$.

- Some overetching, shown above at right, is usually done to ensure complete etching (due to variations in film thickness and etch rate).

- Selectivity is usually excellent. $(S = r_1 / r_2)$ since chemical reactions are very selective.




- Mask erosion can be an issue for both isotropic and anisotropic etching profiles.

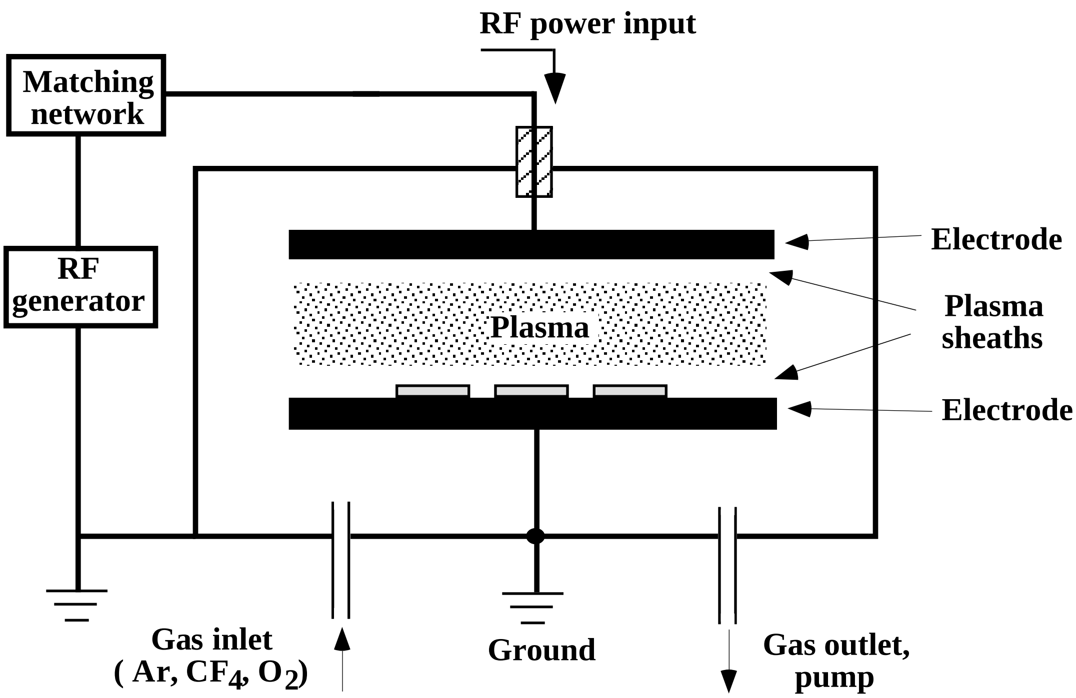
- Table 10.1 in text list some common wet etchants.

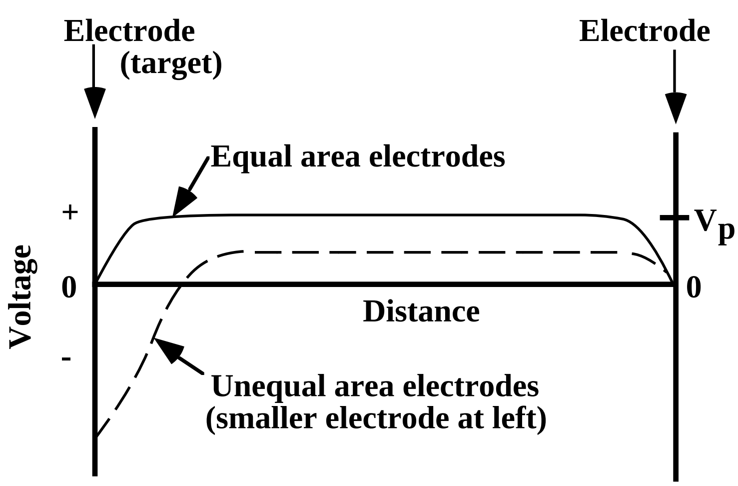
- Because of their isotropic nature, wet chemical etches are rarely used in mainstream IC manufacturing today.

# Plasma Etching

- **Developed and used for:**
  1. **faster and simpler etching in a few cases**
  2. **more directional (anisotropic) etching!!**

- **Both chemical (highly reactive) species and ionic (very directional) species typically play a role.**



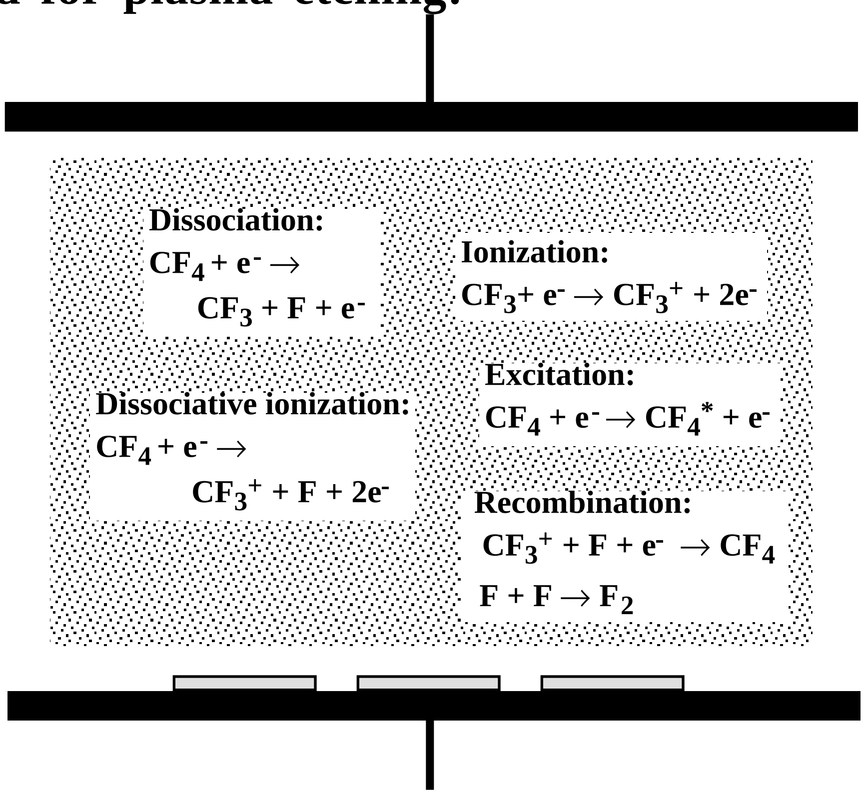
- Typical RF-powered plasma etch system look just like PECVD or sputtering systems.

- $V_P$ is positive to equalize electron and ion fluxes.

- Smaller electrode has much higher fields to maintain current continuity (higher current density).

- Etching gases include halide-containing species such as $CF_4$, $SiF_6$, $Cl_2$, and HBr, in addition to 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 for plasma etching:



- **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 Etching Mechanisms

- **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.**

## Chemical Etching

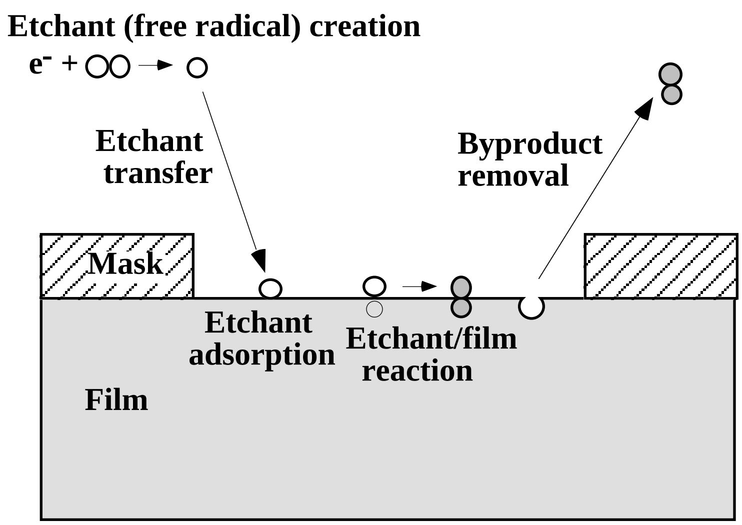
- **Etching done by reactive neutral species, such as "free radicals" (e.g. F, $CF_3$)**

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

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

- **Additives like $O_2$ can be used which react with $CF_3$ and reduce $CF_3$ + F recombination. ∴ higher etch rate.**

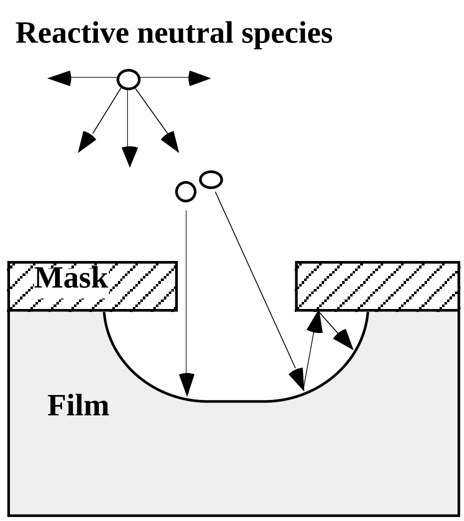
- These processes are purely chemical and are therefore isotropic and selective, just like wet etching.



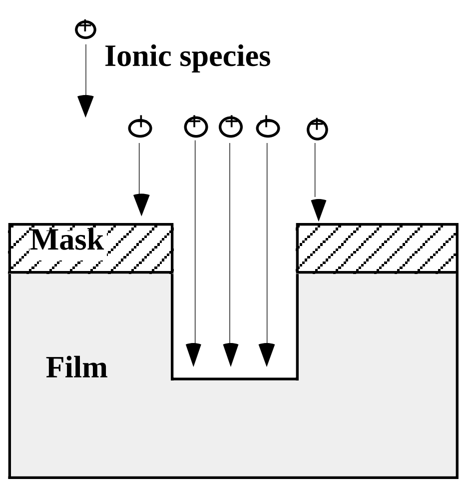

- Generally characterized by $\cos^n\theta$ (n=1) arrival angle and low sticking coefficient ($S_c \approx 0.01$). (Surface reaction takes some time and desorption can occur.)

## Physical Etching

a)




b)



- **Ion etching (right) is much more directional ($\varepsilon$ field across plasma sheath) and $S_c \approx 1$, i.e. ions don't bounce (or if they do they lose their energy.)**

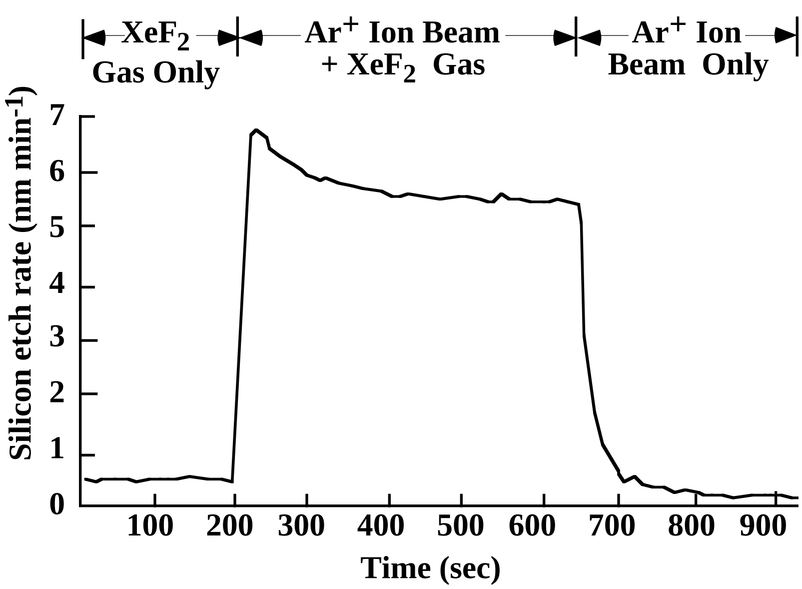
- **Etching species are ions like $CF_4^+$ or $Ar^+$ which remove material by sputtering.**

- **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

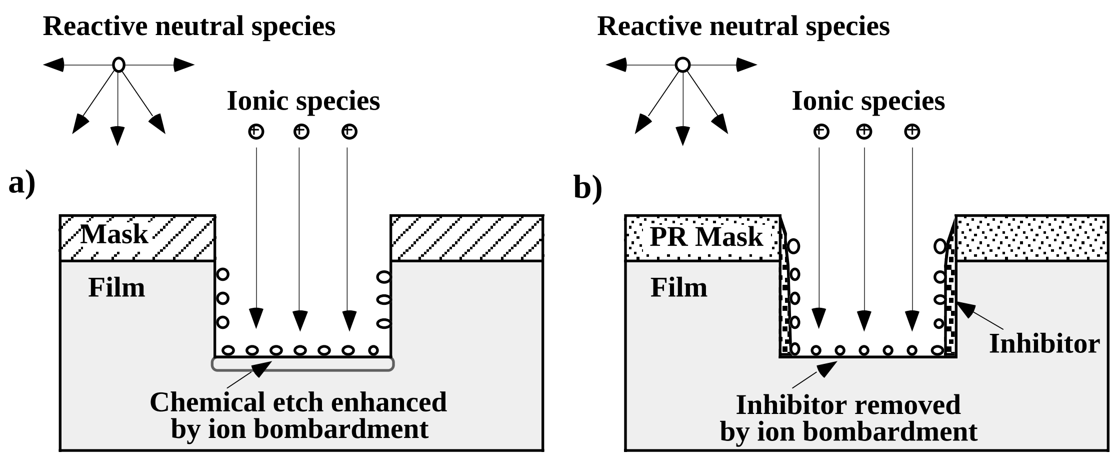
- **It has been observed that chemical and physical components of plasma etching do not always act independently - both in terms of net etch rate and in resulting etch profile.**



- **Figure above 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 anisotopic, and selectivity can be good.**

- **Many different mechanisms proposed for this synergistic etching between physical and chemical components. Two mechanisms are shown below:**

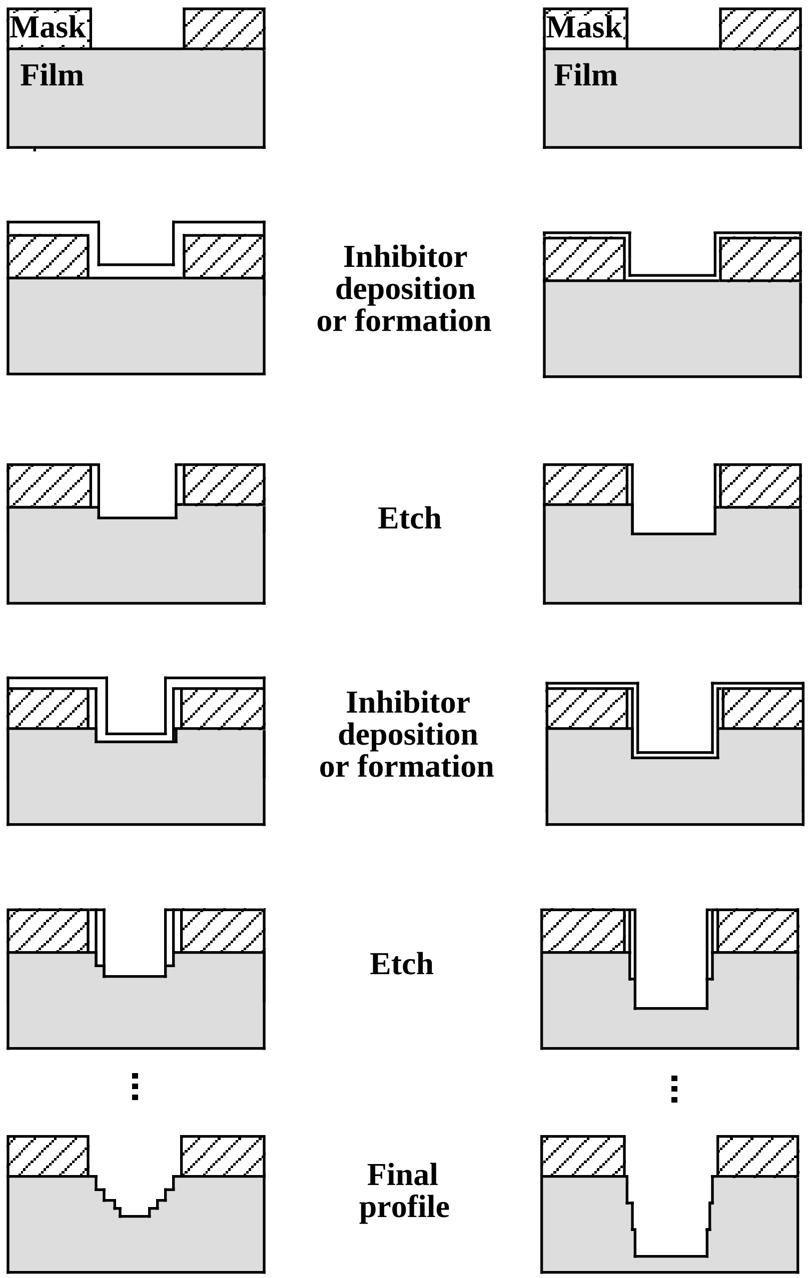



- **Inhibitor could be either direct byproduct of etch process, or indirect byproduct (such as polymer formation from C in gas or from photoresist).**

- **Whatever the exact mechanism (multiple mechanisms may occur at same time):**
    - **the two components act in series.**
    - **get anisotropic etching and little undercutting because of directed ion flux.**
    - **get selectivity due to chemical component.**

- **∴ many applications in etching today.**

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




**a. Inhibitor deposition rate fast compared to etch rate**

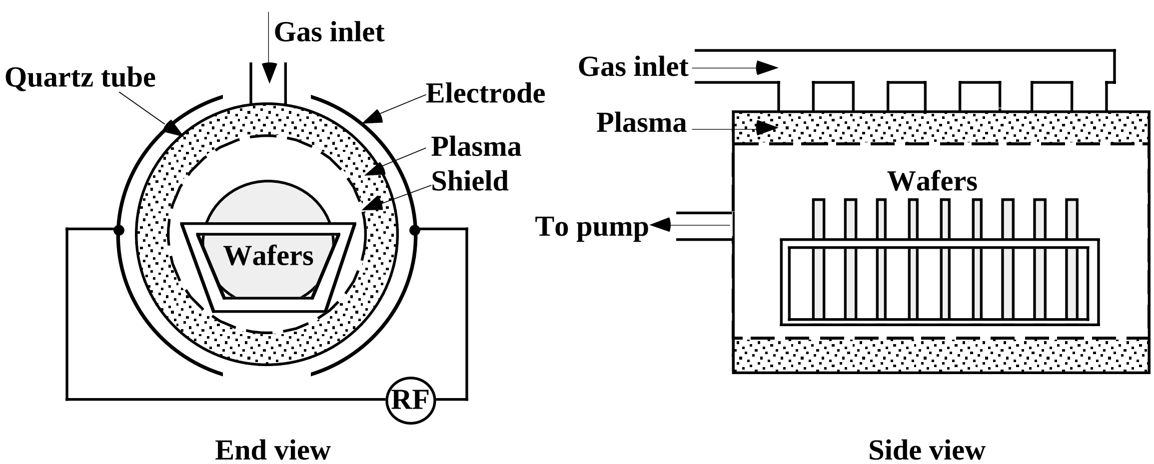
**b. Inhibitor deposition rate relatively slow compared to etch rate**

# 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).

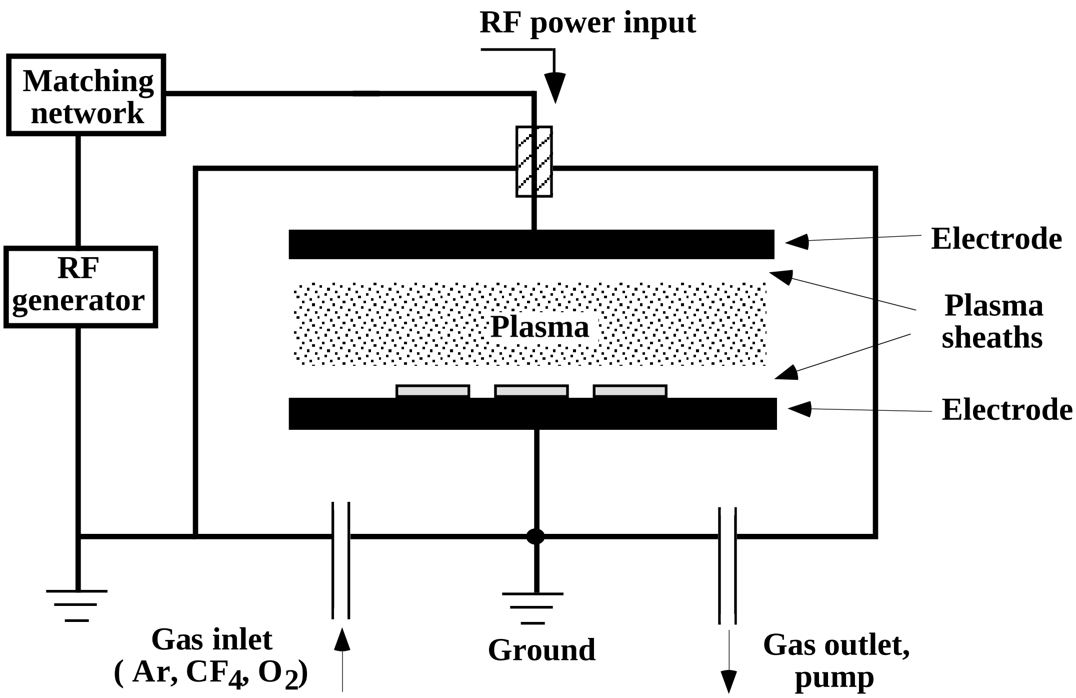


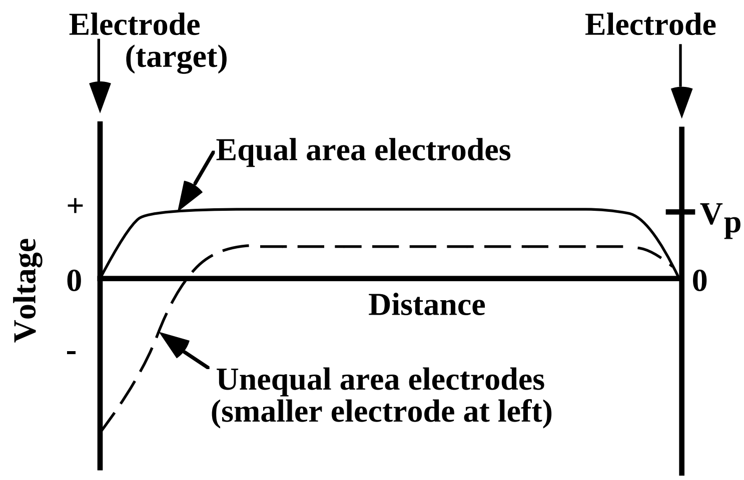

## Parallel Plate Systems - Plasma Mode

- 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 is fairly isotropic and selective.




## Parallel Plate Systems - Reactive Ion Etching (RIE) Mode

- **For more directed etching, need stronger ion bombardment.**

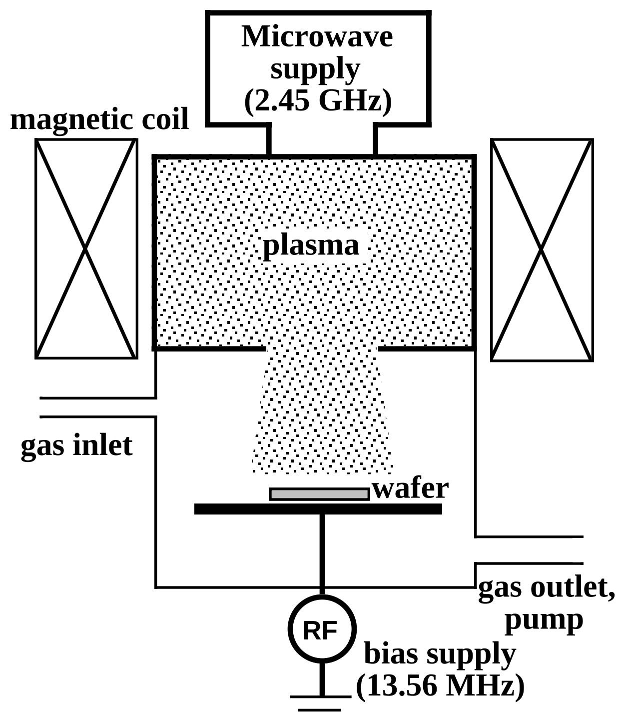
- **Wafers sit on smaller electrode (RF power there).**

- **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 for more directionality. ∴ less selectivity.**

## <u>High Density Plasma (HDP) Etch Systems</u>




- **Use remote, non-capacitively coupled plasma source (Electron cyclotron resonance - ECR, or inductively coupled plasma source - ICP).**

- **Use 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).

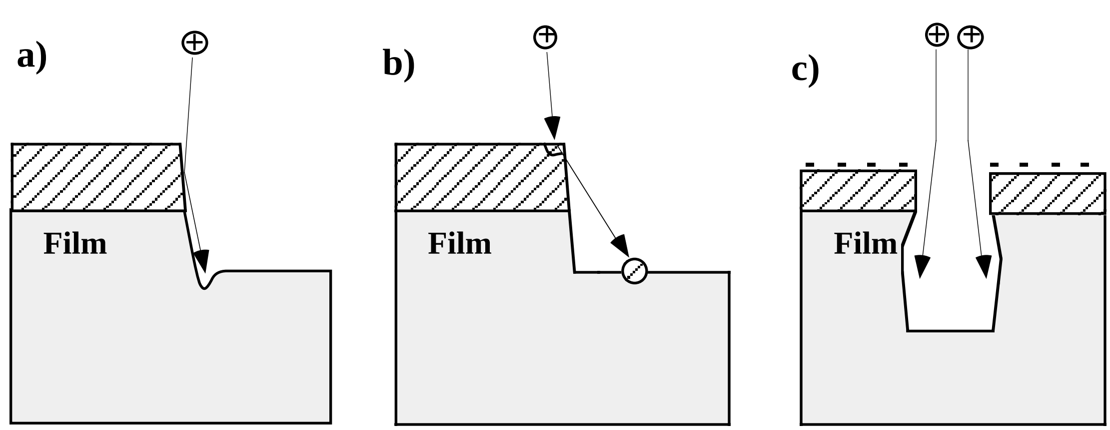
- Lower pressures (1-10 mtorr range) can be utilized due to higher ionization efficiency (longer mean free path and ∴ more anisotropic etching).

- These systems produce high etch rates, decent selectivity, and good directionality, while keeping ion energy and damage low. ∴ widely used.

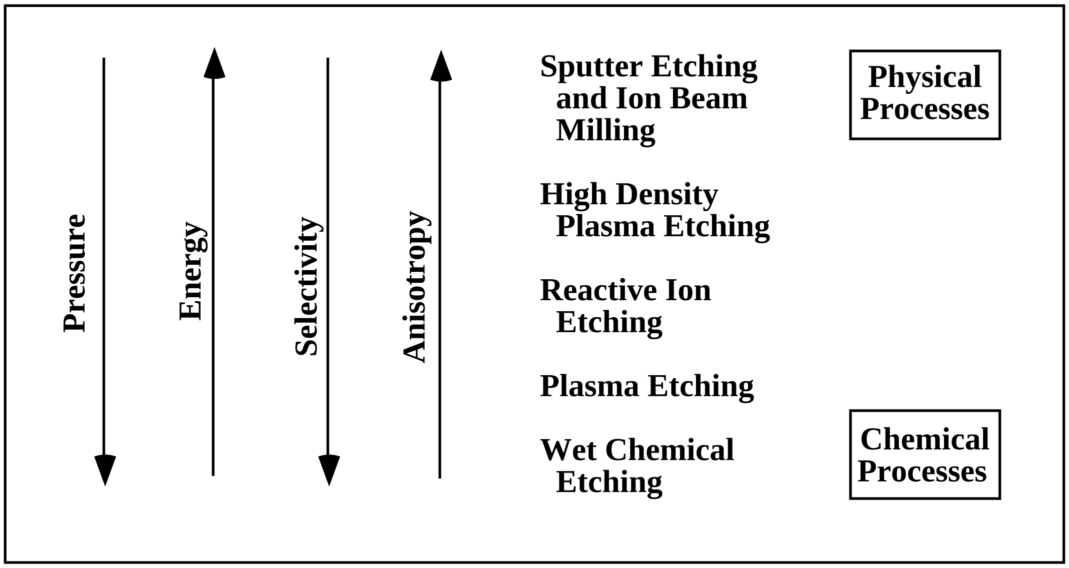
## Sputter Etching and Ion Milling

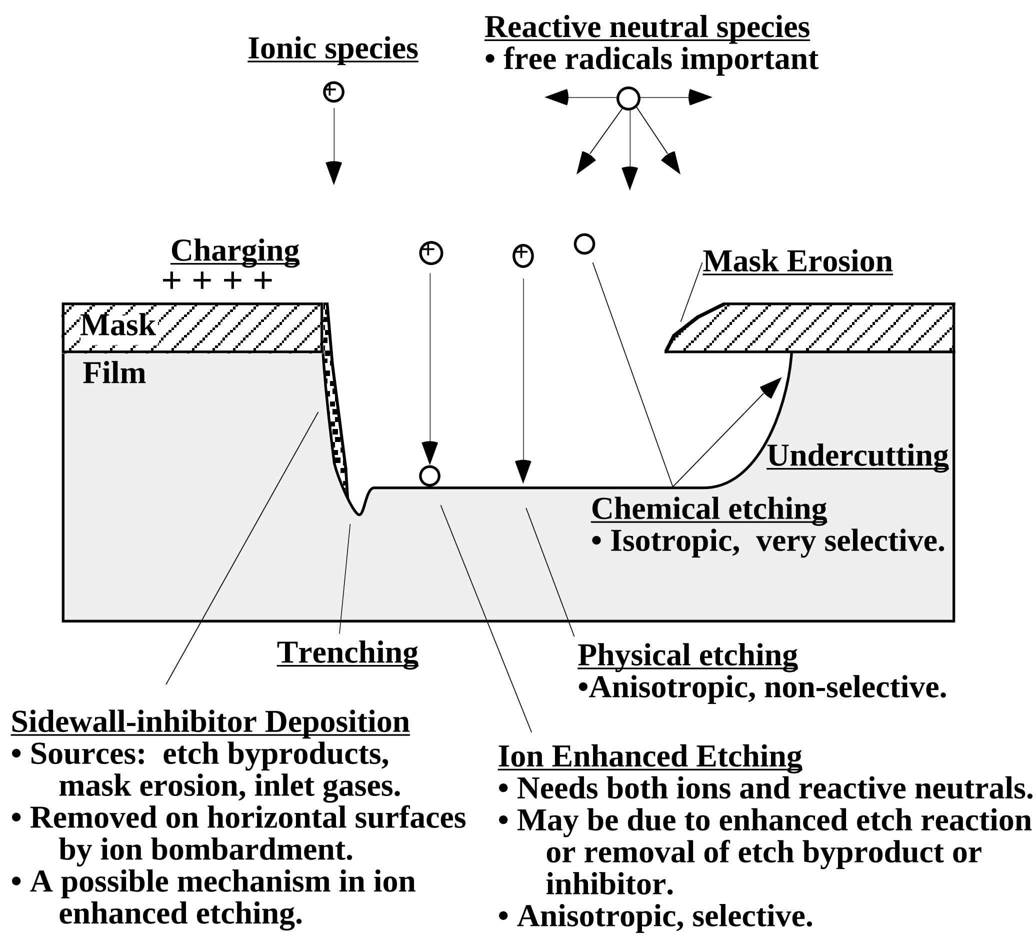
- Purely physical etching:
    - highly directional, with poor selectivity
    - can etch almost anything

- Sputter etching, uses $Ar^+$.
    - damage to wafer surface and devices can occur (trenching, ion bombardment damage, radiation damage, and charging)
    - these can occur in any etch system where physical component is strong.



# Summary:


Pressure
Energy
Selectivity
Anisotropy
Sputter Etching and Ion Beam Milling
Physical Processes
High Density Plasma Etching
Reactive Ion Etching
Plasma Etching
Wet Chemical Etching
Chemical Processes


Ionic species
Reactive neutral species
• free radicals important
Charging
+ + + +
Mask Erosion
Mask
Film
Undercutting
Chemical etching
• Isotropic, very selective.
Trenching
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.

# Manufacturing Methods

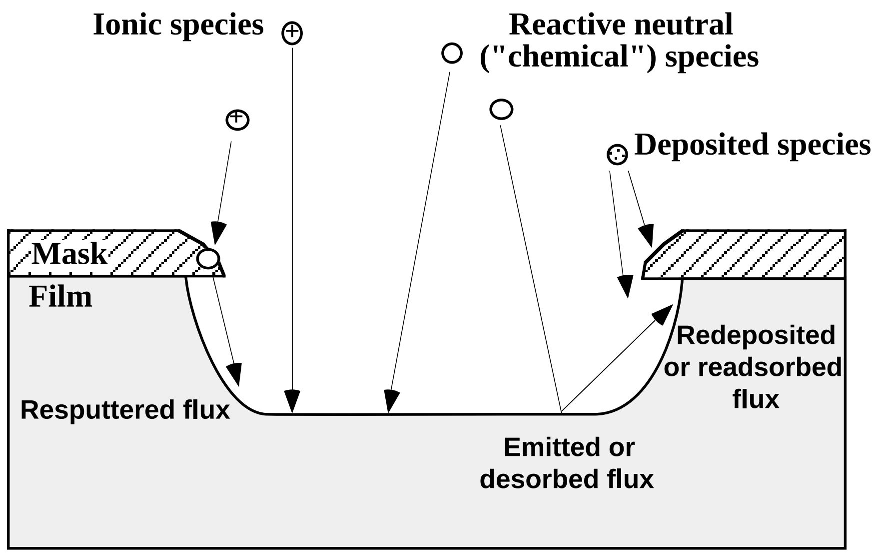
| Material | Etchant | Comments |
|---|---|---|
| Polysilicon | $SF_6$, $CF_4$ | Isotropic or near isotropic (significant undercutting); poor or no selectivity over $SiO_2$ |
| | $CF_4/H_2$, $CHF_3$ | Very anisotropic, non-selective over $SiO_2$ |
| | $CF_4/O_2$ | Isotropic, more selective over $SiO_2$ |
| | 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 isotropic or 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 |

- **Common etchants used for various films in silicon technology.**

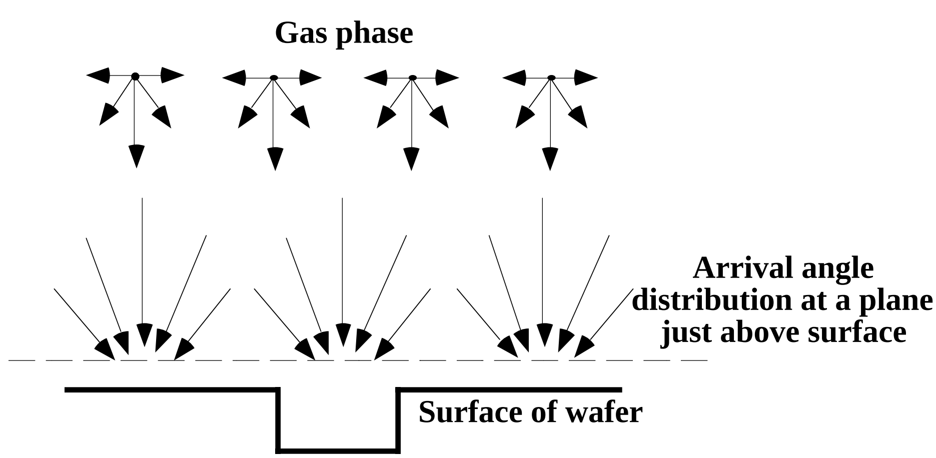
# Models and Simulation

- **There is a great deal of similarity between the deposition models described in Chapter 9 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.**

**<u>Linear Etch Model</u>**

- **While machine specific models have been developed, we will consider here general purpose etch models which can be broadly applied.**

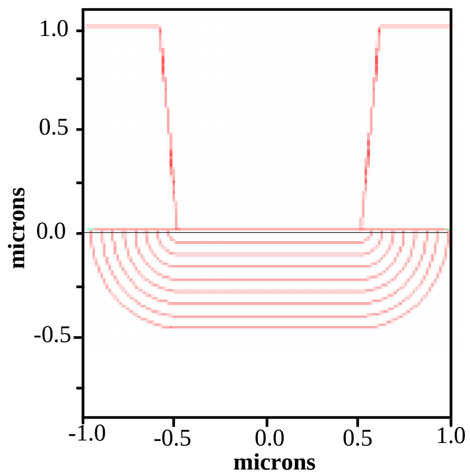
- **Linear etch model assumes chemical and physical components act independently of each other. Appropriate in systems when this is true.**

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

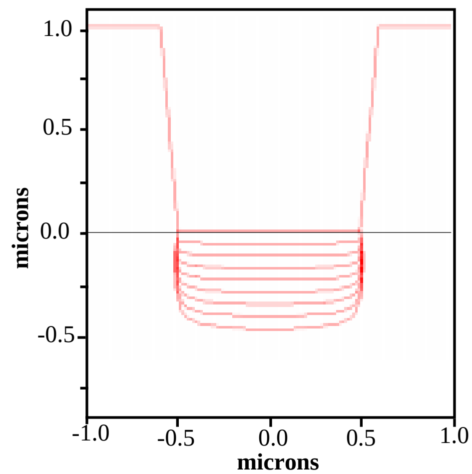
- **$F_c$ and $F_i$ are the chemical flux and ionic flux respectively, which will have different incoming angular distributions and vary from point to point. $K_i$ and $K_f$ are relative rate constants for two components.**

- **Physical component can be due to purely physical sputtering, or can actually be ion-enhanced mechanism in regime where chemical flux not limiting ion etching.**

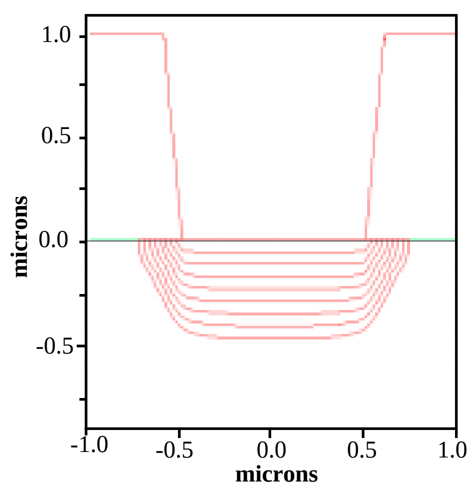
## SPEEDIE Simulations Using the Linear Etch Model




**a.**




**b.**




**c.**

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

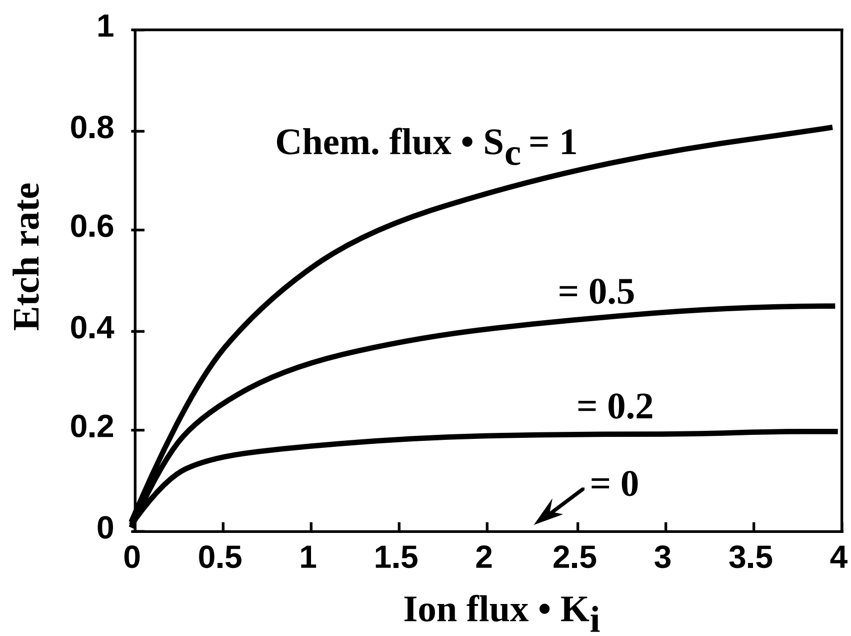
- **See text for other examples.**

## Saturation - Adsorption Etch Model

- **Generally used when chemical (neutral) and ion (physical) etch components are coupled.**

- **Example - the ion flux is needed to remove an inhibitor layer formed by the chemical etching.**

$$\textbf{Etch Rate} = \frac{1}{N}\frac{1}{\left(\frac{1}{K_iF_i}+\frac{1}{S_cF_c}\right)} \qquad \textbf{(8)}$$

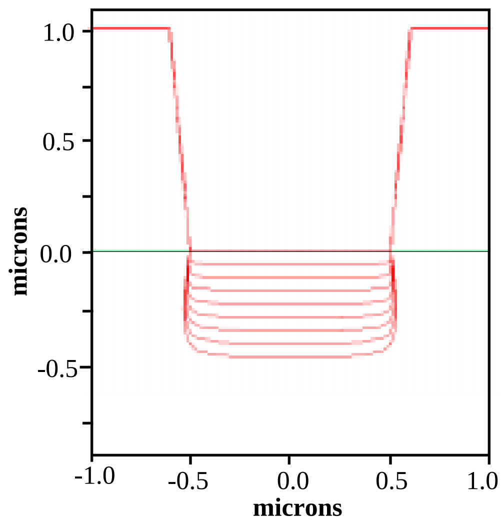



- **If either flux is zero, the overall etch rate is zero since both are required to etch the material.**

- **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.**

- **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 $\cos^n\theta$.**

## Key Ideas in Etching

- **Important issues in etching include selectivity, etch directionality and profile control.**

- **Wet etching gives good selectivity but isotropic etching. Plasma etching can result in very directional, vertical etching while still achieving selectivity.**

- **Two components of plasma etching are chemical (due to reactive neutral chemical species, such as free radicals) and physical (due to ions). These can act independently or in a synergistic manner.**