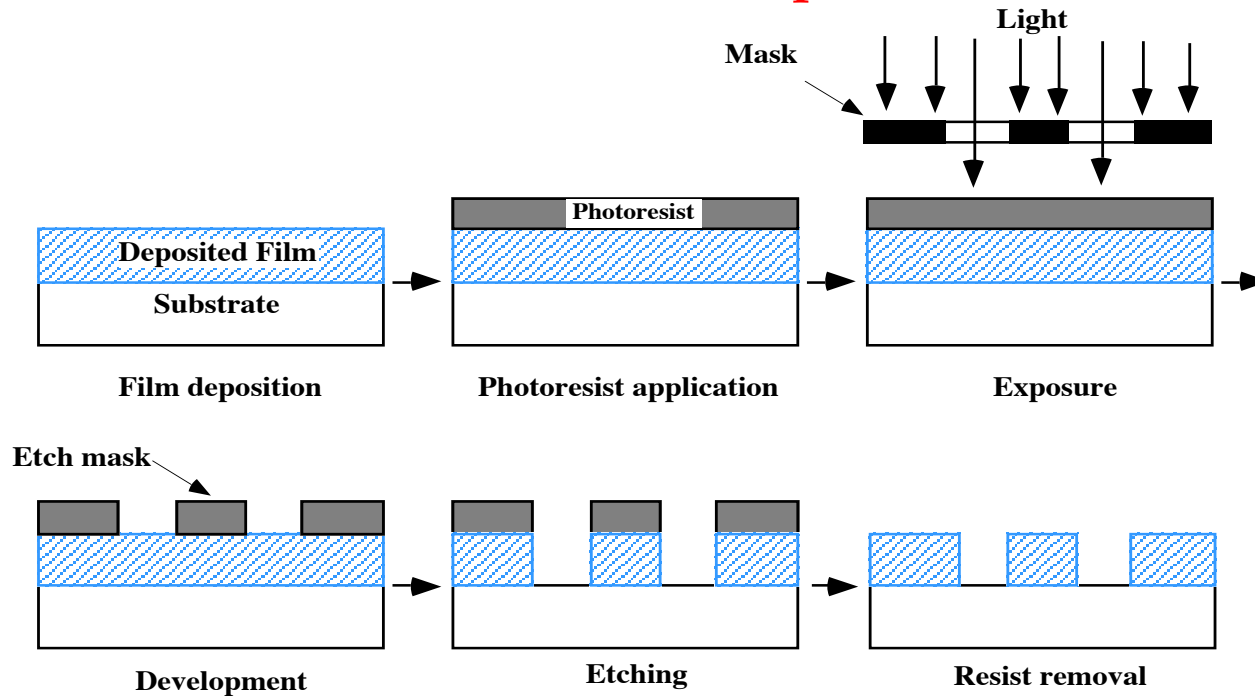
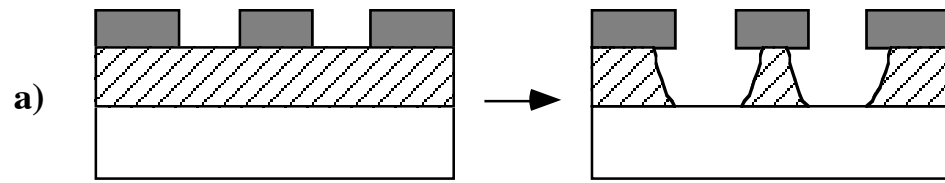


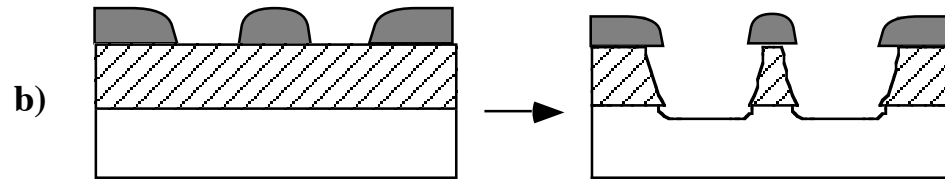
ETCHING – Chapter 10



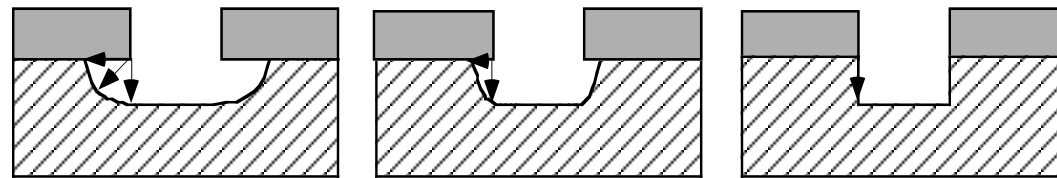
- Etching of thin films and sometimes the silicon substrate are very common process steps.
- Usually selectivity, and directionality are the first order issues.
- Selectivity comes from chemistry; directionality usually comes from physical processes. Modern etching techniques try to optimize both.
- 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.



More directional etching →



a) isotropic

b) anisotropic

c) completely anisotropic

- 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 and General Etching Ideas

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

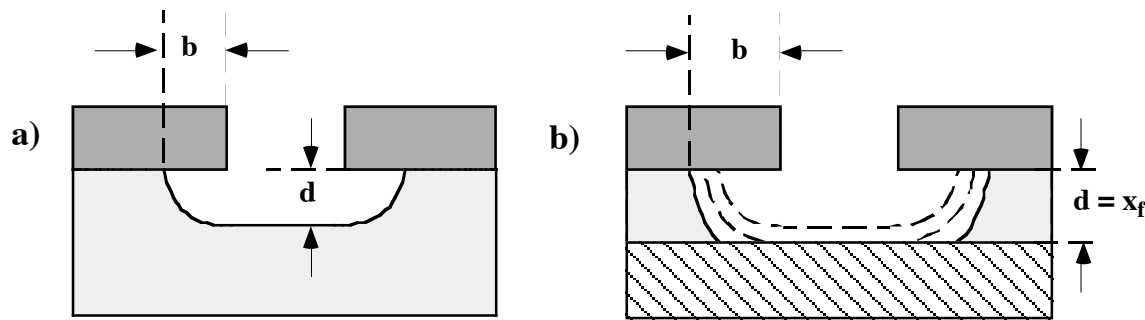
Examples:

Etching of SiO_2 by aqueous HF: $\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{H}_2\text{O}$ (1)

Etching of Si by nitric acid (HNO_3) and HF: $\text{Si} + \text{HNO}_3 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + \text{HNO}_2 + \text{H}_2\text{O} + \text{H}_2$ (2)

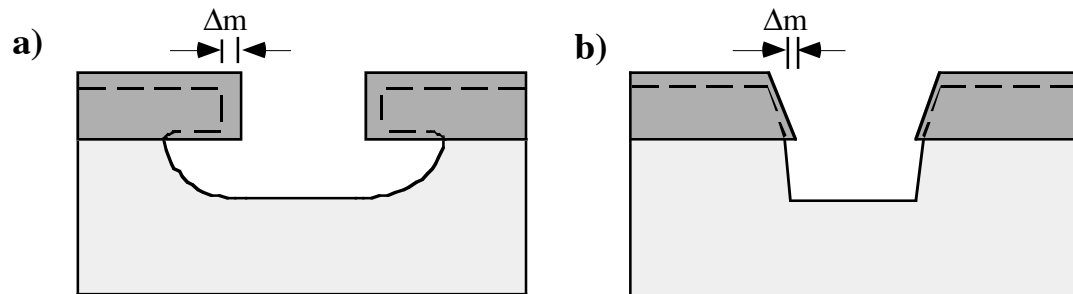
- Wafers typically submerged in specific chemical baths and rinsed in DI H_2O .





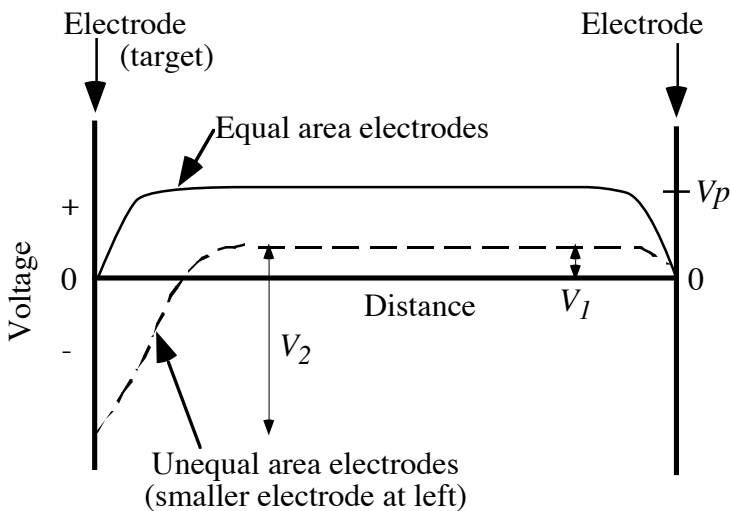
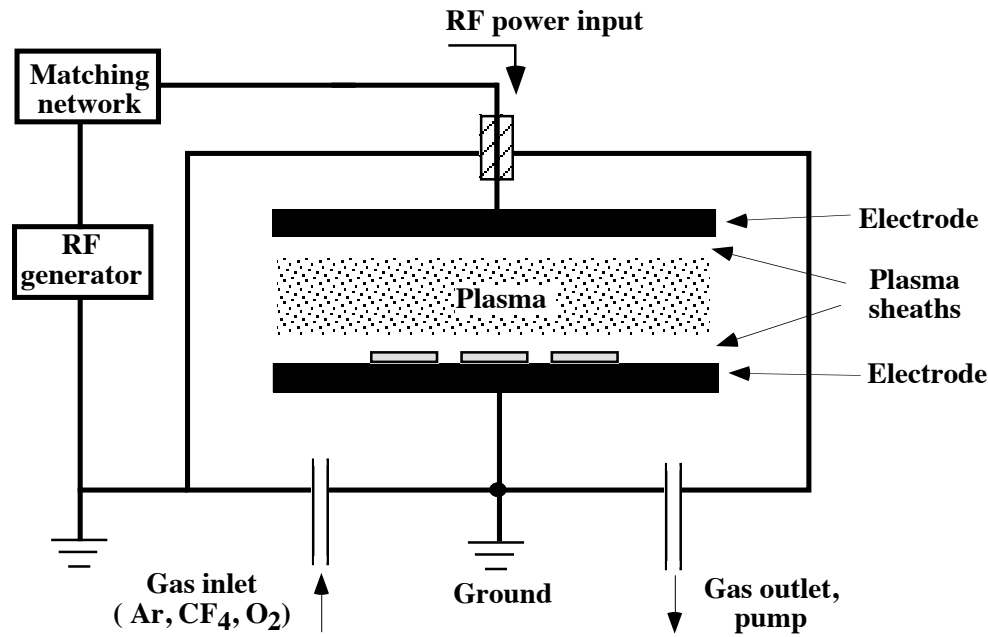
- Isotropic etching implies undercutting. This is often expressed in terms of the etch bias b .
- Etch anisotropy is defined as:

$$A_f = 1 - \frac{r_{\text{lat}}}{r_{\text{ver}}} = 1 - \frac{b}{d} \quad (3)$$
- $A_f = 0$ for isotropic etching since $r_{\text{lat}} = r_{\text{ver}}$.
- 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 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.

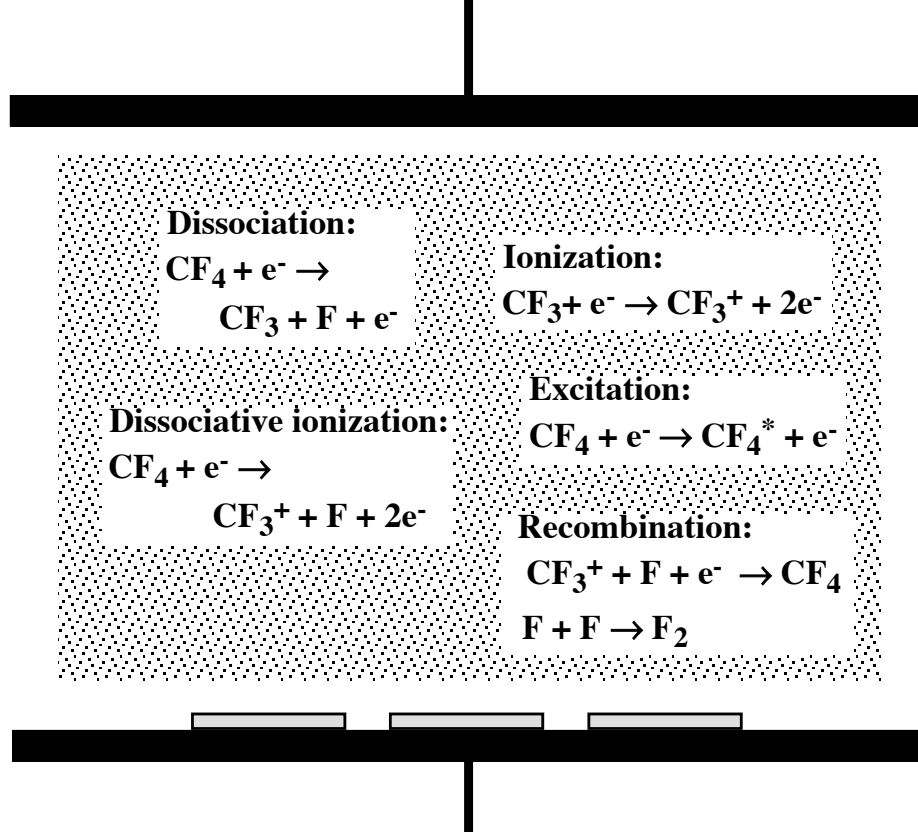
Plasma Etching



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.
- 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.

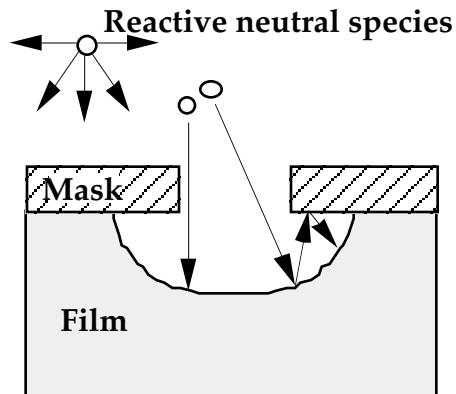
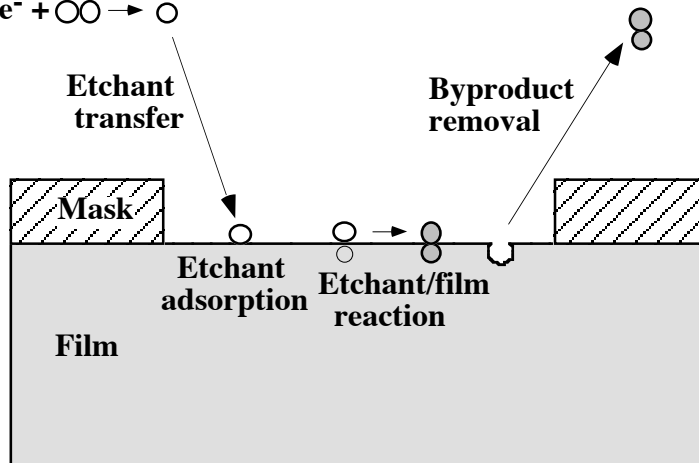
Plasma Etching Mechanisms

- There are three principal mechanisms:

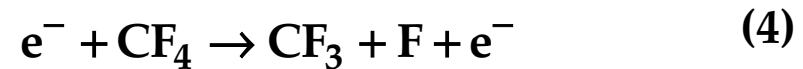
- chemical etching (isotropic, selective)
- physical etching (anisotropic, less selective)
- ion-enhanced etching (anisotropic, selective)

Chemical Etching

Etchant (free radical) creation

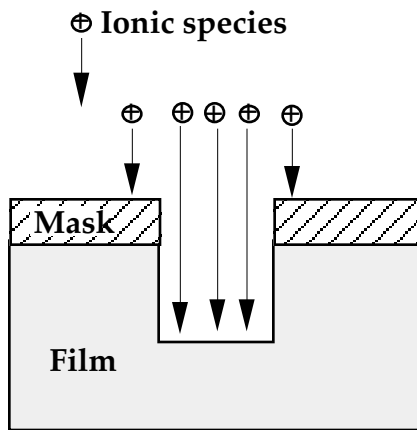


- Etching done by reactive neutral species, such as “free radicals” (e.g. F, CF₃)



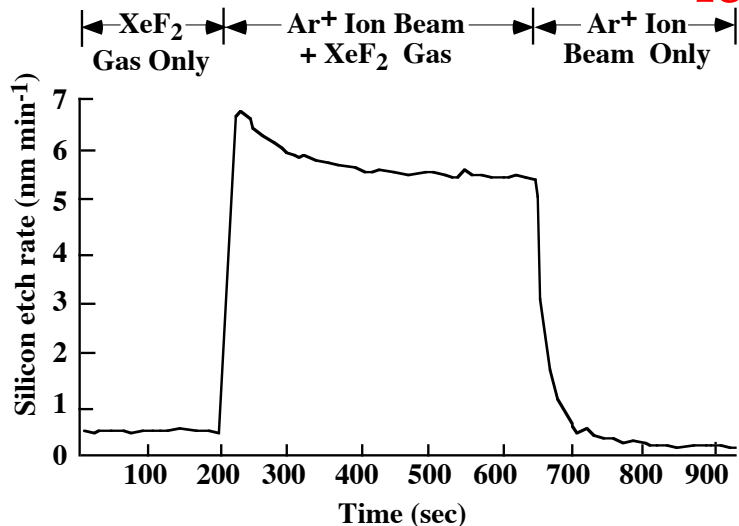
- Additives like O₂ can be used which react with CF₃ and reduce CF₃ + F recombination. **[?]** higher etch rate.
- These processes are purely chemical and are therefore isotropic and selective, like wet etching.
- Generally characterized by $\cos^n \theta$ ($n=1$) arrival angle and low sticking coefficient ($S_c \approx 0.01$).

Physical Etching

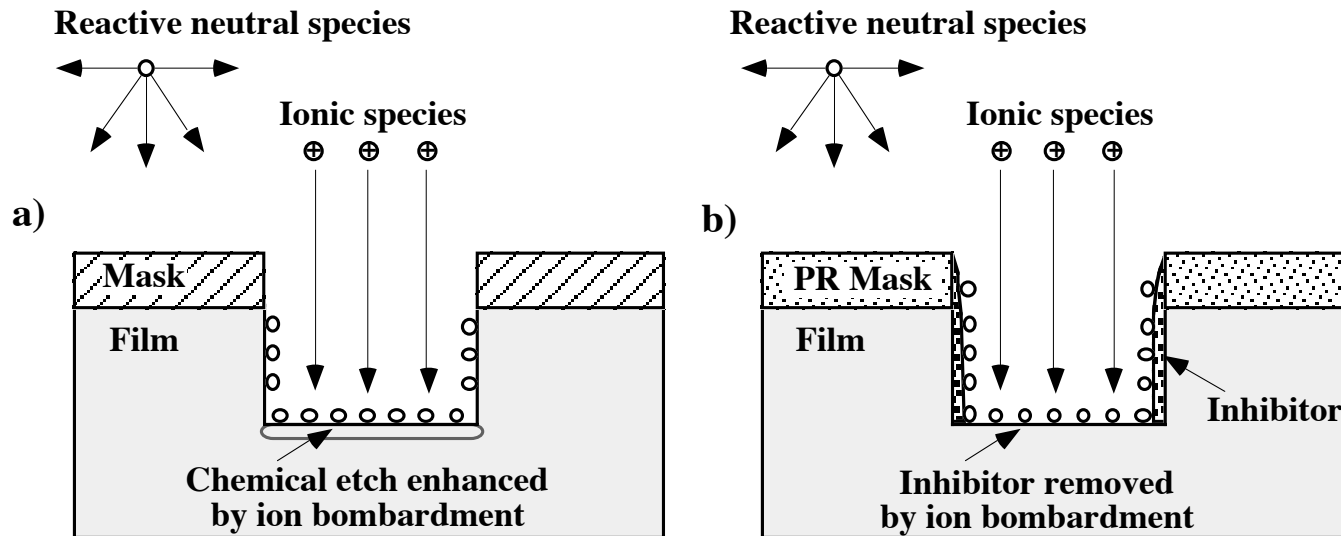


- Ion etching is much more directional (E field across plasma sheath) and $S_c \approx 1$, i.e. ions don't bounce around (or if they do, they lose their energy.)
- Etching species are ions like CF_3^+ or Ar^+ which remove material by sputtering.
- Not very selective since all materials sputter at about 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).

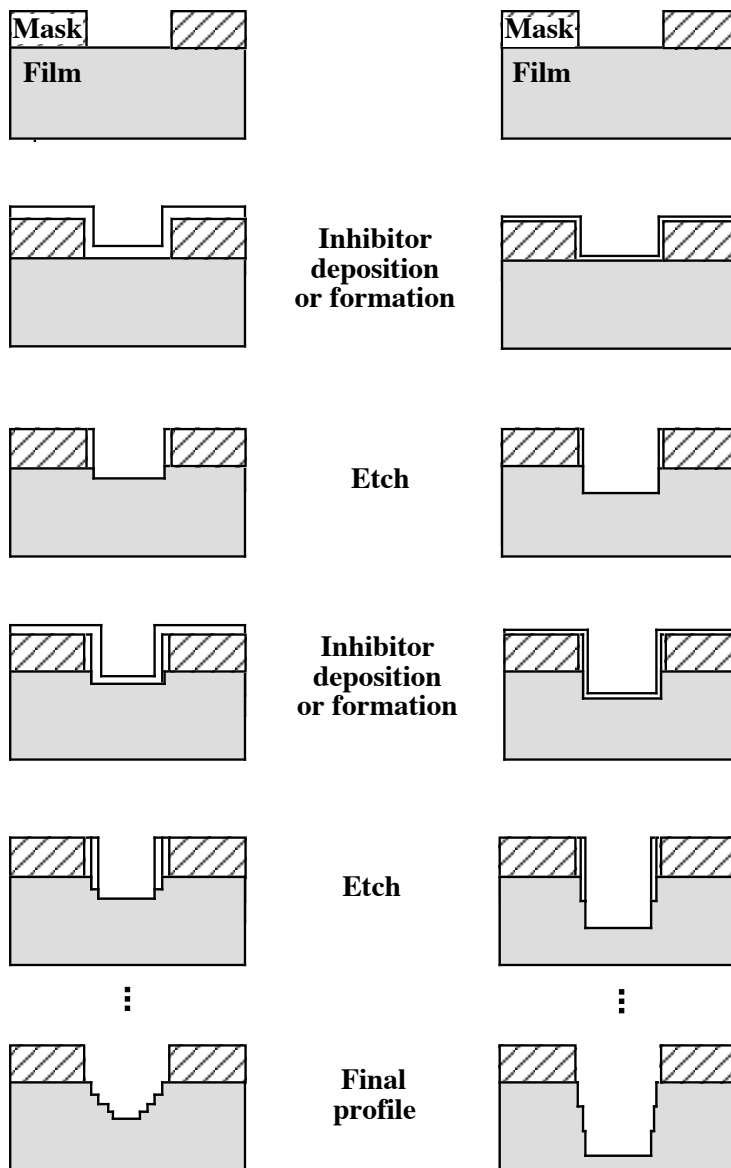
Ion Enhanced Etching



- 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.



- 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.**



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

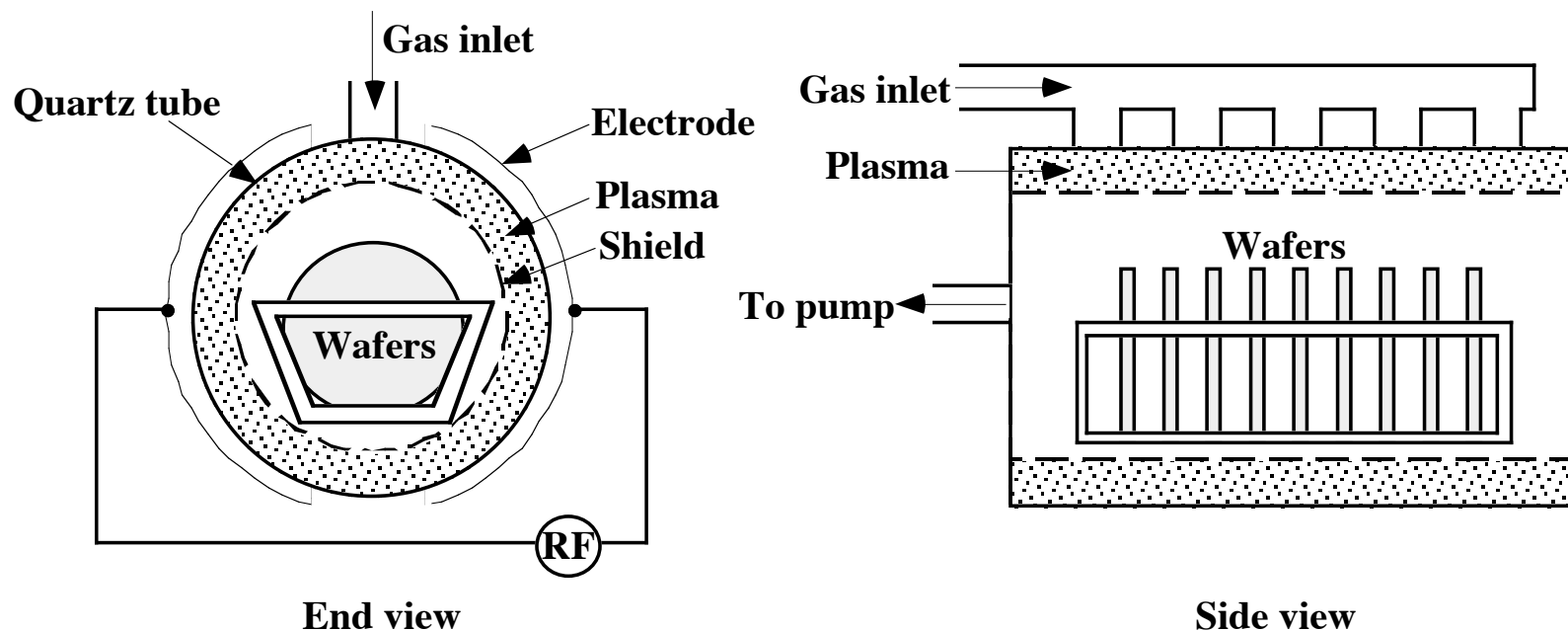
a. Inhibitor deposition rate fast compared to etch rate

b. Inhibitor deposition rate relatively slow compared to etch rate

Types of Plasma Etching Systems

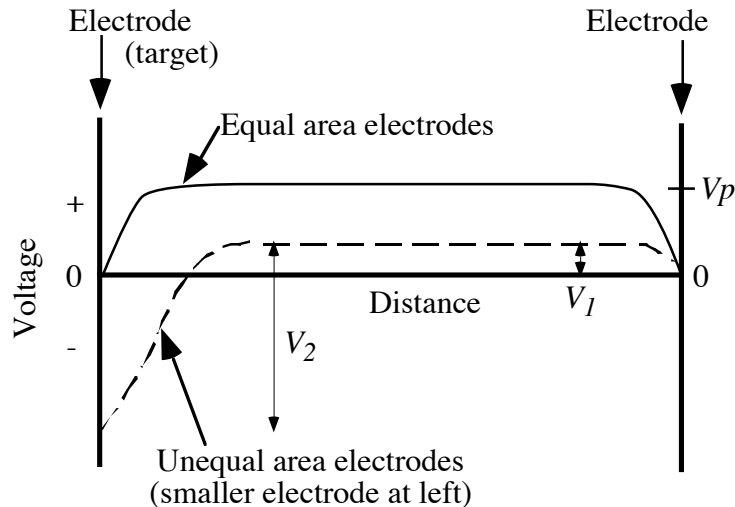
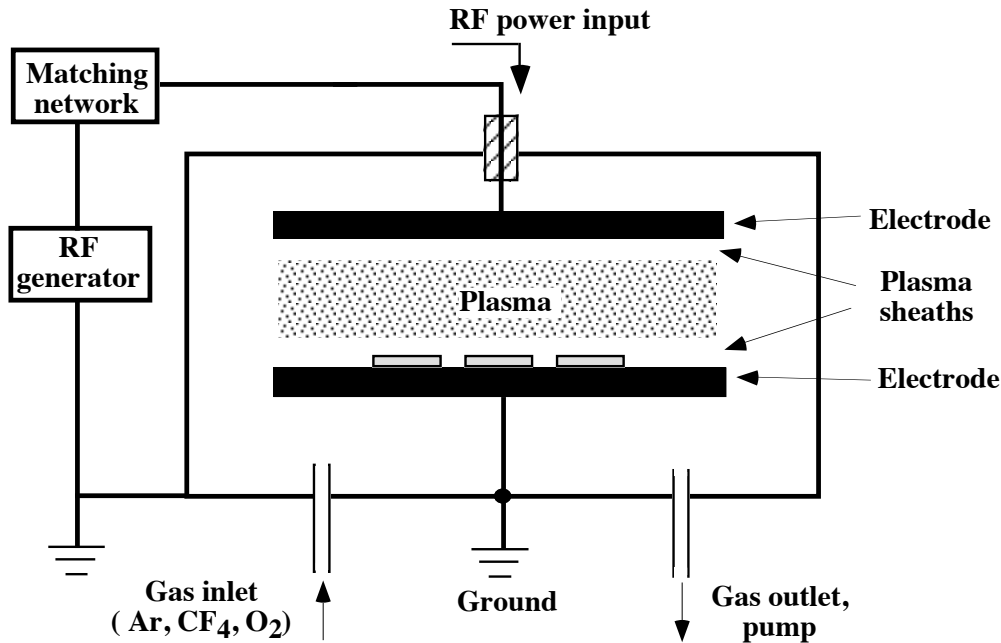
- Different configurations have been developed to make use of chemical, physical or ion assisted etching mechanisms.

Barrel Etchers



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

Parallel Plate Systems - Plasma Mode

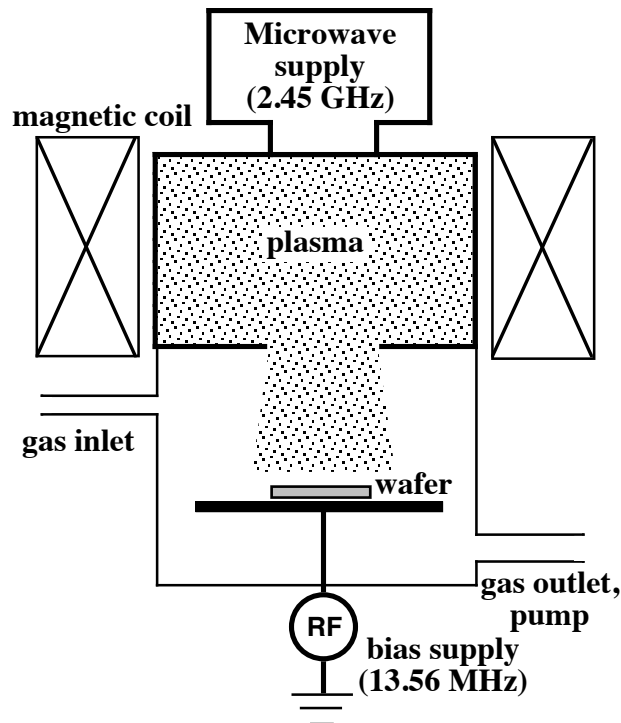


- Electrodes have equal areas (or wafer electrode is grounded with chamber and **[?]** larger)
- Only moderate sheath voltage (10-100 eV), so only moderate ionic component. Strong chemical component.
- Etching can be fairly isotropic and selective.

Parallel Plate Systems - Reactive Ion Etching (RIE) Mode

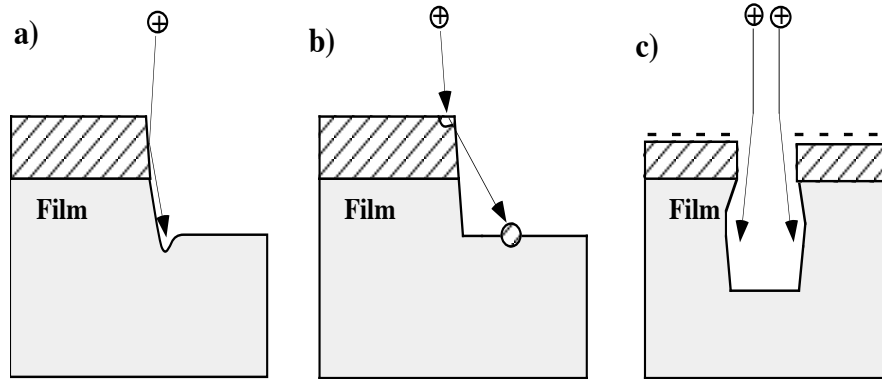
- For more directed etching, need stronger ion bombardment.
- Wafers sit on smaller electrode (RF power there).
- Higher voltage drop across sheath at wafers. (100-700 eV).
- Lower pressures are used to attain even more directional etching (10-100 mtorr).
- More physical component than plasma mode [?]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

High Density Plasma (HDP) Etch Systems



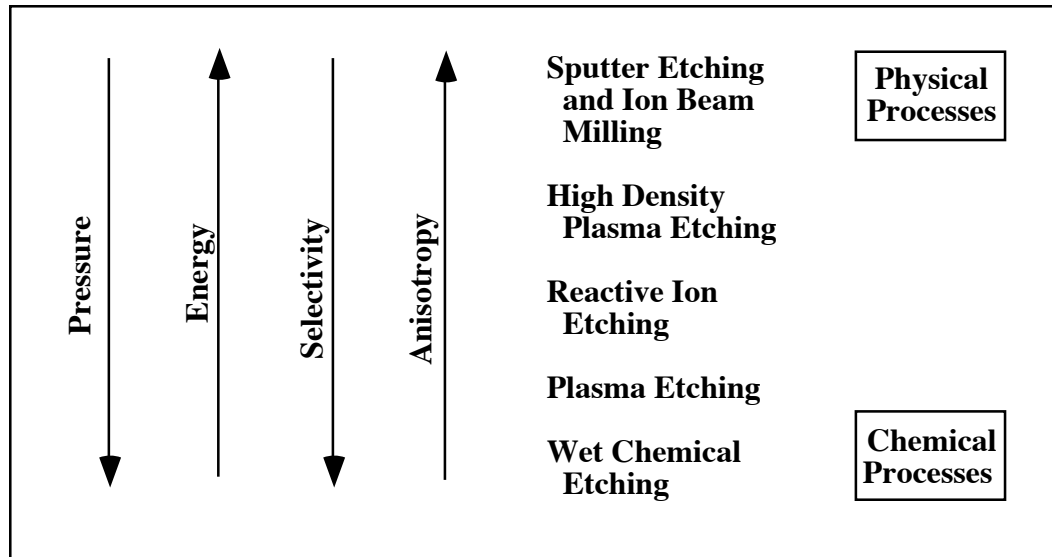
- Uses remote, non-capacitively coupled plasma source (Electron cyclotron resonance - ECR, or inductively coupled plasma source - ICP).
- Uses separate RF source as wafer bias. This separates the plasma power (density), from the wafer bias (ion accelerating field).
- Very high density plasmas (10^{11} - 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.

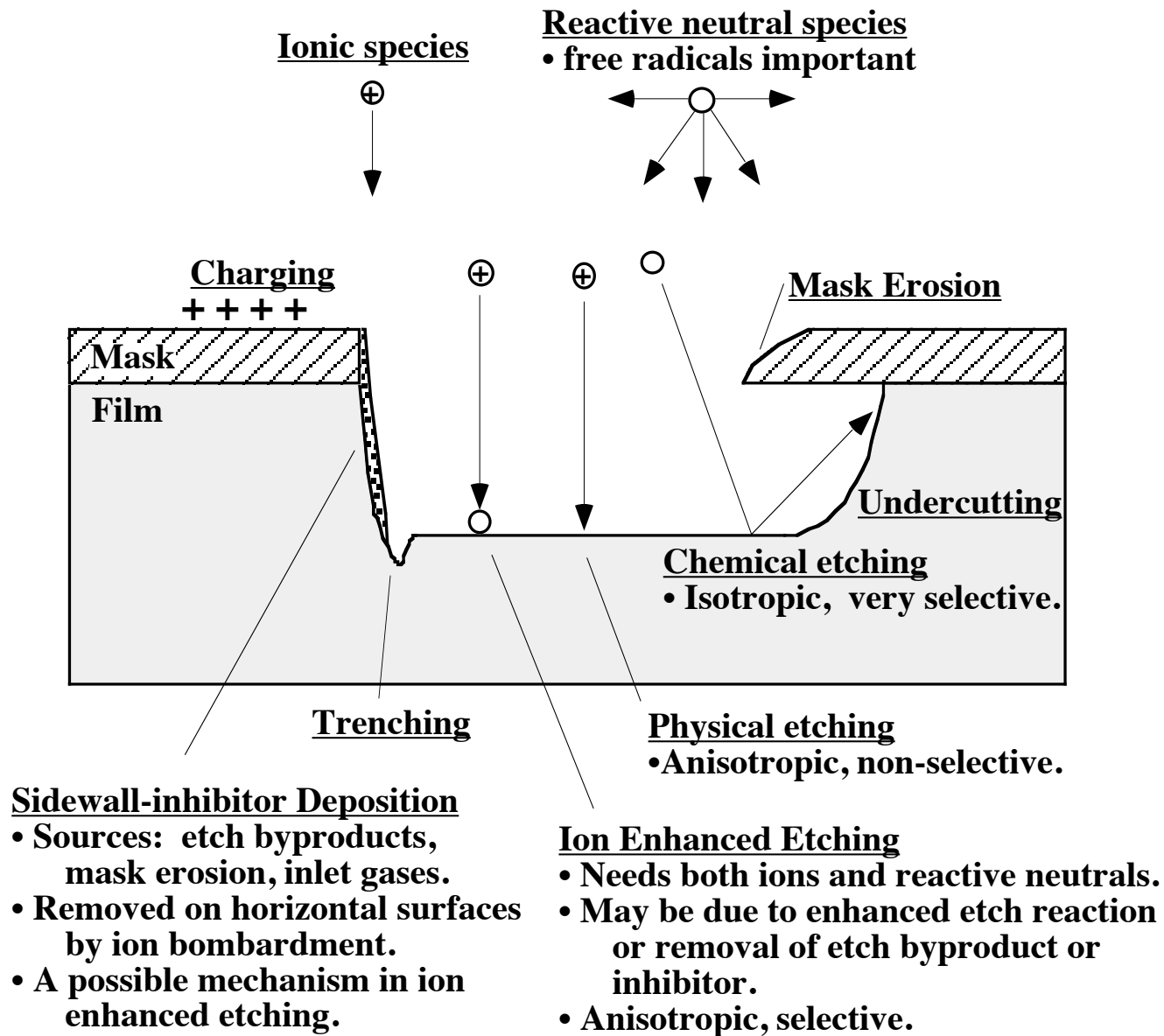
Sputter Etching



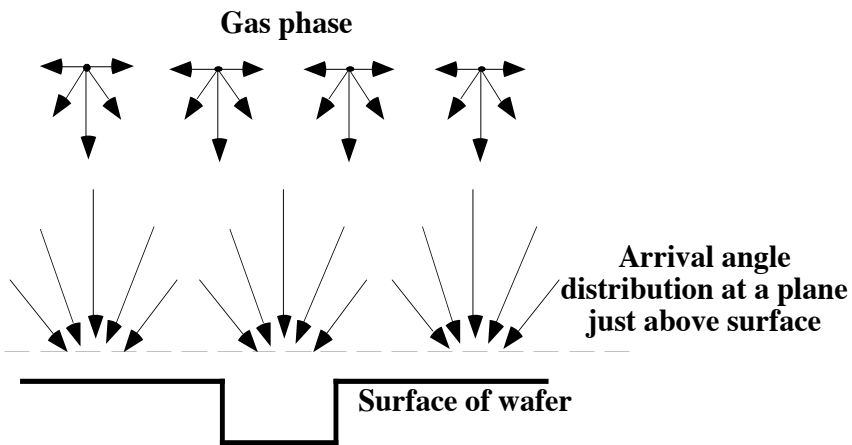
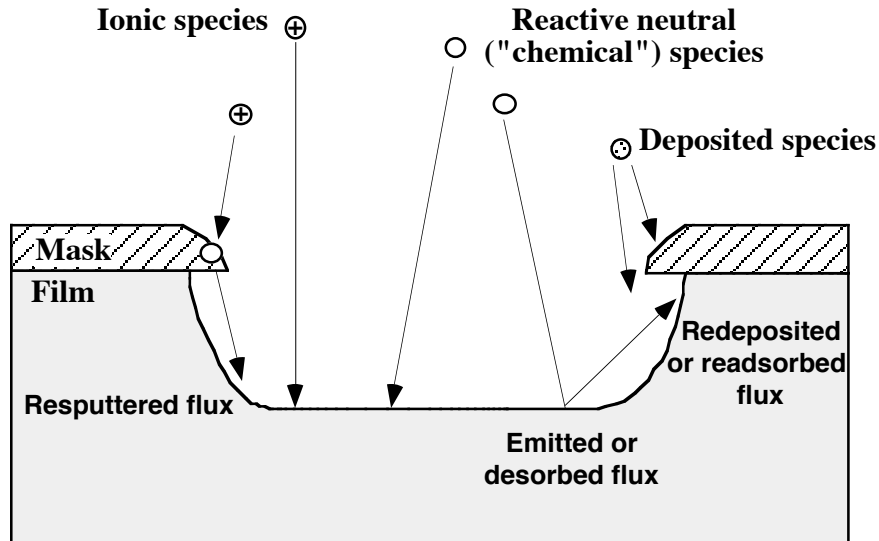
- Purely physical etching:
 - Highly directional, with poor selectivity
 - Can etch almost anything
- Sputter etching, uses Ar^+ .
 - Damage to wafer surface and devices can occur: trenching (a), ion bombardment damage, radiation damage, redeposition of photoresist (b) and charging (c).
 - These can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

Summary





Models and Simulation



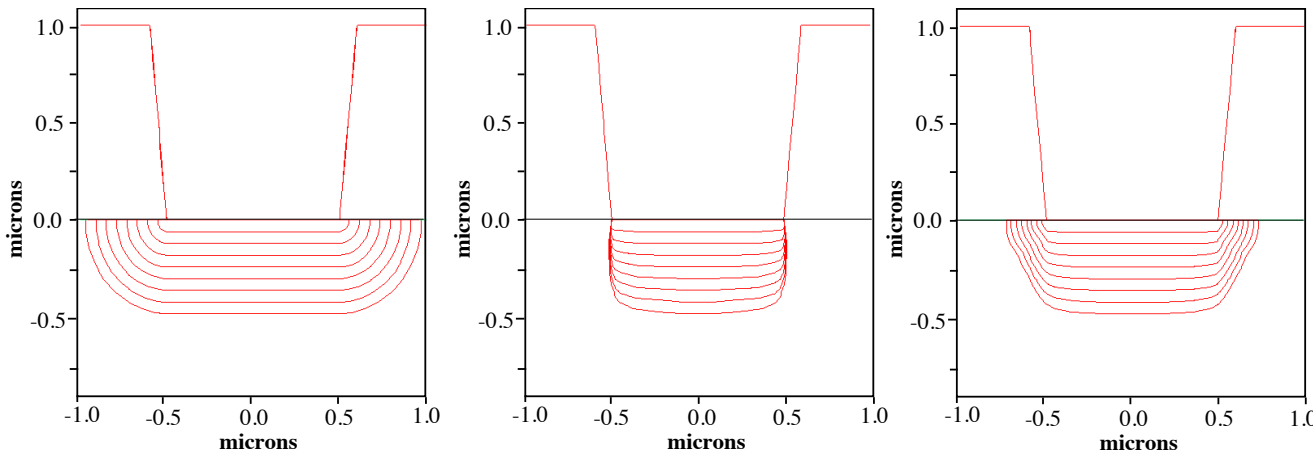
- There is a great deal of similarity between the deposition models described in Chapter 9 and etching models.
- Both use incoming "chemical" (neutral) and ion fluxes and many other similar physical processes.
- As in deposition, the etch rate is proportional to the net flux arriving at each point.
- Chemical etching species are assumed to arrive isotropically ($n = 1$ in $\cos^n \theta$).
- Ionic species are assumed to arrive anisotropically (vertically) ($n \approx 10 - 80$ 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).

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

- 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.

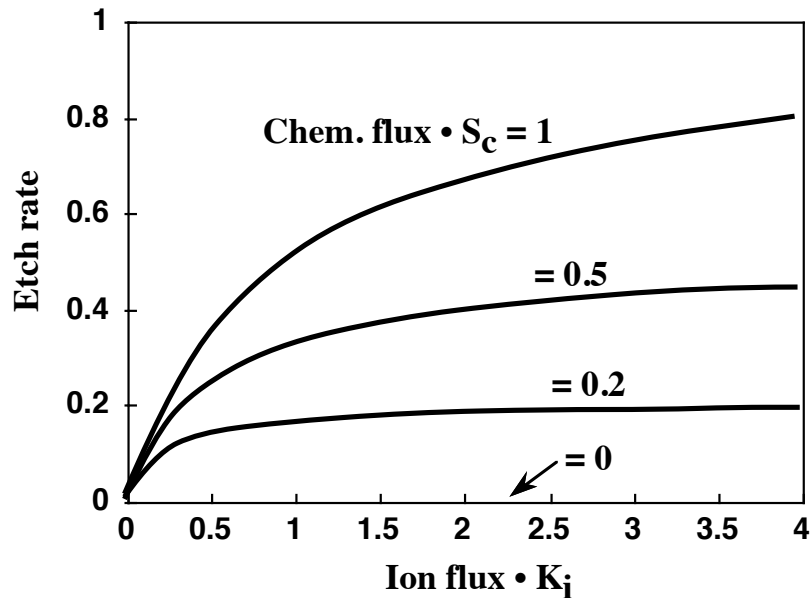


a). all chemical etching (ion flux=0); b). all physical or ionic etching (chem flux=0); c). half chemical, half physical.

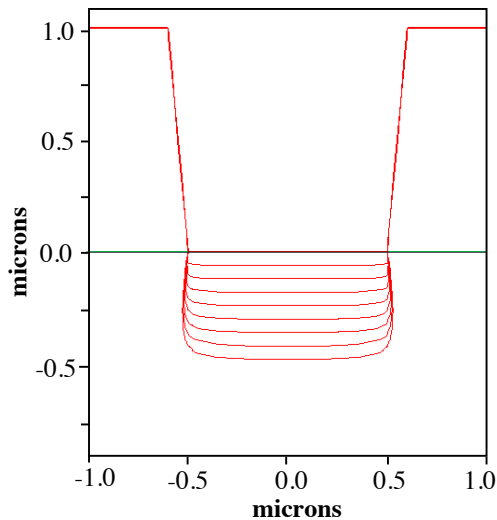
Saturation - Adsorption Etch Model

- 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.

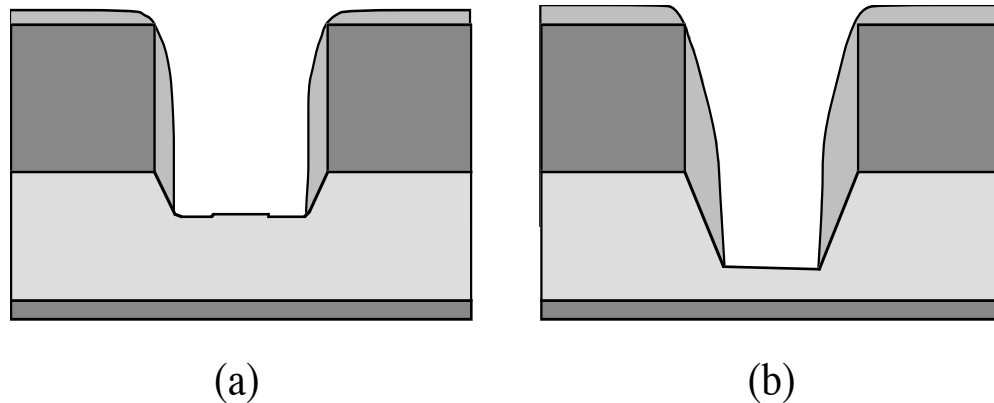
$$\text{Etch Rate} = \frac{1}{N} \left(\frac{1}{K_i F_i} + \frac{1}{S_c F_c} \right) \quad (8)$$



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



- **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.**

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).