Nanometer Scale Patterning and Processing

Spring 2016

Lecture 46

Dry Etching, Part 2

Pressure range for normal glow-discharge plasmas

Necessary conditions:

If pressure is too low, λ is large, too few collisions *in plasma* to sustain energy

1) $\lambda < L$

so collisions exchange energy *within* plasma

$$\boxed{\lambda = \frac{k_B T}{\sqrt{2}\,\pi d^2 P}}$$

If pressure is too high, λ is small, very little acceleration between collisions

2) $E_K >$ ionization potential of Ar^+

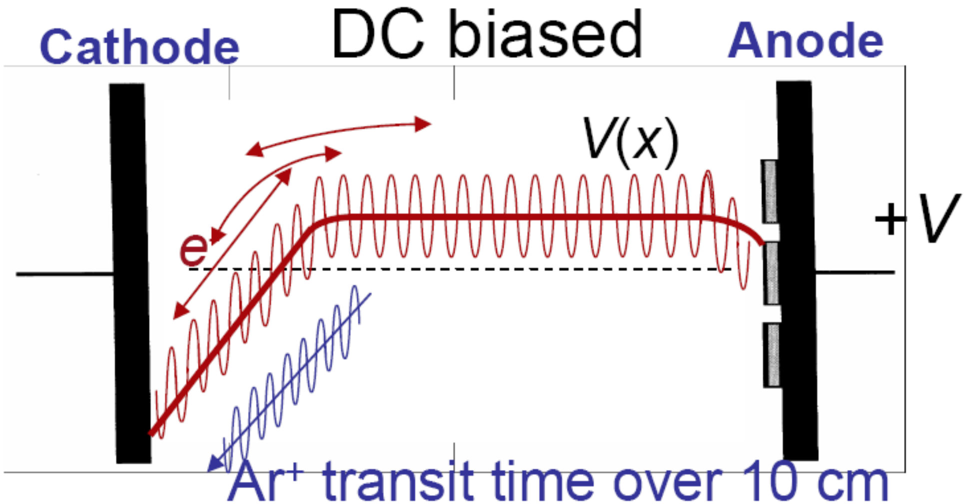
$$\boxed{\frac{1}{2} m v_f^2 = 2ax \approx Eq\lambda}$$

High-density plasmas can sustain at lower pressures

RF Plasma

$f = 13.6$ MHz , $\tau \approx 12$ ns

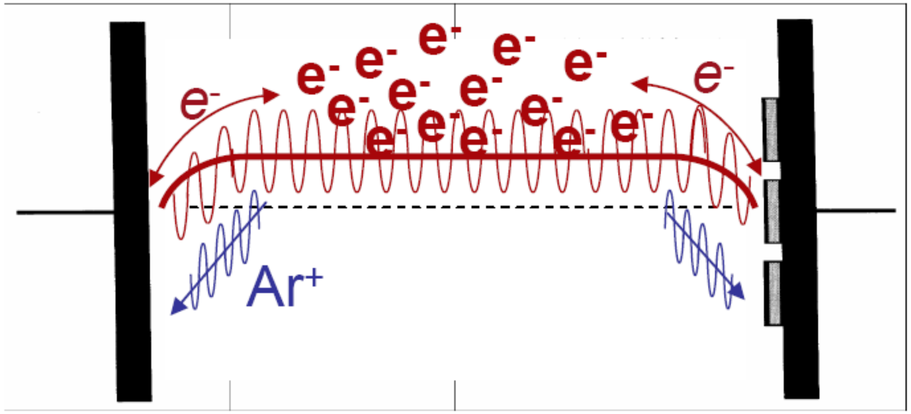
e^- transit time over 10 cm:
$t \approx 10$ ns.
e^- follows RF field



Ar^+ transit time over 10 cm
$t \approx 2$ μs

Ar^+ drifts with DC field

But wait a minute!
If the plasma is
a good conductor,
does the RF field
penetrate it?



Plasma is conductive but not a good one

τ: average time between collisions

$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

We estimated $\tau \approx 0.01\ \mu s$, so at 10 mT, $\sigma \approx 300\ s^{-1}$

Is this a good metal?

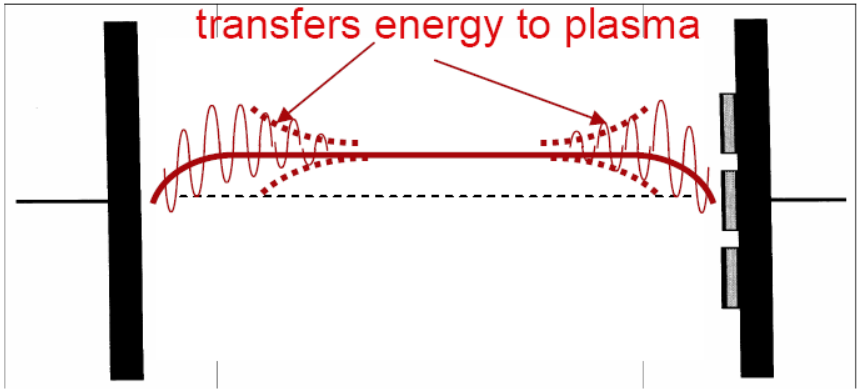
No!

Metals: $\rho_e < 100\ \mu\Omega$-cm = 1 $\mu\Omega$-m, $\sigma > 10^6\ s^{-1}$

What then is the RF field penetration depth, skin depth?

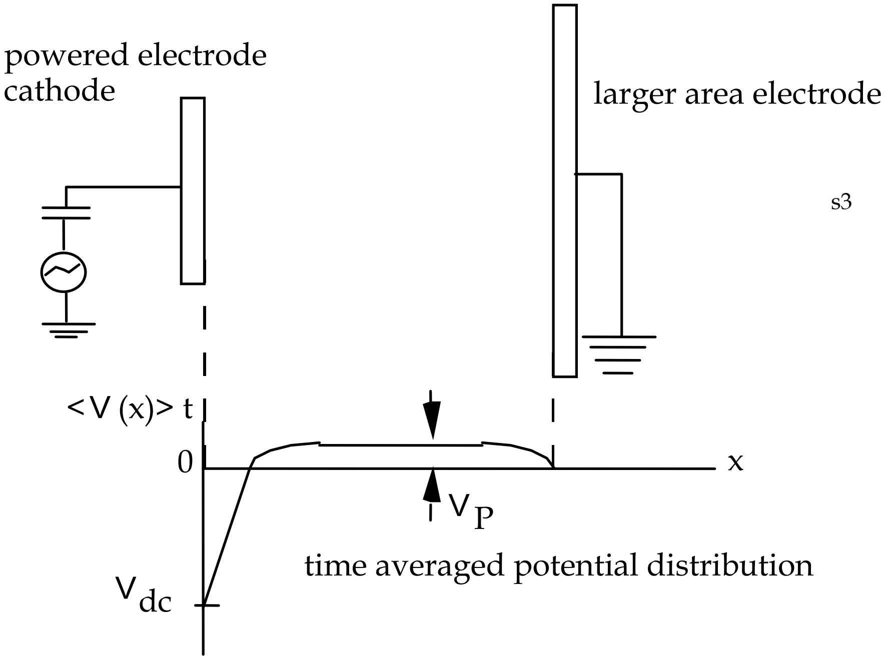
$$\boxed{\delta = \frac{1}{\sqrt{\mu\sigma\omega}} \approx 5\ \text{mm}}$$

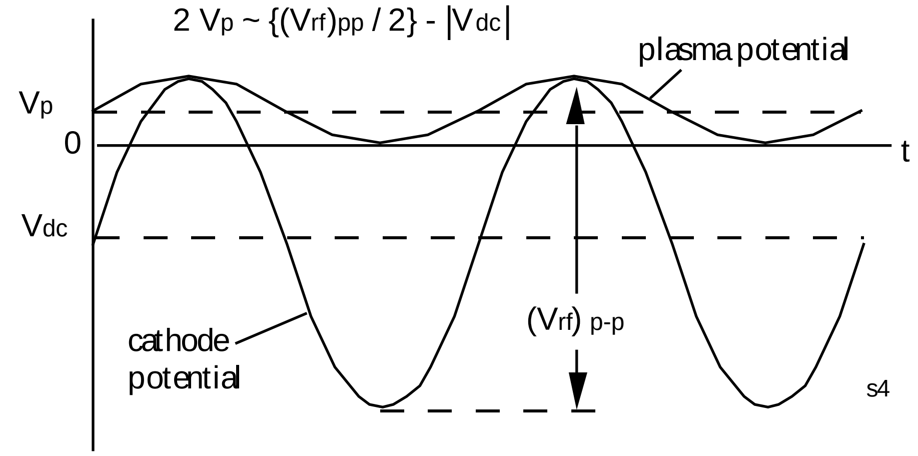
Energy pumped in from edges of plasma



This is where RF field transfers energy to plasma

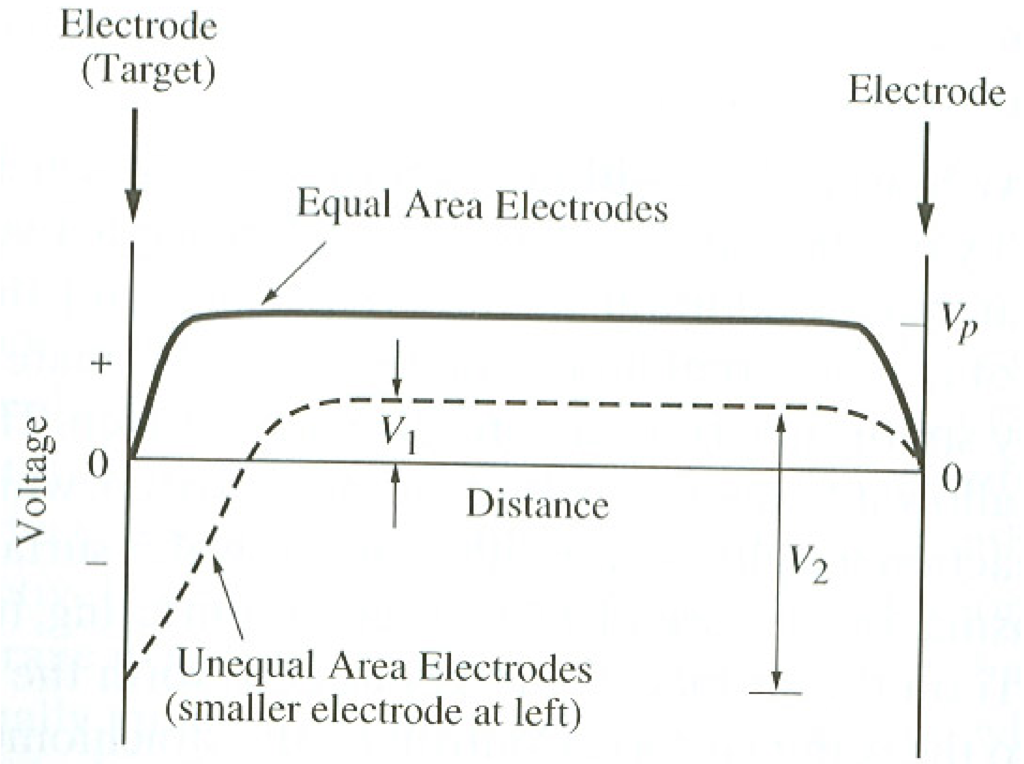
Charge balance in RF plasma





RF plasma allows electrodes to be insulators

Voltages in RF Plasma

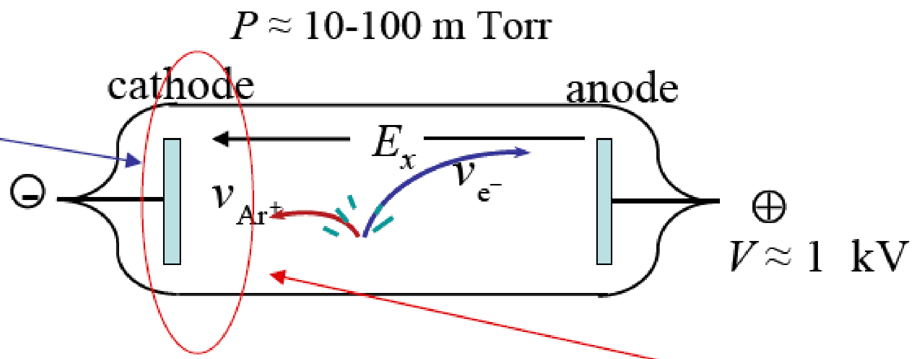


$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^m$$

A_2 and A_1 are areas of the electrodes, m=4 in simple theory, but usually is 1~2.

The larger electrodes are typically the chamber wall.

Sputtering Effect



Cathode
is “target”,
source material

Sputter removal (etching)
occurs here

At 1 keV, $v_{\mathrm{Ar+}} = v_e/43$

Momentum transfer:

$$\left\{ \begin{array}{l} p_e = mv \\ P_{\mathrm{Ar}} = MV = 1832mv/43 \approx 43p_{e-} \end{array} \right.$$

No surprise.

from ion implantation,

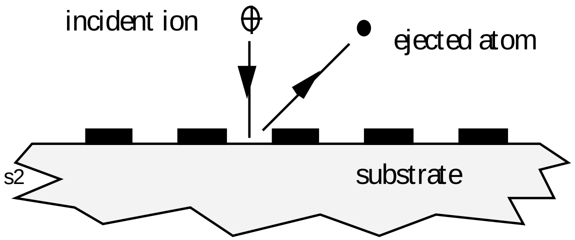
most energy transfer when:

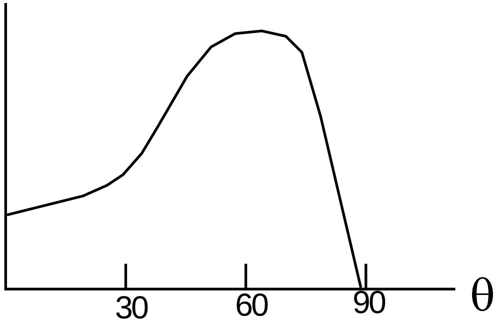
i.e. incoming particle has mass

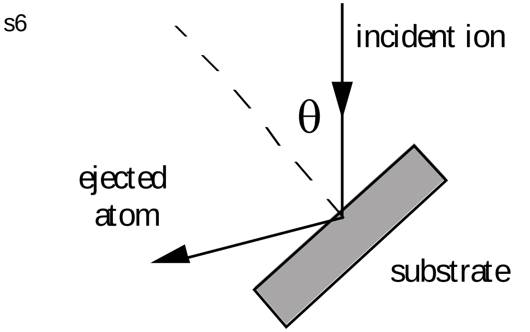
close to that of target.

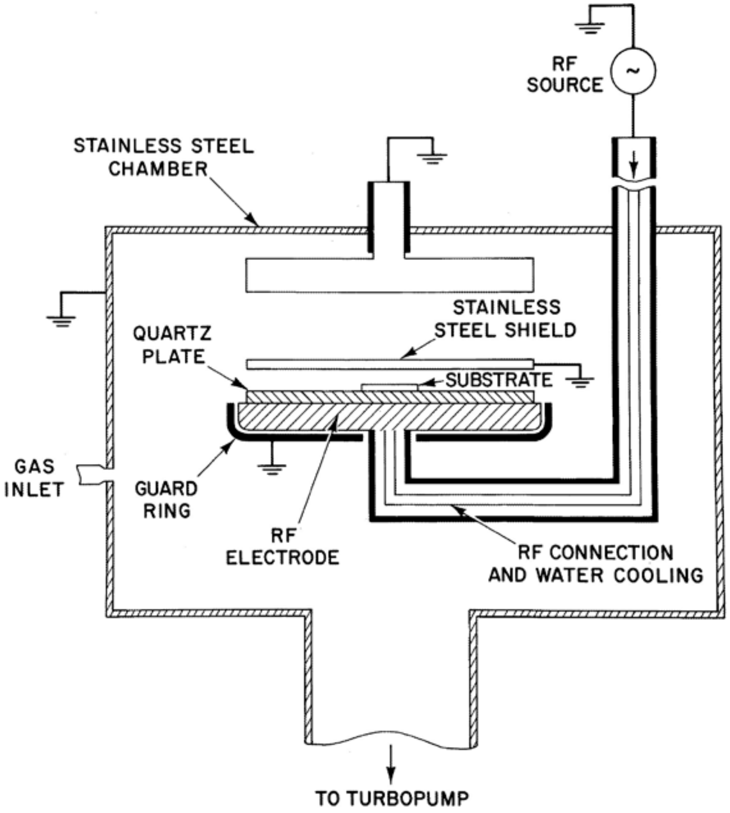
$$\boxed{\Delta E = E_1 \frac{4M_1M_2}{(M_1+M_2)^2}}$$

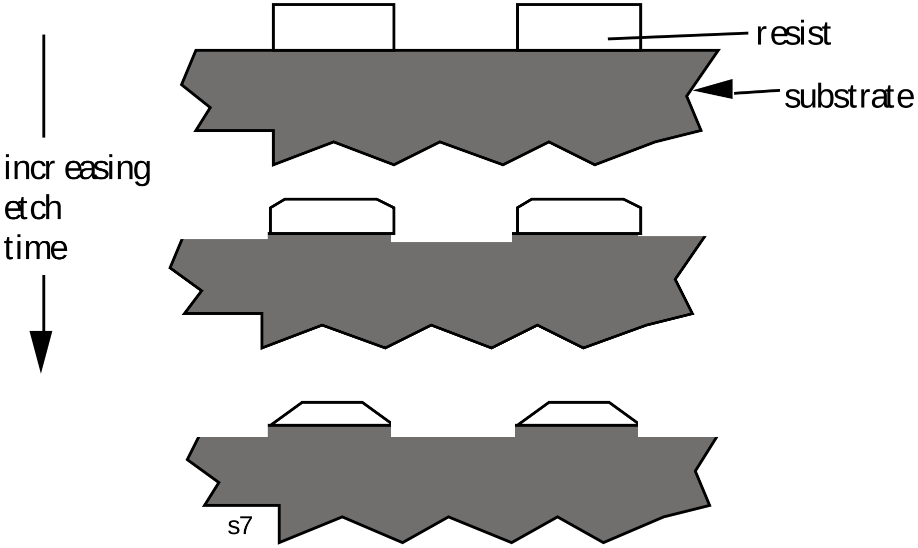
Sputter Etch





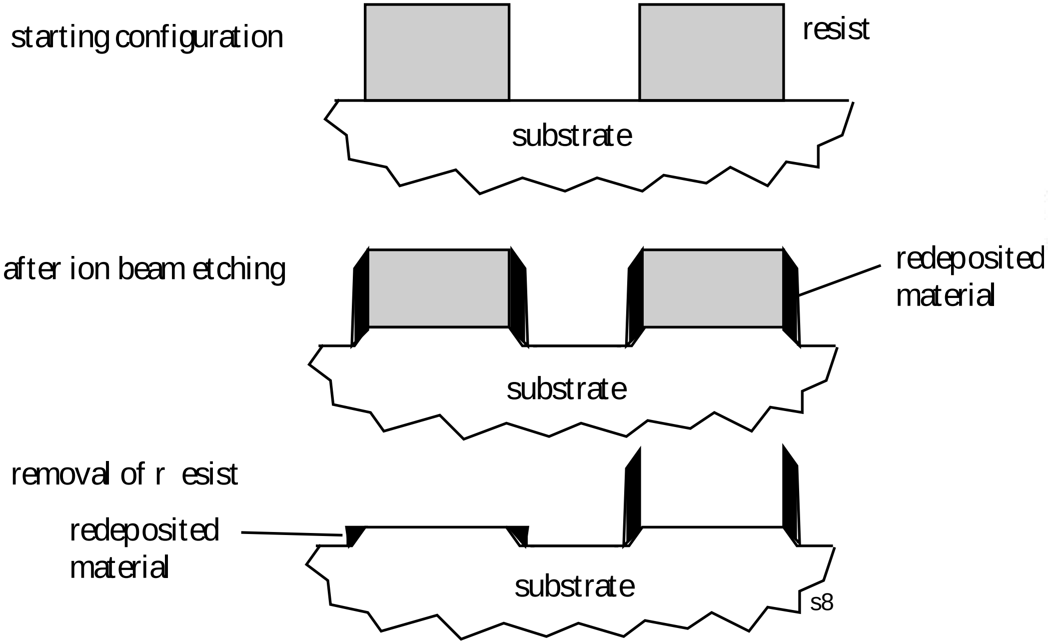






Faceting effect

Re-deposition in Sputter Etch



starting configuration

resist

substrate

after ion beam etching

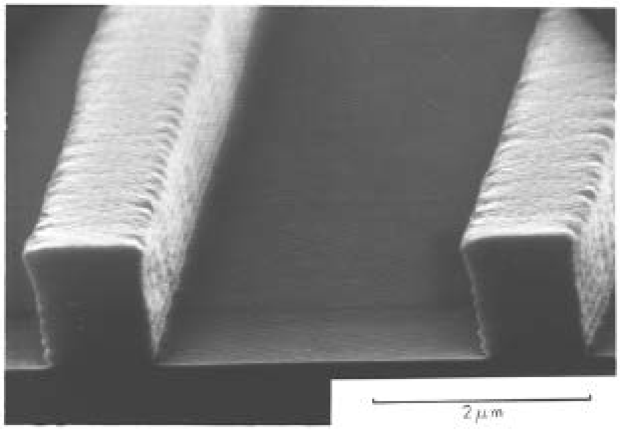
redeposited material

substrate

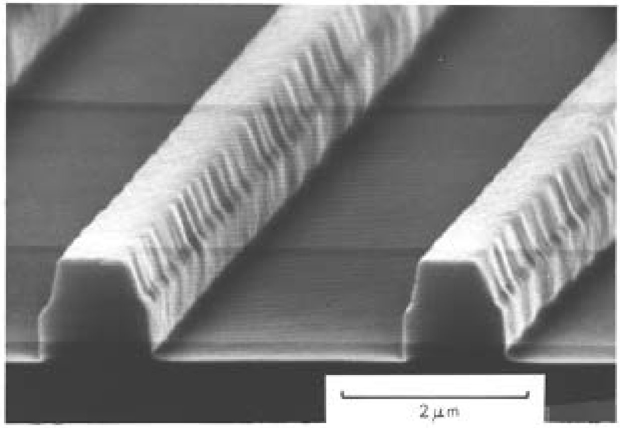
removal of resist

redeposited material

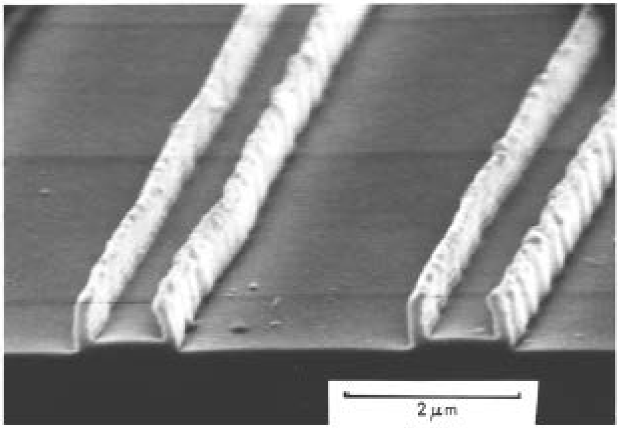
substrate



resist



after ion beam etching

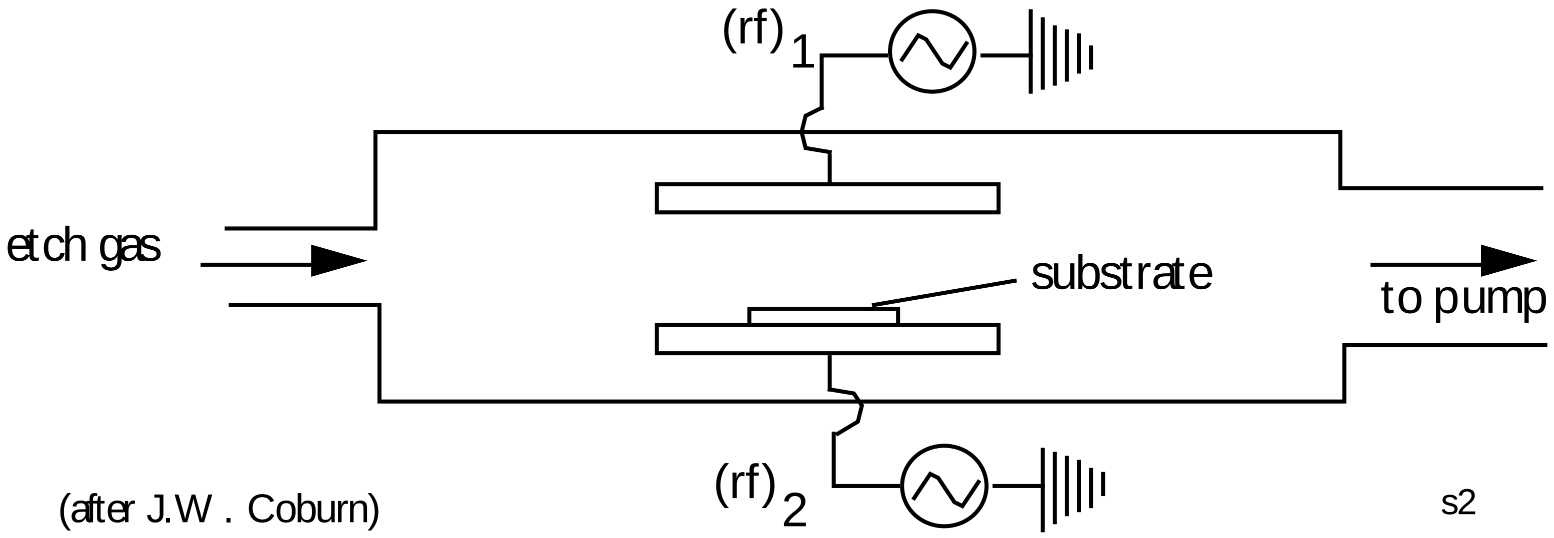


after removal of resist, note redeposit

Solution to Re-deposition:
Forming Volatile Products in plasma

Solid	Etch Gas	Etch Product
Si, SiO_2, Si_3N_4	CF_4, SF_6, NF_3	SiF_4
Si	Cl_2, CCl_2F_2	$SiCl_2$, $SiCl_4$
Al	BCl_3, CCl_4, Cl_2	Al_2Cl_6, $AlCl_3$
Organic Solids (photoresists, etc)	O_2 O_2+CF_4	CO, CO_2, H_2O CO, CO_2, HF
Refractory Metals (W, Ta, Nb, Mo …)	CF_4 Cl_2	WF_6 … WCl_6
III-V GaAs, InP	Cl_2, CCl_2F_2 CH_4/H_2	$GaCl_3$, $AsCl_5$ PH_3, $In(CH_3)_3$

Configurations for Parallel-Plate systems



$(rf)_1 \neq 0 \quad (rf)_2 = 0$ Plasma etching

$(rf)_1 = 0 \quad (rf)_2 \neq 0$ Reactive ion etching

$(rf)_1 \neq 0 \quad (rf)_2 \neq 0$ Triode etching

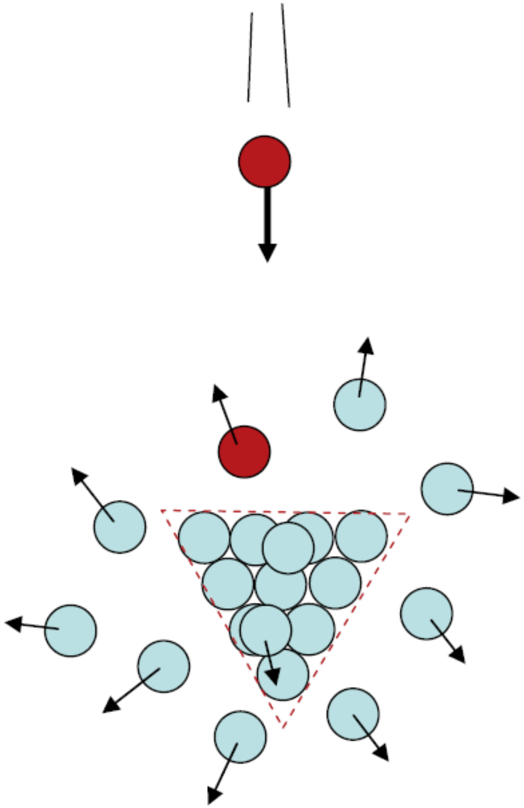
Dry etch combines

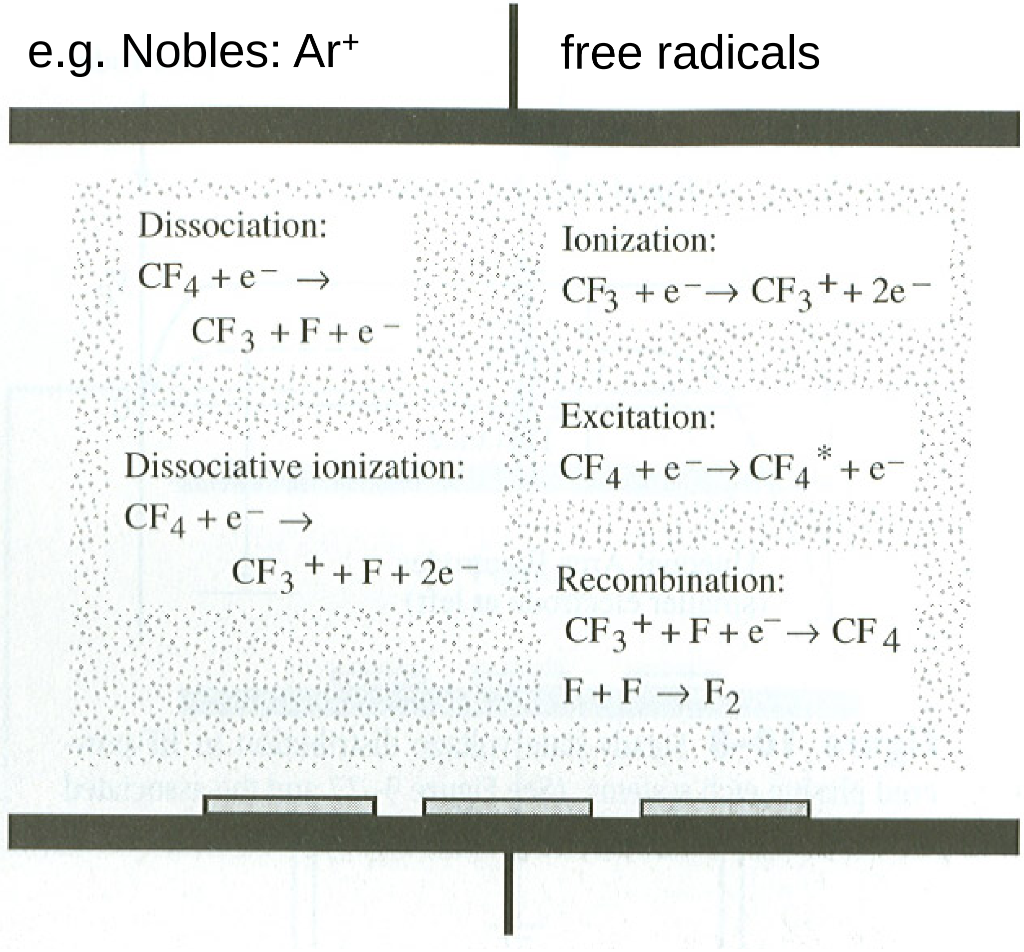
physical etch

e.g. Nobles: Ar^+

+ reactive ions

free radicals





Dissociation:

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

Dissociative ionization:

$CF_4 + e^- \rightarrow CF_3^+ + F + 2e^-$

Ionization:

$CF_3 + e^- \rightarrow CF_3^+ + 2e^-$

Excitation:

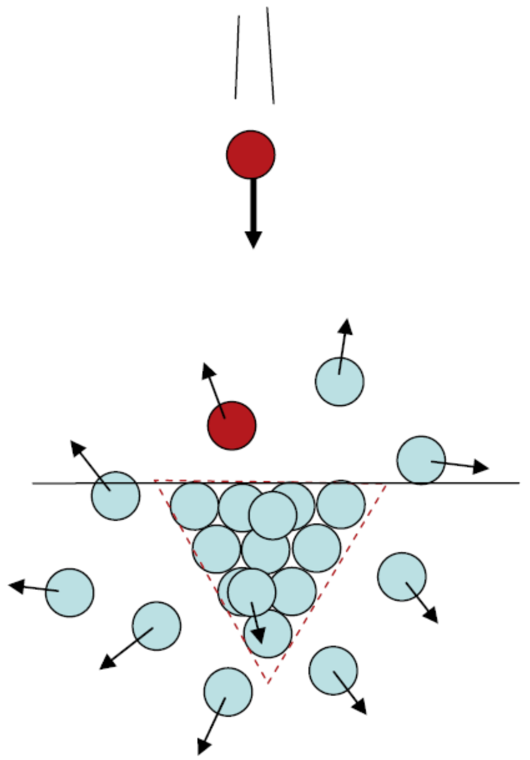
$CF_4 + e^- \rightarrow CF_4^* + e^-$

Recombination:

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

$F + F \rightarrow F_2$

Physical etching
involves *directional momentum transfer by Ar+, Cl+ etc.*

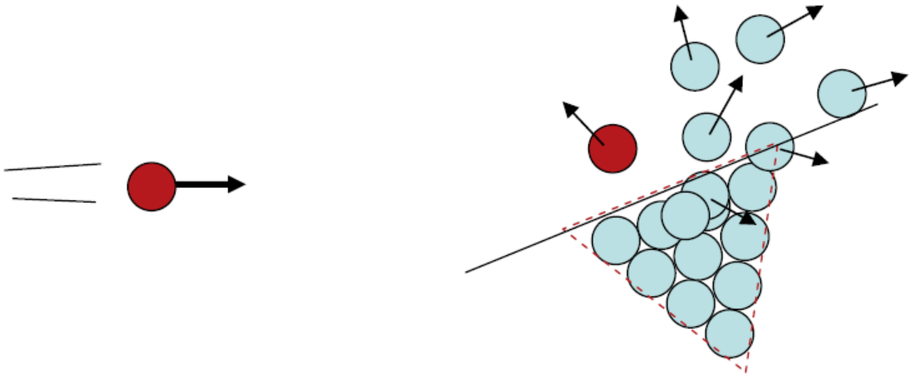


Because momentum is transferred with every collision,

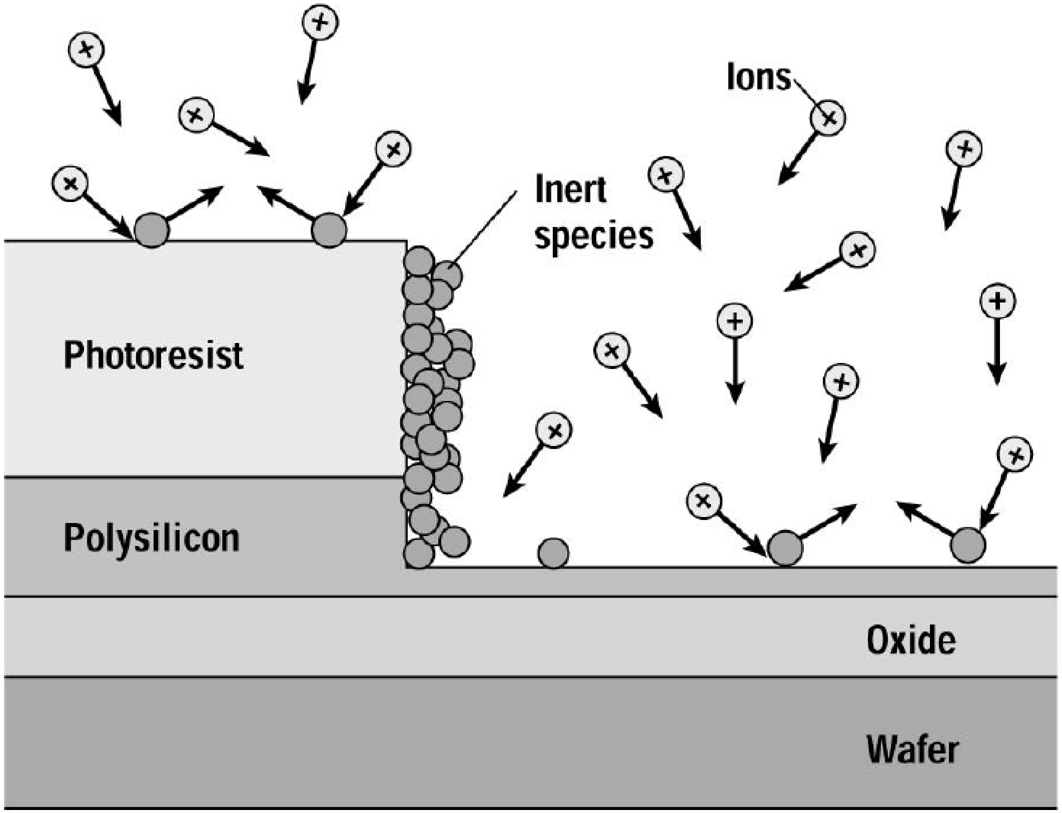
sticking is essentially unity, $S \approx 1$.

This enhances anisotropic character

Sputter yield depends on angle of incidence, helping planaraization



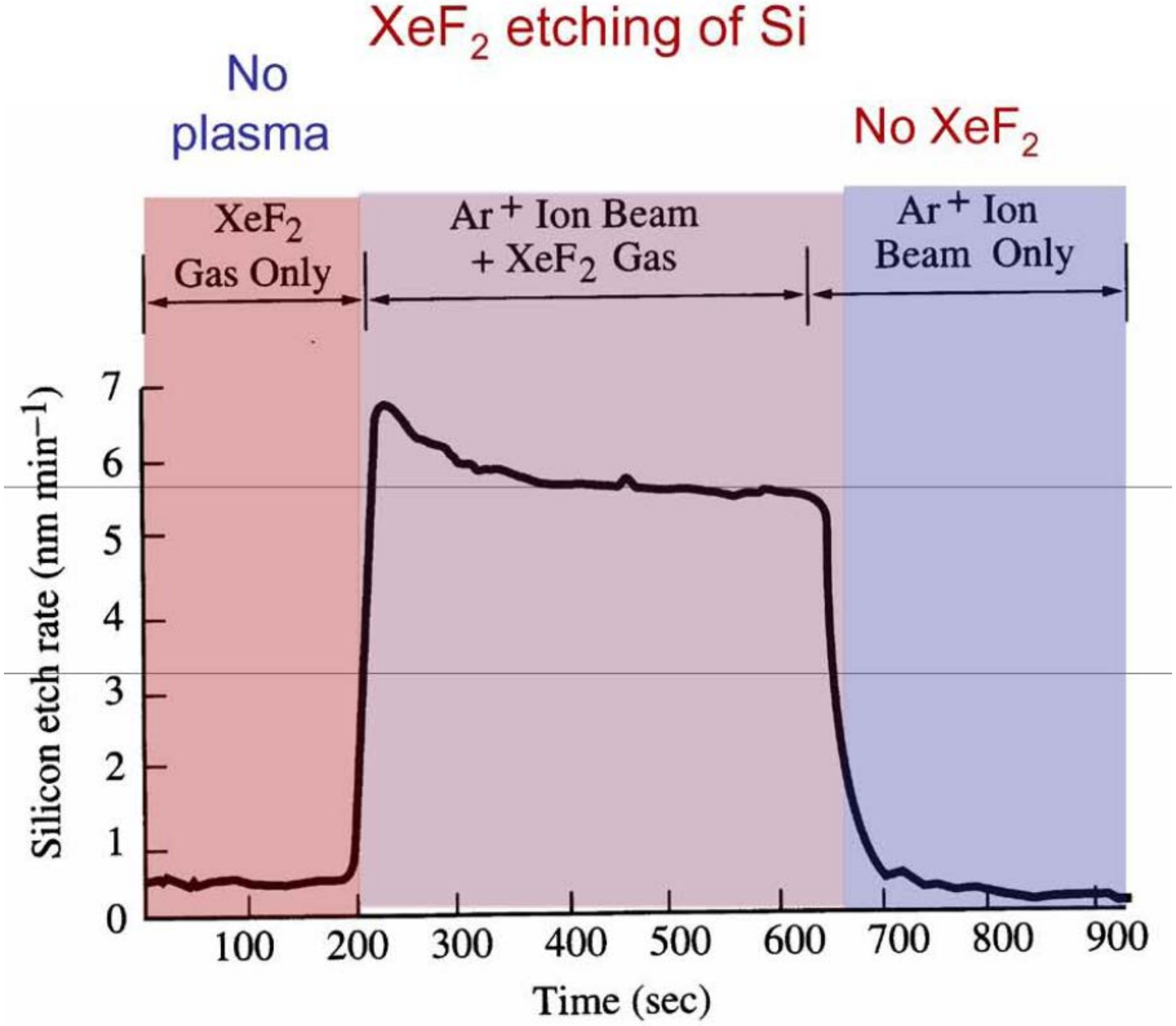
Sidewall Deposition



- REMOVAL of surface film and
- DEPOSITION of plasma reaction products can occur simultaneously
- Sidewall deposition can be passivation

Ion-enhanced Chemical Etching

Physical and chemical processes not just independent of each other.
Ion beam can enhance chemical etching:

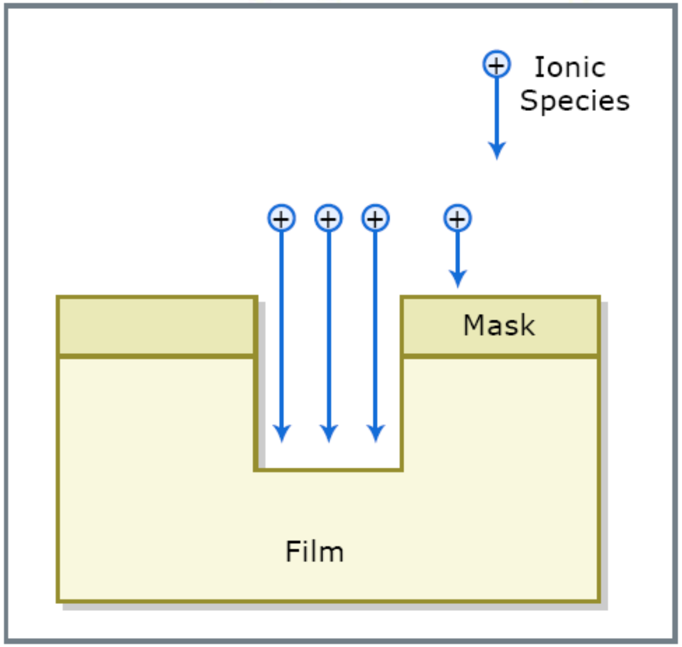


XeF_2 etching of Si

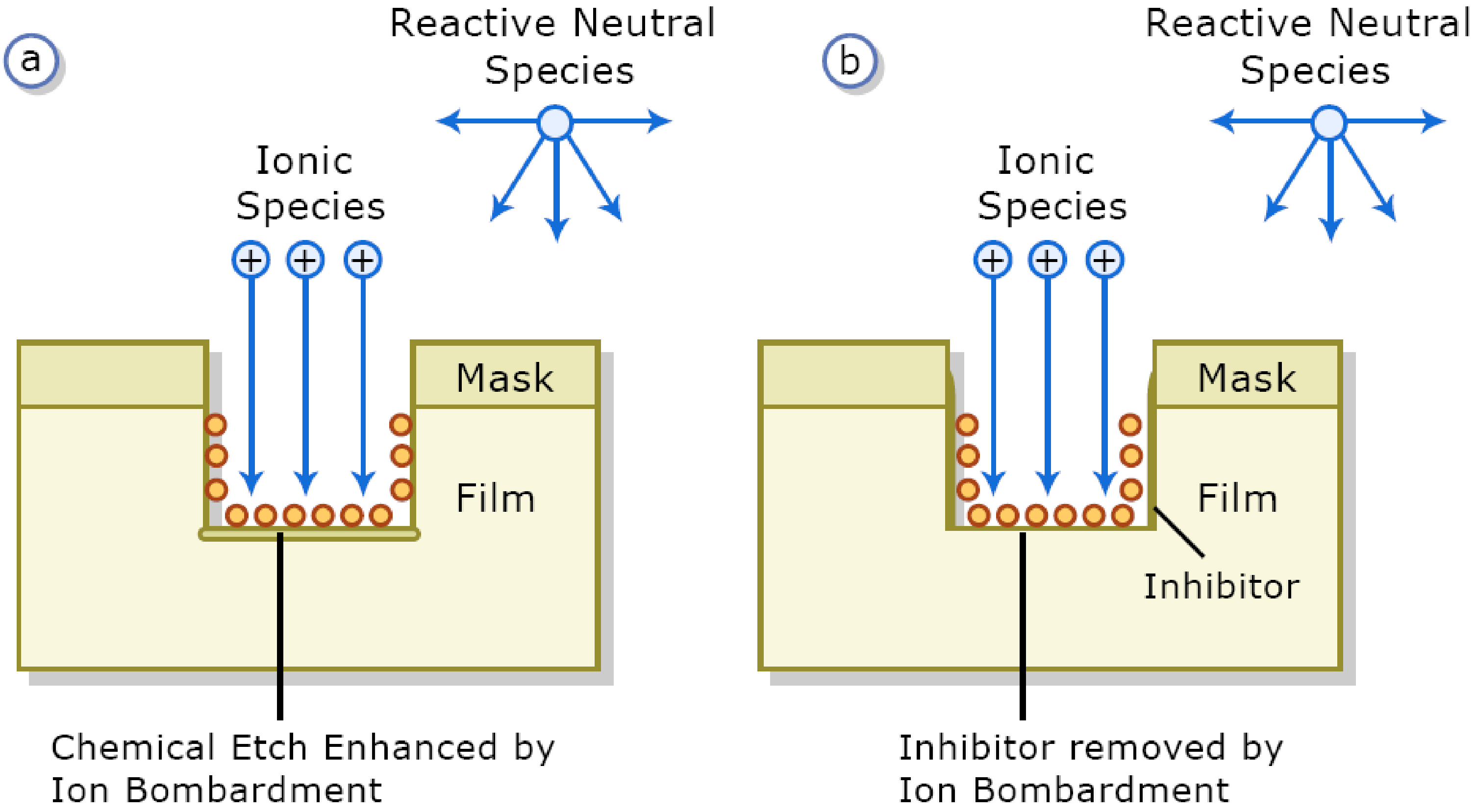
No plasma

No XeF_2

Further, the profile is not linear combo, but highly anisotropic

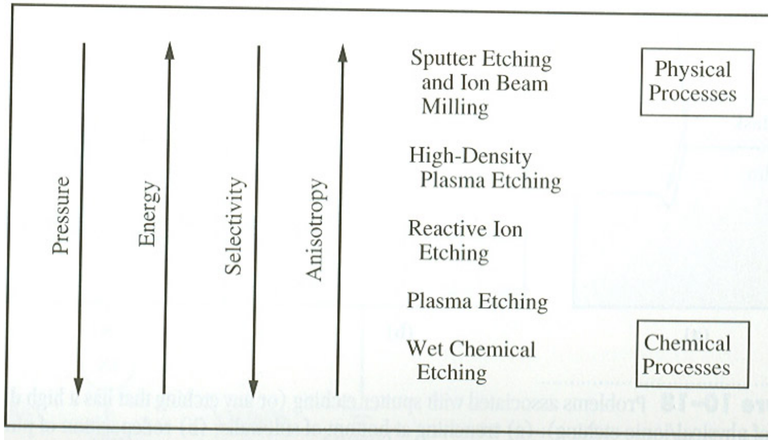


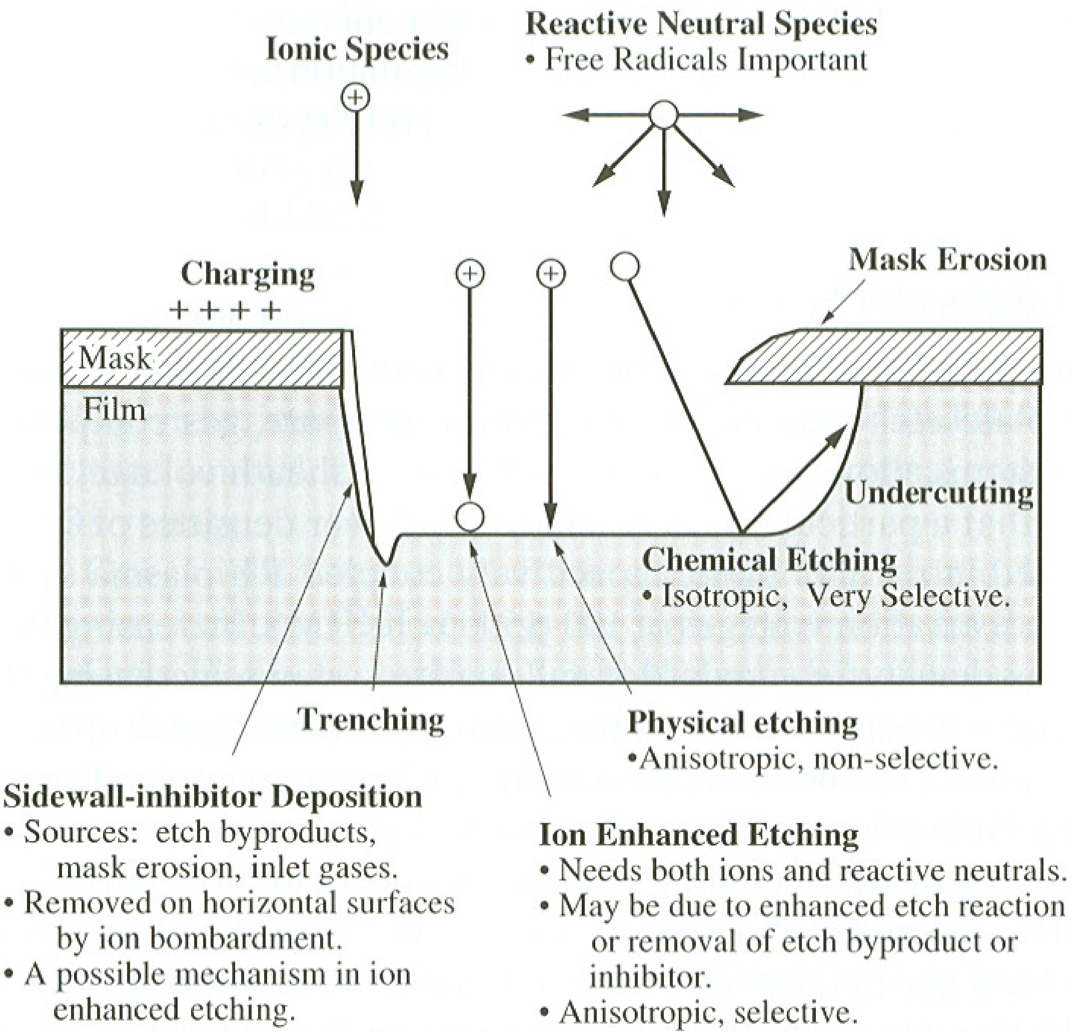
Sidewall control



Tailor mix of gas as well as ion energy & rate to select desired wall profile.

Summary of Plasma Etching





Reactive Neutral Species
- Free Radicals Important

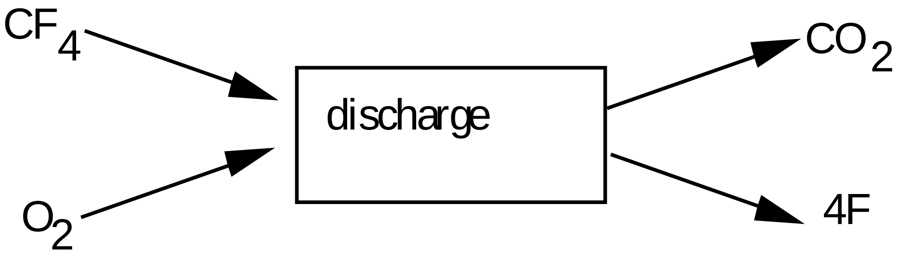
Chemical Etching
- Isotropic, Very Selective.

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.

Etch Rate Increases with large concentration of active ions/radicals



CF_4

O_2

discharge

CO_2

4F

This produces a large amount of atomic F. Compare this to

s11

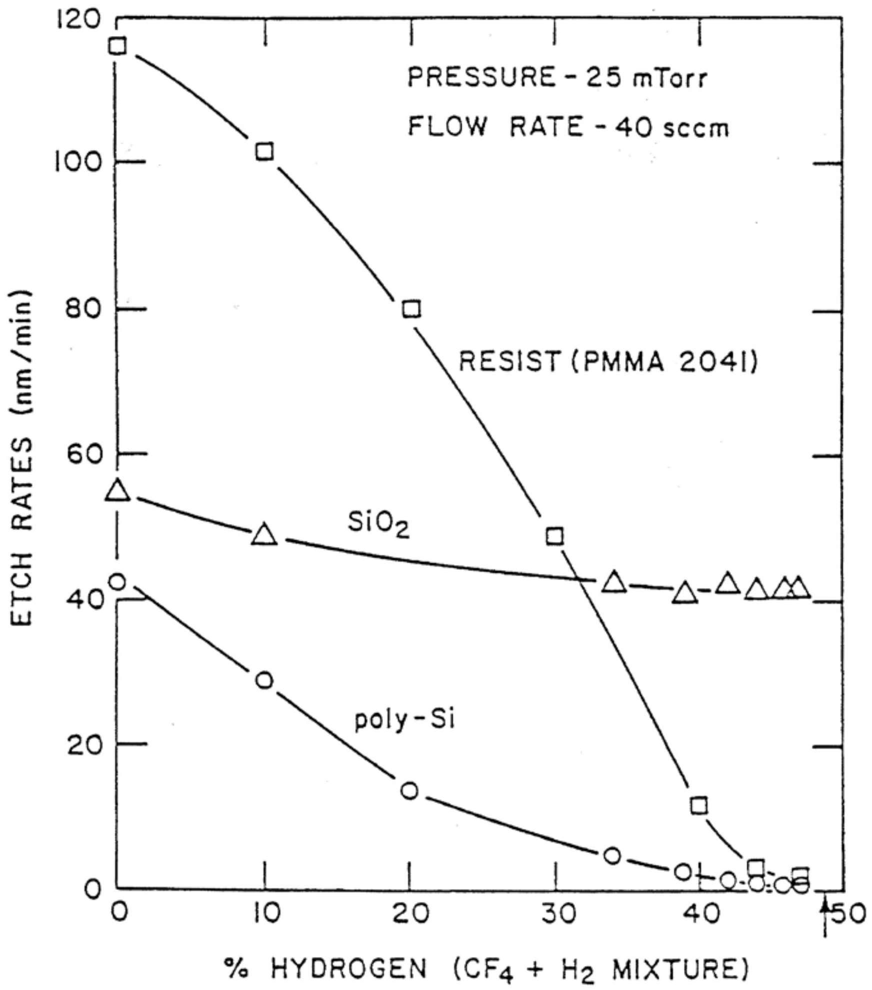
CF_4

discharge

CF_3

F

Hydrogen Concentration in Fluorine based plasmas



- H ties up F, and increases the chance of polymerization (Teflon like).
- CHF_3 etches SiO_2 fast, but Si slowly.
- C_4F_8 is used for polymerization in deep RIE etch.