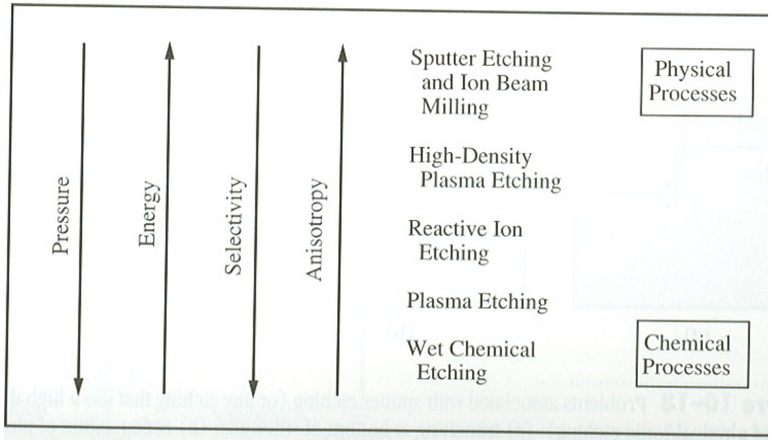
Nanometer Scale Patterning and Processing

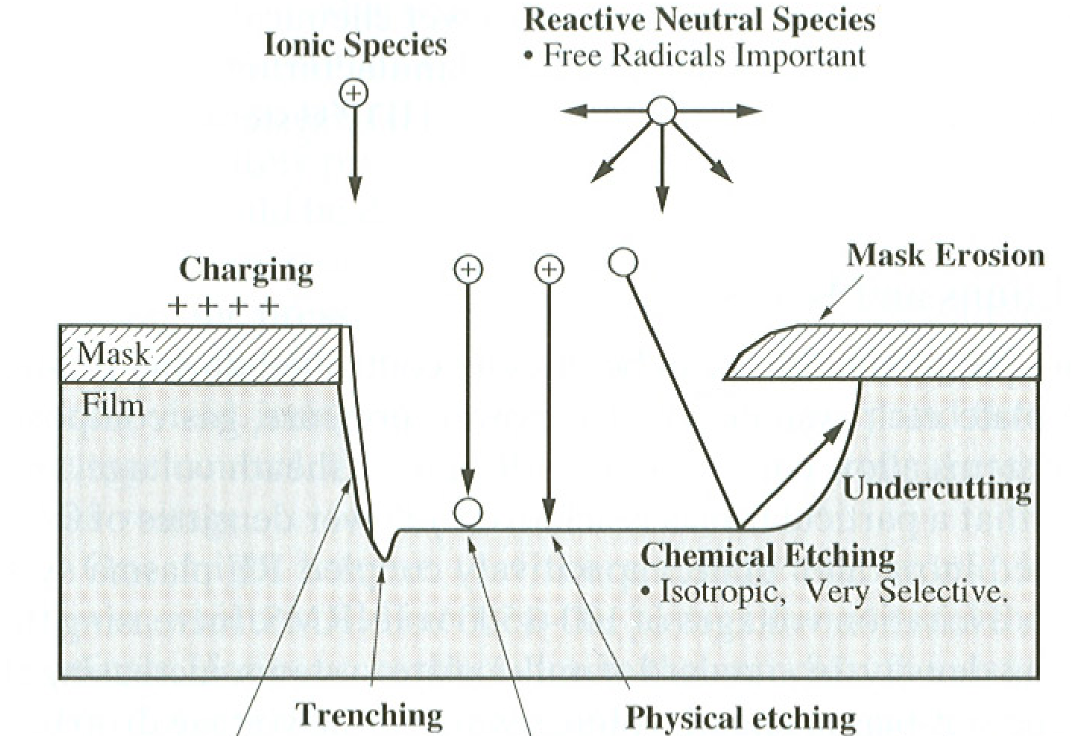
Spring 2016

Lecture 47

Dry Etching, Part 3

Summary of Plasma Etching





Reactive Neutral Species
- Free Radicals Important

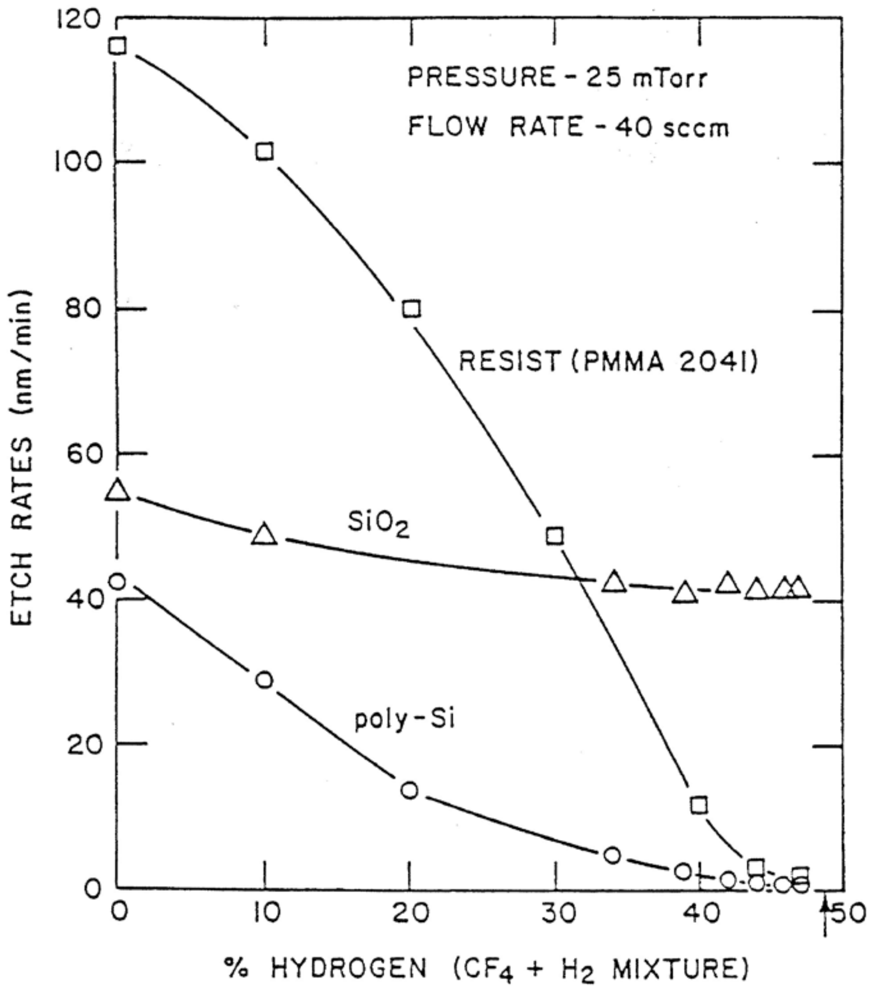
Chemical Etching
- Isotropic, Very Selective.

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.

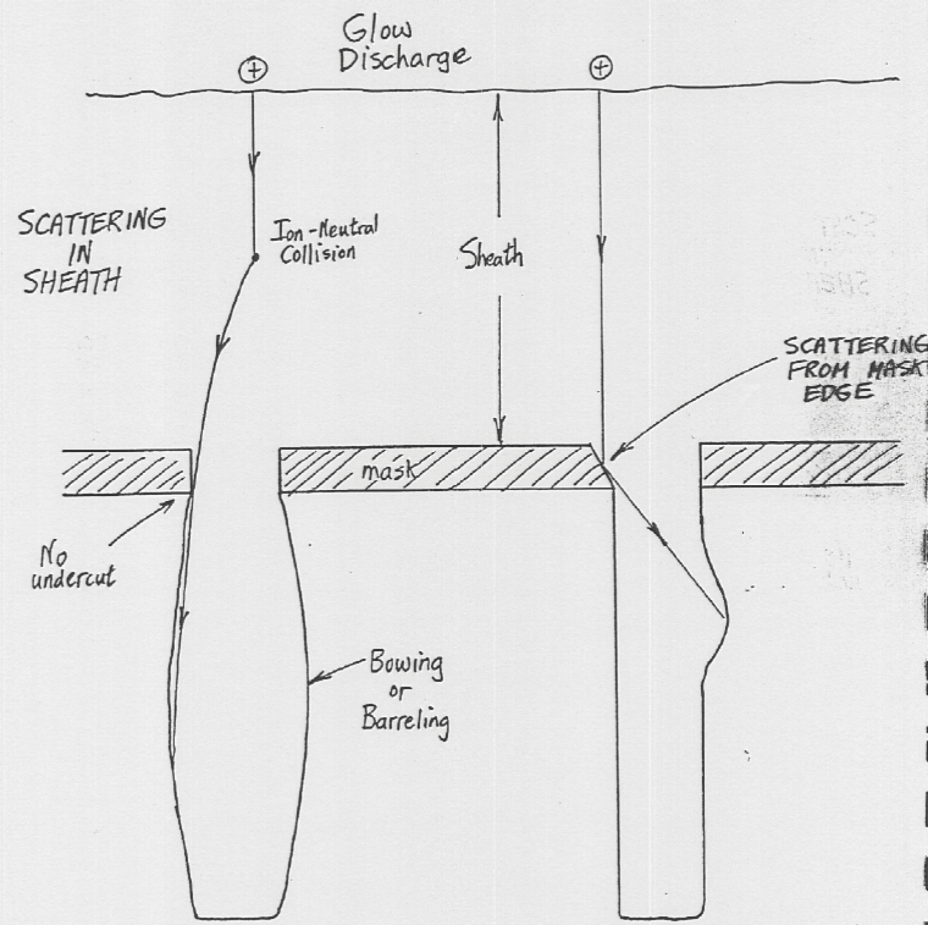
Ion Enhanced Etching
- Needs both ions and reactive neutrals.
- May be due to enhanced etch reaction or removal of etch byproduct or inhibitor.
- Anisotropic, selective.

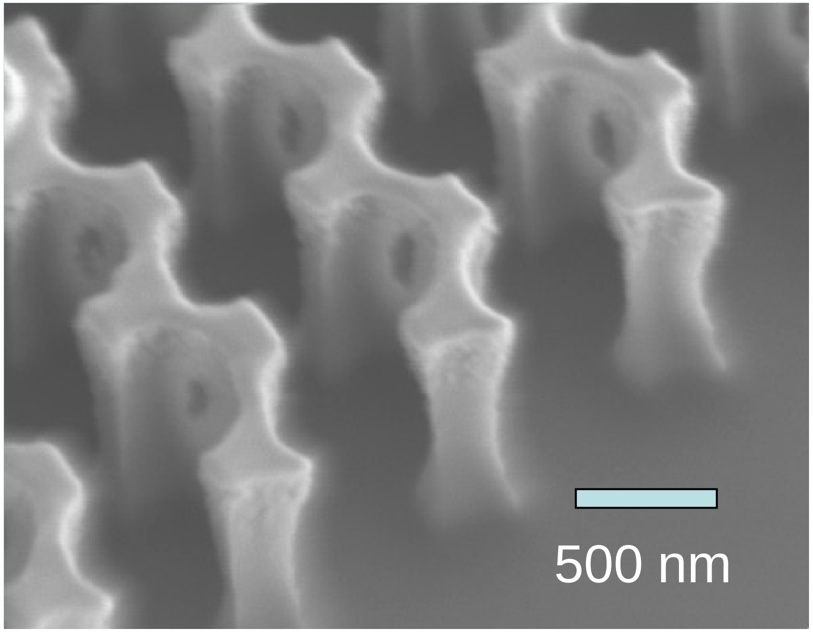
Hydrogen Concentration in Fluorine based plasmas



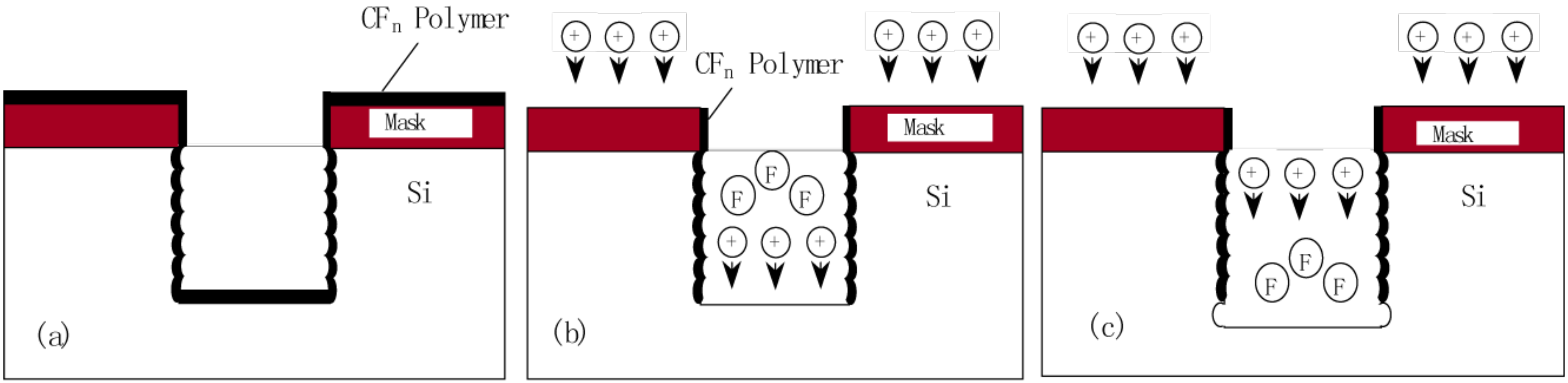
- H ties up F, and increases the chance of polymerization (Teflon like).
- CHF_3 etches SiO_2 fast, but Si slowly.
- C_4F_8 is used for polymerization in deep RIE etch.

Ion Trajectory Problems

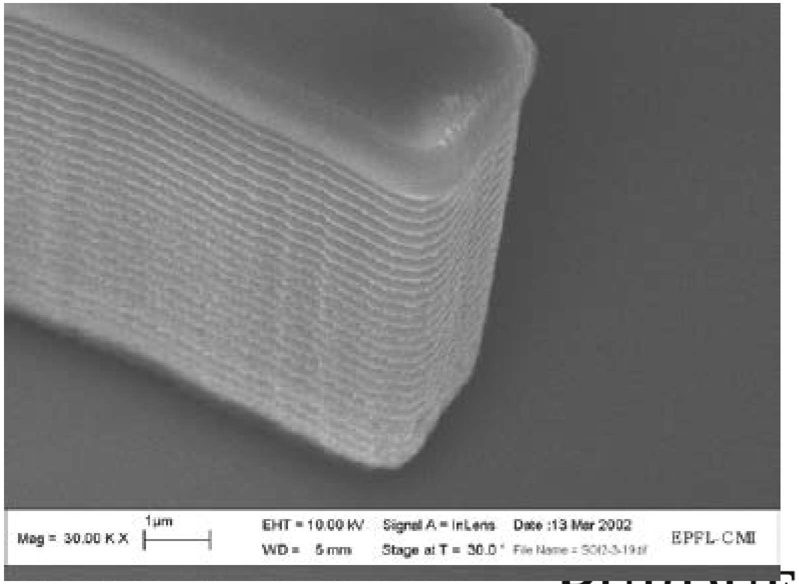




Deep Reactive Ion Etch (Bosch Process)



- Alternating passivation/etch cycles
- High density plasma is required
  - Low pressure to reduce ion scattering
  - Reduces microloading effect

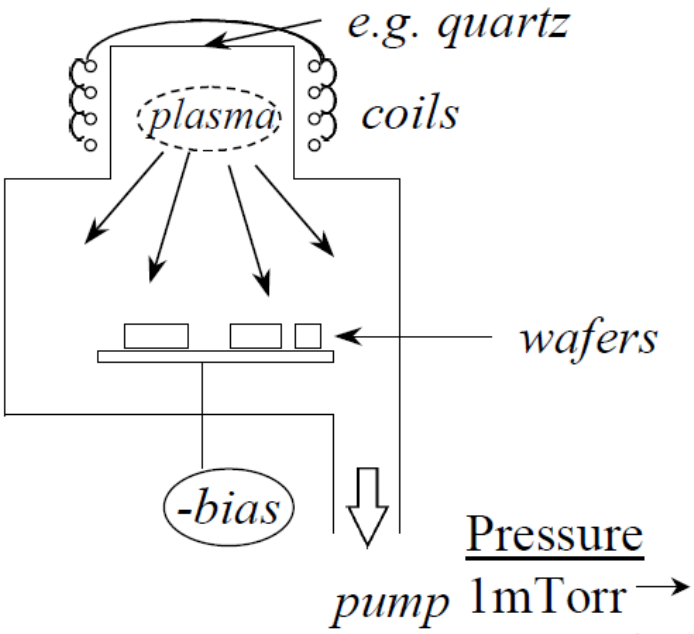


Remote Plasma Reactors

Plasma Sources

(1) Transformer Coupled Plasma (TCP)

(2) Electron Cyclotron Resonance (ECR)



Pressure

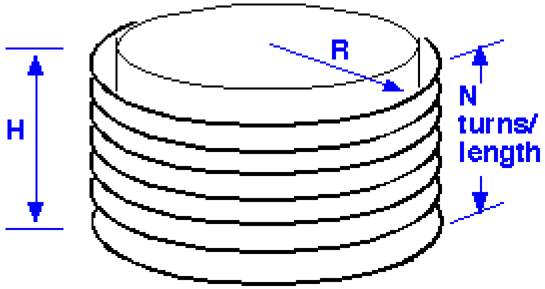
1mTorr → 10mTorr

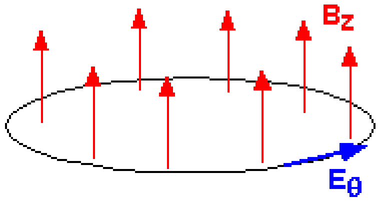
bias~ ≤1kV

- High-density plasma
  - Pressure: 1 mT ~ 10 mT
  - Bias < 1 kV

Inductively Coupled Plasma (ICP)

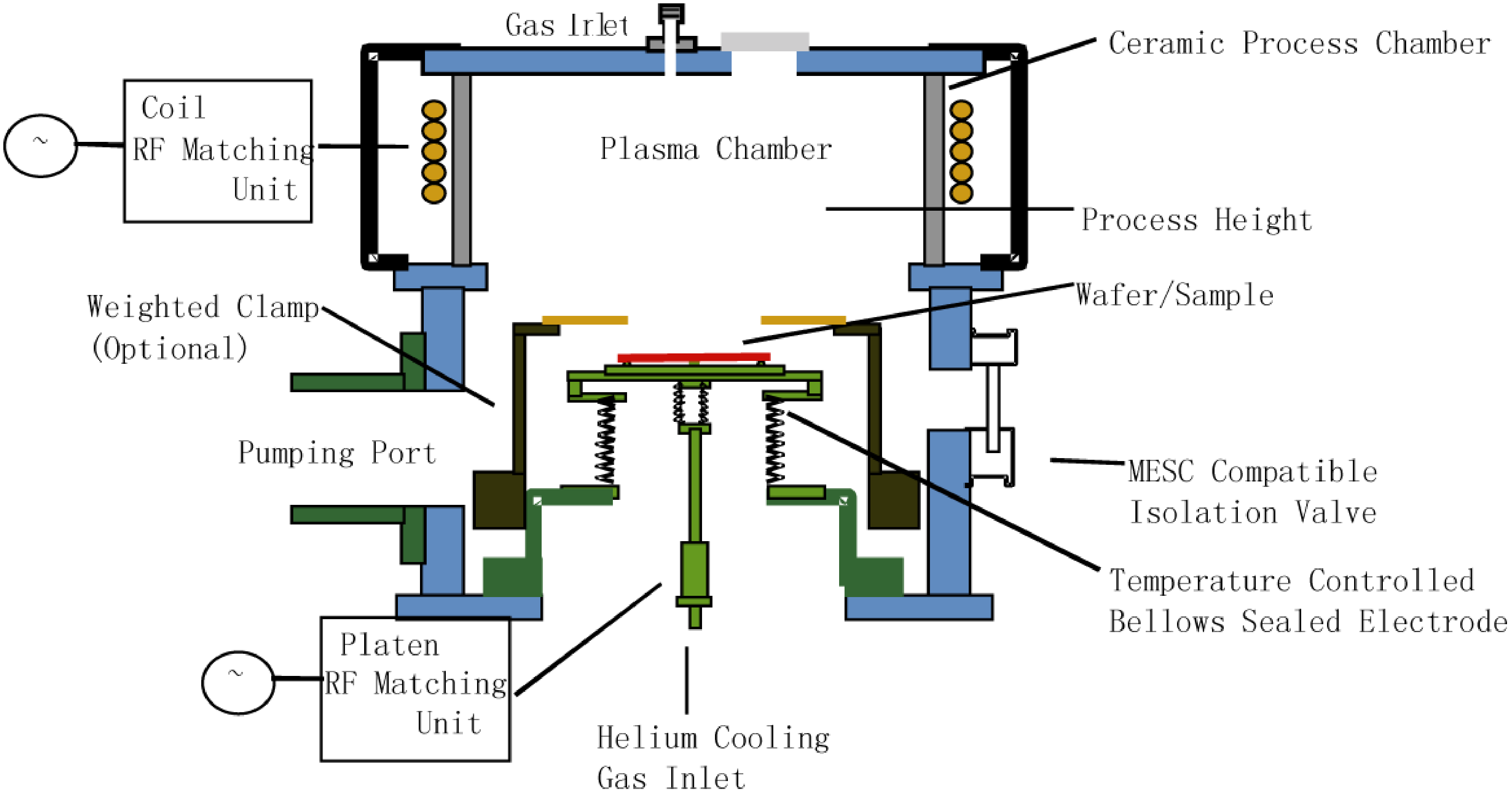
- RF voltage applied to a coil;
- Varying field B_Z leads to circumferential current in plasma, which accelerates the electron energy;
- Can adjust plasma potential (or ion bombardment energy) independent of plasma density.



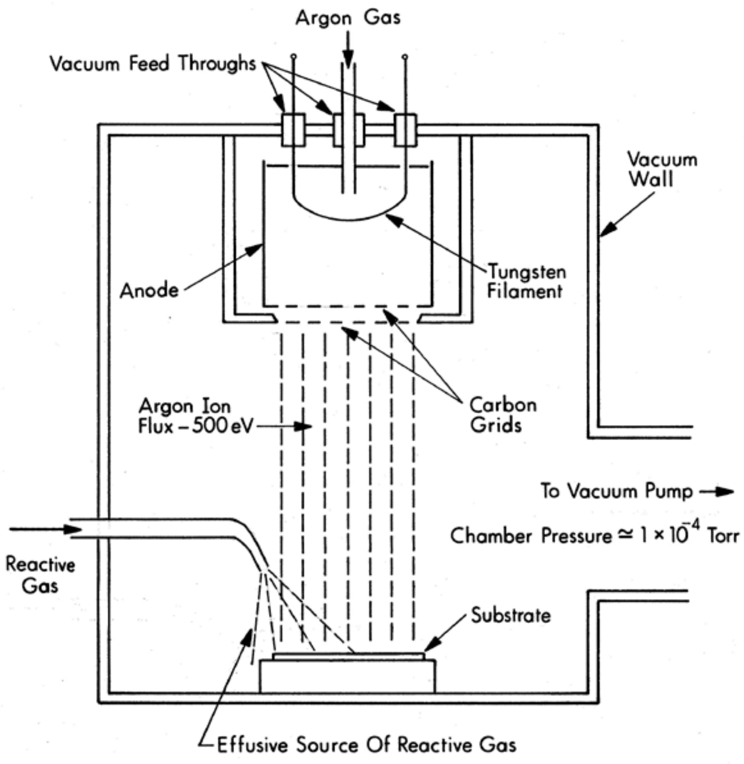


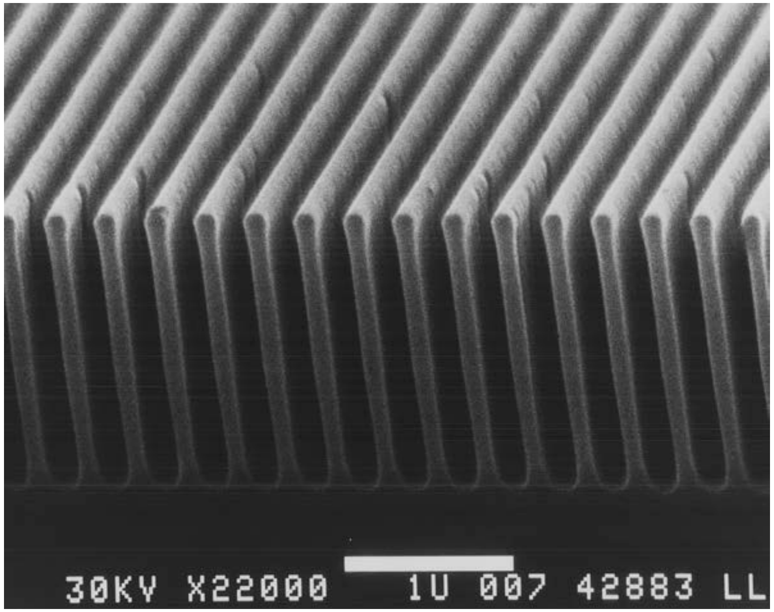
Allows Plasma to sustain in at much lower pressure (1-10 mT)

ICP Advanced Si Etcher (from STS)

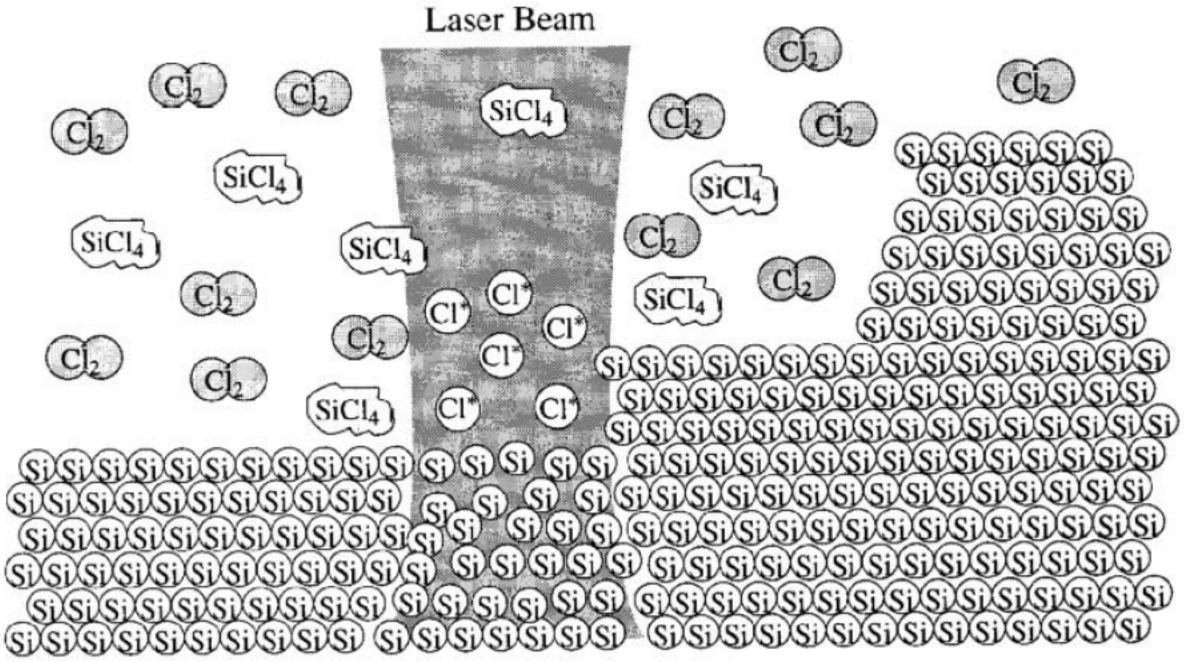


Ion-beam or chemical-beam assisted etching





Photon-Assisted Etching



Laser-assisted chemical etching (LACE) in Cl_2.
Cl^* represents the highly reactive chlorine radicals formed locally by the laser beam.

Issues in etching

- Uniformity
  - Across wafer, and across window
- Rate
  - Fast enough to be practical, slow enough to be controllable
- Selectivity
  - Rate of etching target material relative to mask-etching rate (should be large)
- Anisotropy:
  - Directional dependence of etch rate
- Byproducts
  - Volatile or otherwise easily removed, and environmentally safe

Problems with etching

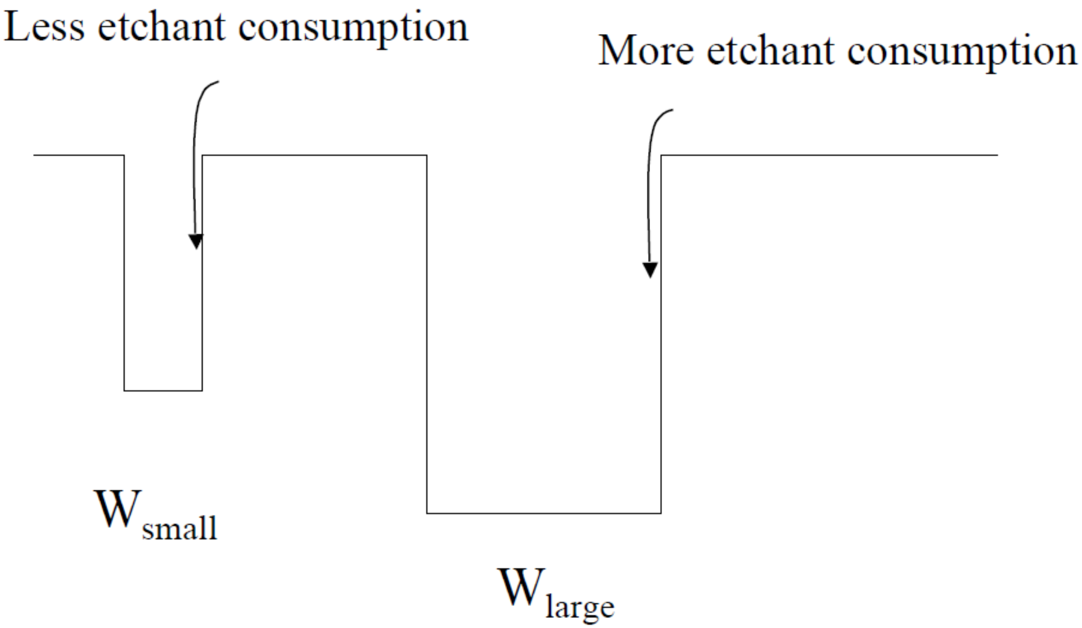
Uniformity:

1. "*bull's eye*": wafer etches faster at outside, less inside
   (barrel etcher)

2. "*Macro-loading*": too many wafers rob others of etchant
   (long-range gas transport problem)

3. "*Micro-loading*": unmasked large areas hoard etchant
   (short-range gas transport problem)

Local Loading Effect



Less etchant consumption

More etchant consumption

W_{small}

W_{large}

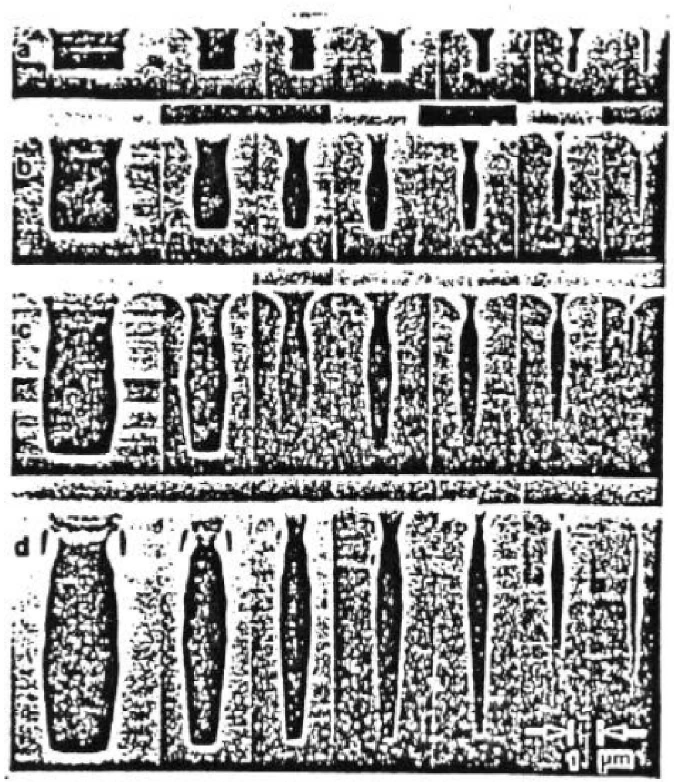


Fig. 2. Silicon trenches with various opening sizes. The etching times are (a) 5, (b) 20, (c) 40, and (d) 60 min, respectively.

CCl_2F_2/O_2 RIE

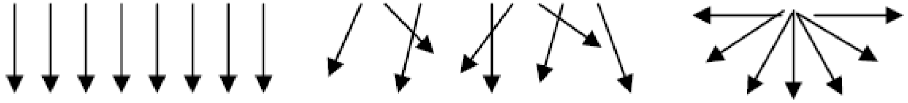
$$\textbf{\textit{Selectivity}} = \frac{\text{Etch rate of material intended to be removed}}{\text{Etch rate of mask}}$$

$S \approx \exp(-G/kT)$

Sputter yield,
$mM/(m+M)$, energy

Chemical reactions can be highly selective (20 - 50)
Physical etch processes (sputter etch) less so (1 - 5)

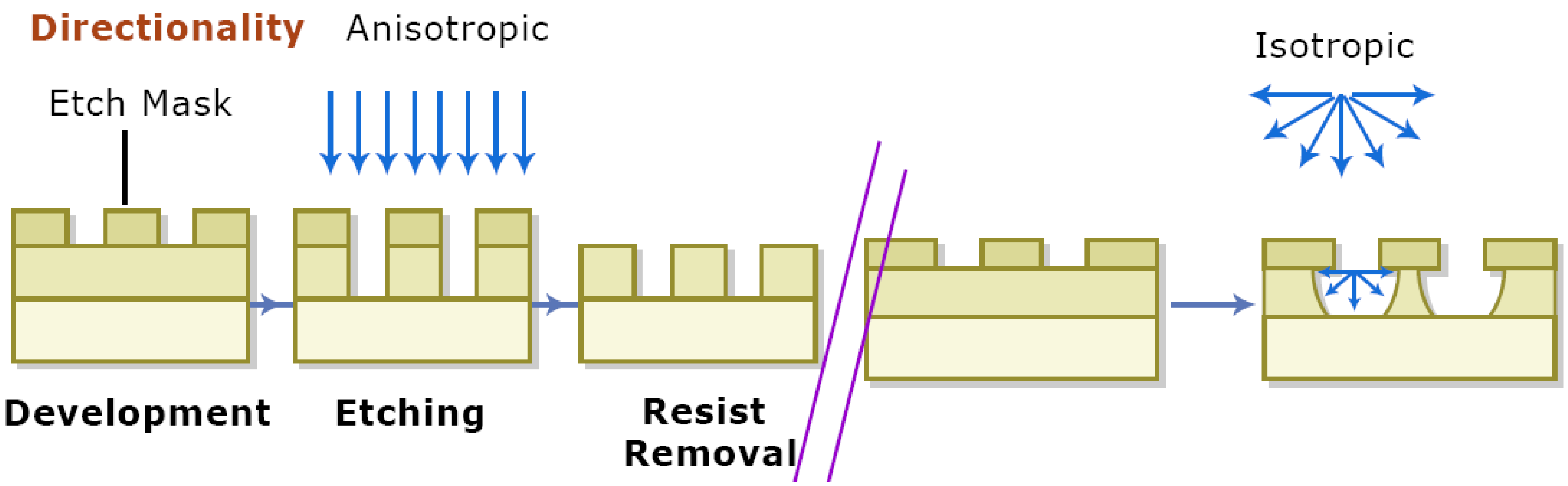
Directionality: From anisotropic to isotropic



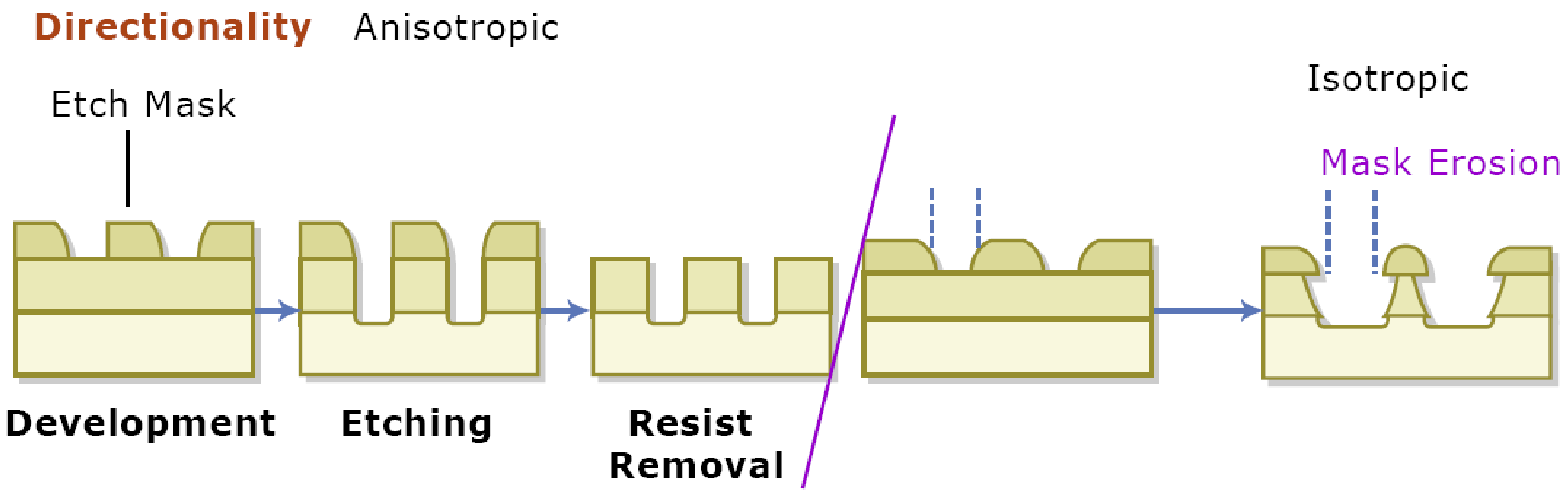
	Wet etch	Dry etch	Deposition techniques	
	(*Chemical*)	(*Physical*)	CVD	Sputtering
Selectivity	**25 - 50**	**1 - 5**	high	(Sputter yield)
Directionality	**low**	**high**	good step coverage	poor step coverage

Removing material *adding material*

High Selectivity

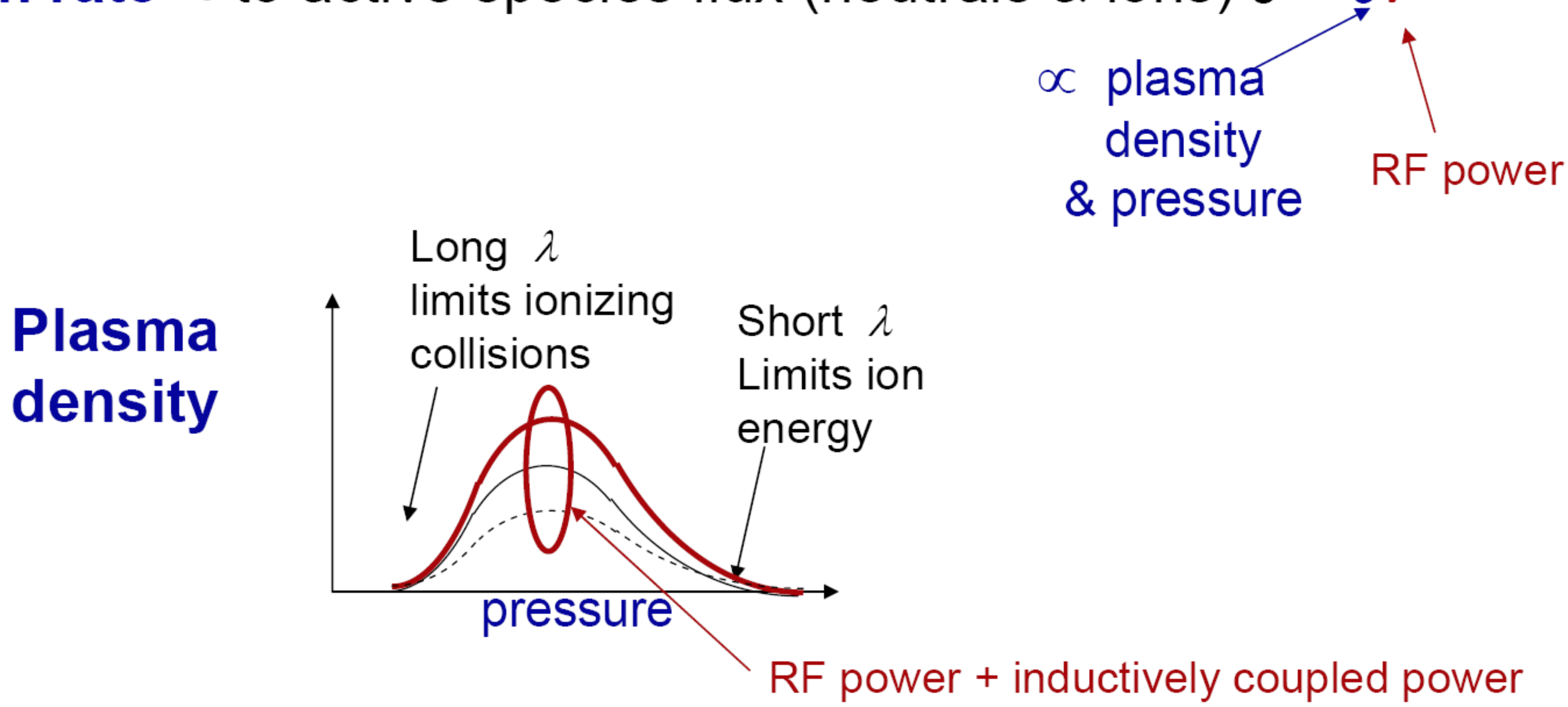


Low Selectivity



Etching miscellany

Etch rate $\propto$ to active species flux (neutrals & ions) $J = cv$



$\propto$ plasma density & pressure

RF power

Plasma density

Long λ limits ionizing collisions

Short λ Limits ion energy

pressure

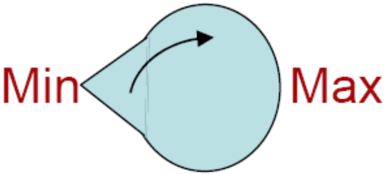
RF power + inductively coupled power

Comparison of Various Etching Processes

		Pressure	Etch rate	Energy (eV)	Selectiv’y	Anisot’y
Physical	Sputter etch Ion milling	1mT-1 T	enhanced		low	high
	HDPE 0.1-3 W/cm^2	1- 10 mT	enhanced	10-500	high	high
	RIE	10-100 mT	enhanced		high	high
	Plasma etch	10-100 mT	low	low	moderate	moderate
	Barrel etcher	10-100 mT	moderate	10 - 700 eV	high	low
Chemical	Wet etch	*irrelevant*	enhanced		high	low

Dial-up the parameters you want:

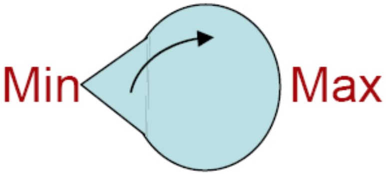
Higher anisotropy



Lower anisotropy

Pressure

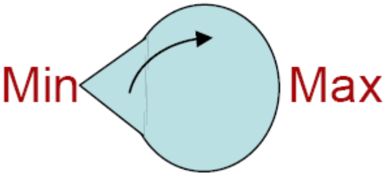
Noble; physical



Reactive; chemical

Gas composition

Lower anisotropy

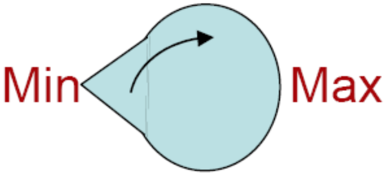


Higher anisotropy

Substrate bias

(Cathode size)

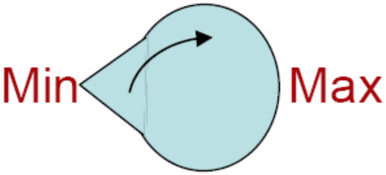
Small => anisotropic



Large => isotropic

Wafer electrode area

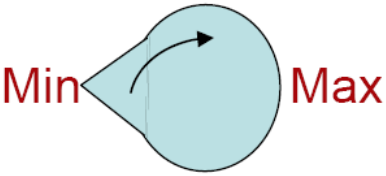
Low damage, better selectivity



Greater plasma den, sheath *V*, physical damage

RF power

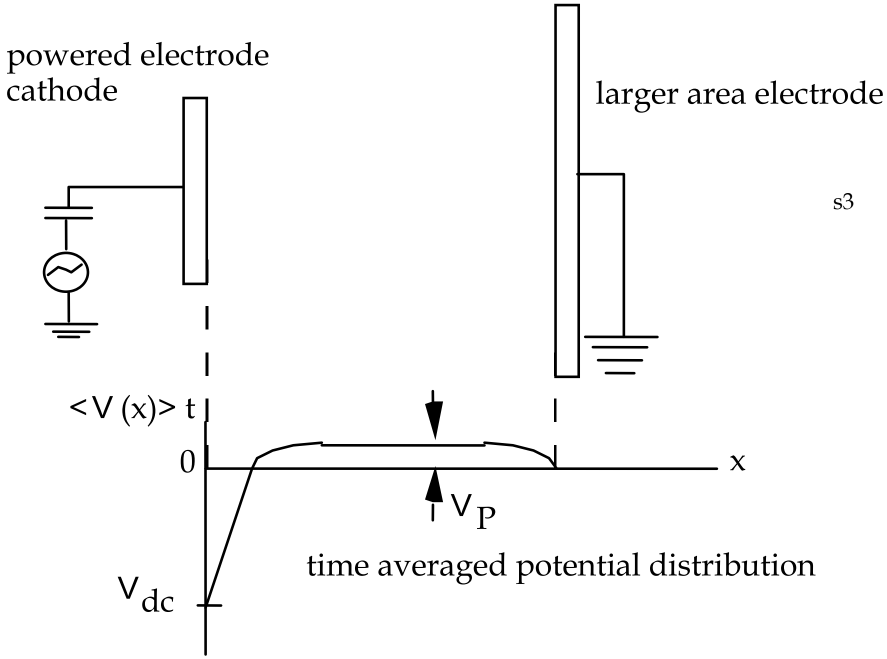
More physical etch, anisotropy



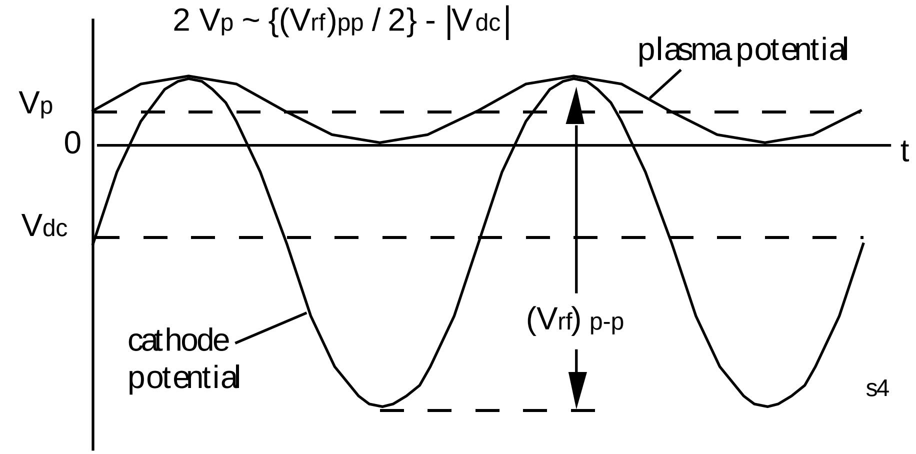
More chemical etch, selectivity

Gas flow rate

Review of RF Plasma



time averaged potential distribution



RF plasma allows electrodes to be insulated

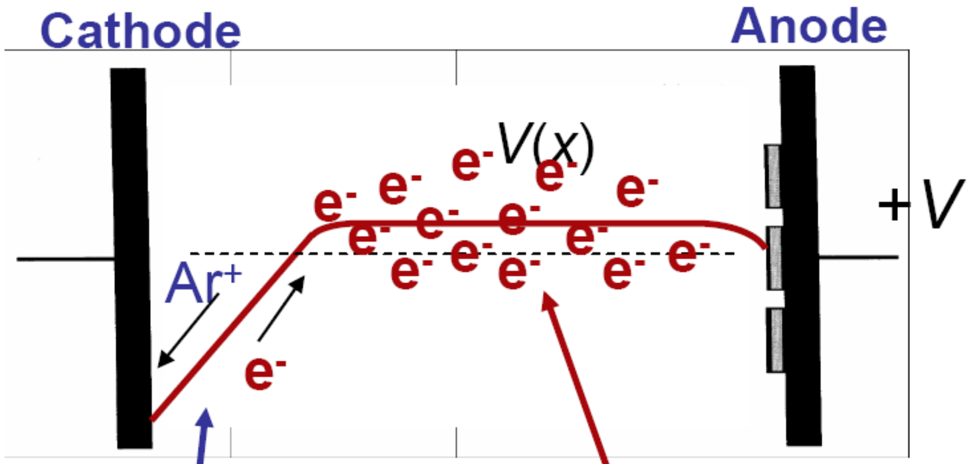
Review of Plasmas

$1\ \text{mT} < p < 100\ \text{mT}$

DC plasma

$\boldsymbol{v_{Ar+} \approx 4 \times 10^5}$ **m/s,**
mean free path ≈ 3 cm

$\boldsymbol{v_{e-} \approx 2 \times 10^7}$ **m/s**
λ much longer



Fewer e^-s found in high-field, dark spaces

Electrons largely confined to positive potential, high conductivity, $V \approx 0$

Limitation: Both Cathode and Anode must be conductive

What if we want to etch SiO_2?