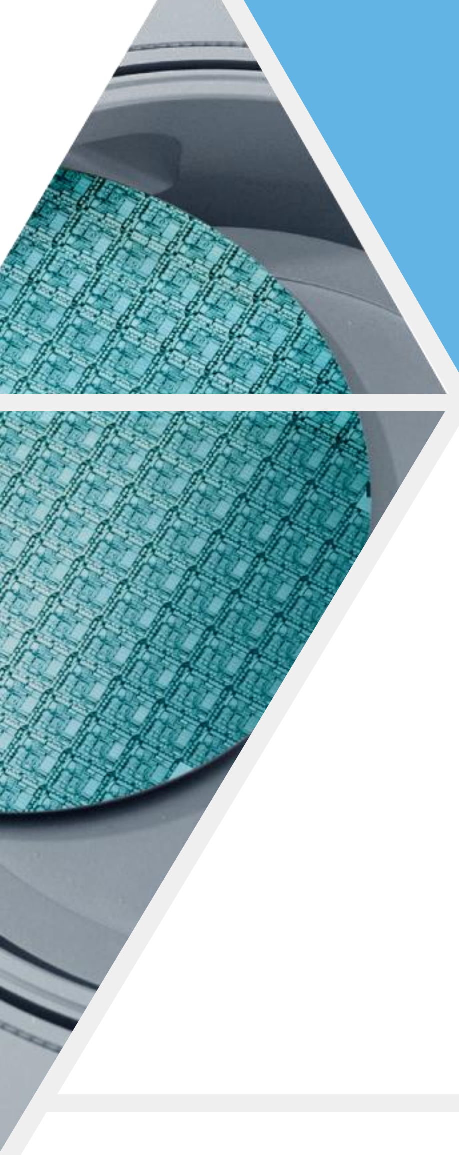


# Introduction to Plasma Etching

**Dr. Steve Sirard**

*Technical Director*

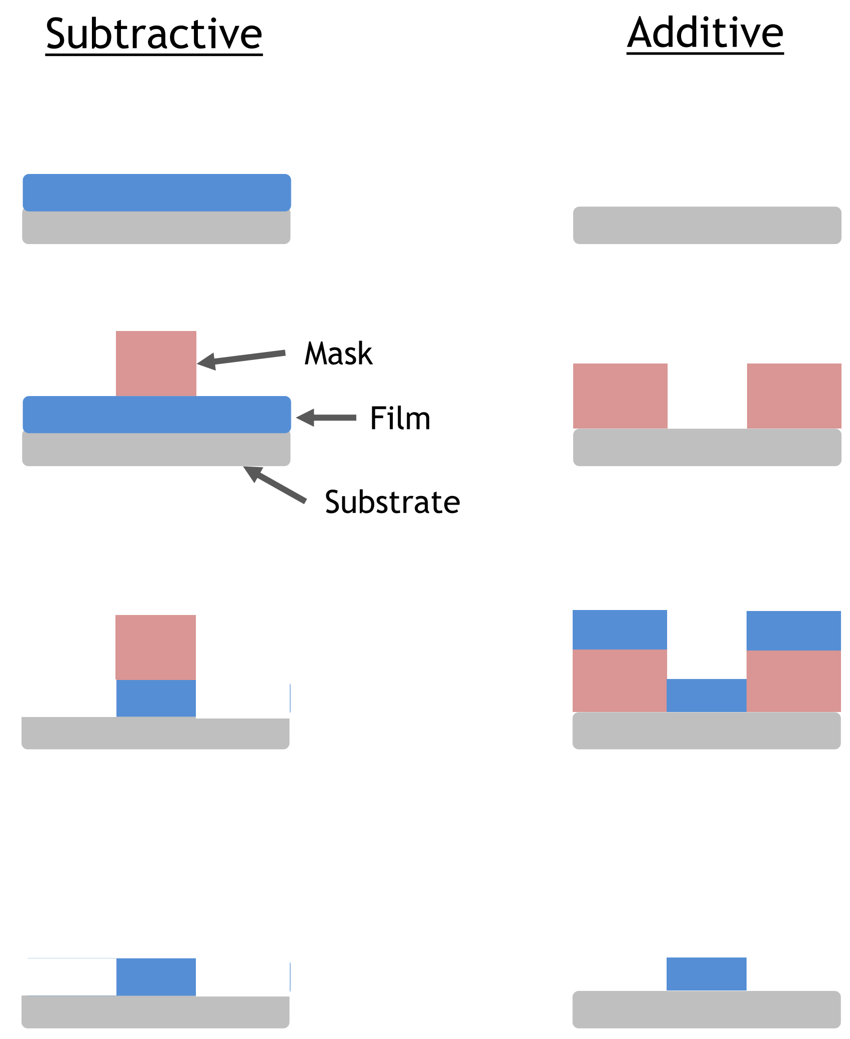
*Lam Research Corporation*

# Outline - Day 1

- Pattern transfer requirements
- What is plasma and why is it needed?
- General plasma fundamentals
- Basic commercial etch hardware
- General plasma etch process fundamentals
- Specific case: Dielectric ($SiO_2$, $Si_3N_4$, etc) etch mechanisms

# Basic Pattern Transfer

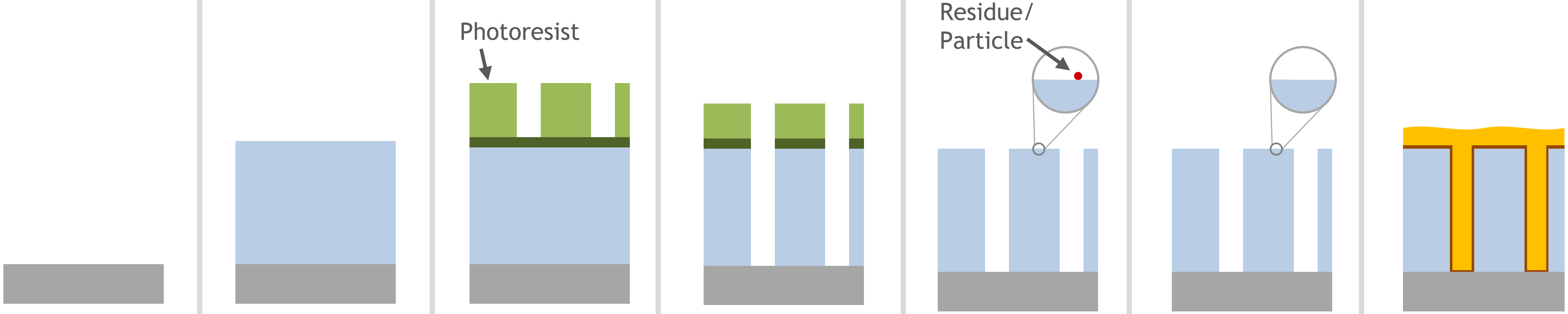
- Objective is to produce a patterned thin film on a substrate
- Patterns are commonly formed by either *additive* or *subtractive* methods
- To pattern film, a mask is formed with photolithography
  - Resist pattern is a stencil that protects underlying films/substrate from dep or etch attack
- Supply etchant (either wet or gaseous) to remove film in undesired areas
- We will generally focus on the *subtractive* process



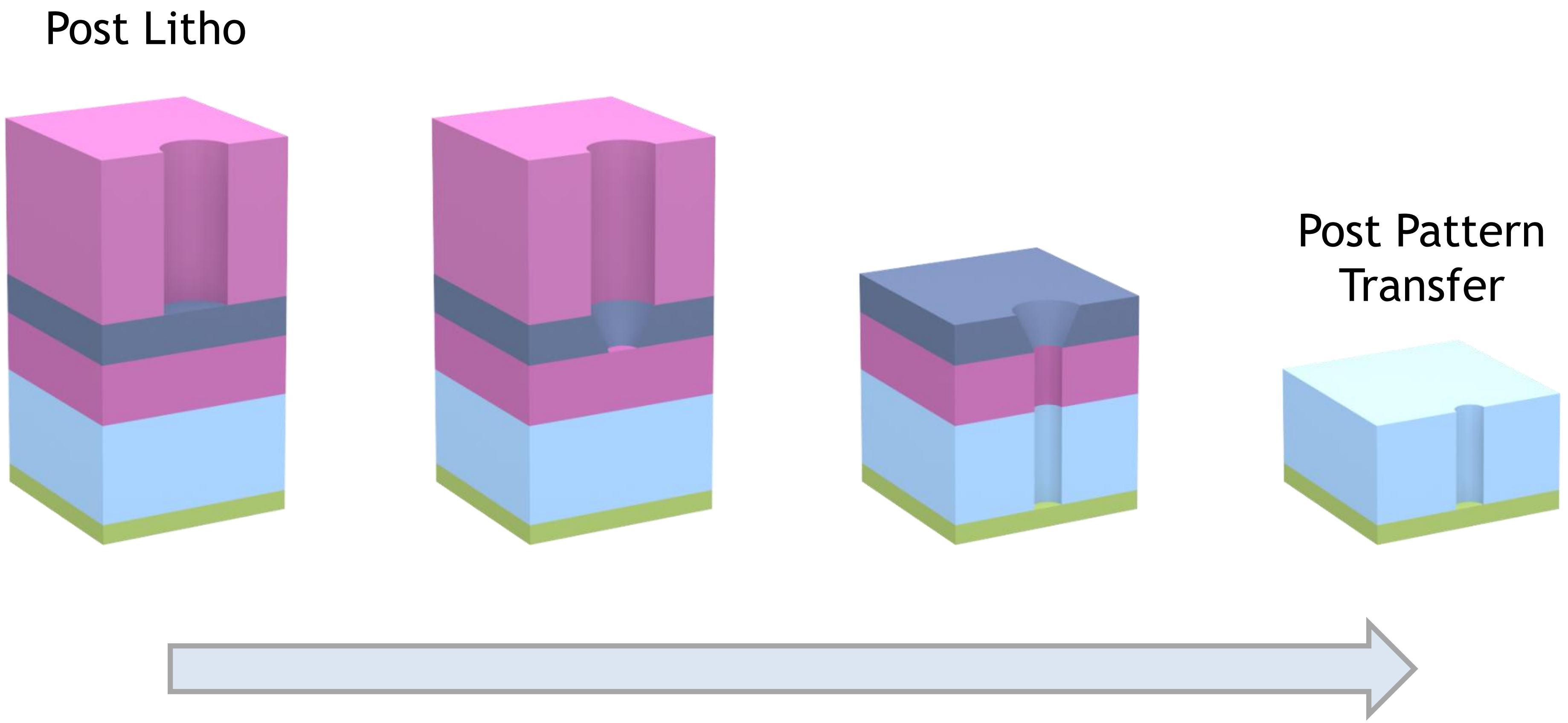
# Wafer Fabrication Process Steps

Segments Lam addresses

| Incoming Wafer | Deposition | Lithography | Etch | Strip | Clean | Deposition |
|---|---|---|---|---|---|---|
| | Put down the film to be patterned | Create the pattern mask | Selectively remove film to define features | Remove photoresist mask | Remove residues and particles | Deposit next materials |

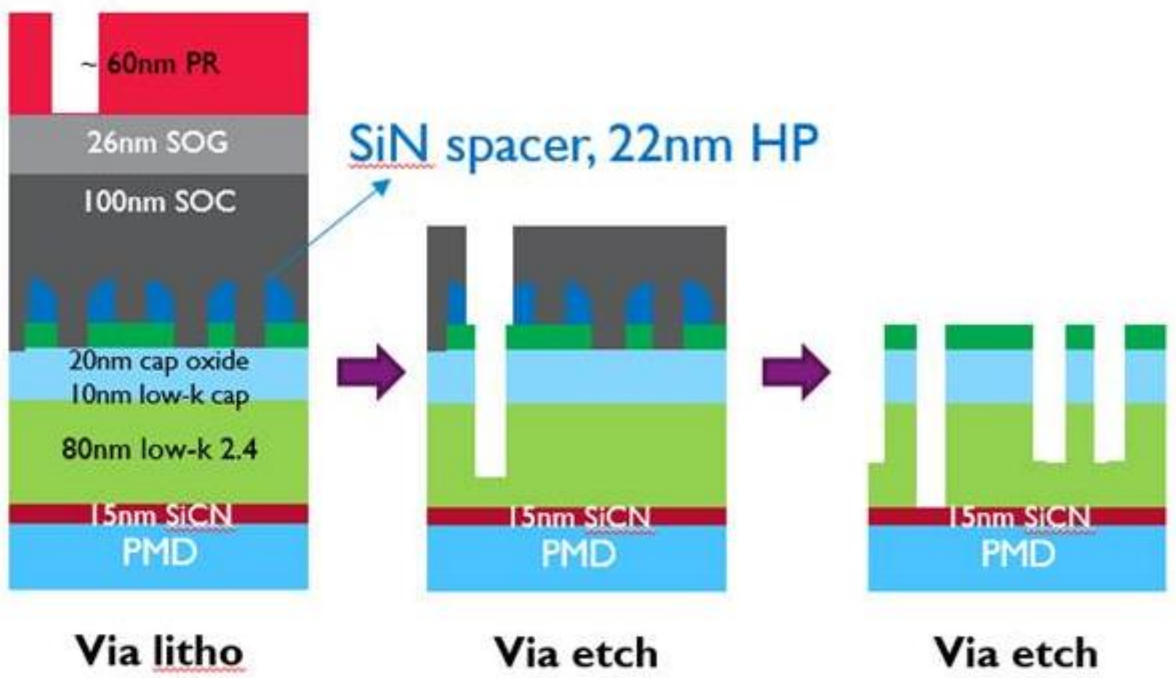


# *Often for pattern transfer, final feature dimensions are required to be different than litho-printed dimensions*




Final hole diameter required to be less than litho-printed hole diameter

# For leading edge fabrication, film stacks can get very complex




<u>Etch Steps</u>

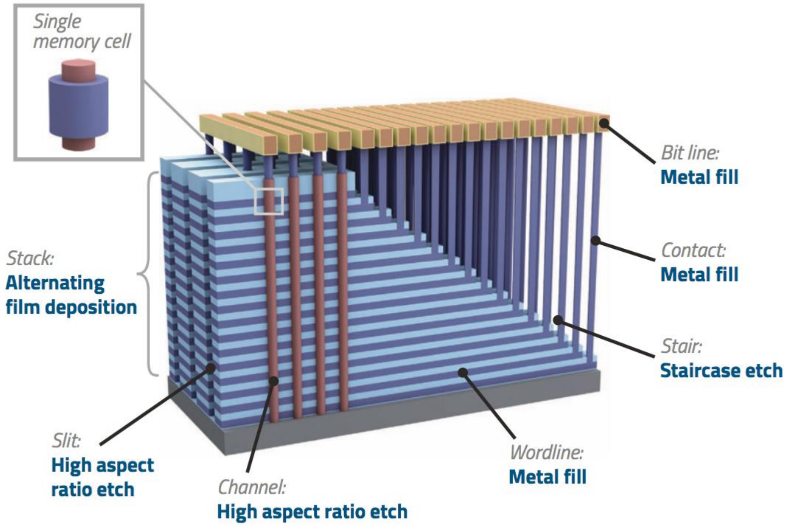
- SOG Open
- SOC Open
- Partial via in oxide/low-k
- SOC Strip
- Trench etch

<u>Sample Requirements</u>

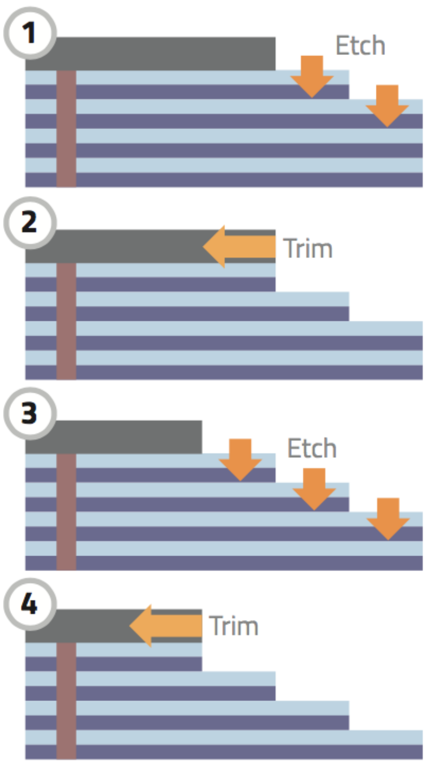
- Shrink PR CD by 15nm
- Trench depth = ½ via depth
- Within wafer uniformity < 2 nm for trench depth and line CDs

# For leading edge fabrication, pattern transfer steps can have vastly different requirements

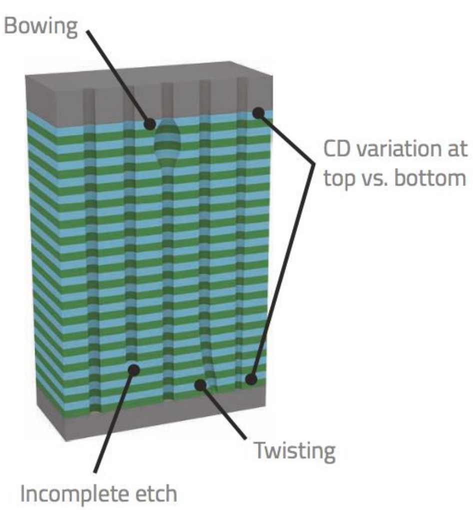
*Singh, SST, 2017*




*Staircase etch → Control lateral and vertical etch*




*Challenges for high-aspect ratio (> 40:1) pattern transfer*

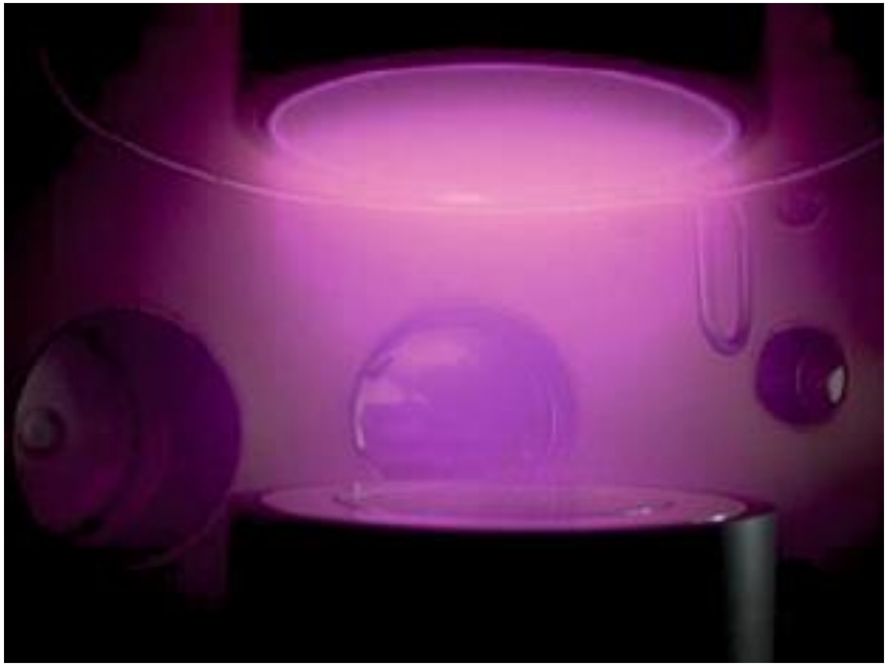


# What do we need to control when transferring patterns?

- Etch rate/Throughput
- Etch rate selectivity (*relative etch rate of one film vs another*)
- Anisotropy (*vertical etch rate vs horizontal etch rate*)
- Sidewall angle/Feature Profile (*straight*, *tapered*, *bowed*, *re-entrant*)
- Faceting (*erosion at top of feature*)
- Critical dimensions
- Uniformity (*within chip*, *within wafer*)
- Repeatability (*wafer-to-wafer*, *chamber-to-chamber*)
- Defects (*e.g.*, *particles*, *etc*)
- Damage (*material modifications that degrade yield or electrical performance*)
- Line edge roughness, line width roughness, local hole uniformity

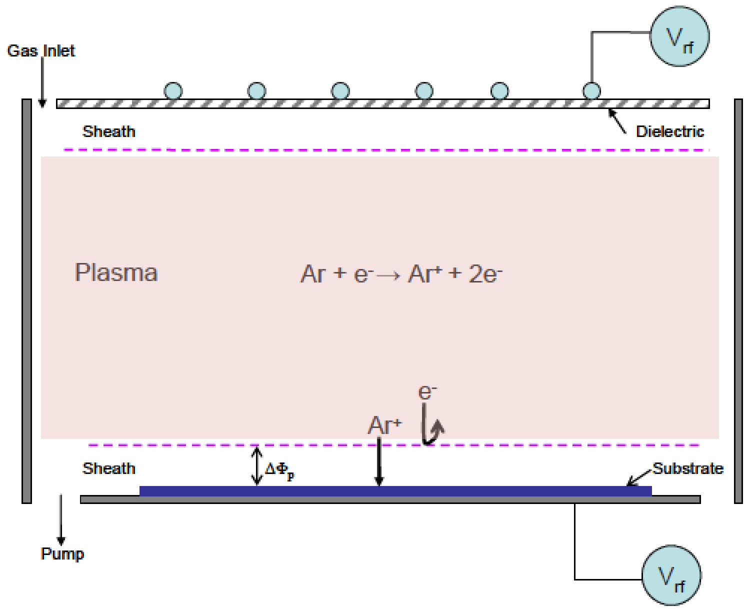
# What is a plasma??

- A plasma is a *quasineutral* gas of charged and neutral particles
- "Quasineutral" means that overall the net charge of the plasma is approximately zero, because fluctuations in charge density in the plasma are small in magnitude and short in duration
- A plasma is created whenever gases are forced to conduct electric current
  - Plasmas generate electrons, reactive neutral species, and ions



# What is a plasma?

- Many of the plasmas used in dry etching are weakly ionized
  - Ionization fraction, $x_i << 1$
  - Quasineutral: $n_i = n_e$ → densities (~$10^9$ - $10^{12}$ $cm^{-3}$); magnitudes lower than the neutral gas density ($n_g$)
- Plasma generated inside etch tool by feeding electrical power into a gas
- Power transferred to the few free electrons initially within the gas excites electrons to higher energies
- High energy electrons can then ionize neutrals and initiate a collision cascade, thus creating and sustaining the plasma



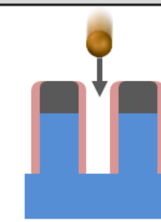
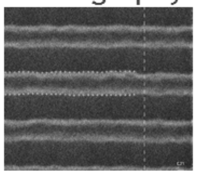
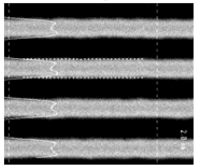
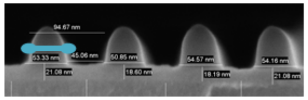
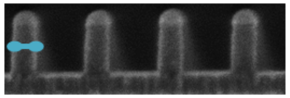
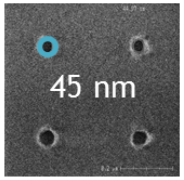
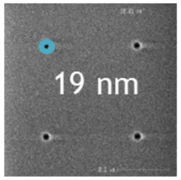
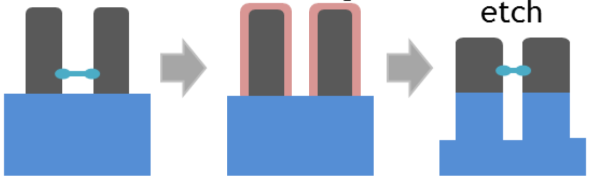
# What is a plasma?

- A plasma generates reactive species which are not available in a bottle and "delivers" them to the substrate of interest
- Electrons are the main current-carriers because they are light and mobile
- Energy transfer between light electrons and gas molecules they collide with is inefficient and electrons can attain a high average energy (thousands of degrees above the gas temperature)
- Elevated electron temperature permits electron-molecule collisions to excite high temperature type reactions (forming free radicals) in a low temperature neutral gas
- Generating same reactive species without a plasma would require temperatures in the $10^3$ - $10^4$ K range!
  - These temperatures would incinerate organic photoresist and melt many inorganic films

# Characteristics of weakly ionized plasma discharges

1. They are driven electrically
2. Charged particle collisions with neutral gas molecules are important
3. There are boundaries at which surface losses are important
4. Ionization of neutrals sustains the plasma in the steady state
5. The electrons are not in thermal equilibrium with the ions

# The Benefits of Plasma Processing (Etching *and* Deposition)

| | Dep/Etch Enablement | Mechanism |
|---|---|---|
| **Anisotropic etching:** |  Isotropic **Vs.** Anisotropic | • Ions accelerated to wafer surface<br>• Sidewalls protected by deposition  |
| **Sidewall smoothness:** | (Top-down) Lithography  **40% smoother** Post-dep/etch  | (Top-down)  Deposition fills in holes; Etch "Knocks-off" sharp corners |
| **Line trim:** | Lithography  CD ~ 55 nm **Thinner** Post-dep/etch  CD ~ 28 nm | Litho → Protection → Iso etch  |
| **Hole shrink:** | (Top-down) Lithography   **Smaller** Post-dep/etch   | Litho → Coating → Directional etch  |

# General Plasma Fundamentals

# Anisotropy? → Thank the Boundary Layer Sheath

- Initially within the system, electrons rapidly move throughout the chamber and are lost to the walls, as opposed to the slower and heavier ions
- To maintain quasineutrality, a confining potential forms at the wall that acts to repel electrons back into the bulk, while simultaneously accelerating ions toward the walls
- Ultimately, this forms a region of net positive charge known as the sheath
- Sheath thickness is typically on the order of a few millimeters (a few debye lengths)
- Ion acceleration energy is typically 10 - 40eV, but can rise to ~1000eV or so if further biased
- Sheath is key for achieving anisotropic etching, as at low pressures where collisions in the sheath are minimized, the ions arrive at near-normal incidence

# Plasma composition

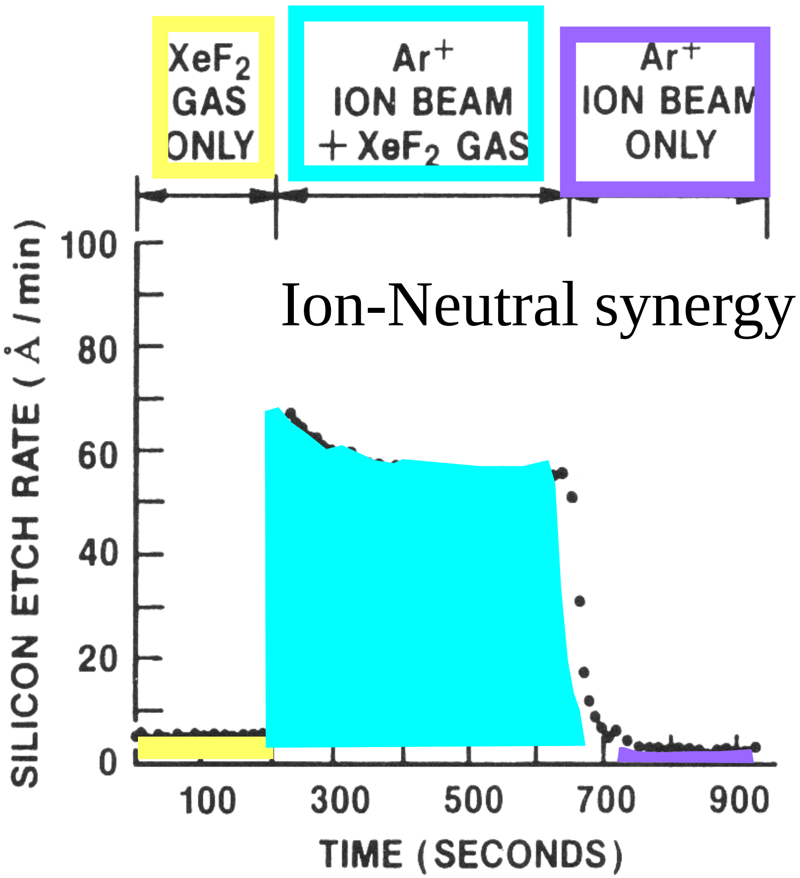
- A plasma generates reactive species which are not available in a bottle and delivers them to the substrate

- Typical species in the plasma
  - Electrons
  - Neutral/Reactive radicals: F, Cl, O, $CF_x$.....
  - Ions: $Ar^+$, $CF_3^+$, $Cl^-$.....

- Ion motion is random in the central glow, but when a positive ion drifts to the sheath boundary, it is accelerated toward the wall/wafer surface

# Ions+Reactants have synergistic effect on etch rate

*Key mechanism for anisotropic etching*




**Silicon Etch**

$$Si(s) + 4F(g) \rightarrow SiF_4(g)$$

Classic experiment of Coburn and Winters - *Alternately exposing Si surface to Molecular beam & ion beam*

- Etch rate of combined is order of magnitude higher than the sum of individual rates → SYNERGY!
- Shows how enhancement of the etch requires energy of activation which is provided by the ion bombardment

# Collisional processes in the plasma

## ▸ Elastic collision:

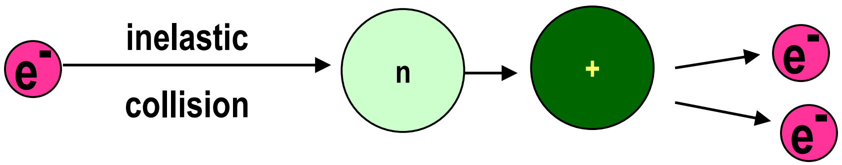
- When the internal energies of the two colliding particles do not change
  - The energy exchange is restricted to kinetic energy
- The sum of the kinetic energies is conserved

## ▸ Inelastic collision:

- When the internal energies of the two colliding particles do change
  - The sum of the kinetic energy is not conserved

# Important Collisional processes in the plasma

- **Ionization**: $e^- + Ar \rightarrow \underline{Ar^+} + 2e^-$




- **Dissociation**: $e^- + AB \rightarrow \underline{A} + \underline{B} + e^-$

- **Dissociative ionization** (molecular gases): $e^- + AB \rightarrow \underline{A} + \underline{B^+} + 2e^-$

- **Electronic excitation**: $e^- + Ar \rightarrow \underline{Ar^*} + e^-$ energy loss process that generates light

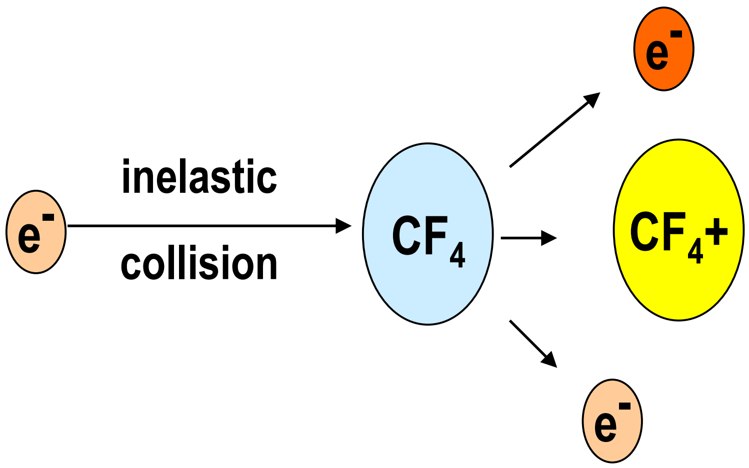
- **Electron attachment**:
  - ⇨ Resonance capture ($e^- + SF_6 \rightarrow \underline{SF_6^-}$).
  - ⇨ Dissociative attachment ($e^- + SF_6 \rightarrow \underline{F} + \underline{SF_5^-}$).

- **Elastic scattering**: $e^- + Ar \rightarrow Ar + e^-$ Transfers momentum & changes angle

## ▶ Ionization

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

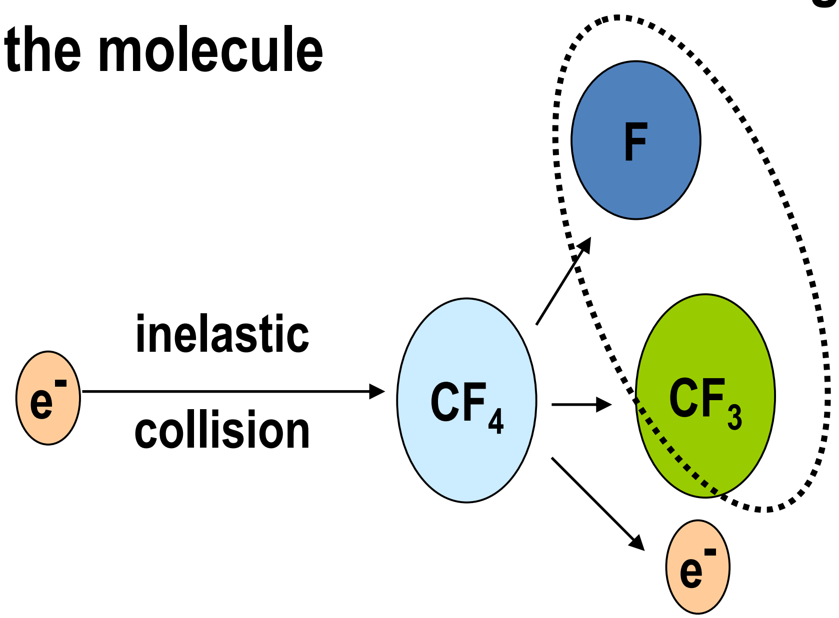
**An electron can ionize an atom or molecule if it has energy greater than the ionization potential of the species**



## ▶ Dissociation

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

An electron can dissociate a molecule if it has energy greater than the weakest bond in the molecule




This is the mechanism for generation of free radicals which are the reactive agents in the plasma

# Excitation processes in the plasma

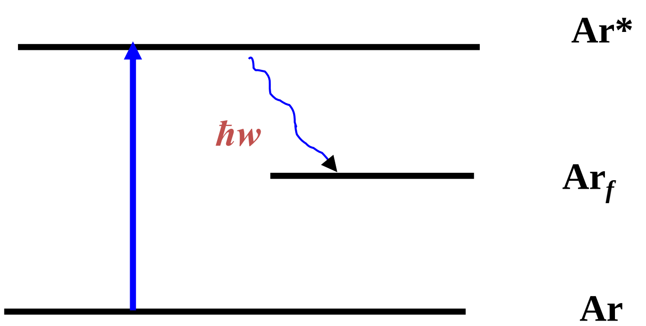
## ▶ Excitation

- Atoms and molecules in their ground states can be excited (by collisions or radiation ) to higher energy bound states

- Most bound states can emit a photon and return to a lower energy or ground state

  - $e^- + Ar \rightarrow Ar^* + e^- \rightarrow Ar + e^- + \hbar\omega$

  - Here $\hbar\omega$ is the photon energy



# Excitation processes in the plasma

## ▶ Excitation

▶ The light emitted by a plasma can provide both a qualitative and quantitative analysis of the plasma

▶ Optical emissions from the plasma are useful for plasma diagnostics and endpointing etch recipes

Ar = 801 +/- 4nm

O = 777 +/- 4nm

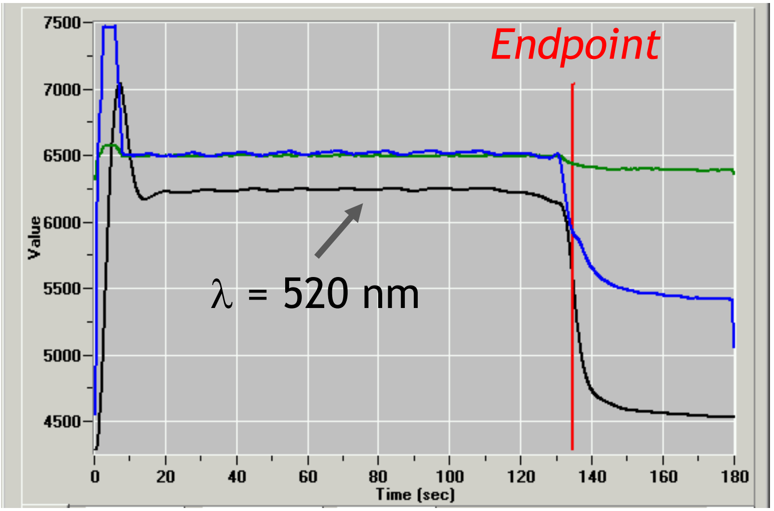
CN = 390 +/- 5 nm

CO = 520 +/- 5nm

SiF = 440 +/- 5nm

CF2 = 304 +/- 4nm

**Endpoint Detection**



# Collisional energy transfer by metastables

- Lifetime of typical excited state is ~$10^{-9}$ s and is typically de-excited by photon emission

- However, certain metastable states are longer lived (up to a few sec) which is long enough for a collision to occur before it eventually decays

  - Electronic excitation (excitation transfer):

    $$Xe^* + CO \rightarrow CO^* + Xe$$

  - Penning ionization:

    $$He^* \text{ excited } (\varepsilon_{ex} = 19.8\text{ eV}) + Ar \rightarrow Ar^+ \ (\varepsilon_{iz} = 15.8\text{ eV}) + He + e^-$$

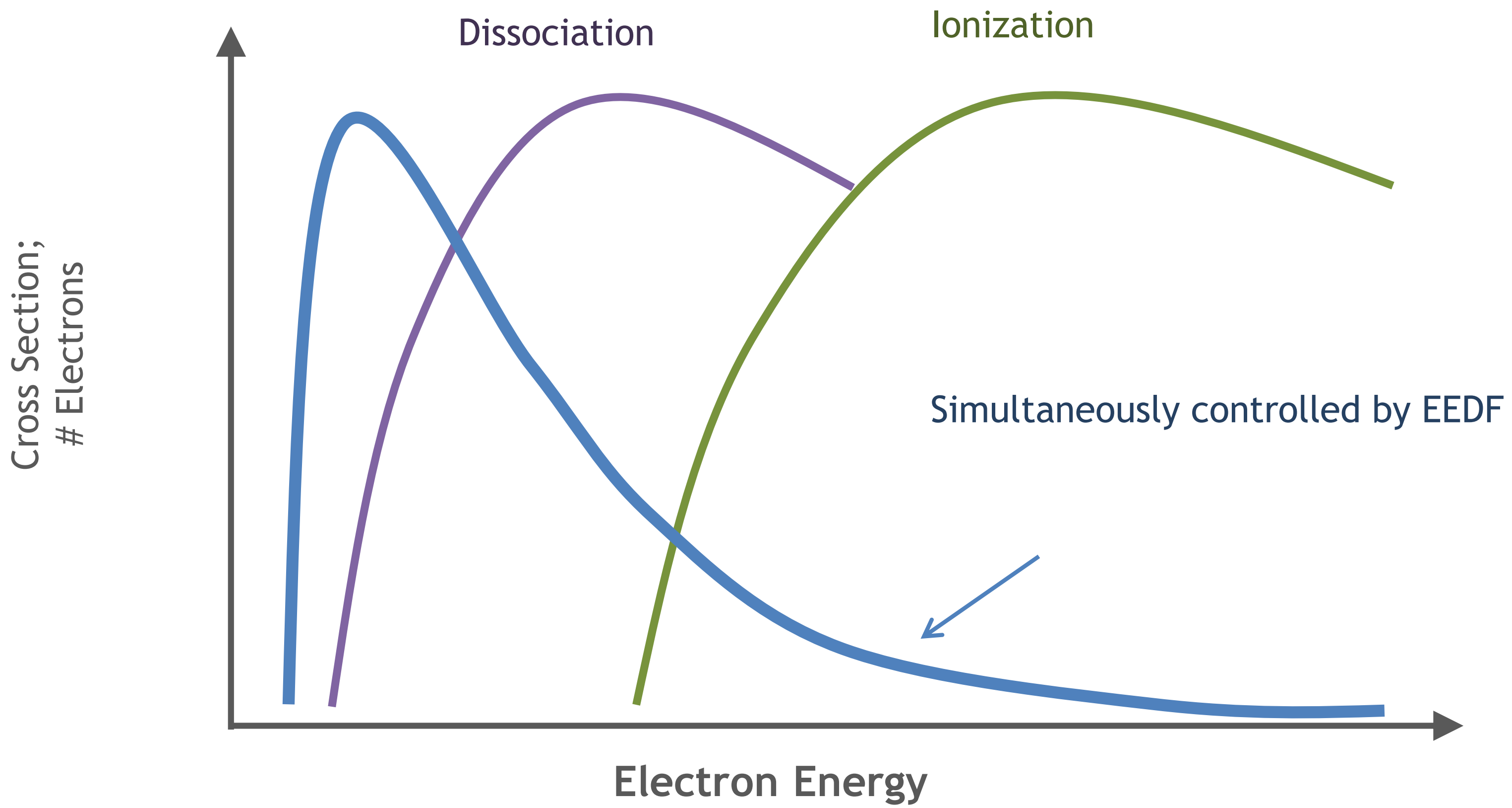
  - Penning Dissociation:

    $$Ar^* \text{ excited state} + AB \rightarrow \underline{A} + \underline{B} \quad (\text{where } \varepsilon_{diss} < 11.6\text{eV}).$$

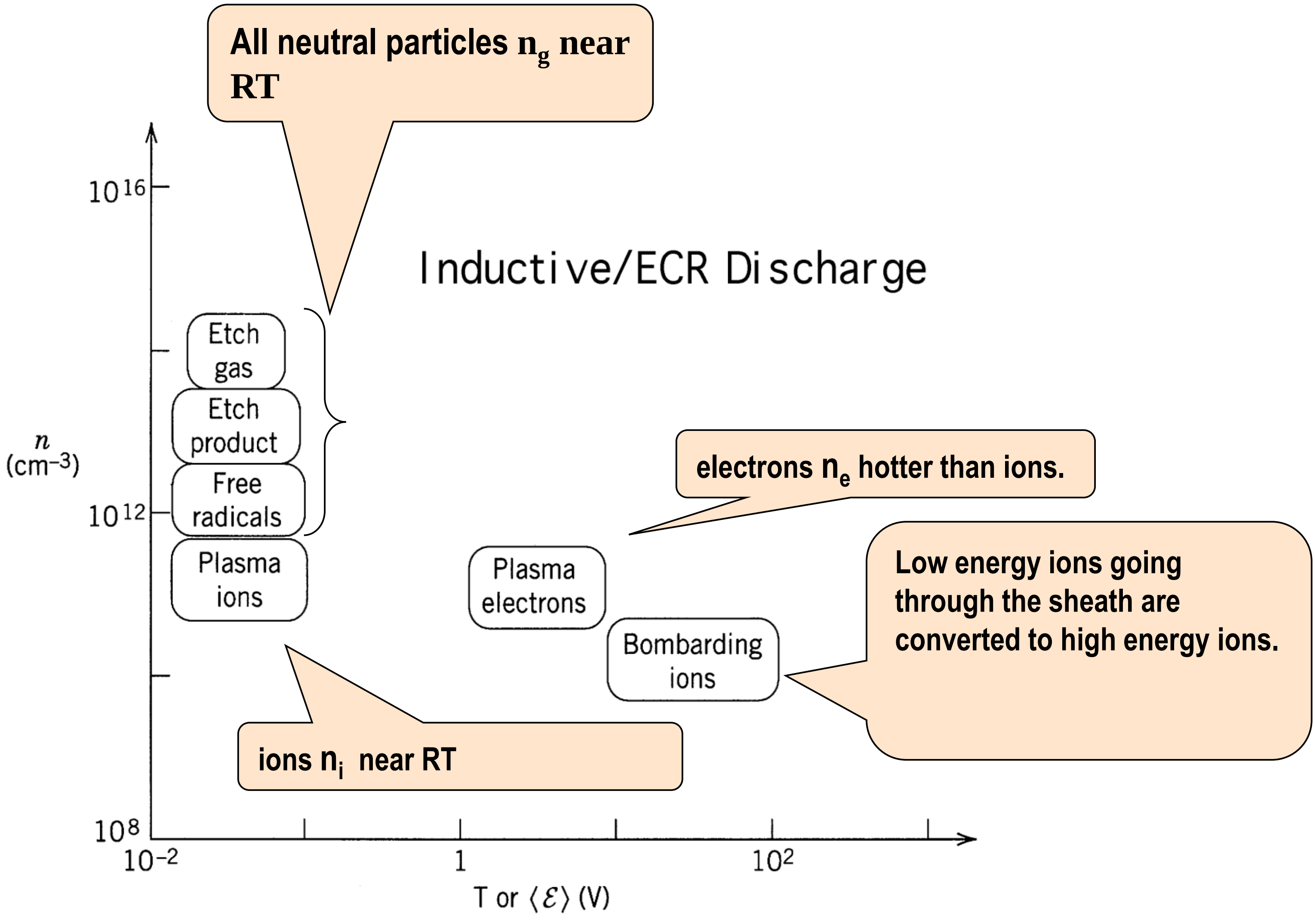
    $$Ar^* \text{ excited state} + O_2 \rightarrow \underline{O} + \underline{O} \quad (\text{where } \varepsilon_{diss} = 5.2\text{eV}).$$

# Energy distribution for collisional processes

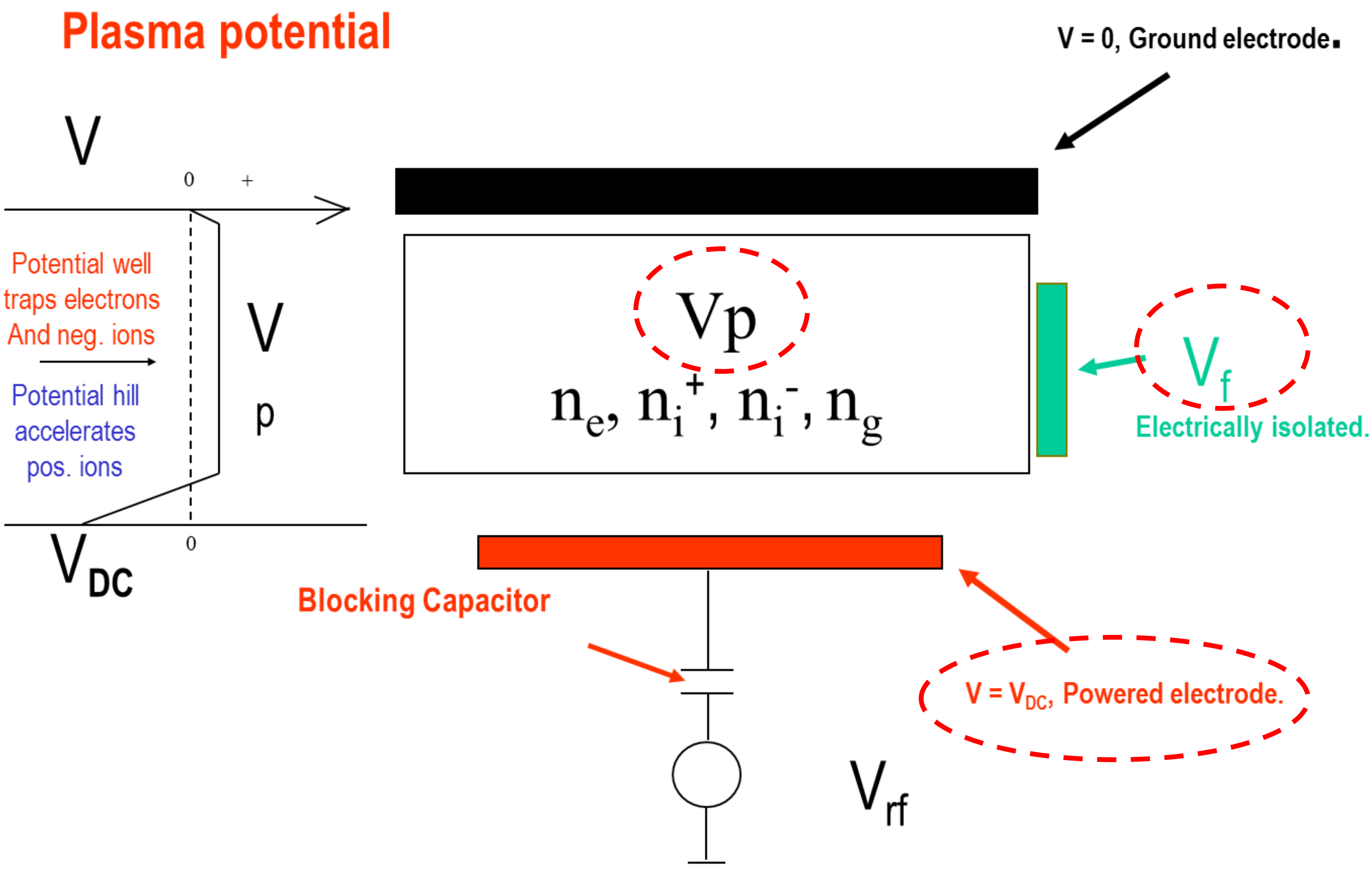
***Cross-Section*** **can be thought of as a probability of an occurrence. In this case - for Electron Attachment, Dissociation and Ionization**



# Plasma Density and relative energies of species

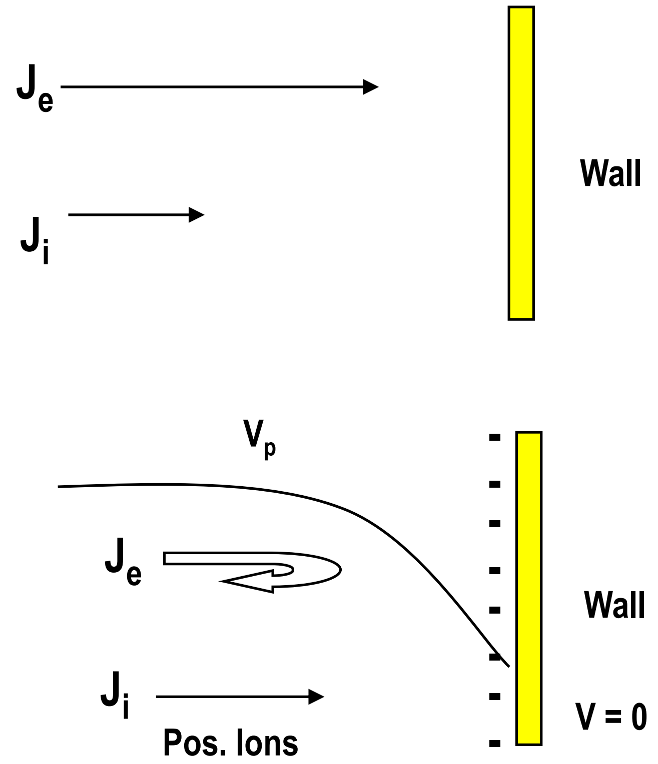


# Important Potentials



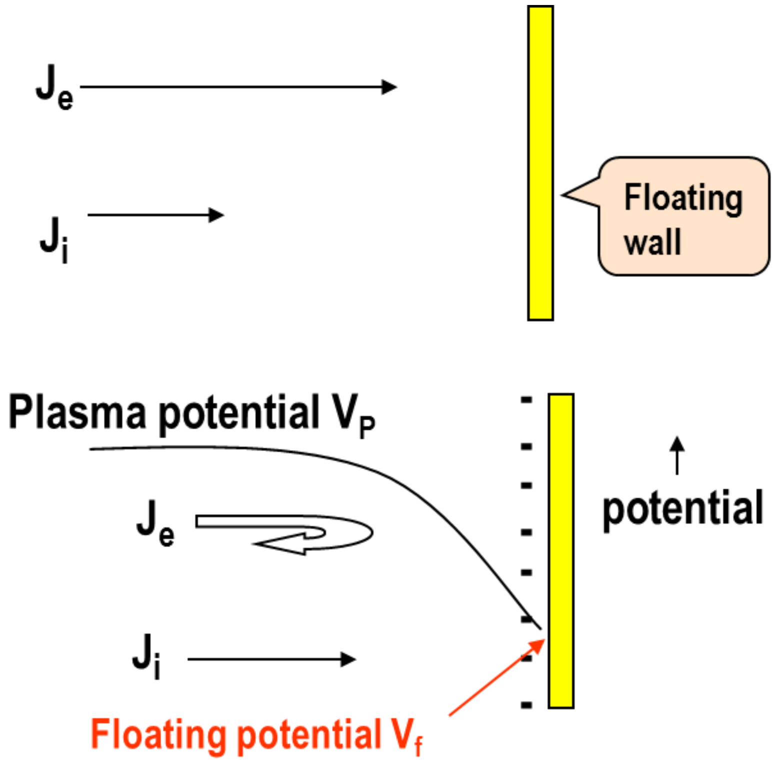
# Plasma Potential, $V_p$

- The high mobility of electrons creates thin positive ion sheaths near the walls/electrodes
- Positive ions are left behind, and the plasma charges up positive
  - This is the plasma potential, $V_p$, which is positive relative to the walls in contact with the plasma
- With respect to ground (V=0), if the time averaged plasma potential is +100V, then ions hitting the ground electrode would have an energy of 100eV



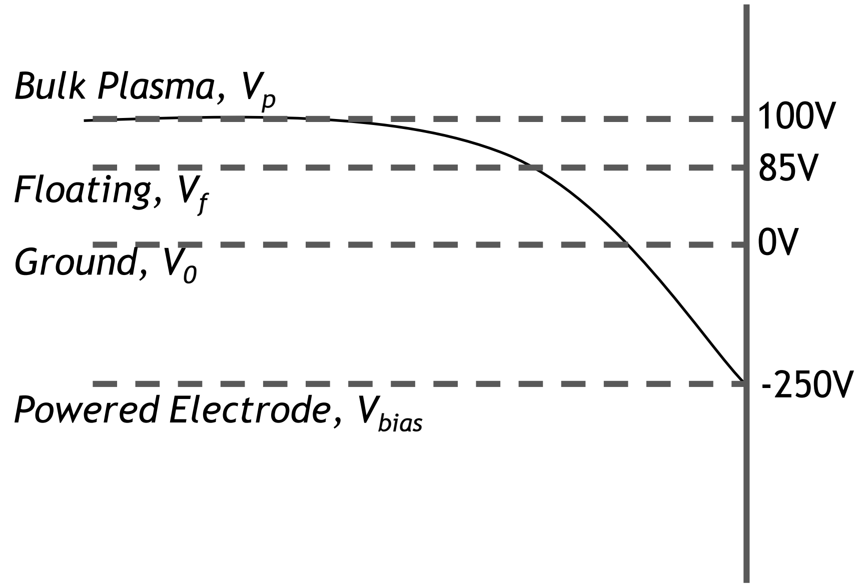
# Floating Potential, $V_f$

- Electrons will move much faster than ions to a surface in the plasma, charging up the surface negative with respect to the plasma
- This charge retards further electron loss from the plasma
- If the surface is a floating wall (electrically isolated surface), a steady state is reached where the reduced flow of electrons is balanced by the flow of ions (fluxes balance, so net current is 0)
- $V_f$ is ~ -10 to -20V with respect to the plasma potential ($V_p$)



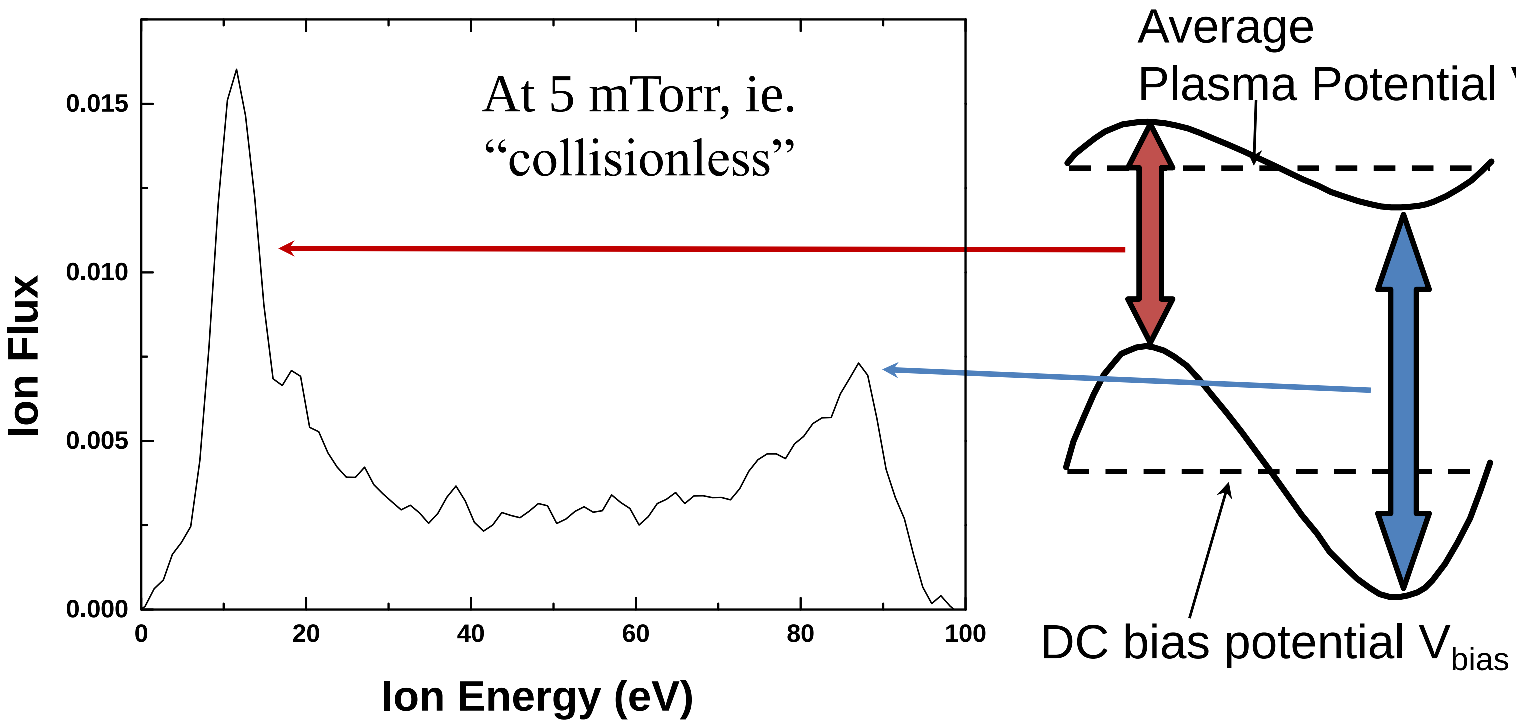
# Self-bias Voltage, $V_{bias}$

- Time-averaged value of the powered electrode voltage is called the self-bias voltage when measured with respect to ground
- $V_{bias}$ is negative with respect to the plasma potential, $V_p$
- The potential drop across the sheath at the powered electrode is the sum of the plasma potential and the self-bias
  - $V_{sh} = V_p + |V_{bias}|$
- The powered electrode will be bombarded with much higher energy ions than that of a grounded or floating wall



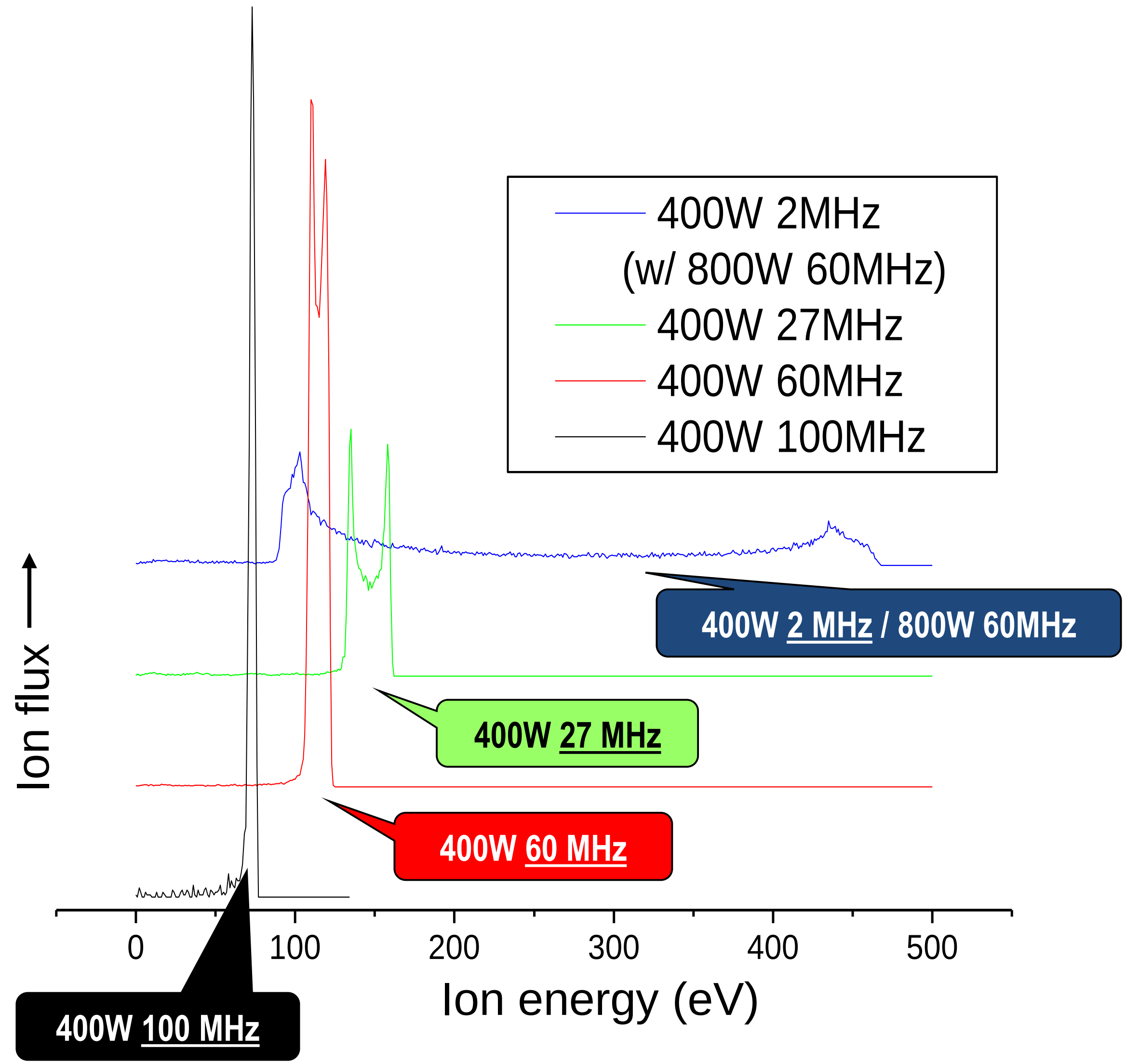
# Ion energy distributions

- We've been discussing time-averaged potential behavior
- In actuality, the plasma (e.g., sheath potentials) are oscillating at the applied RF frequency
- This has implications for the ion energy distribution (IED)



# RF excitation frequency has a big effect on the Ion Energy Distribution Function

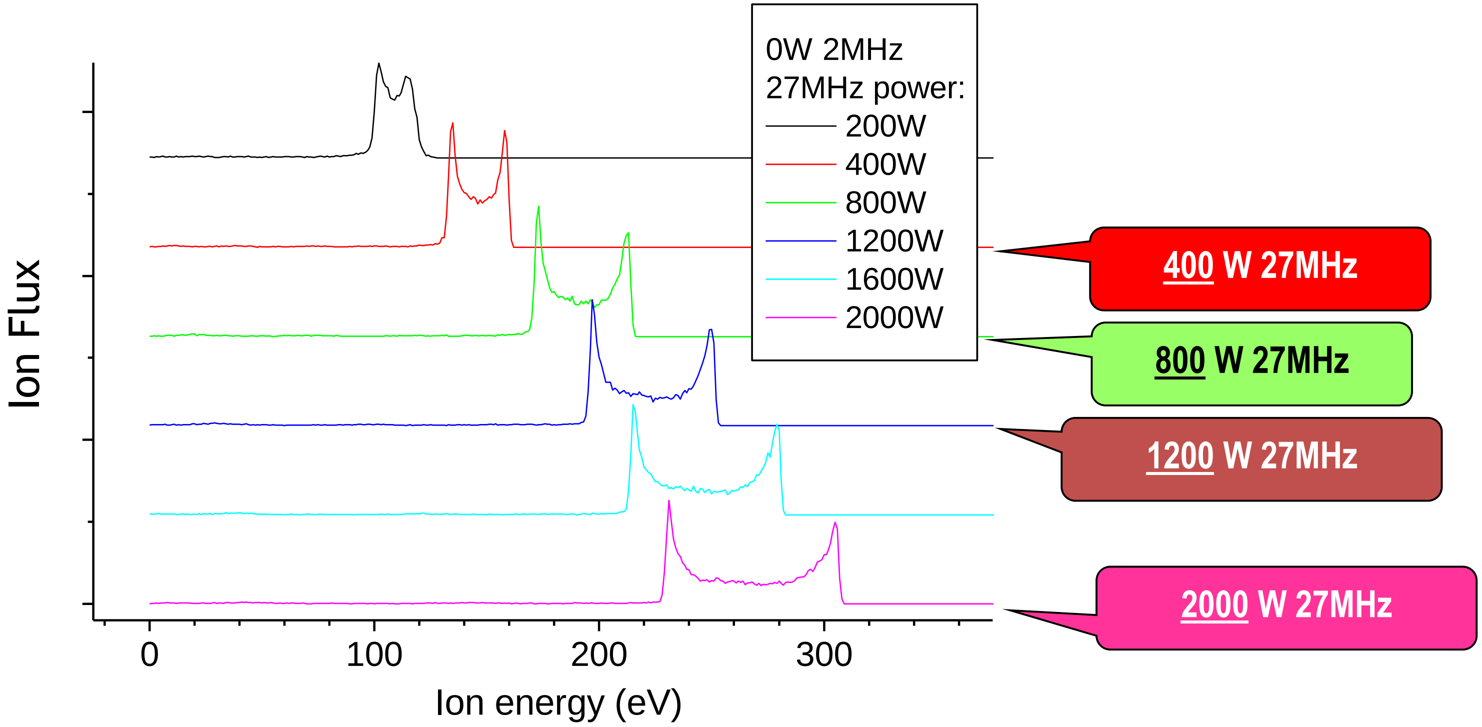
- **Lower frequency** produces broader distribution and higher mean energy
- **Higher frequencies** produce narrower distribution and lower mean energies
- **IEDF plays a key role in modulating etch behavior**



# RF excitation frequency has a big effect on the Ion Energy Distribution Function

▶ **Trends with increasing RF power (single frequency - 27MHz)**

- Higher mean ion energy
- Wider IEDF



# Key points for plasma fundamentals

- **A plasma generates reactive species which are not available in a bottle**
  - Plasmas consist of electrons, neutrals/radicals, and ions generated through collisional processes

- **Ions are accelerated through the boundary layer sheath at near normal incidence (Directional)**

- **Reactant exposure with simultaneous ion bombardment enhances etch rate of materials (Synergistic, anisotropy mechanism)**

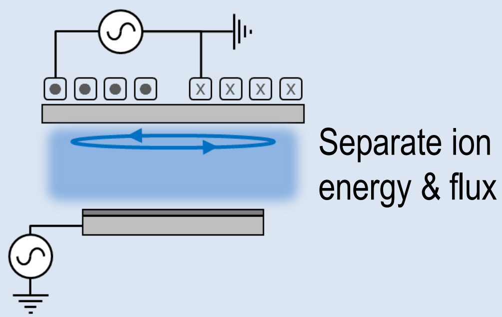
- **RF excitation frequency has a big impact on the ion energy distribution**
  - High RF frequency leads to lower mean ion energies, narrower distribution
  - Low RF frequency leads to higher mean ion energies, broader distribution

# Basic Commercial Etch Hardware

# Conductor and Dielectric Etch Tools

## Conductor Etch

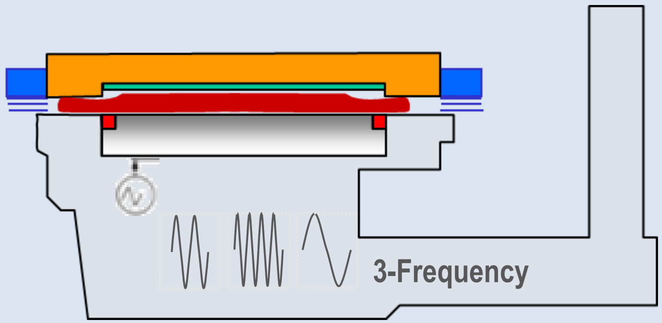
***Inductively Coupled Plasma (ICP)***




**STI, Gate, DPT, TiN Mask Open, Non-volatiles, TSV**

## Dielectric Etch

***Capacitively Coupled Plasma***



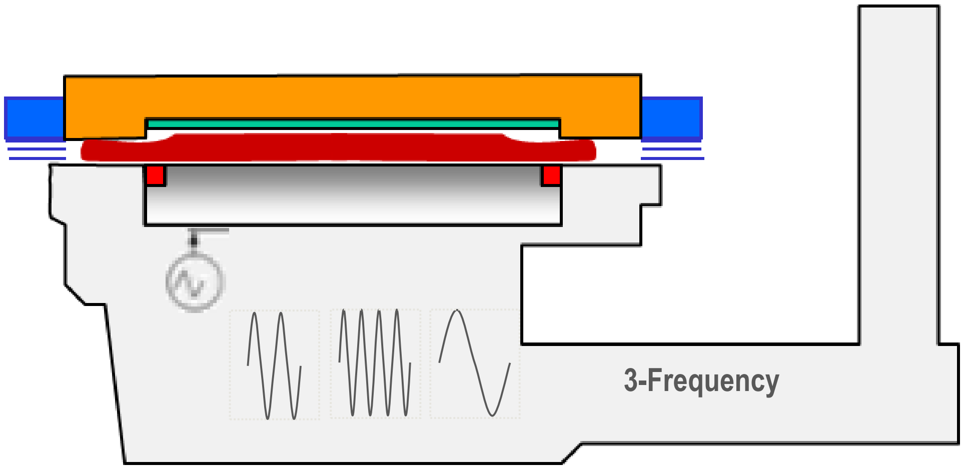

**Contact, Metal Hard Mask All-in-One, Via, Trench**

**Common design principles for critical etch performance:**

- **Symmetrical chambers** – including pumping & RF
- **Independent tuning knobs** – including step-by-step control
- **Repeatable performance** – die-to-die, wafer-to-wafer, and chamber-to-chamber

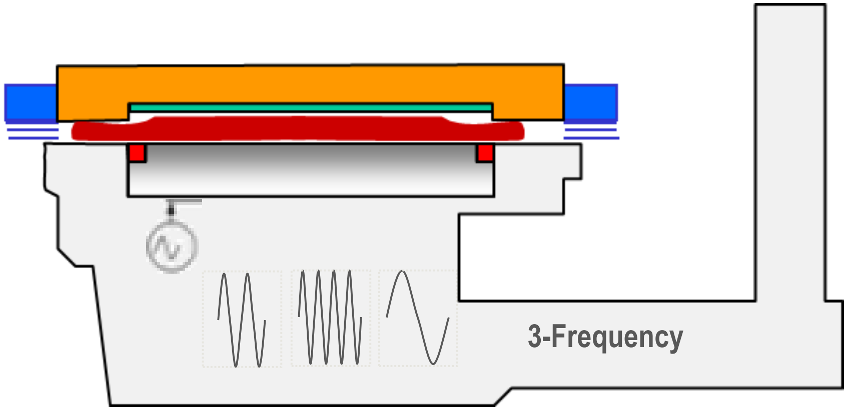
# Capacitively Coupled Plasma (CCP) (Voltage coupling)

- Deliver energy to the electrons in the plasma discharge by applying a RF voltage to electrode
- Typically, when energetic ion bombardment is needed (like in etching of oxides) capacitively coupled RF power is required
- Multiple RF excitation frequencies can be used individually or simultaneously to alter plasma characteristics (e.g., ion energies, ion flux, etc)



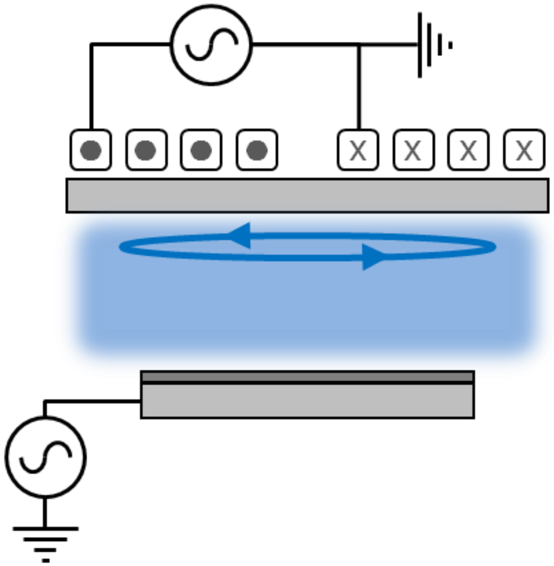
# CCP Etch Chamber Characteristics

- Large fraction of RF power goes to ion acceleration
- High ion energies but lower plasma density
- Operating pressure regime 10mT - 2000mT
  - Most advanced processes operate less than 200mT, rarely above 500mT
- Low fractional ionization: $10^{-6}$ - $10^{-3}$
- Low plasma density ($10^{8}$ - $10^{10}/cm^{3}$)
- Low fractional dissociation of species → Larger fragments remain
- Cannot control plasma density and ion energy independently



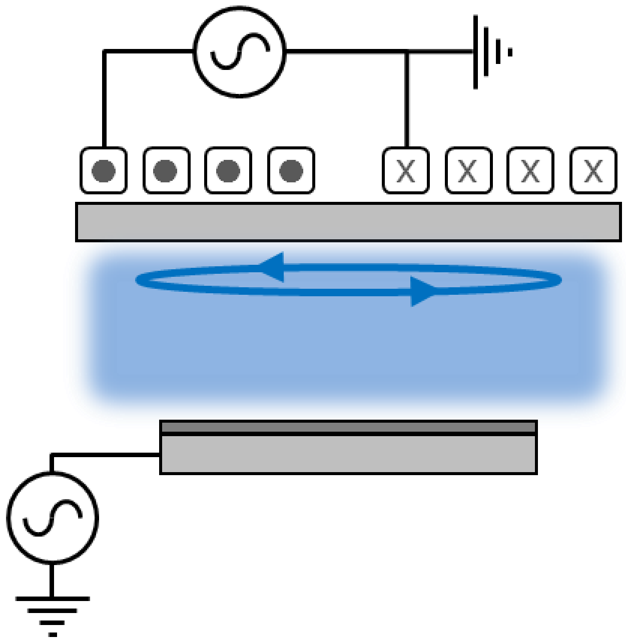
# Inductively Coupled Plasma (ICP) (Current Coupled)

- Inductive coupling is another commonly used method of delivering RF power to the electrons in a plasma
- High RF current in the external coil generates an RF magnetic field in the plasma region which, in turn, generates an RF electric field in the plasma zone
  - RF electric field can couple energy into the plasma electrons
- ICP tools generate high density plasmas and lower ion bombardment of surfaces



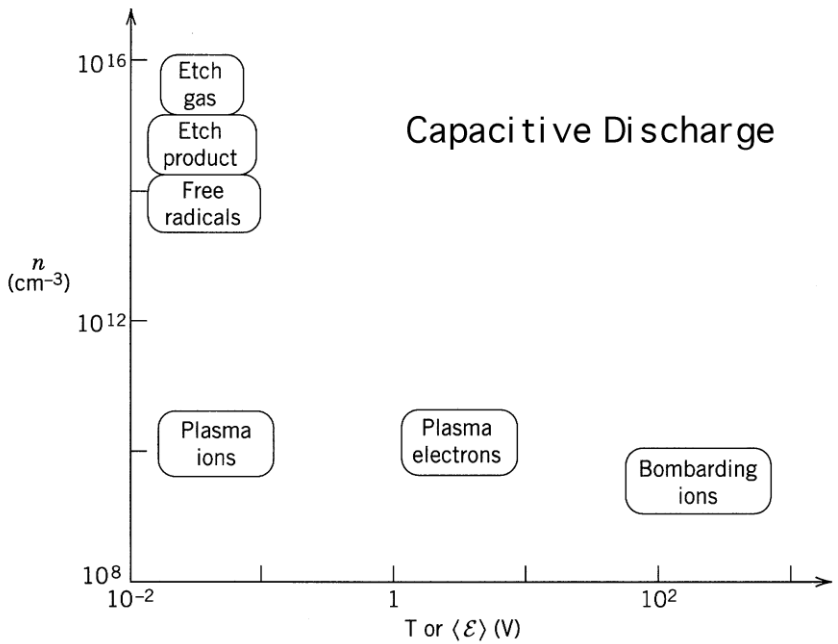
# ICP Etch Chamber Characteristics

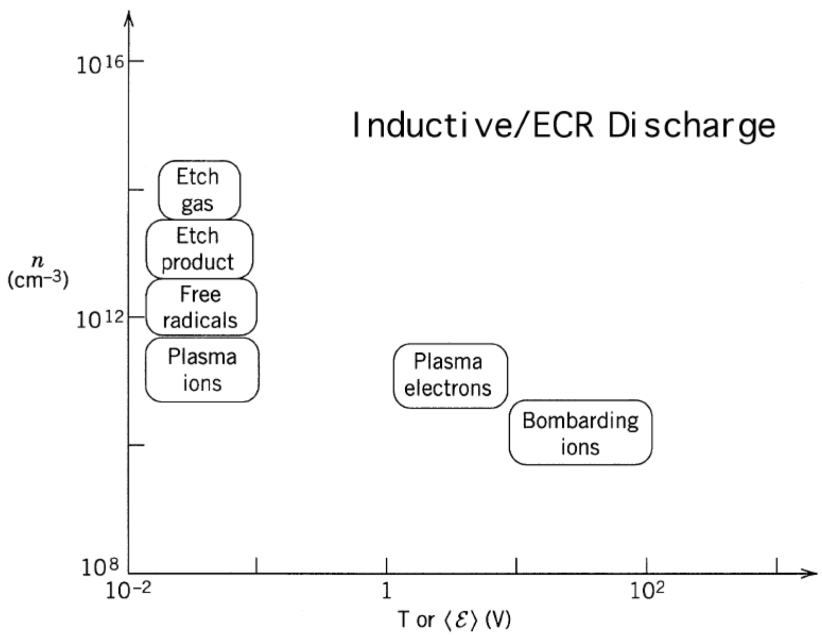
- Generates large RF current as little power is used for ion accelerations
  - No high ion energy ion bombardment without bias power
- With 2 RF generators, both plasma density and ion energy can be controlled independently
- Typical operating pressures 1 - 80 mT
- High fractional ionization ($10^{-3}$ - $10^{-1}$)
- High plasma density ($10^{11}$ - $10^{13}$)
- High fractional dissociation, smaller fragments remain
- Larger gap to give required uniformity



# Comparison of ICP vs CCP Characteristics

## Relative Densities and Energies



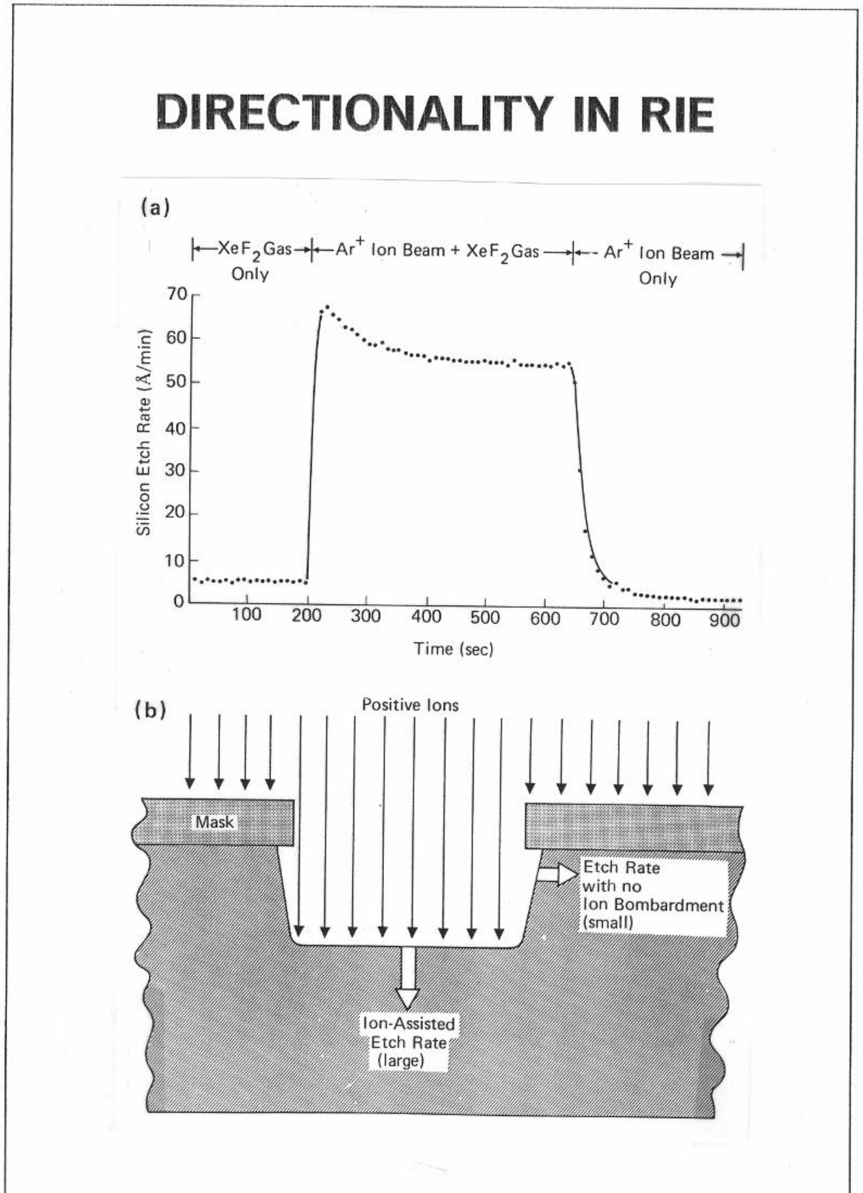




- Higher pressure operation
- Higher ion energies
- Plasma density and ion energy are coupled

- Higher plasma densities
- Decoupled control of plasma density and ion energy

# Plasma Etch Process Fundamentals

# Mechanisms for etch directionality & profile control




- Ions are accelerated through the sheath and the ion flux is mostly normal to the wafer
- This is the only anisotropic process in the plasma discharge, and leads to anisotropic etching of the features
- Sidewall etching is usually chemical in nature and is slow due to glancing ions or even ion shading (minimal synergy)

# Etch kinetics: Special etch regimes

- **Simple model for etch rate depends on ion flux, ion energy, and neutral flux/surface coverage**
  - Neglecting role of pure sputtering by inert or reactive ions
  - Neglecting role of thermally activated neutral etching

$$\text{EtchRate} \approx \frac{1}{\dfrac{A}{\left(\varepsilon_i^{1/2} - \varepsilon_{th}^{1/2}\right) \cdot J_i} + \dfrac{B}{J_N}}$$

where:

$\varepsilon_i$ = ion energy
$\varepsilon_{th}$ = threshold energy
$J_i$ = ion flux

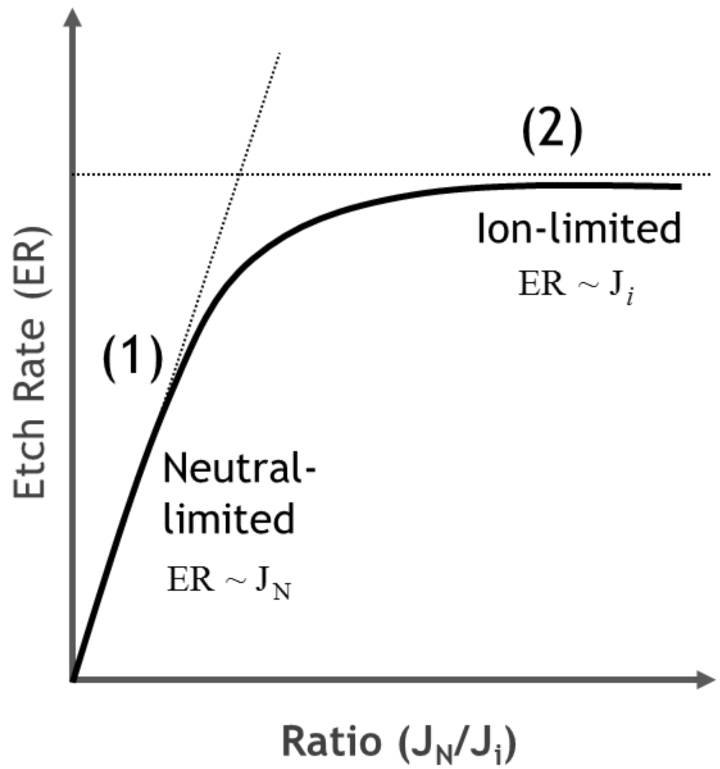
$J_N$ = neutral flux
A ~ ion efficiency
B ~ sticking efficiency

Source: Gottscho et al., JVSTB (1992), Steinbruchel (1989)

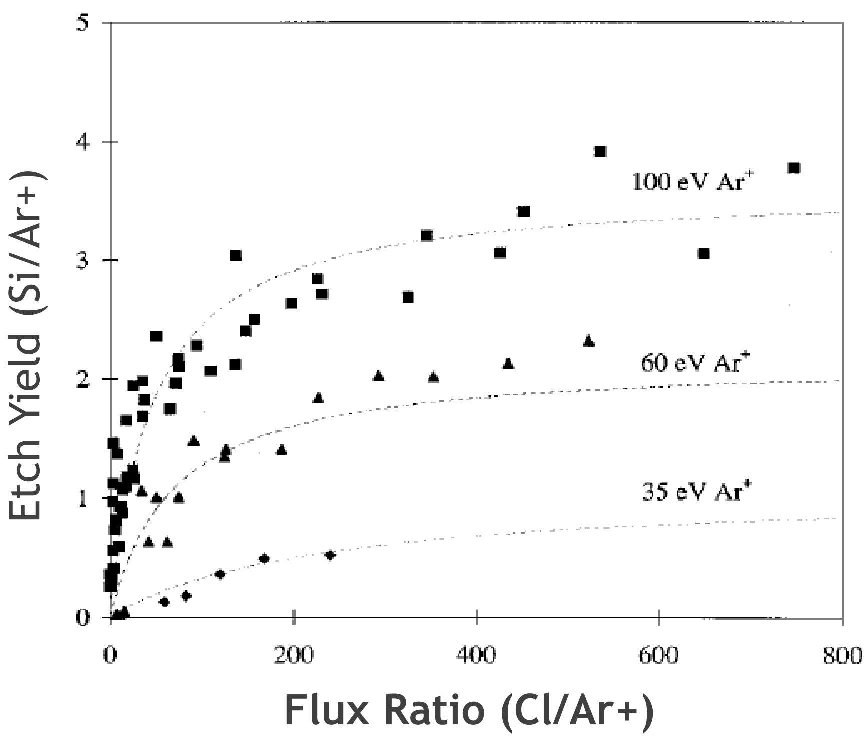
- **Special/Limiting cases**
  - When ion flux is negligible ($J_i$ = 0) → Etch Rate vanishes
  - When neutral flux is negligible ($J_N$ = 0) → Etch Rate vanishes
  - At constant ion energy flux, the etch rate will initially increase in proportion to the neutral flux (neutral-limited regime), but then saturate at higher neutral fluxes (ion-limited regime)

# Etch kinetics: Special etch regimes

## Model Prediction

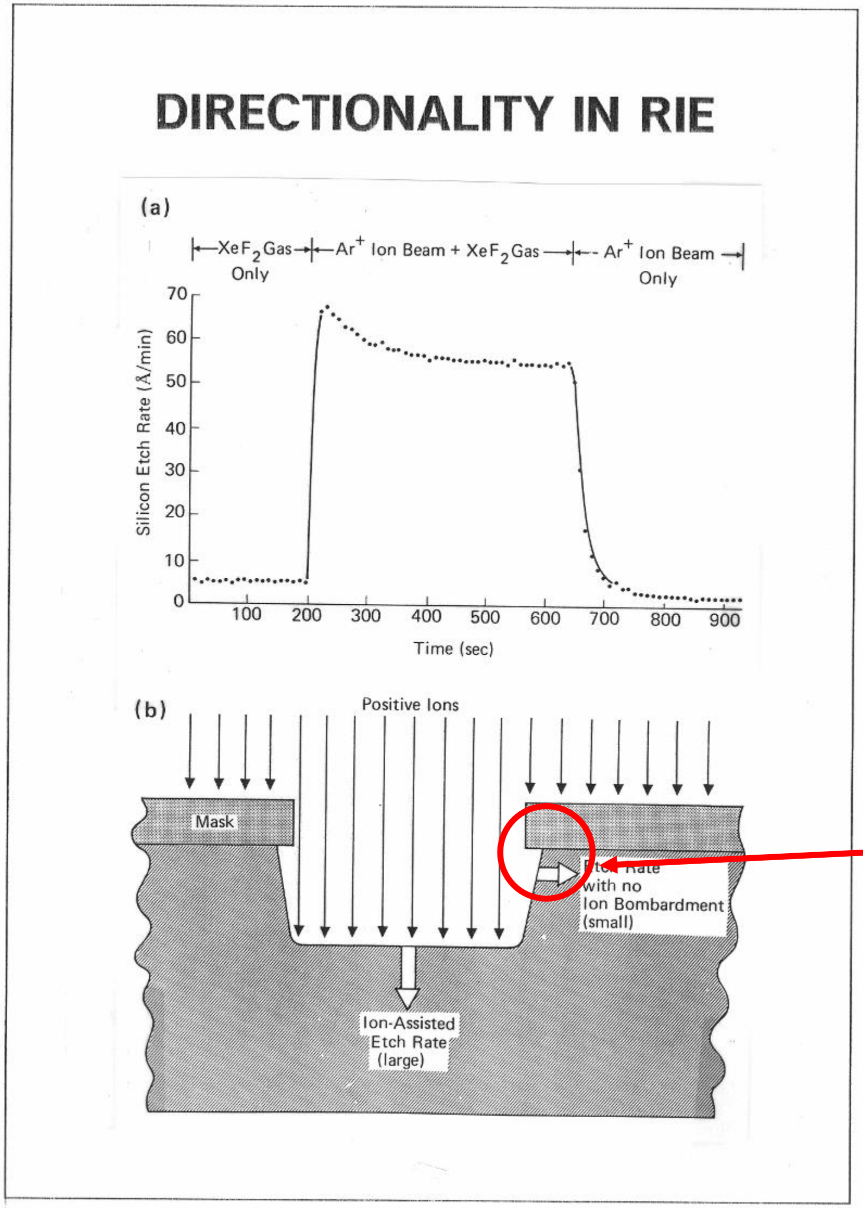



## Si etching with Cl and Ar+




Chang et al., JVSTA 15(4), 1997

# Mechanisms for etch directionality & profile control




*Often, this type of undercut is unacceptable*

# Mechanisms for etch directionality & profile control

## ▸ Condensable species

- Tend to form films on surfaces
- Very dependent on the surface temperature

## ▸ Reactive species

- Tend to react chemically with the surface
- Often saturate at one monolayer coverage

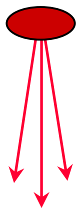
## ▸ Examples at room temperature

- Halogen atoms: Cl, F….. – reactive but not condensable
- Inert Gas atoms: Ar, Xe, He…. – not reactive or condensable
- Polymer Precursors ($C_xF_y$ radicals): often both condensable and reactive

# Mechanisms for etch directionality & profile control

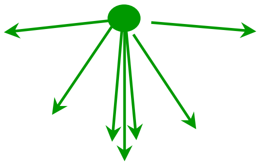
**Ion's Angular Distribution**

**- narrow**

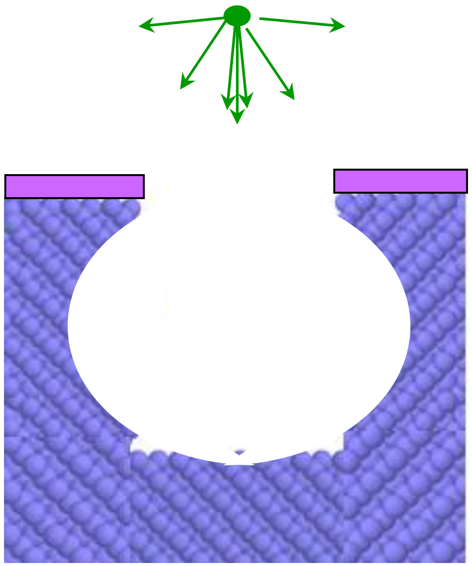


**Neutral's Angular Distribution**

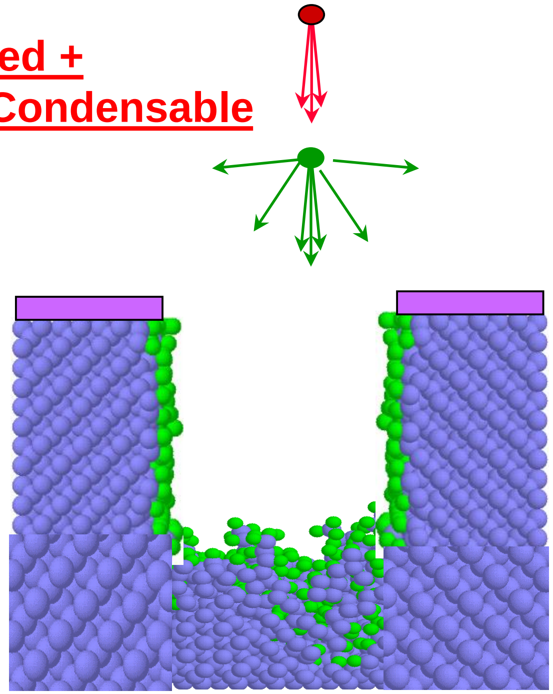
**- wide**



**Reactive neutrals**



**Ion assisted + Reactive/Condensable neutrals**



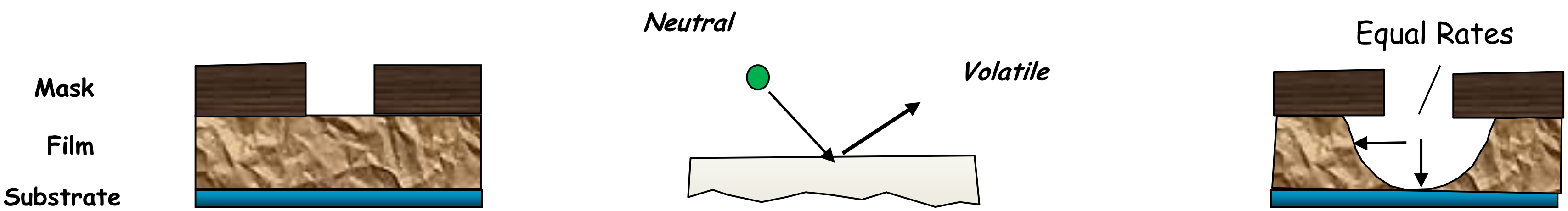
# Mechanism for etch directionality & profile control

## Four basic etching processes

1. Pure chemical etching
2. Sputtering
3. Ion enhanced etching
4. Ion enhanced inhibitor etching

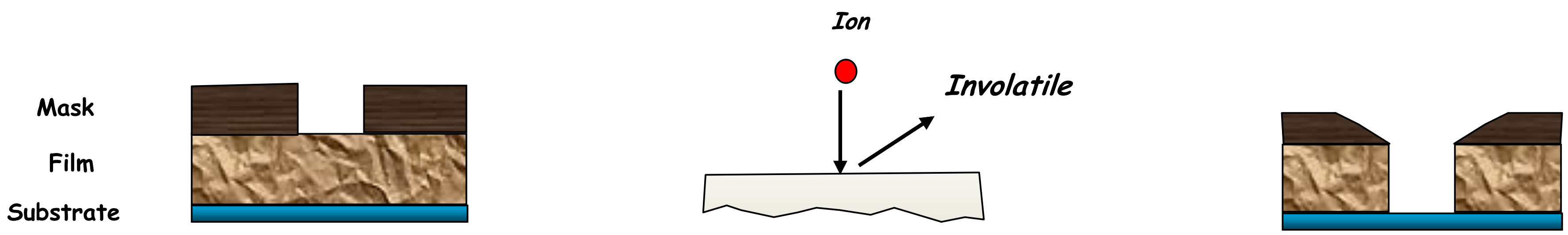
# 1. Pure Chemical Etch

- <u>Selective</u>, slow process - due to etchant atoms or molecules (like F or O) reacting at the surface and forming volatile products
- <u>Isotropic</u>



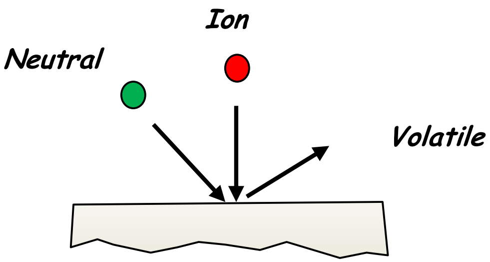
# 2. Sputtering

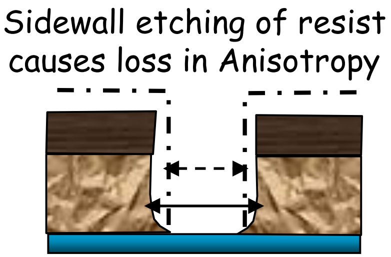
- Non-selective, slow - physical process due to energetic ion bombardment ejecting surface atoms
- Anisotropic



# 3. Ion Enhanced Etching

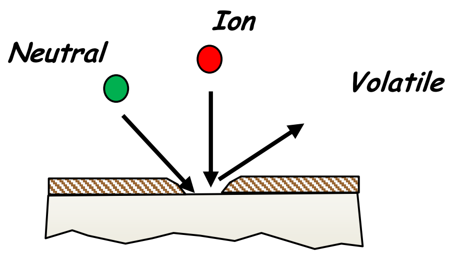
- May have lower selectivity than pure chemical etch
- Enhanced vertical etch rate due to synergy between ions and chemical etching
- Anisotropic

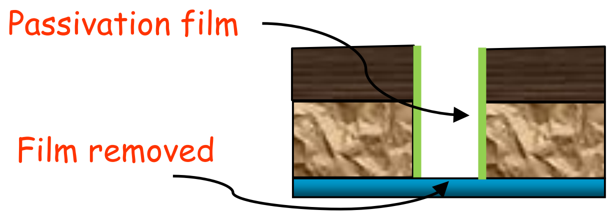



# 4. Ion Enhanced Inhibitor Etching

- Similar to ion enhanced etching, but may have <u>higher selectivity</u>
- Inhibitor (e.g., polymer film) deposited on the sidewalls where ions are not effective at removing
- <u>Anisotropic</u>

# What variables influence etch directionality?

- Ion flux
- Ion energy
- Neutral/ion flux ratio
- Deposition or passivation chemistry
- Temperature of surface being etched
- Pressure (sheath collisions may deflect ions at higher pressures)

# Dielectric Etch Mechanisms

# Overview of $SiO_2$ etch

- **Typical process gases: (hydro)fluorocarbons with Ar and $O_2$**
  - Also will see CO, $N_2$, $H_2$

- **High bias voltage/wattage for promotion of product formation**

- **$SiO_2(s) + C_xF_y + I^+(E_i) \rightarrow SiF_4(g) + CO(g)$**

- **Selectivity (to Si and PR) provided by polymer formation**

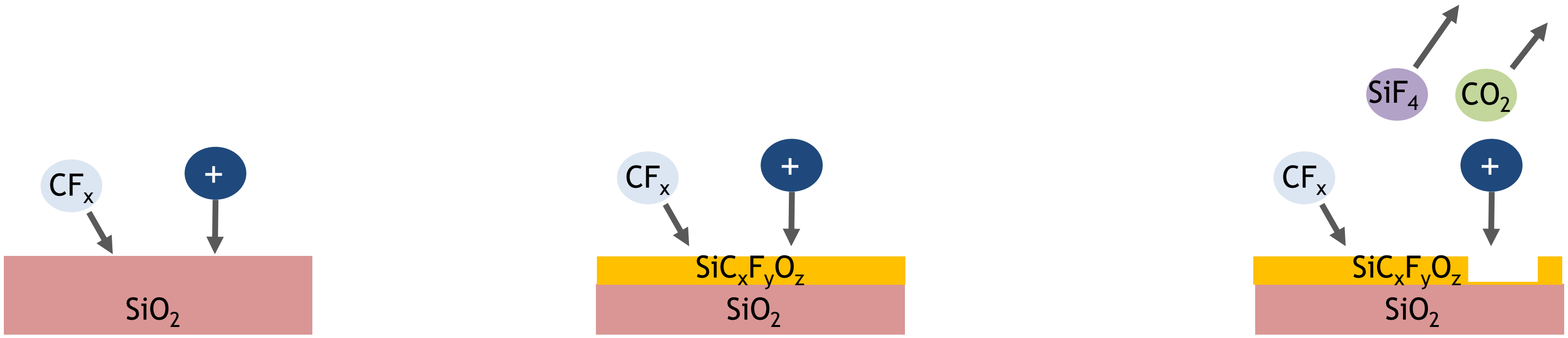
- **F atoms etch silicon dioxide slowly at room temperature; low reaction rate compared to ion bombardment assisted etch**
  - <u>All observed etching of $SiO_2$ is ion energy driven</u>
  - Energetic flux breaks bonds and forms reactive sites for F to form volatile products ($SiF_4$)

# Common etchant gases for silicon dioxide

- **Perfluorocarbons: $CF_4$, $C_4F_8$, $C_4F_6$**
  - F/C ratio is a key parameter that can control how polymerizing an etch process is
  - Important for selectivity and profile control
- **Hydrofluorocarbons: $CHF_3$, $CH_2F_2$, $CH_3F$, $CH_4$**
  - Addition of hydrogen can scavenge F in the plasma and increase polymerization
    - $H + F \rightarrow HF$
- **Oxygen**
  - Added to increase F and decrease polymer precursors
- **Inert gases: He, Ar, Xe**
  - Control the neutral radical/ion flux ratio
  - Manipulate plasma density and/or electron temperature
  - Dilute the reactants
  - Improve heat transfer (He)

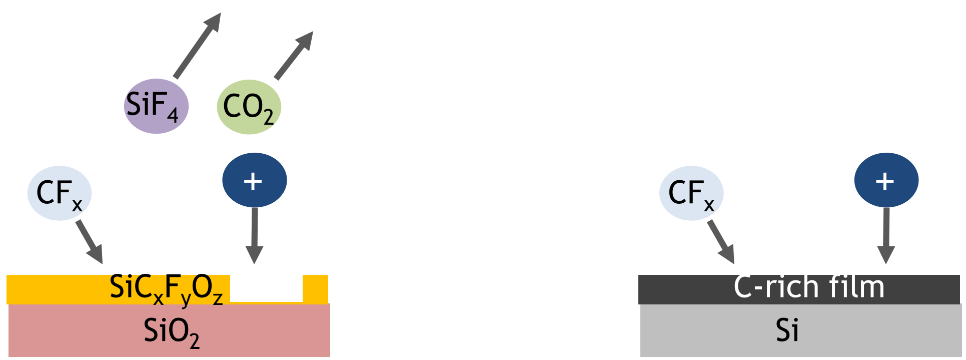
# $SiO_2$ etch mechanism

- **An $SiO_2$ surface with a $CF_x$ radical flux under ion bombardment forms a layer of $SiC_xF_yO_z$**
  - Ion beam mixing of $CF_x$ radicals plays an important role in the formation
- **The key etch mechanism is likely the breaking and reforming of bonds of the $SiC_xF_yO_z$ layer due to energetic ions colliding with and penetrating the surface**
  - This produces easily desorbed etch products, weakly bound to the surface
    - $SiF_4$, $SiF_2$, $SiOF_2$, $CO$, $CO_2$, $COF_2$, $O_2$
  - A layer of C is prevented from building up due to reaction with O within the film



# $SiO_2$ etch selectivity mechanisms

- For F-rich discharges, there is little selectivity for $SiO_2$ over Si
- High selectivity is obtained by using unsaturated fluorocarbon gases or by adding $H_2$ to scavenge fluorine (*decrease F/C ratio*)
- The oxygen in $SiO_2$ permits formation of volatile $CO_x$, preventing buildup of carbon on the surface
  - $SiO_2$ etches while a carbon layer builds up on the Silicon → <u>Etch Selectivity!</u>

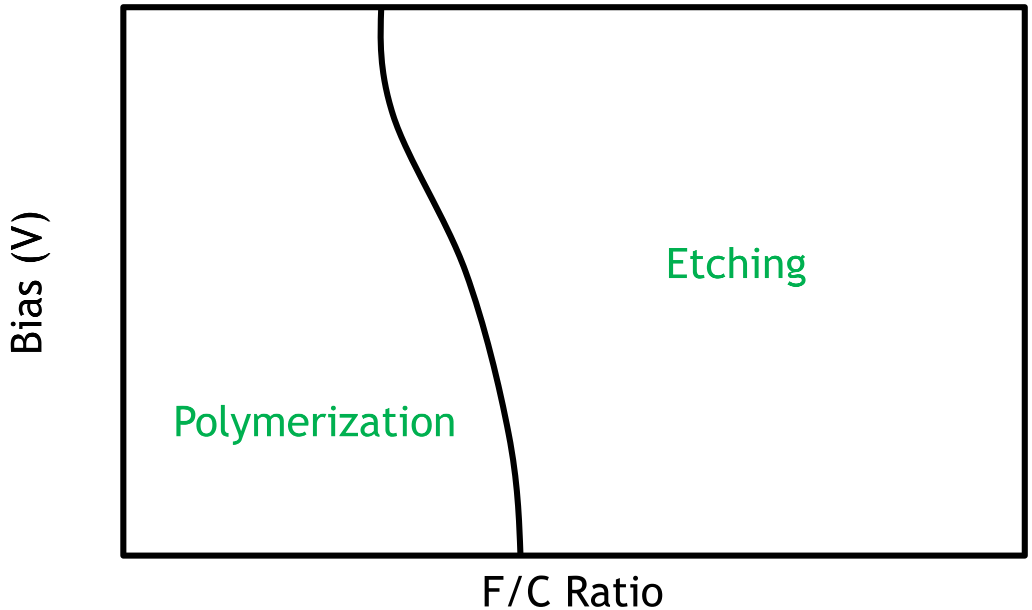


# Effect of Oxygen

- Addition of oxygen can increase photoresist etch rate, thereby decreasing oxide etch selectivity to resist
- If the etch is more polymerizing (i.e., low F/C ratio), then oxygen addition will increase the oxide etch rate without as large an increase in the resist etch rate (thus, increasing selectivity)
  - Due to additional oxygen liberated by $SiO_2$ as it is etched

# Fluorine/Carbon ratio

- **If the plasma is made too fluorine deficient, polymer deposition will dominate over etching of $SiO_2$ → Etch Stop!**
  - The F/C ratio where this occurs is dependent on energetic ion flux
  - At higher energies, etching will take place
  - At lower energies, deposition will take place
- **For high selectivity, we often have to operate close to this boundary**



# Etching $Si_3N_4$

- **Mechanistically not as well understood as Si or $SiO_2$ etching**

- **Often said that $Si_3N_4$ etch behavior is in between Si and $SiO_2$**
  - Relative reactivity to F atoms without ion bombardment is in between Si and $SiO_2$
  - The effectiveness in removing polymeric blocking material is in between Si and $SiO_2$

- **$SiF_4$ is the dominant Si-containing etch product**

- **How is nitrogen evolved?**
  - In pure Fluorine plasma (F atoms only), nitrogen leaves as $N_2$
  - When nitride is etched in a fluorocarbon plasma, optical emission from the CN radical is observed (FCN has been observed in such situations)

# Nitride etching selectivity

- **$SiO_2/Si_3N_4$ and $Si_3N_4/Si$ selective etching can be obtained with fluorine-deficient fluorocarbon plasmas such as $CF_4/H_2$, $CHF_3$, $C_4F_8$, etc**

- **The mechanism responsible for $SiO_2/Si_3N_4$ selective etching is similar to that discussed previously for $SiO_2/Si$ etching**

- **For $SiO_2/Si_3N_4$ selective etching, the key factor is that nitrogen is less efficient than oxygen in removing carbon**
  - Therefore, conditions can be found where $SiO_2$ etches and $Si_3N_4$ does not

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