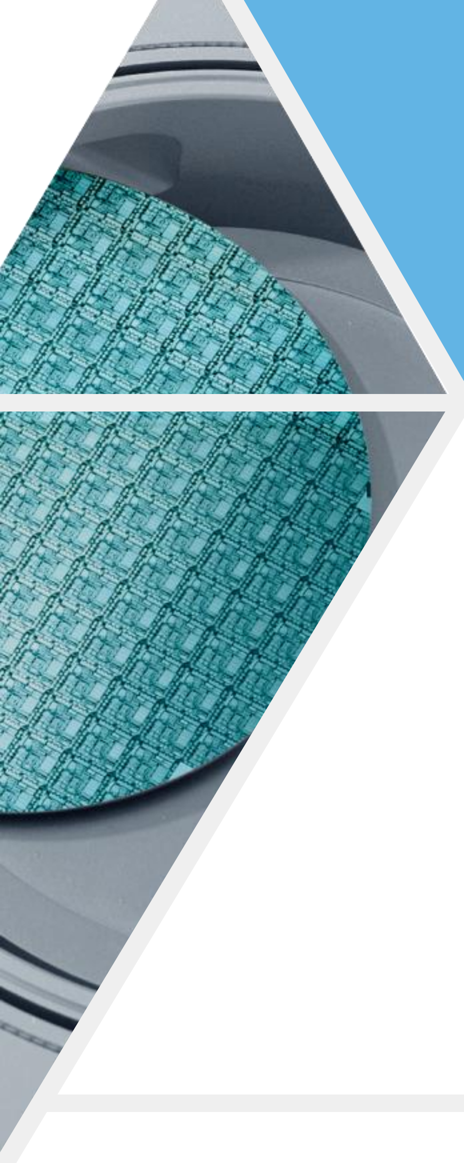
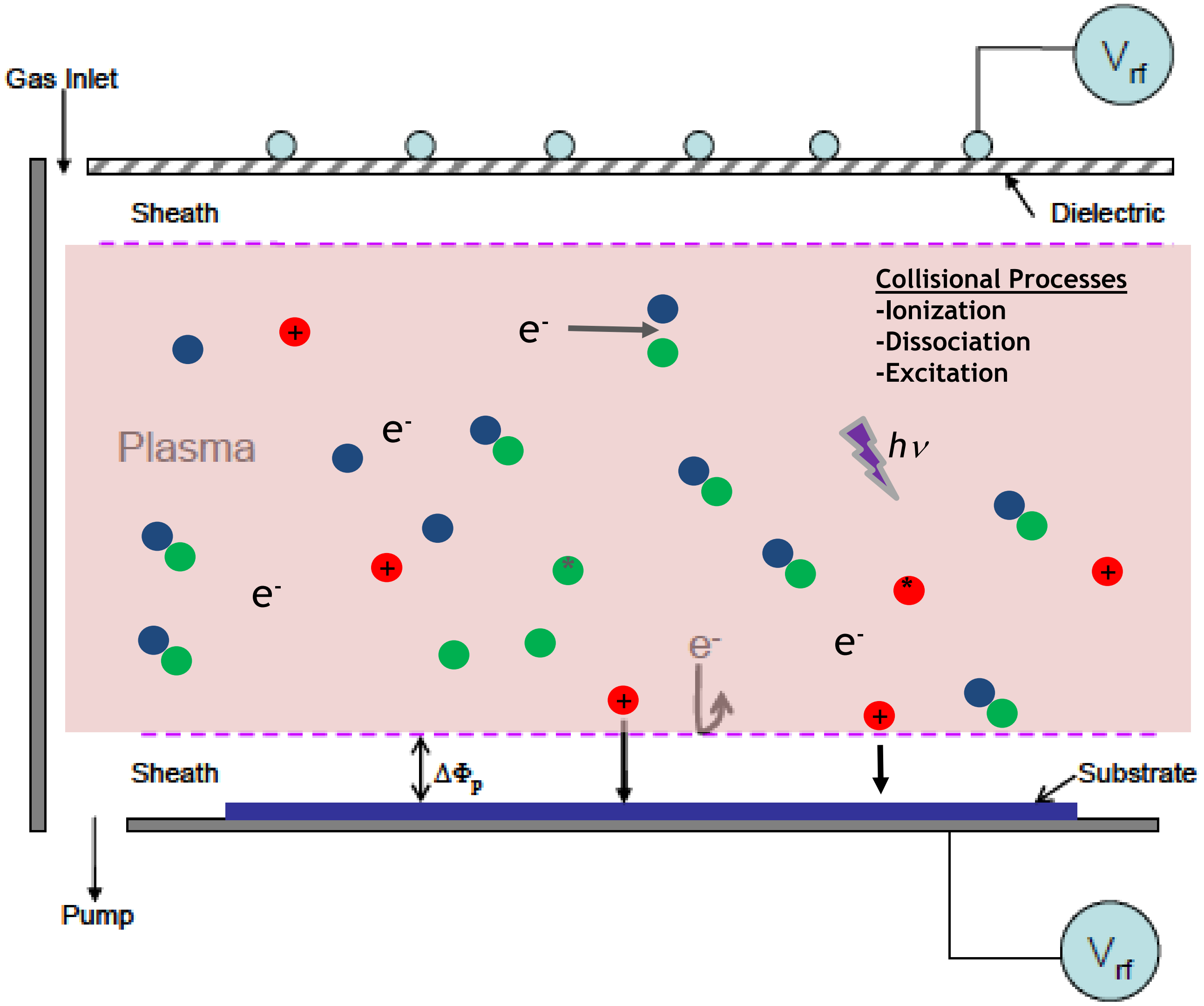


Introduction to Plasma Etching

Dr. Steve Sirard

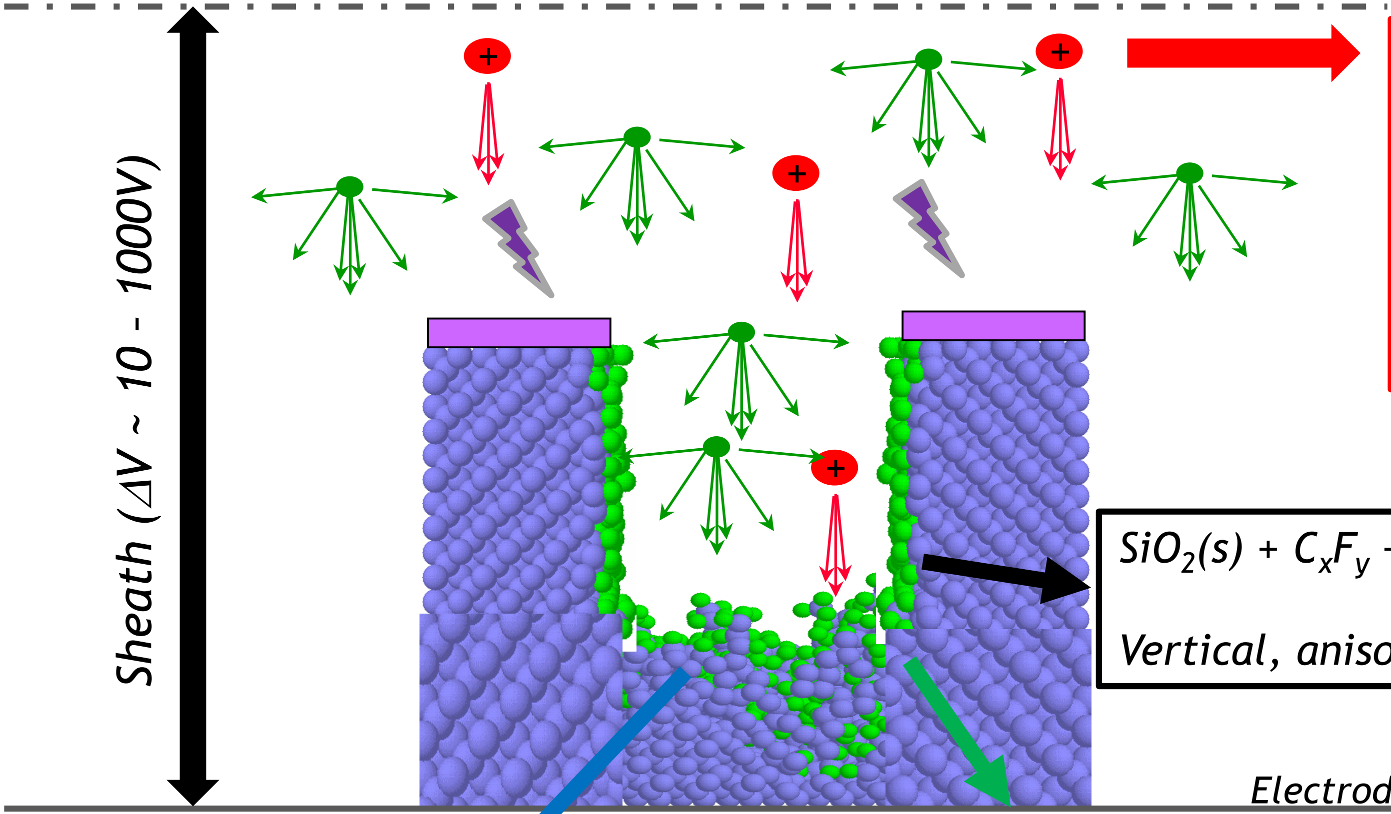
Technical Director
Lam Research Corporation

Day 1 Review - *Plasma Fundamentals*



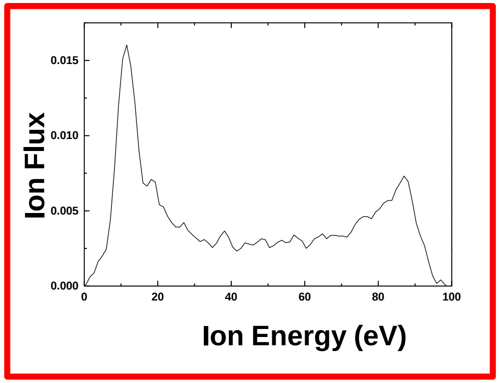
- **Plasmas consists of electrons, ions, neutrals, radiation**
  - $n_e \sim n_i << n_g$ (weakly ionized)
- **Collisional processes sustain the plasma and create radicals (etchant)**
  - Electrons are very hot
- **Sheaths form at the walls/substrate to confine electrons and <u>directionally</u> accelerate ions**

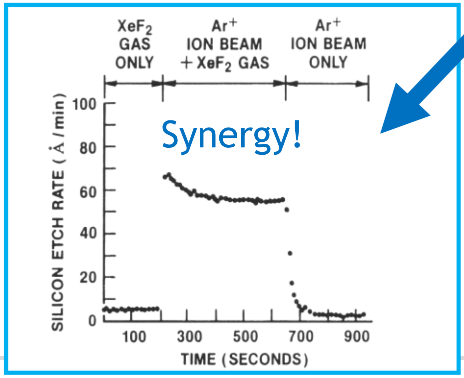
Day 1 Review - *Anisotropic Plasma Etching*

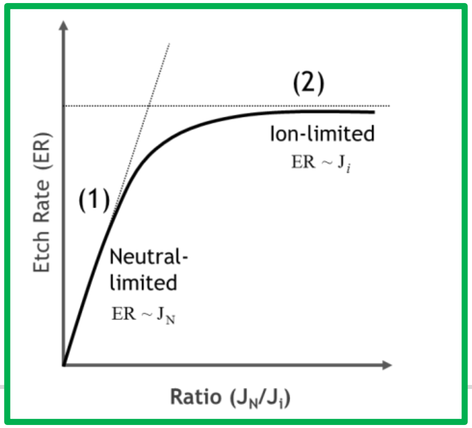


$SiO_2(s) + C_xF_y + I^+(E_i) \rightarrow SiF_4(g) + CO(g)$

Vertical, anisotropic etch







Day 2 - Outline

- Primary etching variables available to process engineers
- Common pattern transfer issues
- Advanced etch strategies: Pulsing strategies, Atomic layer etching
- Within-wafer etch uniformity control
- Plasma & surface diagnostics

What "knobs" are available to tune etch processes?

- **Etching in general is very complex!**
- **Advanced plasma etch chambers are equipped with a lot of "knobs" for controlling the etch process**
  - Wafer temperature
  - Upper electrode temperature
  - Temperature gradients
  - Chamber pressure
  - Gas chemistry (*~20 gases on a chamber to choose from*)
  - Gas ratios (*gas partial pressures*)
  - Gas flow rate (*residence time*)
  - Total RF power
  - Multiple RF excitation frequencies (*up to 3 generators*)
  - Pulsing of RF powers (*duty cycle, frequency*)
  - Pulsing of gases (*duty cycle, frequency*)
  - Etch time
  - Multiple uniformity knobs
- **Overall, a tremendously large process space → long development cycles!**

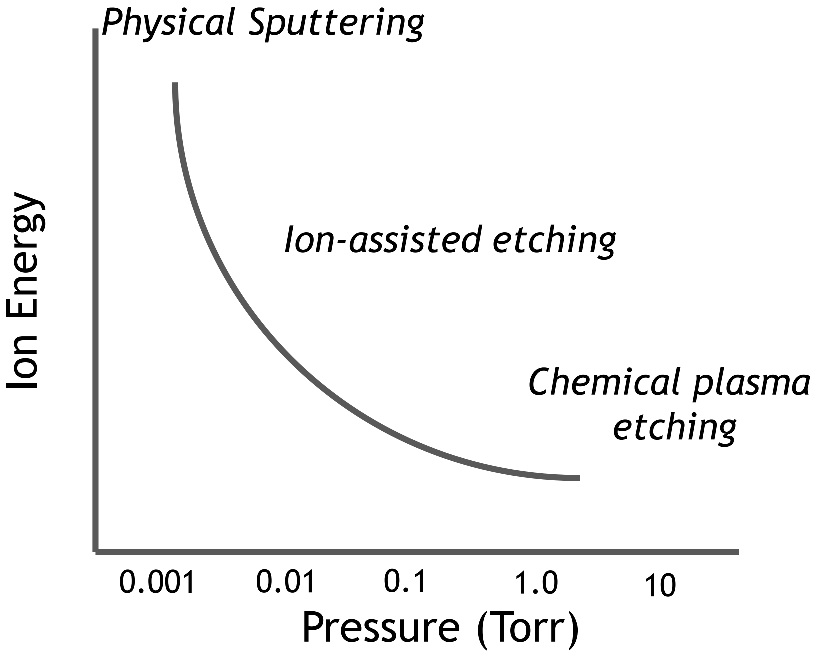
Key etch variables: Gas Chemistry

- **Etchant gases (e.g., CF_4, Cl_2, C_4F_8)**
  - Provide reactants to etch materials of interest
  - May provide polymer precursors for anisotropy, selectivity
- **Oxidants (e.g., O_2)**
  - Used to increase etchant concentrations
  - Suppress polymer formation
- **Radical-Scavengers (e.g., H_2)**
  - Increase polymer formation, selectivity
  - Reduce etchant concentration
- **Inhibitor-Former (e.g., CH_3F, CH_4)**
  - Induce anisotropy
  - Improve selectivity
- **Inert Gases (e.g., Ar, He)**
  - Dilute etchant
  - Stabilize plasma
  - Enhance anisotropy
  - Improve heat transfer

Key etch variables: Chamber Pressure

- Pressure directly influences major phenomena that control plasma etching

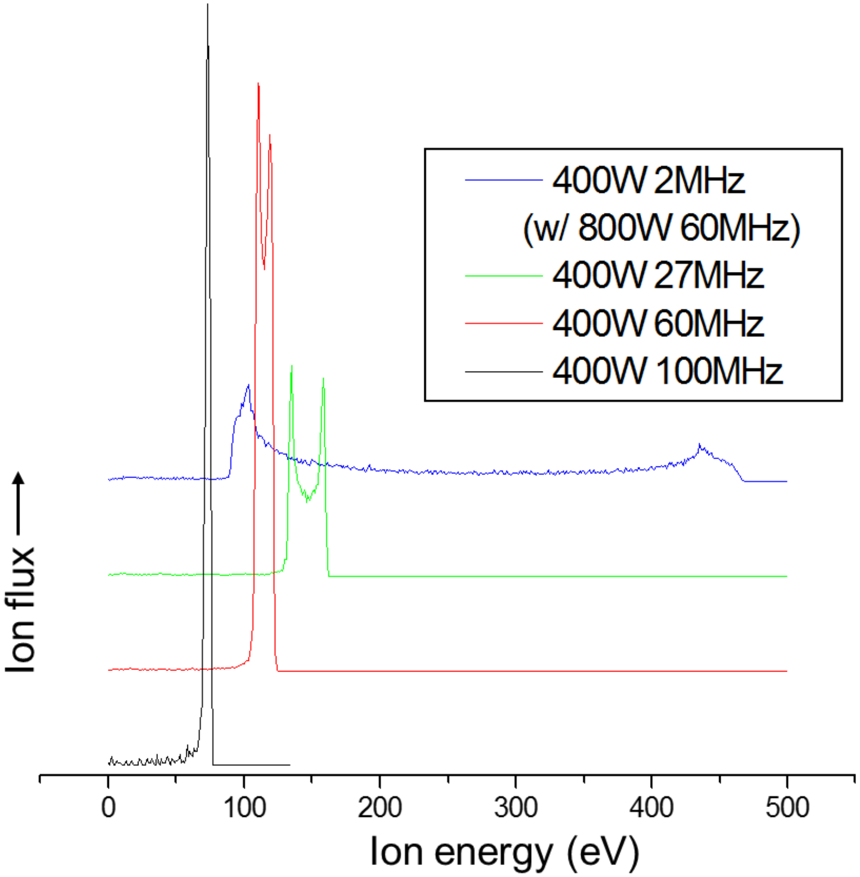
1. Energy of ions bombarding surfaces
2. Ion-to-neutral ratio/flux
3. Polymerization potential
4. Electron energies
5. Surface coverage by physisorption
6. Chemical kinetics
7. Relative rates of mass transport processes
8. Etch rate uniformity across wafer



Key etch variables: RF Power/Frequency

- RF Power/Excitation Frequency can influence:

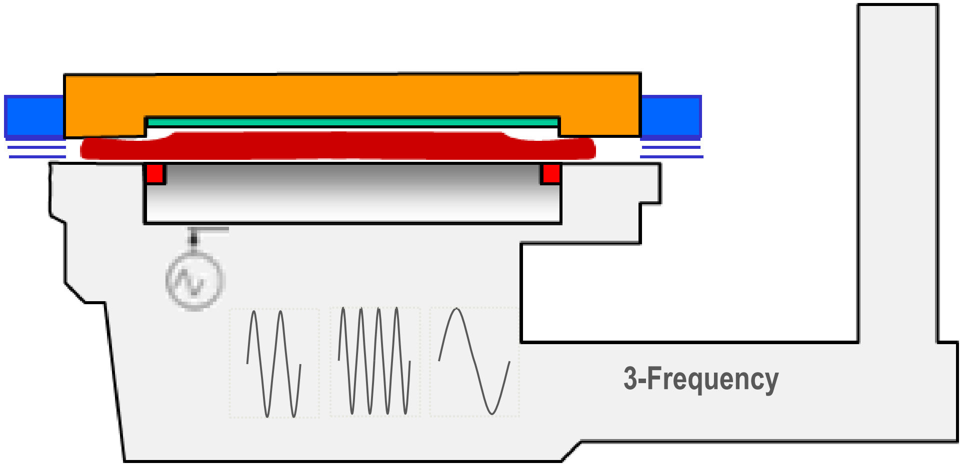
1. Spatial distributions of species across the plasma (Uniformity)
2. Ion energy distribution
3. Plasma density
4. Effects plasma chemistry
    - For example, one frequency may promote polymer deposition, while another frequency may etch polymer
5. Selectivity

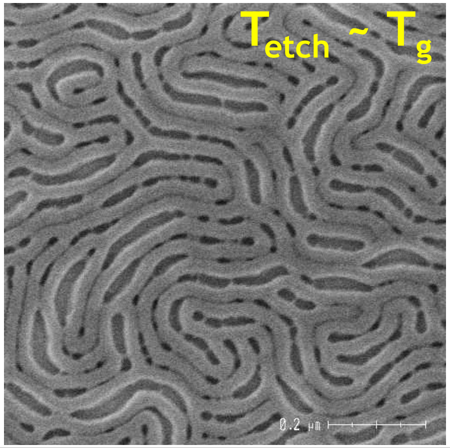


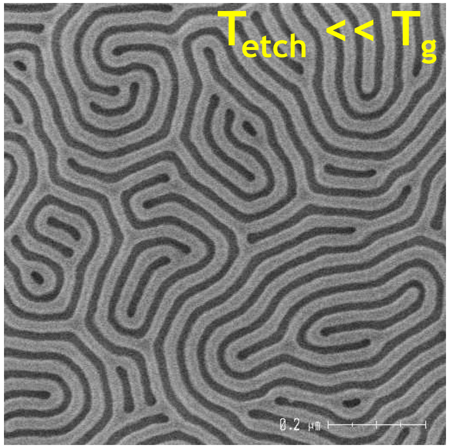
Key etch variables: Surface Temperatures

- Surface temperatures can effect:

1. Surface morphology
2. Polymer deposition
3. Selectivity
4. Resist flowing/wiggling/roughness
5. Product volatility/Etch rate
6. Temperature gradients → Thermophoresis effects → Selectivity/Uniformity impact







Common Pattern Transfer Issues

Process Issues → Loading Effects: Macro-loading

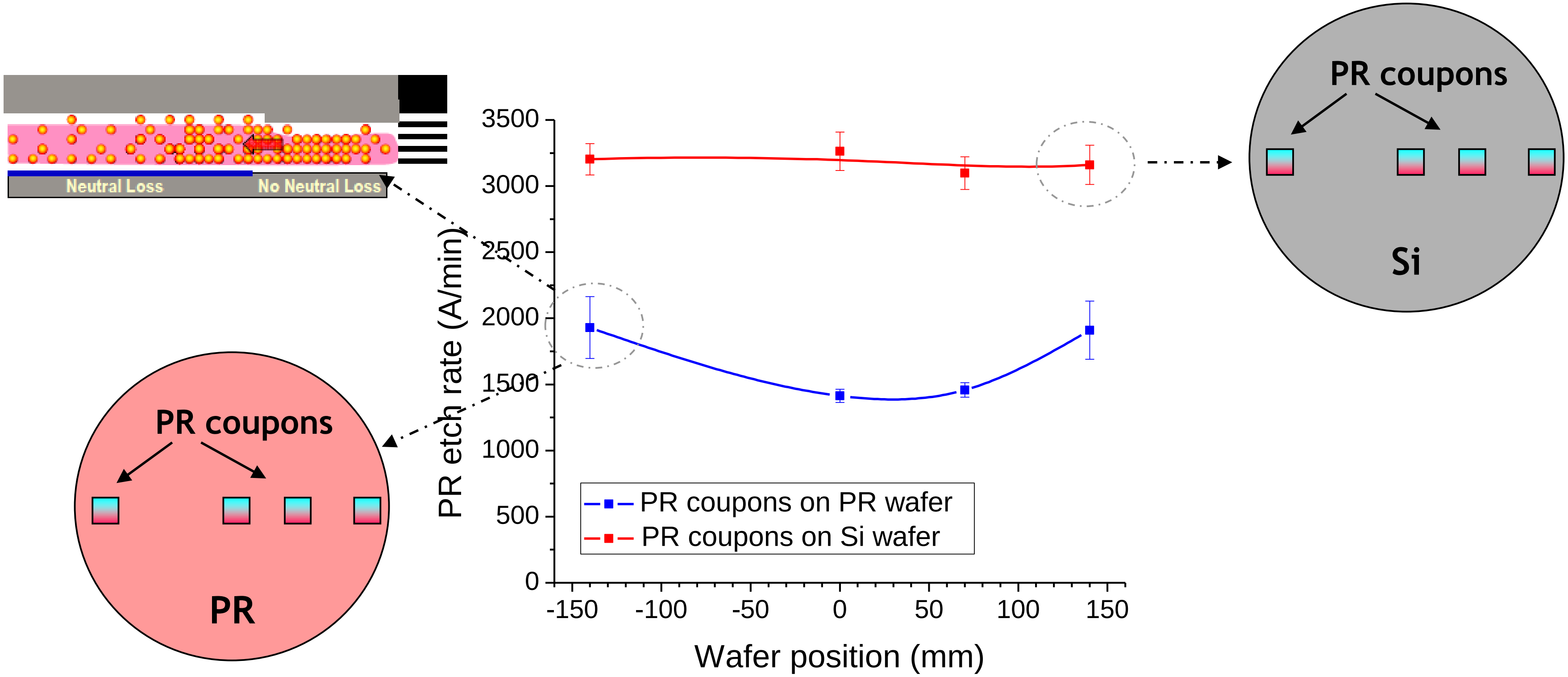
- **Macro-loading**
  - Etch rate for a given process becomes slower with more exposed etch area
    - Due to overall depletion of reactant with more exposed area to etch

- **Examples of macro-loading issues in industry**
  - Process shift on two different wafers with same features but different etchable area
  - Chamber etch rate drift due to build up of polymer on chamber parts during etch processing

Macro-loading Example: *Depletion of reactant with larger exposed area*

▸ Photoresist etch with oxidizing plasma chemistry

- When exposed area of resist is large, etch rate is reduced everywhere, but even more so in the wafer center
- When exposed area of resist is small, etch rate is higher and more uniform
- Typical edge fast etch rate of resist is due to loading of plasma by large area of resist



Macro-loading Characteristics

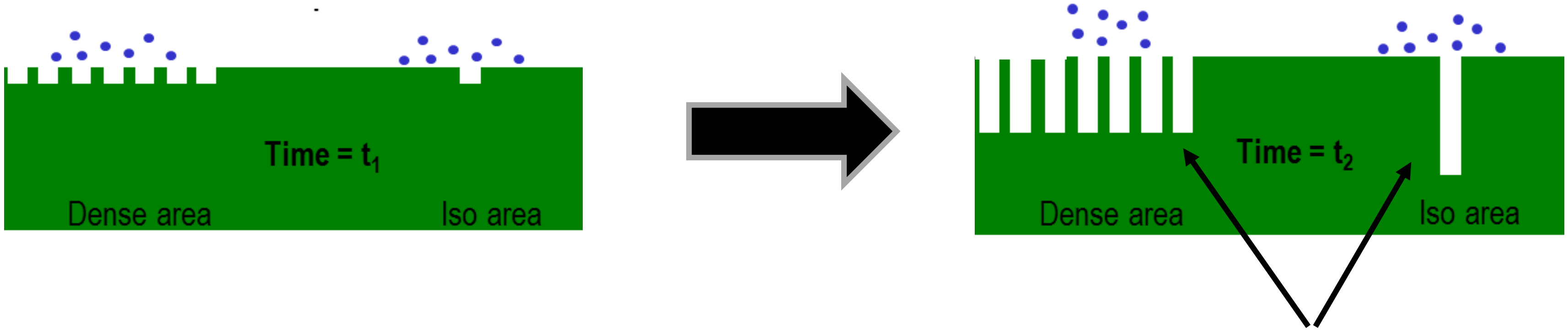
- **Etch rate is limited by the arrival of neutrals (*neutral-limited regime*)**
- **Macro-loading is a function of total exposed area reacting with gas phase species**
- **Center-to-edge uniformity variations can be a result of macro-loading**

- **Compensation Strategies**
  - General process fine-tuning and uniformity compensation
  - Increase etchant flux to make less neutral-limited (e.g., pressure, gas ratio change, higher RF power to increase dissociation)

Loading effects: Micro-loading

- Macro-loading - etch rate becomes slower due to overall depletion of reactant with more exposed etch area

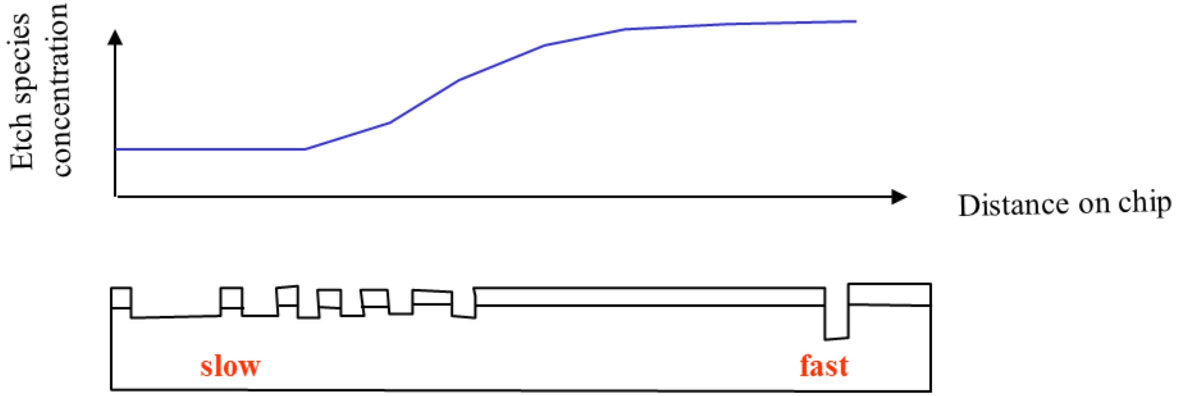
- Micro-loading - etch difference between a given feature located in an area of high density compared to the same feature in an area of low density (isolated) on the same chip (*assumes same nominal aspect ratio*)
  - Due to local depletion of reactant



Isolated trench etches faster than dense area

Is Micro-loading real??

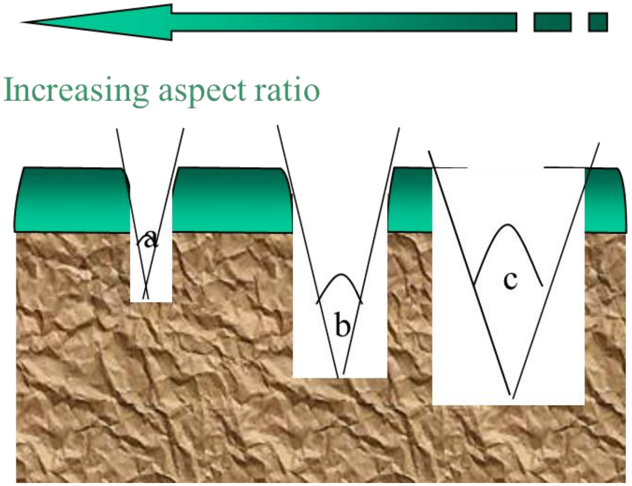
- **Unequal consumption across the chip results in lateral concentration gradients**
  - However, significant gradients may require 100s of microns at low pressures

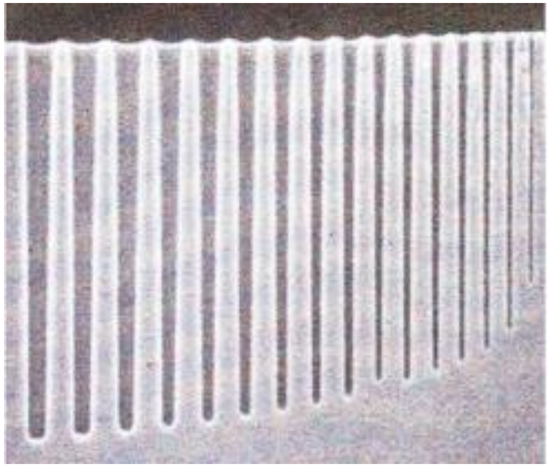


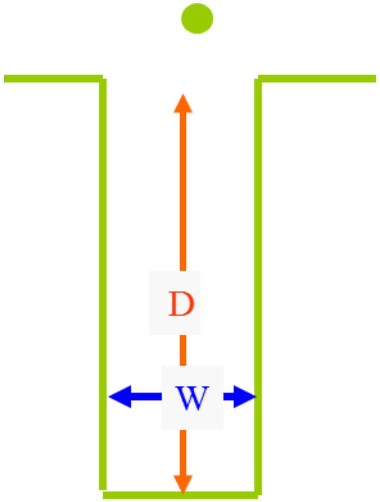
- **Compensation**
  - Lower pressure → fewer collisions → higher diffusion rate → less micro-loading
  - Increase etchant flux (e.g., Change gas ratio, increase source power)

Aspect Ratio Dependent Etching (ARDE)

- **ARDE - etch rate becomes slower with higher aspect ratio or smaller critical dimensions**
  - Sometimes the phenomena is also called "RIE Lag"







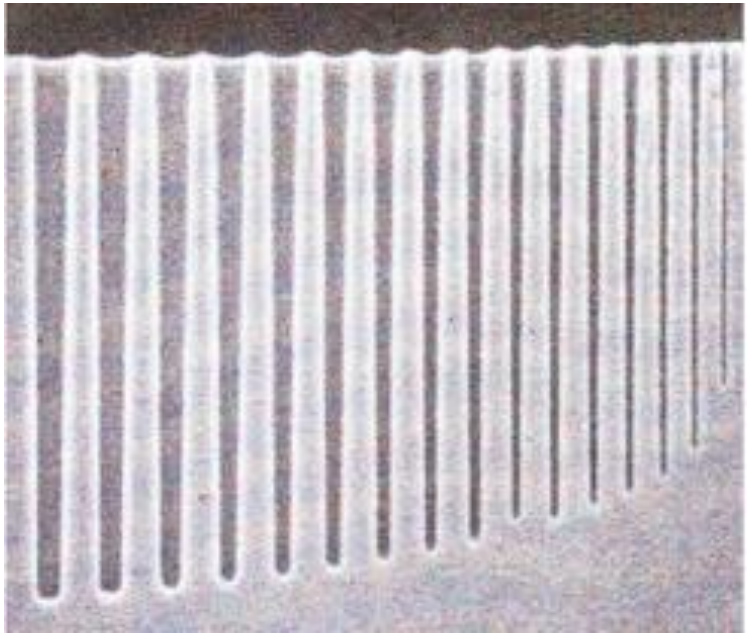
Aspect Ratio = Depth / Width

Primary ARDE Mechanisms

- Classical-ARDE: Higher aspect ratio features generally etch slower than smaller aspect ratio features

- Four primary mechanisms used to explain ARDE:

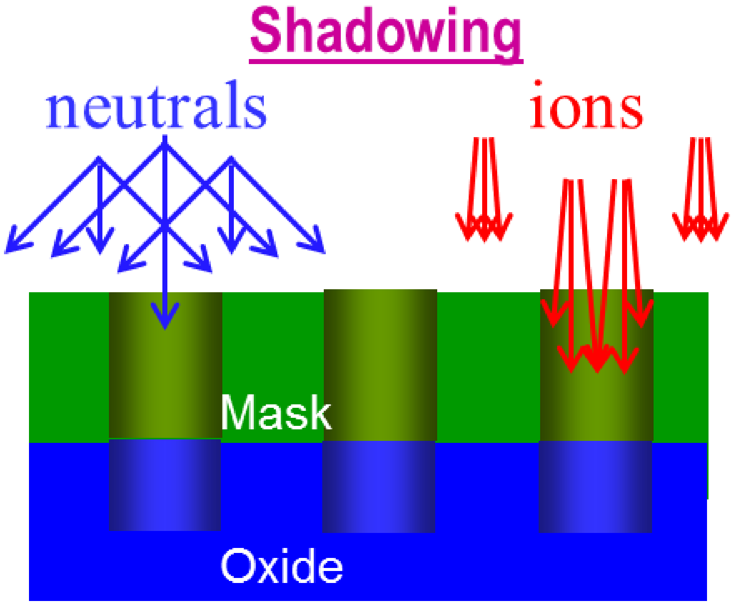
1. Neutral shadowing
2. Ion shadowing
3. Differential charging
4. Knudsen transport



ARDE Mechanisms: Neutral Shadowing

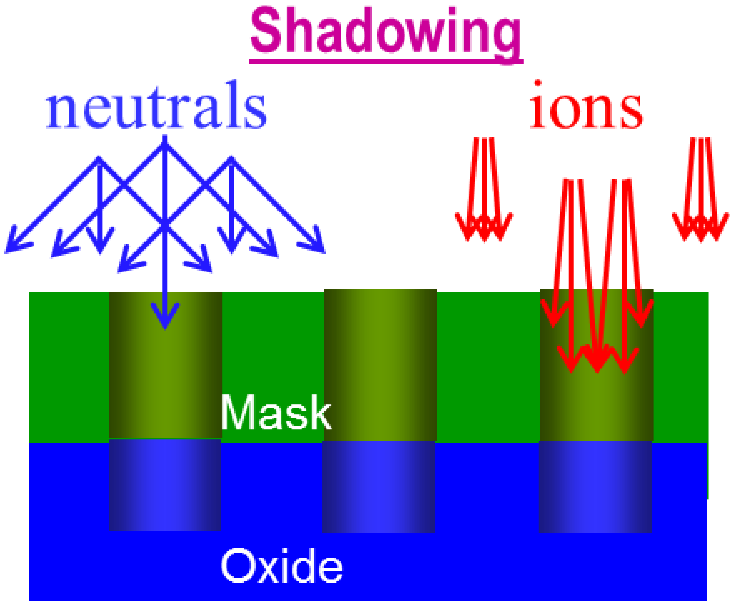
- The neutral angular distribution is isotropic

- Neutrals incident at a large angle to the normal will hit the top or sidewall of the feature, and can be lost (e.g., recombination) before reaching the bottom of the feature
  - They will be "shadowed" by the walls of the feature
  - Ion/neutral flux ratio is aspect ratio dependent due to different angular distributions
  - High aspect ratio features may become "starved" for neutrals (ER slows down in HAR feature)



ARDE Mechanisms: Ion Shadowing

- The ion angular distribution is generally anisotropic
- Higher pressures can cause ion scattering in the sheath, causing spread in ion energies/angular distributions
- Ions incident at larger angles to the normal hit the top or sidewall of the feature, but not the bottom (*i.e, they are shadowed*)
- Similar to neutral shadowing, ion shadowing shifts the ion/neutral flux ratio in different AR features

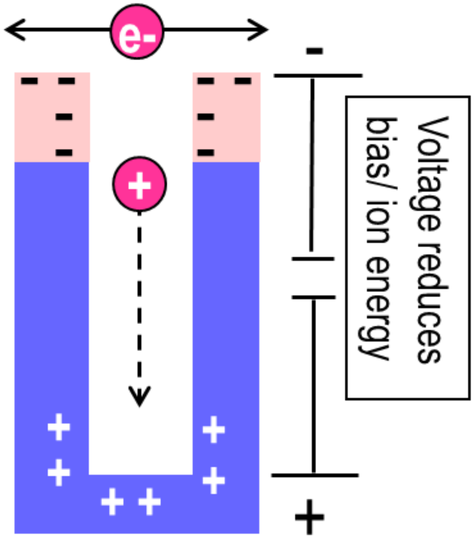


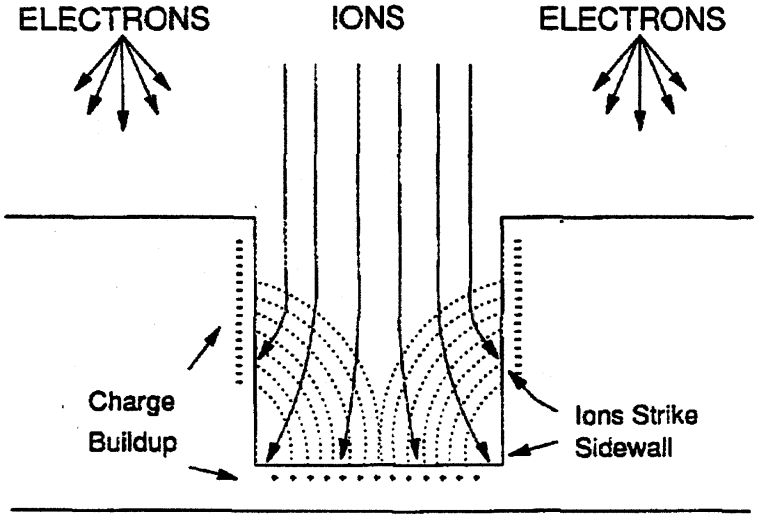
ARDE Mechanisms: Differential Charging

- Electron flux to the wafer periodically occurs as the sheath oscillates, and has a much less anisotropic angular distribution

- Differential charging can result in potentials large enough to deflect ions (alters flux to feature bottom)

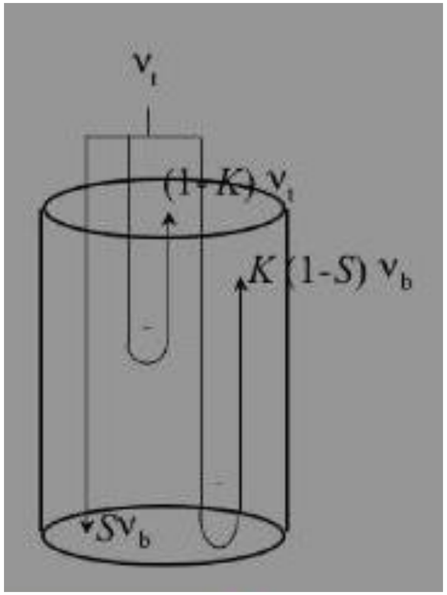
- Others have reported ion energy drops of ~30% for AR ~ 3



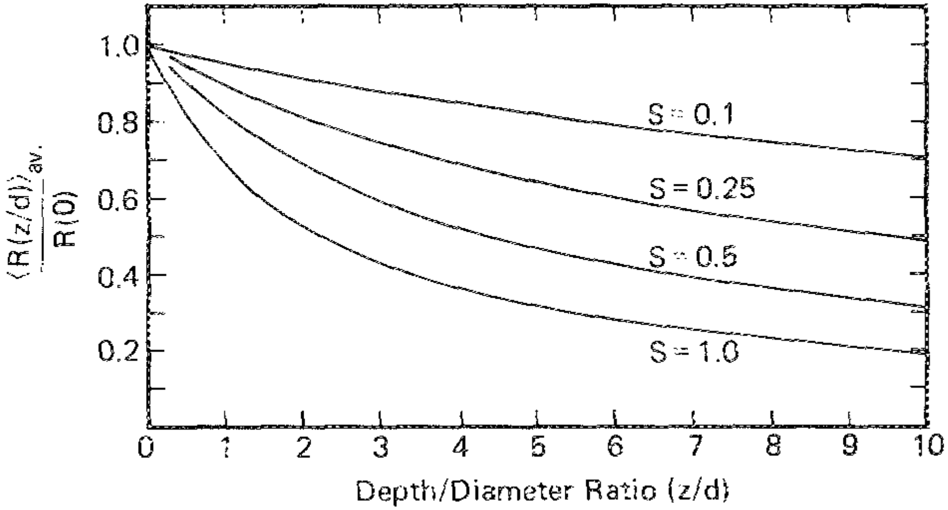


ARDE Mechanisms: Knudsen transport

- **Knudsen transport -** Neutral reactants travel to the bottom of the feature by being reflected diffusively from the sidewalls without reacting
- From Coburn & Winters, APL, (1989)
  - $J_bS_b = J_t - (1-\kappa)J_t - \kappa(1-S_b)J_b$ *(describes gas fluxes into and out of feature)*
    - J_b, J_t = flux to the bottom or top of feature
    - S_b = reaction probability at the bottom of the feature
    - κ = transmission probability (decreases with increasing aspect ratio)

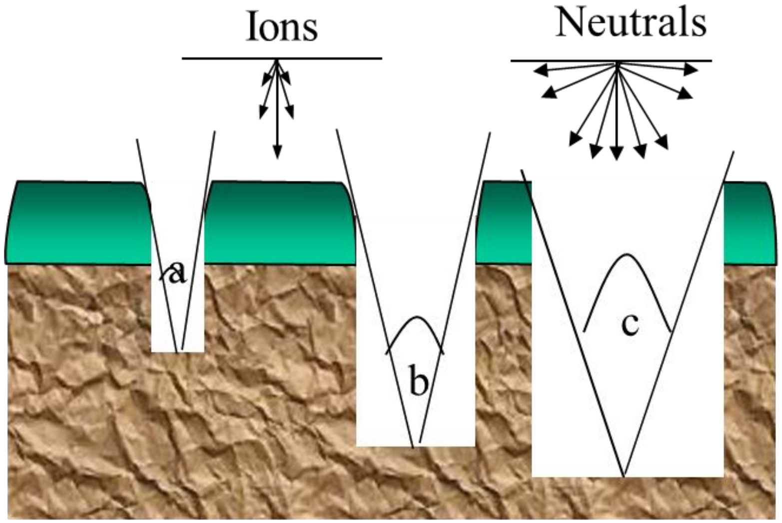


Etch Rate Ratio (bottom/top) vs Aspect Ratio

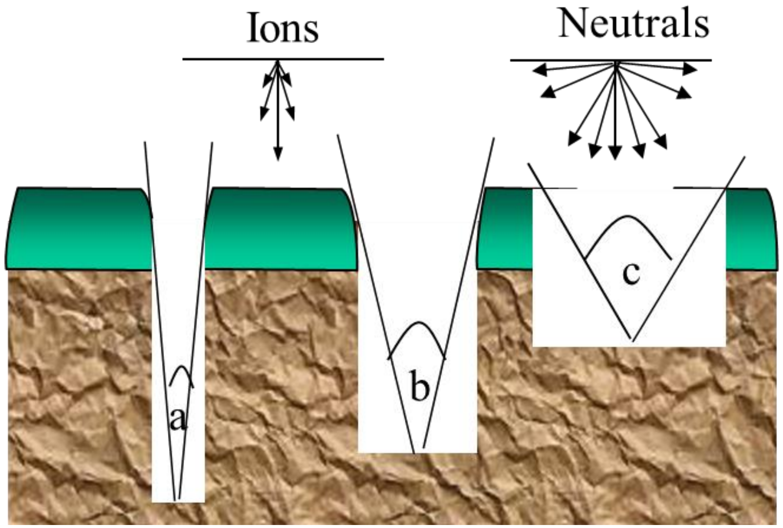


What about Inverse-ARDE (or Reverse-RIE Lag)?

Classical ARDE

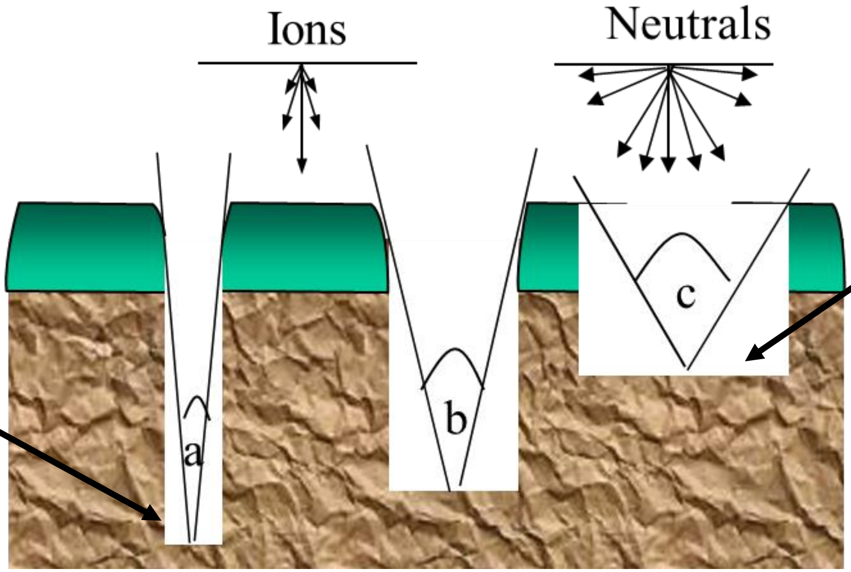


Inverse ARDE



Inverse-ARDE (or Reverse-RIE Lag)

- **Mechanism → Polymer-precursor shadowing**
  - Less polymer forms in high aspect ratio feature, thus higher etch rate



Shadowing gives less polymer deposition here

More polymer deposition here

How do we fix ARDE??

- **Multiple mechanisms can lead to ARDE in plasma etching**
  - Neutral shadowing
  - Ion shadowing
  - Differential charging
  - Knudsen transport

- **Solution to ARDE issues can depend on which mechanism(s) is/are responsible**

- **In previous dielectric etch study, we observed that <u>differential charging</u> was a <u>primary mechanism</u> for <u>classical ARDE</u>**
  - To mitigate, low pressures improve (as long as not too low → neutral limited)
  - Higher RF powers (higher ion energies) improve
  - Balancing the etchant/deposition flux can also compensate (gas chemistry, gas ratios)
  - RF pulsing/atomic layer etching improves

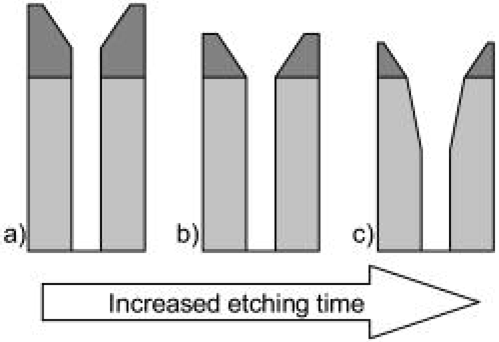
- **<u>Inverse-ARDE</u> is related to <u>shadowing of polymer precursors</u> in narrow features**
  - Shift etch chemistry to less polymerizing condition (increase F/C ratio, add O_2, etc)

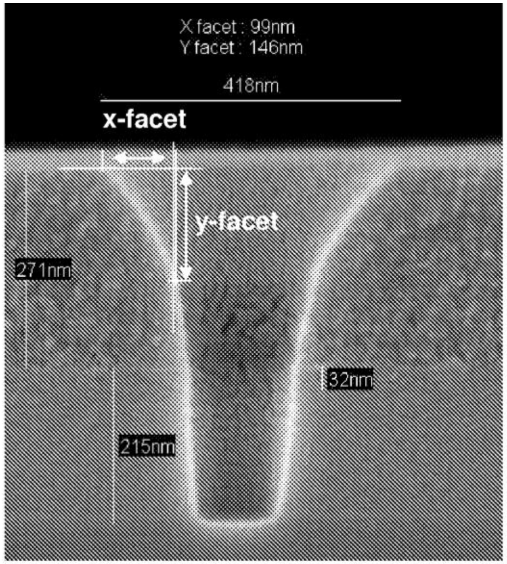
Other issues: Faceting and Necking

Strasser, JVSTB, 2007
Lee, JECS, 2010

▸ Faceting

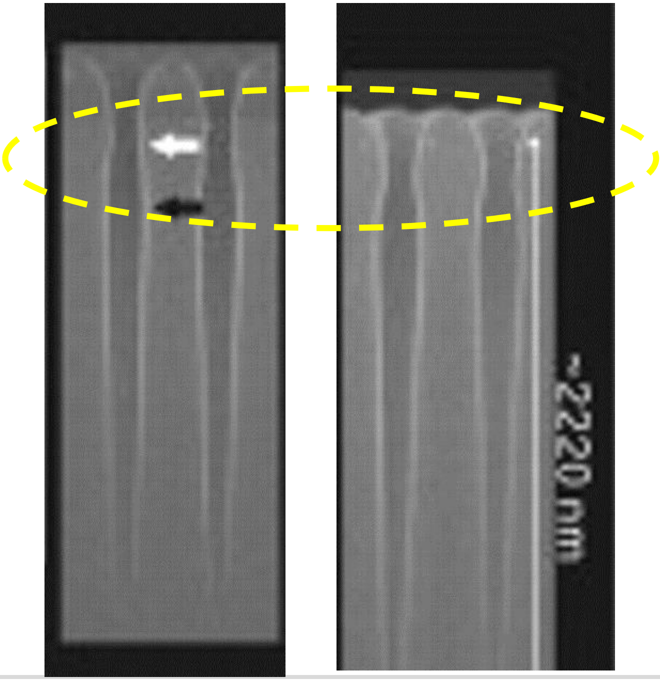
- Generally due to increased yield per ion at a corner (Dependent on ion energy/flux)





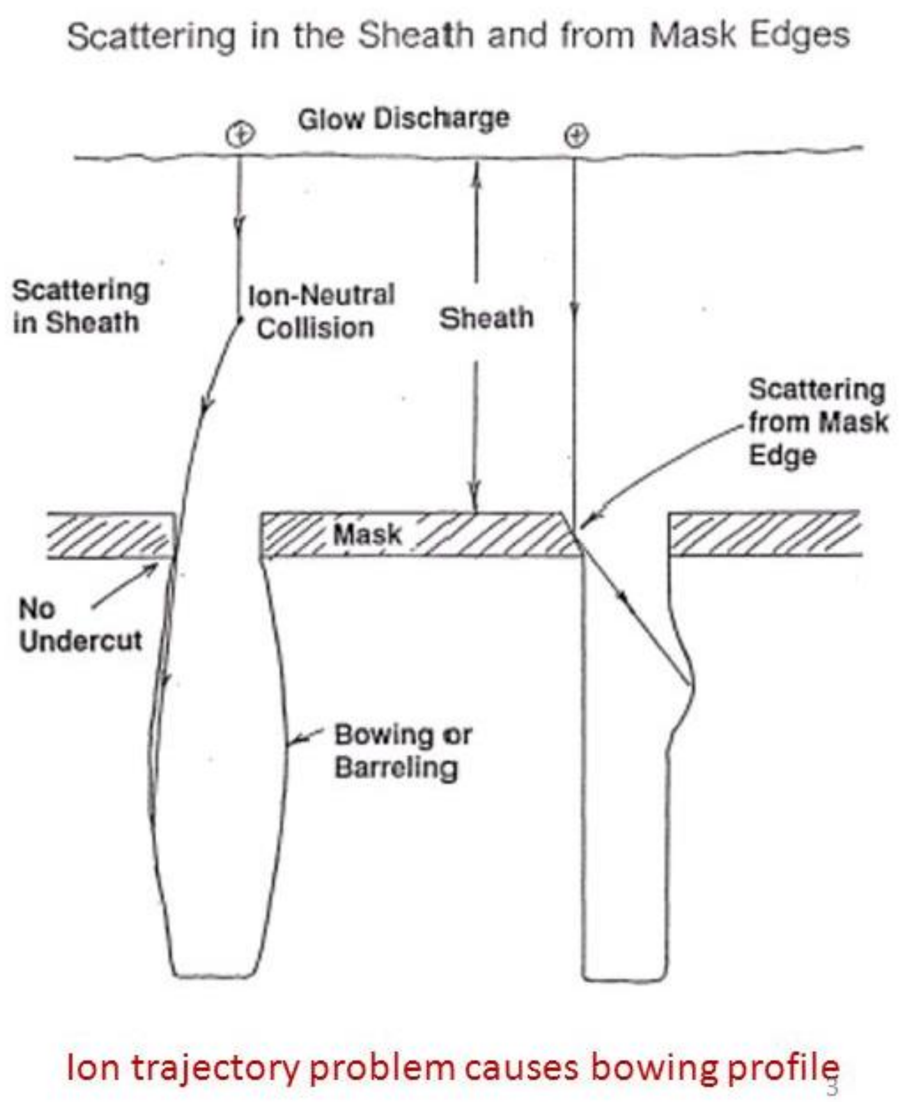
▸ Necking

- Can be due to heavy polymer deposition at the top of the contact or from re-deposition of polymer precursors, forward scattered from photoresist
- Position of neck may be dependent on the angle in the resist



Bowing

- **Bowing of the feature sidewall can have several root causes**
  - Ion scattering from the resist mask (dependent on facet angle)
  - Ion scattering in the sheath (lower pressure may help)
  - Too much oxygen in the process (less sidewall polymer protection, leads to more isotropic etch)
  - Exacerbated by polymers that deposit well at the top of features, but deposit poorly deeper down the feature



Scattering in the Sheath and from Mask Edges

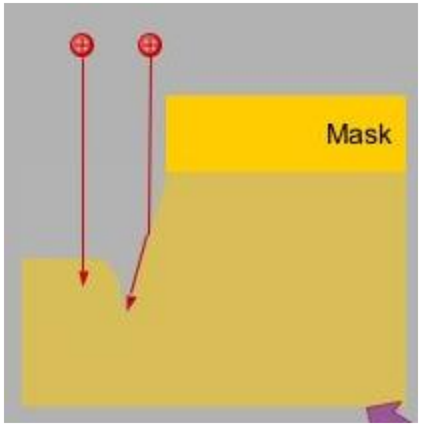
Ion trajectory problem causes bowing profile

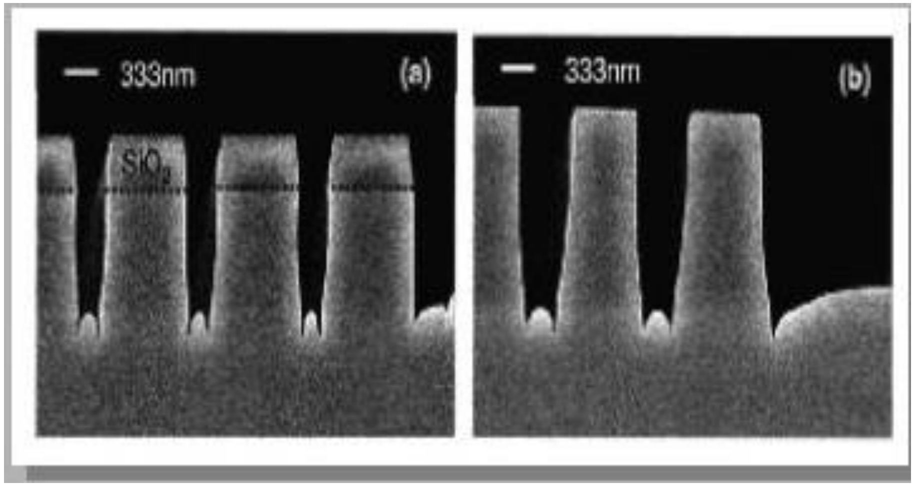
Microtrenching

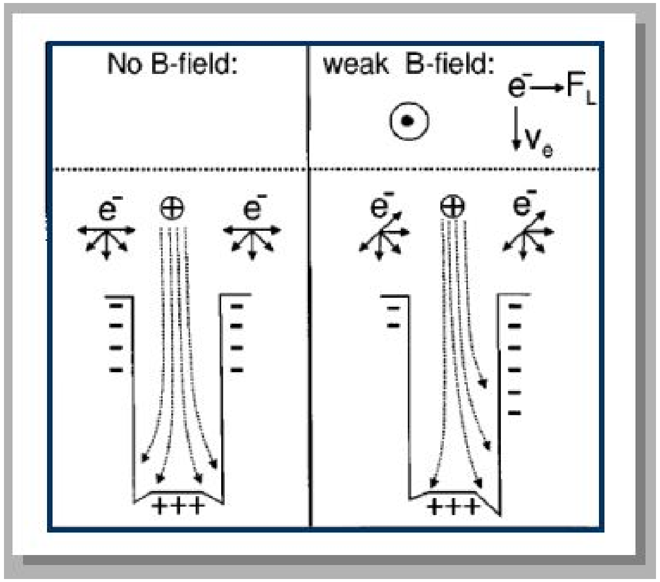
Clarycon
Schaepkens, APL, (1998)
Bogart, JVSTA, (2000)

- **Microtrenching - Localized higher etch rate at bottom corners of trench**

- **Potential Mechanisms**
  1. Ion scattering from sloped trench sidewalls
  2. Ion deflection due to differential charging of microstructures

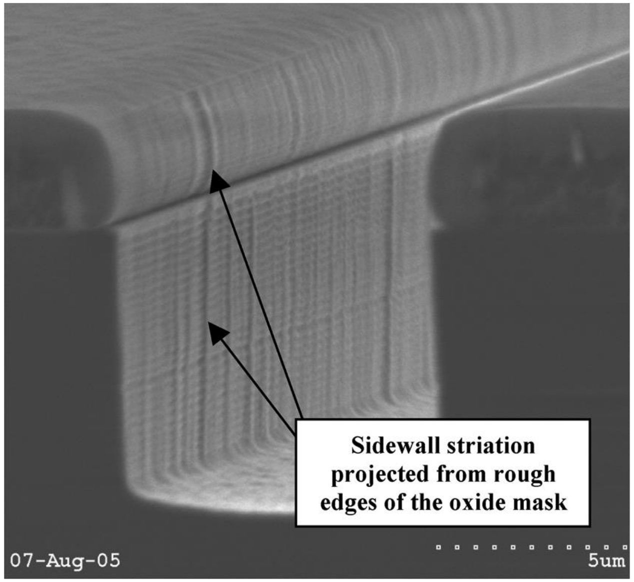




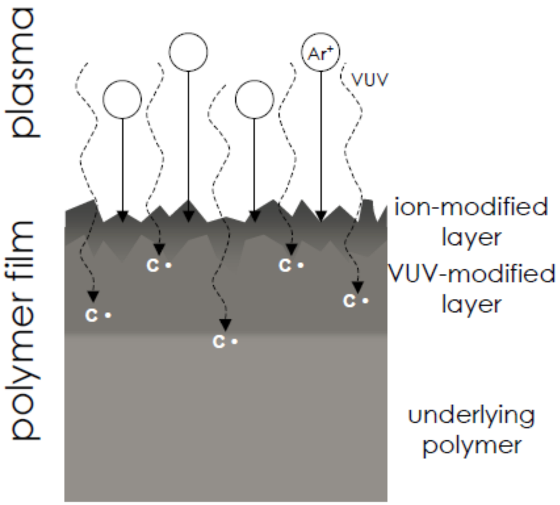


Striations

- Extended roughness on the sidewalls of etched features
  - Seen on both holes and trenches
- Due to roughness/striation formation in the resist being transferred to underlayers
- Exacerbated with 193nm resists
- Likely related to how plasma modifies the resists at different length scales
  - Ions impact ~2nm of surface, causing graphitic-densified region
  - VUV radiation may either chain scission or cross-link at deeper depths (~100nm)
  - Different mechanical properties of modified layers can lead to resist buckling or roughening

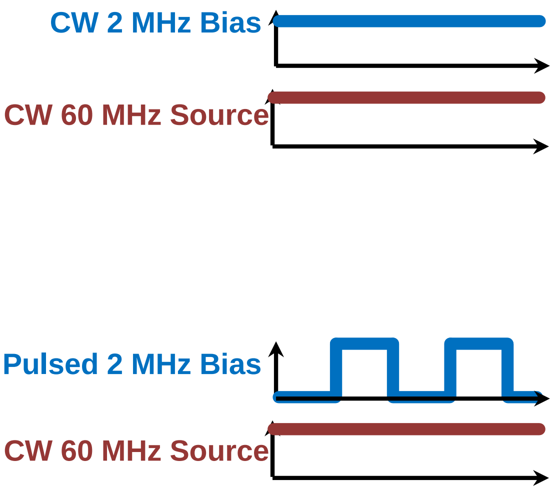


Sidewall striation projected from rough edges of the oxide mask



Advanced Etch Strategies

RF Pulsing Can Lower Ratio of High:Low Ion Energy Flux

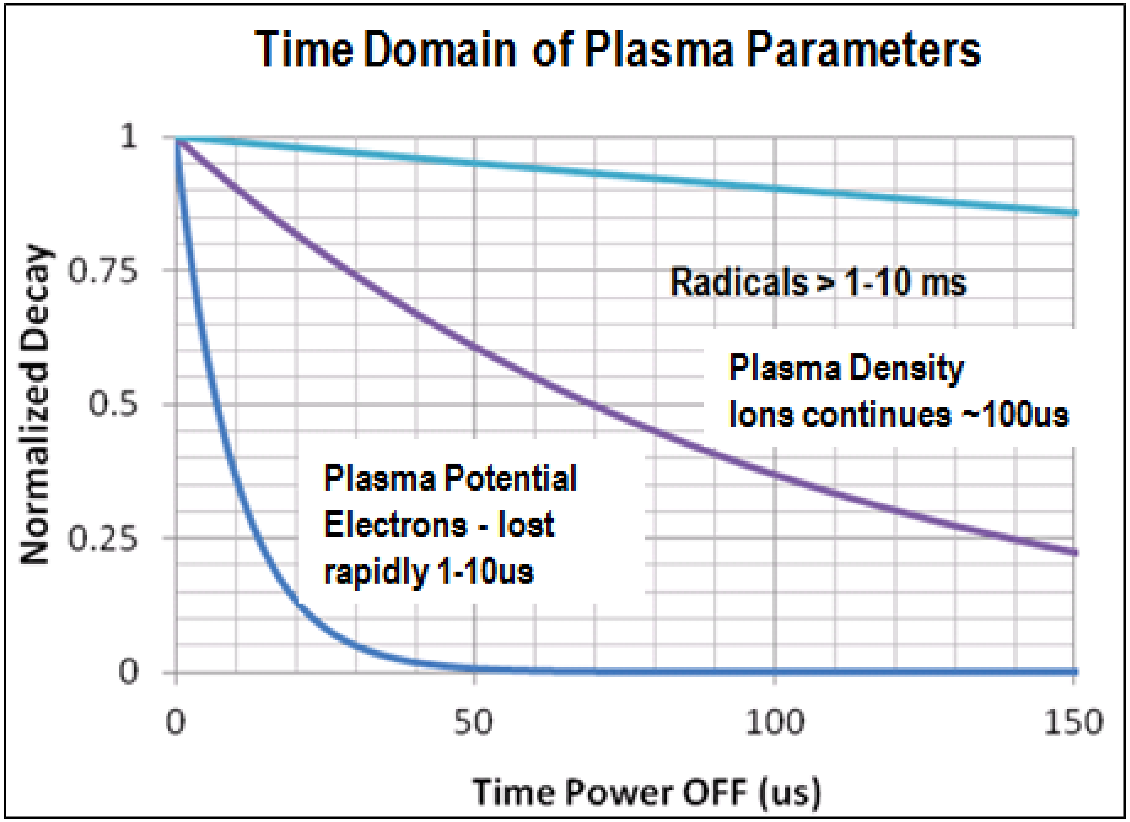


- Pulsing reduces the ratio of high to low energy ions (constant *peak* power)
  - $[\Gamma_{hi}/\Gamma_{lo}]_{pulsed} < [\Gamma_{hi}/\Gamma_{lo}]_{cw}$

- RF pulsing can be used to access energy distributions not available in continuous operation

RF pulsing can access new process regimes to break existing tradeoffs

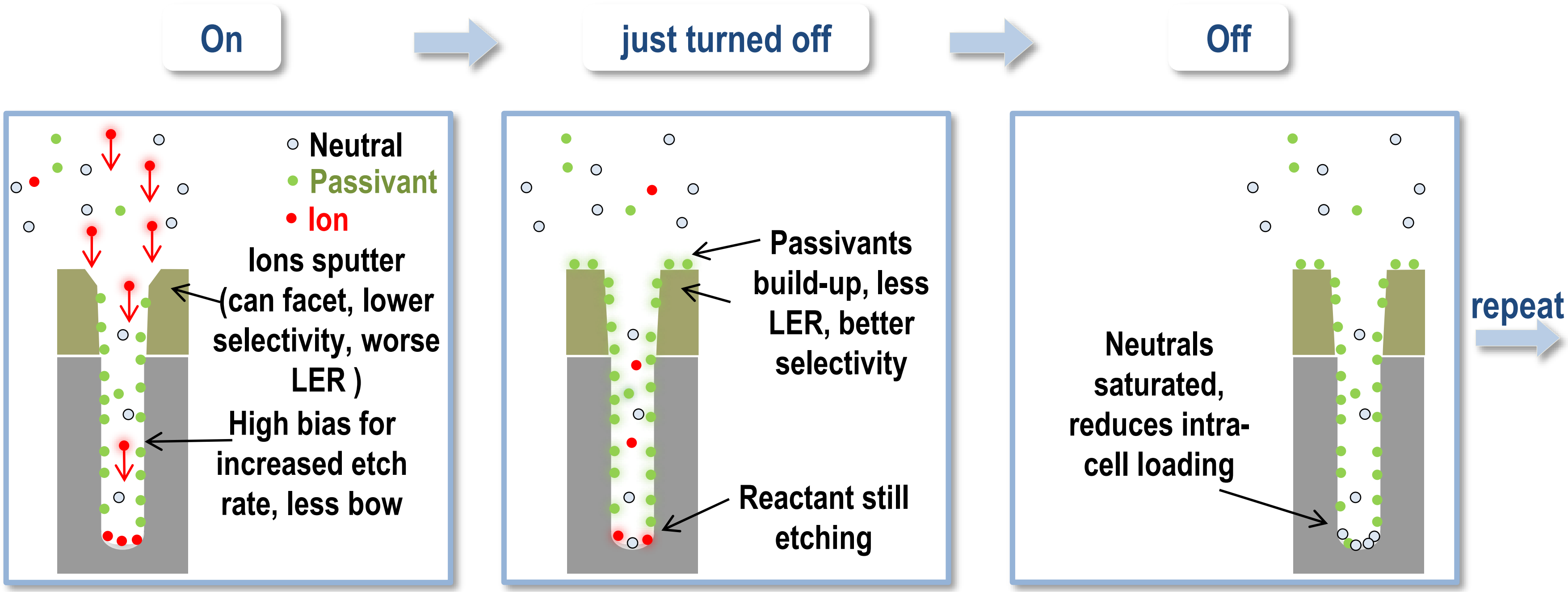
RF Pulsing Controls Neutral:Ion Flux



Different decay time constants allows to vary Ion/Neutral flux over larger range

Pulsing improves selectivity and controls ARDE

Bias pulsing can improve line edge roughness



On → just turned off → Off

○ Neutral

● Passivant

● Ion

Ions sputter (can facet, lower selectivity, worse LER)

High bias for increased etch rate, less bow

Passivants build-up, less LER, better selectivity

Reactant still etching

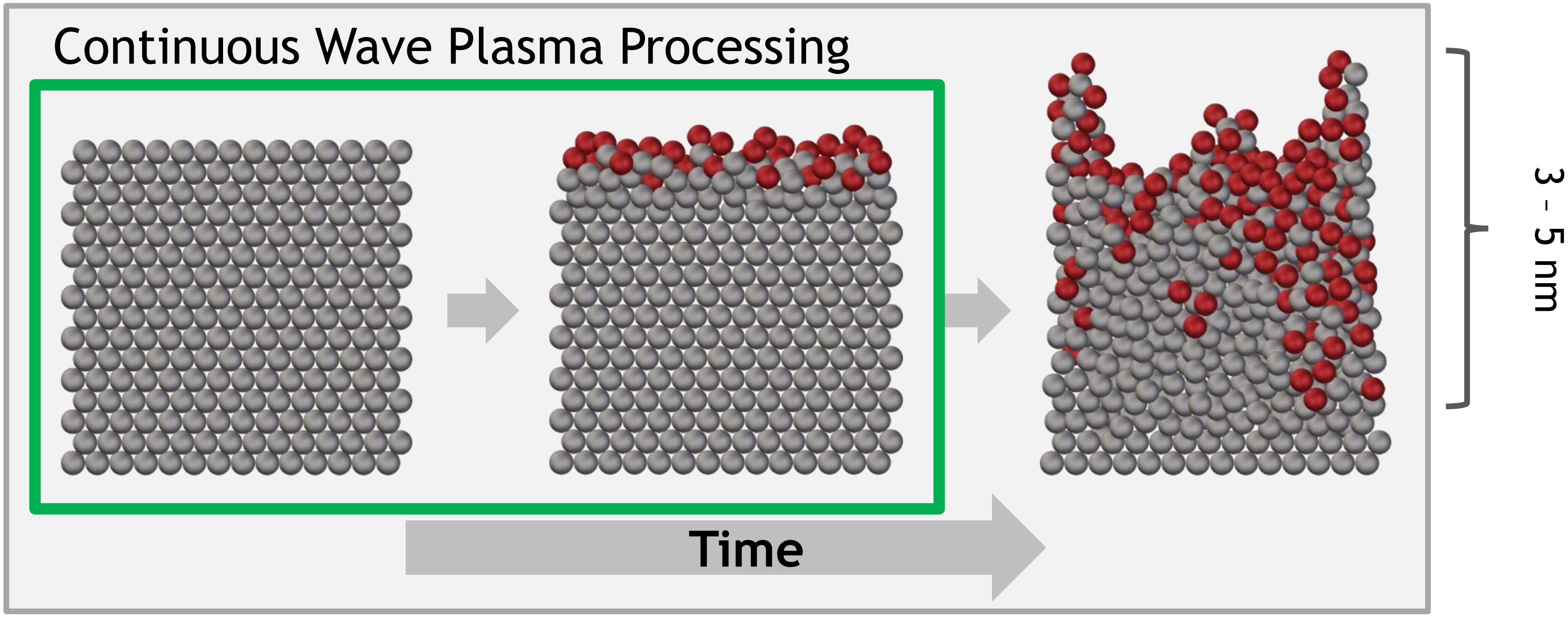
Neutrals saturated, reduces intra-cell loading

repeat

3x Improvement on LER observed

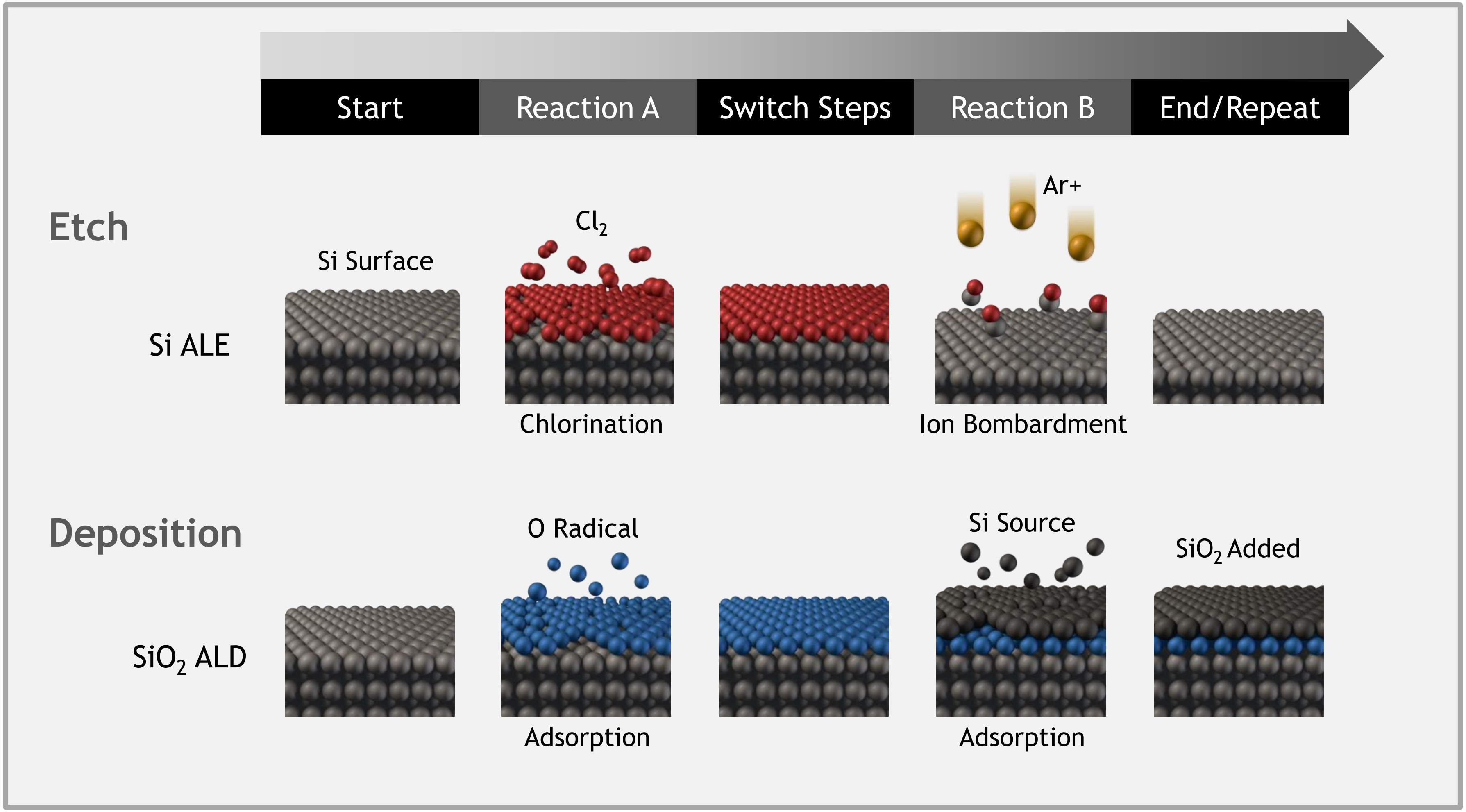
Atomic Layer Etching

How can we achieve a more precise etch??



- **At the atomic scale, continuous plasmas "surface precision" degrades as we etch for longer times**
  - Ions are damaging surface
  - Mixing occurring in the reaction layer (~3 – 5 nm thick)

Directional “Atomic Layer” Processing: The *Penultimate* Means of Reducing Variability



Start | Reaction A | Switch Steps | Reaction B | End/Repeat

Etch

Si ALE

Si Surface

Cl_2

Chlorination

Ar+

Ion Bombardment

Deposition

SiO_2 ALD

O Radical

Adsorption

Si Source

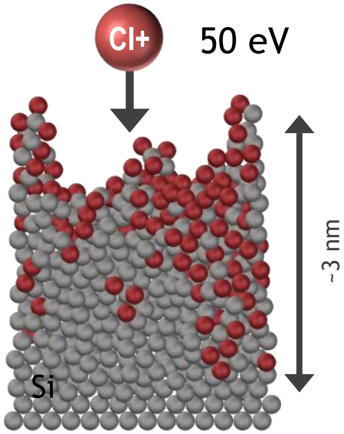
Adsorption

SiO_2 Added

- ▸ **Use separate, self-limiting steps for atomic layer removal**

Avoid Use of Energetic Reactive Ions to Achieve "Atomic" Layer Precision

Efficient in breaking bonds, creating more mixing and disorder



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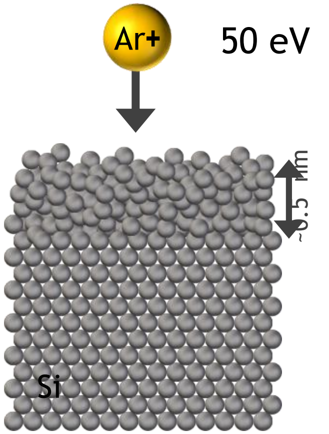
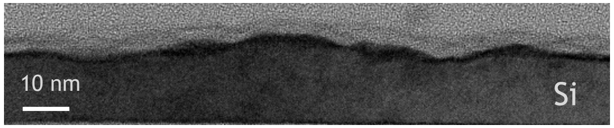


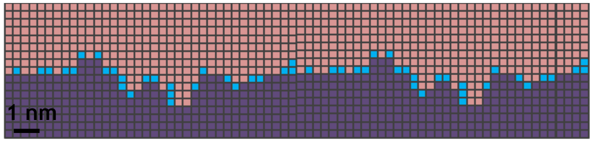
Inert ions create disordered regions near surface and also re-crystallize these regions

Source: Humbird and Graves, 2004

- Roughening effect, inhomogeneity
- Used in conventional etching:

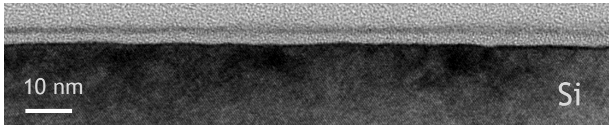


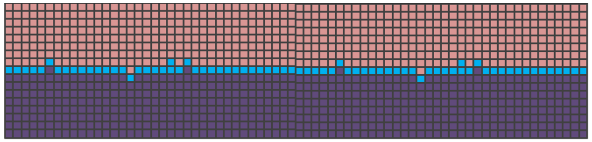
Source: Lam, 2010



Source: Agarwal & Kushner, 2007

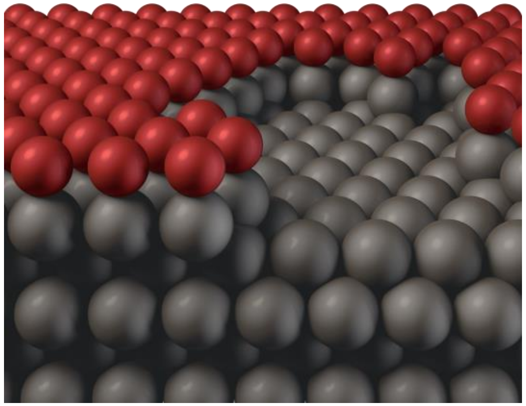
- Smoothing effect
- Used in directional ALE schemes:





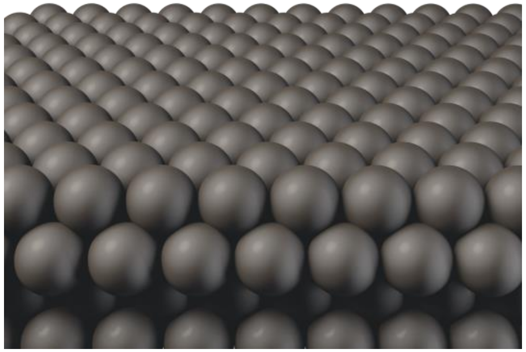
ALE Process Window

Ion Energy too low



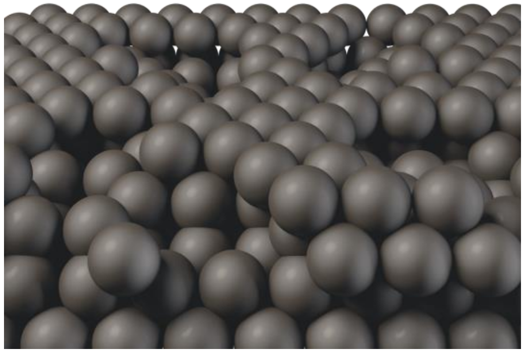
Incomplete Removal

Ideal Regime



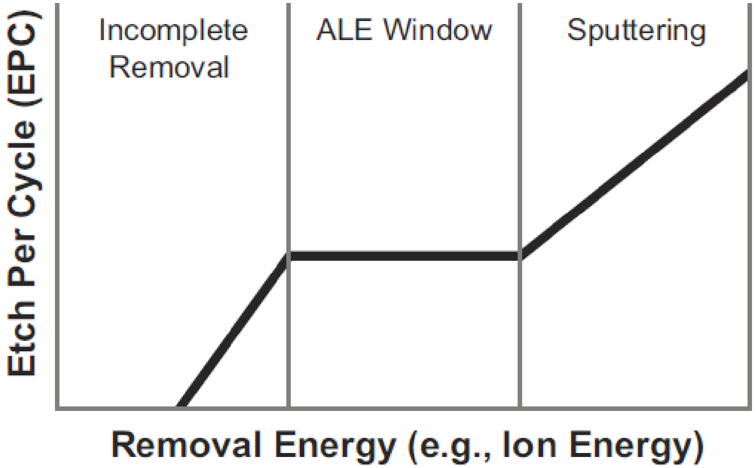
ALE Window

Excessive ion energy/bombardment

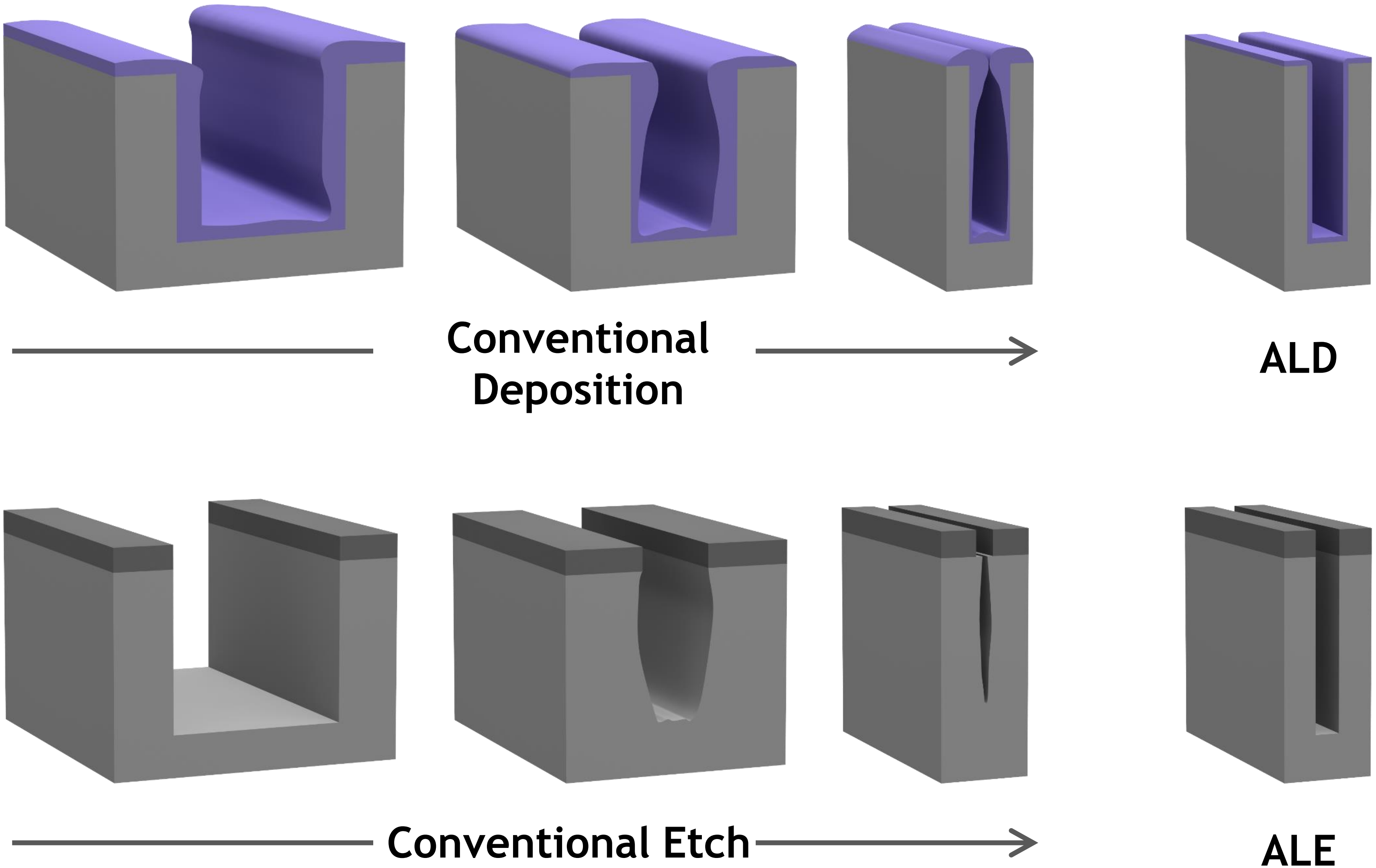


Sputtering

1. **Saturate the surface with reactant (without ion bombardment)**
2. **Bombard surface with ions at the proper ion energy, in the absence of excess reactant**



Profile benefits of using separated and self-limiting steps



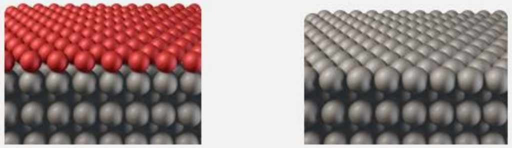
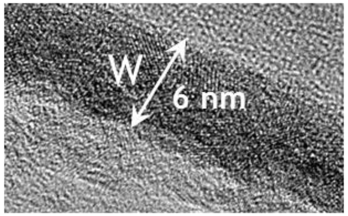
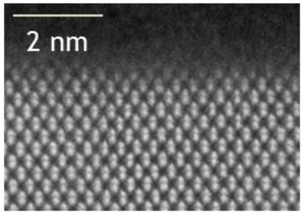
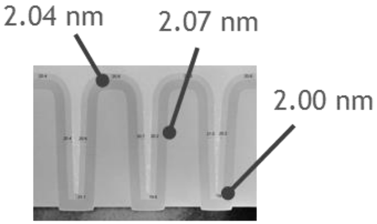
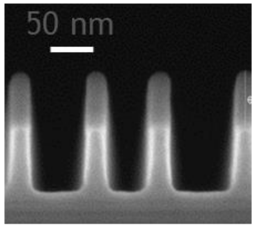
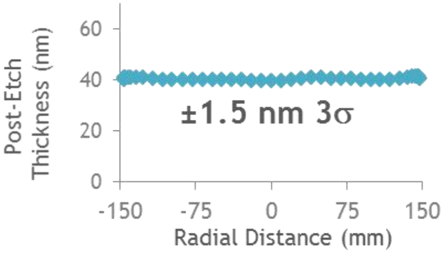
Conventional Deposition

ALD

Conventional Etch

ALE

Other benefits from separated and self-limiting steps

	Mechanism	Example Benefits - ALD	Example Benefits - ALE
Surface	Smooth 	 	
Feature	Aspect ratio independence 	 	
Wafer	Uniform 	 ±0.15% range on 1,200 Å film	

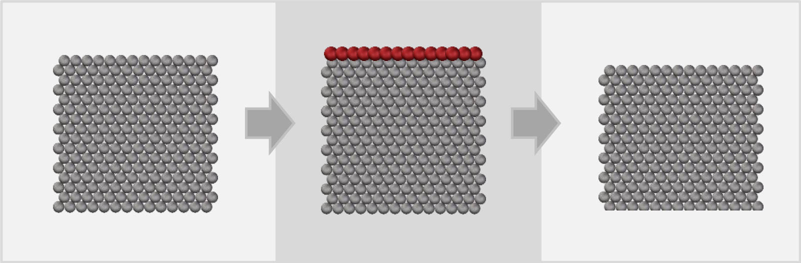
Atomic layer etch process Limitations

"But I am not afraid to consider the final question as to whether, ultimately---in the great future---we can arrange the atoms the way we want; the very atoms, all the way down!
-Richard P. Feynman, Dec 29th 1959 at the annual meeting of American Physical Society

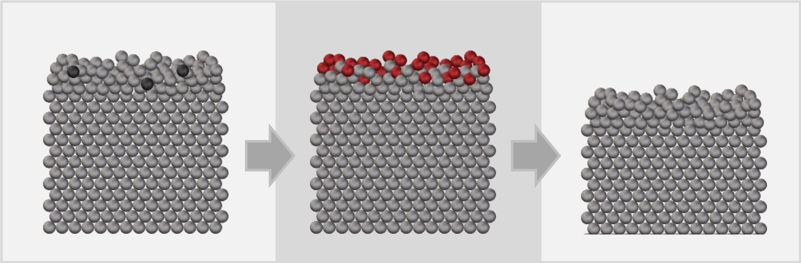
▸ Limitations from the process:

- Photon-induced etching and damage
- Ion-induced mixing and damage even with inert ions at low energies
- Steric hindrance preventing fully saturated coverage
- Adsorbed reactants on chamber walls compromise separation of dosing and activation steps
- Trade-off between atomic layer processing benefits and throughput

***ALD/ALE:** Feynman's dream…*



***ALD/ALE:** Penultimate reality*

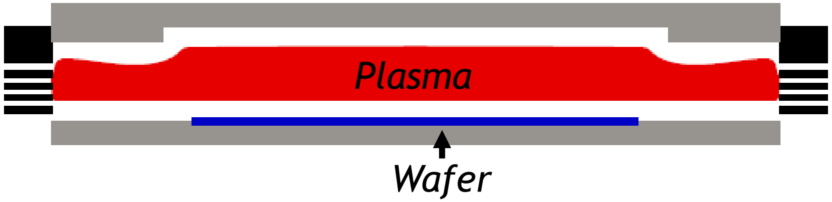


Etch Uniformity Control

Etch uniformity control

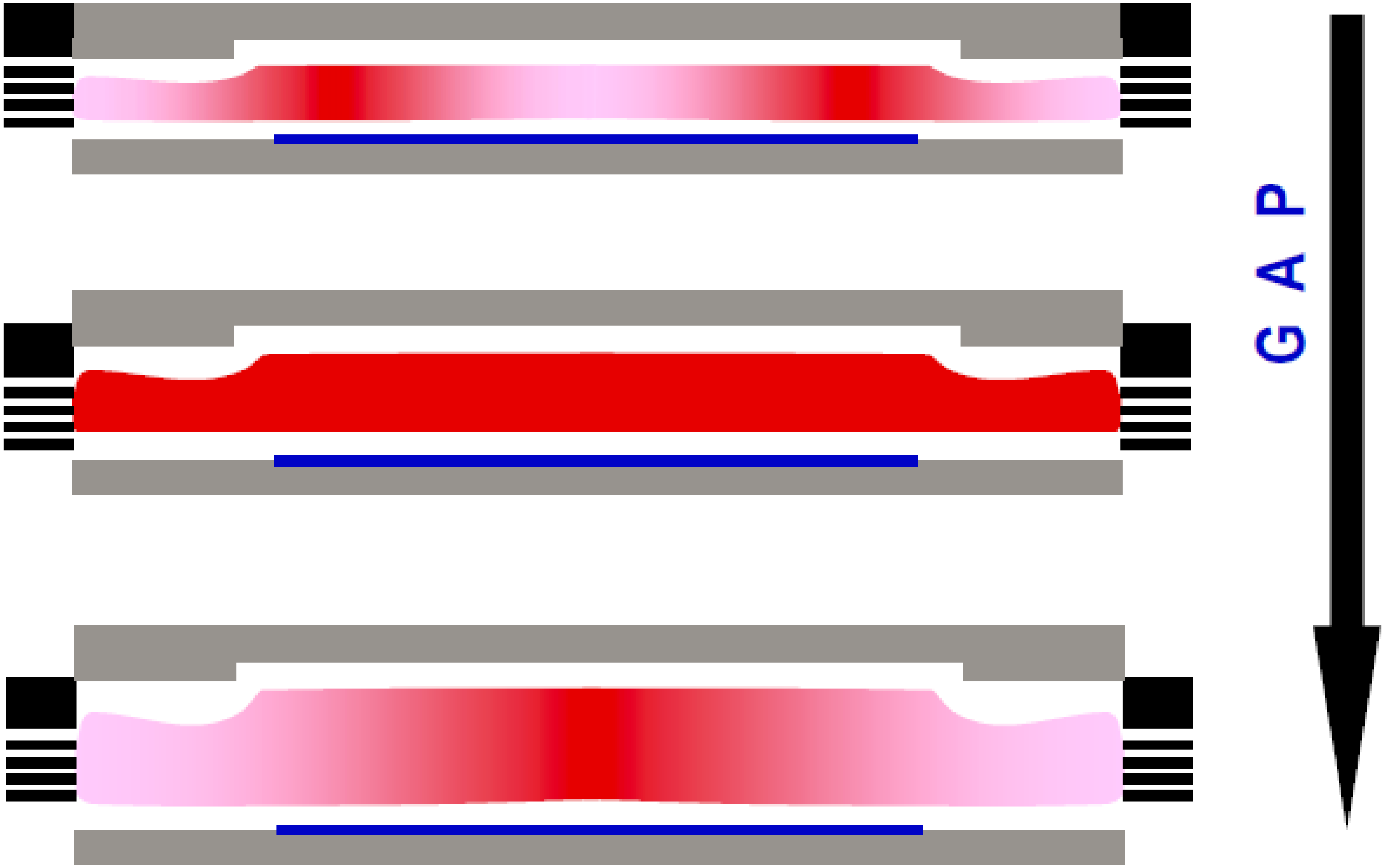
- Leading edge wafer fabrication processes require very tight uniformity control across the wafer (Out to <3mm from the edge of the wafer; Require specs ~ $\leq$1 nm 3-sigma)
  - Uniformity in etch depths
  - Uniformity in critical dimensions

- Center-to-edge uniformity in plasma processes are difficult due to discontinuities that occur at the wafer edge
  - Impact on local chemistry and ion flux
  - Temperature gradients



- Advanced etch tools use a variety of compensation strategies to achieve uniformity across the wafer

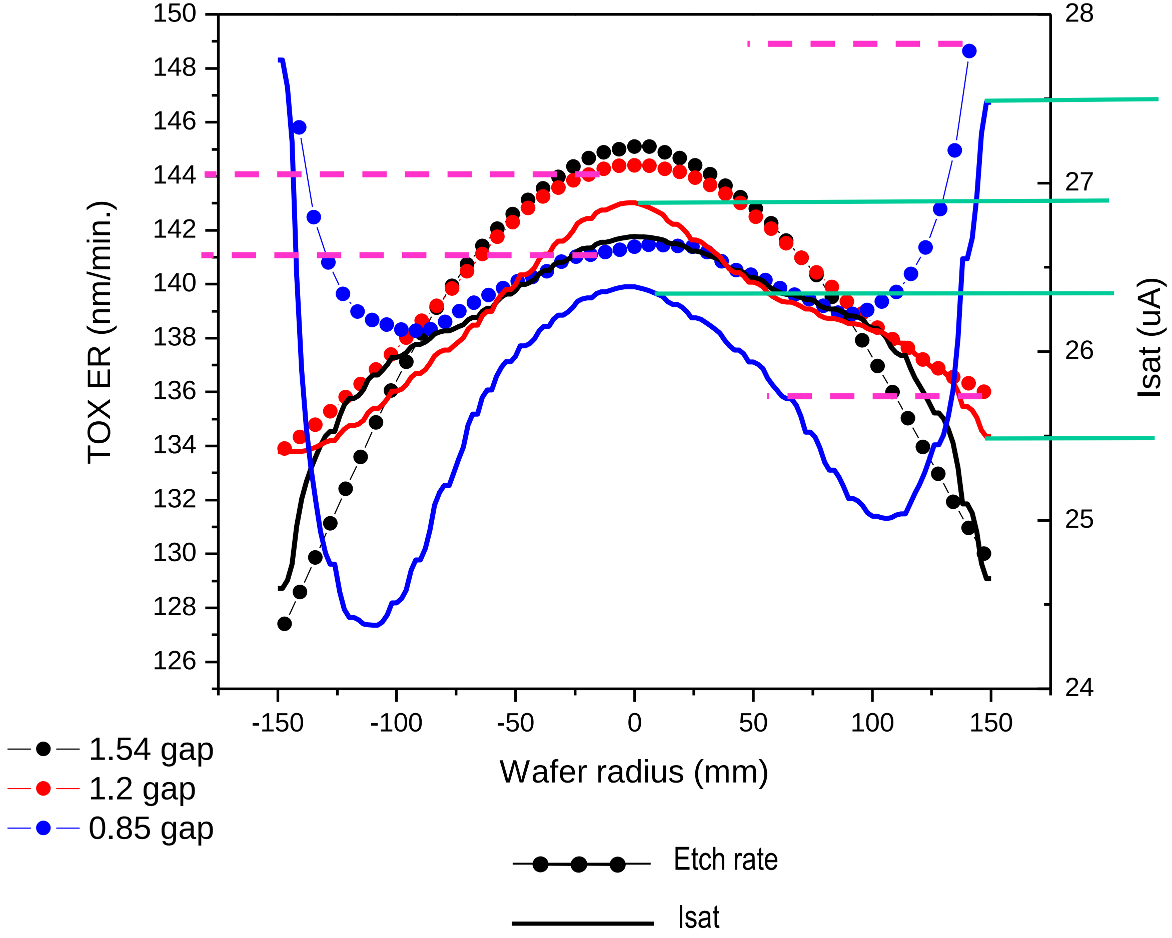
Adjusting the gap distance between upper and lower electrodes tunes the plasma uniformity across the wafer



For ion-limited etch regimes, etch rates can be flipped from center-fast to edge-fast by changing gap distance

Pilot™ wafer measurement results

– Ar/CF4 process



At wafer center

Etch rate changes by ~2.1%

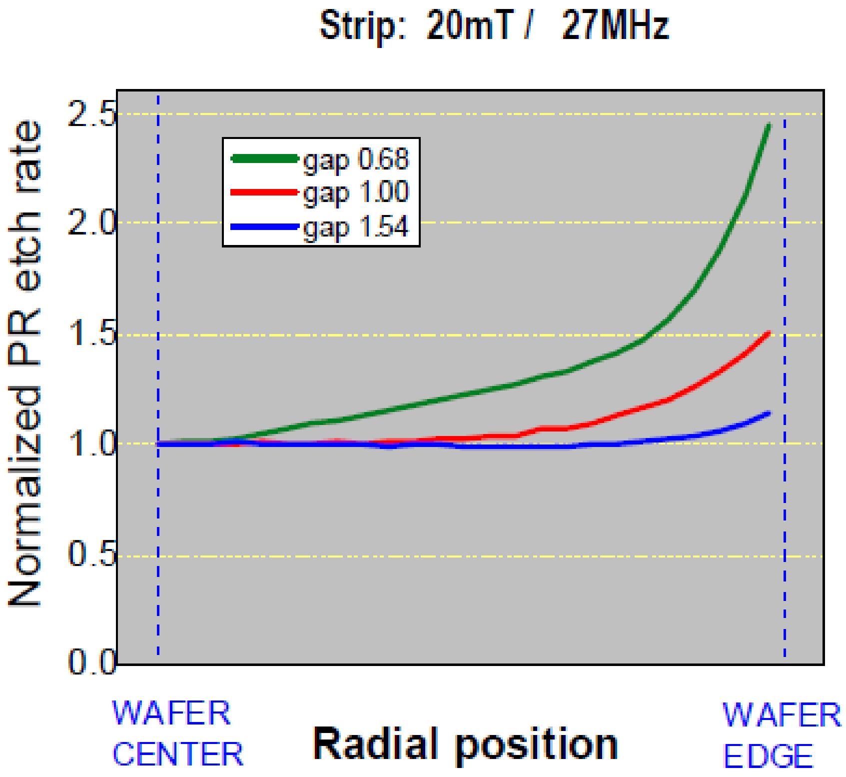
Ion flux changes by ~2.2%

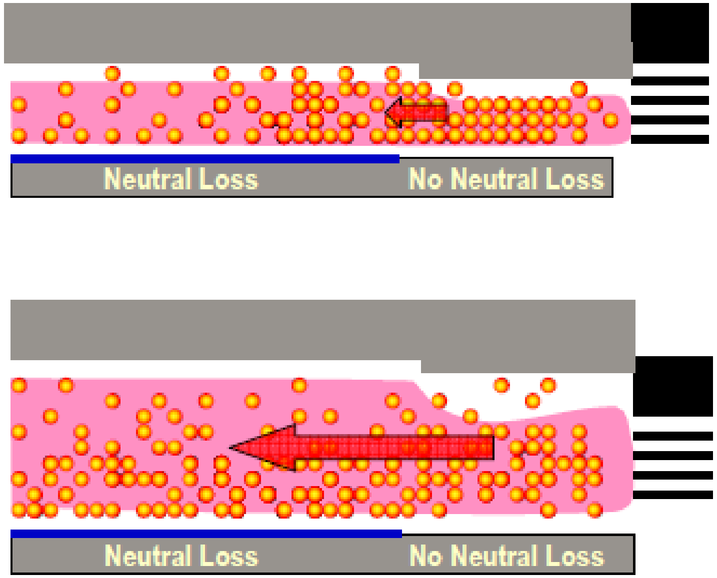
At wafer edge

Etch rate changes by ~-8%

Ion flux changes by ~-7%

Gap changes can also impact etch uniformity of neutral-limited processes



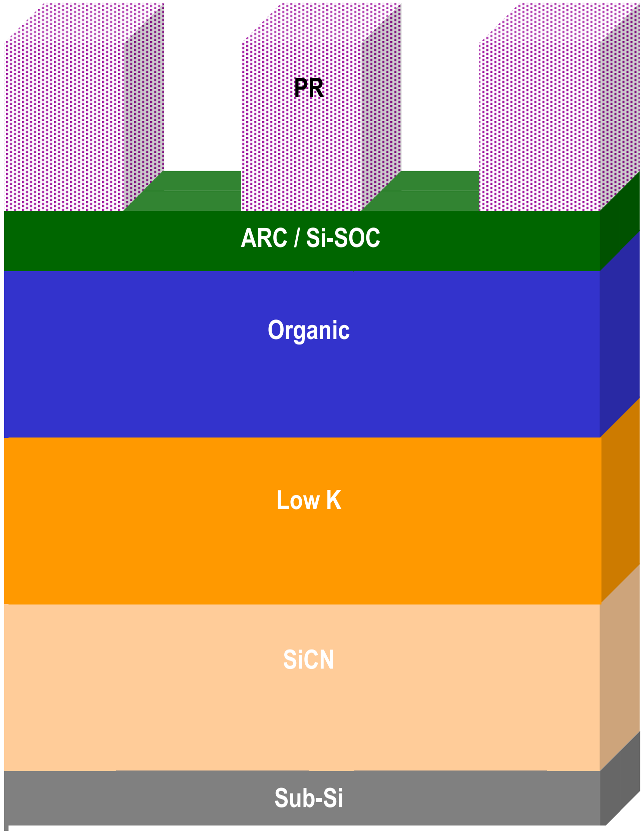


Low-pressure strip is neutral limited: etch rate depends on flux of etchant to surface

Narrower gap: etchant depleted over wafer, less depletion near edge due to diffusion

Wider gap: better radial diffusion of etchant and better uniformity across wafer

Effective Tuning Knobs for ER and CD Uniformity for *In situ* Mask + Dielectric Etching



Typical Operation Mode

High gap (>1.07)

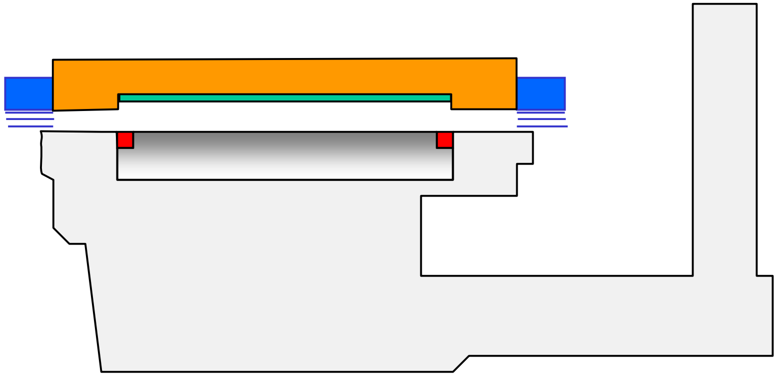
+ tuning gas

Low gap (0.85)

+ tuning gas

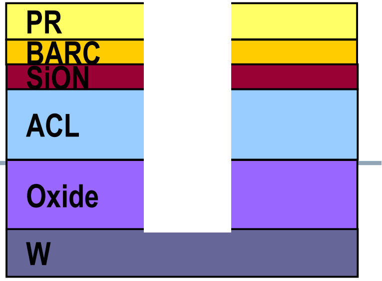
Medium gap (1.07)

+ tuning gas

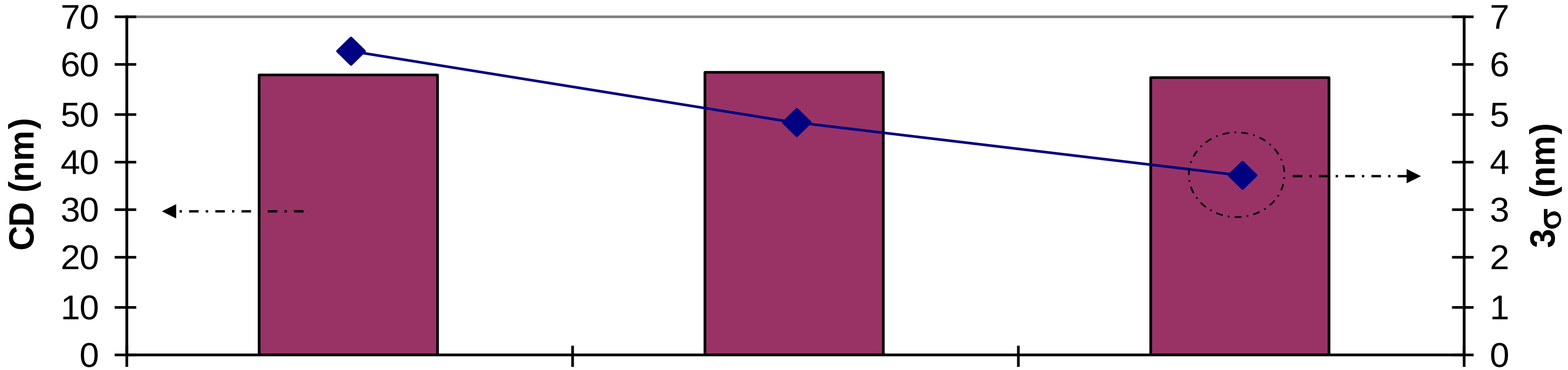


Enables all in one etching with optimized uniformity in each step

Case study: Effect of gap and tuning gas on CD uniformity for in-situ mask + dielectric etching



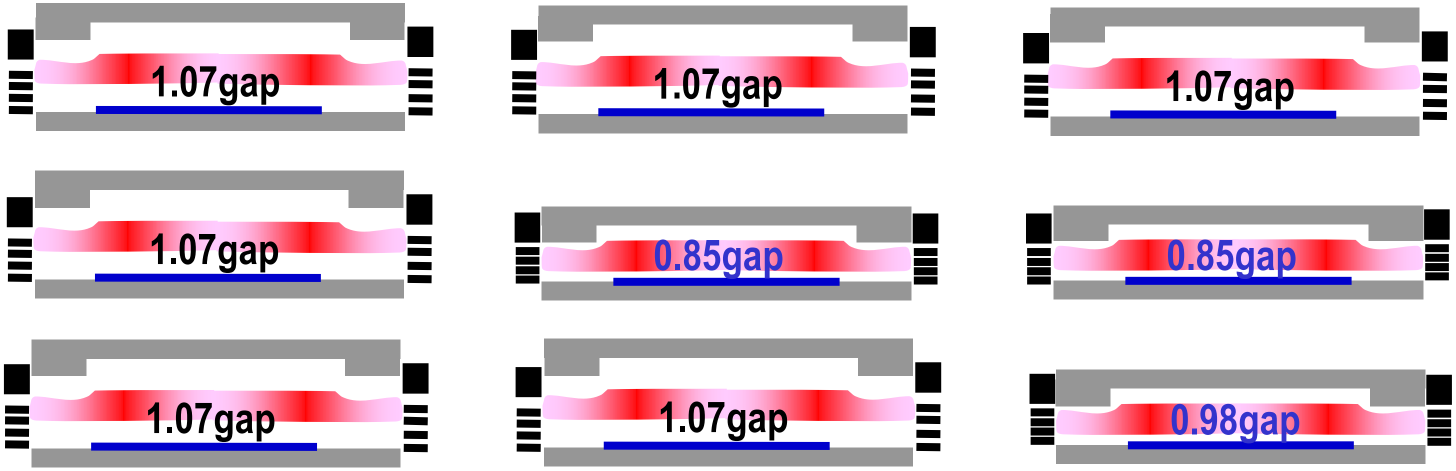
Example: **Line CD Uniformity Data on Patterned Wafers**



BARC

ACL

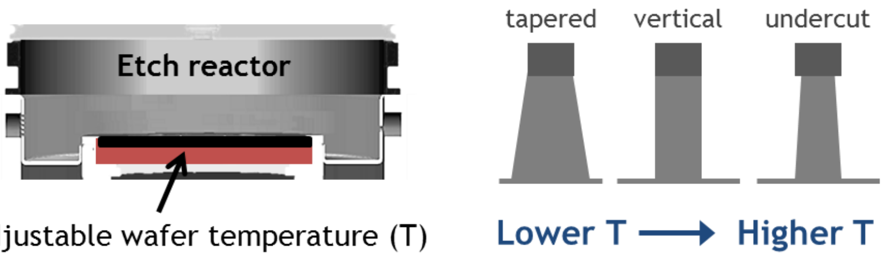
OXIDE



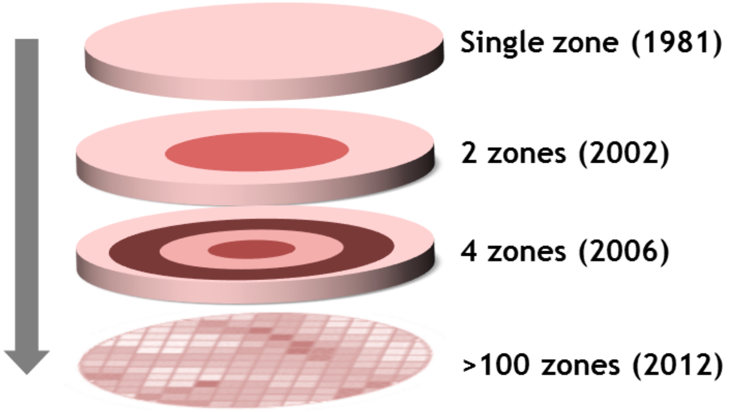
While maintaining the average CD values, uniformity is improved by optimizing the gap height for each step.

Increased temperature control across the wafer

Profile and CD can be tuned by adjusting wafer temperature:

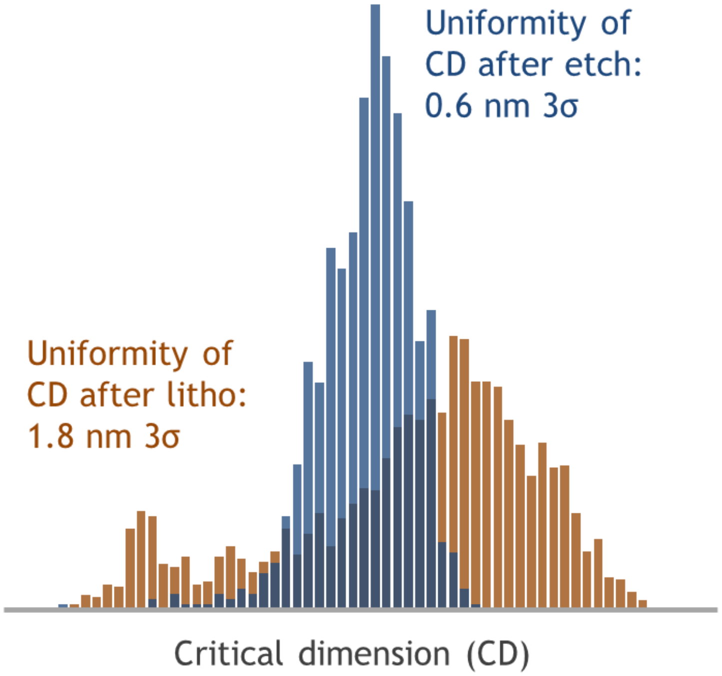


Driving increased spatial resolution for temperature tuning:

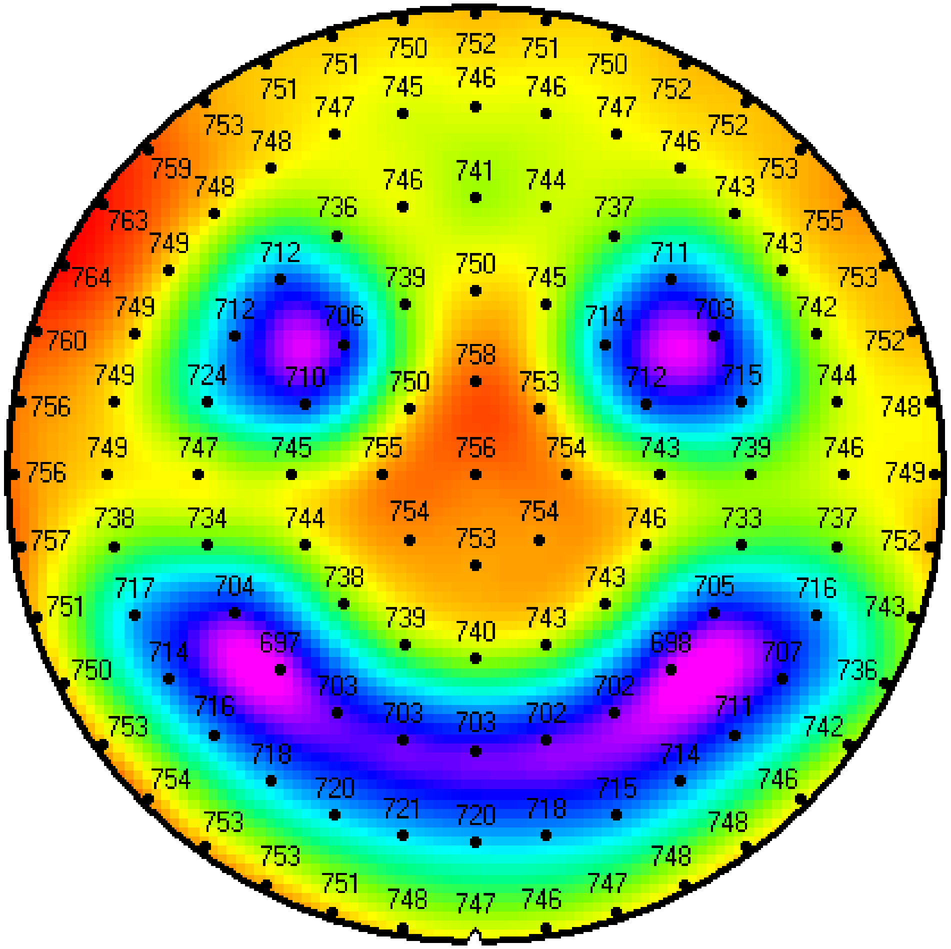


>70 patents/applications worldwide

Distribution of CDs before and after Etch:



Multi-zone electrostatic chuck (ESC) temperature control allows precise etch rate tuning



Plasma & Surface Diagnostics

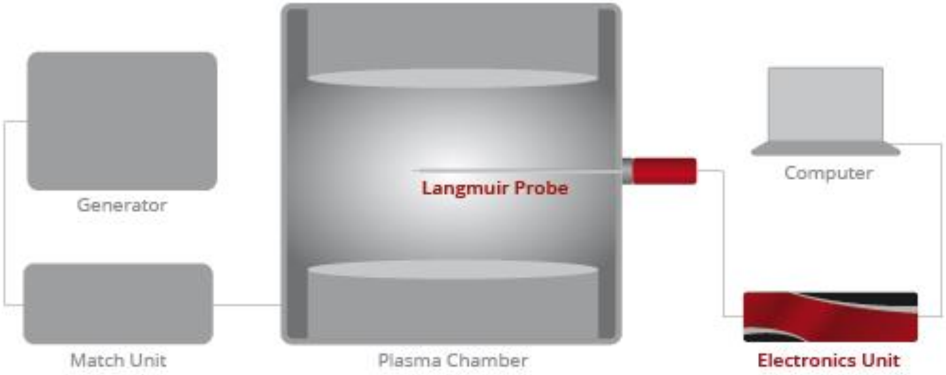
Plasma & Surface Diagnostics

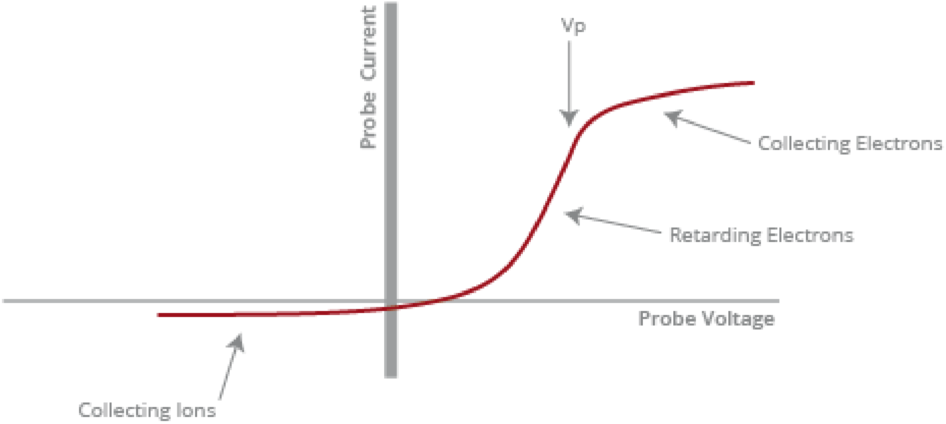
- **Because of the complexity of the chemical and physical environments in a plasma, a large array of techniques are required to characterize them**

- **Parameters that are of normal interest**
  - Electron and ion densities
  - Neutral densities (both species created in the plasma and byproducts of etch process)
  - Respective temperatures of these species
  - Energy distributions
  - Characterization of electric fields
  - Surface modification
  - Relative importance of different species within plasma

Plasma Diagnostics

- Langmuir Probe - Conducting wire placed in the plasma with a variable bias, V, applied. The current (I) is measured as a function of V.
  - What can you measure?
    - Floating potential
    - Plasma potential
    - Plasma density
    - Ion current density
    - EEDF/Electron temperature



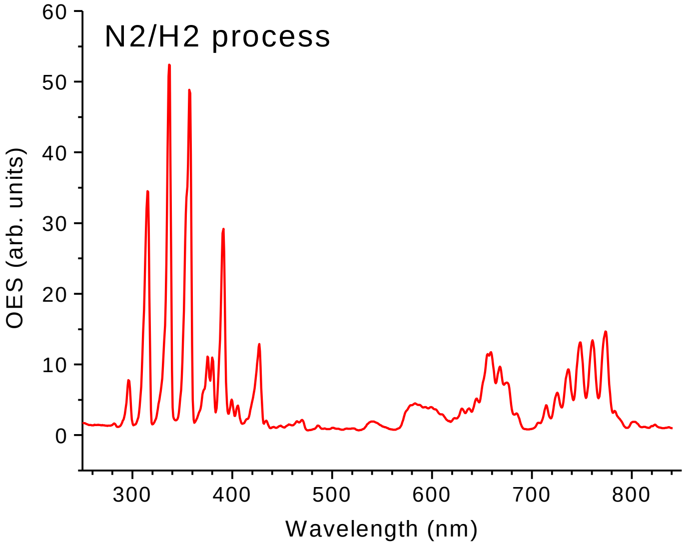


Plasma Diagnostics

- **Residual Gas Analyzers - uses mass spec to analyze gases present in vacuum environment**
  - What can you measure?
    - Gas species analysis/leak detection
    - Insight into reaction mechanisms

- **Optical Emission Spectroscopy (OES) - examines photon emissions from the plasma**
  - Characteristic set of wavelengths emitted for a given species
  - What can you measure?
    - Monitor species in the plasma
    - End-pointing etch process

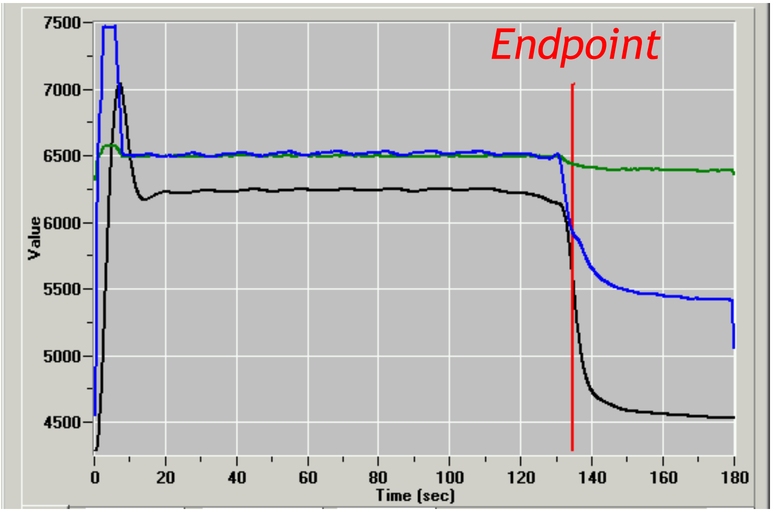
Snapshot OES of N_2/H_2 Plasma



Plasma Diagnostics - Optical Emissions

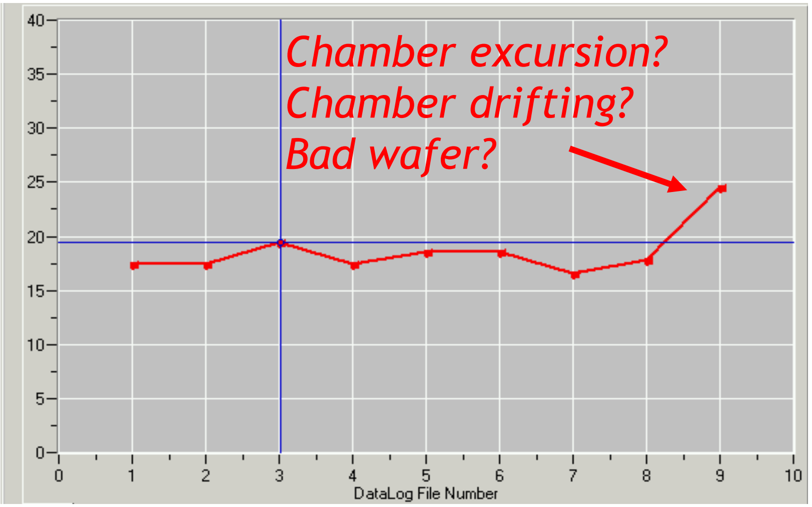
- OES - continued
  - Endpointing – measure emission from a key species as a function of time to determine when to stop etch
  - Troubleshoot chamber drifts

Endpoint Detection



Endpoint

Endpoint Time Trend Charts



Chamber excursion?
Chamber drifting?
Bad wafer?

Plasma Diagnostics

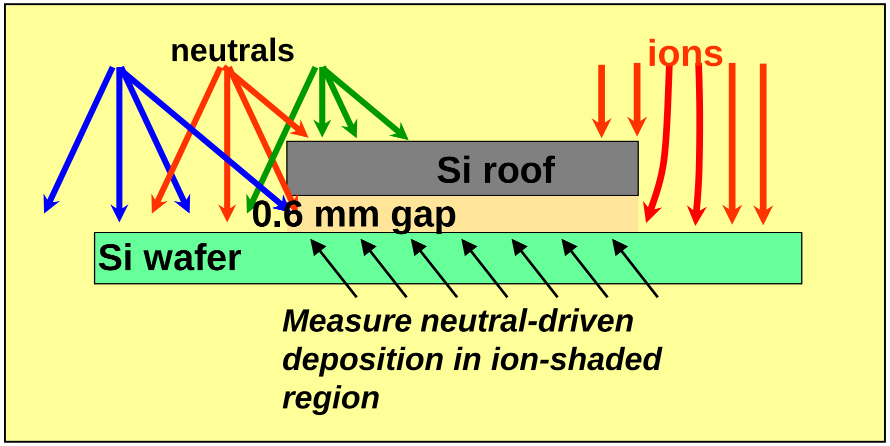
- **Actinometry using OES - add small/known amount of noble gas (e.g., Ar) to a reactive plasma and concurrently monitor the emissions of the noble gas and the reactive species (e.g., F).**
  - Infer densities of certain species (e.g., [F])
  - Many assumptions have to be met, so be careful
    - Excited state emission energy of noble gas is similar to emission in reactive species
    - Same group of electrons responsible for excitation of both levels
    - Excitation efficiencies of these levels will have similar dependence on plasma parameters

- **Absorption Spectroscopy - use stable, well-defined light source to excite radicals from ground electronic state**
  - What can we measure?
    - Measure absolute densities of plasma species

Plasma/Surface diagnostics - Shaded structures

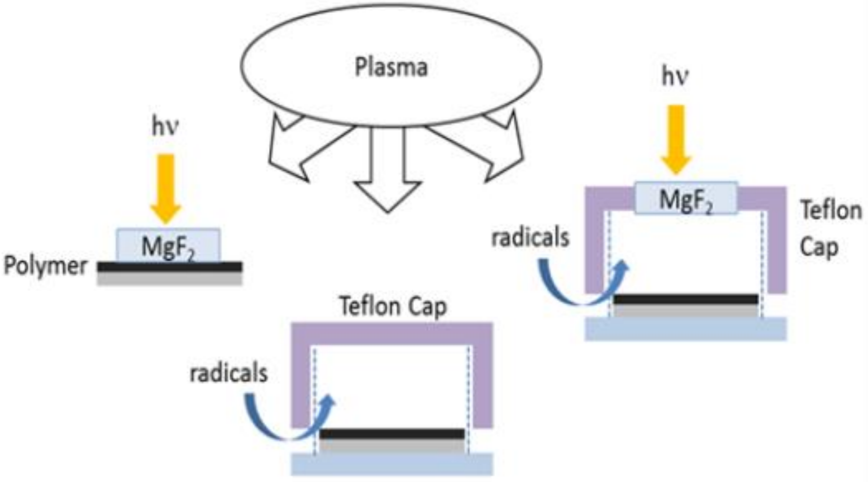
- Shaded structures - structures or windows that are often placed on the substrate to "shade" or block out targeted species from the plasma
  - What can be measured?
    - Separate out the effects of radicals, radiation, and ions

Impact of Radicals (block ions, radiation)



Measure neutral-driven deposition in ion-shaded region

Impact of Radicals, UV/VUV, and Radical+UV/VUV



Surface Diagnostics

- Spectroscopic ellipsometry
  - Measure optical constants and film thickness
  - Used ex-situ and in-situ to study plasma effects/kinetics
- IR absorption
  - Provide chemical identification
- XPS
  - Surface elemental analysis
  - Chemical identification (bonding info, etc)
  - Adsorbate coverage
- Spinning Wall (Donnelly group at UH)
  - Elemental analysis and chemical identification (with proper diagnostic)
  - Adsorbate coverages
  - Recombination probabilities
- ***Plasmas causes a lot of damage to near surface region, so often will see significant oxidation when performing ex situ surface analysis***

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