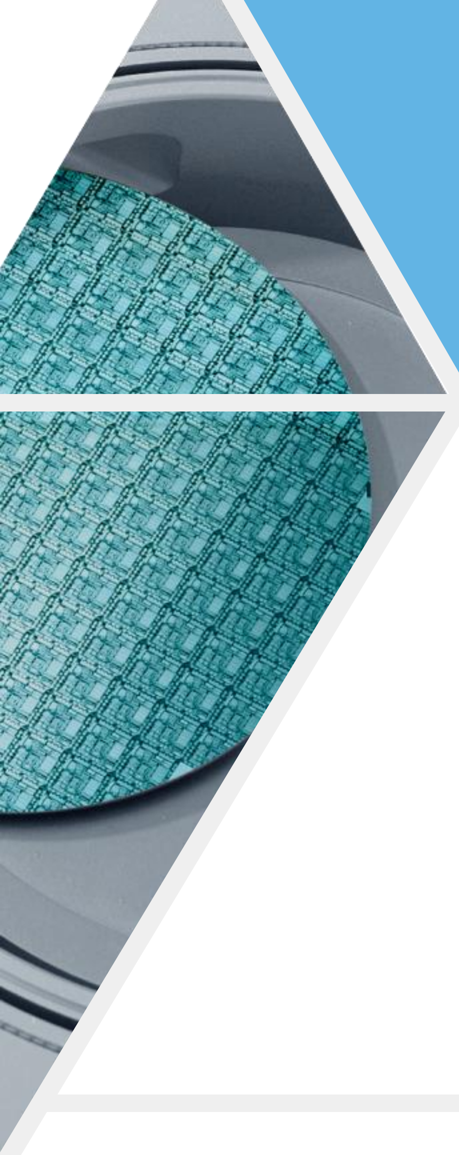


Introduction to Plasma Etching

Dr. Steve Sirard

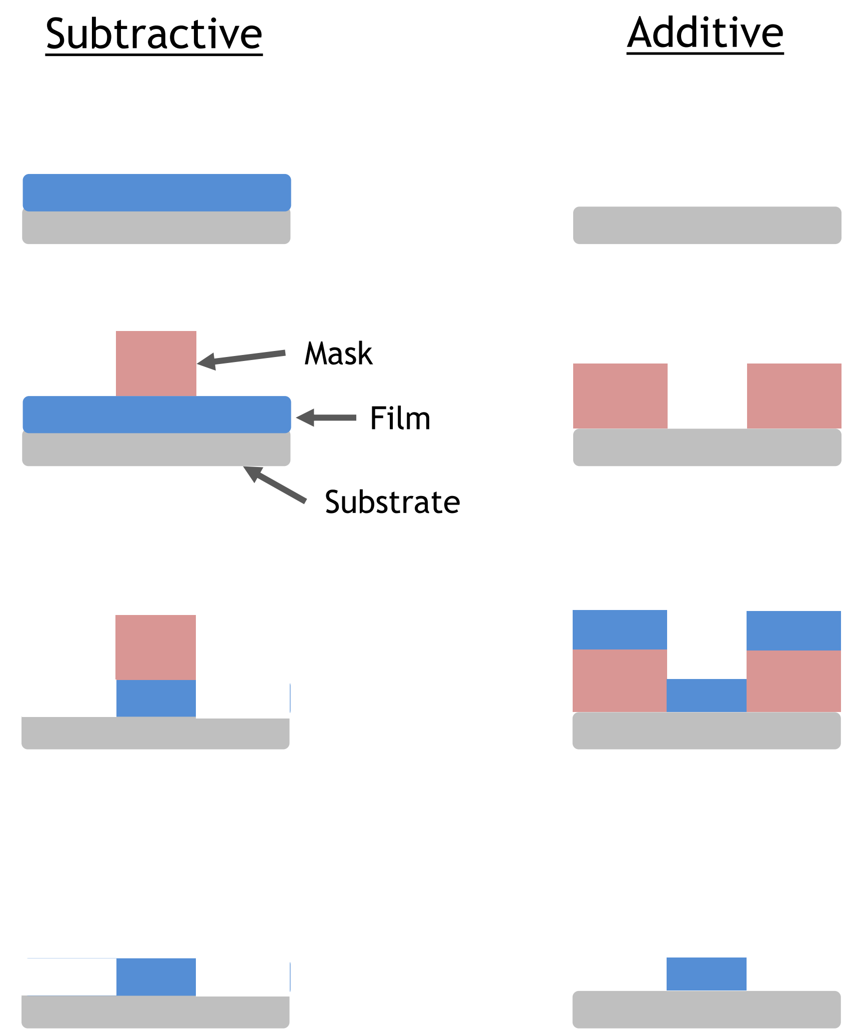
Technical Director

Lam Research Corporation

Lam RESEARCH

Basic Pattern Transfer

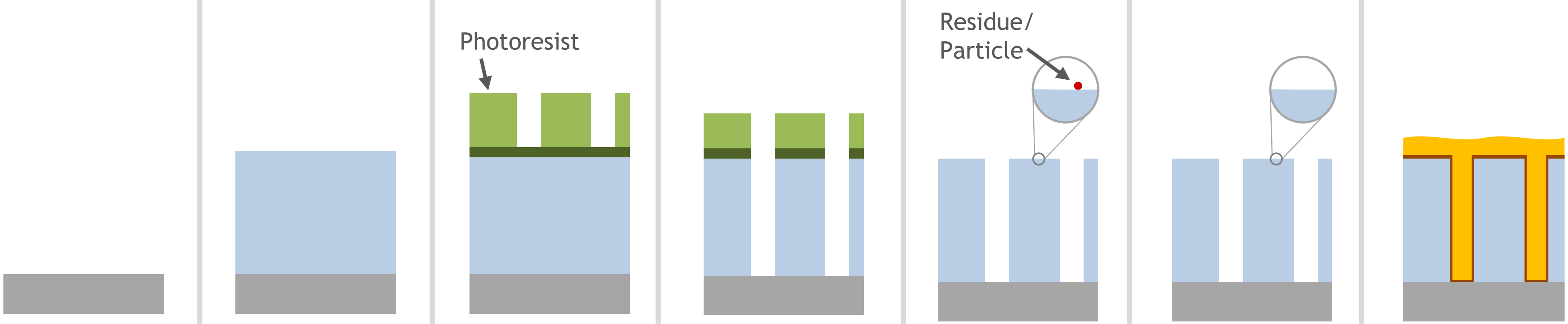
- Objective is to produce a patterned thin film on a substrate
- Patterns are commonly formed by either *additive* or *subtractive* methods
- To pattern film, a mask is formed with photolithography
  - Resist pattern is a stencil that protects underlying films/substrate from dep or etch attack
- Supply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



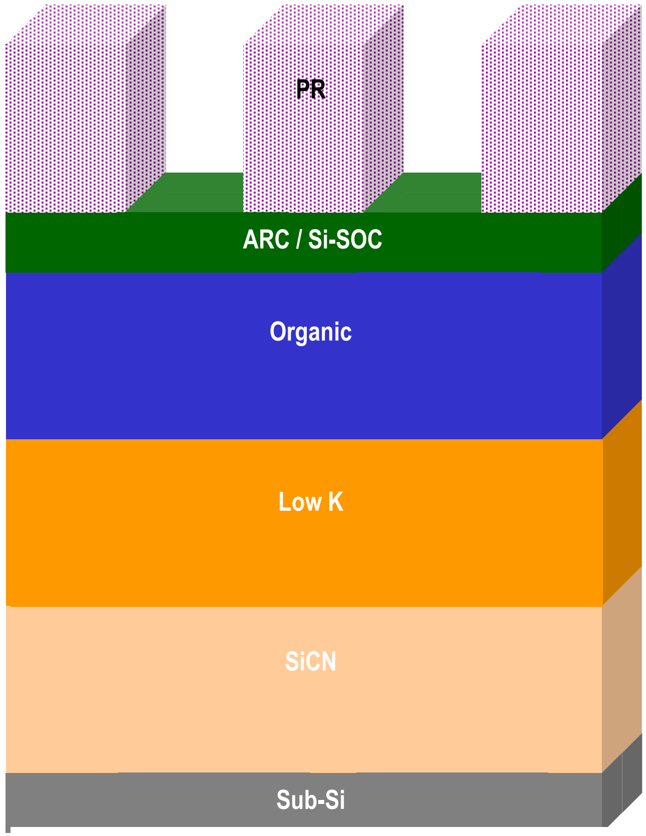
Wafer Fabrication Process Steps

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

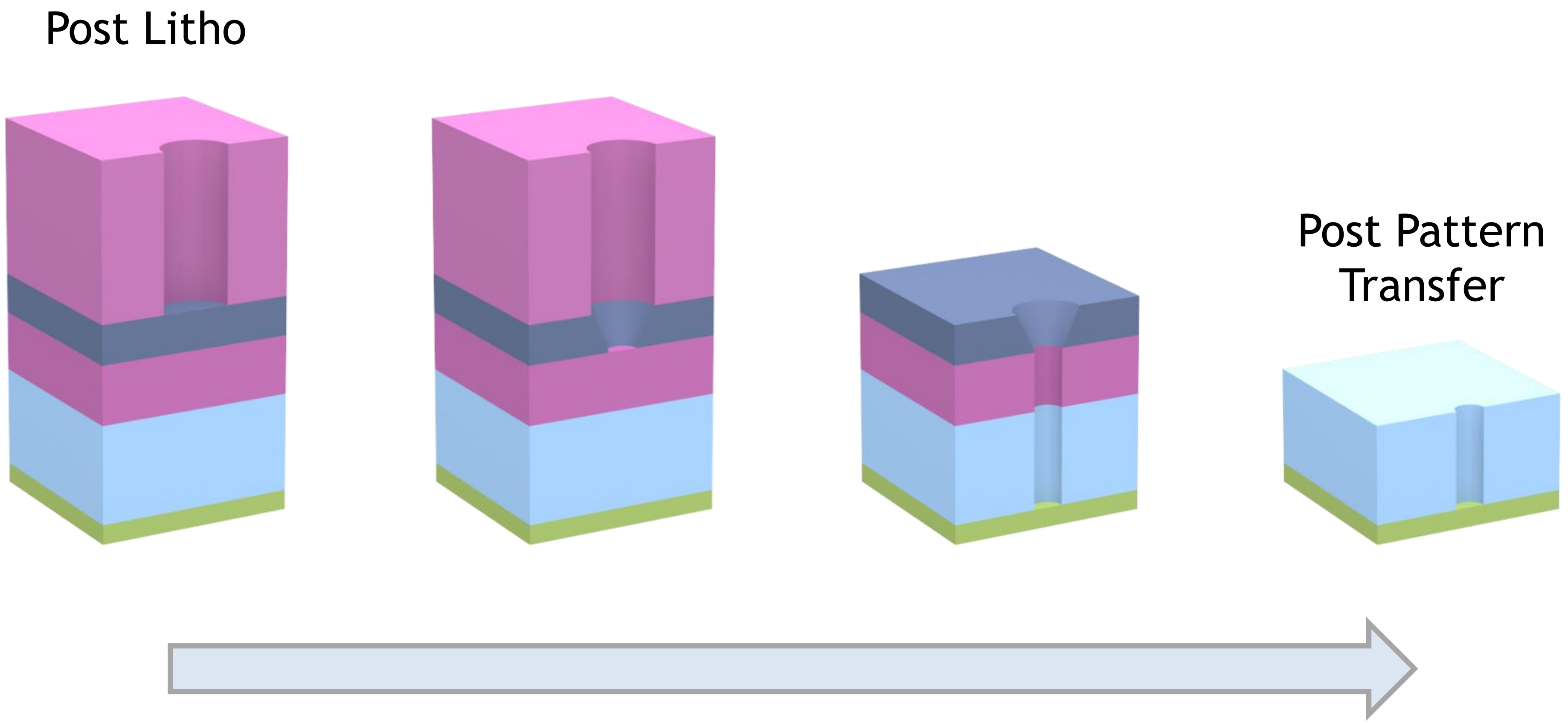


Often, we need to transfer the litho pattern into multiple film types in a single etch pass



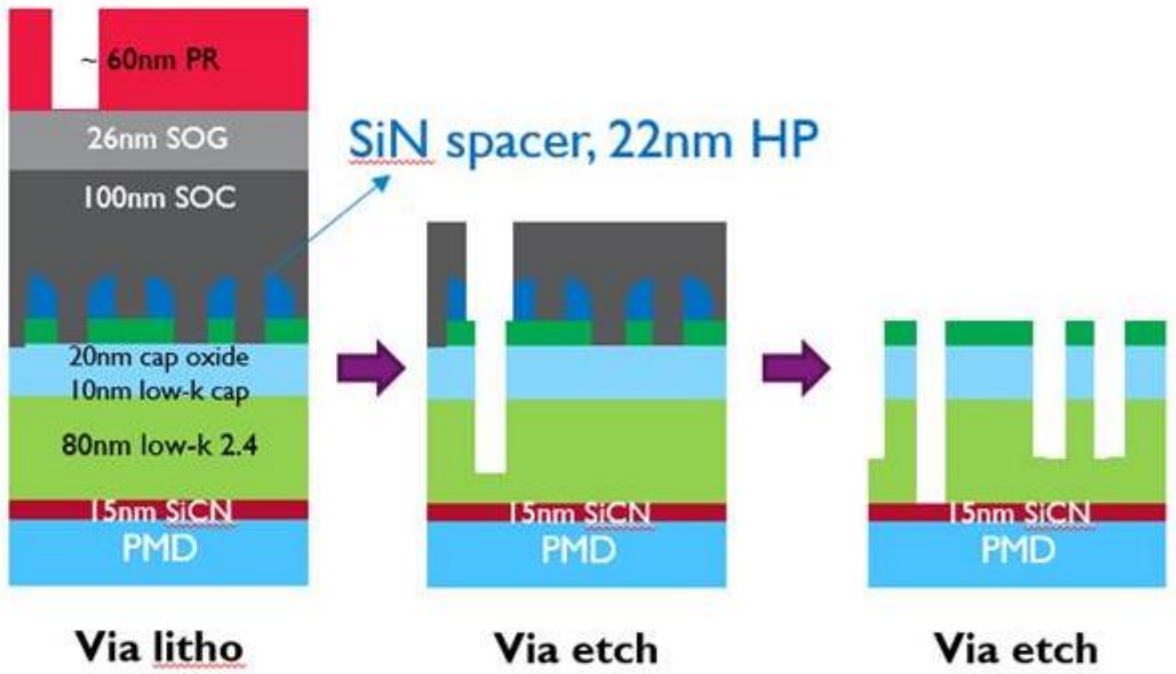
- ▶ **What is the best way to do this pattern transfer???**
  - Remove multiple film types in a single pass
  - High aspect ratio
  - Anisotropic

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>

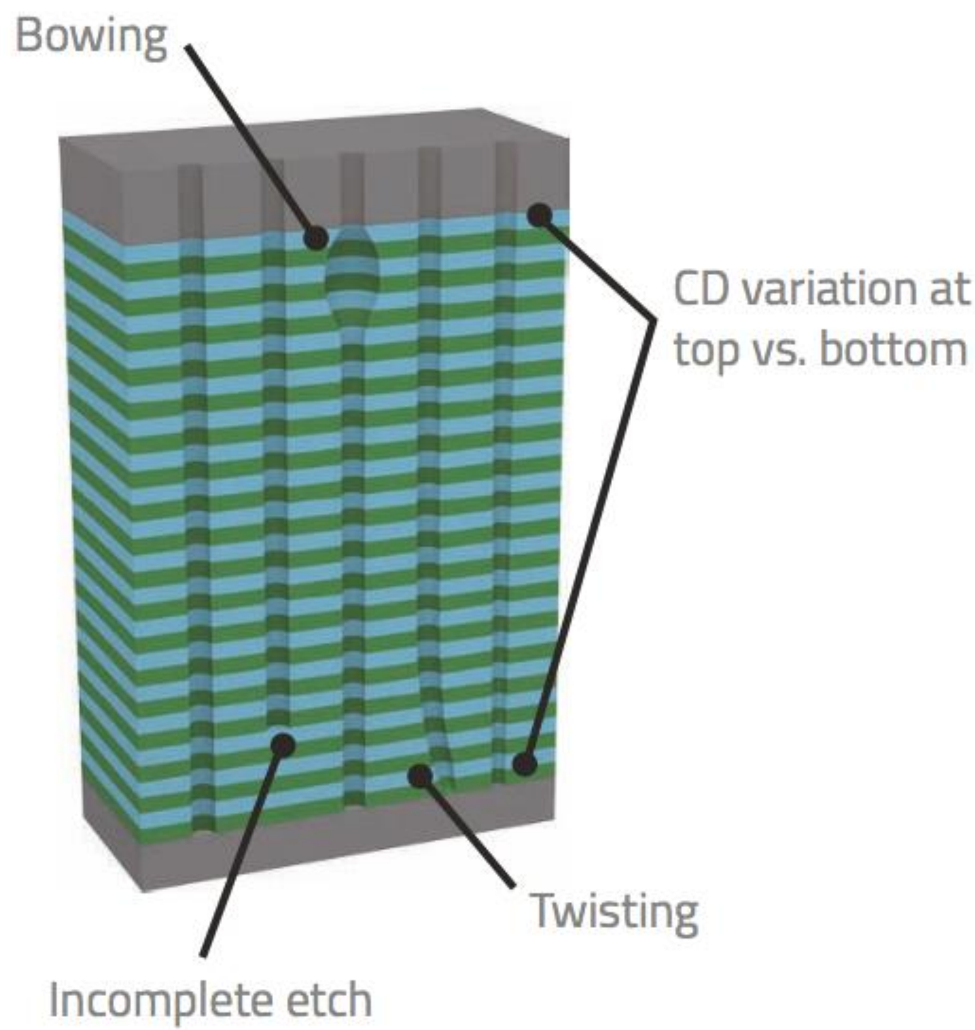
- SOG Open
- SOC Open
- Partial via in oxide/low-k
- SOC Strip
- Trench etch

<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, patterns may require very high aspect ratios

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



Singh, SST, 2017

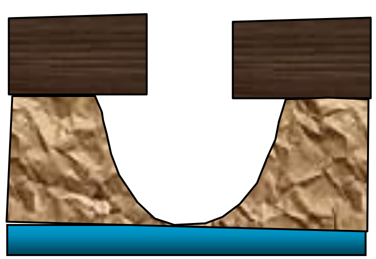
What do we need to control when transferring patterns?

- 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

Dry plasma etch typically required for desirable anisotropic profile

Wet Etch

$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$



Isotropic

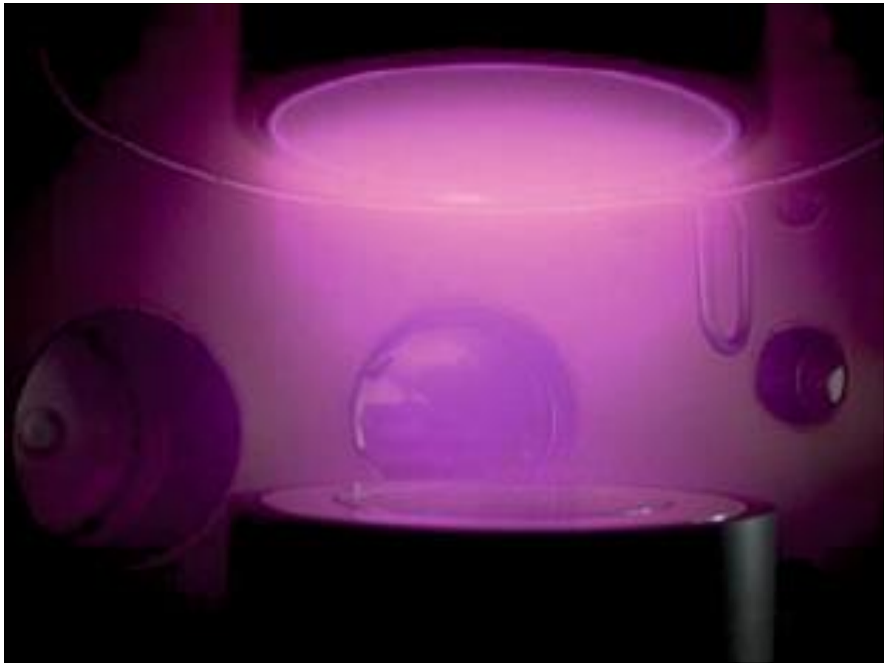
Dry Plasma Etch

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

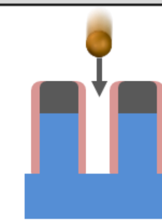
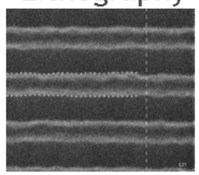
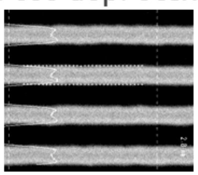
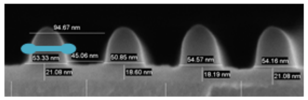
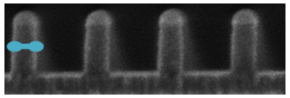
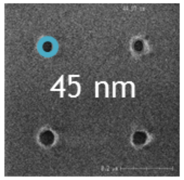
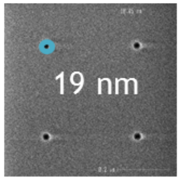
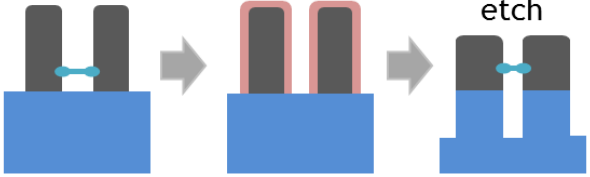
Anisotropic

What is a plasma??

- A plasma is created whenever gases are forced to conduct electric current
  - Plasmas generate electrons, reactive neutral species, and ions
- 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

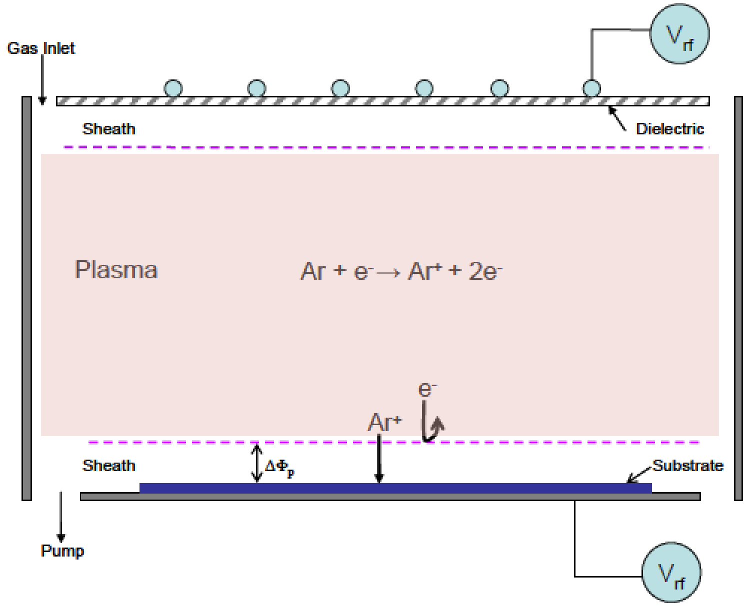


The Benefits of Plasma Processing (Etching *and* Deposition)

	Dep/Etch Enablement	Mechanism
Anisotropic etching:	 Isotropic **Vs.**  Anisotropic	• Ions accelerated to wafer surface • Sidewalls protected by deposition 
Sidewall smoothness:	Lithography (Top-down)  **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:	Lithography (Top-down)  **Smaller** Post-dep/etch  	Litho → Coating → Directional etch 

Generating plasmas inside etch tools

- 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
- 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)



Plasmas can generate unique reactive species

- 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

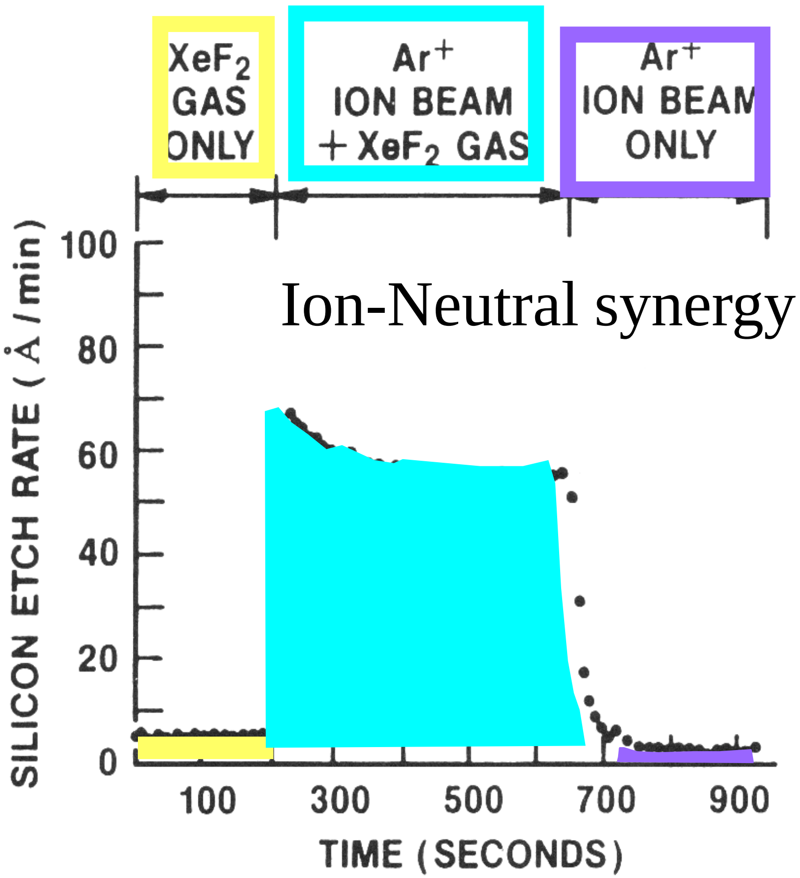
1. They are driven electrically
2. Charged particle collisions with neutral gas molecules are important
3. There are boundaries at which surface losses are important
4. Ionization of neutrals sustains the plasma in the steady state
5. The electrons are not in thermal equilibrium with the ions

General Plasma Fundamentals

Anisotropy Mechanisms

Collisional Processes

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

Anisotropy in Plasma? → 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

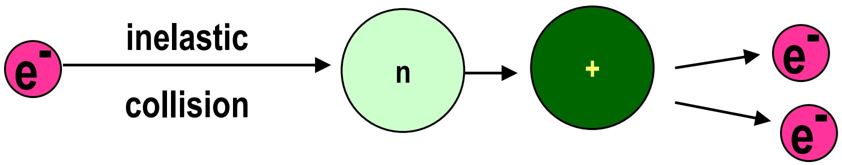
Plasma composition

- **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**

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

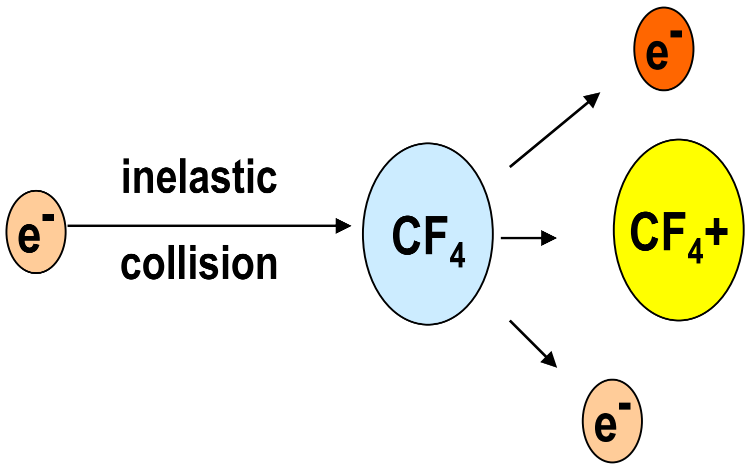
Silicon dioxide etch with CF_4 Plasma

$$SiO_2(s) + CF_4 + I^+(E_i) \rightarrow SiF_4(g) + CO_x(g)$$

▶ Ionization

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

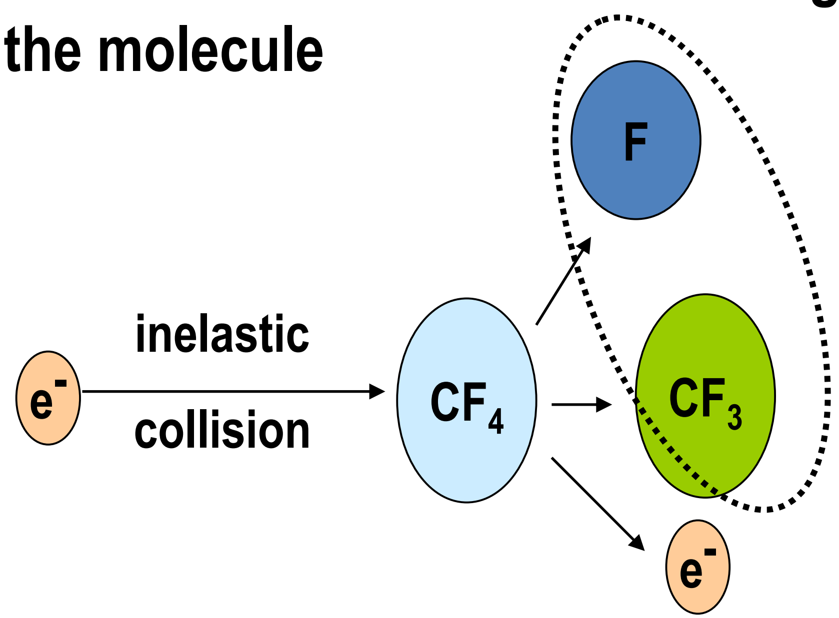
An electron can ionize an atom or molecule if it has energy greater than the ionization potential of the species



▶ Dissociation

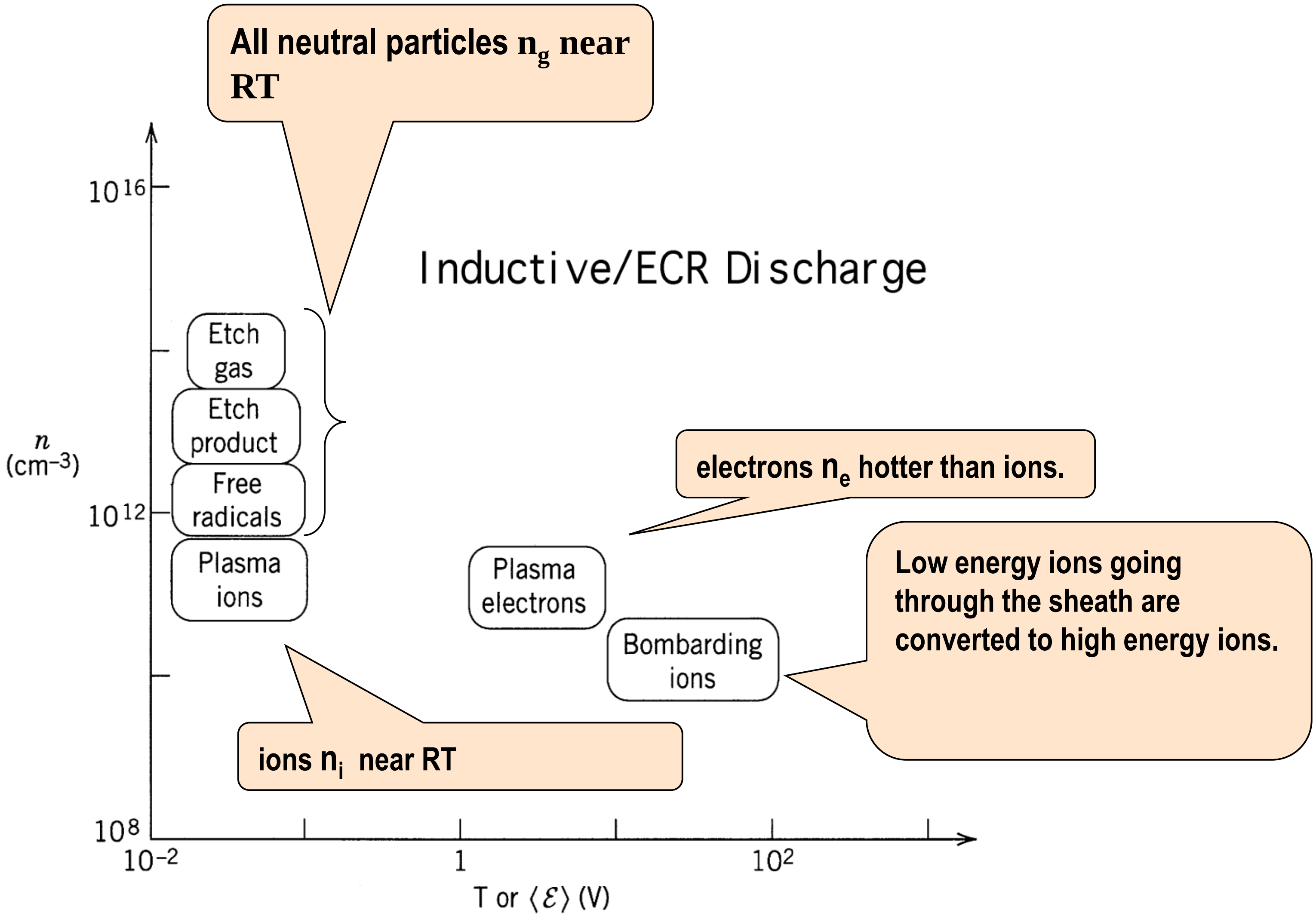
$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

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

Plasma Density and relative energies of species



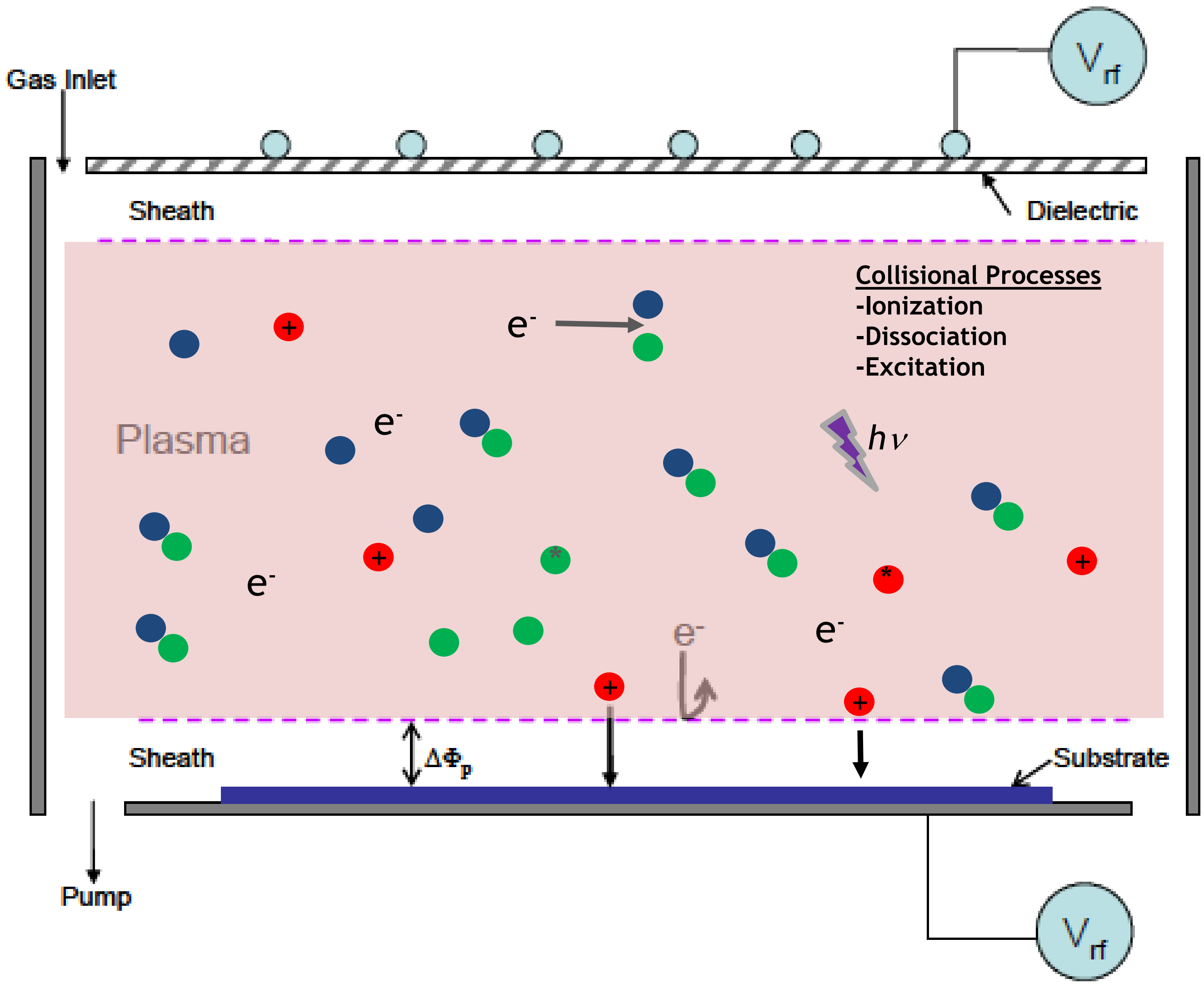
Key points for plasma fundamentals

- **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 (<u>Directional</u>)**

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

Review - *Plasma Fundamentals*

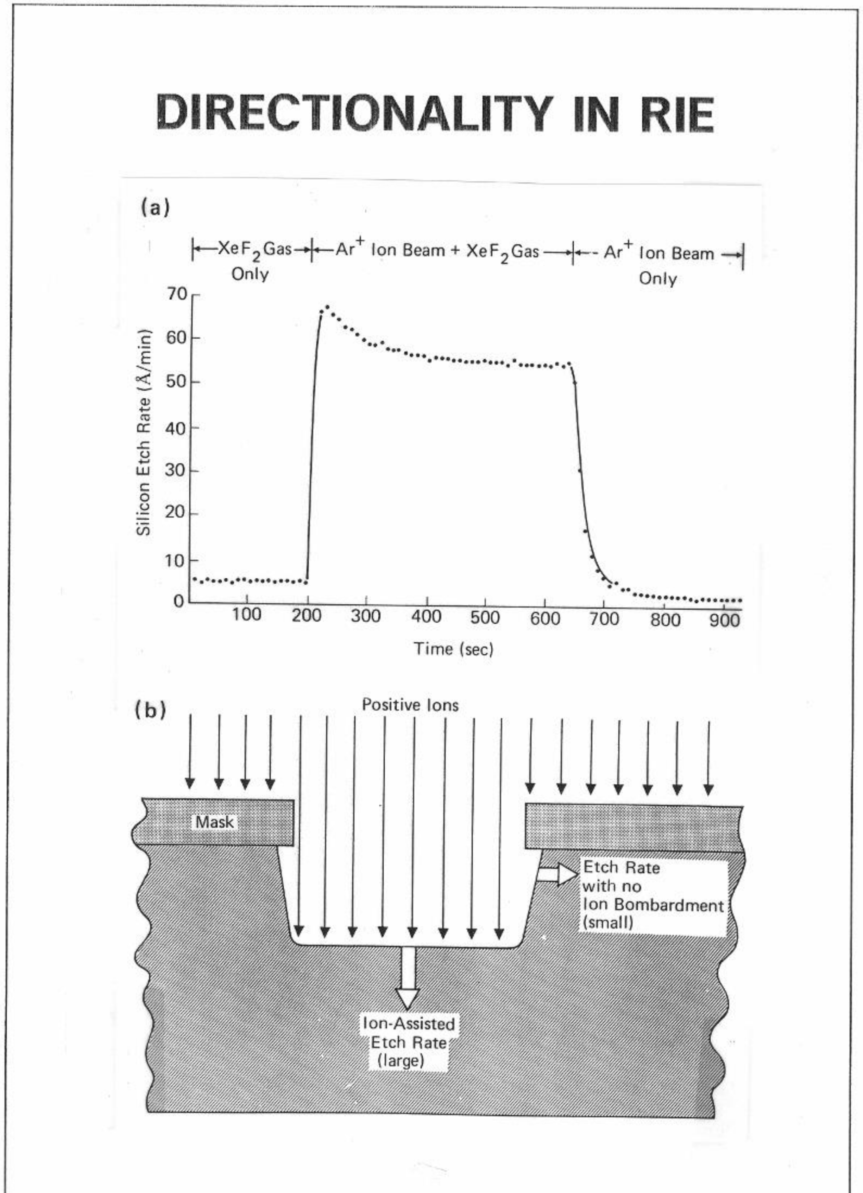


- Plasmas consists of electrons, ions, neutrals, radiation
  - $n_e \sim n_i << n_g$ (weakly ionized)
- Collisional processes sustain the plasma and create radicals (etchant)
  - Electrons are very hot
- Sheaths form at the walls/substrate to confine electrons and directionally accelerate ions

Plasma Etch Process Fundamentals

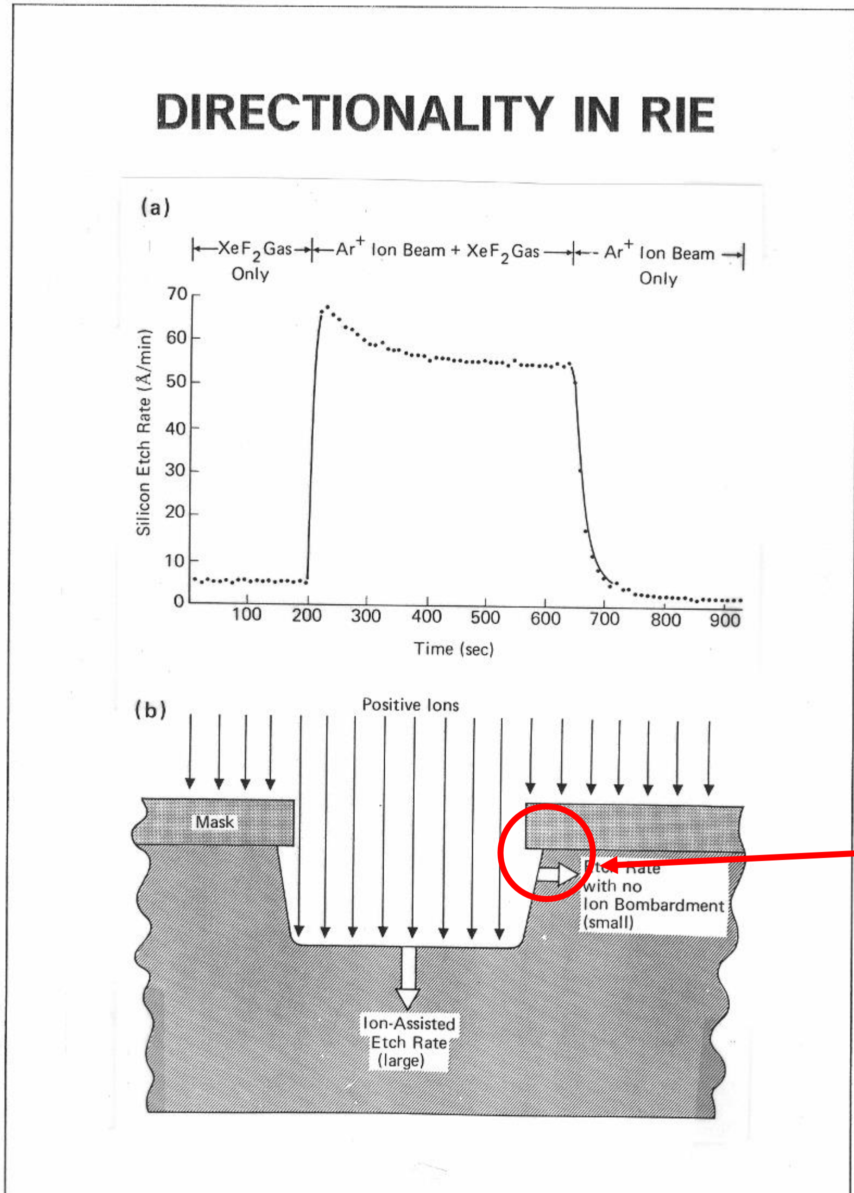
Etch Directionality and Profile Control

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)

Mechanisms for etch directionality & profile control



Often, this type of undercut is unacceptable

Etch chemistry for 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

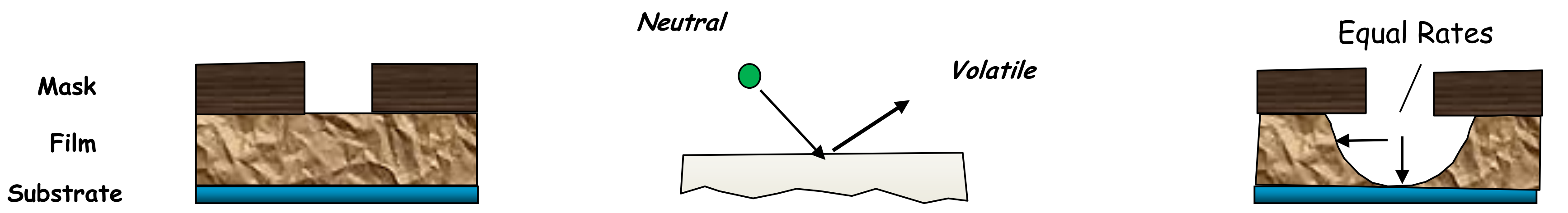
Mechanism for etch directionality & profile control

Four basic etching processes

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

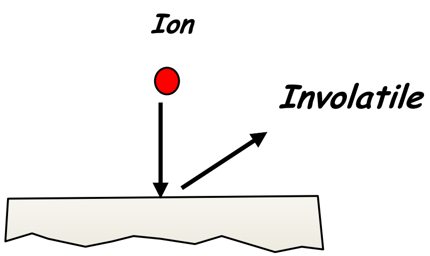
1. Pure Chemical Etch

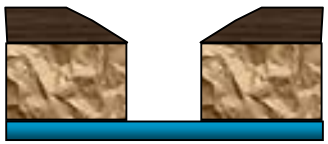
- Selective, slow process - due to etchant atoms or molecules (like F or O) reacting at the surface and forming volatile products
- Isotropic



2. Sputtering

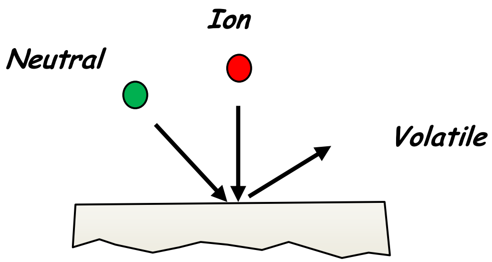
- Non-selective, slow - physical process due to energetic ion bombardment ejecting surface atoms
- Anisotropic

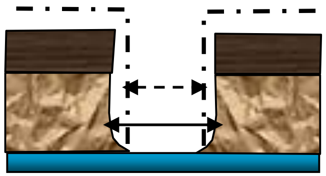




3. Ion Enhanced Etching

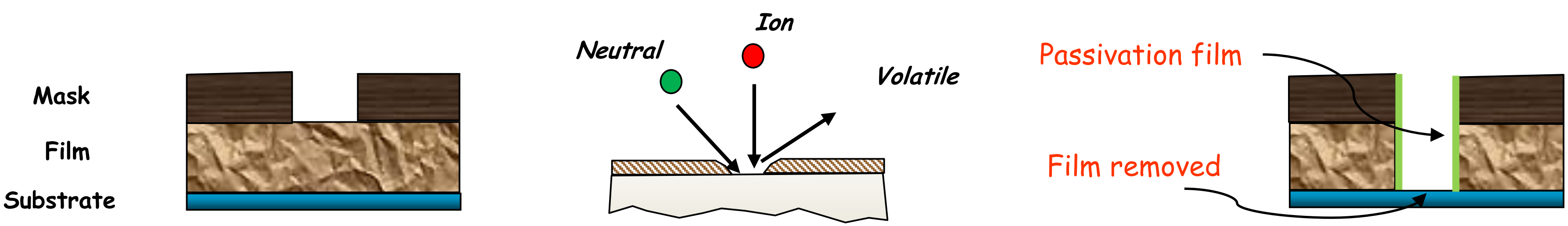
- May have <u>lower selectivity than pure chemical etch</u>
- Enhanced vertical etch rate due to <u>synergy</u> between ions and chemical etching
- <u>Anisotropic</u>





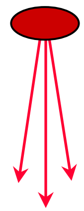
4. Ion Enhanced Inhibitor Etching

- 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>

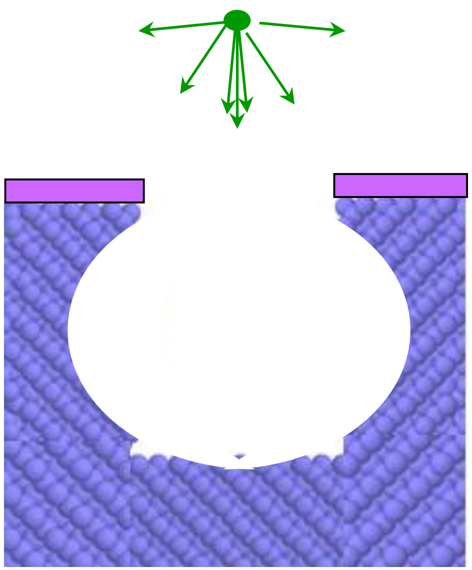


Mechanisms for etch directionality & profile control

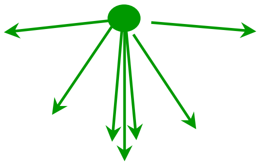
Ion's Angular Distribution
- narrow



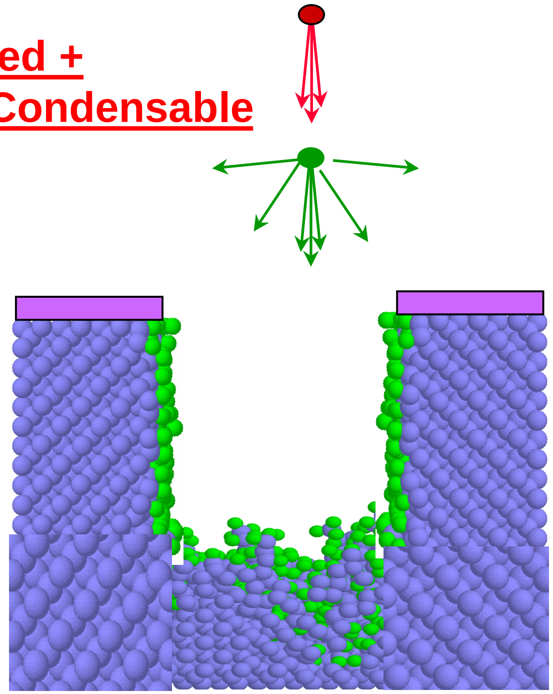
Reactive neutrals



Neutral's Angular Distribution
- wide



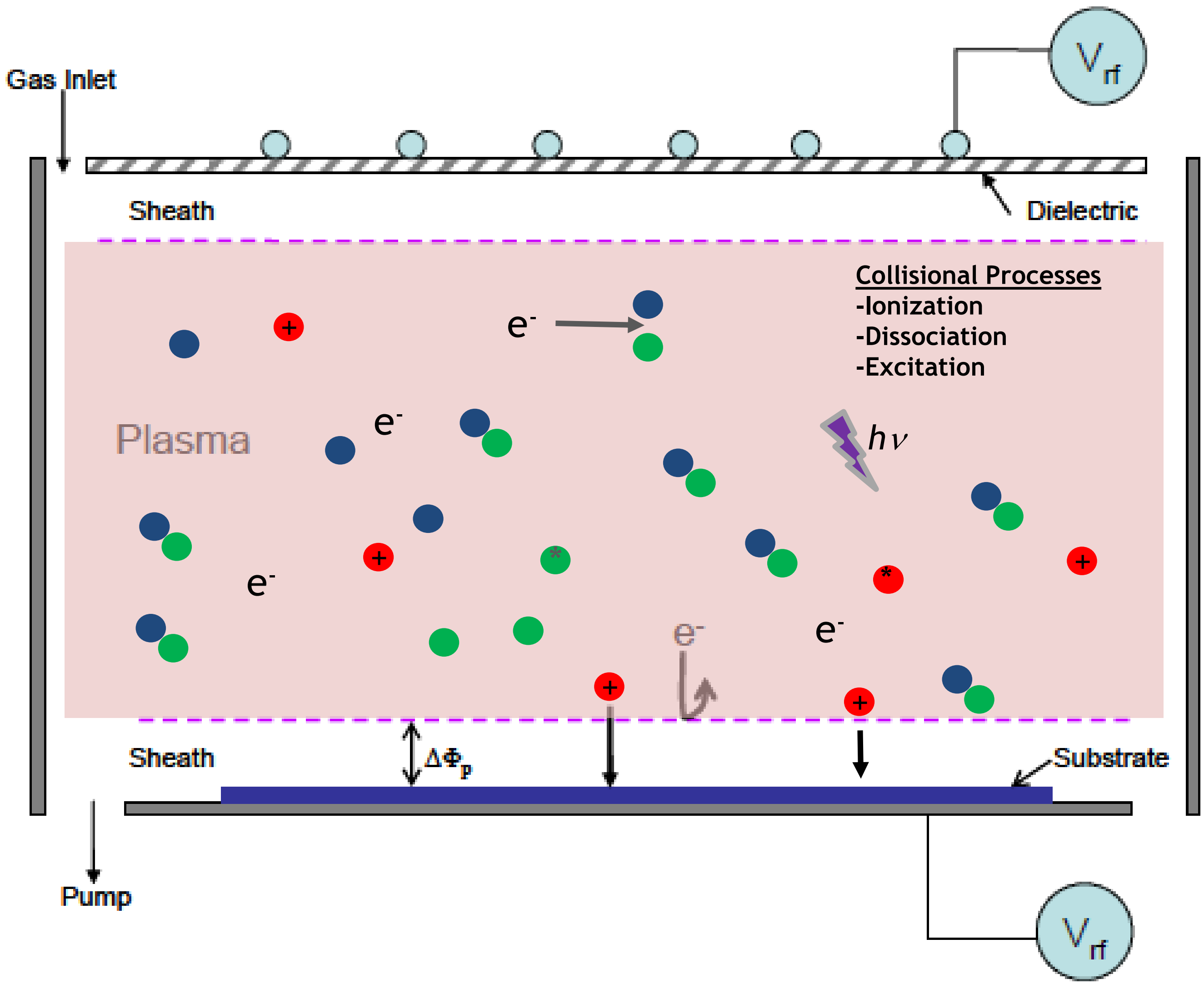
Ion assisted + Reactive/Condensable neutrals



What variables influence etch directionality?

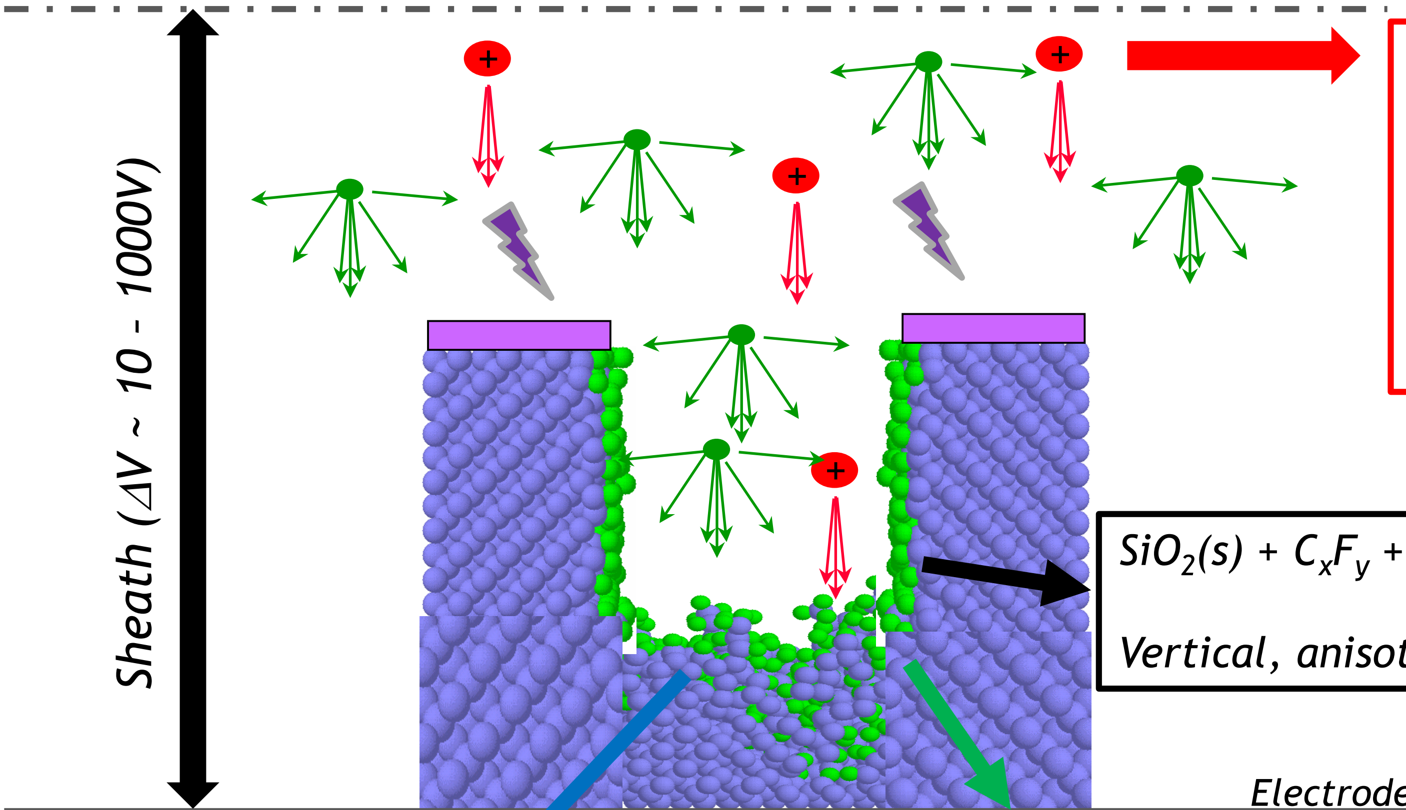
- Ion flux
- Ion energy
- Neutral/ion flux ratio
- Deposition or passivation chemistry
- Temperature of surface being etched
- Pressure (sheath collisions may deflect ions at higher pressures)

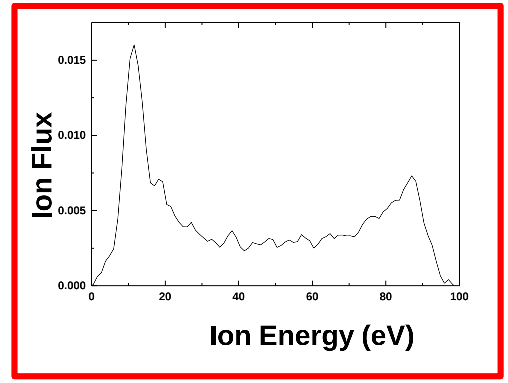
Review - *Plasma Fundamentals*



- 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

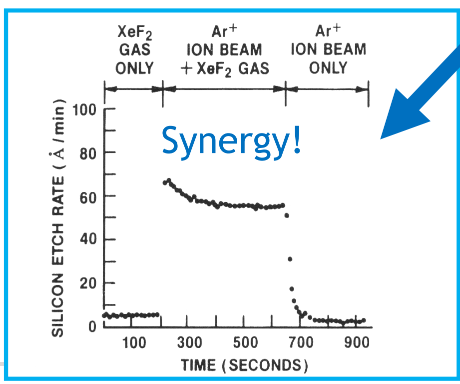
Review - *Anisotropic Plasma Etching*

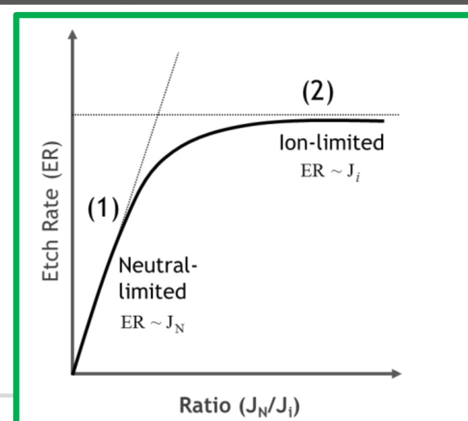




$SiO_2(s) + C_xF_y + I^+(E_i) \rightarrow SiF_4(g) + CO(g)$

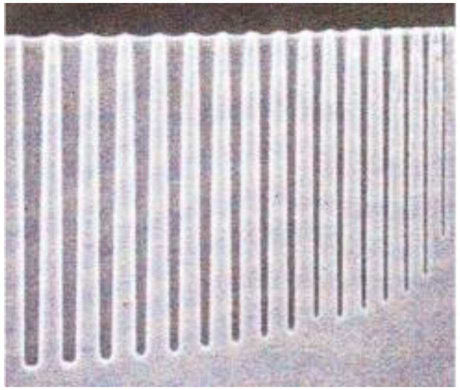
Vertical, anisotropic etch



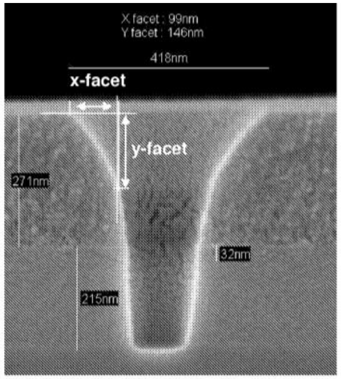


Common pattern transfer issues observed in plasma etching

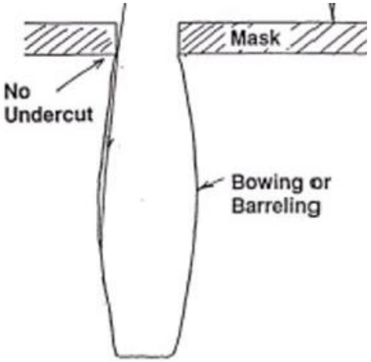
Aspect Ratio Dependent Etching



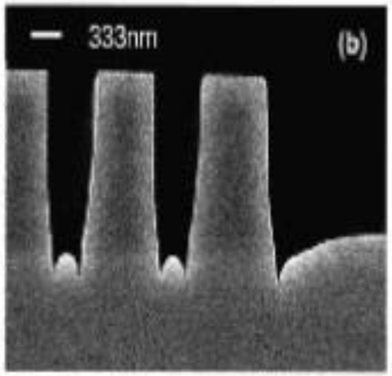
Faceting



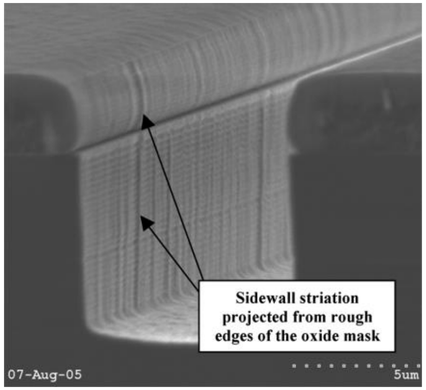
Bowing



Microtrenching



Striations



Micromasking

What "knobs" are available to tune etch processes?

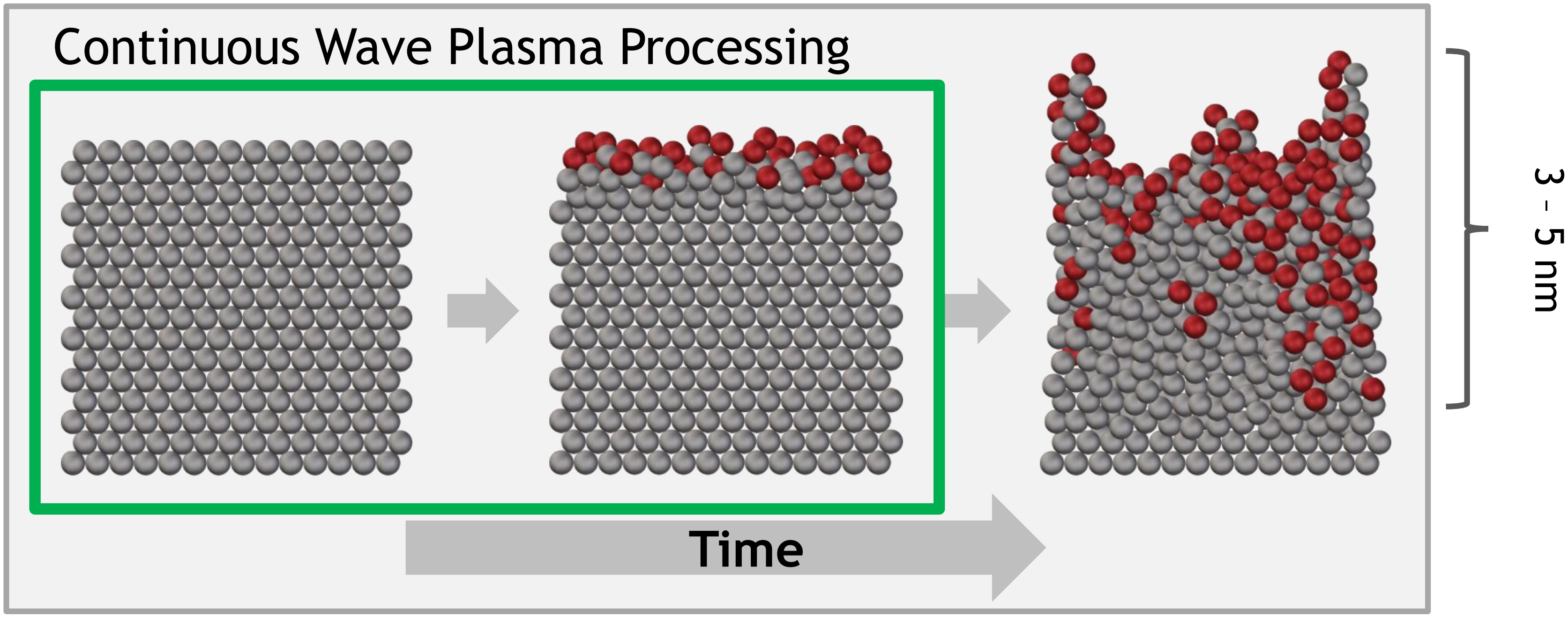
- **Etching in general is very complex!**
- **Advanced plasma etch chambers are equipped with a lot of "knobs" for controlling the etch process**
  - Wafer temperature
  - Upper electrode temperature
  - Temperature gradients
  - Chamber pressure
  - Gas chemistry (*~20 gases on a chamber to choose from*)
  - 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!**

Future Glimpse: Atomic Layer Processing

Richard P. Feynman (*Nobel Prize Physics 1965*)
Dec 29th 1959 at the annual meeting of American Physical Society

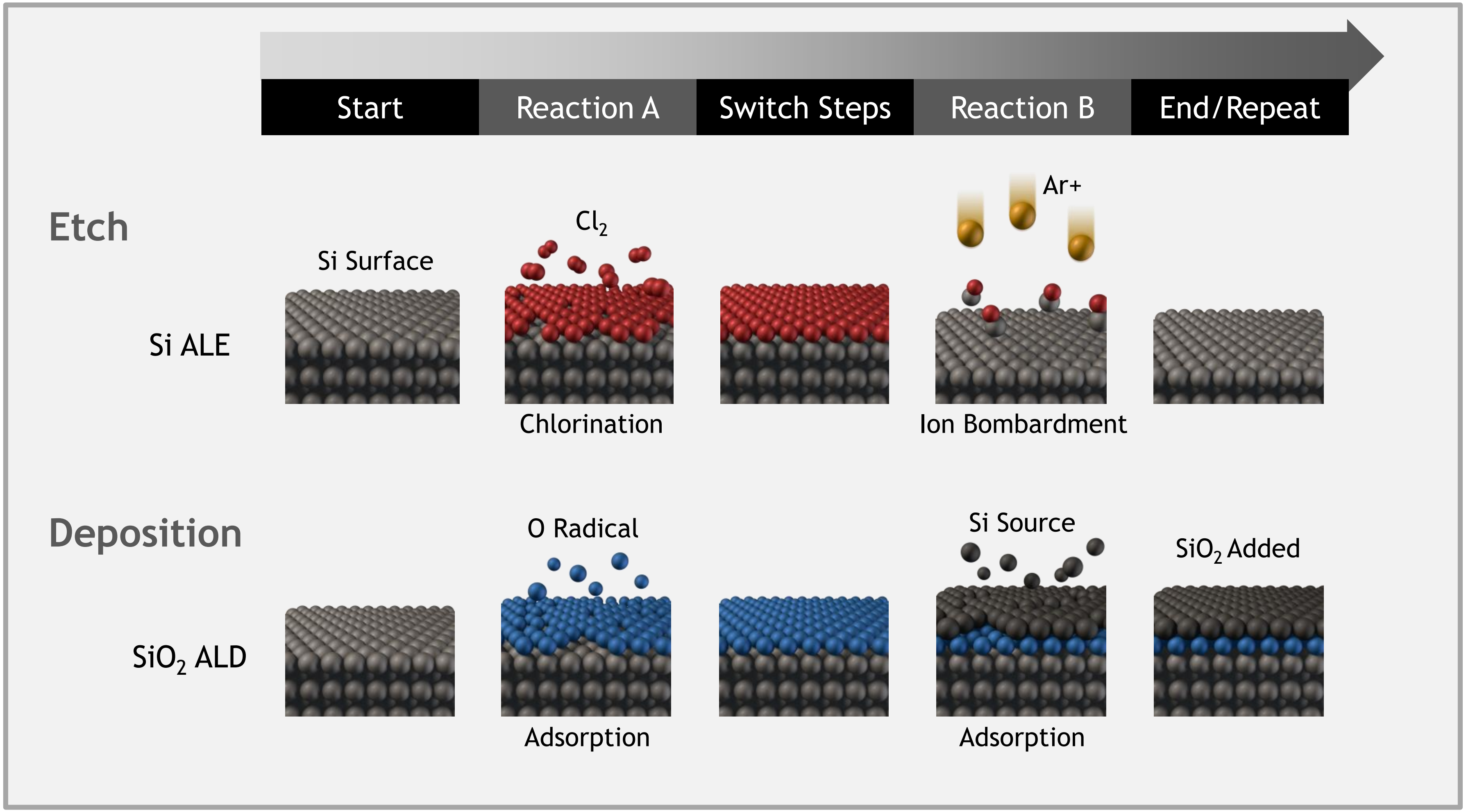
"But I am not afraid to consider the final question as to whether, ultimately --- in the great future --- we can arrange the atoms the way we want; the very atoms, all the way down!"

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)

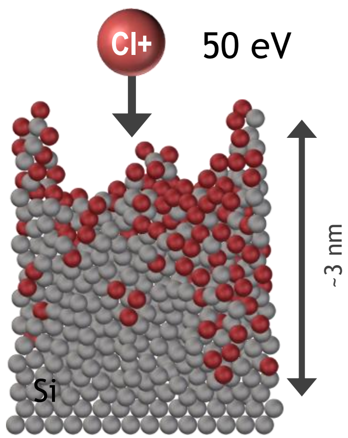
Directional "Atomic Layer" Processing



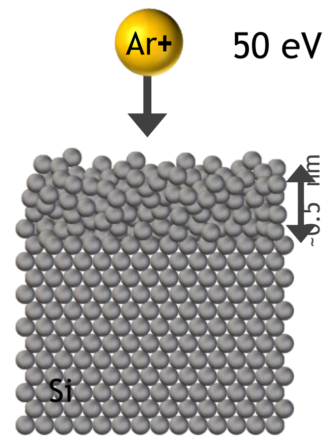
▶ **Use separate, self-limiting steps for atomic layer removal**

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

Efficient in breaking bonds, creating more mixing and disorder



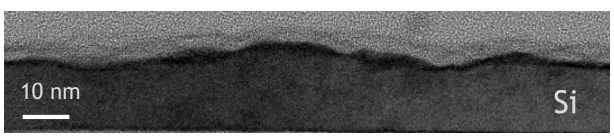
Vs.



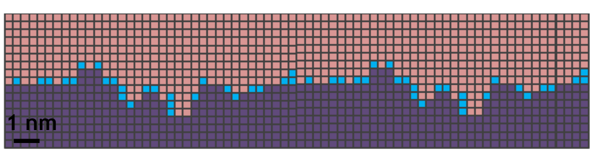
Source: Humbird and Graves, 2004

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

- Roughening effect, inhomogeneity
- Used in conventional etching:

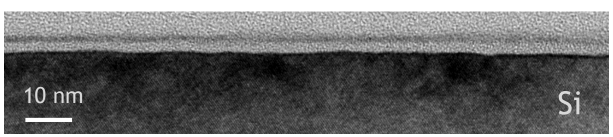


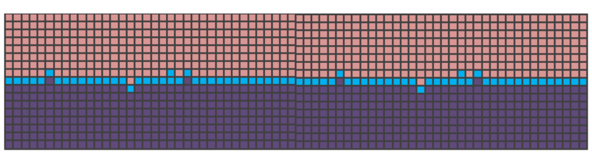
Source: Lam, 2010



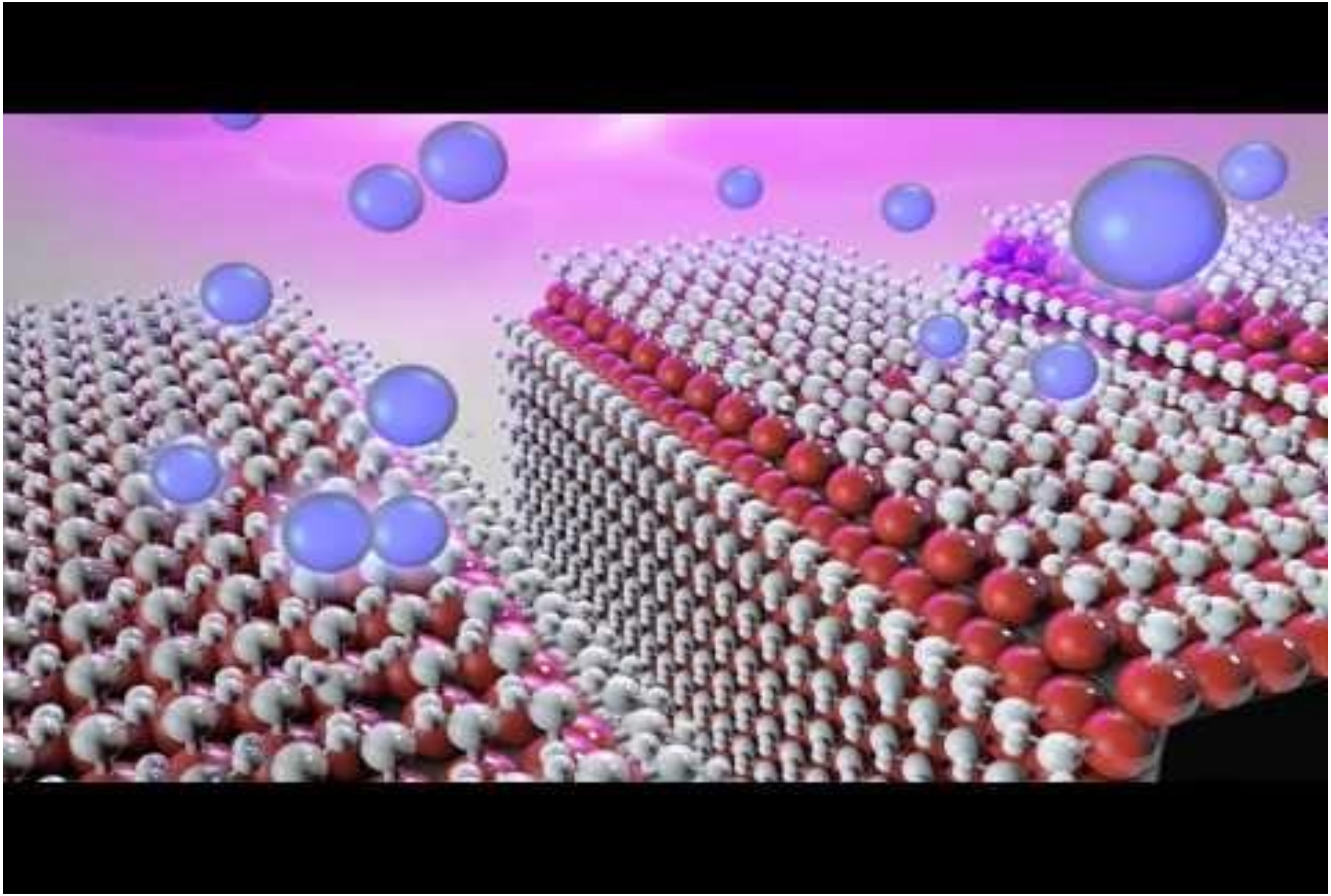
Source: Agarwal & Kushner, 2007

- Smoothing effect
- Used in directional ALE schemes:

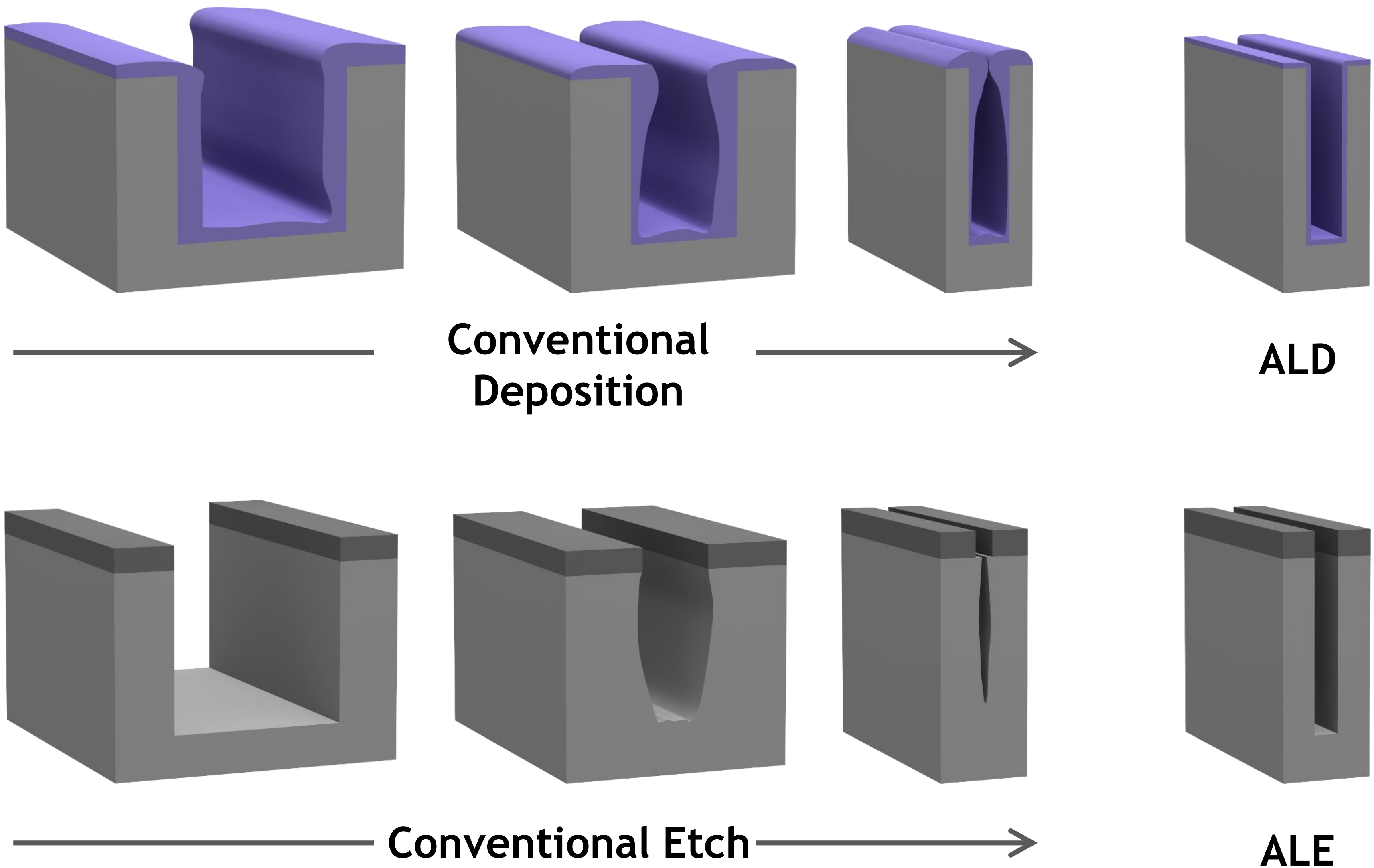




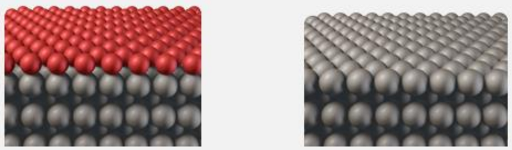
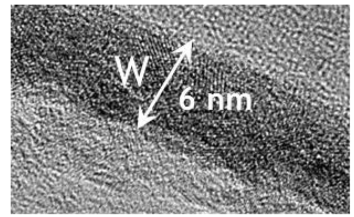
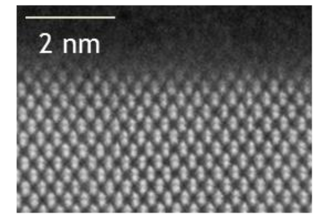
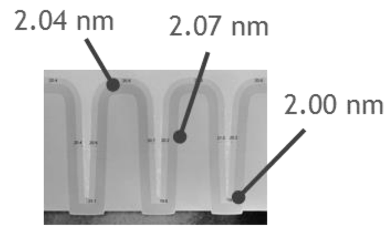
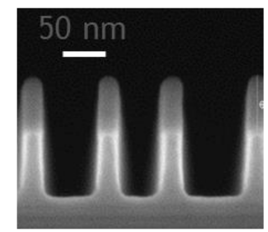
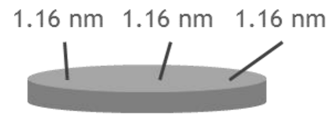
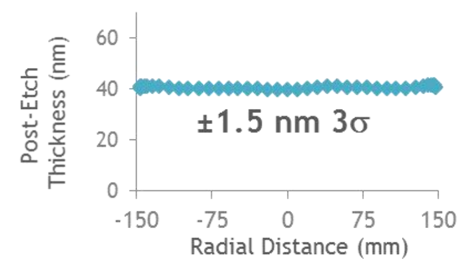
Video – Atomic Layer Etching



Profile benefits of using separated and self-limiting steps



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	

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