NACK NETWORK

Building College-University Partnerships for Nanotechnology Workforce Development

Plasma Removal Process

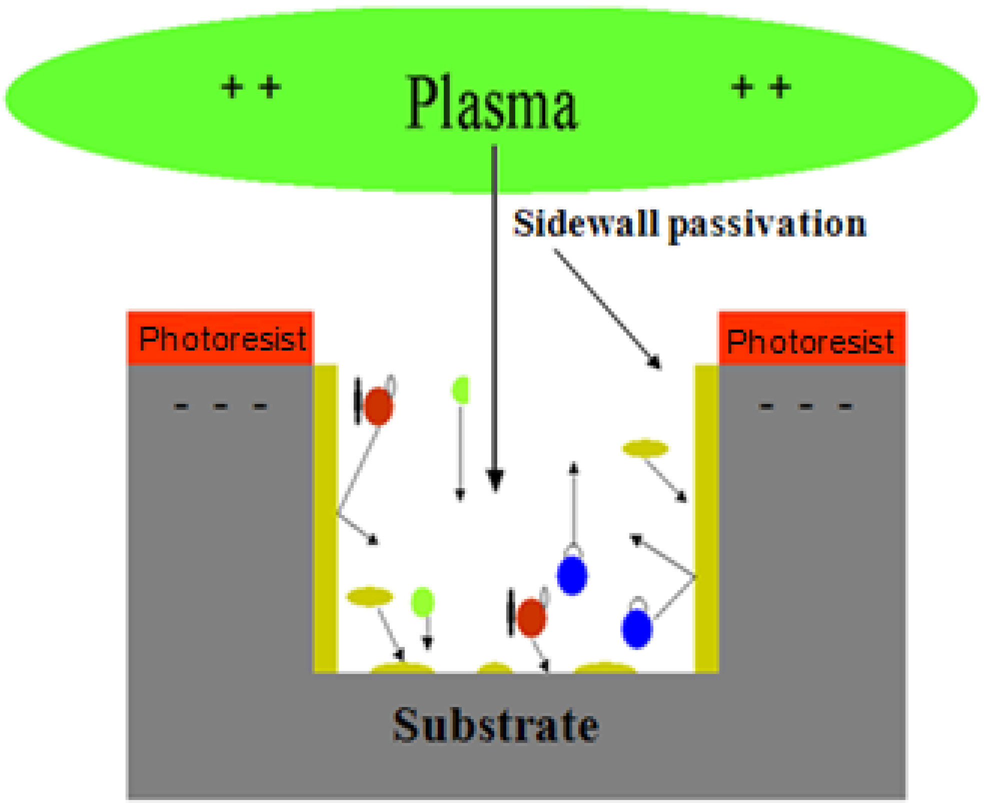
Outline

- Introduction
- Models to understand the plasma process
- Chemistry
- Analyzing recipe parameters, and the resultant etch profiles
- Endpoint

Sidewall Passivation

- Sidewall passivation can be used in an etch process to control sidewall profile
- A film forms on the sidewalls, preventing the material from being etched isotropically
- The film is actually a polymer formed from the process gases and the photoresist layer on the substrate
- The polymers are basically combinations of carbon and hydrogen. May contain oxygen and nitrogen and other etch byproducts. Polymer chemistry depends on process conditions.
- Specific gases can be added to the recipe to insure passivation film formation

Etch Profile with Sidewall Passivation



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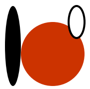
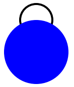


Radicals: reactive etching species



Reaction Products: volatile etch products

Film formers: provide sidewall passivation, photoresist can be a large contributor

Positive ions: provide physical bombardment on surface, breaking surface film formers at bottom, physically etching and providing energy to help drive chemical reactions

Sidewall Passivation

- Polymers coat the sidewalls and act as a “pseudo-mask” for protection from chemical attack
- Ions, for the most part, strike vertically and remove polymer buildup at the bottom of the etch
- The sidewall polymers are removed by using O_2 plasma at 500-750mT
  - This exposure uses a lot of chemistry and little bombardment

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Controlling the Etch Process by Balancing Chemistry and Bombardment

- In dry etch processes choosing the correct chemistries can greatly increase the etch rate
- Increasing MFP of the plasma (decreasing the pressure) also increases the etch rate, this will aid uniformity
- Combining chemistry and bombardment will produce an etch rate that is greater than either contributor alone
- Combining chemistry and bombardment allows the profile to be “tuned” between isotropic and anisotropic
- The etch profile can also be enhanced with side wall passivation

Example Sidewall Chemistries

Material	Chemistry	Volatile Etch Product	Sidewall Material
Oxide Etch	$SiO_2 + CF_4 + CHF_3 + Ar \rightarrow$	SiF, $SiOF$, SiF_4, $SiH_4 \uparrow$	Si, C, CH_x, $F \downarrow$
Poly Si Etch	$Si + HBr + Cl_2 \rightarrow$	$SiBr_x \uparrow$ $SiCl_x$	$Si, Br, C, Cl \downarrow$
Al Etch	$Al + BCl_3 + Cl_2 + N_2 \rightarrow$	$AlCl_3 \uparrow$	$Al, B, C, N, Cl \downarrow$

Some etching Gases

Formula	Common Name	Chemical Name	Formula	Chemical Name
CF_4	Freon 14	Tetrafluoro-methane	$SiCl_4$	Silicon Tetrachloride
C_2F_6	Freon 116	Perfluoro-ethane	BCl_3	Boron-trichloride
C_3F_8	Freon 218	Perfluoro-propane	Cl_2	Chlorine
CHF_3	Freon 23	Trifluoro-methane	HCl	Hydrogen Chloride
CF_3Br	Freon 13B1	Bromo-trifluoro-methane	HBr	Hydrogen Bromide
SF_6		Sulfur Hexafluoride	He	Helium
NF_3		Nitrogen Trifluoride	N_2	Nitrogen
SiF_4		Silicon Tetrafluoride	O_2	Oxygen

Some Materials and Selected Etchants

Material	Chemistry	Material	Chemistry
PolySilicon	Cl_2 or BCl_3/CCl_4 HBr /CF_4 /$CHCl_3$ /CHF_3	WSi_2,$TiSi_2$,$CoSi_2$	CCl_2F_3
Aluminum	Cl_2 BCl_3 + passivating gases $SiCl_4$	Single crystal Si	Cl_2 or BCl_3 + passivating gases
AlSi(1%)-Cu(0.5%)	same as Al	SiO_2 (BPSG)	CCl_2F_2,CF_4,C_2F_6, C_3F_8
Al-Cu(2%)	$BCl_3/Cl_2/CHF_3$	Si3N4	CCl_2F_2 CHF_3
Tungsten	$SF_6/Cl_2/CCl_4$	GaAs	CCl_2F_2
TiW	$SF_6/Cl_2/O_2$		

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The “Egg” Chart

- This analytical model is a graphical representation of various process parameters. The Y axis represents bombardment energy, the X axis represents chemical energy, and the “dog leg” boundary represents polymer formation.
- For an ideal anisotropic etch, the required parameter zone resembles an “egg” in the middle of the chart
- This chart shows the combined effects of chemistry, bombardment, and polymerization (C*B+P) to predict sidewall profiles
- There are also other factors that determine the etch profile that are not included in this exercise. These parameters will be discussed after this first iteration analysis.

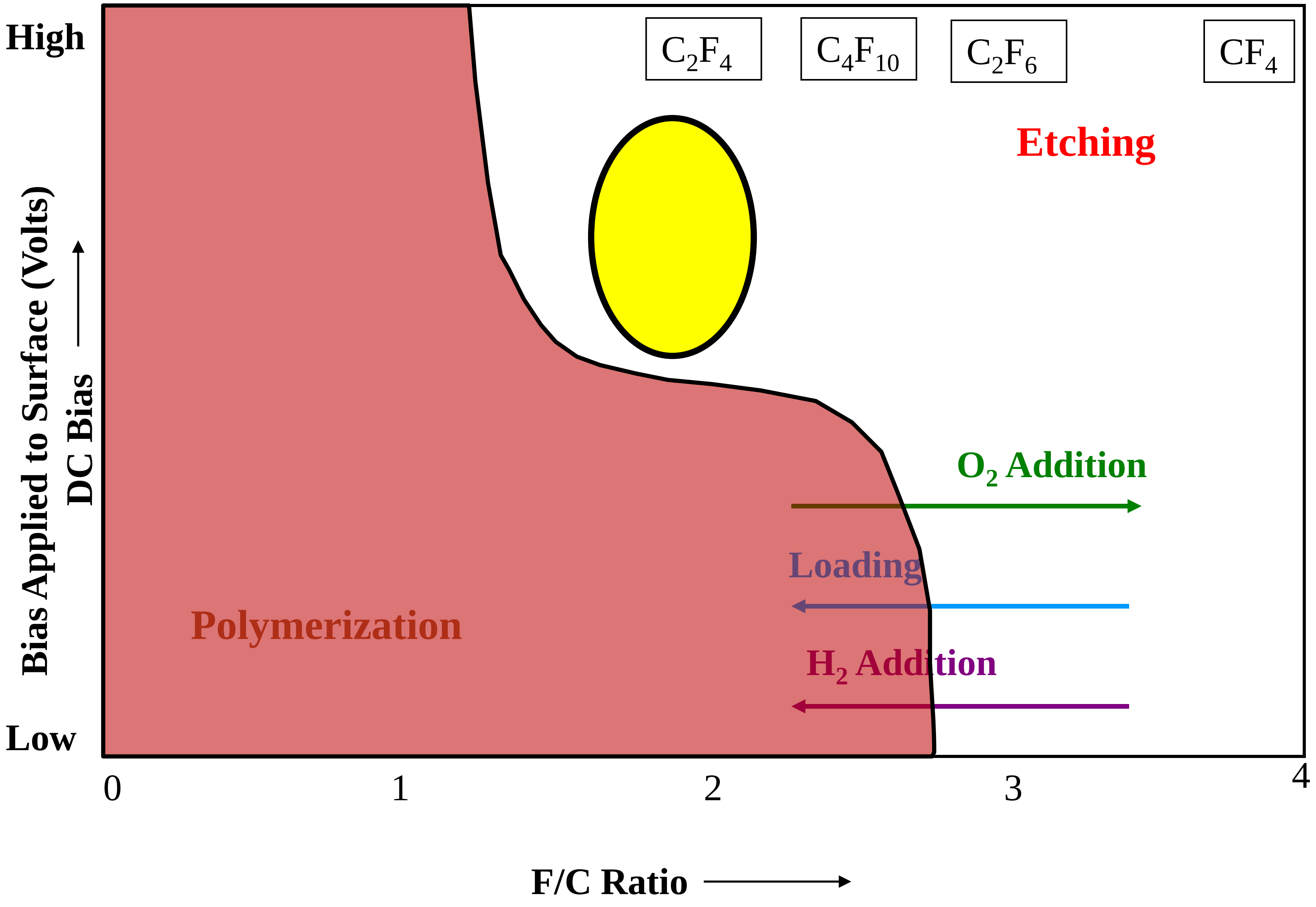
The "Egg" Chart

- A chart like this can be found and/or generated for any dry etchable material
- Due to its wide use in micro and nanofabrication, we will analyze the egg chart for SiO_2
- Naturally this chart is not "exact", but can be used as a starting point for building a etch recipe.

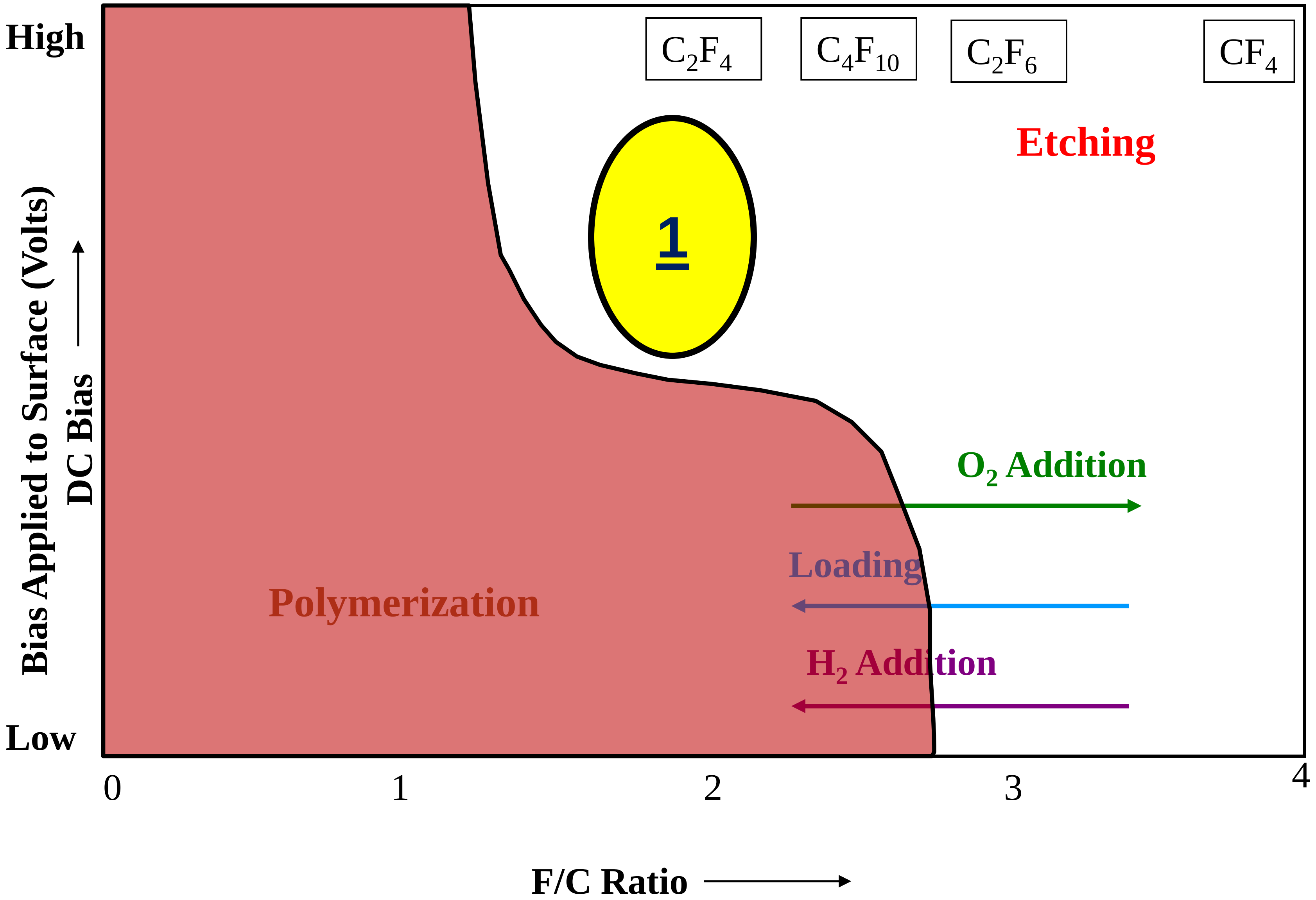
Oxide Egg Chart Considerations

- F/C Ratio- the ratio of fluorine to carbon etching species
- Increasing DC bias, increases bombardment
- The addition of H_2 to the chamber increases polymerization
- The addition of O_2 to the chamber increases free fluorine
- Aspect Ratio- the ratio of depth to width for a small gap, trench, or hole

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



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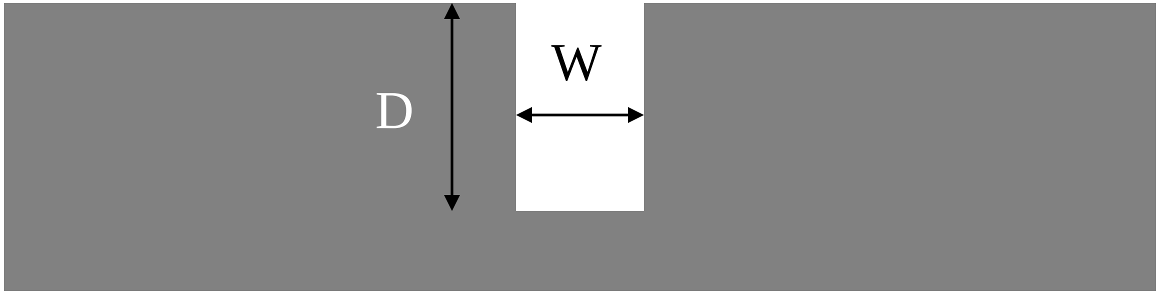
The Ideal Profile

- To be “in the egg” is to achieve the ideal anisotropic etch
  – The ideal F/C ratio is approximately 2
  – An equal mix of hydrogen and oxygen to balance polymerization and etch
  – DC bias level that provides just enough bombardment

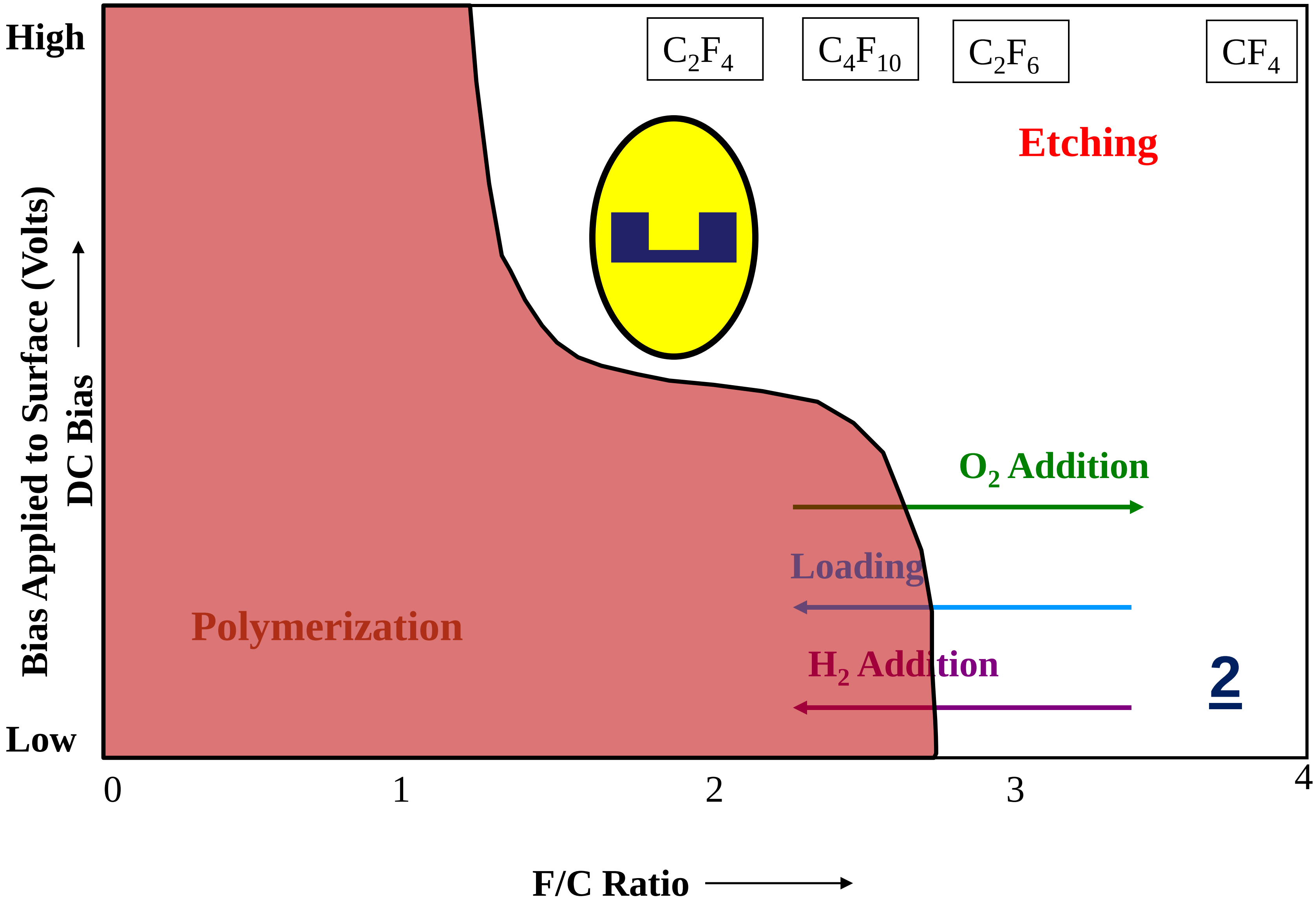
The Ideal Profile



Sidewall Profile Two

- Low DC bias – little/no bombardment
- No H_2 - no polymerization
- A lot of O_2 – can increase etching
- F/C ratio = 4, SiF_4 is formed
- Aspect ratio < 1, an isotropic etch profile

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



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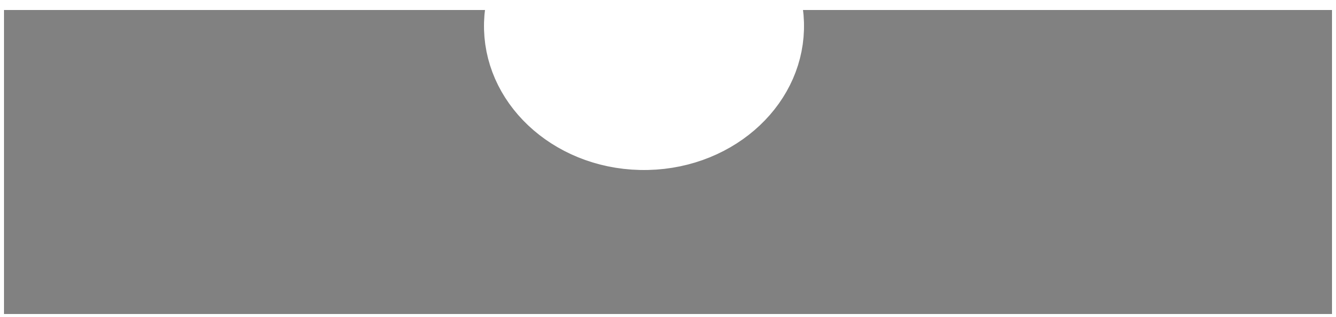
Sidewall Profile Two



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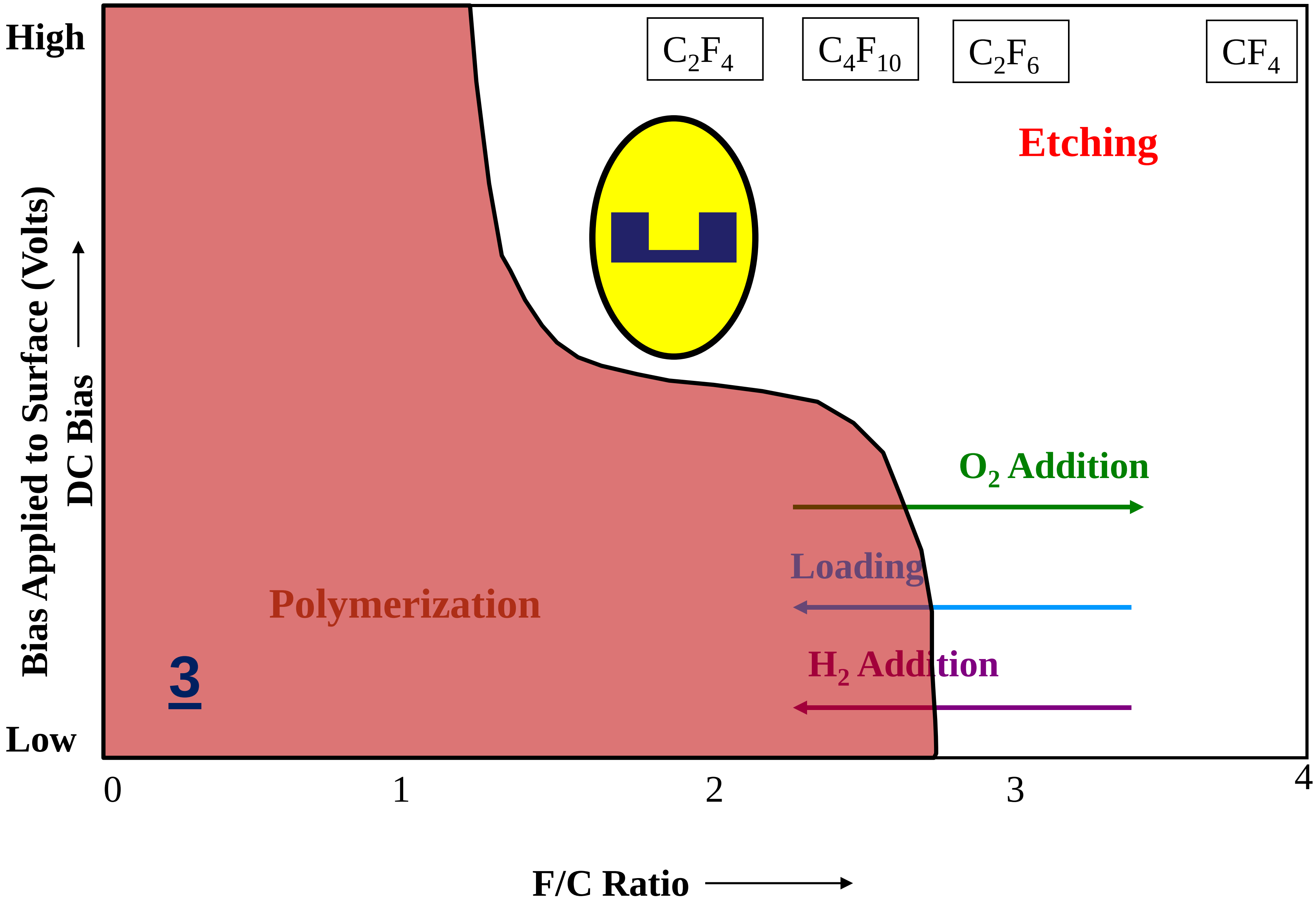
Sidewall Profile Three

- Low DC bias – no bombardment
- A lot of H_2 - a lot of polymerization
- No O_2 – no etch
- F/C = $^1/_3$, SiF_4 is not formed

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



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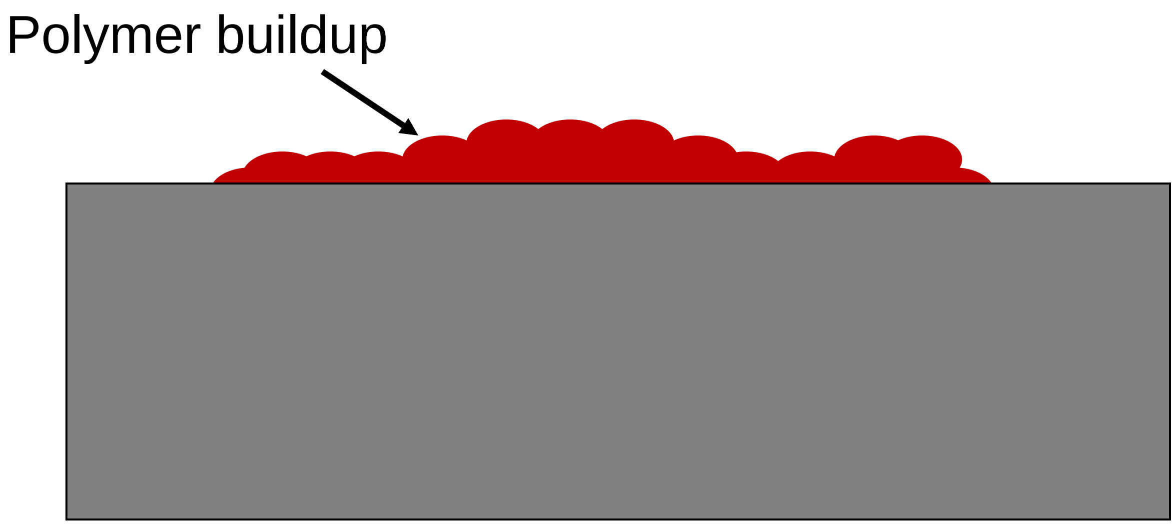
Sidewall Profile Three



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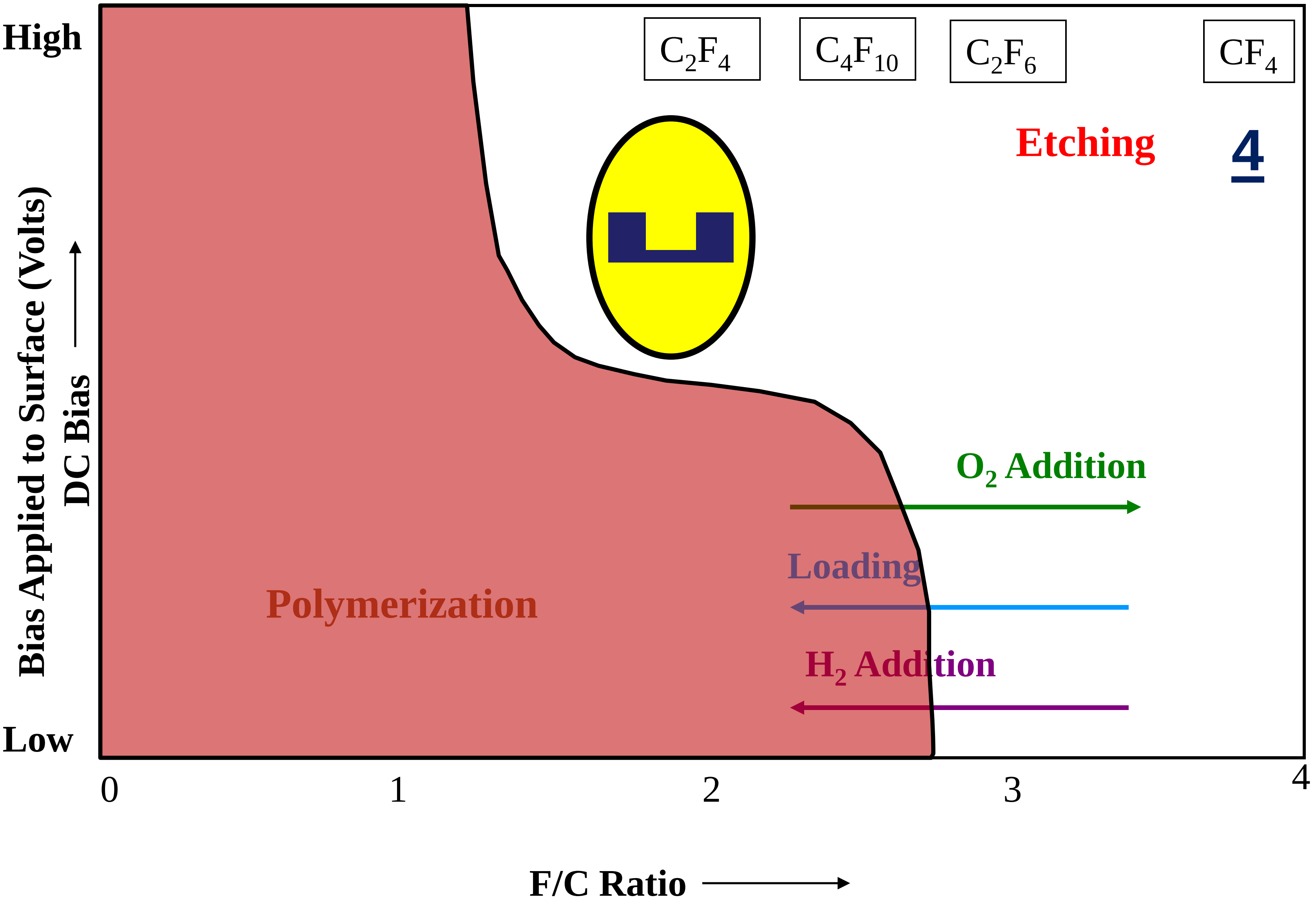
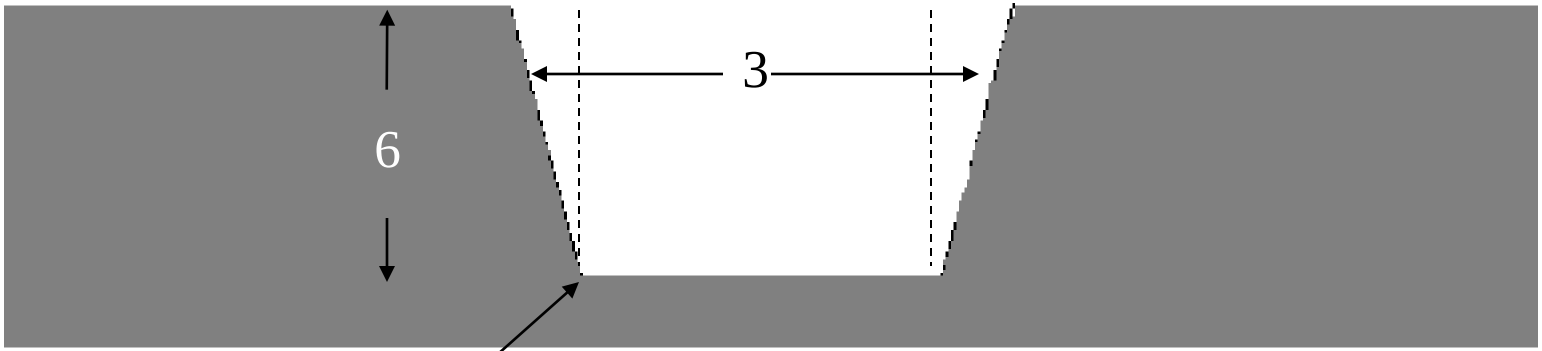
Sidewall Profile Four

- High DC bias – high bombardment
- No H_2 – no polymerization
- A lot of O_2 – high etch
- F/C ratio = 4, SiF_4 is formed
- Aspect ratio >1, a dry etch profile

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



Sidewall Profile Four



Sharp angles due
to high bombardment
with no polymerization

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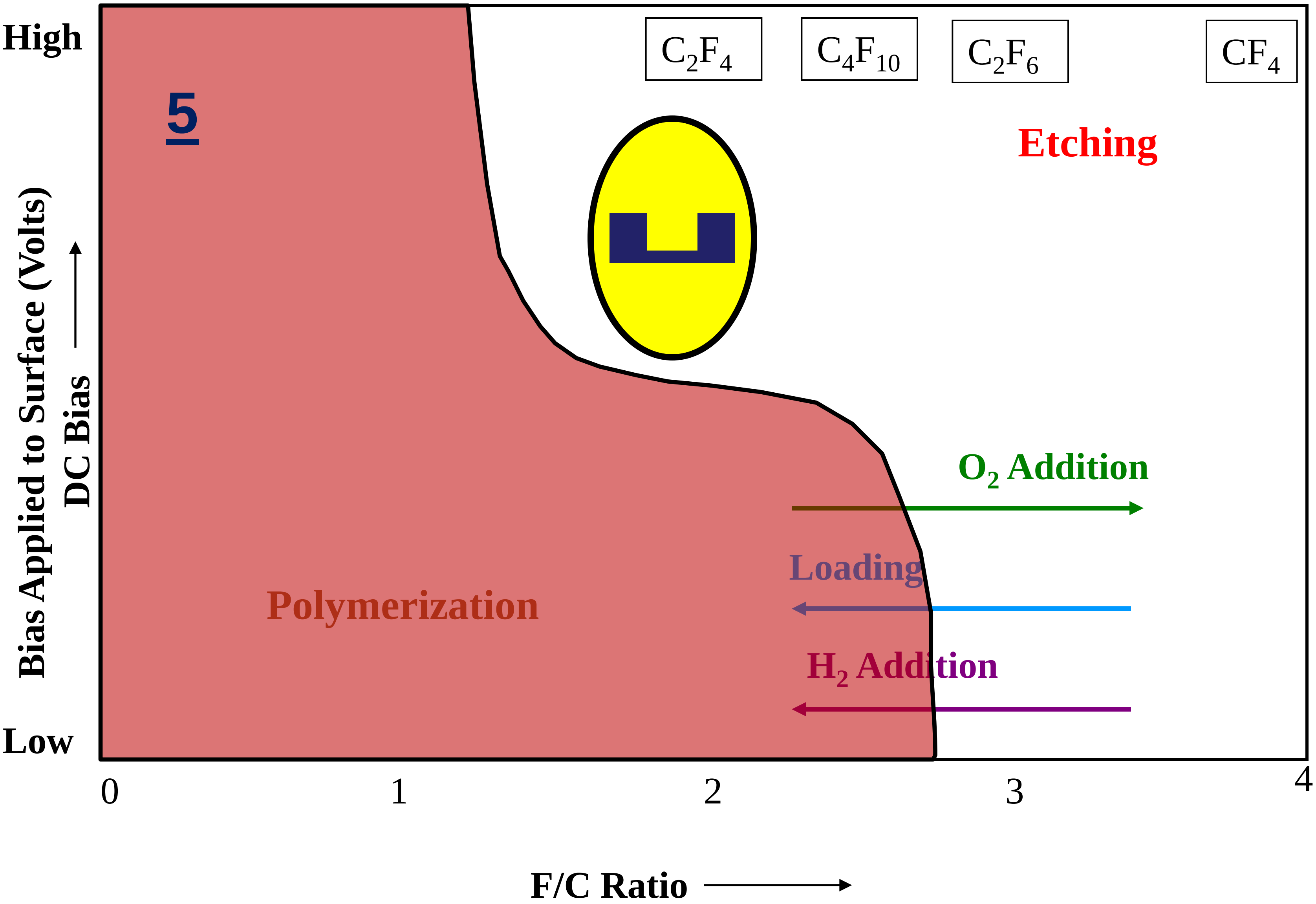
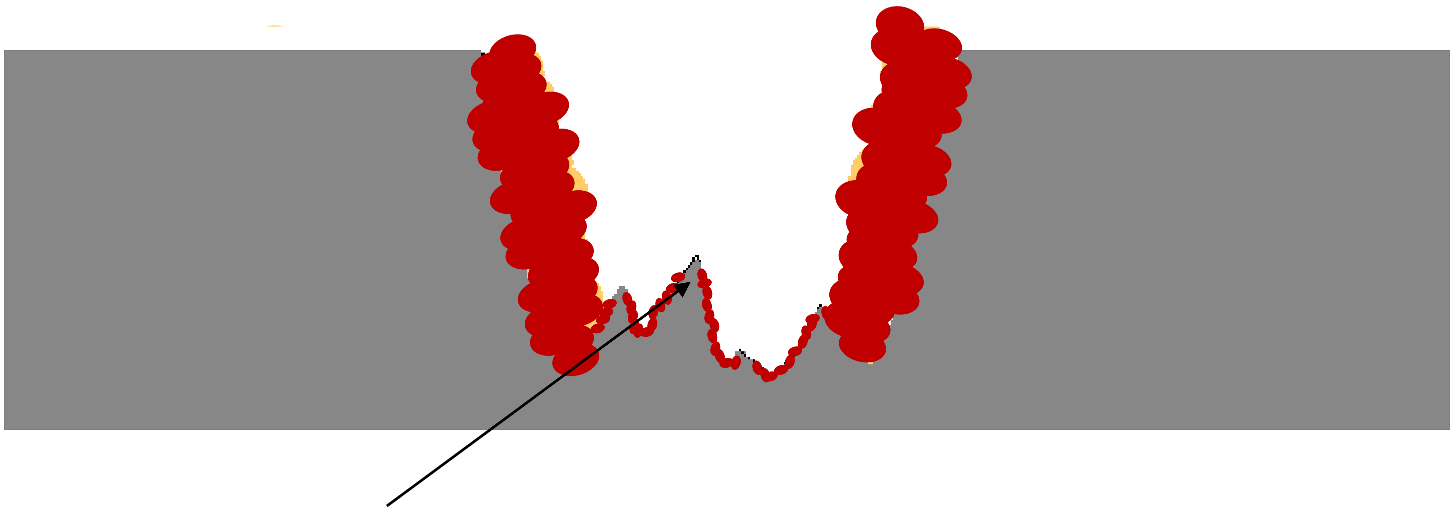
Sidewall Profile Five

- High DC bias – high bombardment
- A lot of H_2 – a lot of polymerization
- No O_2 – no etch
- F/C ratio $= {}^{1}/_{5}$, SiF_4 is not formed
- Aspect ratio > 1, Dry etch profile with undesirable features

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



Sidewall Profile Five



Jagged features
due to
polymer buildup

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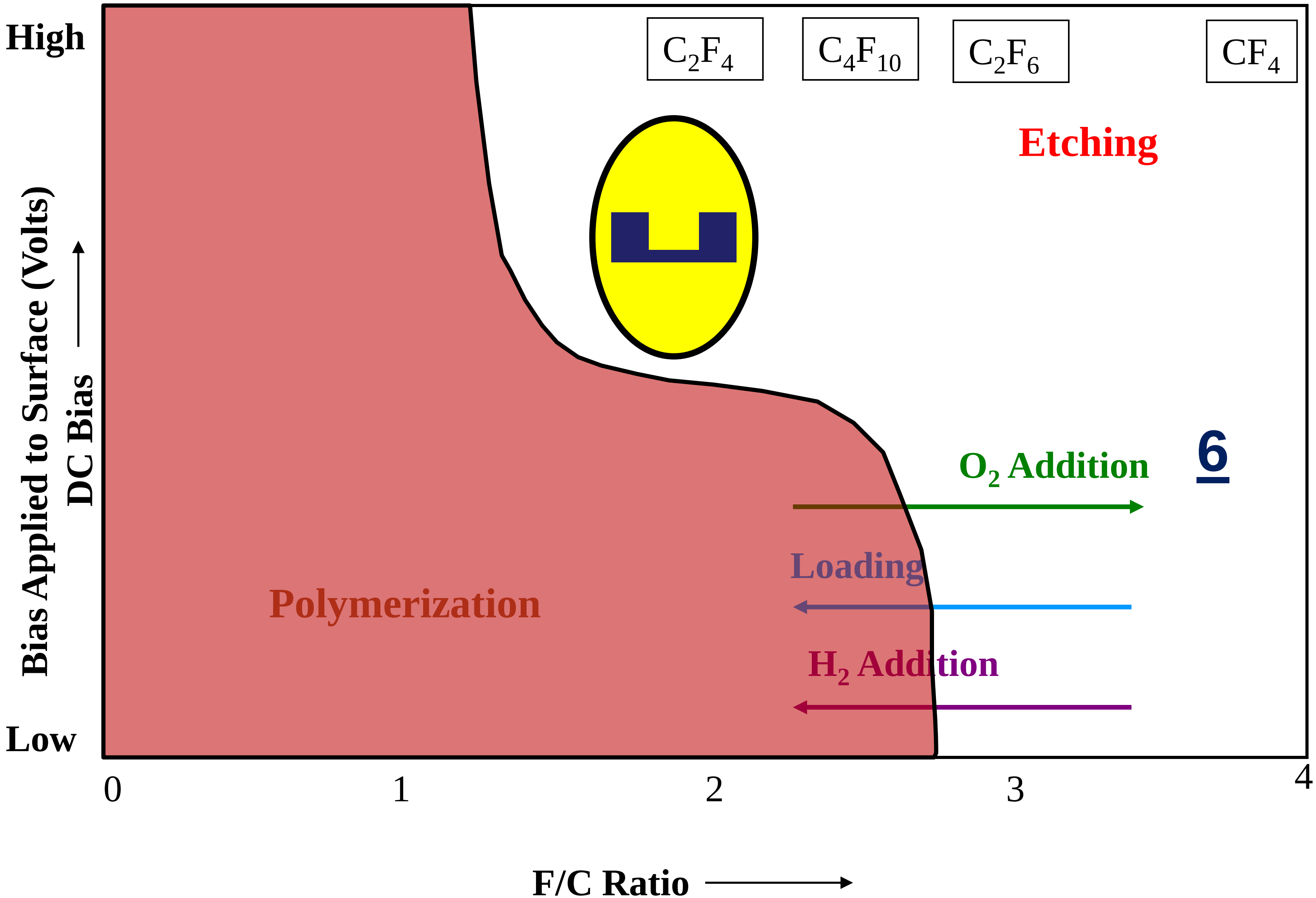
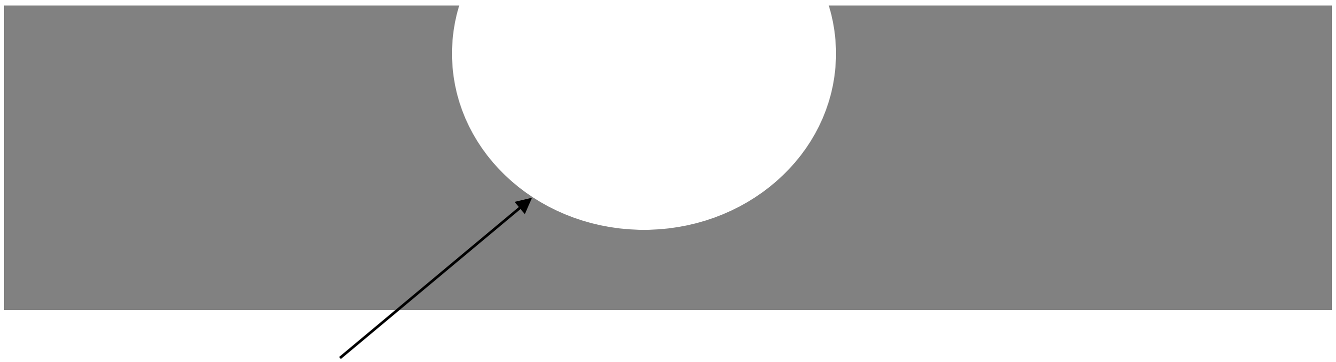
Sidewall Profile Six

- Medium DC bias – medium bombardment
- No H_2 – no polymerization
- A lot of O_2 – high etch
- F/C = 4, SiF_4 is formed
- Aspect ratio < 1, a wet etch profile

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



Sidewall Profile Six



Wider and deeper than profile one due to increased bombardment

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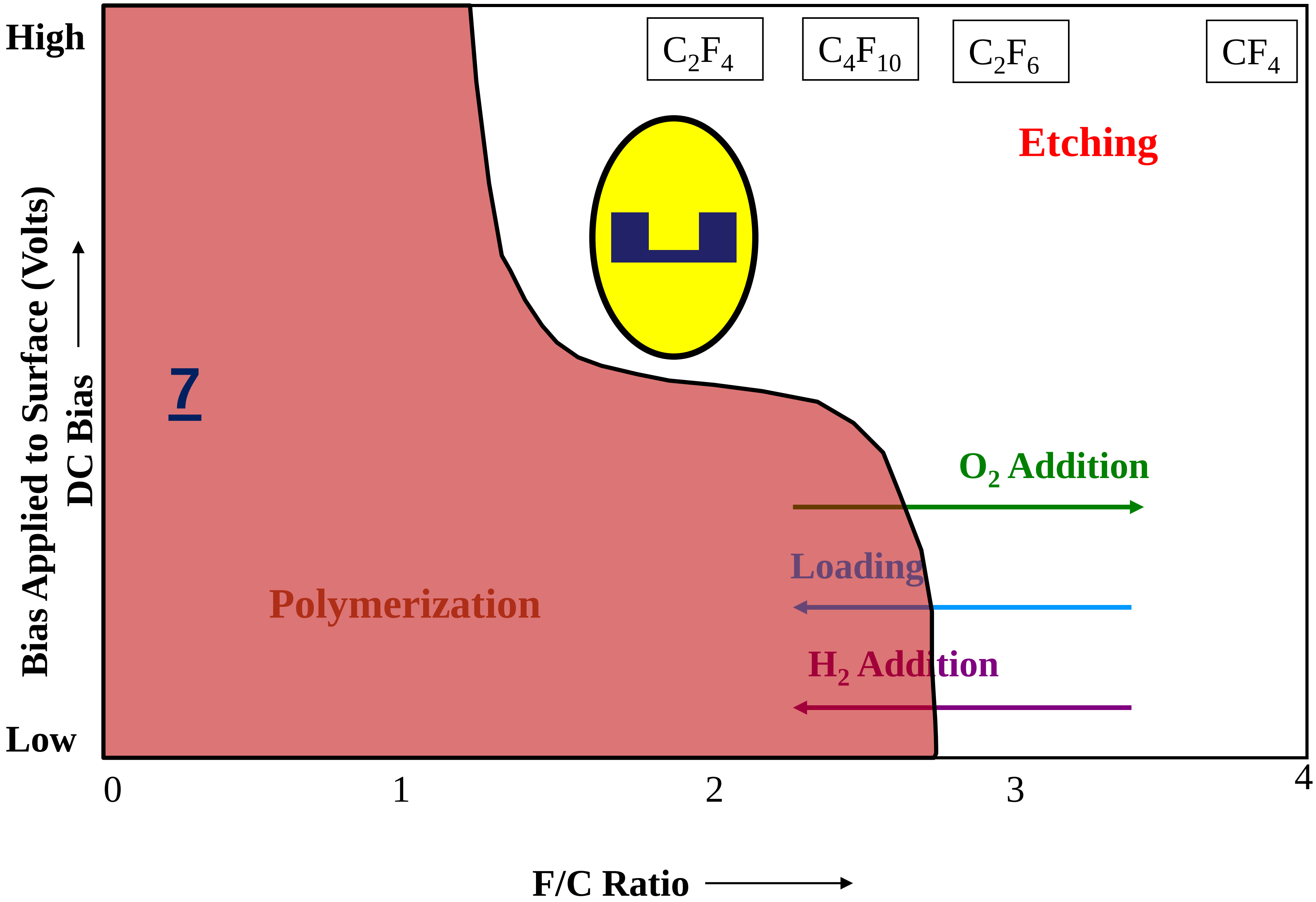
Sidewall Profile Seven

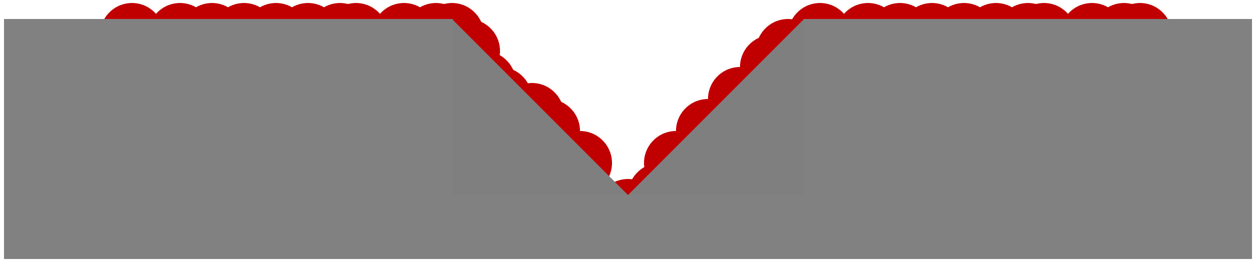
- Medium DC bias – medium bombardment
- A lot of H_2 – a lot of polymerization
- No O_2 – no etch
- F/C ratio = ¼, SiF_4 is not formed
- Aspect ratio > 1, Dry etch profile with undesirable features

Fluorine to Carbon Ratio (F/C) of Gas Phase Etching Species vs DC Bias Level



Sidewall Profile Seven

Less bombardment than profile four



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Considerations Beyond the Egg Chart

- The “egg chart” is a useful first approximation to define some process parameters, but it does not cover some important considerations.
- We will discuss 4 additional considerations:
  - Residence time
  - Microloading
  - Proximity effect
  - Post etch evaluation

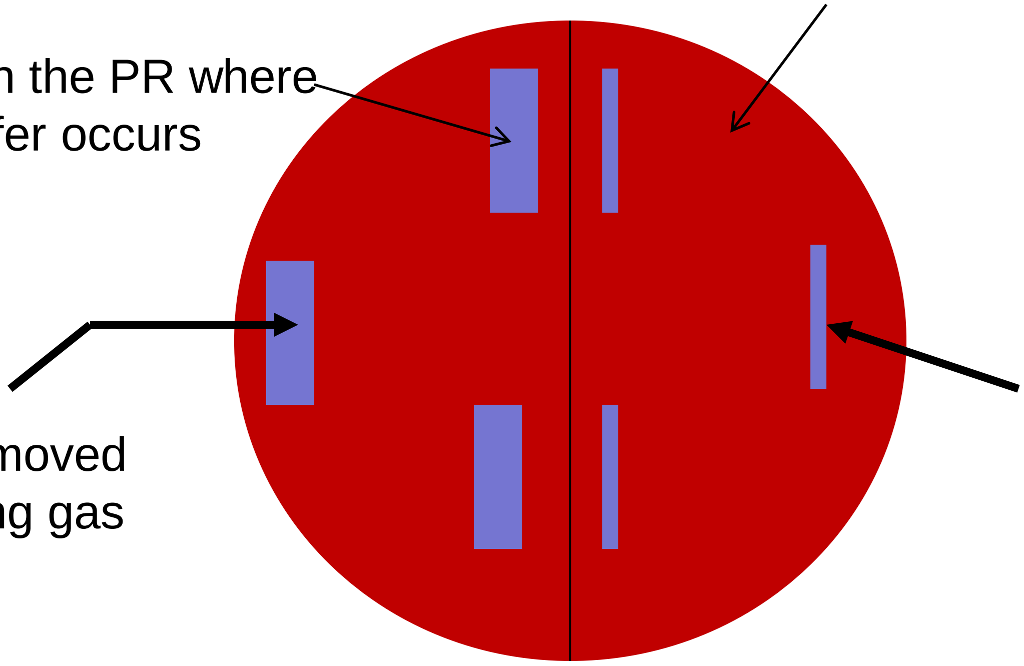
Residence Time

- The average time gas is present in the chamber (seconds)
- The residence time is a balance of the pressure, input gas flow, and the pump efficiency
- Naturally the residence time will impact the etch process, because etch chemistry and byproducts are constantly being pumped away at a certain rate

Microloading

- The change in local etch rate relative to the whole area of material being etched
  - A large area will load the etching process with volatile etch products, slowing the etch down in that area while a smaller etch area proceeds at a faster rate
- Etch rates change according to pattern and exposed area

Microloading



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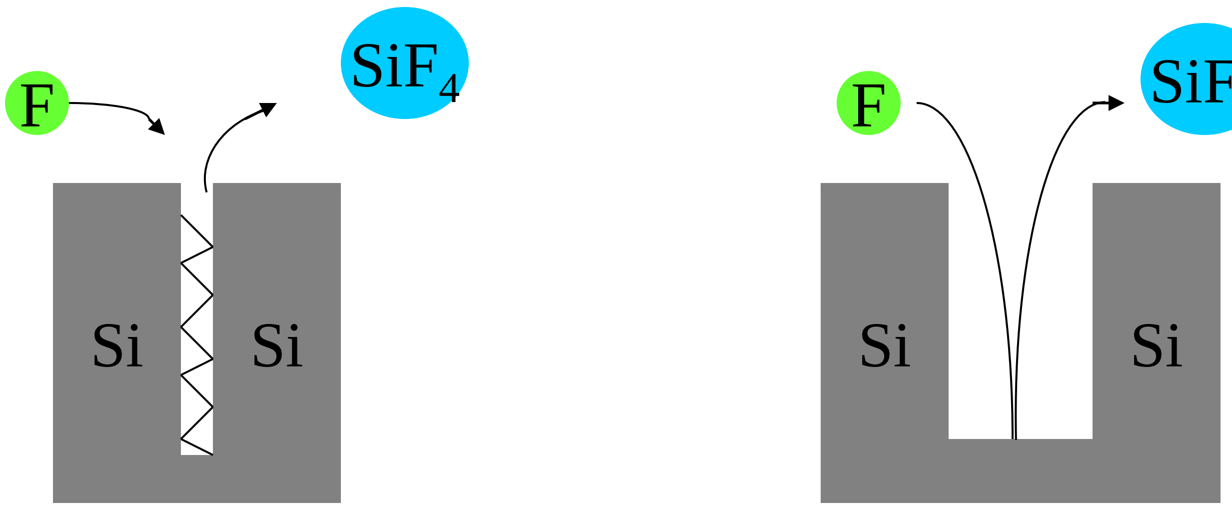
Proximity Effect- Etch Rate Based on Feature Size



"Crowded"-
harder to remove byproducts, slower etch rate

Easier to remove byproducts, faster etch rate

Etch Evaluation

- Process quality parameters:
  - Etch rate, selectivity, uniformity
  - Sidewall Profile
  - Loss or gain of critical dimensions
  - Corrosion (in metal etch)
  - Reproducibility

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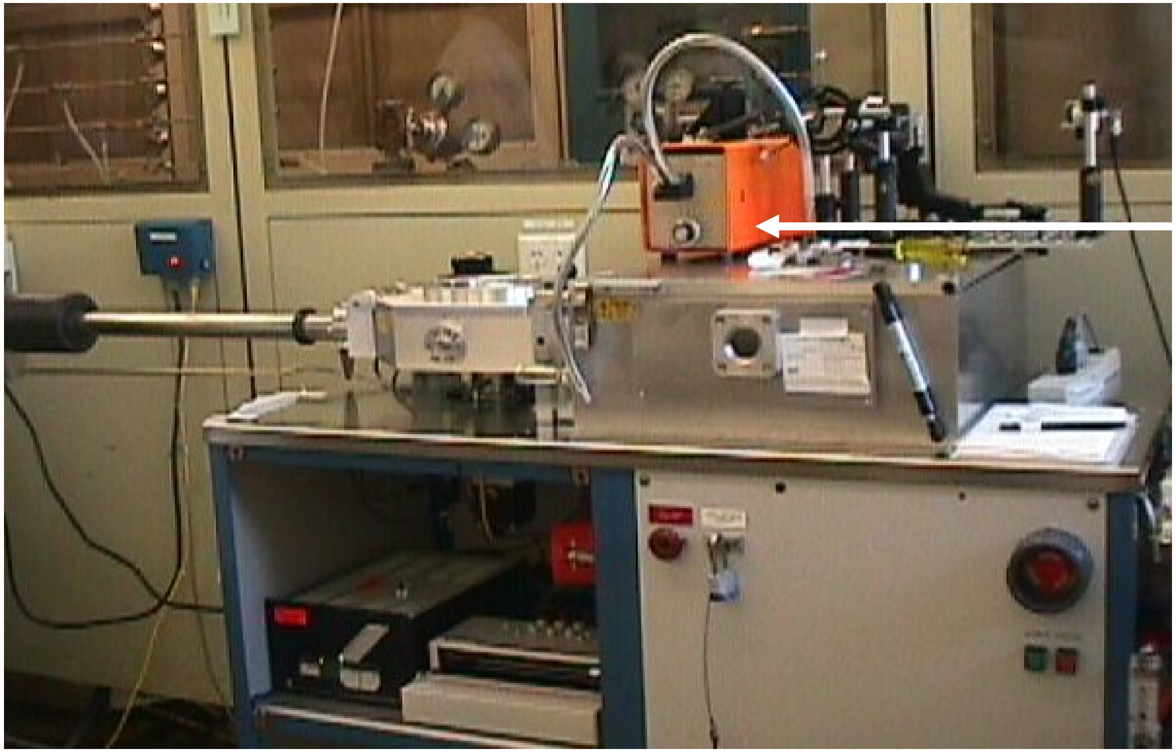
Endpoint Detection

- General term describing when an etch process has finished
- Two common methods of detection
  - Optical emission
  - Mass spectroscopy

Optical Emission

- Each volatile etch product emits a specific wavelength
- The wavelength intensity shows the relative amounts of products being formed
- A decrease in intensity corresponds to a decrease in etch products.

RIE With Optical Endpoint Detector



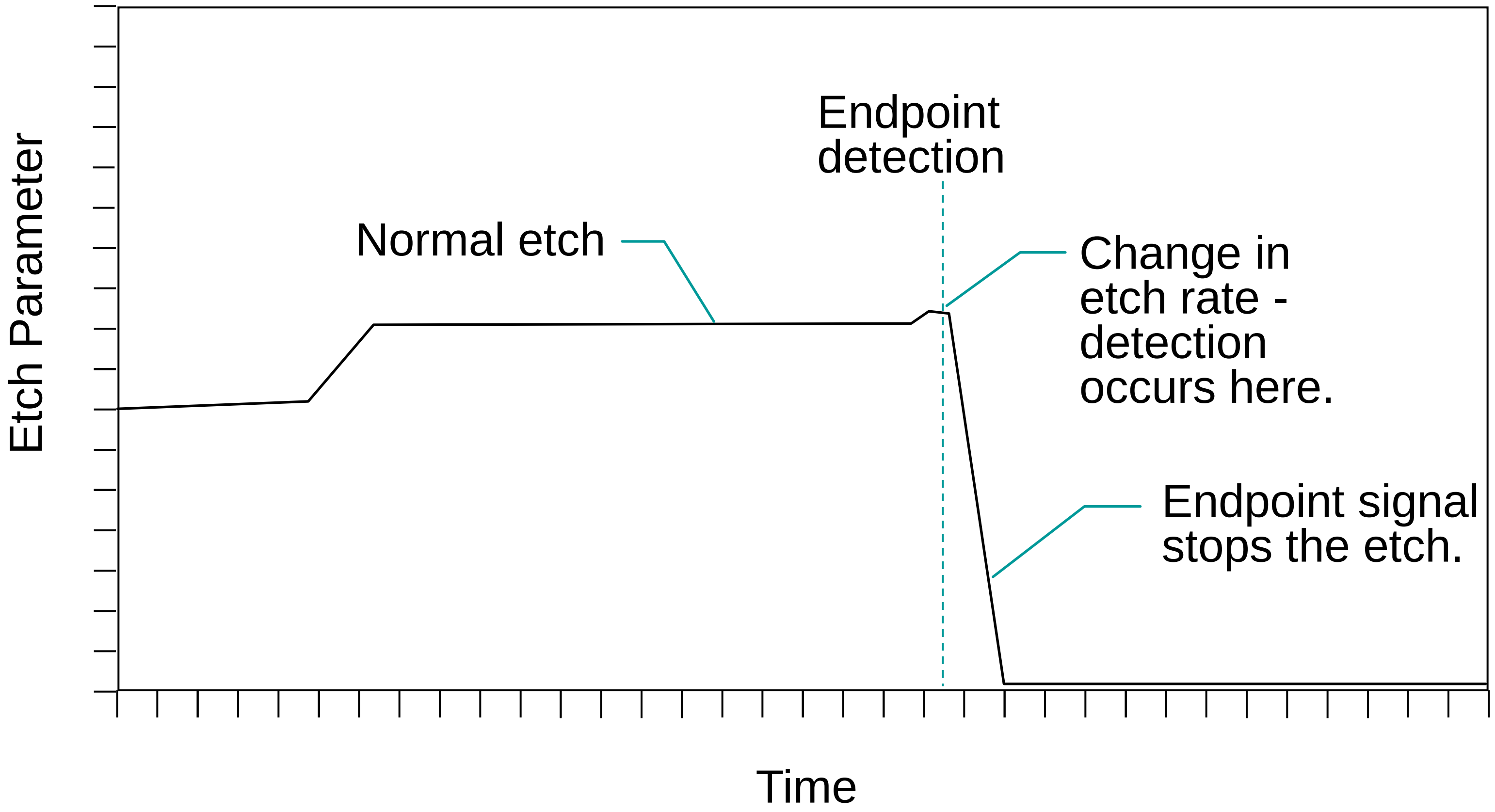
Endpoint Detector

Oxford Instruments Plasmalab System 100

Optical Emission

Material to be etched	Etchant Gases	Emitting Species	λ(nm)
Silicon	CF_4/O_2; SF	F(product)	704
	CF_4/O_2; SF	SiF(product)	440, 777
	Cl_2	SiCl(product)	287
SiO_2	CHF_3	CO(product)	484
Si_3N_4	CF_4/O_2	N_2(product)	337
	CF_4/O_2	CN(product)	387
	CF_4/O_2	N(product)	674
	CF_4/O_2	F(etchant)	704
Al	Cl_2; BCl_3	Al(product)	391, 394, 396
	Cl_2; BCl_3	AlCl(product)	261
Resist	O_2	O(etchant)	777, 843
	O_2	CO(product)	484
	O_2	OH(product)	309
	O_2	H(product)	656

Example Graph of Optical Endpoint Detection



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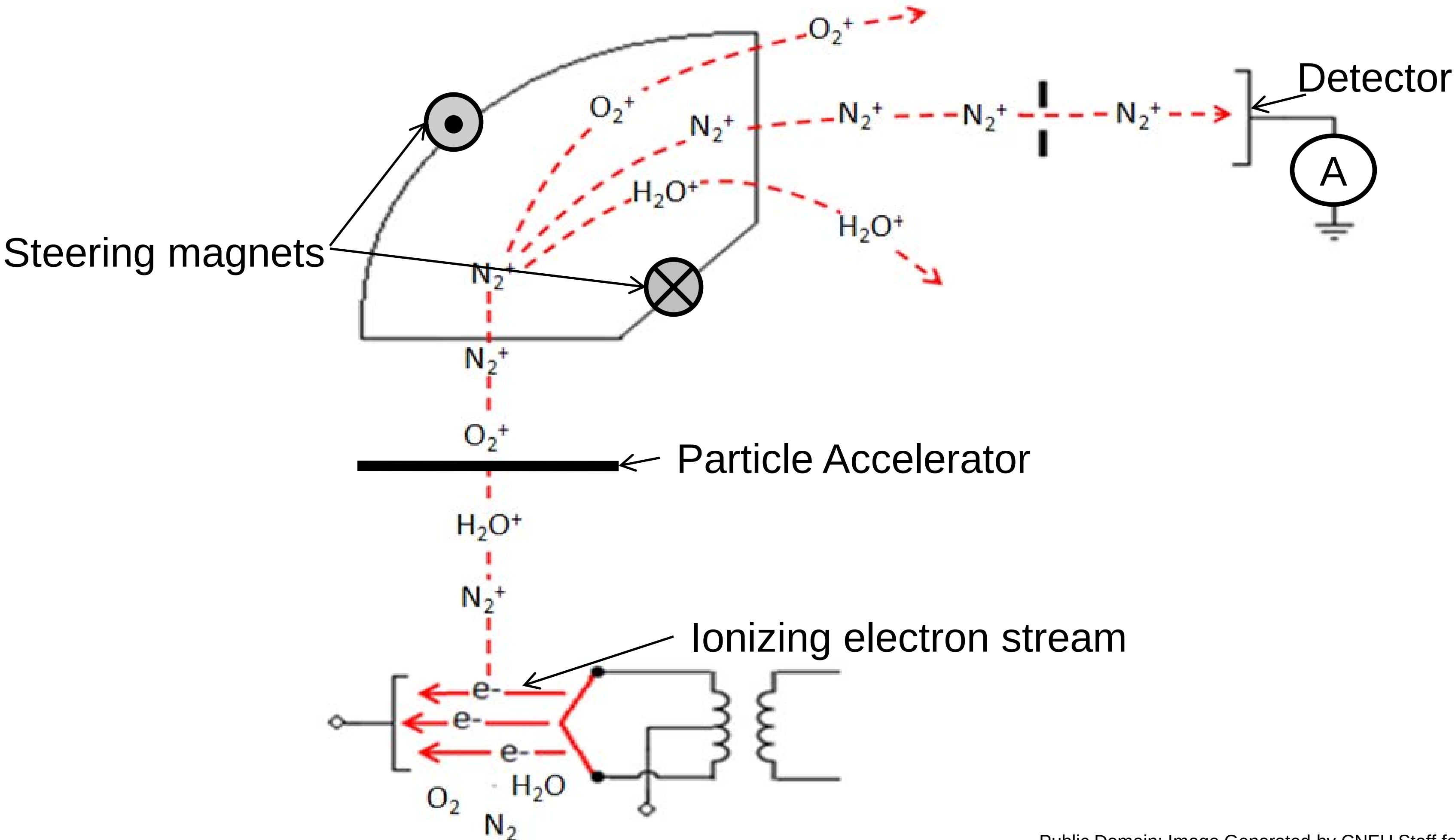
Mass Spectroscopy

- This method of endpoint detection measures the mass/charge ratio of the etch products
- As the mass/charge ratio peak declines, the products being generated by the etch decline due to the material being etched away
- A residual gas analyzer is a mass spectrometer

Mass Spectrometer Schematic



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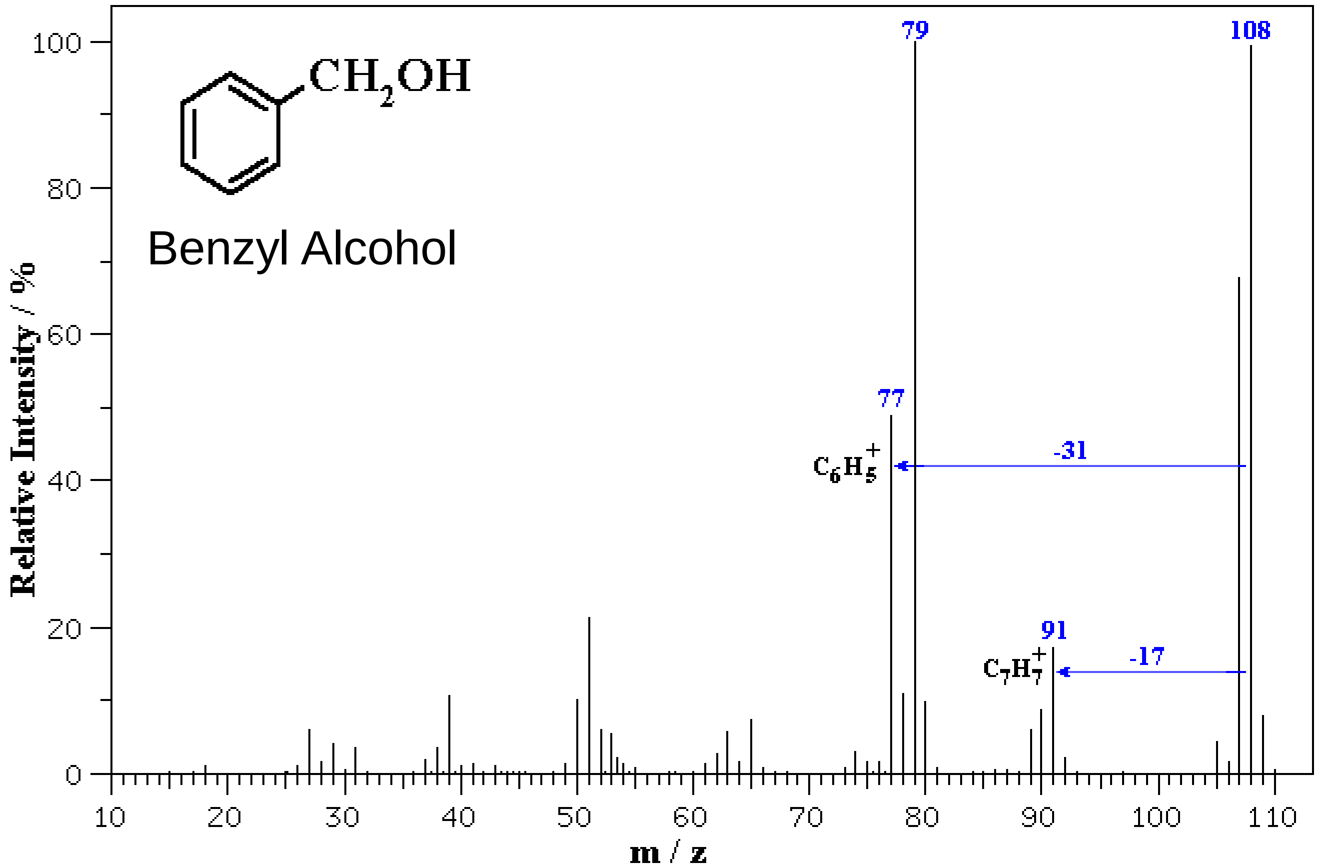
Example Mass Spectra: Benzyl Alcohol



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