PLASMA RIE ETCHING FUNDAMENTALS AND APPLICATIONS

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Purdue University

Outline

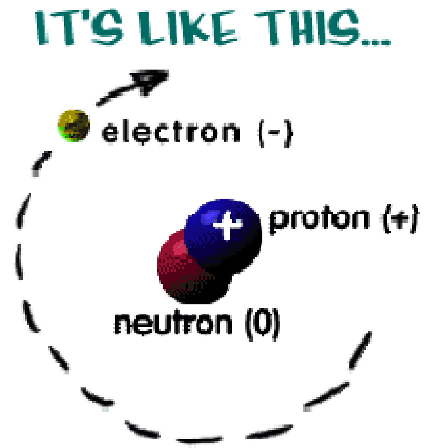
1. Introductory Concepts
2. Plasma Fundamentals
3. The Physics and Chemistry of Plasmas
4. Anisotropy Mechanisms
5. The Etching of Si and its Compounds
6. The Etching of Other Materials

DEFINITIONS

- **Electron (e^-)**

- **Positive ion** (Ar^+, Cl^+, SiF_4^+, CF_3^+)

  Positive ion mass in RIEs >>mass of electron



- **Radical** (F, Cl, O, CF3)

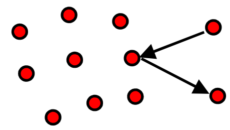
  Uncharged atoms with unsatisfied chemical bonding

DEFINITIONS (continued)

- Mean free path ⇨ average distance a particle travels before collisions

$$\lambda(cm) \approx \frac{5}{P(mT)}$$

(Dependent on the species)



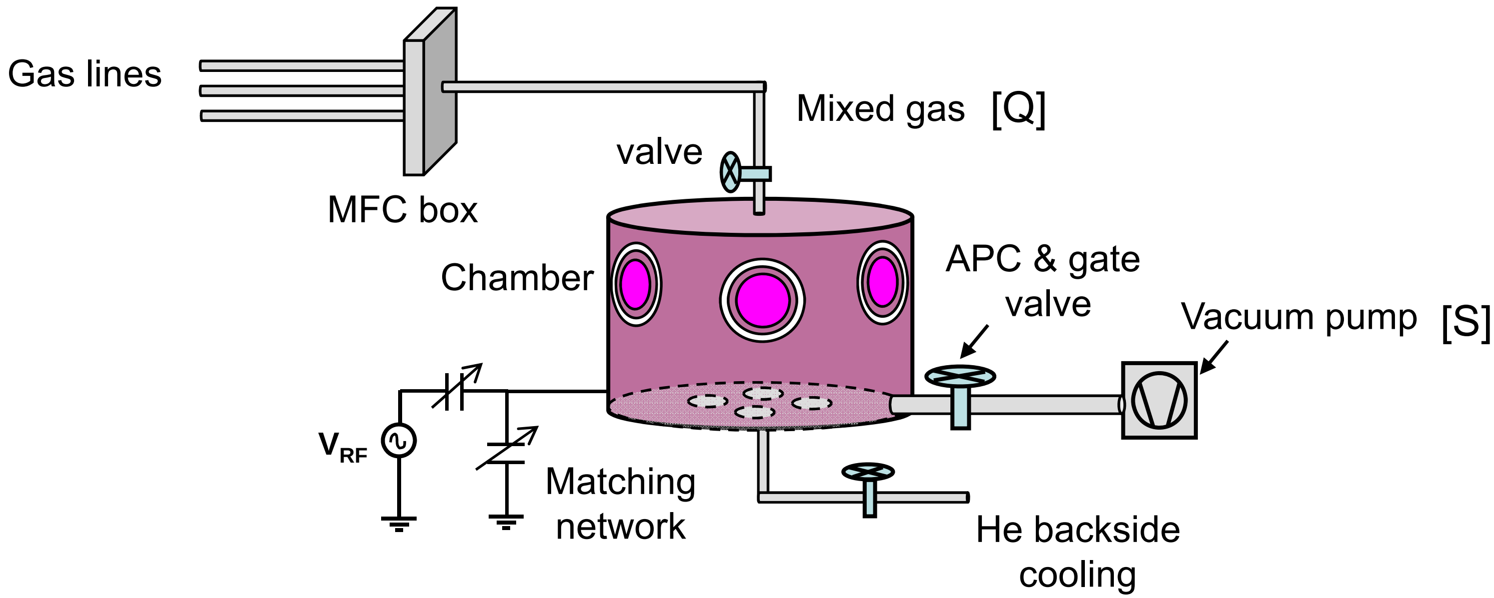
- Pressure

1atmosphere= 760 Torr = 1*10^5 Pascals

- Pumping speed (S) [liters/sec]

- Gas flow rate (Q) [Torr-liters/sec] or [sccm]

Plasma Vacuum System



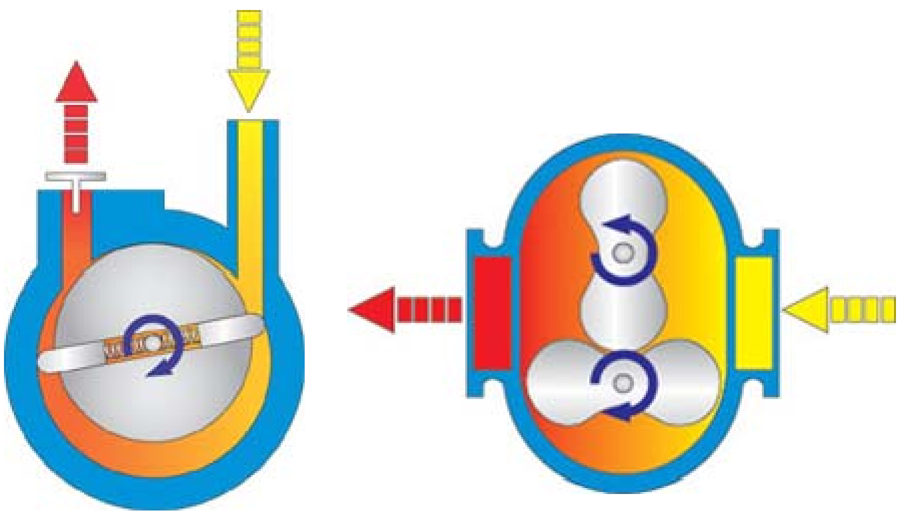
$$\frac{dP(t)}{dt} = \frac{(Q - S \cdot P(t))}{V}$$

V= chamber volume

$$\text{In Steady state}: Q = S \cdot P$$

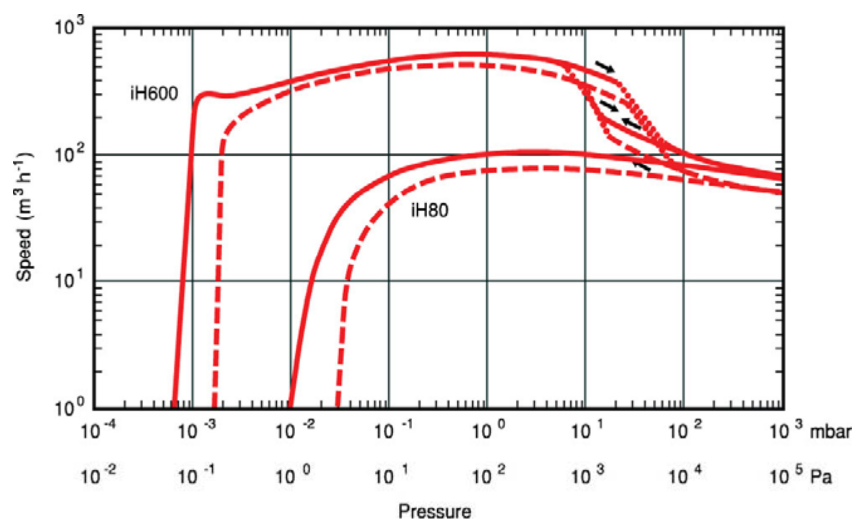
Mechanical Pumps

Wet and Dry Pumps
Pumping speed: 20-500 m^3/h
Ultimate pressure: 1-10 mTorr



[Kurt J. Lesker]

[BOC Edwards Dry Pump]

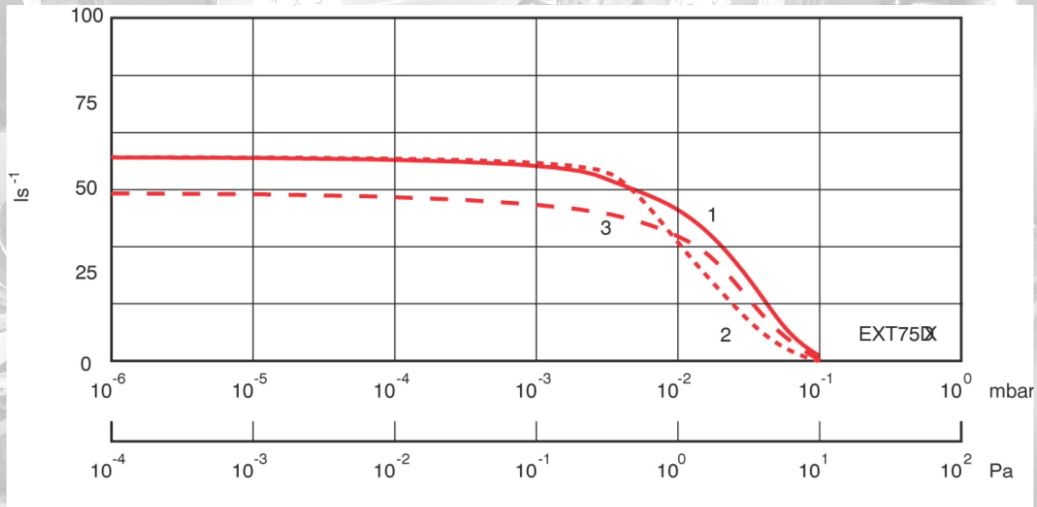


Turbo Pumps

Rotation speed= 20000-90000 rpm
Pumping speed: 50-3000 l/s
Ultimate pressure: 10^{-5}-10^{-8} Torr

[Wiki]

[TP controller]

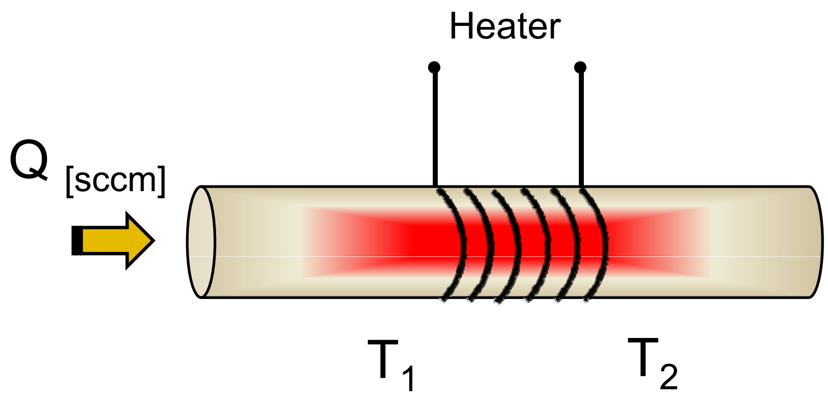


[BOC Edwards Turbo Pump]

Mass Flow Controller (MFC)

[HORIBASTEC]

Thermal-based flow meter

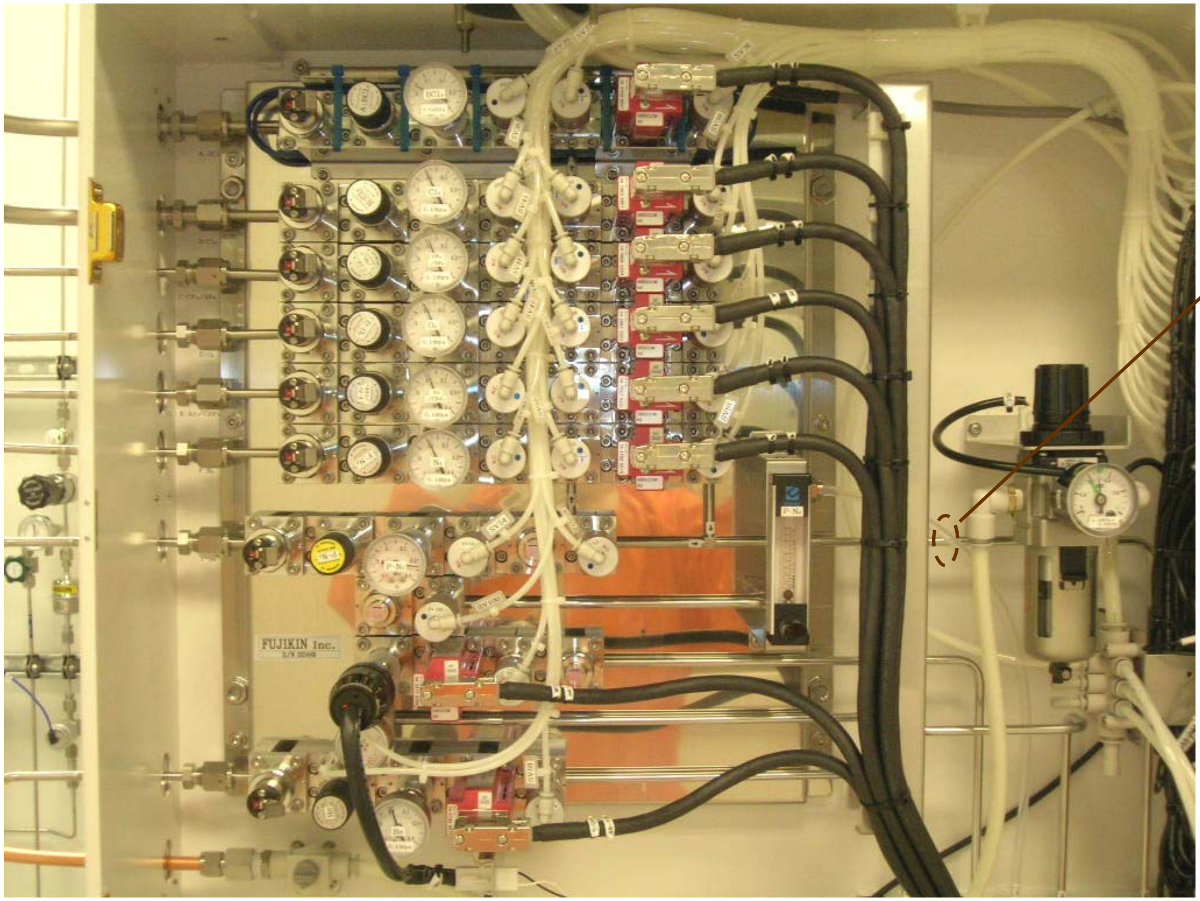


$$T_2 - T_1 = C_p \times Q$$

C_p is specific heat.

MFC or Gas Box

Gas lines



Mixed gas line

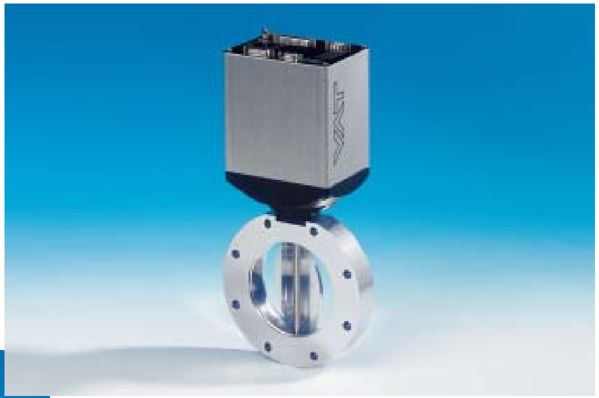
Panasonic MFC Box

Automatic Pressure Controller (APC) & Gate Valve

Pendulum valve

$$Q = S \times P$$

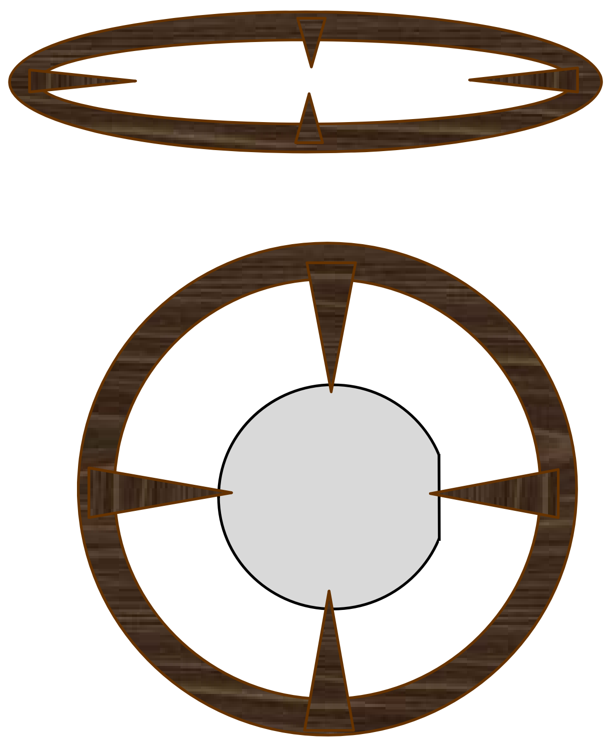
Butterfly valve



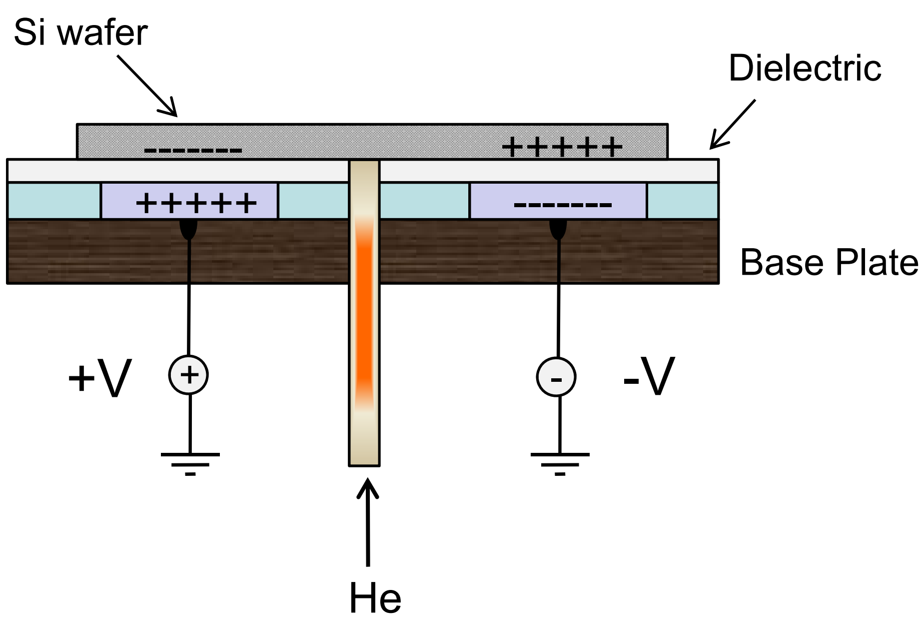
[VAT]

Clamp or Electrostatic Chuck

Clamp



Electrostatic Chuck (ESC)



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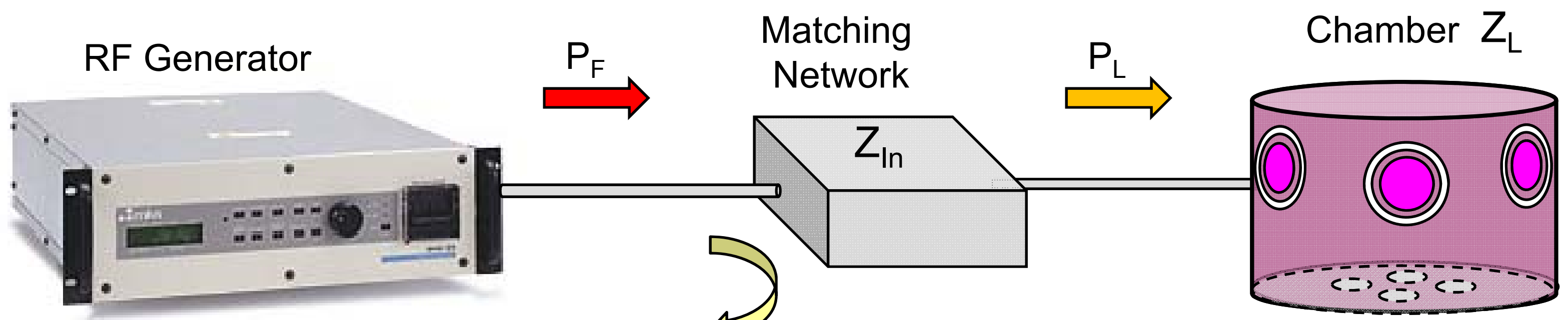
RF Generator & Matching Network



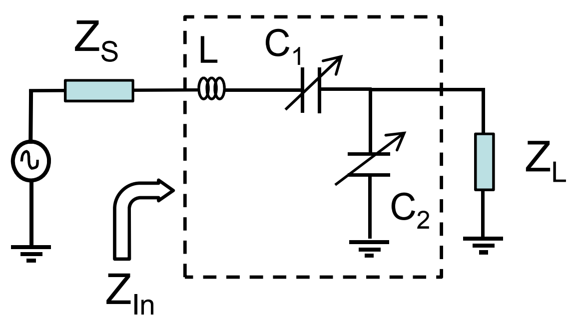
Z_S= 50Ω

P_L=P_F- P_R

In general: $Z_L \neq Z_S$

Purpose of Matching Network: Z_{in}= Z_S to maximize power delivery from source.

Manual or Automatic Matching Network



[Gambetti]

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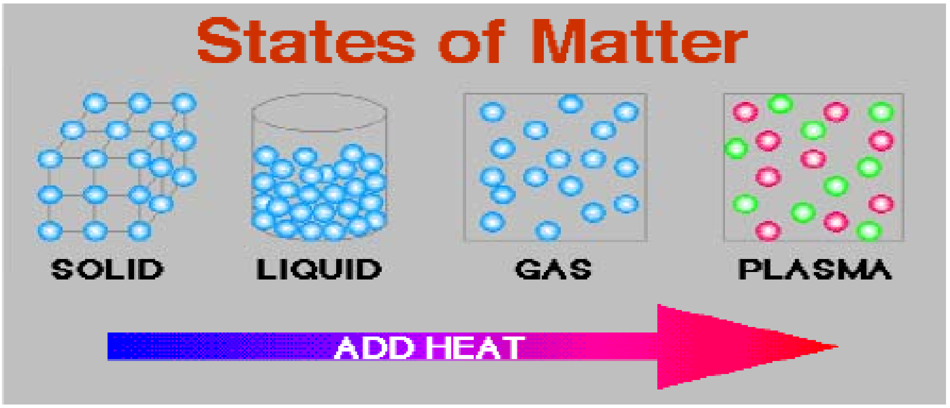
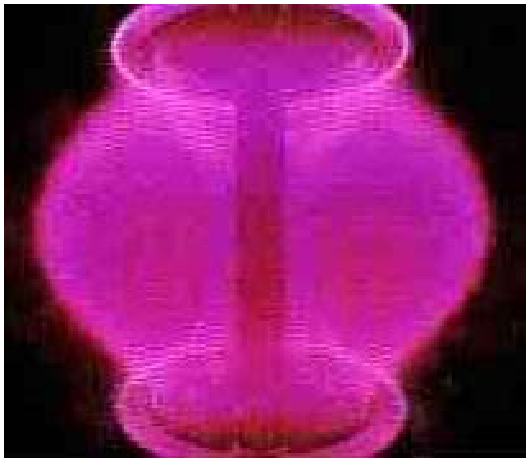
[Plasmas.org]

What is Plasma?

- Plasma is the fourth state of matter. It is an ionized gas, a gas into which sufficient energy is provided to free electrons from atoms or molecules and to allow both species, ions and electrons, to coexist.





[Plasmas.org]

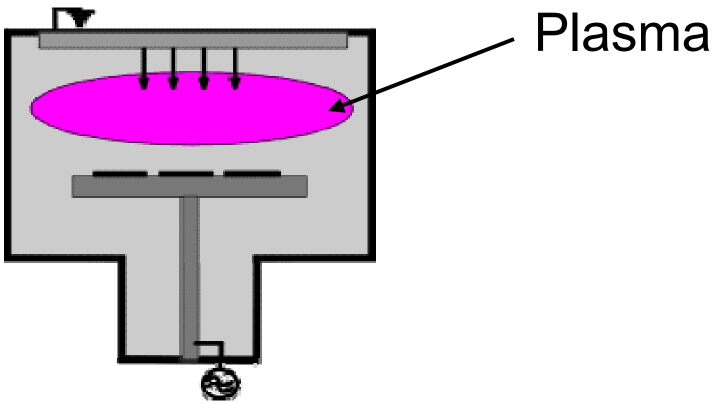
How to Make Plasma?

➢ Capacitive RIE

- Low density plasma

$n_e \approx 10^9$ [electron/cm^3]

Ionization efficiency ≈ 10^{-7}

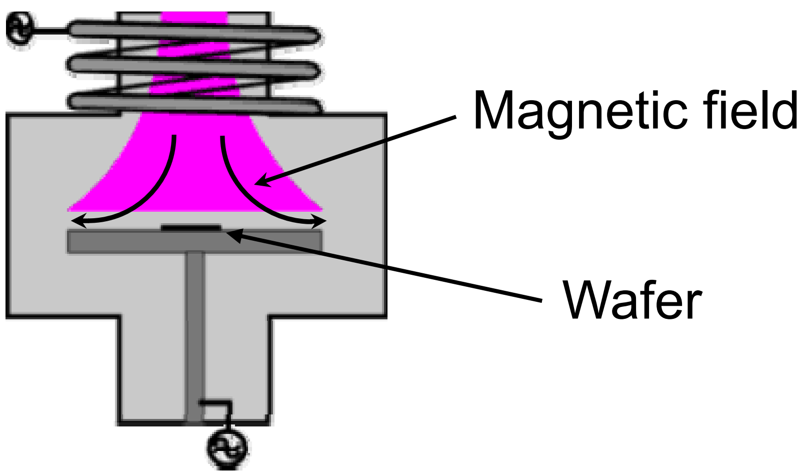


➢ Inductive RIE

- High density plasma

$n_e \approx 10^{13}$ [electron/cm^3]

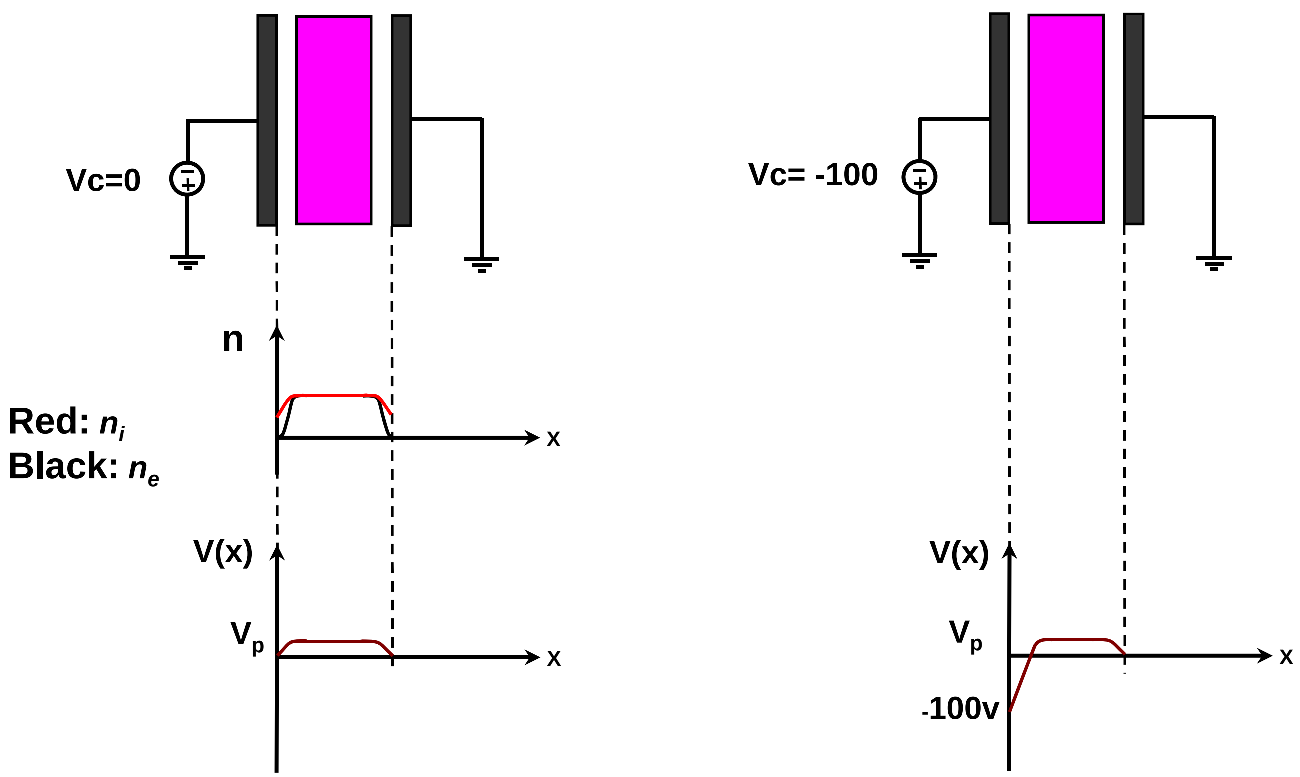
Ionization efficiency ≈ 10^{-3}



[Oxford Instruments]

DC Glow Discharge

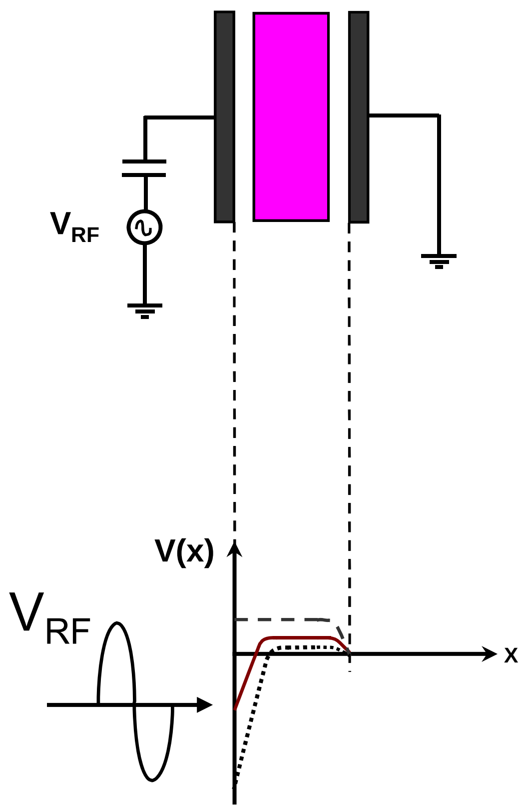
- **Only used for sputtering system not for etching.**

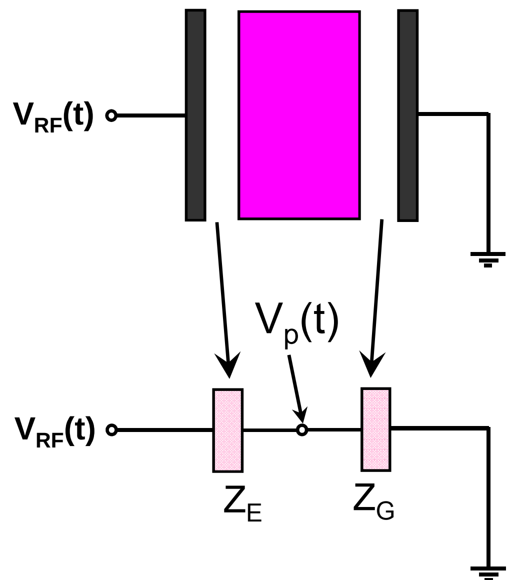


V_p= a few volts

RF Glow Discharge

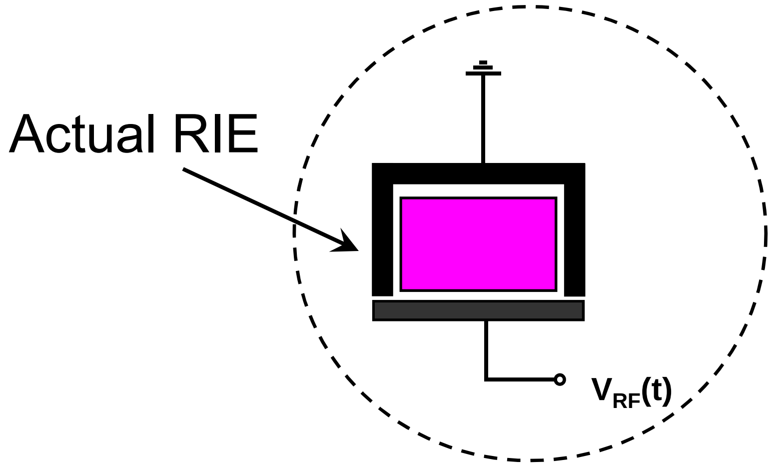
- **Used for any materials (insulating and conductive) .**





$$V_p(t) = \frac{Z_G}{Z_G + Z_E} V_{RF}(t)$$

RF Glow Discharge



$$V_p(t) = \frac{Z_G}{Z_G + Z_E} V_{RF}(t)$$

$A_E << A_G \Rightarrow Z_E >> Z_G$

$V_p(t) \approx 0$

- Ion transit time (T_{ion}) is the time it takes the ion to traverse the sheath.
- $1/Freq << T_{ion}$!

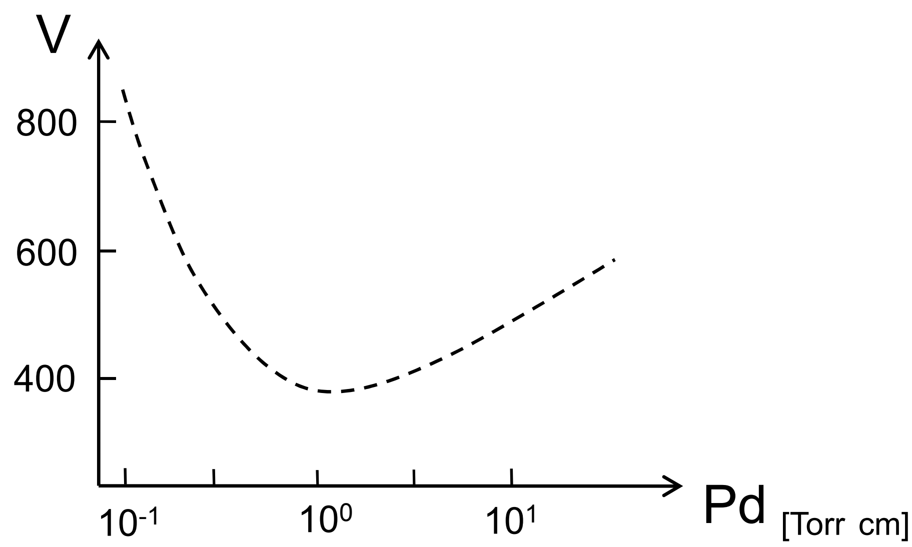
Freq= 13.56 MHz

Paschen’s Law

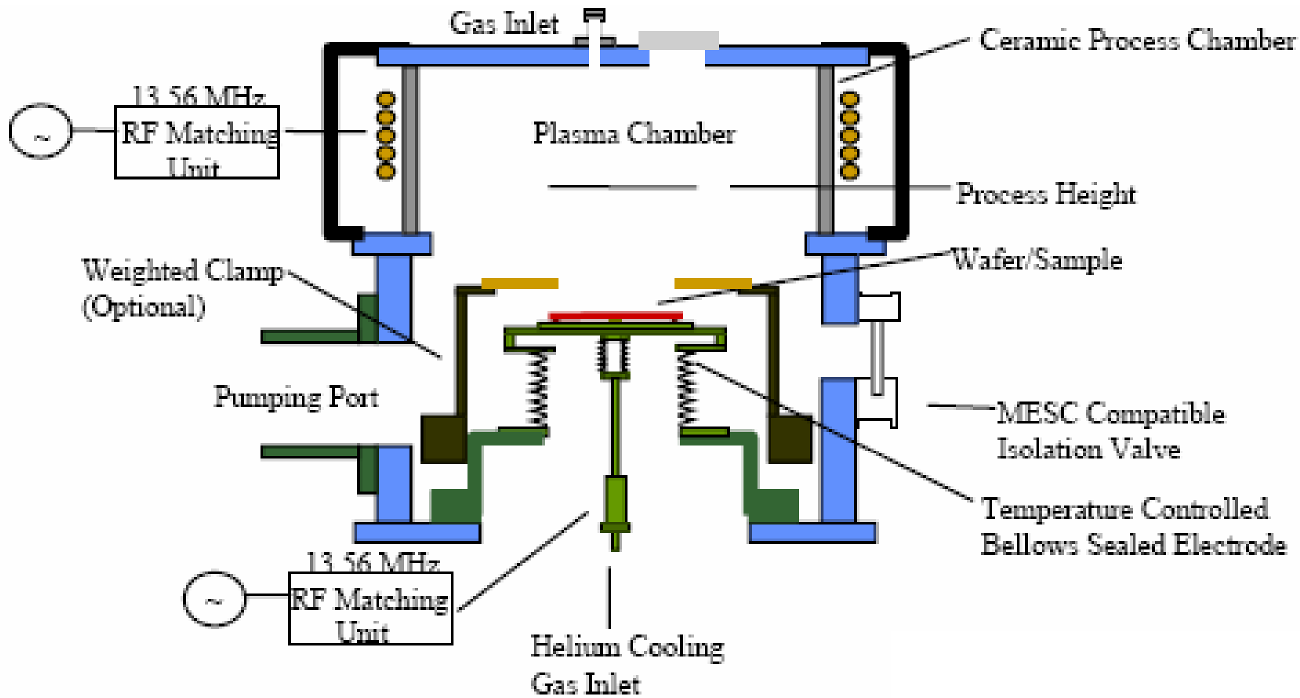
Describes how the breakdown voltage depends on electrode separation and the pressure based on ideal gas law.

$$V = \frac{a \times (p.d)}{\ln(p.d) + b}$$

V: Voltage
p: Pressure
d: gap distance
a & b: constants



Inductive Coupled Plasma RIE



STS ASE and AOE systems

Why High Density Plasmas?

- Lower ion bombardment energies improve selectivity and reduce ion-bombardment-induced physical damage of the wafer surface.
- Lower ion energies, however, result in the lower etch rates and reduced anisotropy!
- However, the etch rate can be increased by using much higher ion fluxes due to high density plasmas.
- The anisotropy can also be restored by operating at low pressure.

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Electron-Molecule Collisions

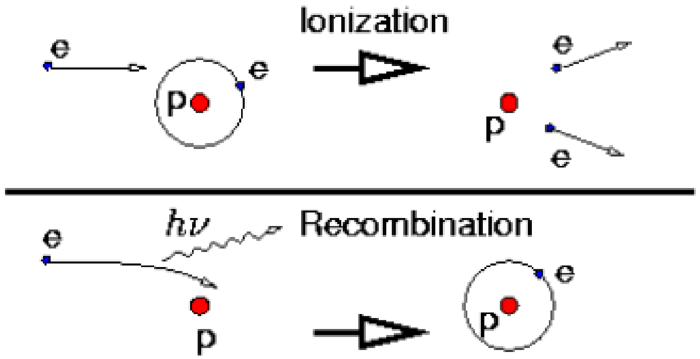
- An energetic electron colliding with a neutral etch gas molecule can create any of the following processes:

✓ Dissociation $AB + e^- \rightarrow A + B + e^-$ ⟶ $CF_4 + e^- \rightarrow CF_3 + F + e^-$

✓ Ionization $AB + e^- \rightarrow AB^+ + 2e^-$ ⟶ $Ar + e^- \rightarrow Ar^+ + 2e^-$

Often dissociation and ionization Occur in one collision:

$CF_4 + e^- \rightarrow CF_3^+ + F + 2e^-$



Radicals and Ions in Plasmas

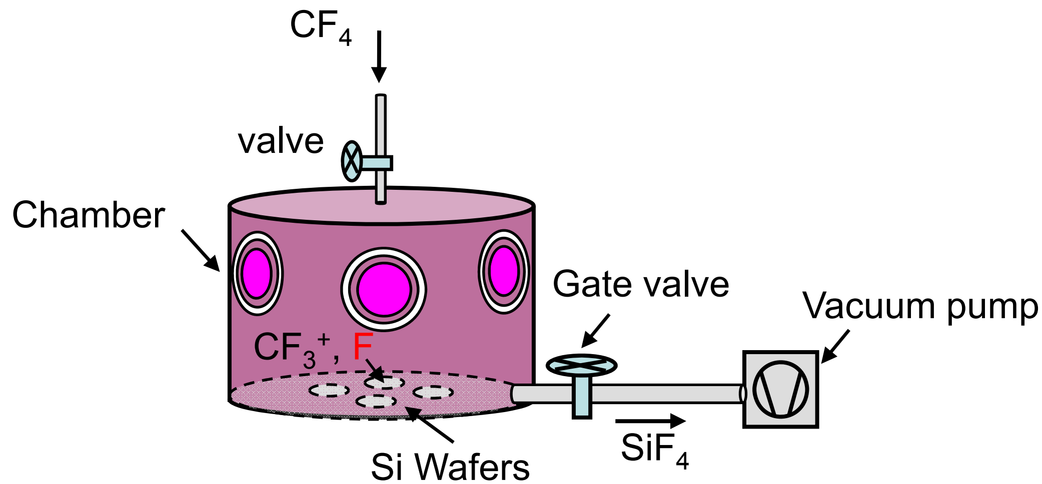
- Positive ions are very important for etching processes.
- Radicals are more numerous than ions in gas glow discharges because:

1. The electron energy required in order to break chemical bonds in the molecules is usually less than the energy required to ionize these molecules.
2. Radicals have a longer lifetime in the plasma compared to ions because an ion is almost always neutralized during a collision with a surface while radicals often do not react with a surface and are reflected back into the plasma.

What is Plasma Etching?

$CF_4 + e^- \rightarrow CF_3^+ + F + 2e^-$

$Si + 4F \rightarrow SiF_4$ (gas)



1- Need an etching gas

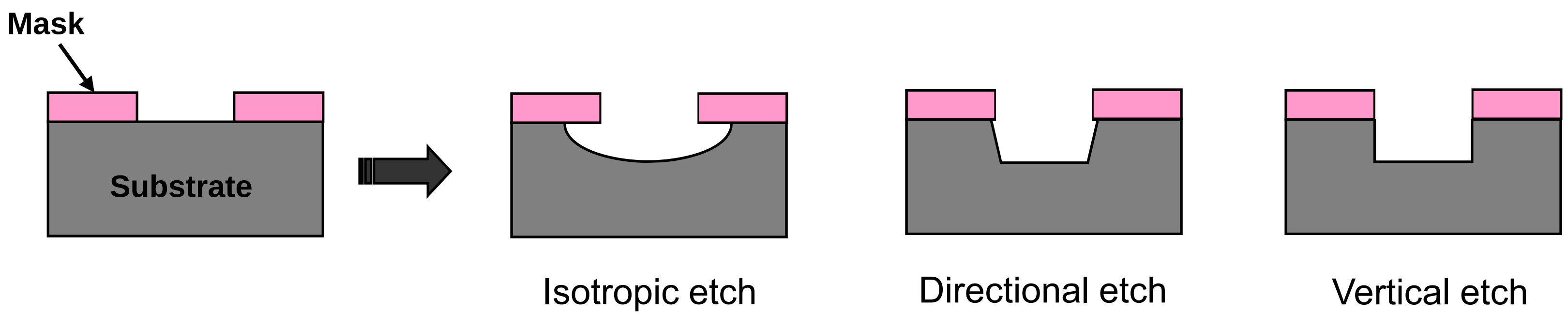
2- Establish a glow discharge

3- Choose chemistry so that the reactive species react with the substrate to form a volatile by-product

4- Pump away the volatile by-product

Why Plasma Etching?

- Clean process
- Compatible with automation
- Anisotropic etching
- Precise pattern transfer especially for Nano-scale features



Gas-Solid Systems

Solid	Etch Gas	Etch Product
Silicon	CF_4,Cl_2, SF_6	SiF_4, $SiCl_4$, $SiCl_2$
SiO_2, SiN_x	CF_4, C_4F_8, CHF_3, SF_6	SiF_4, CO, O_2, N_2, FCN
Al	BCl_3/Cl_2	Al_2Cl_6, $AlCl_3$
Ti, TiN	Cl_2, CF_4	$TiCl_4$, TiF_4
Organic Solids	O_2, O_2/CF_4	CO, CO_2,
GaAs & III-V	Cl_2/Ar, BCl_3	Ga_2Cl_6, $AsCl_3$
Cr	Cl_2/O_2	CrO_2Cl_2

Difficult materials to etch:

Fe, Ni, Co, Au, Ag, Pt ➡ halides not volatile

Cu ➡ Cu_3Cl_3 is volatile above 200^C

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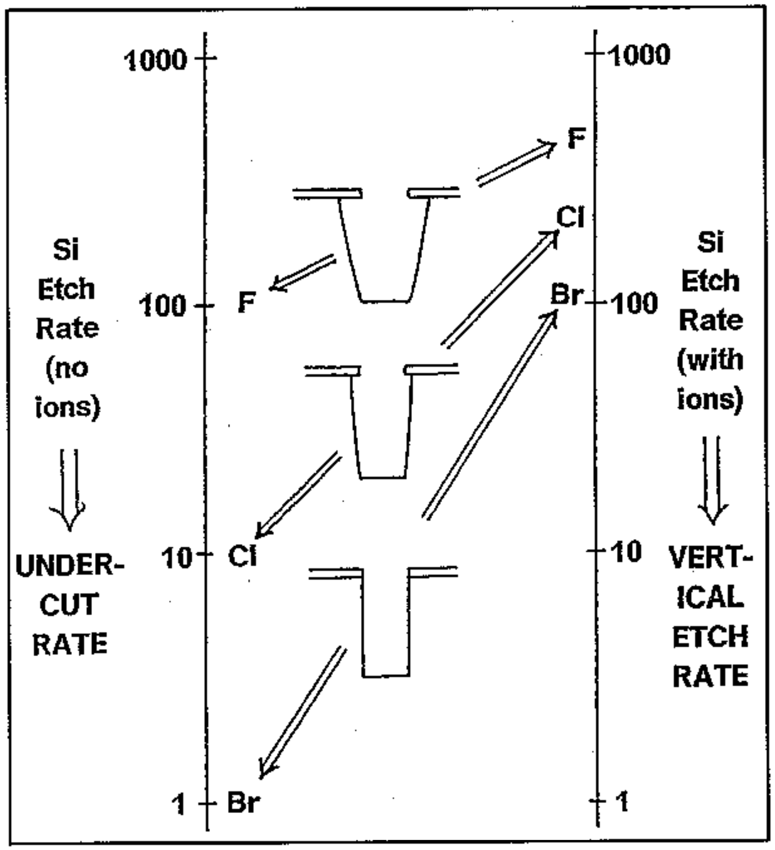
Halogen Size Effect



[Handbook of Advanced Plasma Processing Techniques by Pearton]

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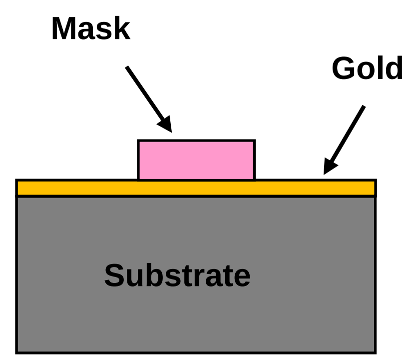
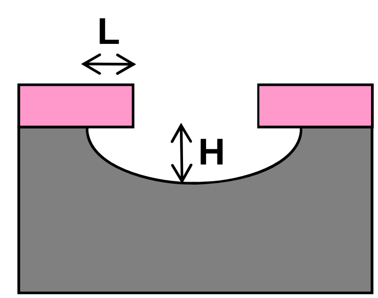
Definition

- Etch rate
- Mask (Photoresist, Metal, SiO_2, …)
- Selectivity
- Anisotropy degree

$$A_f \equiv 1 - \frac{L}{H}$$

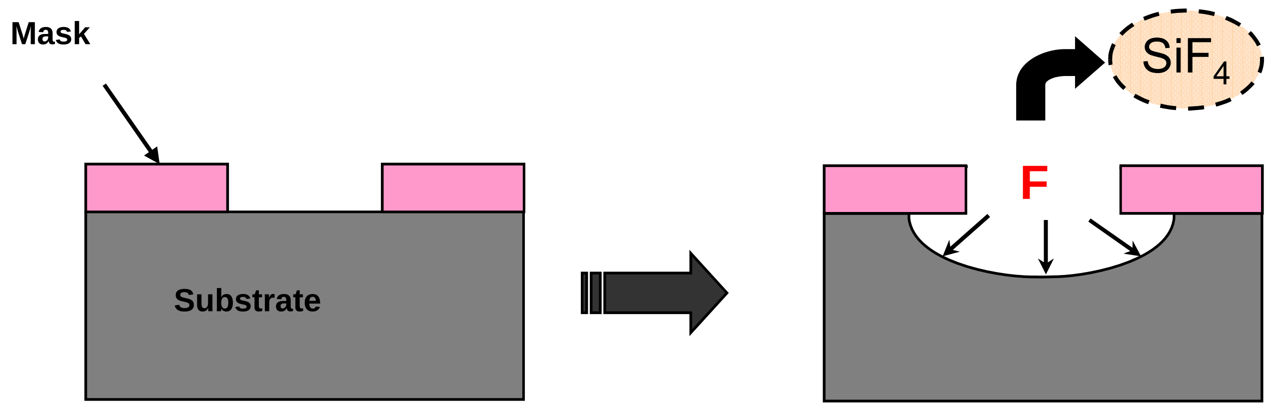




Reactive etching

- Reactive etching is an isotropic process!
- Has very high selectivity!

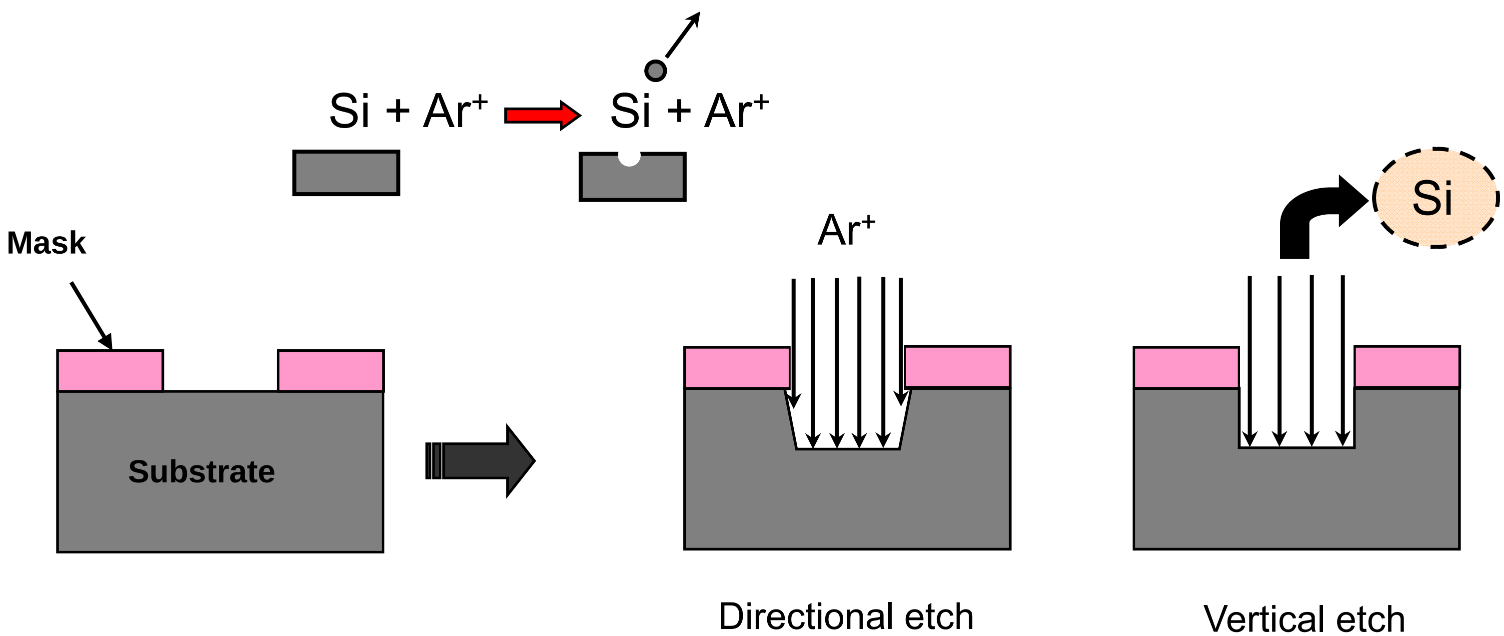
$Si + 4F \rightarrow SiF_4$ (gas)



Isotropic etch

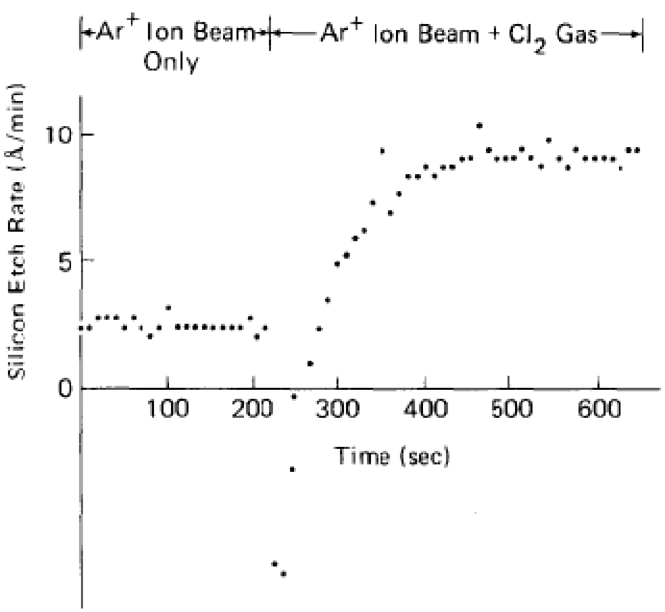
Ion etching

- **Ion etching or mechanical etching is an anisotropic process!**
- **Has lower selectivity and etch rate!**

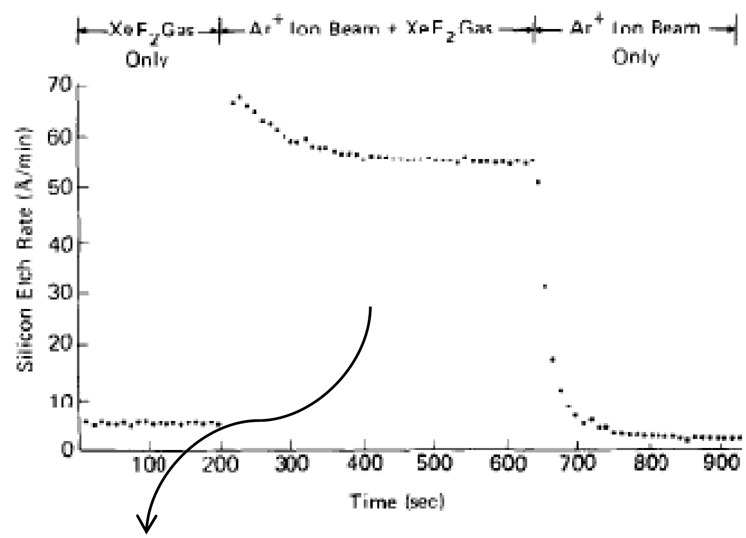


Reactive ion etching

- **Reactive ion etching is an anisotropic process!**
- **Has better selectivity and much higher etch rate!**



[J. Appl. Phys. 50, 3189 (1979)]



Effect of Ions:

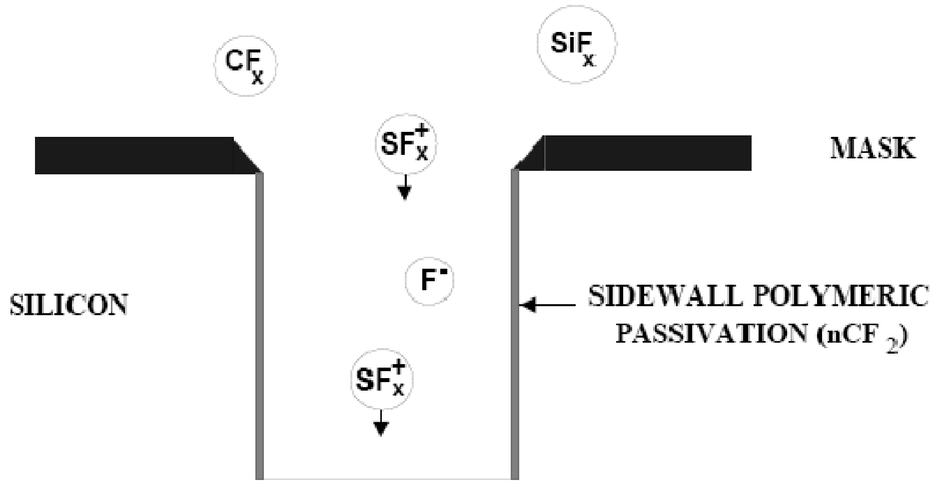
Breaks bonds, raises temperature locally on the surface and provides activation energy

Sidewall Passivation

➢ Deposition of carbon polymer material on the sidewalls where:

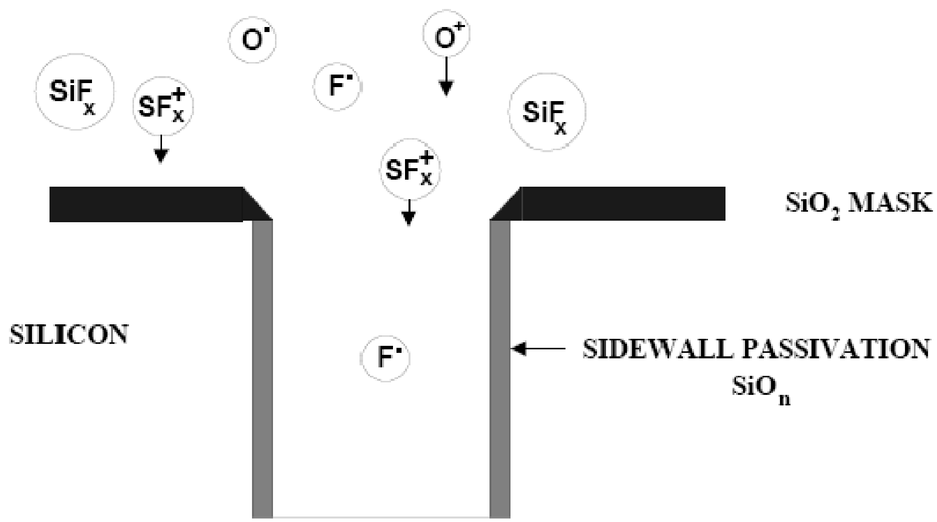
(a) Either the carbon is provided by the feed gas through the chamber such as CHF_3, C_4F_8.

(b) Or the carbon is provided by the erosion of the photoresist etch mask.



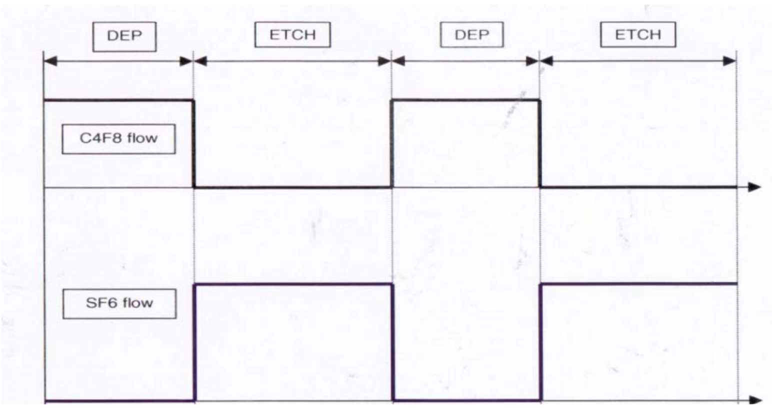
Sidewall Passivation

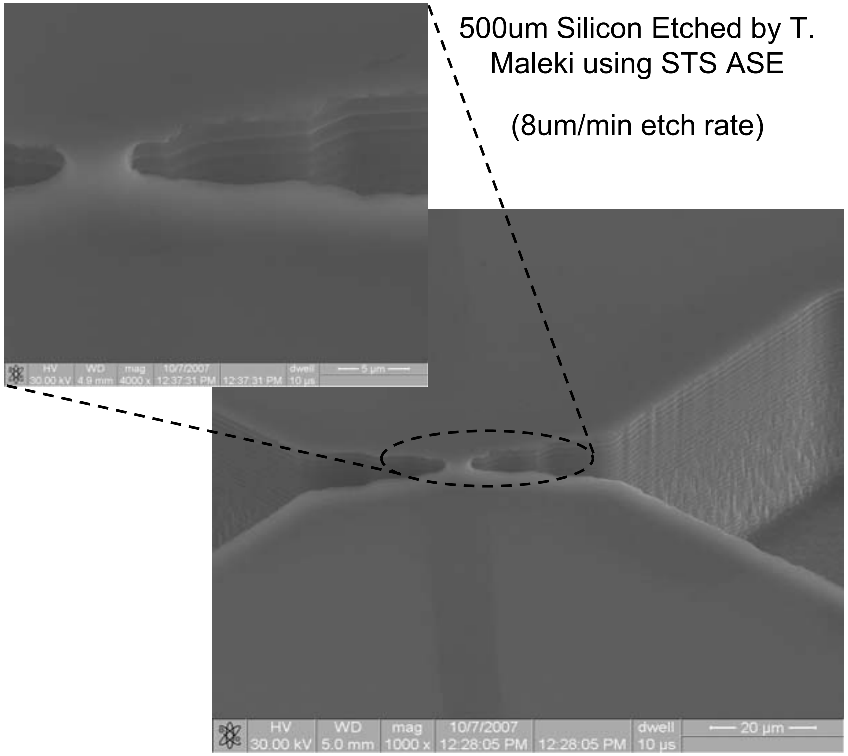
- Oxidation of the sidewall by adding O_2 gas.



Bosch Process

Switching SF_6 and C_4F_8





The sidewall film thickness depends to the deposition or passivation time.

Temperature effects in plasma etching

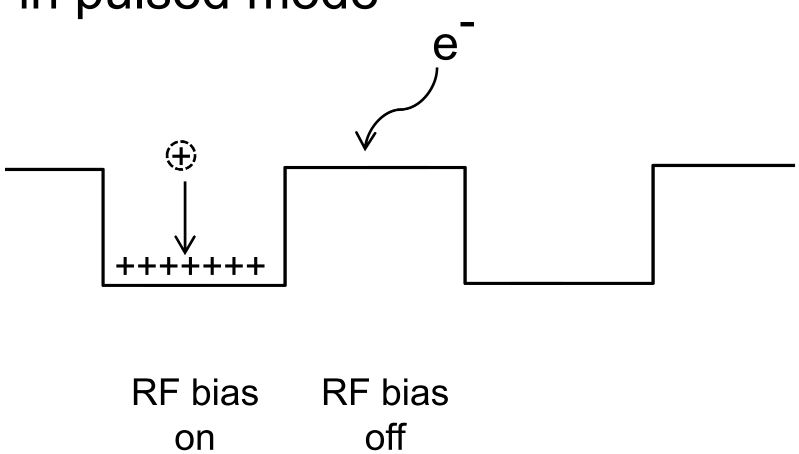
➢Wafer surface temp. depends on:
- Chuck temperature
- Ion’s energy and density

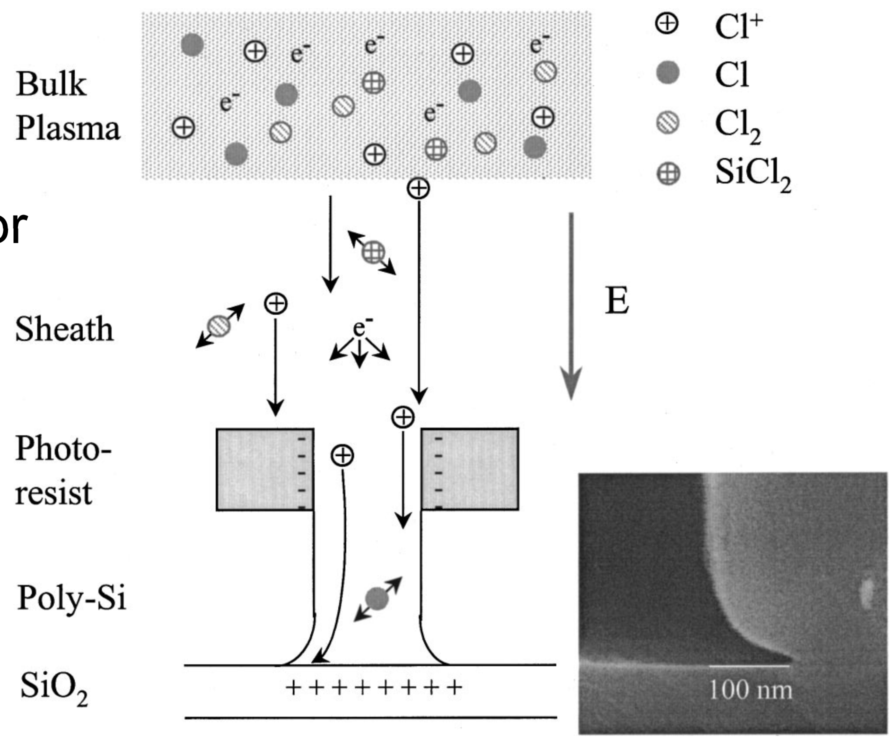
➢Reaction probability of radicals depends on substrate temperature.

➢Helium backside cooling helps anisotropic etch by preventing or reducing reaction of F and Cl species with sidewalls.

Notch Effect

- Notching effect due to charging oxide by ions
- Can be reduced by using low frequency (LF) 380kHz bias generator in pulsed mode



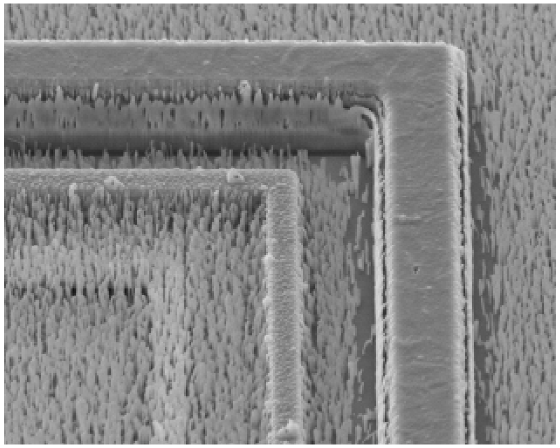


[J. Vac. Sci. Technol. B 19.5., Sep/Oct 2001]

STS ASE has LF pulsed generator!!

Other Effects

- Grass or micromasking issue mainly because of metal mask sputtered on the wafer

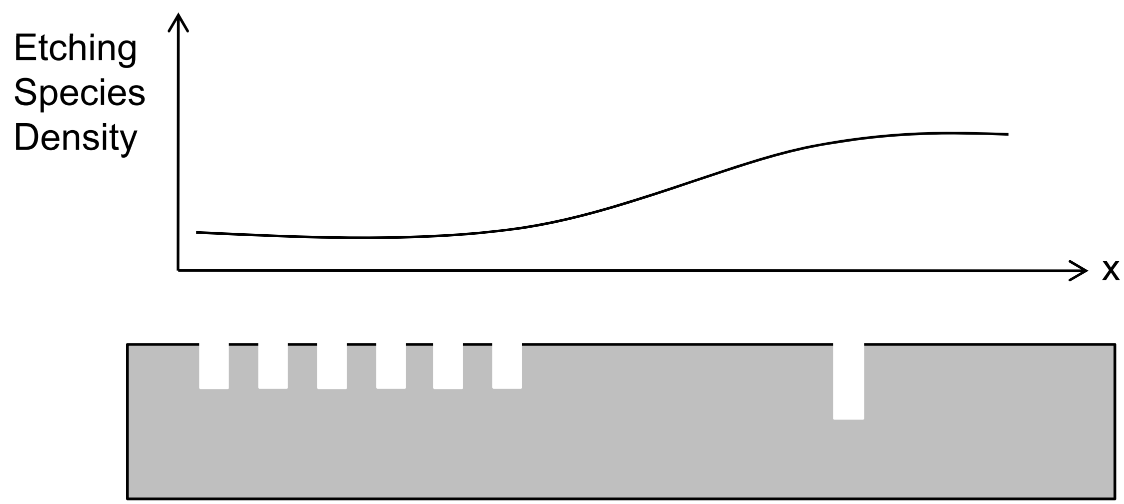


- Aspect Ratio Dependent Effect (ARDE) Typically large open areas etch faster than smaller features!

Other Effects

- Microloading effect:

Feature of the same size etch more slowly in dense patterns
Than in wide open areas!



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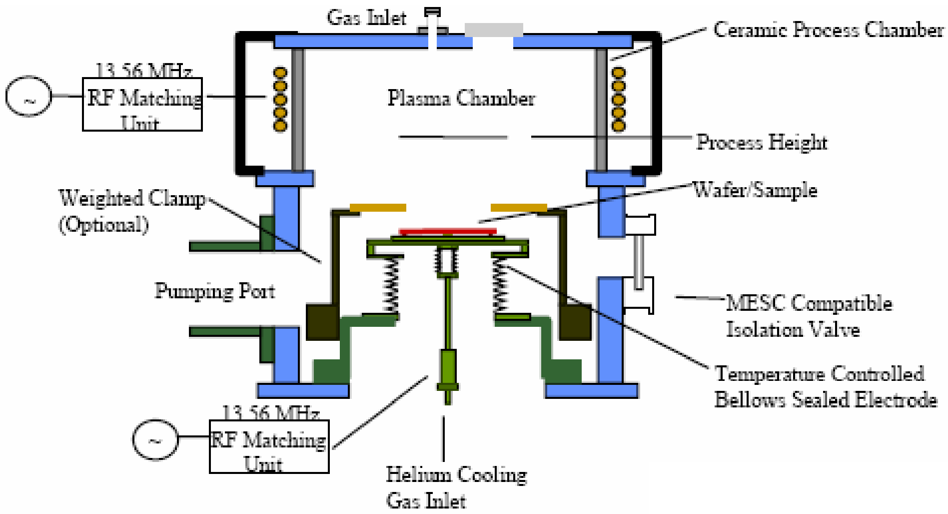
S4800 5.0kV x30 SE(M) 1.00mm

STS ASE DRIE

It's a 6" ICP Bosch process dedicated for silicon etching!

Gases:

SF_6	C_4F_8
O_2	Ar



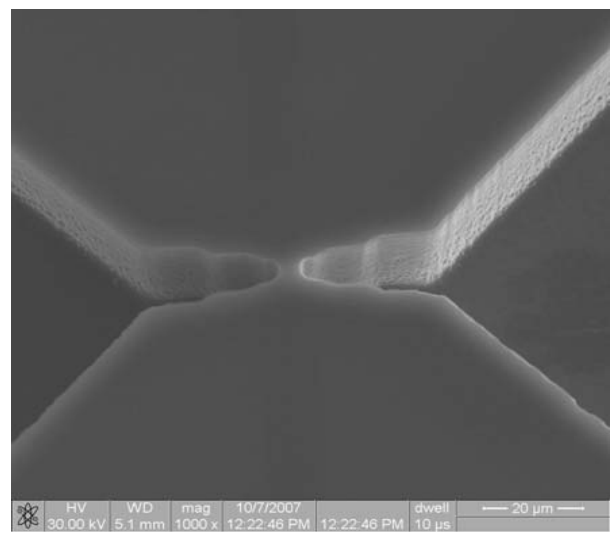
STS ASE DRIE

High etch-rate recipe:

	Switching time	Pressure	RF coil power	RF bias power	Gas flow [sccm]
Etch	8.5 sec	40mTorr	2200W	40W	450 SF_6
Passivation	3 sec	14mTorr	1500W	20W	200 C_4F_8

Etch rate ≈ 8µm/min for 500 µm feature size with ~ 20% exposed area

High selectivity to PR ≈ 75-100



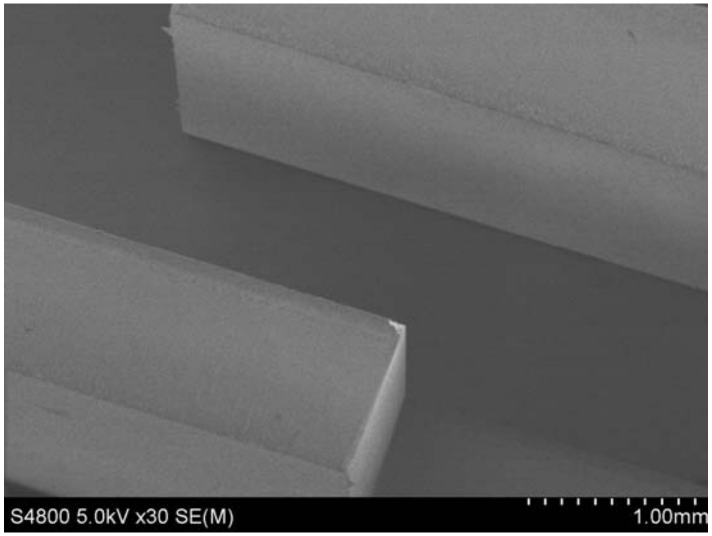
STS ASE DRIE

Low etch-rate recipe:

	Switching time	Pressure	RF coil power	RF bias power	Gas flow [sccm]
Etch	13 sec	5mTorr	800W	25W	160 SF_6
Passivation	7 sec	1mTorr	600W	20W	85 C_4F_8

Etch rate ≈ 2μm/min for 500 μm feature size with ~ 20% exposed area

High selectivity to PR ≈ 50
Smooth side wall



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STS AOE DRIE

It's a 4" ICP tool dedicated for etching of oxide, nitrite, and polymers!

Gases:

SF_6	**C_4F_8**	**CF_4**
O_2	**Ar**	**He**

	Pressure	RF coil power	RF bias power	Gas flow [sccm]
Oxide Etch	2mTorr	600W	50W	13 CF_4

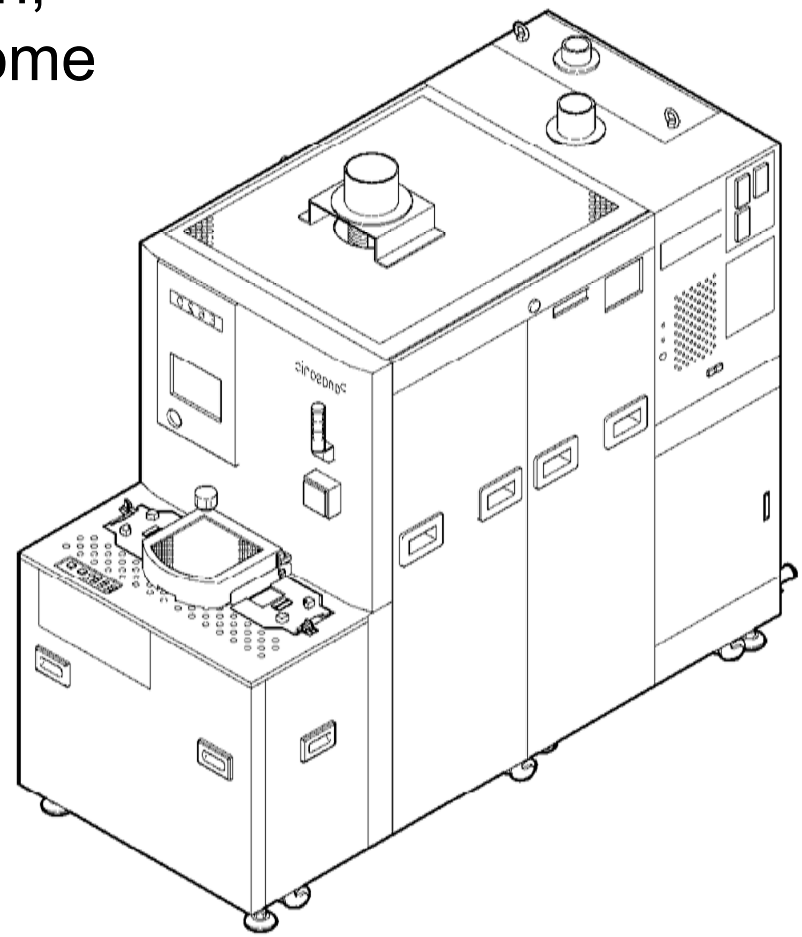
Etch rate ≈ 0.3μm/min
Selectivity to PR≈ 1-2

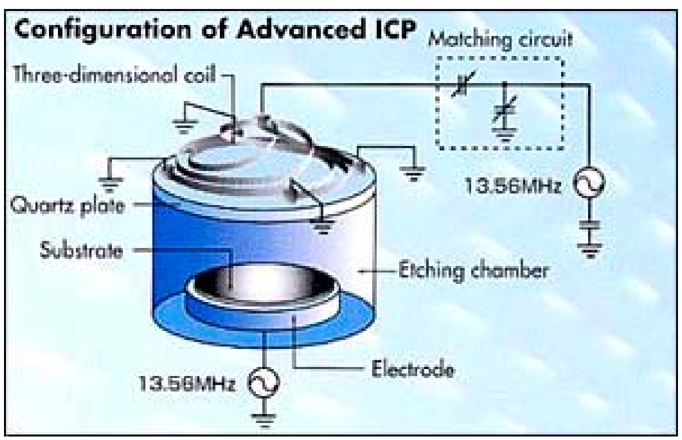
Panasonic RIE

It's a 6" ICP tool for etching of silicon, oxide, nitrite, III-V, polymers, and some metals!

Gases:

SF_6	CHF_3	Cl_2	O_2
CF_4	Ar	BCl_3	N_2





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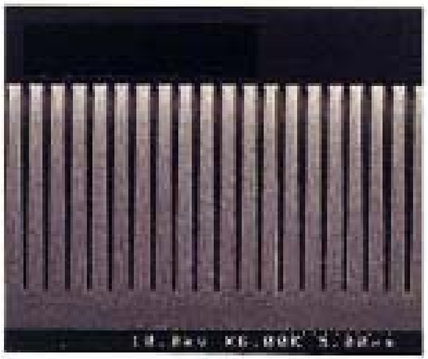
Panasonic RIE

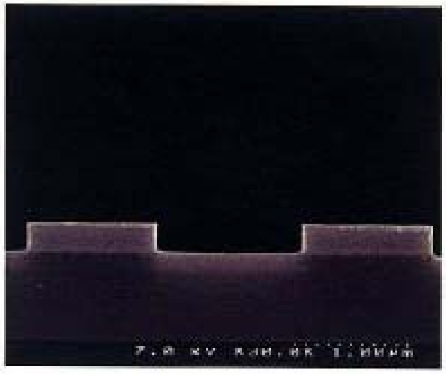
	Pressure	RF coil power	RF bias power	SF_6 flow [sccm]	O_2 flow [sccm]
Si Etch	11Pa	900W	75W	30	30



[Panasonic]

Etch rate ≈ 1µm/min

	Pressure	RF coil power	RF bias power	Cl_2flow [sccm]	O_2 flow [sccm]
Si Etch	0.8Pa	350W	50W	63	1.2



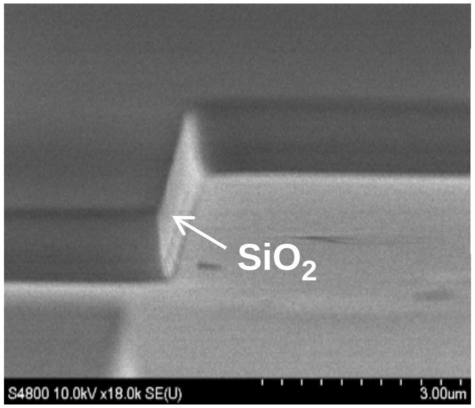
[Panasonic]

Etch rate ≈ 200nm/min

Panasonic RIE

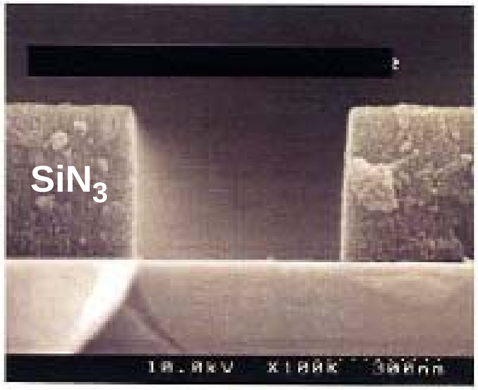
	Pressure	RF coil power	RF bias power	CHF_3 flow [sccm]
Oxide Etch	0.16 Pa	450W	50W	40

Etch rate ≈ 60 nm/min



	Pressure	RF coil power	RF bias power	CF_4 flow [sccm]	CHF_3 flow [sccm]
SiN_3 Etch	2 Pa	400W	30W	48	50

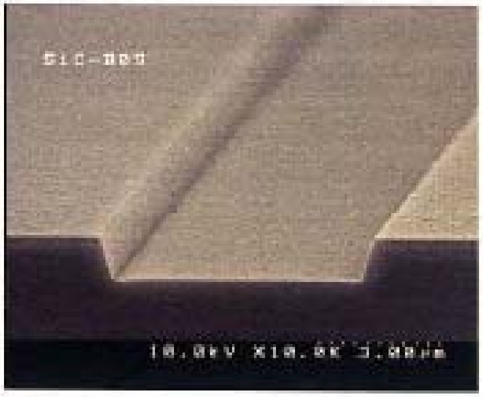
Etch rate ≈ 100 nm/min



[Panasonic]

Panasonic RIE

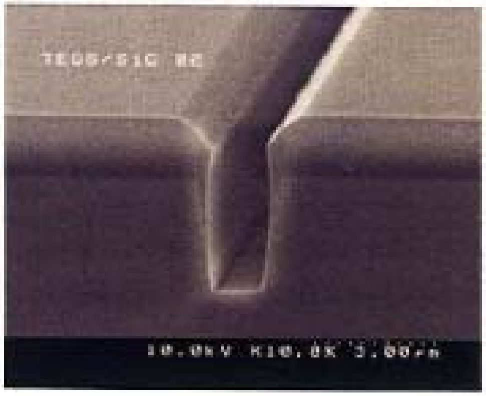
	Pressure	RF coil power	RF bias power	SF_6 flow [sccm]
SiC Etch	4 Pa	700W	280W	50



[Panasonic]

Etch rate ≈ 0.46 μm/min

	Pressure	RF coil power	RF bias power	Cl_2 flow [sccm]	O_2 flow [sccm]
SiC Etch	1.5 Pa	500W	150W	30	20



[Panasonic]

Etch rate ≈ 0.19 μm/min

Plasma Tech RIE

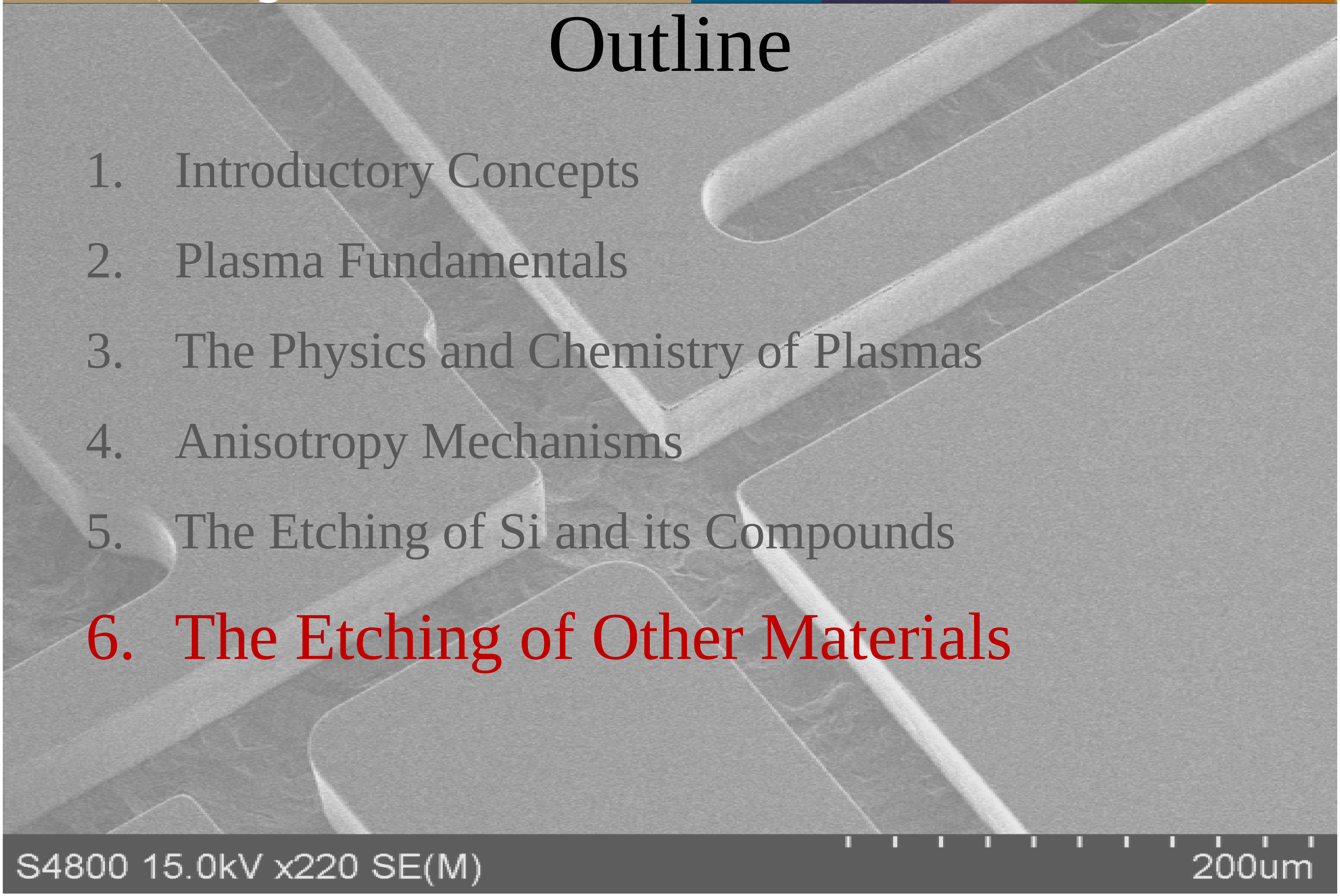
- ✓ It’s a simple RIE.
- ✓ It can be used for etching silicon, oxide, nitrite, SiC, and polymers.

Gases:

SF_6	O_2	Ar

Outline

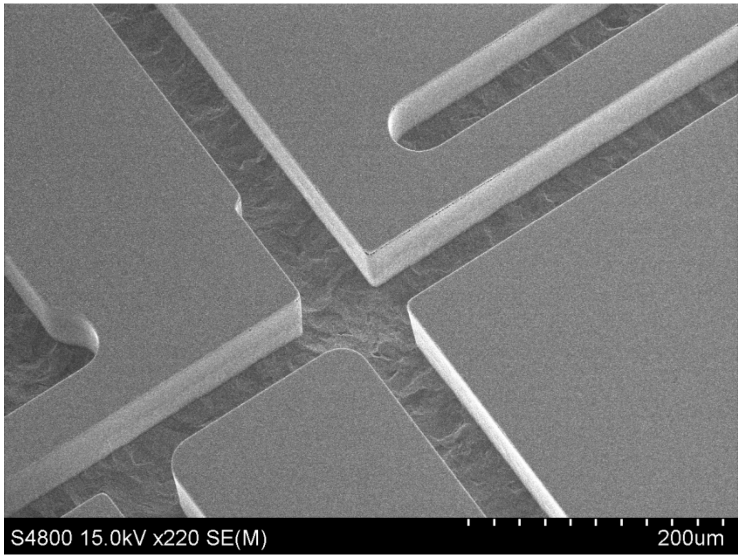
1. Introductory Concepts
2. Plasma Fundamentals
3. The Physics and Chemistry of Plasmas
4. Anisotropy Mechanisms
5. The Etching of Si and its Compounds
6. The Etching of Other Materials



Panasonic RIE

	Pressure	RF coil power	RF bias power	Cl_2 flow [sccm]	Ar flow [sccm]
Ti Etch	2 Pa	400W	100W	100	5

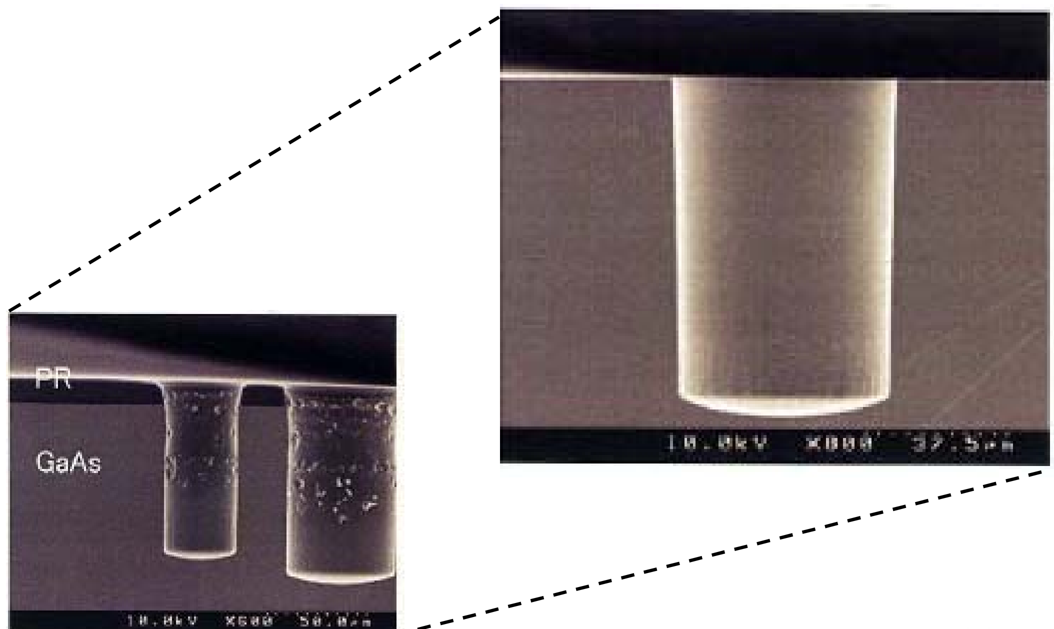
Etch rate ≈ 3 μm/min



Panasonic RIE

	Pressure	RF coil power	RF bias power	BCl_3 flow [sccm]	Cl_2 flow [sccm]	Ar flow [sccm]
GaAs Etch	3 Pa	900W	75W	50	150	20

Etch rate ≈ 5.3μm/min
Selectivity to PR≈ 5

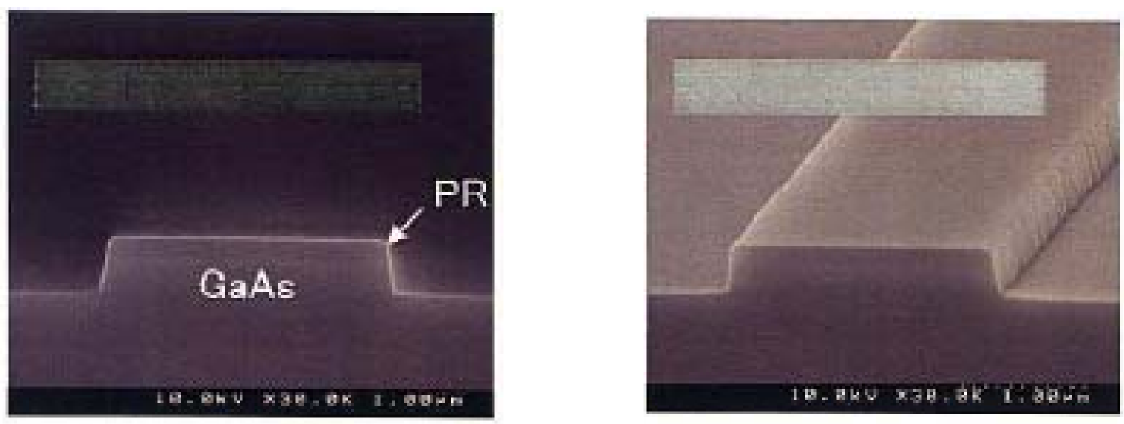


[Panasonic]

Panasonic RIE

	Pressure	RF coil power	RF bias power	BCl_3 flow [sccm]	Ar flow [sccm]
GaAs Etch	0.6 Pa	500W	50W	15	60

Etch rate ≈ 120 nm/min
Selectivity to PR≈ 4

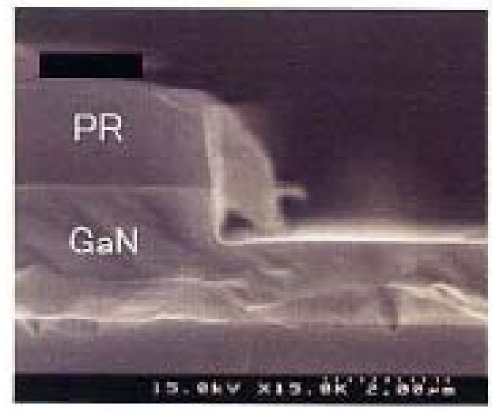


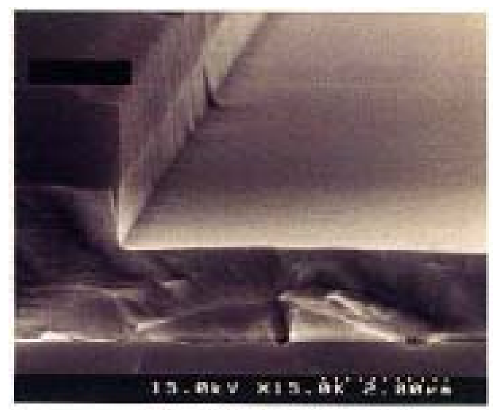
[Panasonic]

Panasonic RIE

	Pressure	RF coil power	RF bias power	Cl_2 flow [sccm]
GaN Etch	4 Pa	900W	90W	50

Etch rate ≈ 500 nm/min
Selectivity to PR≈ 0.5
Selectivity to SiO_2≈ 5





[Panasonic]

General Process Trends

<u>How to Increase Etch Rate?</u>

- Increasing Main Coil Power
- Increasing Platen or Bias Power
- Increasing Process pressure
- Increasing etching flow
- Increasing Etch cycle time (for Bosch process)

<u>How to Reduce Sidewall Roughness/Scallops?</u>

- Keep etch and deposition cycle times to minimum, (for Bosch process)
- Reduce process pressure
- Reduce etch gas flow
- Increase deposition component, time, power, or flow (for Bosch process)

<u>How to Increase Selectivity?</u>

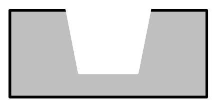
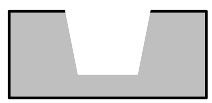
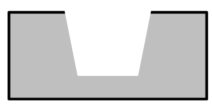
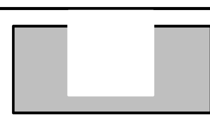
- Increasing the pressure
- Reducing platen power

General Process Trends

How to Straighten the Profile?

- Using low pressure
- Decreasing etch cycle time or increasing deposition cycle time (for Bosch process)
- Optimizing platen power

General Process Trends

Trends for Controlling process results	Etch rate	Profile	Selectivity	Sidewall Roughness
Etch gas increase	↑↑		↑	↑
Pressure increase	↑↑		↑	↑
Etch Coil Power increase	↑		↑	↑
Platen Power increase	↑↔		↓	↔

Acknowledgment

- We would like to thank faculty members, staff, and students for their support.

Questions?

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