플라즈마와 플라즈마 진단 기술

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2017. 11. 3

한국진공기술연구조합 진공실무수련회

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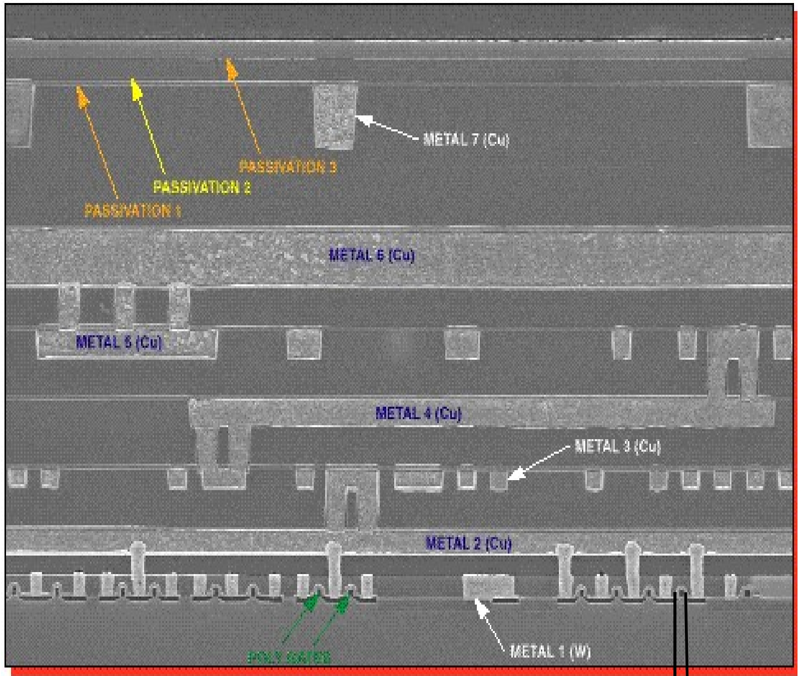
Outline

- Introduction
  - Devices and Plasma Processing
  - Plasma Fundamentals
- Physical Diagnostics
  - Langmuir Probe and Other Probe
  - RF V-I Probe
- Chemical Diagnostics
  - Mass Spectroscopy (MS)
  - Optical Emission Spectroscopy (OES)
- Chamber Monitoring Technologies
  - Endpoint Detection for Plasma Etching
  - Algorithms for signal enhancement

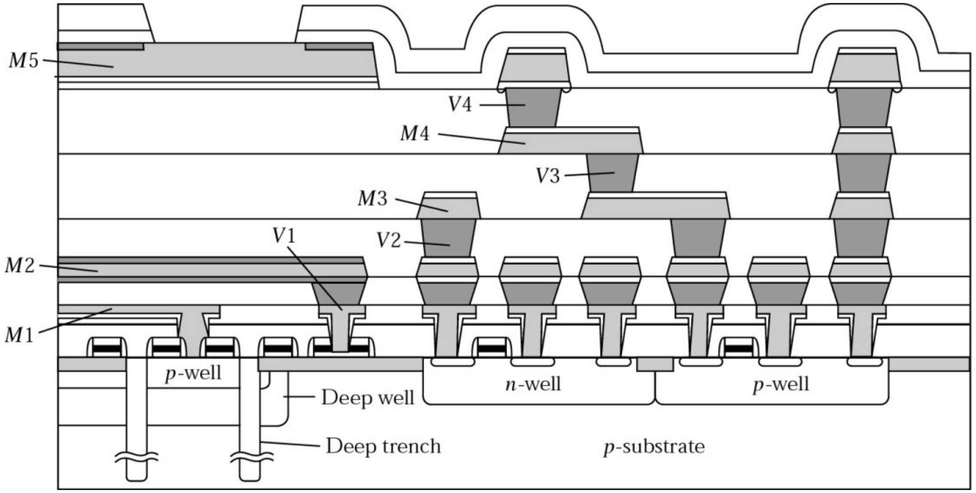
Introduction: Devices and Plasma Processing

Micro/Nanoscale Integrated Circuit (IC)

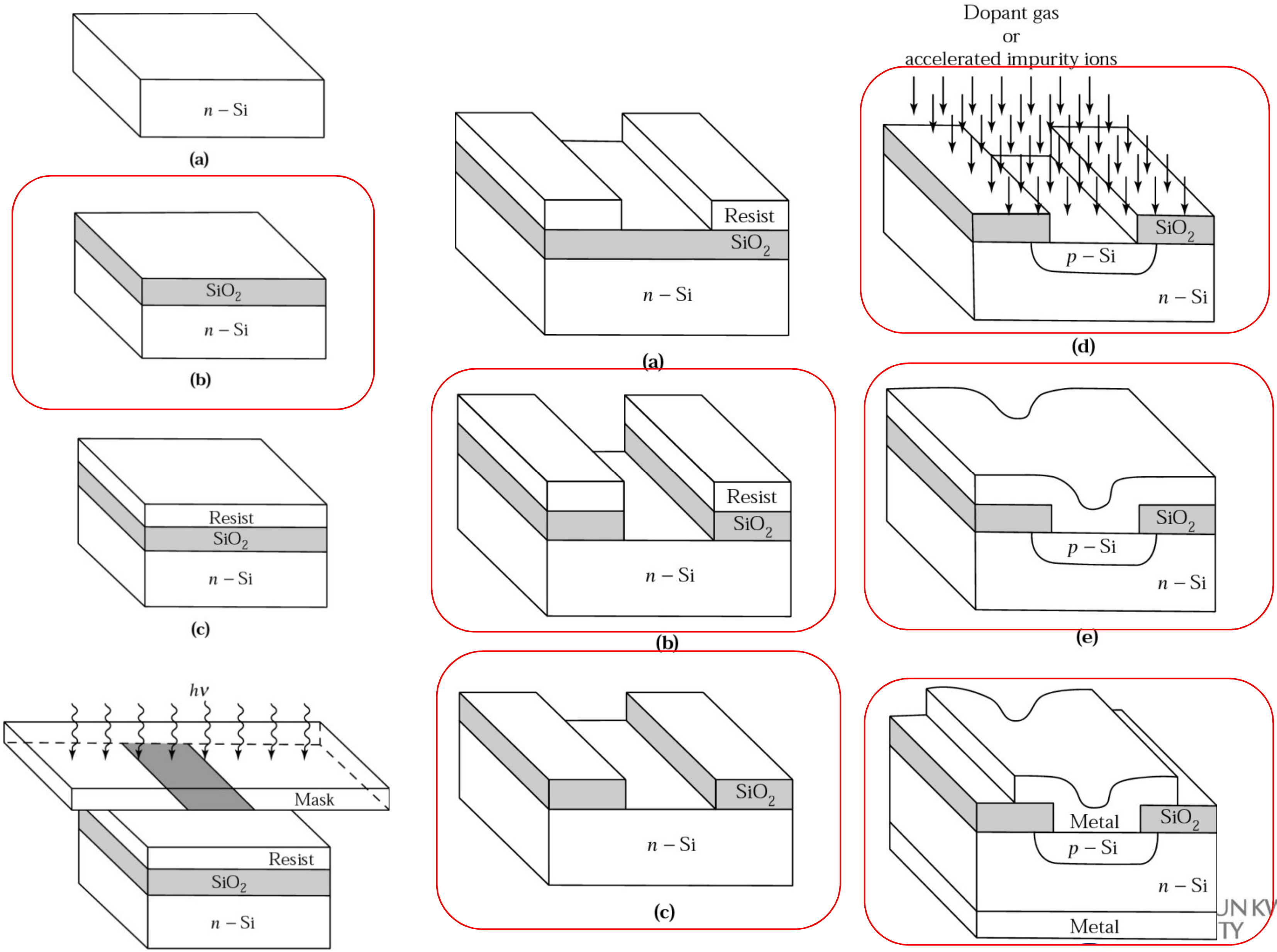
- Plasma processing steps are 30~40% of IC fabrication processing.



Minimum CD
< 20nm @ 2017

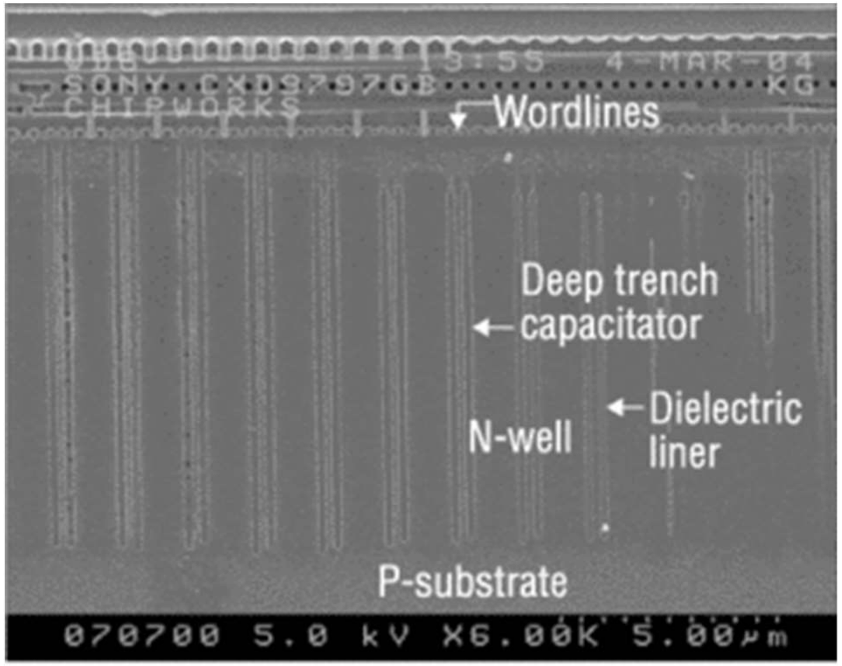


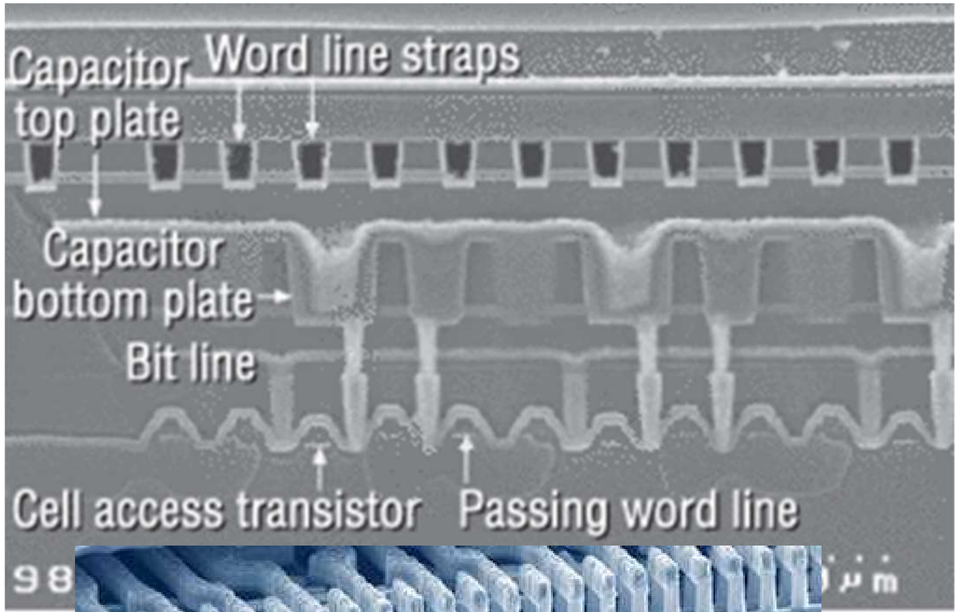
Process Steps and Plasma Processes

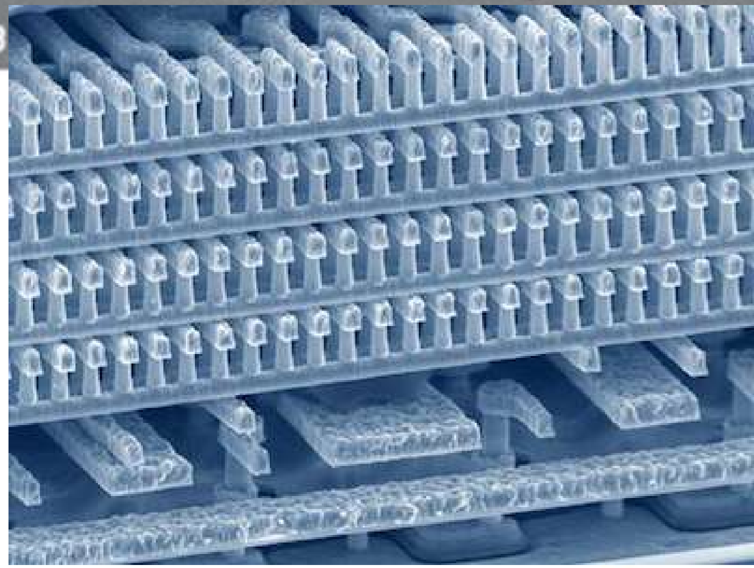


Cross-section of DRAM and Flash Memory Devices

- **Minimum critical dimension is < 100 nm.**



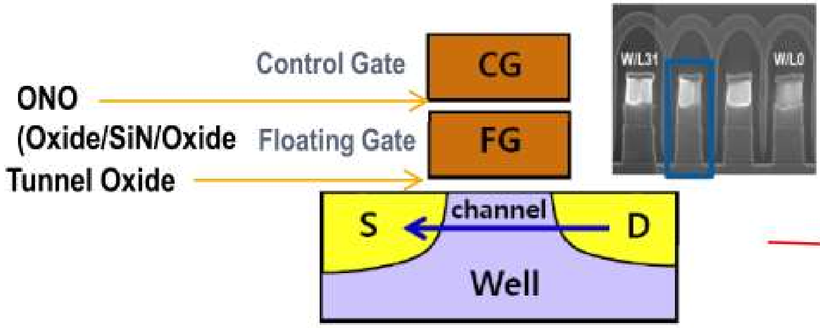




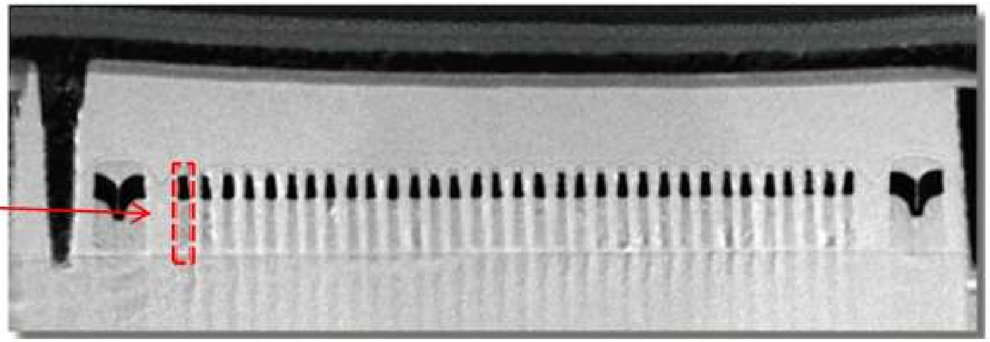
Minimum CD
< 30nm @ 2014

3D cells require high aspect ratio plasma etching

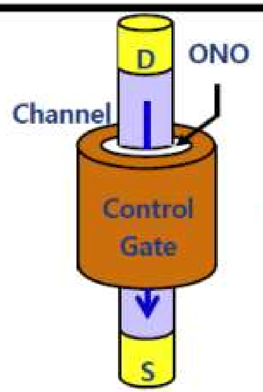
2D cell



- Single crystal Si channel
- Floating gate (or TANOS)
- 1-side gate



3D cell (Vertical String)

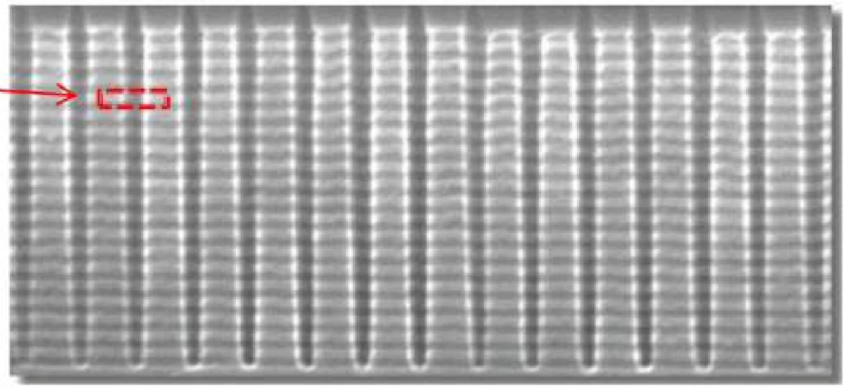


Charges stored in FG
Charges in/out through the tunnel oxide.

- Poly-Si channel
- SONOS (Si / Oxide / SiN / Oxide / SiN)
- All-around gate
- Channel-last process
- 1 step litho (hole)

http://gigglehd.com/zbxe/613729(

Micron
Wednesday, August 10, 2011



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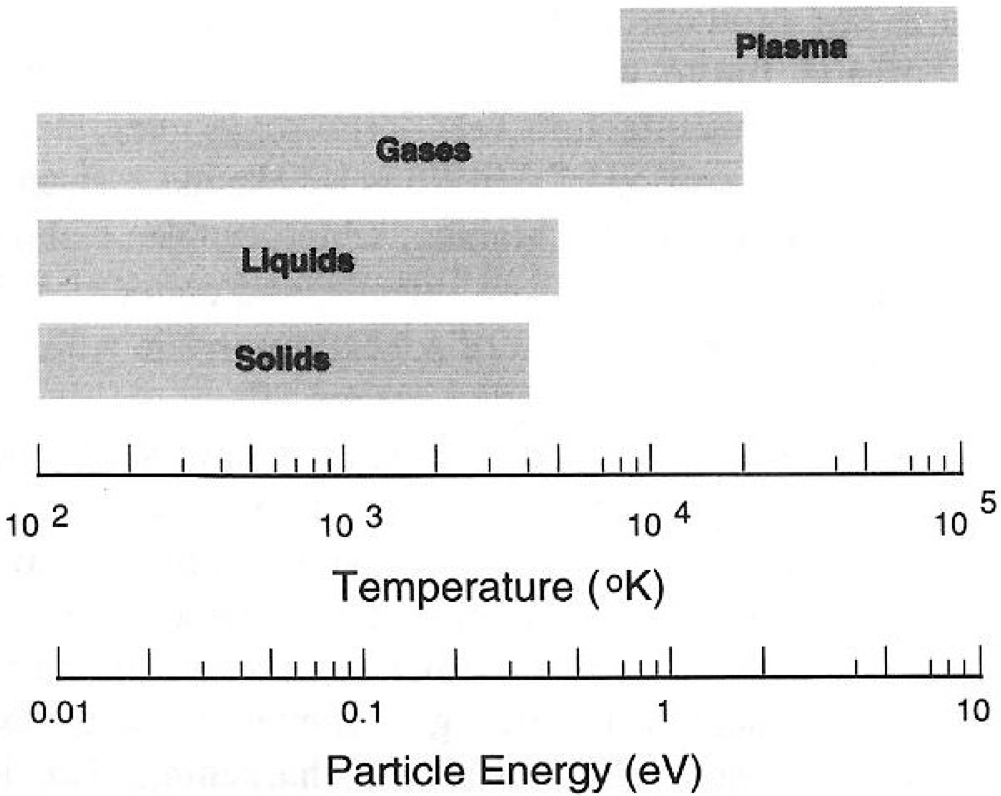
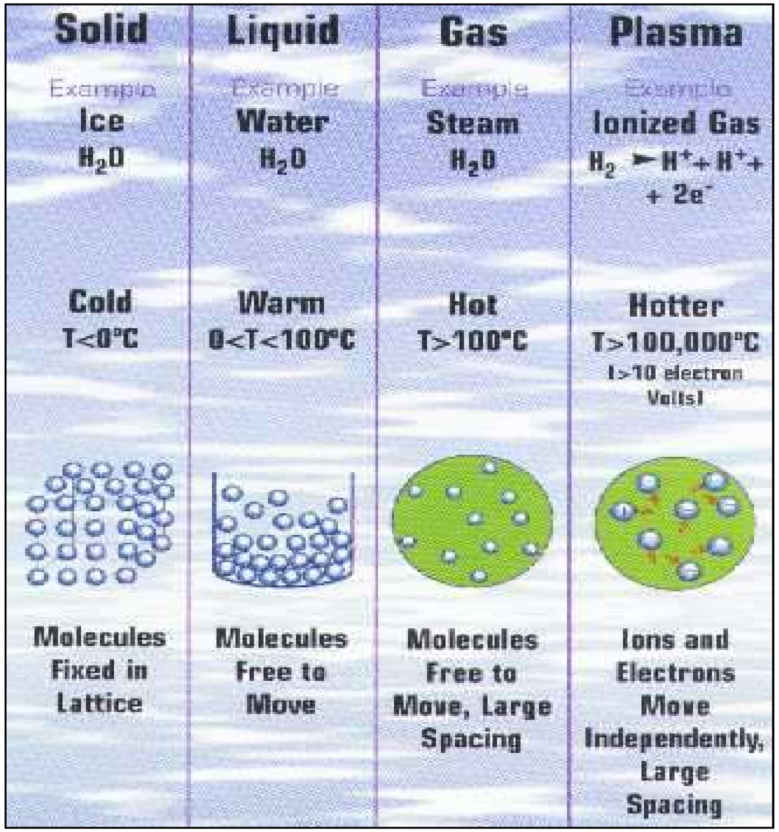
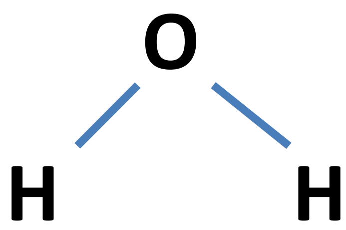
Plasma

- Plasma (soup of ions, electrons & neutrals)
  - 4^{th} state of matter
  - Ionized Gas





Breakdown of H_2O molecules



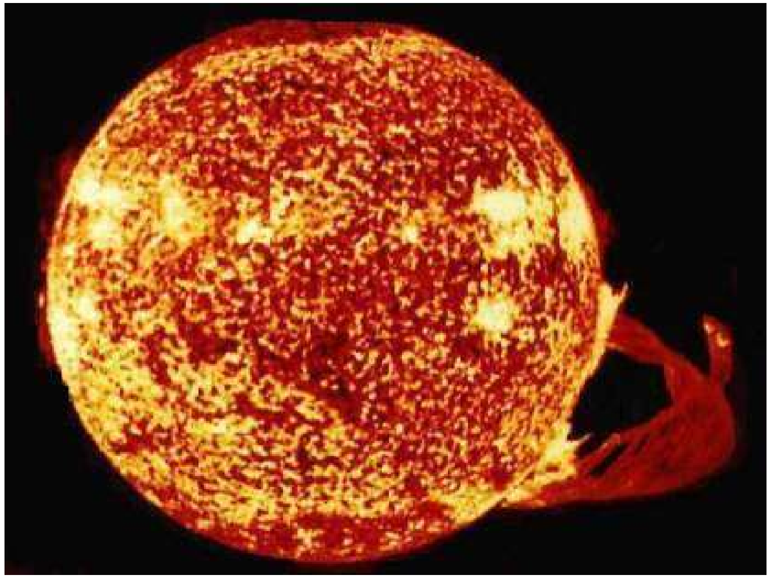
$$H \longrightarrow H^+ + e^-$$

$$O \longrightarrow O^+ + e^-$$

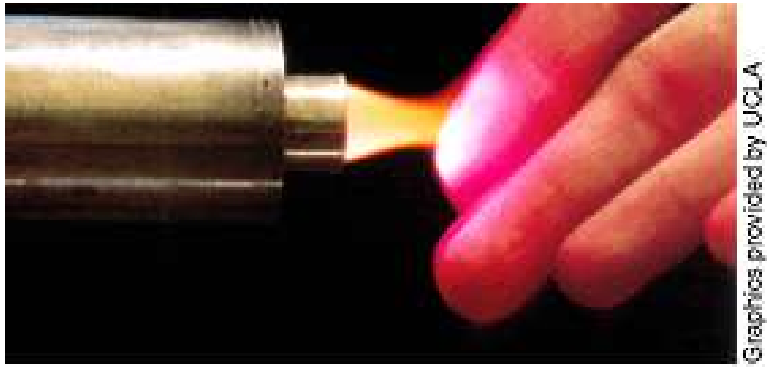
$$O-H \longrightarrow OH^+ + e^-$$

Radicals   Ions   Electrons

Plasmas in Nature & Homes

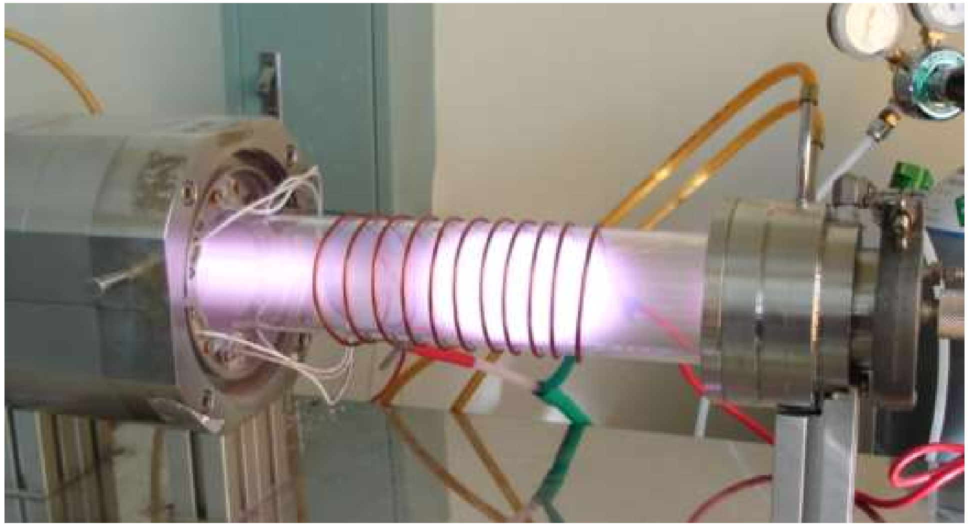


Plasmas in Material Processing



The low effluent temperature of atmospheric-pressure plasma makes the device ideal for several decontamination applications.

http://www.p2pays.org/ref/14/0_initiatives/init/spring01/plasma.htm



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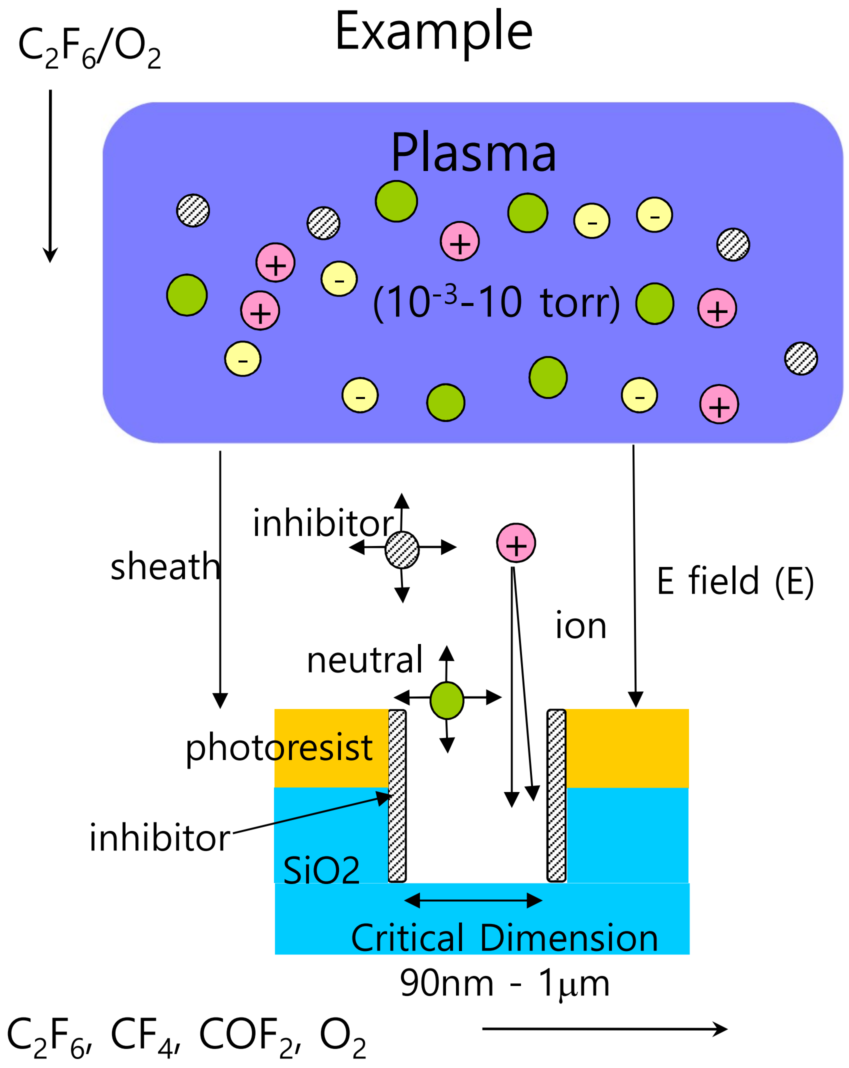
Plasma – Generation Process



Plasma = Ionized Gas

Step1 : Electric energy transferred to electron (1-5eV) (plasma physics)

Step2: Electron collides with molecules to generate radicals and ions (plasma chemistry)

Step3: Surface reaction of ions and radicals with surface (surface reaction)

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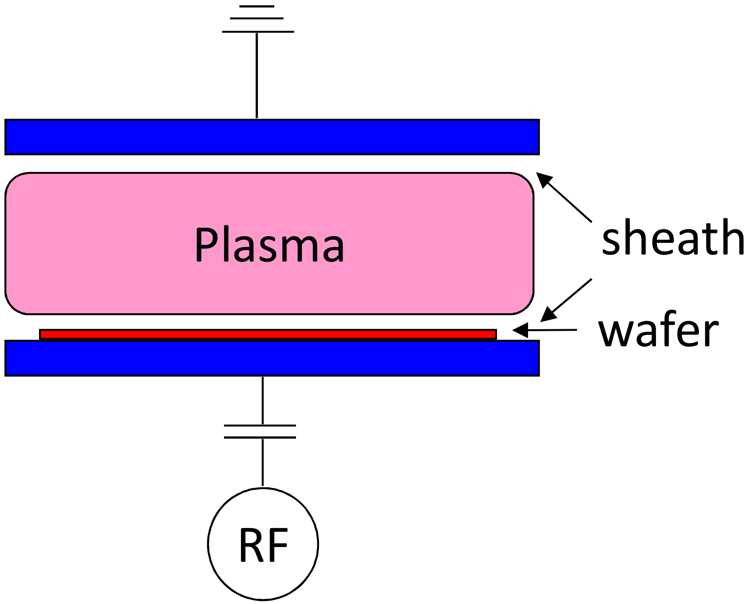
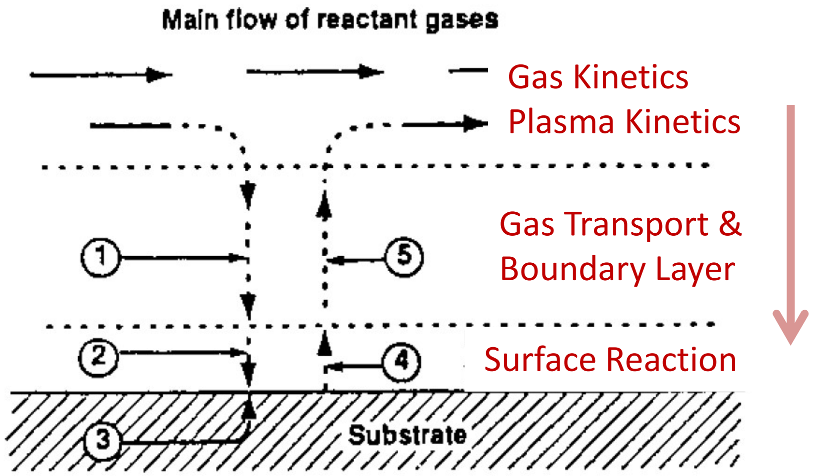
Charge Particles and Neutral Species in Plasma





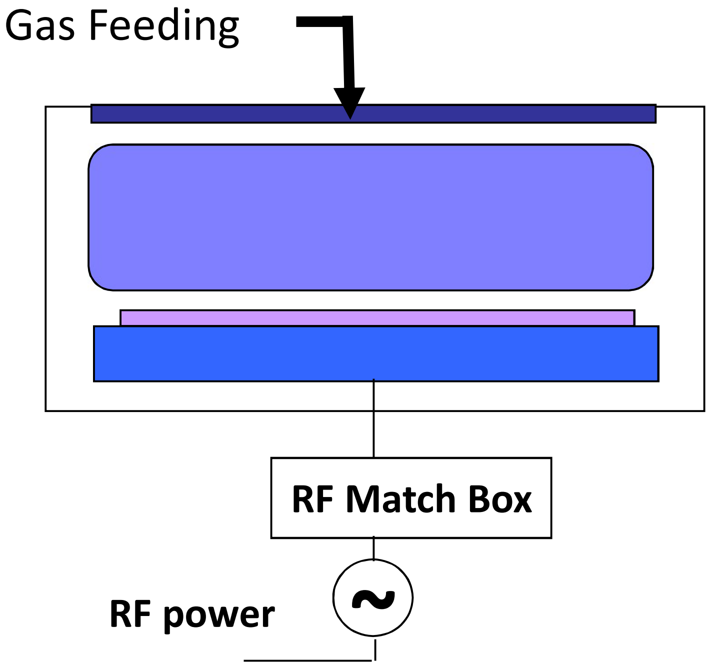
1. Diffusion in of reactants through boundary layer
2. Adsorption of reactants on substrate
3. Chemical reaction takes place
4. Desorption of adsorbed species
5. Diffusion out of by-products

Things to think about

- Plasma properties
- Chamber configuration (molecules, heat, electrical power)
- Gas delivery, gas in vacuum and pumping
- Temperature of wafers and chamber walls
- Surface reactions and mass transfer
- RF technology
- Plasma diagnostics
- Data mining and analysis

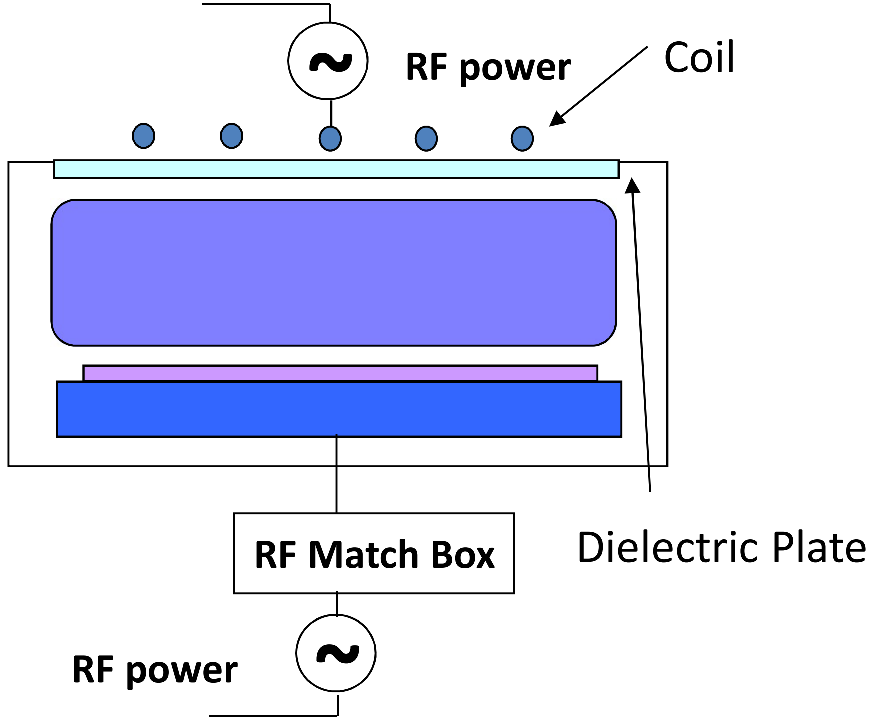
CCP and ICP

Capacitively Coupled Plasma (CCP)



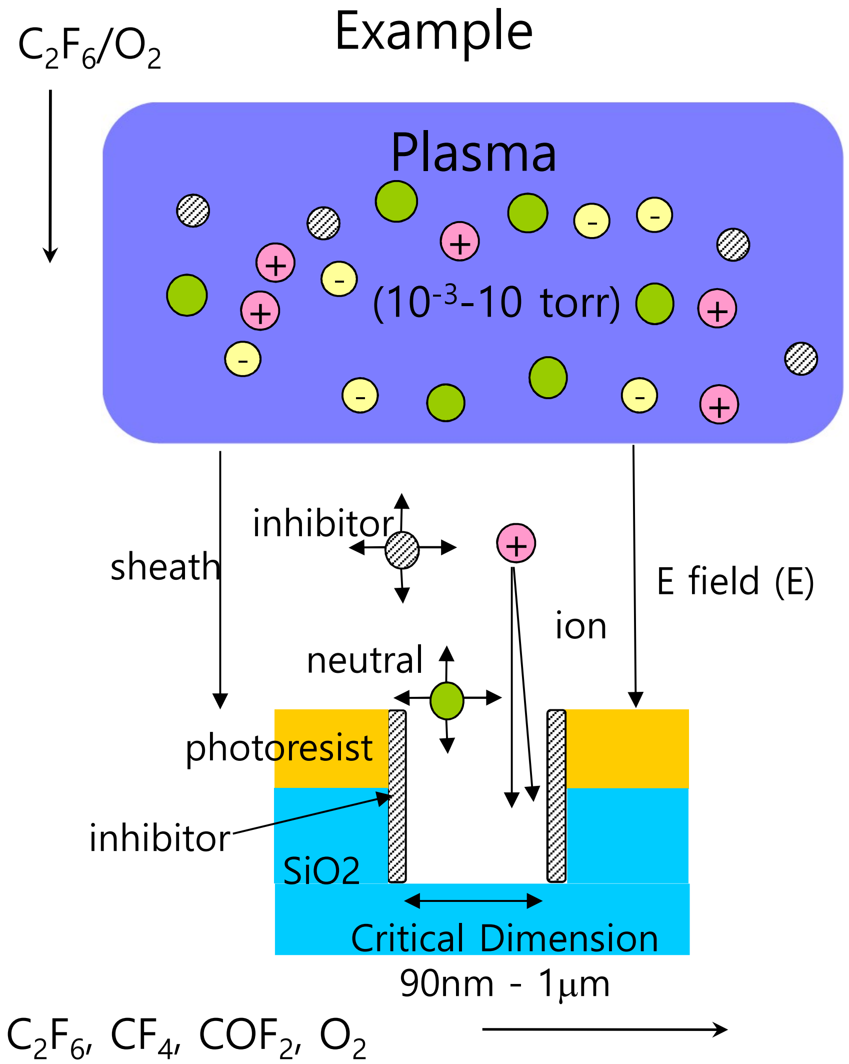
- Power delivered through parallel plates
- Relatively uniform plasma
- Low-to-medium density plasma :
  $10^{8} \sim 10^{11}$ cm^{-3}
- High energy ion acceleration

Inductively Coupled Plasma (ICP)



- Power delivered through coils
- Relatively non-uniform plasma
- Medium-to-High density plasma (10^{10} $\sim 10^{12}$ cm^{-3})
- Independent ion energy control is possible with separate power

Plasma – Generation Process



Plasma = Ionized Gas

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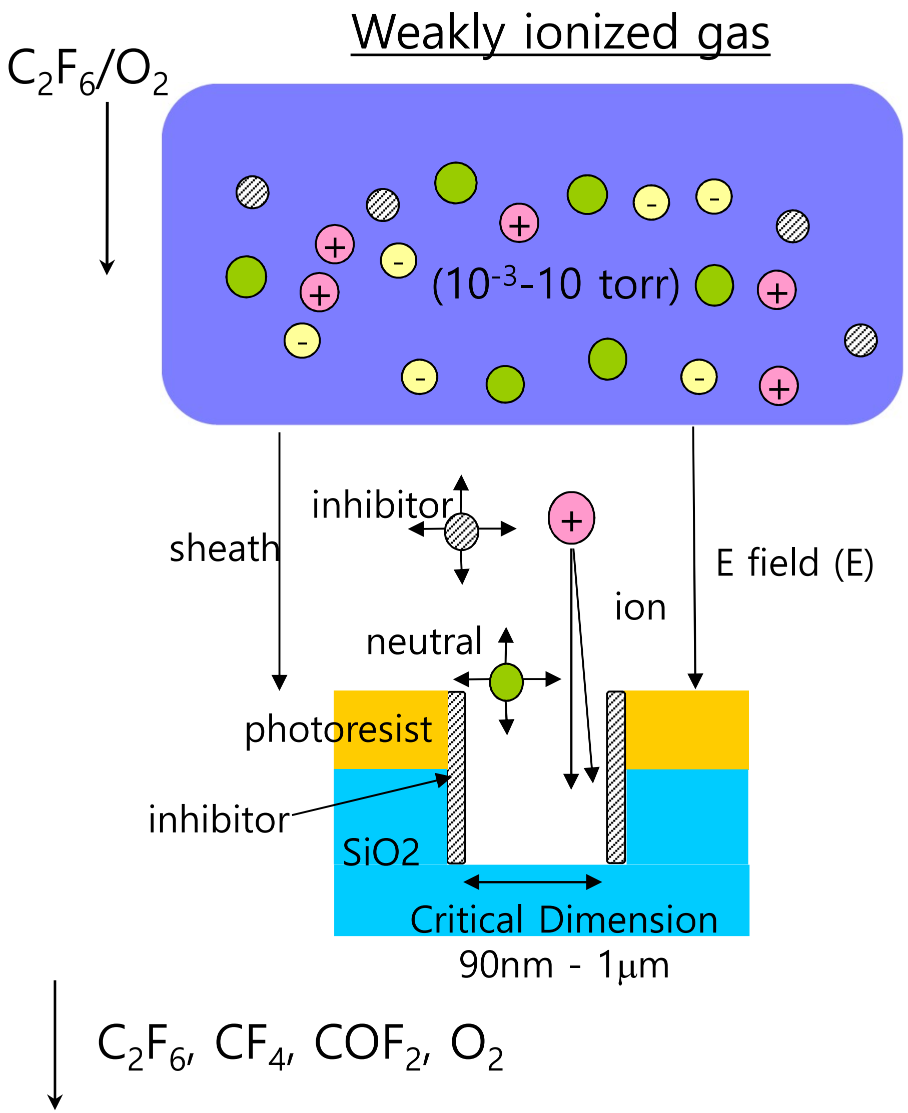
Plasma – Reaction Example



Example

Dominant Reactions in Plasma (example)

$C_2F_6 + e^- \rightarrow 2CF_3 + e^-$

$CF_3 + e^- \rightarrow CF_2 + F + e^-$

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

Dominant Surface Reactions (example)

Deposition : $CF_2 + CF_2 \rightarrow (CF_2)_2$

Etching: $4F + SiO_2 \rightarrow SiF_4 + O_2$

1. Low T processing due to reactive radicals & ions
2. Directionality due to ion and electric field

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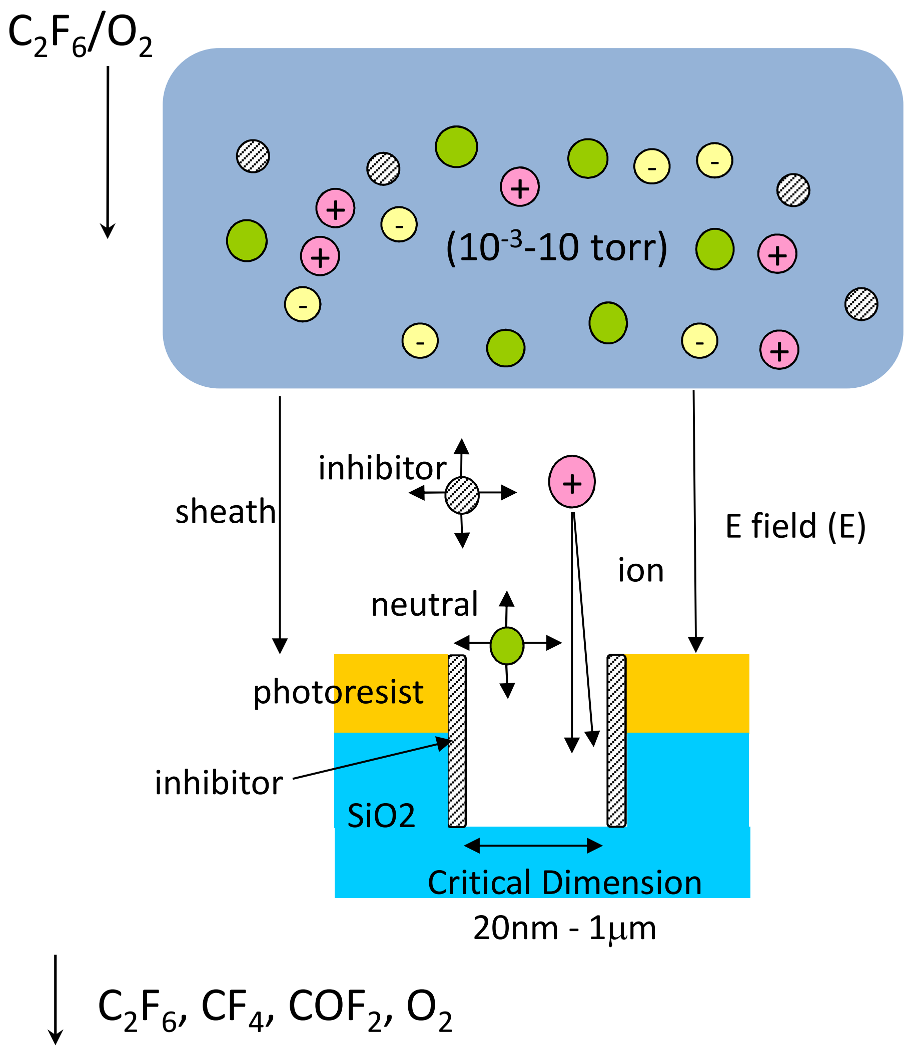
Why Plasma ?

- Radicals:
  - atomic or molecular species with unpaired electrons on an otherwise open shell configuration. These unpaired electrons are usually highly reactive, so radicals are likely to take part in chemical reactions. (Ex: CH, CF, CF2, OH, …)
  - For PECVD, cleaning, ashing, etc
- Ion
  - Ions deliver energy to surface with electric field in sheath.
  - For sputtering and anisotropic etching
- UV light
  - Plasma emits UV and visible light.
  - Applied to plasma display panel

Plasma

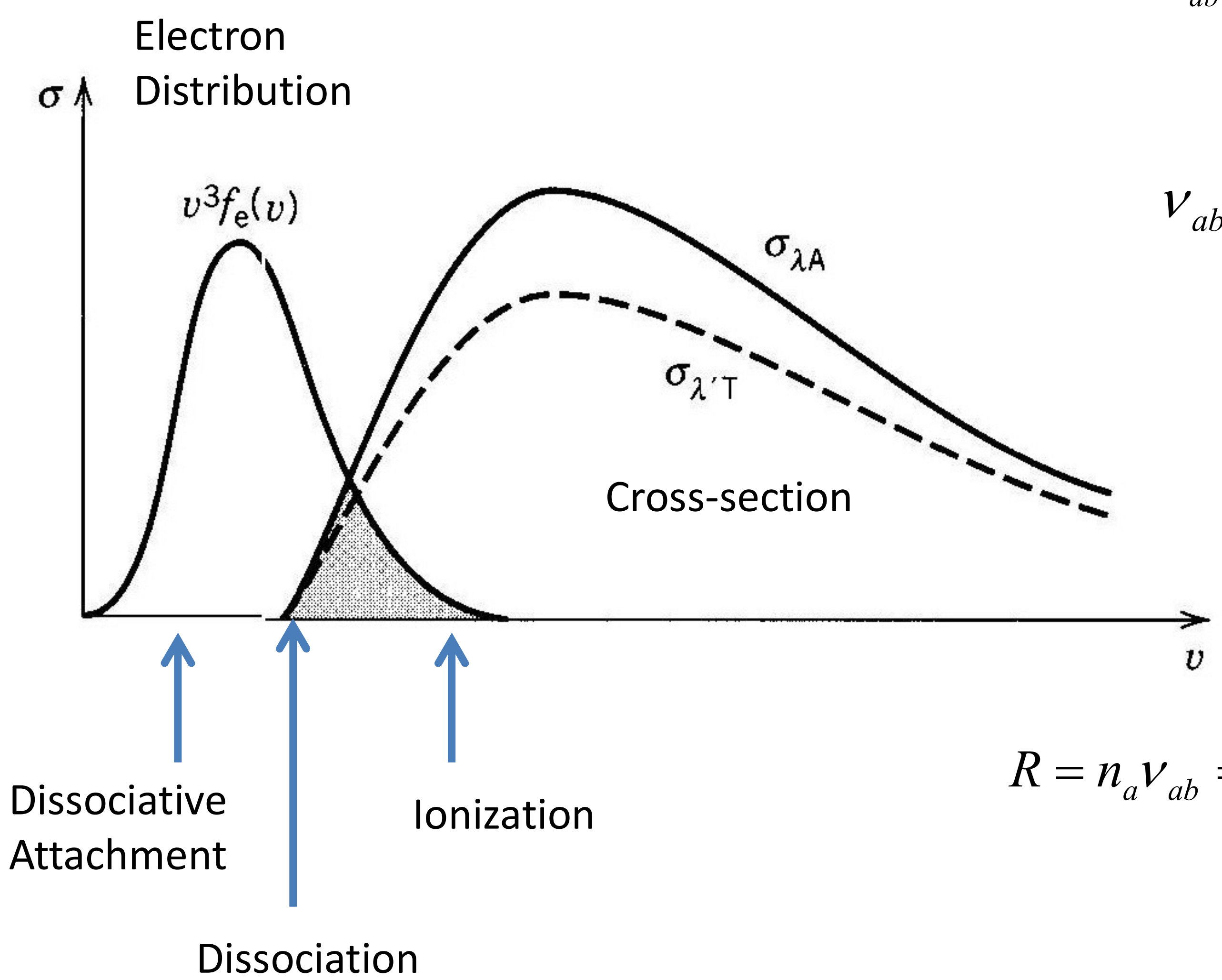
	Electron	Ion	Radical	Molecules
Mass				
Fraction				
Density				
Energy				
Function				

Major Parameters in Plasmas



- Physical (charged species)
  - Electron density
  - Electron energy distribution
  - Ion density
  - Ion energy distribution
- Chemical (neutral species)
  - Radical density
  - Gas phase reaction rate
  - Surface reaction rate
- Transport
  - Mass
  - Heat
  - Momentum

Plasma Density & Electron Temperature



$$\lambda_{ab} = \frac{1}{\sigma_{ab} n_b}$$

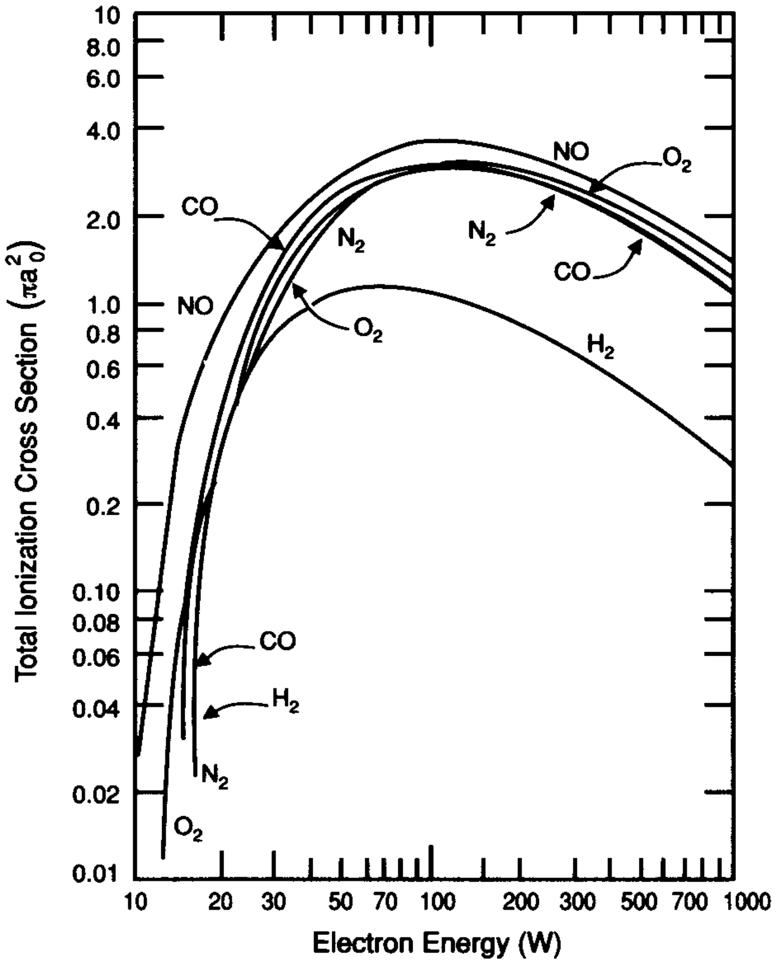
moving *a*, stationary *b* particle

$$\nu_{ab} = \frac{u_a}{\lambda_{ab}} = u_a \sigma_{ab} n_b$$

λ_{ab} = mean free path
σ_{ab} = cross section for the interaction
n_b = density of particles of type b
u_{ab} = moving velocity
ν = collision frequency

$$R = n_a \nu_{ab} = n_a n_b \sigma_{ab} u_a \ (cm^3 - \sec)^{-1}$$

Cross Sections



Plot of cross section for ionization versus electron energy (from [6], reprinted by permission of John Wiley & Sons, Inc.).

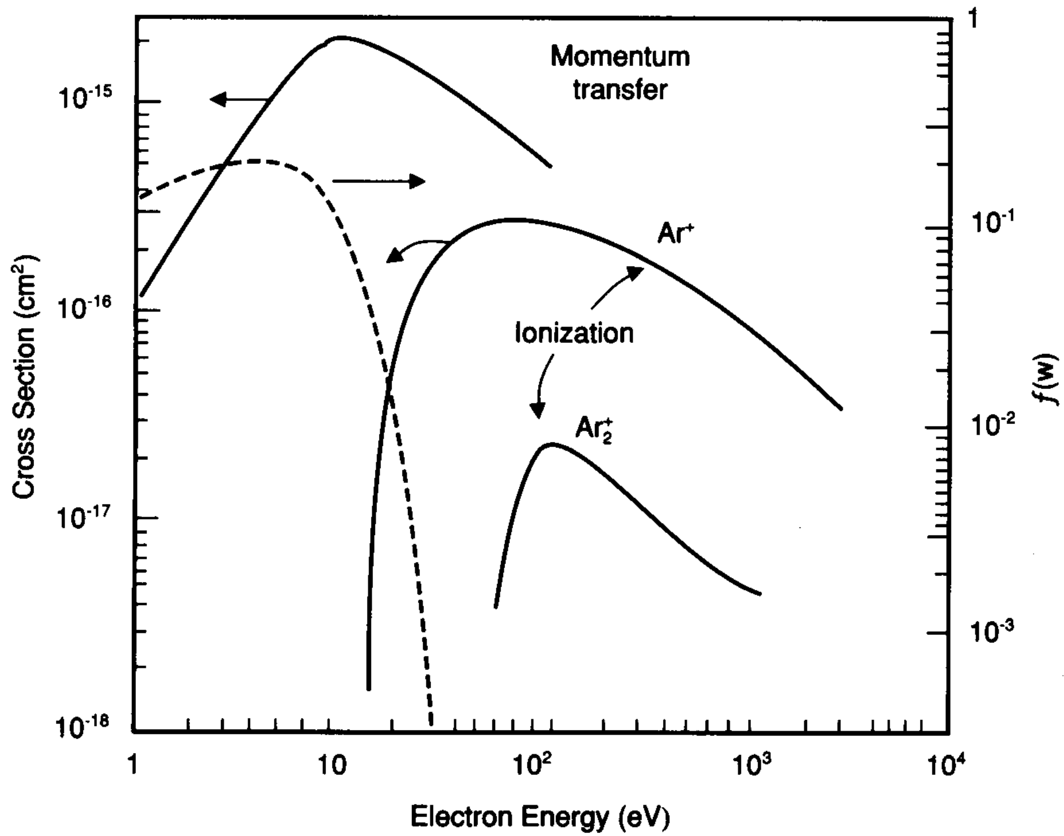
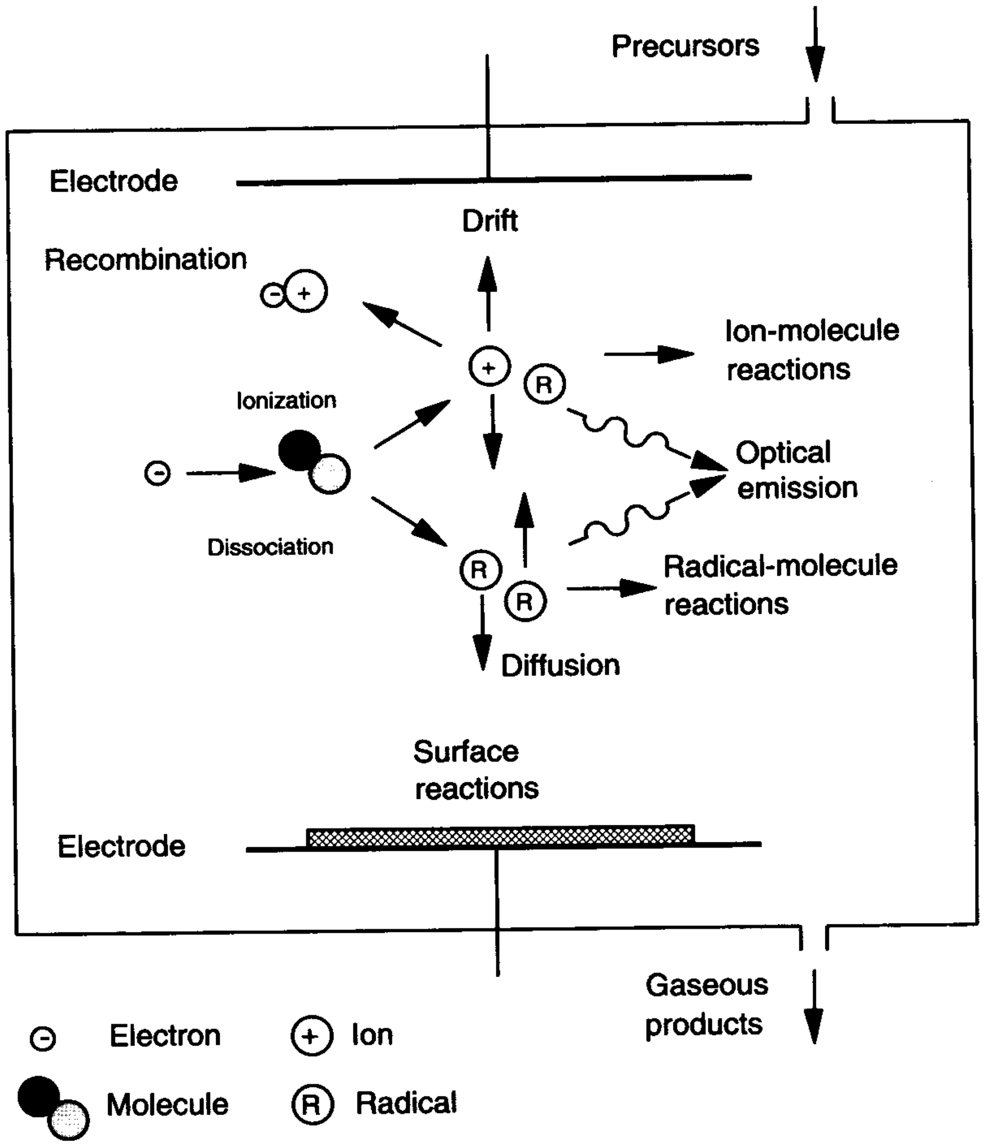


Fig. 3-3 Cross sections versus electron energy (—) and Druyvesteyn energy distribution for T_e = 5 eV (- -).

Reactions in Plasma



Homogeneous Reactions

- Recombination of Ions:
- Charge Transfer:
- Transfer of heavy reactants:
- Radical-Molecule Reaction:
  - Electron Transfer
  - Penning Ionization
  - Attachment of Atoms
  - Recombination of radicals
  - Chemiluminescence

Hetetrogenous Reactions

- Adsorption
- Metastable deexcitation
- Polymerization

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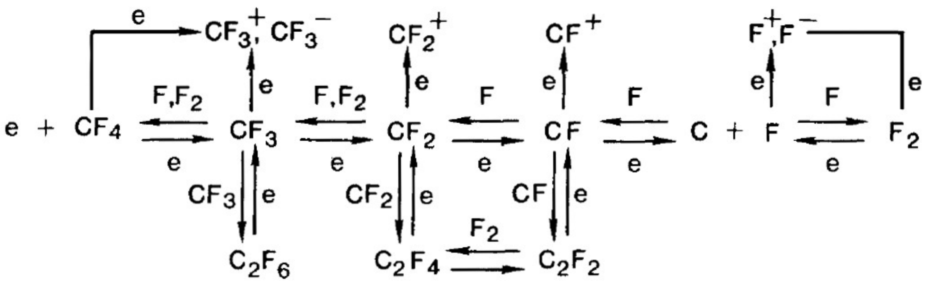
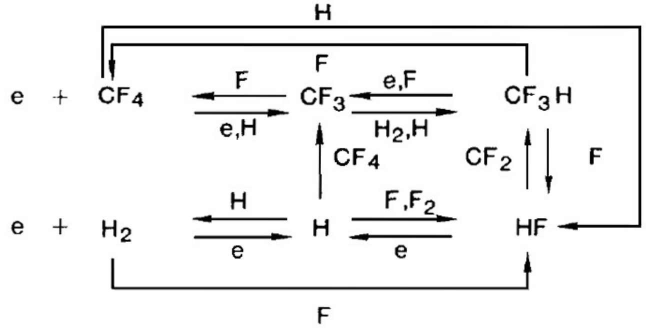
플라즈마공정의 복잡성 (플라즈마 내 화학반응)

- CF_4 플라즈마에서 발생하는 Ions, Radicals, Electrons(예시)





- O_2 플라즈마내의 화학반응

Reaction	k	σ_{max} (cm^2)
Ionization		
1. $e + O_2 \rightarrow O_2^+ + 2e$		2.72×10^{-16}
2. $e + O \rightarrow O^+ + 2e$		1.54×10^{-18}
Dissociative ionization		
3. $e + O_2 \rightarrow O^+ + O$		1.0×10^{-16}
Dissociative attachment		
4. $e + O_2 \rightarrow O^- + O$		1.41×10^{-18}
5. $e + O_2 \rightarrow O^- + O + e$		4.85×10^{-19}
Dissociation		
6. $e + O_2 \rightarrow 2O + e$		2.25×10^{-18}
Metastable formation		
7. $e + O_2 \rightarrow O_2(^1\Delta_g) + e$		3.0×10^{-20}
Charge transfer		
8. $O^+ + O_2 \rightarrow O_2^+ + O$	2×10^{-11} cm³/sec	
9. $O_2^+ + O \rightarrow O + O_2$		8×10^{-16}
10. $O_2^+ + O_2 \rightarrow O_3^+ + O$		1×10^{-16}
11. $O_2^+ + 2O_2 \rightarrow O_4^+ + O_2$	2.8×10^{-30} cm⁶/sec	
	2.5×10^{-14} cm³/sec at $E/p = 20$ V/cm torr	
12. $O^- + O_2 \rightarrow O_2^- + O$	3.4×10^{-12} cm³/sec at $E/p = 45$ V/cm torr	
13. $O^- + O_3 \rightarrow O_3^- + O$	5.3×10^{-10} cm³/sec	
14. $O^- + 2O_2 \rightarrow O_3^- + O_2$	$1.0 \pm 0.2 \times 10^{-30}$ cm⁶/sec	
15. $O_2^- + O \rightarrow O^- + O_2$	5×10^{-10} cm³/sec	
16. $O_2^- + O_2 \rightarrow O_3^- + O$		$< 10^{-18}$
17. $O_2^- + O_3 \rightarrow O_3^- + O_2$	4.0×10^{-10} cm³/sec	
18. $O_2^- + 2O_2 \rightarrow O_4^- + O_2$	3×10^{-31} cm⁶/sec	
19. $O_3^- + O_2 \rightarrow O_2^- + O_3$		4×10^{-17}
20. $O_4^- + O \rightarrow O_3^- + O_2$	4×10^{-10} cm³/sec	
21. $O_4^- + O_2 \rightarrow O_2^- + 2O_2$	6×10^{-15} cm³/sec	
Detachment		
22. $O^- + O \rightarrow O_2 + e$	3.0×10^{-10} cm³/sec	
23. $O^- + O_2 \rightarrow O + O_2 + e$		7×10^{-16}
24. $O^- + O_2(^1\Delta_g) \rightarrow O_3 + e$	$\sim 3 \times 10^{-10}$ cm³/sec	
25. $O_2^- + O \rightarrow O_3 + e$	5.0×10^{-10} cm³/sec	
26. $O_2^- + O_2 \rightarrow 2O_2 + e$		7×10^{-16}
27. $O_2^- + O_2(^1\Delta_g) \rightarrow 2O_2 + e$	$\sim 2 \times 10^{-10}$ cm³/sec	
Electron-ion recombination		
28. $e + \left\{ \begin{matrix} O \\ O_2^+ \\ O_3^+ \\ O_4^+ \end{matrix} \right\} \rightarrow \left\{ \begin{matrix} O \\ 2O \\ O + O_2 \\ 2O_2 \end{matrix} \right\}$	$\lesssim 10^{-7}$ cm³/sec	
Ion-ion recombination		
29. $\left\{ \begin{matrix} O^- \\ O_2^- \\ O_3^- \\ O_4^- \end{matrix} \right\} + \left\{ \begin{matrix} O^+ \\ O_2^+ \\ O_3^+ \\ O_4^+ \end{matrix} \right\} \rightarrow \left\{ \begin{matrix} O \\ O_2 \end{matrix} \right\}$	$\sim 10^{-7}$ cm³/sec	
Atom recombination		
30. $2O + O_2 \rightarrow 2O_2$	2.3×10^{-33} cm⁶/sec	
31. $3O \rightarrow O + O_2$	1.5×10^{-34} cm⁶/sec	
32. $O + 2O_2 \rightarrow O_2 + O_2$	$1.9 \times 10^{-35} \exp(2100/RT)$ cm⁶/sec	
33. $O + O_3 \rightarrow 2O_2$	$2.0 \times 10^{-11} \exp(-4790/RT)$ cm³/sec	
34. $O \underset{wall}{\rightarrow} O_2$	$\gamma = 1.6 \times 10^{-4}$ to 1.4×10^{-2} ($T = 20 - 600$ °C)	

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플라즈마공정의 복잡성 (플라즈마 내 전달현상)

Theory of Ion-electron

$$\frac{\partial n_e}{\partial t} + \frac{\partial \Gamma_e}{\partial x} = r_i - r_a + k_d n_n N^*$$

$$\frac{\partial n_p}{\partial t} + \frac{\partial \Gamma_p}{\partial x} = r_i - k_r n_n n_p$$

$$\frac{\partial n_n}{\partial t} + \frac{\partial \Gamma_n}{\partial x} = r_a - k_r n_n n_p - k_d n_n N^*$$

$$\Gamma_e = n_e \upsilon_e = -\mu_e n_e E - D_e \frac{\partial n_e}{\partial x}$$

$$\Gamma_p = n_p \upsilon_p = \mu_p n_p E - \frac{n_p}{\nu_h}\frac{\partial \nu_p}{\partial t}$$

$$\Gamma_n = n_n \upsilon_n = -\mu_n n_n E - \frac{n_n}{\nu_h}\frac{\partial \nu_n}{\partial t}$$

$$\frac{\partial E}{\partial x} = \frac{e}{\epsilon_0}(n_p - n_n - n_e)$$

$$\frac{\partial}{\partial t}(n_e u_e) + \frac{5}{3}\frac{\partial}{\partial x}(\Gamma_e u_e) - \frac{2}{3}\frac{\partial}{\partial x}\left(\frac{K_e}{k}\right)\frac{\partial u_e}{\partial x} + \Gamma_e E + k_\epsilon (u_e) n_e N = 0$$

Theory of Flow Module

Mass Conservation

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{V}) = 0$$

Momentum Conservation

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = \frac{\partial(-p+\tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} v) = \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial(-p+\tau_{yy})}{\partial x} + \frac{\partial \tau_{zy}}{\partial z} + S_{My}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} w) = \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \frac{\partial(-p+\tau_{zz})}{\partial x} + S_{Mz}$$

Navier-Stokes Equations

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial x} + \nabla \bullet (\mu \nabla u) + S_{Mx}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial y} + \nabla \bullet (\mu \nabla u) + S_{My}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial z} + \nabla \bullet (\mu \nabla u) + S_{Mz}$$

Theory of Chemistry Module

Reaction Kinetics

$$\alpha A + \beta B \rightarrow C + D$$

$$r = k_o T^n (P / P_{atm})^m e^{-E_a/(RT)} [A]^\alpha [B]^\beta$$

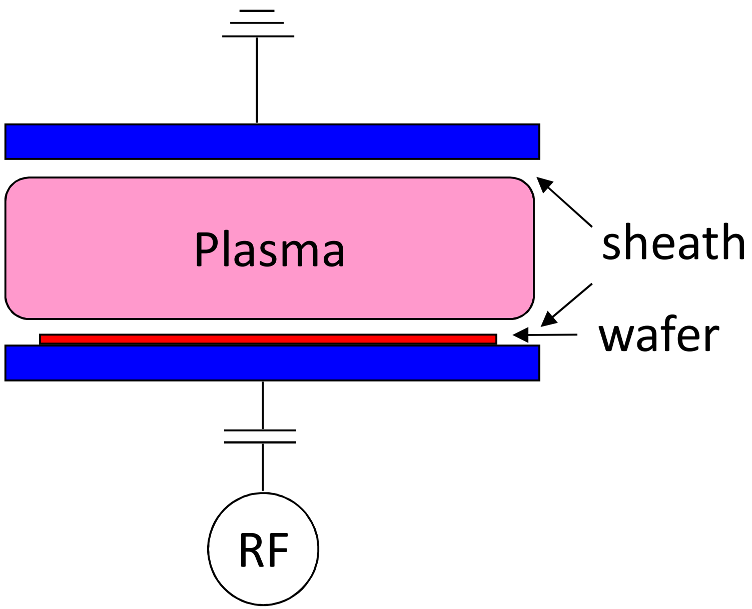
$$r = k'_o T^n e^{-E_a/(RT)} [A]^\alpha [B]^\beta$$

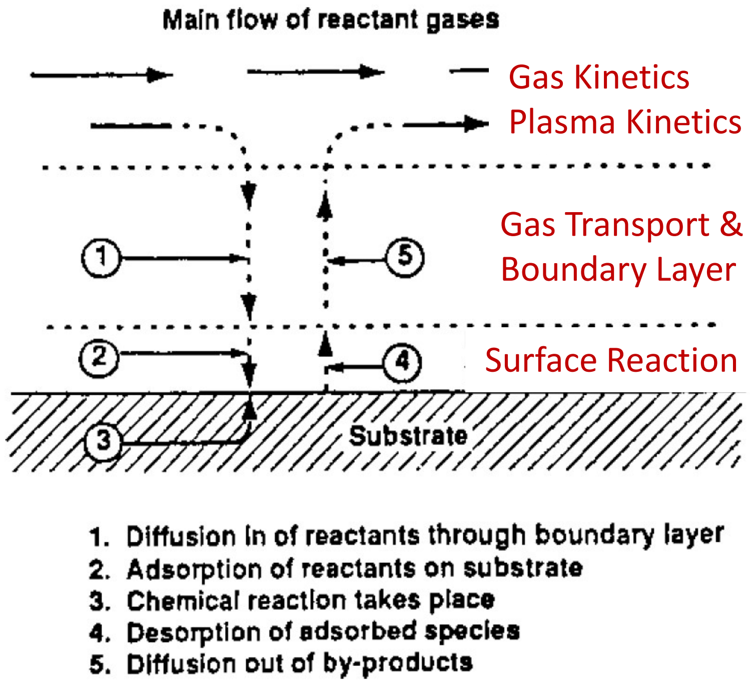
- k_0 = pre-exponential constant
- n = temperature exponent
- E_a/R = activation temperature
- m = exponent on pressure dependency

r is expressed in *kmoles/m³s*

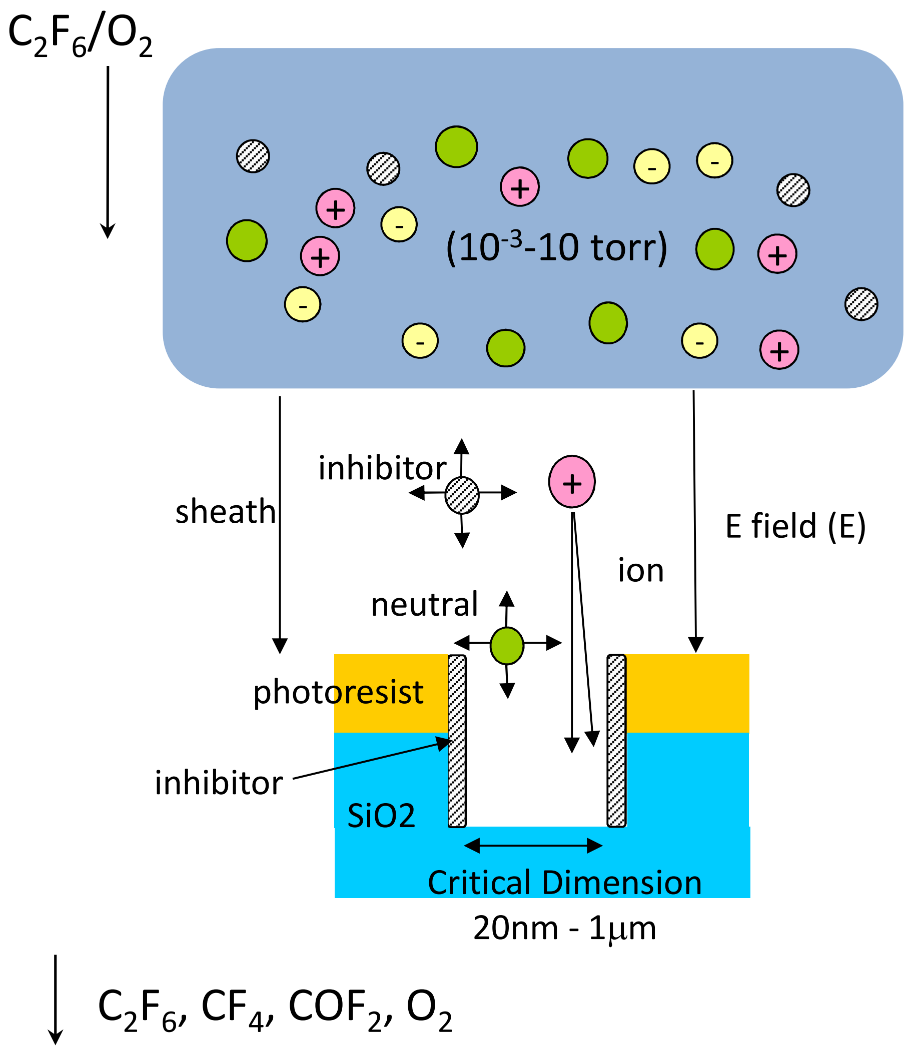
Unit of k_0 = $\frac{m^{3\alpha+3\beta-3}}{kmol^{(\alpha+\beta-1)} s K^n}$

Charge Particles and Neutral Species in Plasma





Major Parameters in Plasmas



- Physical (charged species)
  - Electron density
  - Electron energy distribution
  - Ion density
  - Ion energy distribution
- Chemical (neutral species)
  - Radical density
  - Gas phase reaction rate
  - Surface reaction rate
- Transport
  - Mass
  - Heat
  - Momentum

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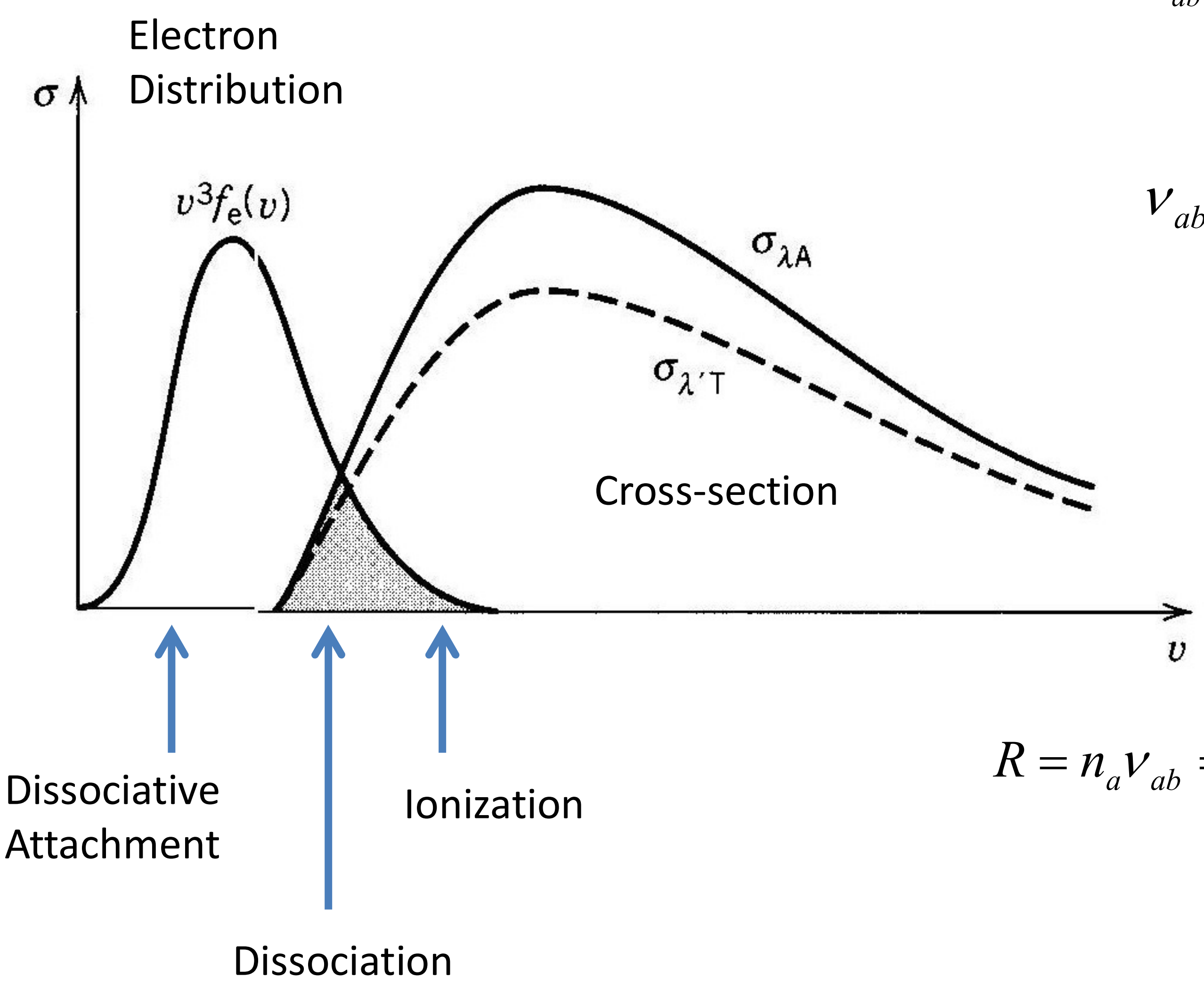
Plasma Density & Electron Temperature



$$\lambda_{ab} = \frac{1}{\sigma_{ab} n_b}$$

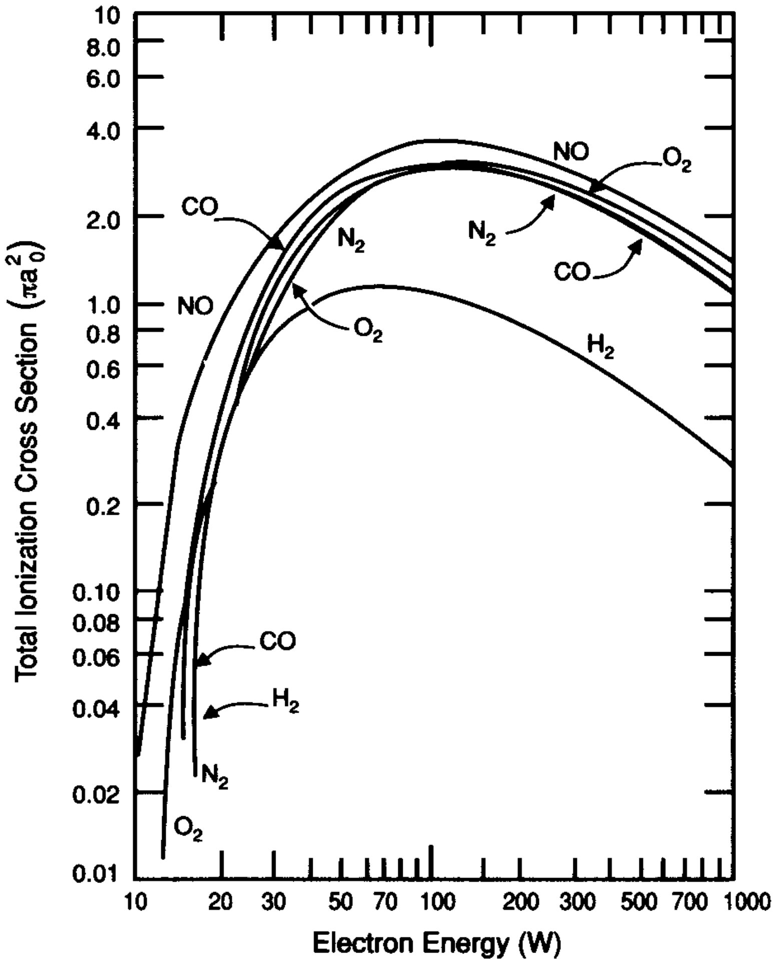
moving *a*, stationary *b* particle

$$\nu_{ab} = \frac{u_a}{\lambda_{ab}} = u_a \sigma_{ab} n_b$$

λ_{ab} = mean free path
σ_{ab} = cross section for the interaction
n_b = density of particles of type b
u_{ab} = moving velocity
ν = collision frequency

$$R = n_a \nu_{ab} = n_a n_b \sigma_{ab} u_a \ \ (cm^3 - \sec)^{-1}$$

Cross Sections



Plot of cross section for ionization versus electron energy (from [6], reprinted by permission of John Wiley & Sons, Inc.).

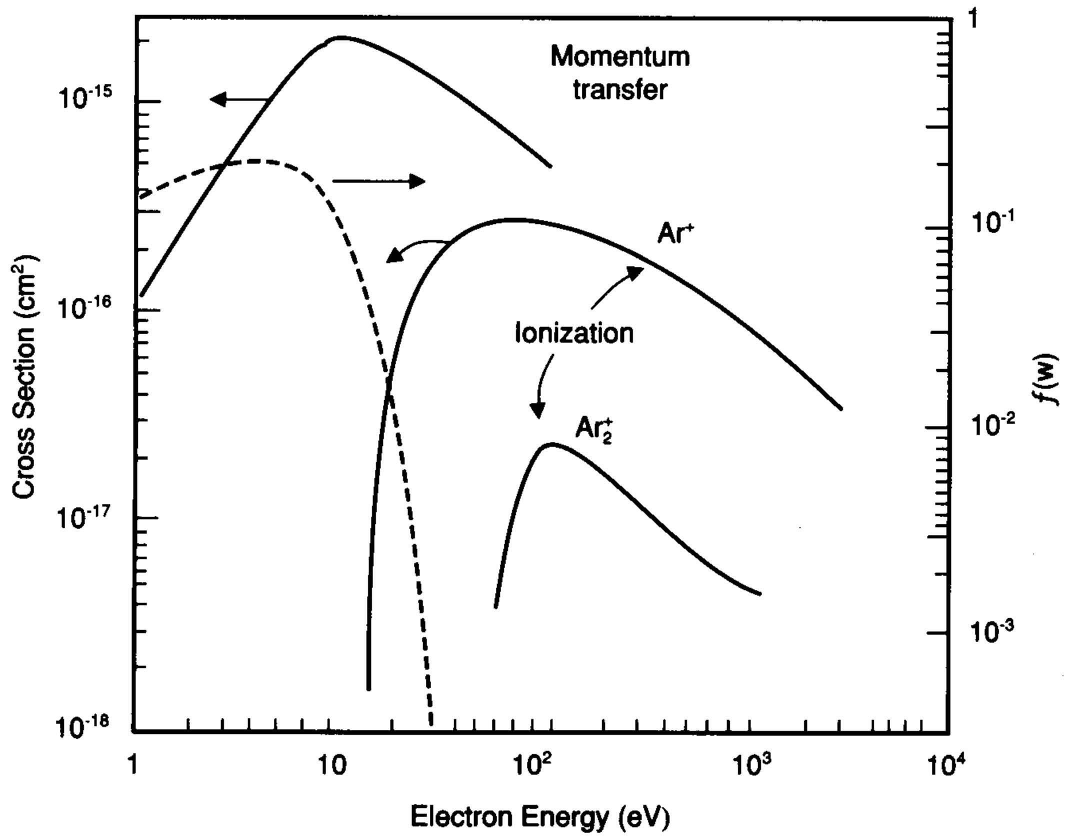
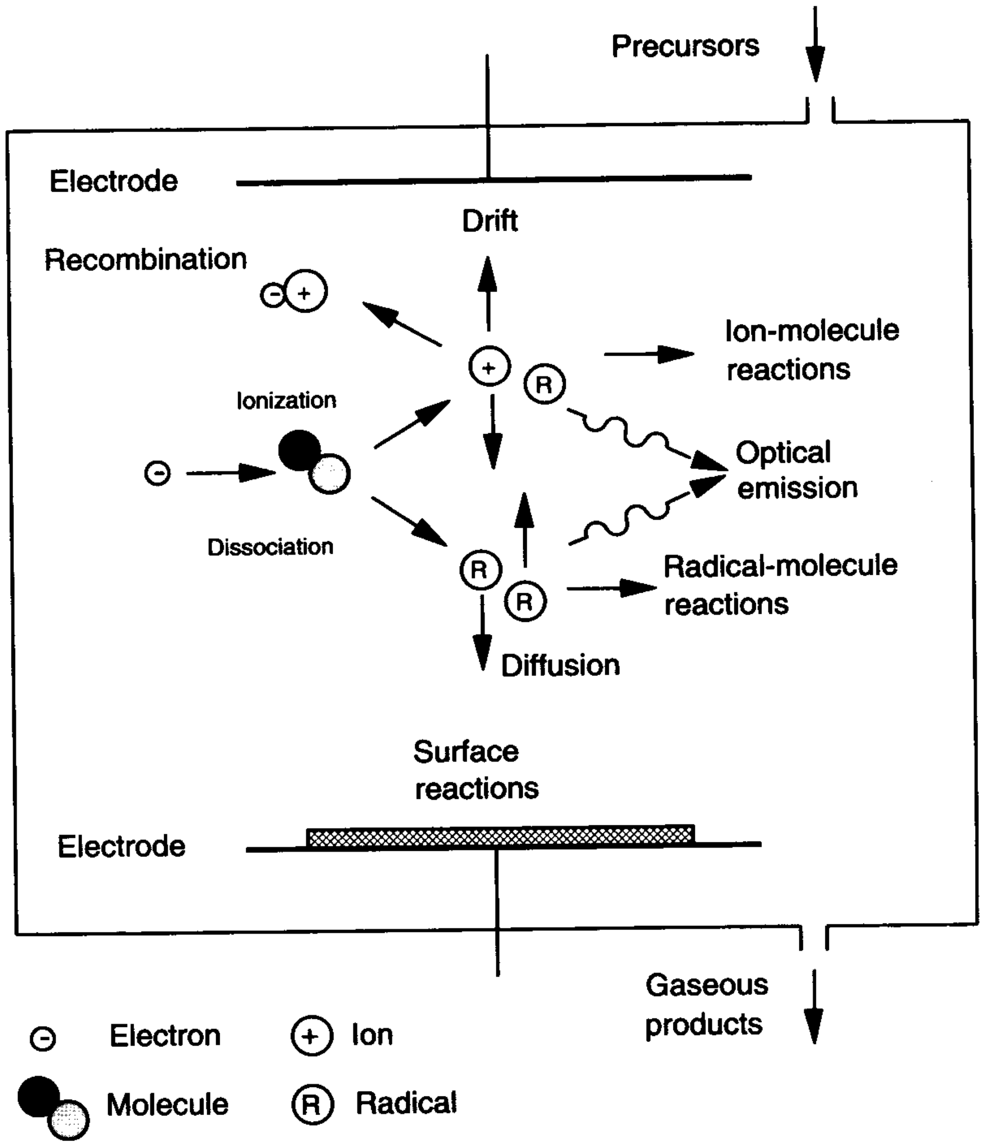


Fig. 3-3 Cross sections versus electron energy (—) and Druyvesteyn energy distribution for $T_e = 5$ eV (- -).

Reactions in Plasma



Homogeneous Reactions

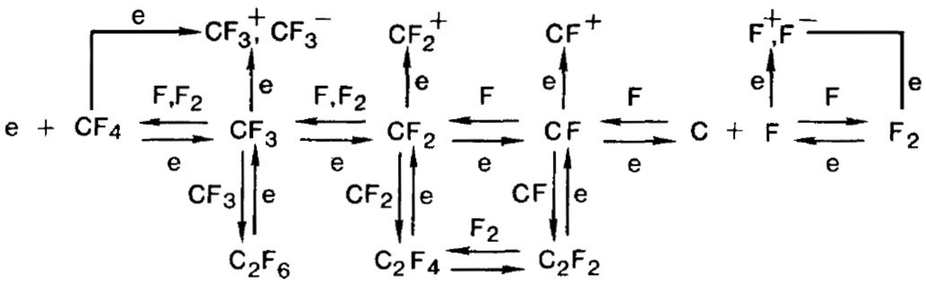
- Recombination of Ions:
- Charge Transfer:
- Transfer of heavy reactants:
- Radical-Molecule Reaction:
  - Electron Transfer
  - Penning Ionization
  - Attachment of Atoms
  - Recombination of radicals
  - Chemiluminescence

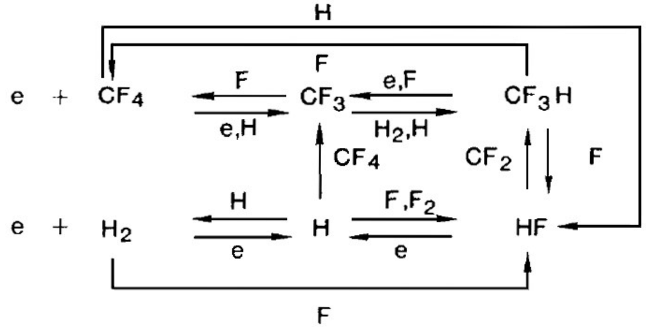
Hetetrogenous Reactions

- Adsorption
- Metastable deexcitation
- Polymerization

플라즈마공정의 복잡성 (플라즈마 내 화학반응)

- CF_4 플라즈마에서 발생하는 Ions, Radicals, Electrons(예시)





- O_2 플라즈마내의 화학반응

Reaction	k	σ_{max} (cm²)
Ionization		
1. $e + O_2 \to O_2^+ + 2e$		2.72×10^{-16}
2. $e + O \to O^+ + 2e$		1.54×10^{-18}
Dissociative ionization		
3. $e + O_2 \to O^+ + O$		1.0×10^{-16}
Dissociative attachment		
4. $e + O_2 \to O^- + O$		1.41×10^{-18}
5. $e + O_2 \to O^- + O + e$		4.85×10^{-19}
Dissociation		
6. $e + O_2 \to 2O + e$		2.25×10^{-18}
Metastable formation		
7. $e + O_2 \to O_2(^1\Delta_g) + e$		3.0×10^{-20}
Charge transfer		
8. $O^+ + O_2 \to O_2^+ + O$	2×10^{-11} cm³/sec	
9. $O_2^+ + O \to O + O_2$		8×10^{-16}
10. $O_2^+ + O_2 \to O_3^+ + O$		1×10^{-16}
11. $O_2^+ + 2O_2 \to O_4^+ + O_2$	2.8×10^{-30} cm⁶/sec	
	2.5×10^{-14} cm³/sec at $E/p = 20$ V/cm torr	
12. $O^- + O_2 \to O_2^- + O$	3.4×10^{-12} cm³/sec at $E/p = 45$ V/cm torr	
13. $O^- + O_3 \to O_3^- + O$	5.3×10^{-10} cm³/sec	
14. $O^- + 2O_2 \to O_3^- + O_2$	$1.0 \pm 0.2 \times 10^{-30}$ cm⁶/sec	
15. $O_2^- + O \to O^- + O_2$	5×10^{-10} cm³/sec	
16. $O_2^- + O_2 \to O_3^- + O$		$< 10^{-18}$
17. $O_2^- + O_3 \to O_3^- + O_2$	4.0×10^{-10} cm³/sec	
18. $O_2^- + 2O_2 \to O_4^- + O_2$	3×10^{-31} cm⁶/sec	
19. $O_3^- + O_2 \to O_2^- + O_3$		4×10^{-17}
20. $O_4^- + O \to O_3^- + O_2$	4×10^{-10} cm³/sec	
21. $O_4^- + O_2 \to O_2^- + 2O_2$	6×10^{-15} cm³/sec	
Detachment		
22. $O^- + O \to O_2 + e$	3.0×10^{-10} cm³/sec	
23. $O^- + O_2 \to O + O_2 + e$		7×10^{-16}
24. $O^- + O_2(^1\Delta_g) \to O_3 + e$	$\sim 3 \times 10^{-10}$ cm³/sec	
25. $O_2^- + O \to O_3 + e$	5.0×10^{-10} cm³/sec	
26. $O_2^- + O_2 \to 2O_2 + e$		7×10^{-16}
27. $O_2^- + O_2(^1\Delta_g) \to 2O_2 + e$	$\sim 2 \times 10^{-10}$ cm³/sec	
Electron-ion recombination		
28. $e + \begin{Bmatrix} O \\ O_2^+ \\ O_3^+ \\ O_4^+ \end{Bmatrix} \to \begin{Bmatrix} O \\ 2O \\ O + O_2 \\ 2O_2 \end{Bmatrix}$	$\lesssim 10^{-7}$ cm³/sec	
Ion-ion recombination		
29. $\begin{Bmatrix} O^- \\ O_2^- \\ O_3^- \\ O_4^- \end{Bmatrix} + \begin{Bmatrix} O^+ \\ O_2^+ \\ O_3^+ \\ O_4^+ \end{Bmatrix} \to \begin{Bmatrix} O \\ O_2 \end{Bmatrix}$	$\sim 10^{-7}$ cm³/sec	
Atom recombination		
30. $2O + O_2 \to 2O_2$	2.3×10^{-33} cm⁶/sec	
31. $3O \to O + O_2$	1.5×10^{-34} cm⁶/sec	
32. $O + 2O_2 \to O_2 + O_2$	1.9×10^{-35} exp $(2100/RT)$cm⁶/sec	
33. $O + O_3 \to 2O_2$	2.0×10^{-11} exp $(-4790/RT)$cm³/sec	
34. $O \xrightarrow[\text{wall}]{} O_2$	$\gamma = 1.6 \times 10^{-4}$ to 1.4×10^{-2} ($T = 20 - 600$ °C)	

플라즈마공정의 복잡성 (플라즈마 내 전달현상)

Theory of Ion-electron

$$\frac{\partial n_e}{\partial t} + \frac{\partial \Gamma_e}{\partial x} = r_i - r_a + k_d\, n_n\, N^*$$

$$\frac{\partial n_p}{\partial t} + \frac{\partial \Gamma_p}{\partial x} = r_i - k_r\, n_n\, n_p$$

$$\frac{\partial n_n}{\partial t} + \frac{\partial \Gamma_n}{\partial x} = r_a - k_r\, n_n\, n_p - k_d\, n_n\, N^*$$

$$\Gamma_e = n_e\, \upsilon_e = -\mu_e\, n_e\, E - D_e \frac{\partial n_e}{\partial x}$$

$$\Gamma_p = n_p\, \upsilon_p = \mu_p\, n_p\, E - \frac{n_p}{\nu_h}\frac{\partial \nu_p}{\partial t}$$

$$\Gamma_n = n_n\, \upsilon_n = -\mu_n\, n_n\, E - \frac{n_n}{\nu_h}\frac{\partial \nu_n}{\partial t}$$

$$\frac{\partial E}{\partial x} = \frac{e}{\in_0}(n_p - n_n - n_e)$$

$$\frac{\partial}{\partial t}(n_e u_e) + \frac{5}{3}\frac{\partial}{\partial x}(\Gamma_e u_e) - \frac{2}{3}\frac{\partial}{\partial x}\left(\frac{K_e}{k}\right)\frac{\partial u_e}{\partial x} + \Gamma_e E + k_{\in}(u_e) n_e N = 0$$

Theory of Flow Module

Mass Conservation

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{V}) = 0$$

Momentum Conservation

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = \frac{\partial(-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} v) = \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial(-p + \tau_{yy})}{\partial x} + \frac{\partial \tau_{zy}}{\partial z} + S_{My}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} w) = \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \frac{\partial(-p + \tau_{zz})}{\partial x} + S_{Mz}$$

Navier-Stokes Equations

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial x} + \nabla \bullet (\mu \nabla u) + S_{Mx}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial y} + \nabla \bullet (\mu \nabla u) + S_{My}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla \bullet (\rho \vec{V} u) = -\frac{\partial p}{\partial z} + \nabla \bullet (\mu \nabla u) + S_{Mz}$$

Theory of Chemistry Module

Reaction Kinetics

$$\alpha A + \beta B \rightarrow C + D$$

$$r = k_o T^n (P / P_{atm})^m e^{-E_a/(RT)} [A]^\alpha [B]^\beta$$

$$r = k'_o T^n e^{-E_a/(RT)} [A]^\alpha [B]^\beta$$

k_0 = pre-exponential constant
n = temperature exponent
E_a/R = activation temperature
m = exponent on pressure dependency

r is expressed in *kmoles/m³s*

Unit of k_0 = $\dfrac{m^{3\alpha+3\beta-3}}{kmol^{(\alpha+\beta-1)} s K^n}$

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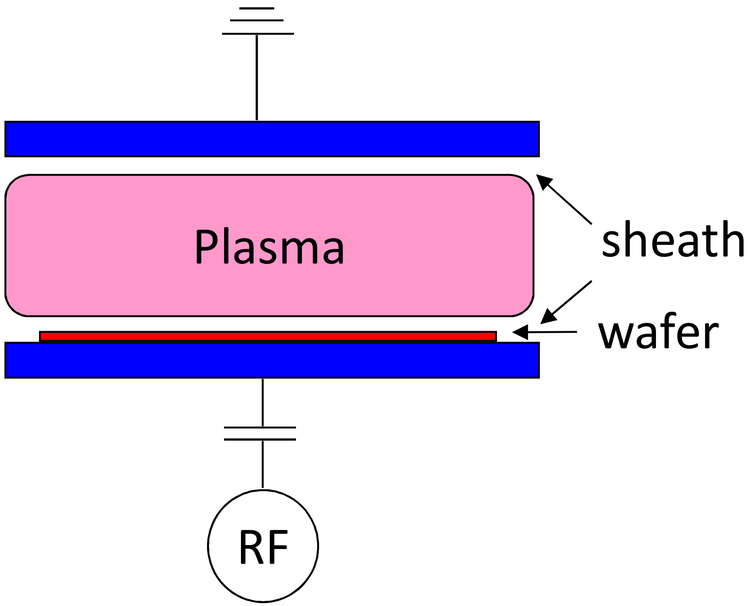
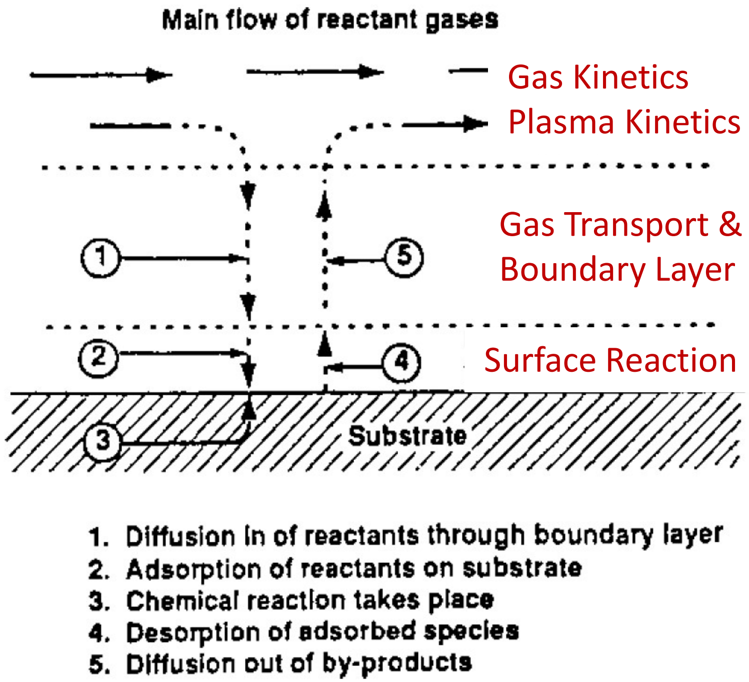
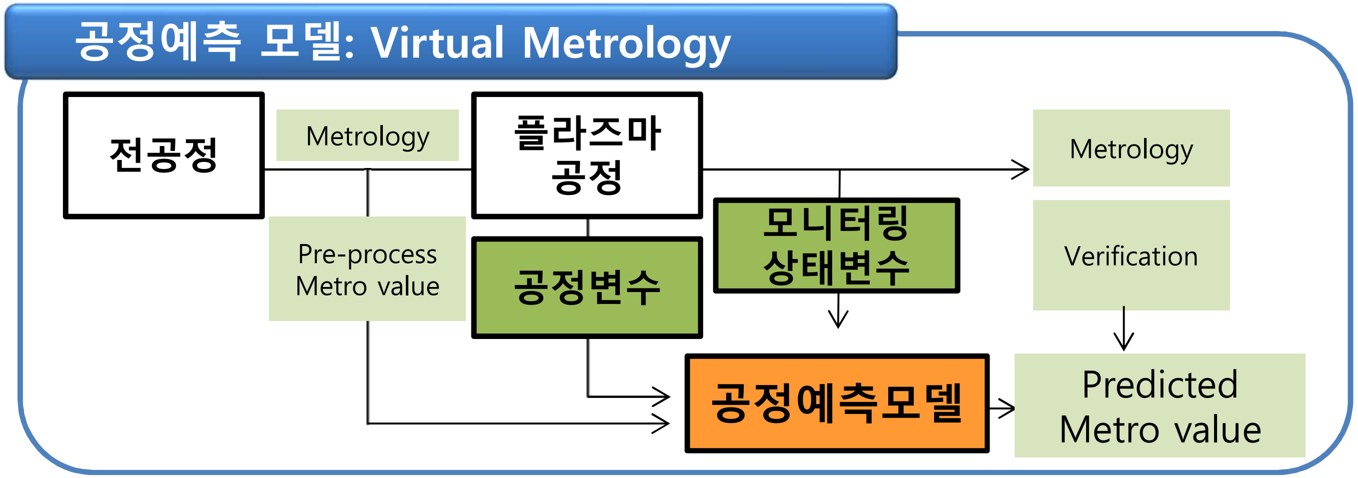
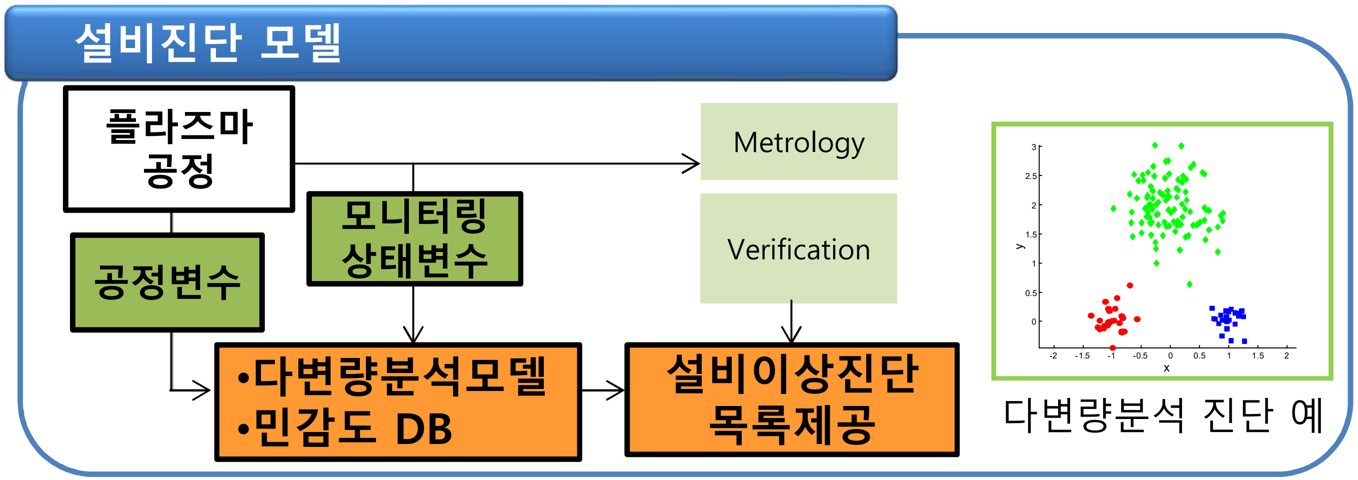
Charge Particles and Neutral Species in Plasma



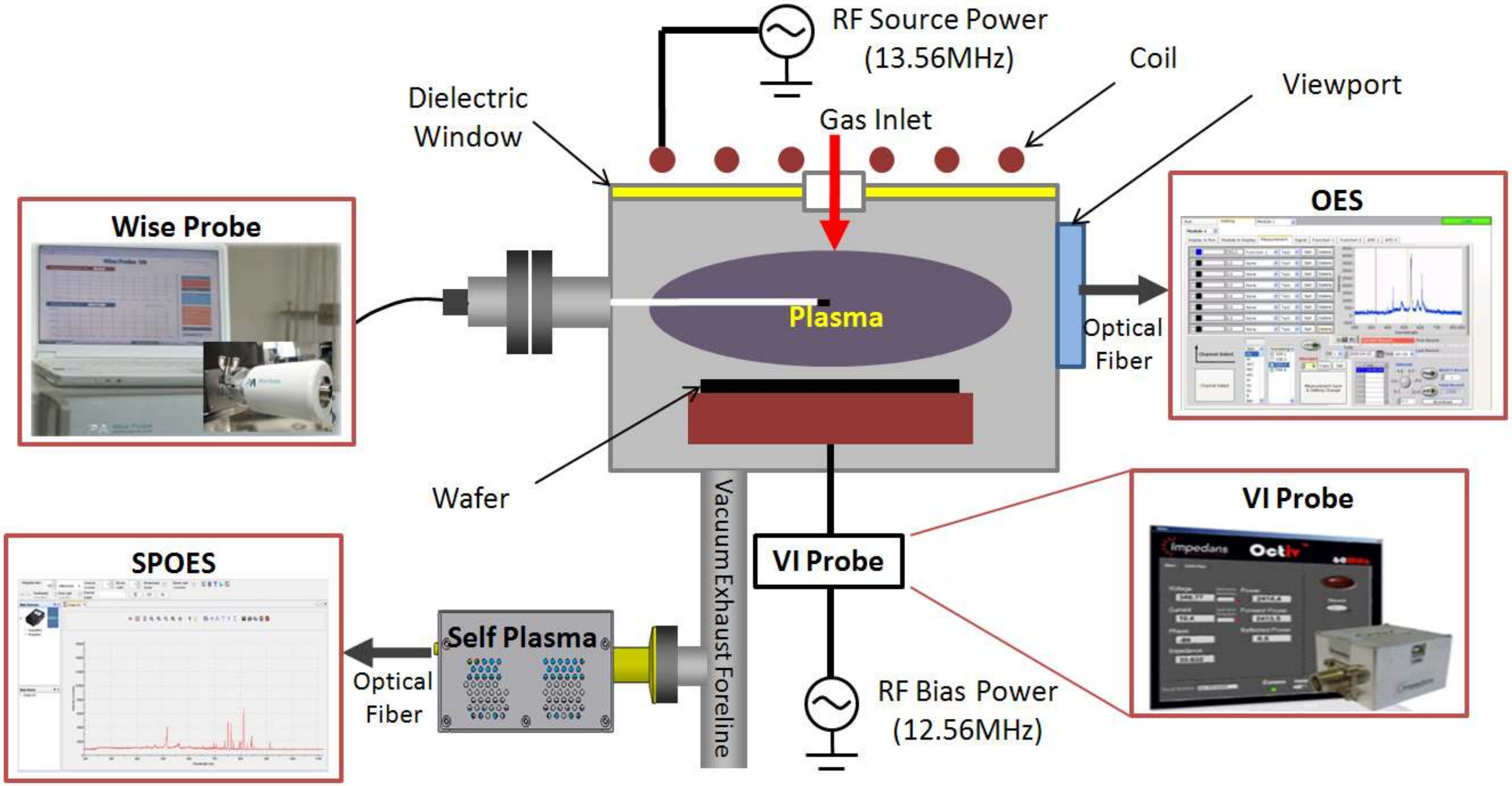


플라즈마 진단 및 모니터링의 필요성

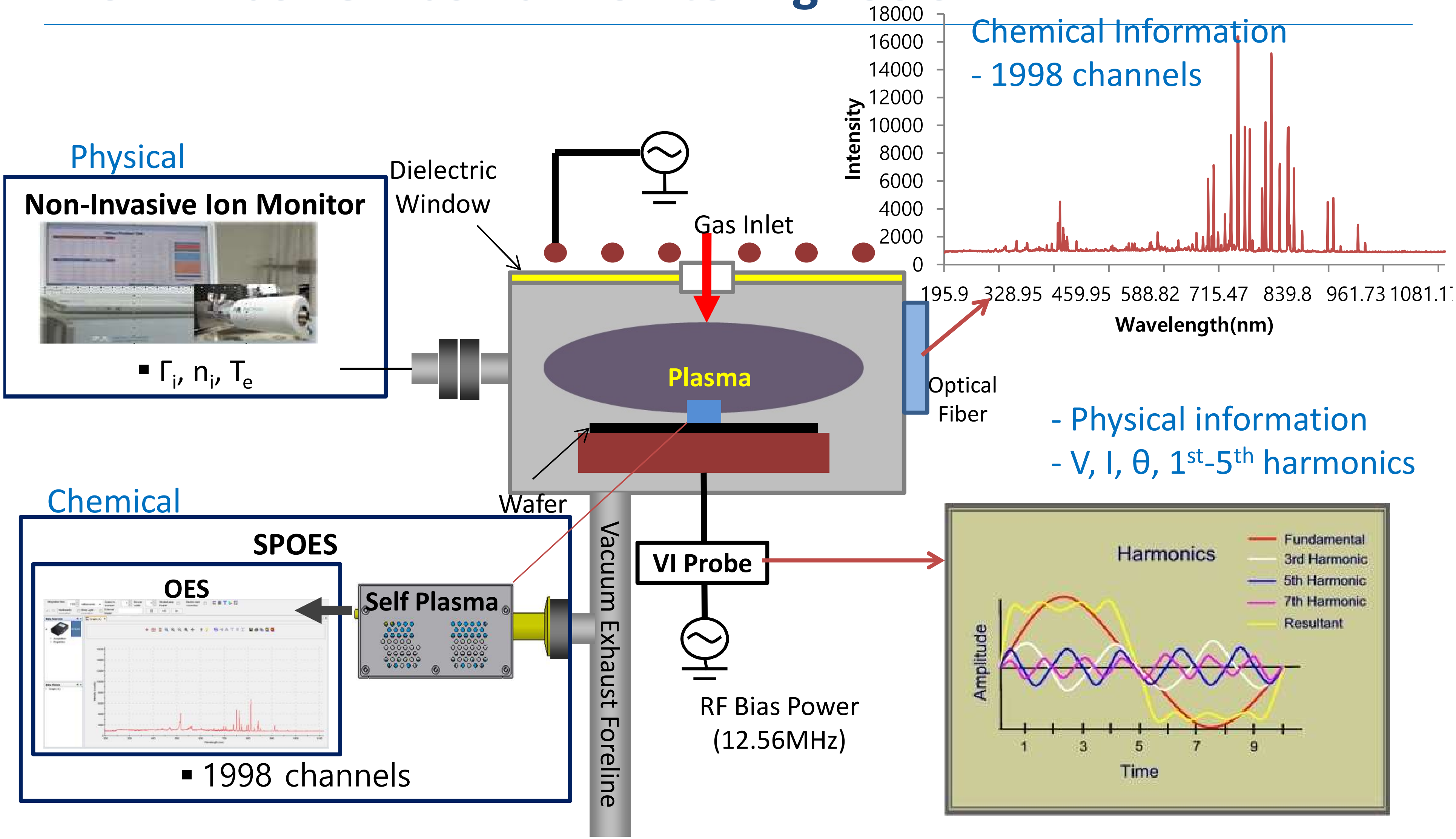




Non-Invasive Plasma Monitoring Tools

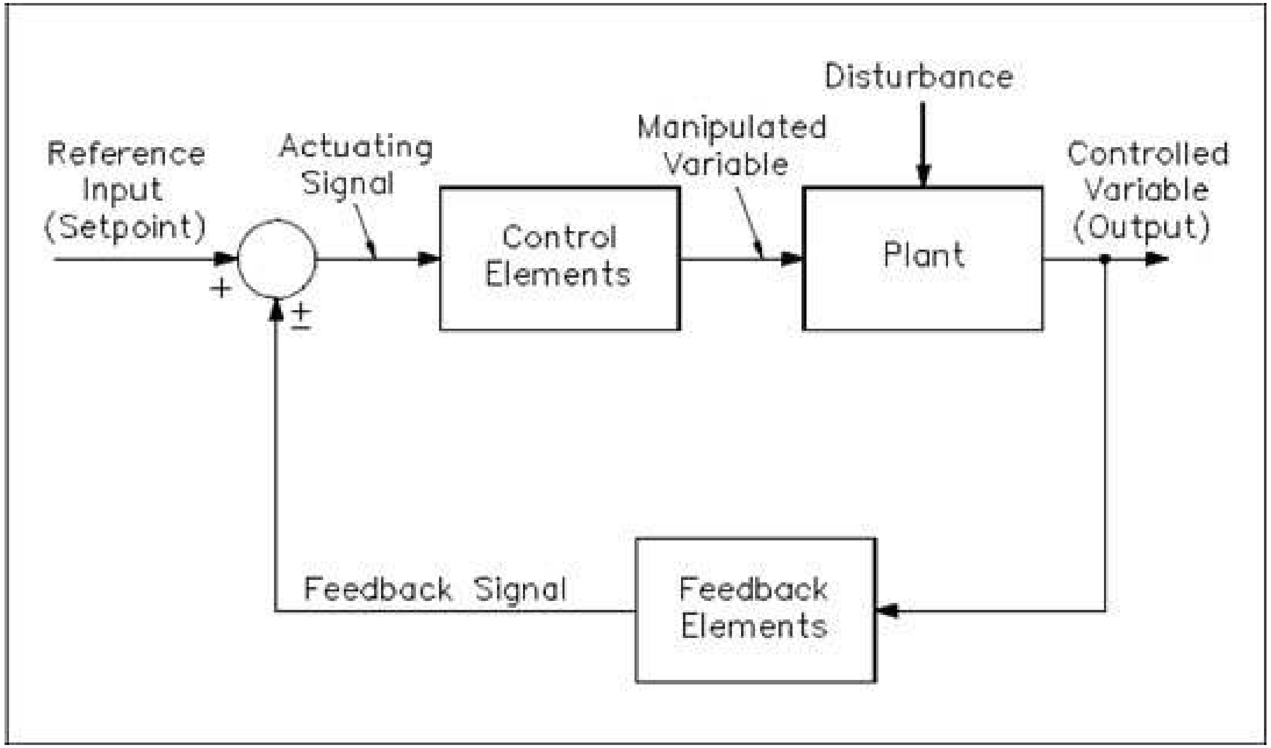


Non-Invasive Plasma Monitoring Tools



SISO/MIMO

- SISO/MIMO 제어모델이 플라즈마 공정에 적용된 경우가 보고됨.



www.techtransfer.com

- 하지만 실제공정에는 주요변수가 많아 제한적으로만 적용가능함.

Run-to-Run Control

Post Process Results
(Current Process)

Post Process Results
(Upstream Process - Optional)

Feedback Control

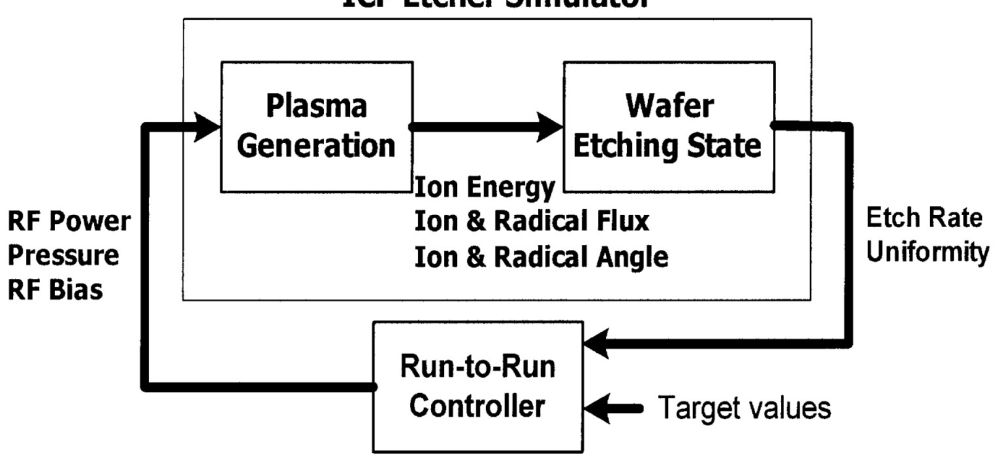
Process Recipe
(Current Process)

- **Process Control Models**
  - Dynamic
  - Configurable
- **Process Optimization Targets**
- **Process History**
- **Wafer-to-Wafer or Lot-to-Lot Control**

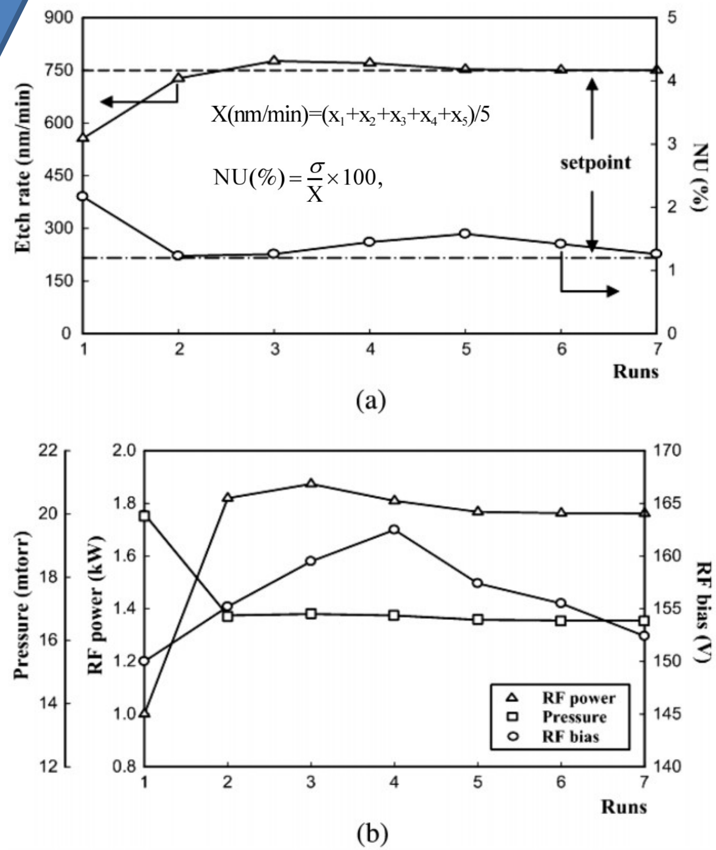
Recipe Advice
(Future Run)

Feedback Control

- Designed to minimize a quadratic cost of control error for the **oxide etch rate** and **etch uniformity** by run-wise integral action of the **RF power, chamber pressure and RF bias voltage**.



Block diagram for the run-to-run control system



S. T. Seo *et al.*, Korean J. Chem. Eng., 23 (2006) 199

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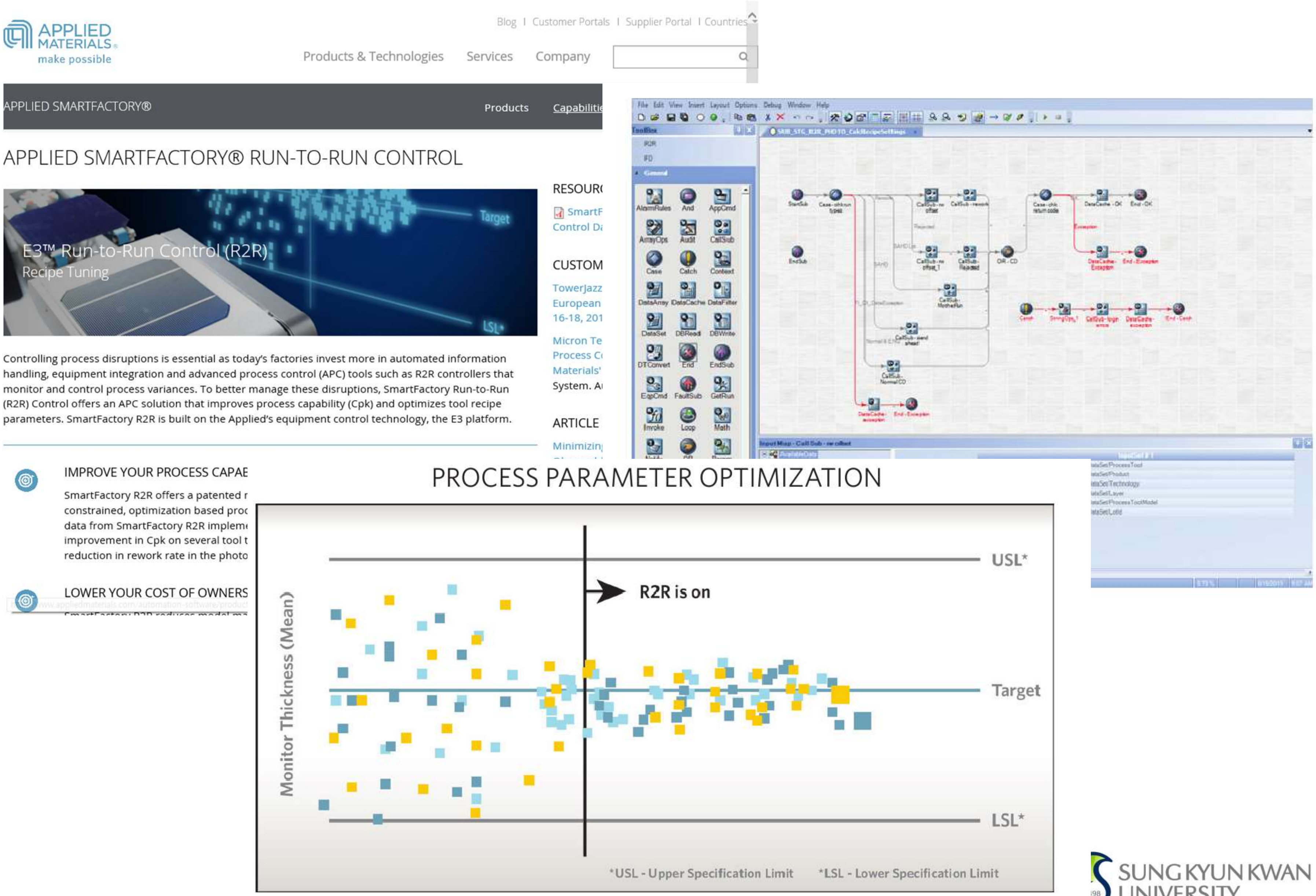
Run-to-Run Control @ AMAT



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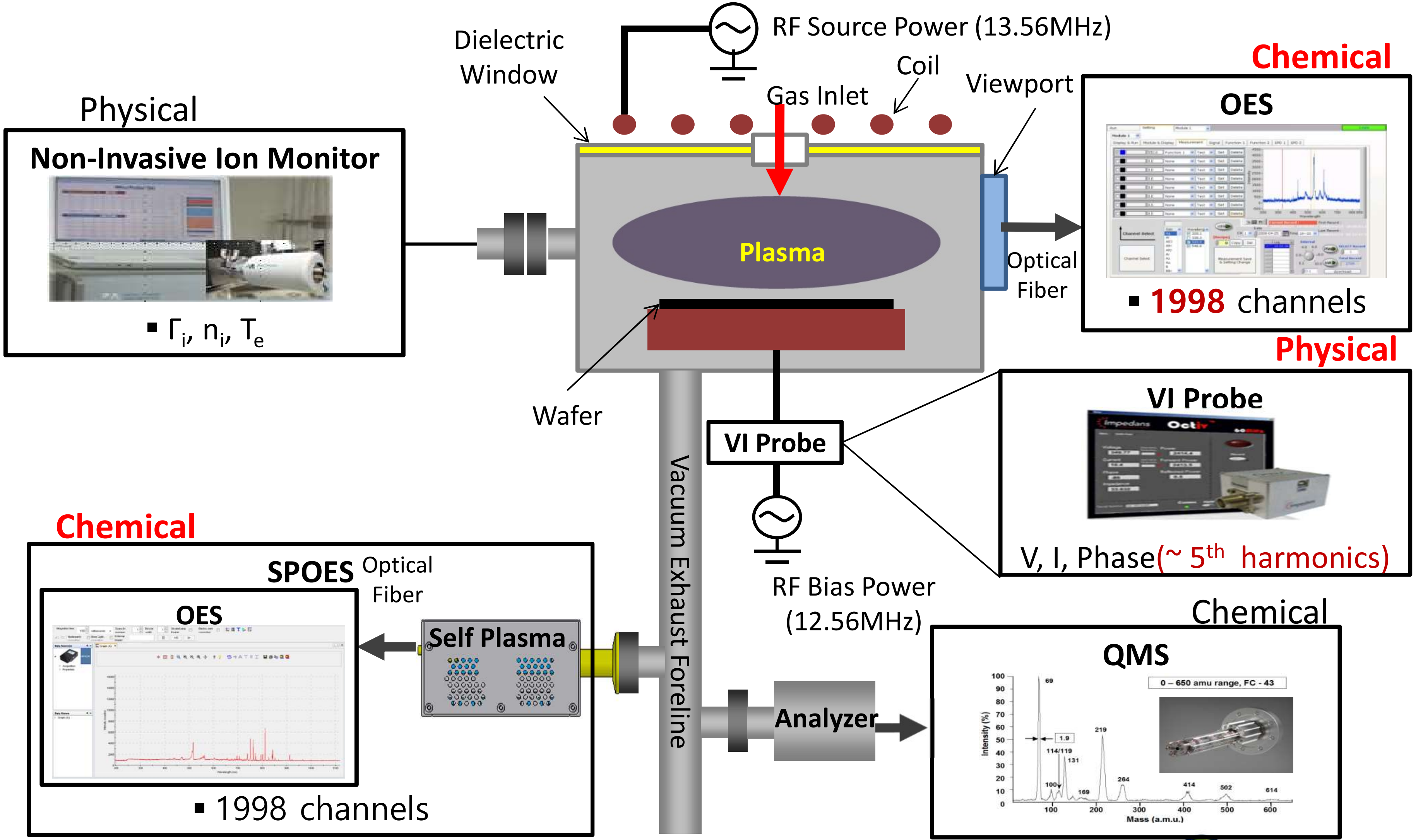
Physical and Electrical Diagnostics

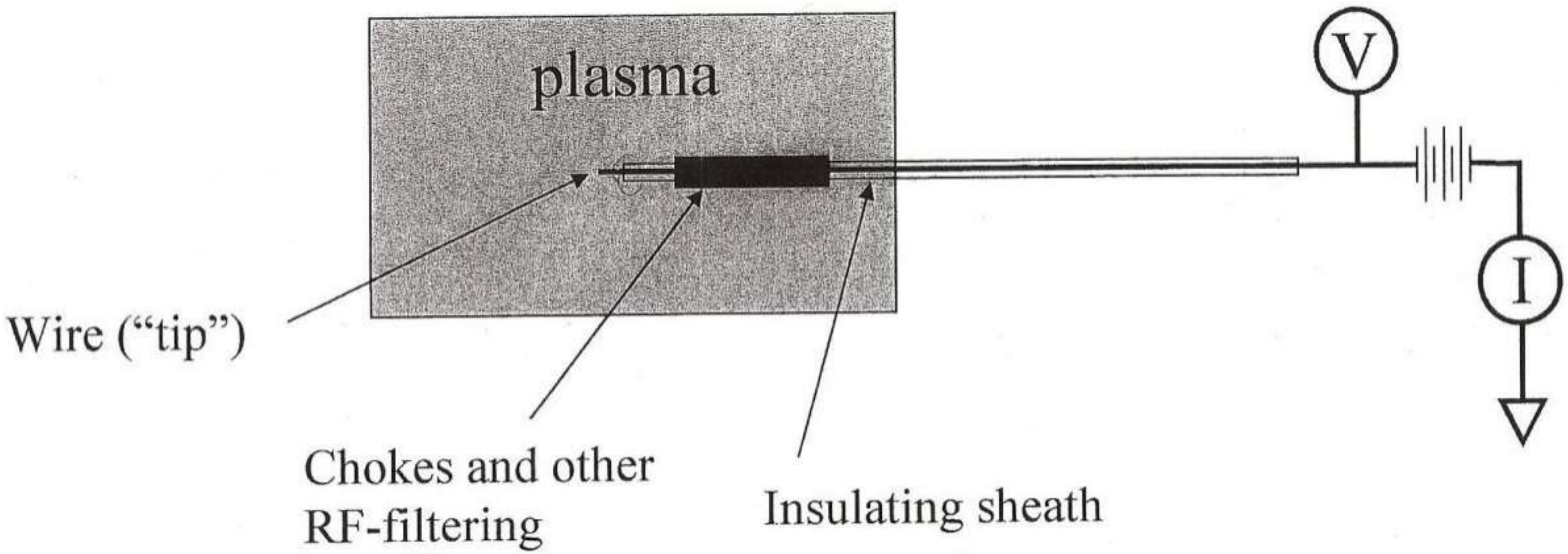
Monitoring Tools

- Non-invasive chemical and physical monitoring tools

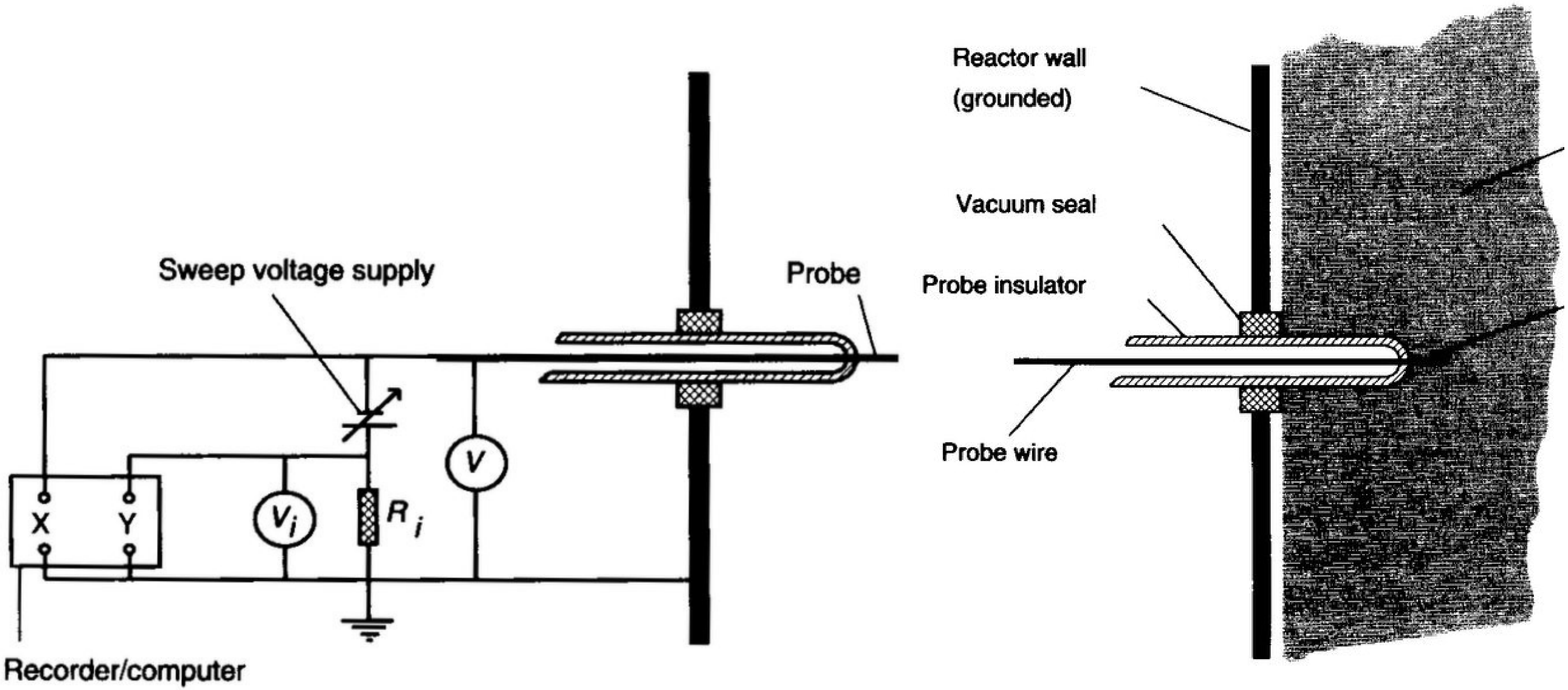


Langmuir Probe

- Electron and ion energy distribution

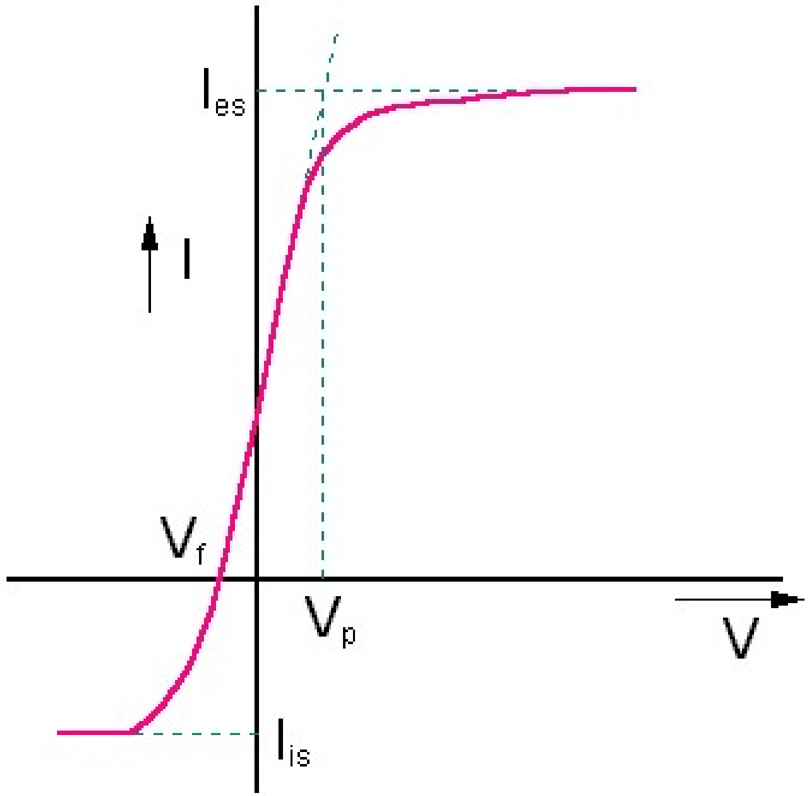


Langmuir Probe



Langmuir Probe

1. $V_{probe} = V_p$ (plasma potential)
   : The probe collects both ions and electrons from a plasma. → The probe draws an electron current.
2. $V_{probe} > V_p$: electron saturation region
   : The probe repels ions and accelerates electrons, reaching electron saturation current, I_{es}.
3. $V_{probe} < V_p$: transition region
   : Electrons are repelled and the current is decreased exponentially.
4. $V_{probe} << V_p$: ion saturation region region
   : Only ions are collected, reaching ion saturation region, I_{is}.



Langmuir Probe

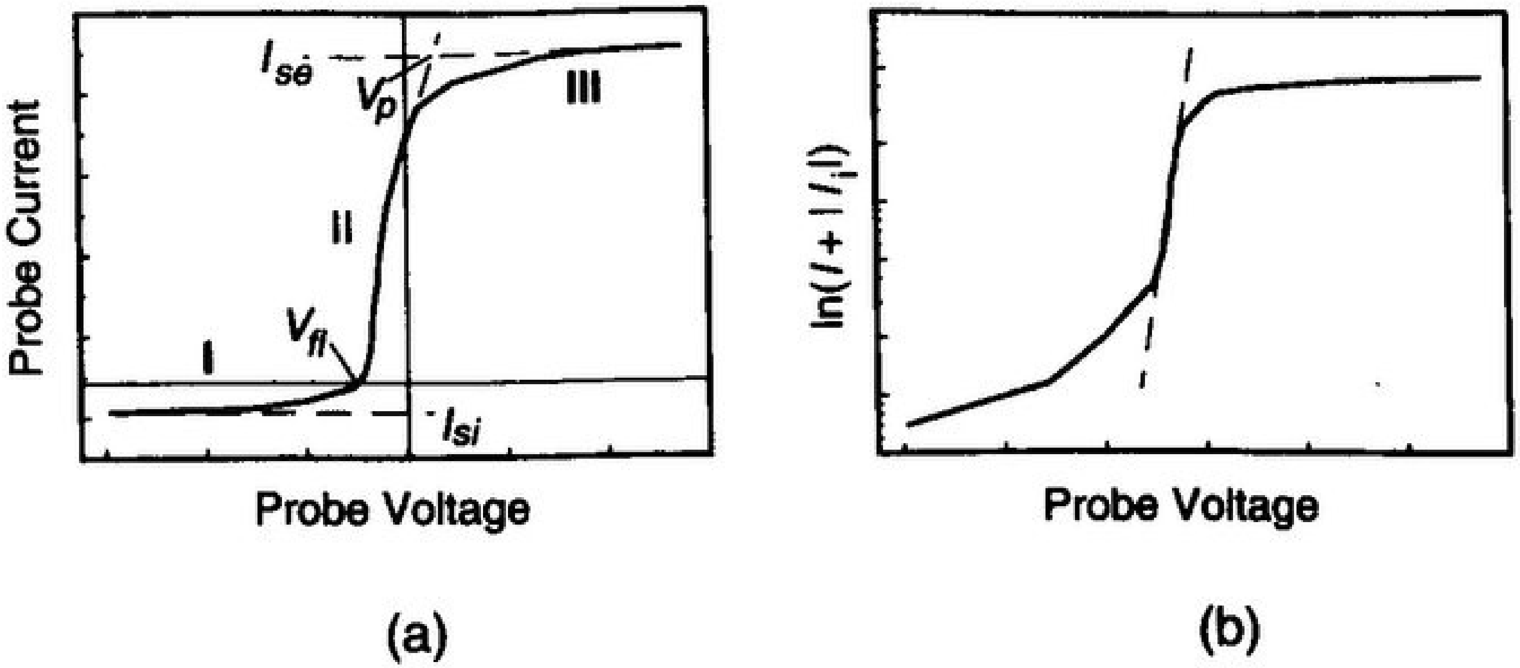


Fig. 5-8 I-V characteristic of a single Langmuir probe: (a) linear display; (b) semilogarithmic display.

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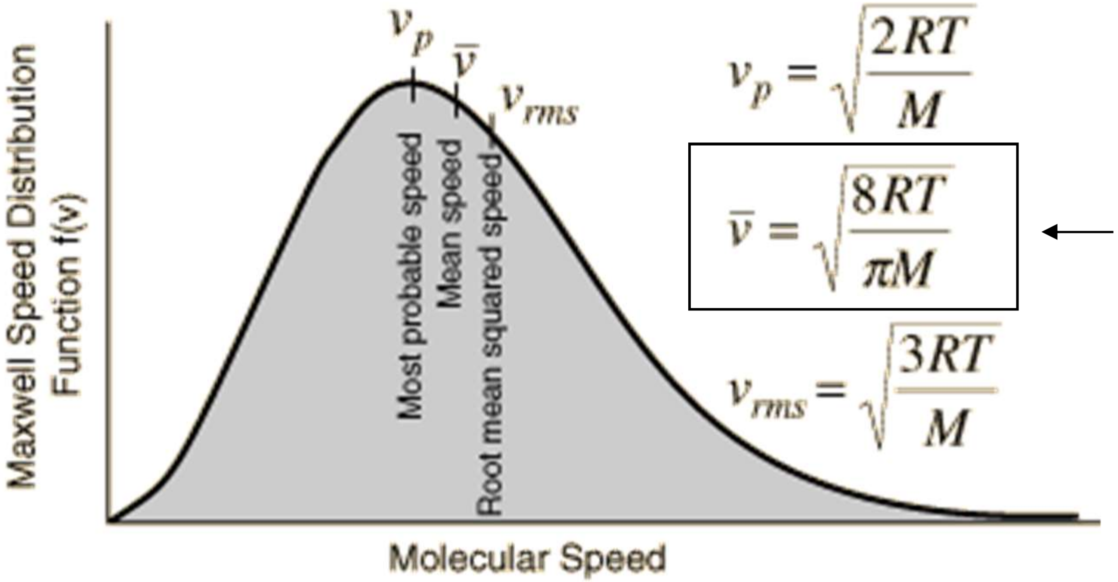
Maxwell-Boltzmann Distribution in 3D

- Gas distribution as function of speed

$$f(v) = 4\pi\left[\frac{M}{2\pi RT}\right]^{\frac{3}{2}} v^2 \exp\left[\frac{-Mv^2}{2RT}\right]$$

v = speed
M = molar mass
T = temperature
k_B = Boltzmann's constnat



$$v_p = \sqrt{\frac{2RT}{M}}$$

$$\bar{v} = \sqrt{\frac{8RT}{\pi M}} \leftarrow \bar{v} = \int v f(v)\, dv$$

$$v_{rms} = \sqrt{\frac{3RT}{M}}$$

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Langmuir Probe Characteristics

From Maxwell-Boltzmann distribution function, (Fig3.5, Chapman)

$$\frac{n_e'}{n_e} = \exp\left(\frac{e\left(V_p - V_f\right)}{kT_e}\right)$$

$$\frac{n_e' \overline{c_e'}}{4} = \frac{n_i \overline{c_i}}{4}$$

$$V_p - V_f = \frac{kT}{e}\ln\left(\frac{\overline{c_e}}{\overline{c_i}}\right) = \frac{kT}{e}\ln\left(\frac{m_i T_e}{m_e T_i}\right)$$

$$j_e = \frac{e n_e' \overline{c_e}}{4} = \frac{e n_e \overline{c_e}}{4}\exp\left(-\frac{e\left(V_p - V\right)}{kT_e}\right)$$

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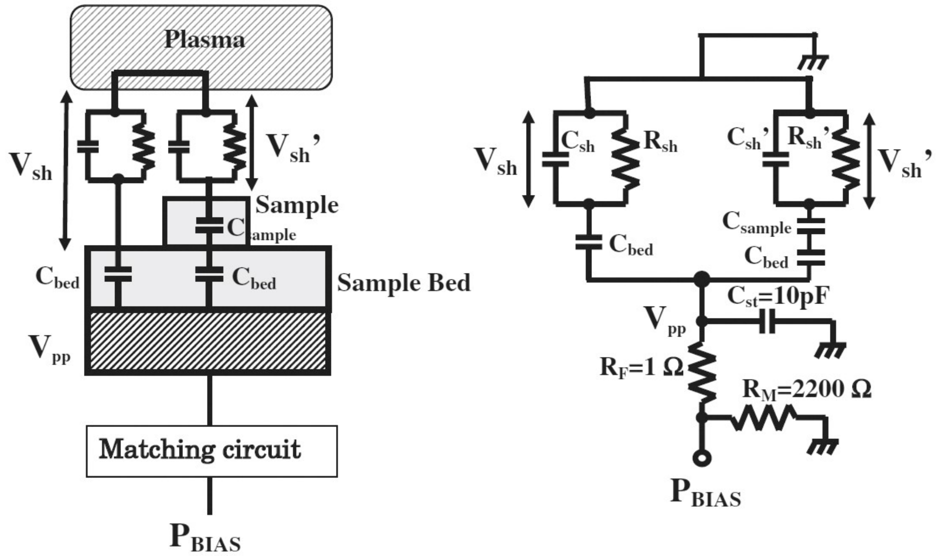
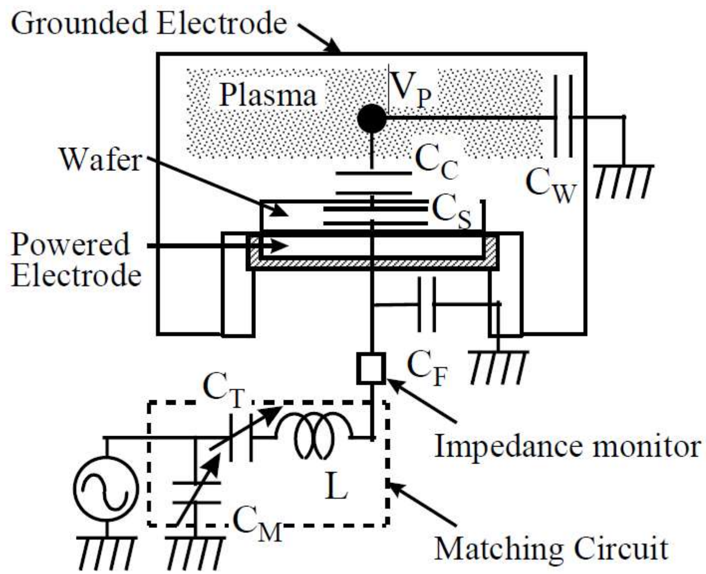
VI probe / Equivalent Circuit Model

◆ **Equivalent circuit model for plasma impedance monitoring**



H. Kawata *et al.*, *Jpn. J. Appl. Phys.*, 47 (2008) 6914



H. Takada et al, *Jpn. J. Appl. Phys.* 40 (2001) 1457

- Non-invasive method
- Plasma → Conductor / Sheath → Capacitor

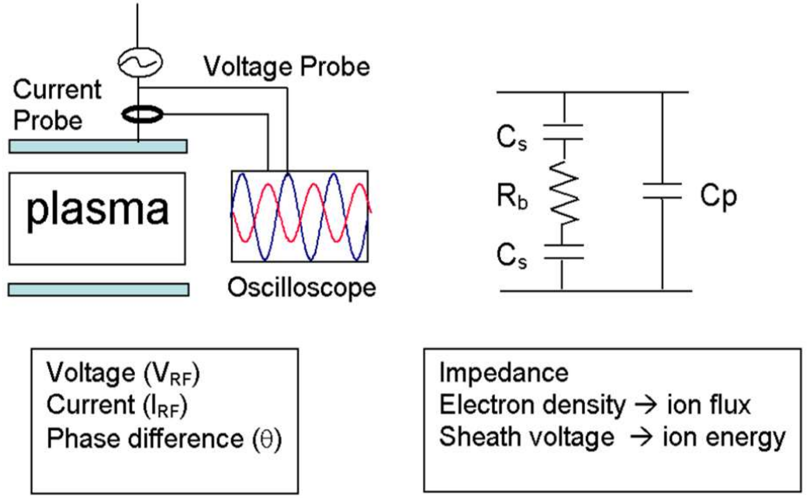
→ **Physical information can be monitored with impedance analysis.**

→ **Viewport is not necessary.**

VI probe / Equivalent Circuit Model

Bias Electrode의 VI를 모니터링하여 Sheath 거동을 모델링

◆ Estimation of the ion density & the ion energy



Experimental Impedance analysis setup & Equivalent Circuit model

$$Z = A + Bi$$

$$A = \frac{V_{RF}}{I_{RF}} \cos\theta$$

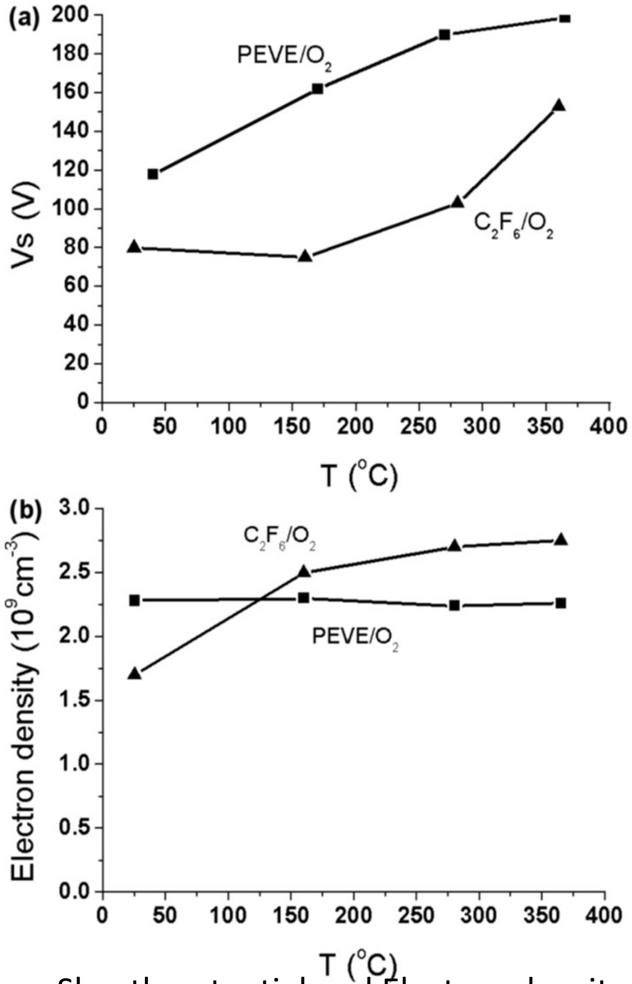
$$B = \frac{V_{RF}}{I_{RF}} \sin\theta$$

$$R_b = \frac{A}{C_p^2 A^2 \omega^2 + C_p^2 B^2 \omega^2 - 2C_p^2 B \omega^2 + 1}$$

$$C_b = -2 \frac{C_p^2 A^2 \omega^2 + C_p^2 B^2 \omega^2 - 2C_p^2 B \omega^2 + 1}{C_p^2 A^2 \omega^2 + C_p^2 B^2 \omega^2 - B}$$

$$V_S = \frac{I_{RF}}{\omega C_S}$$

$$n_e = \frac{d}{q S R_b \mu_e}$$



Sheath potential and Electron density vs. Temperature

H. Chae et al., *Journal of the Korean Physical Society*, 51 (2007) 978

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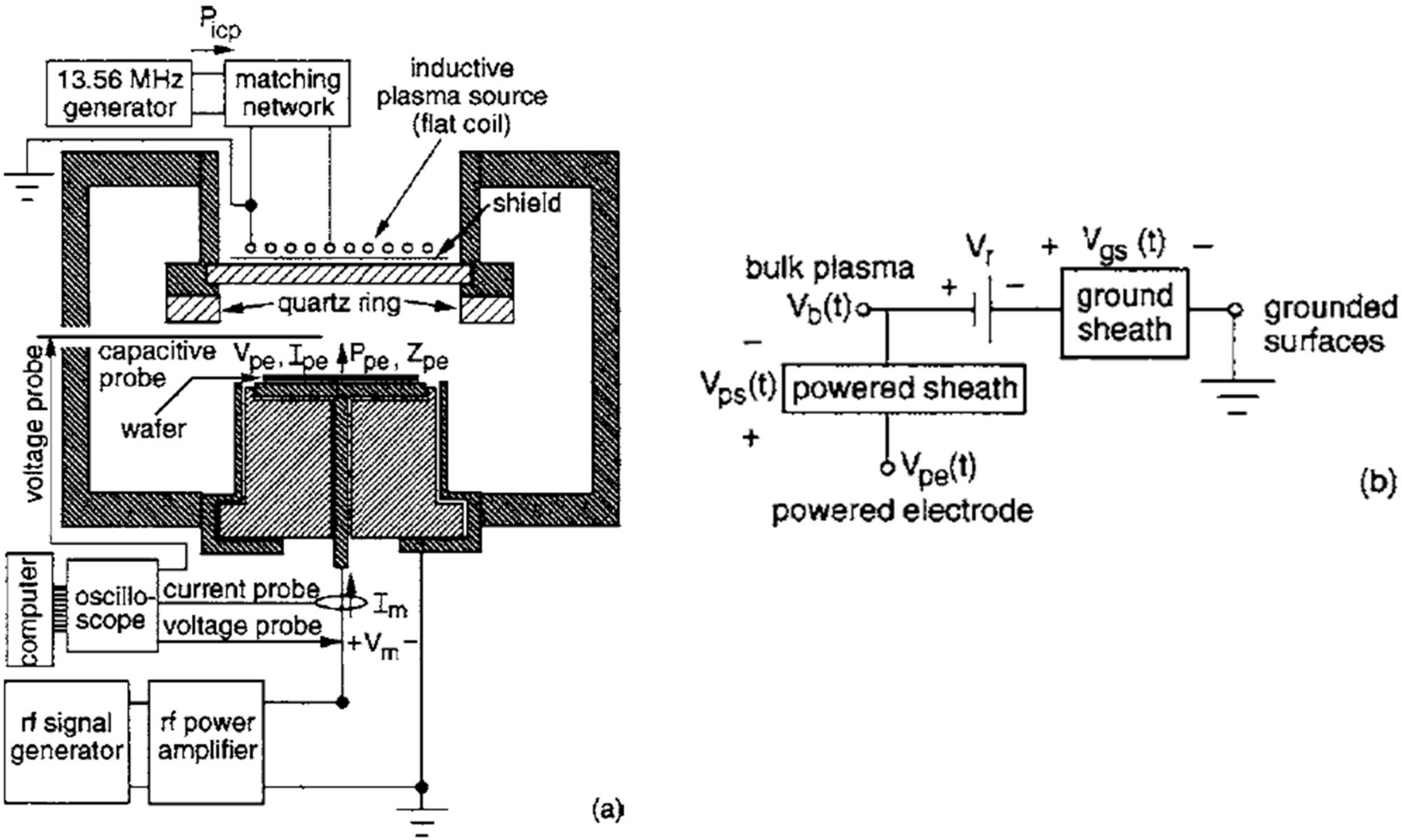
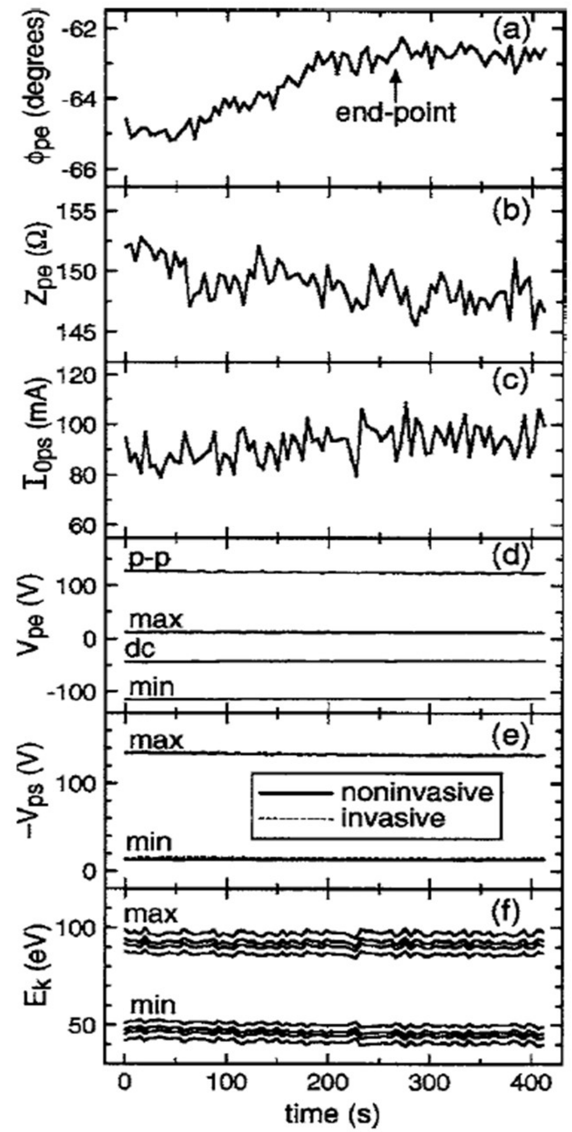
VI probe / Non-invasive *In-situ* Ion Energy Distribution

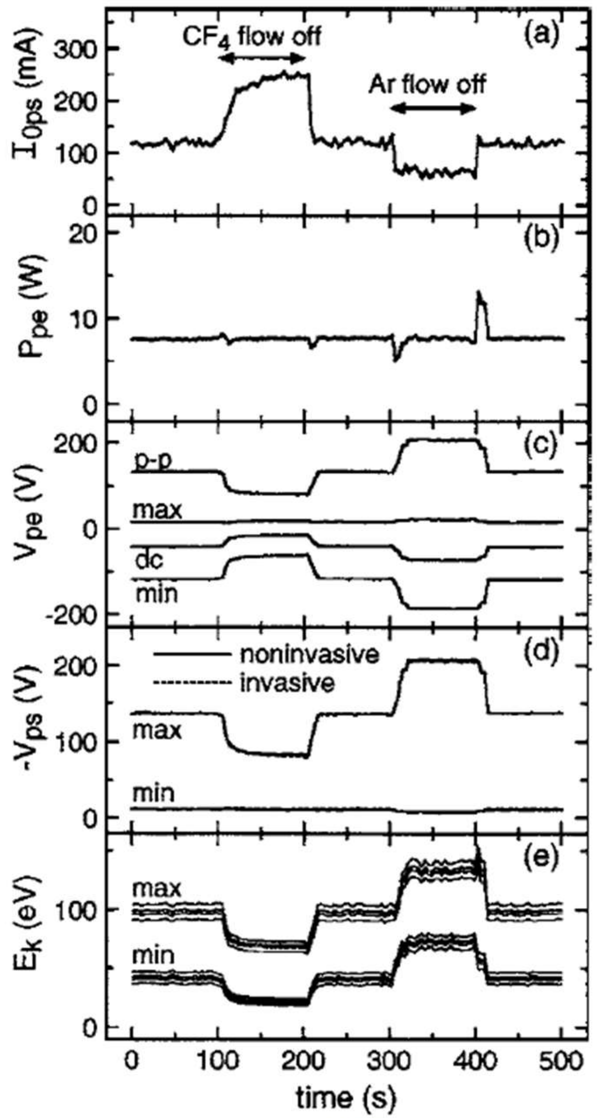
Non-invasive방식으로 In-situ Ion energy distribution 측정 방법 소개



VI probe / Non-invasive *In-situ* Ion Energy Distribution

SiO_2 etching

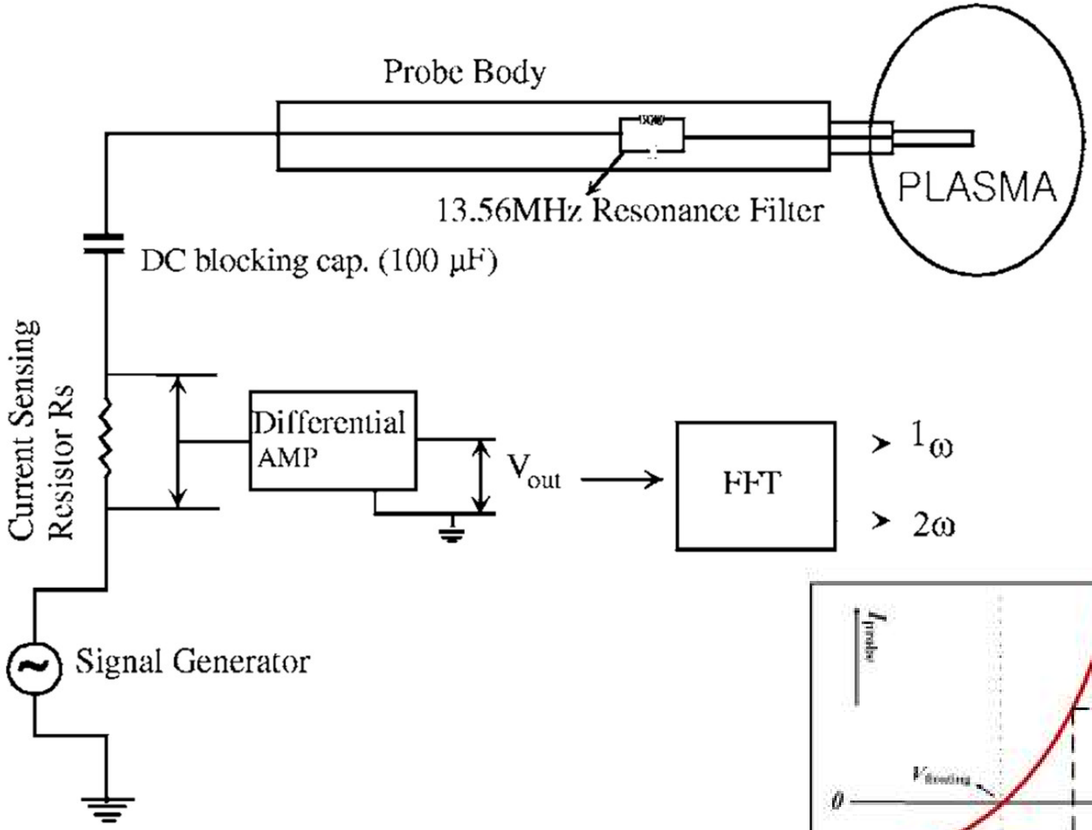


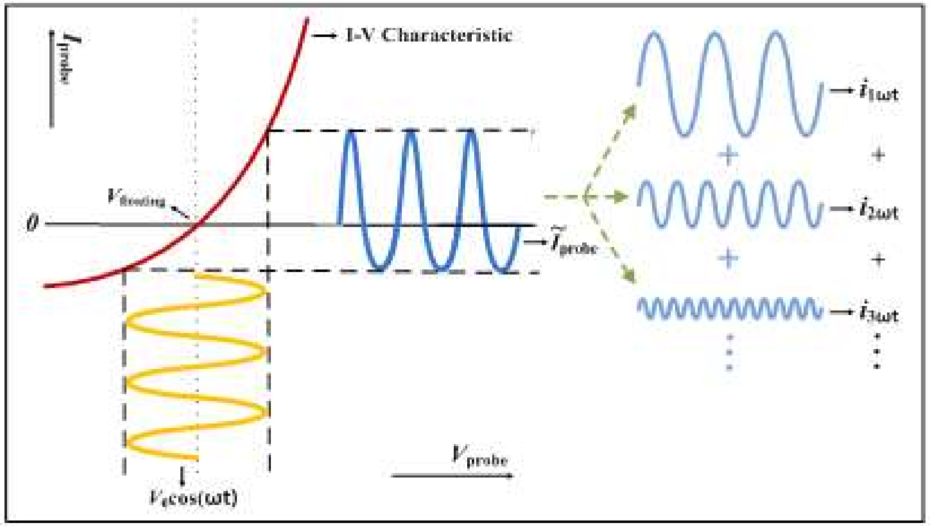


M. A. Sobolewski, *J. Vac. Sci. Technol. A*, 24 (2006) 1892

Floating Harmonic Probe / Ion Flux & Plasma Density

◆ **Non-invasive *In-situ* Ion Energy Distribution**





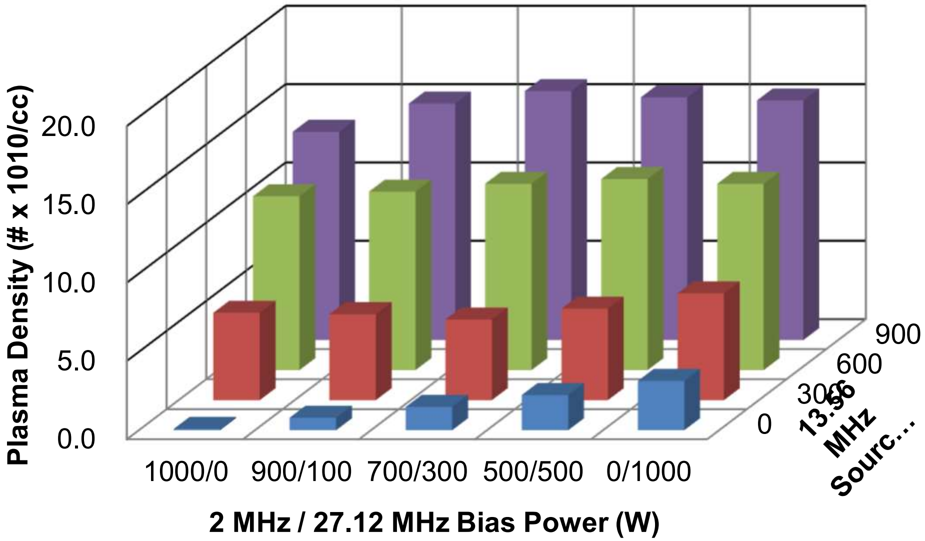
Ion-enhanced etching model

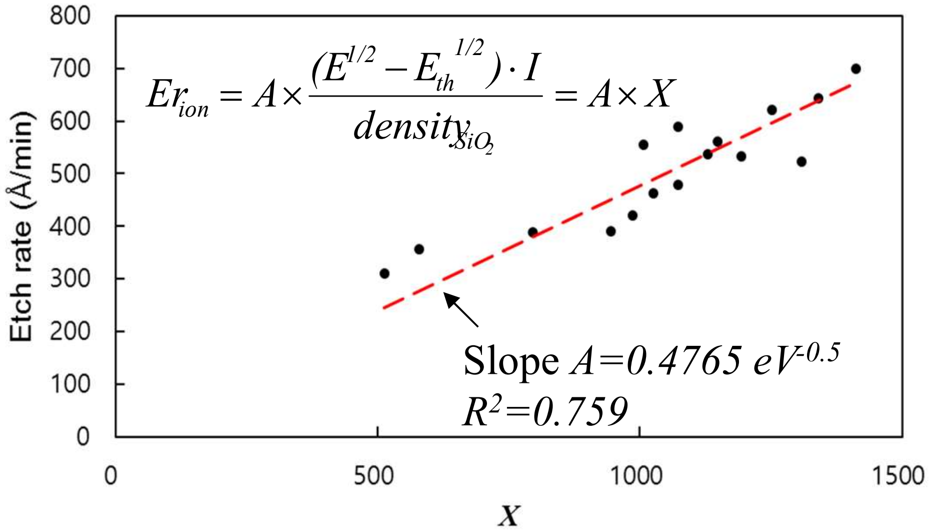
Applications of voltage and current information

◆ Etch Rate Model

Ion-enhanced etching model

$$Er_{ion} = A \times \frac{(E^{\frac{1}{2}} - E_{th}{}^{\frac{1}{2}}) \cdot I}{\rho}$$





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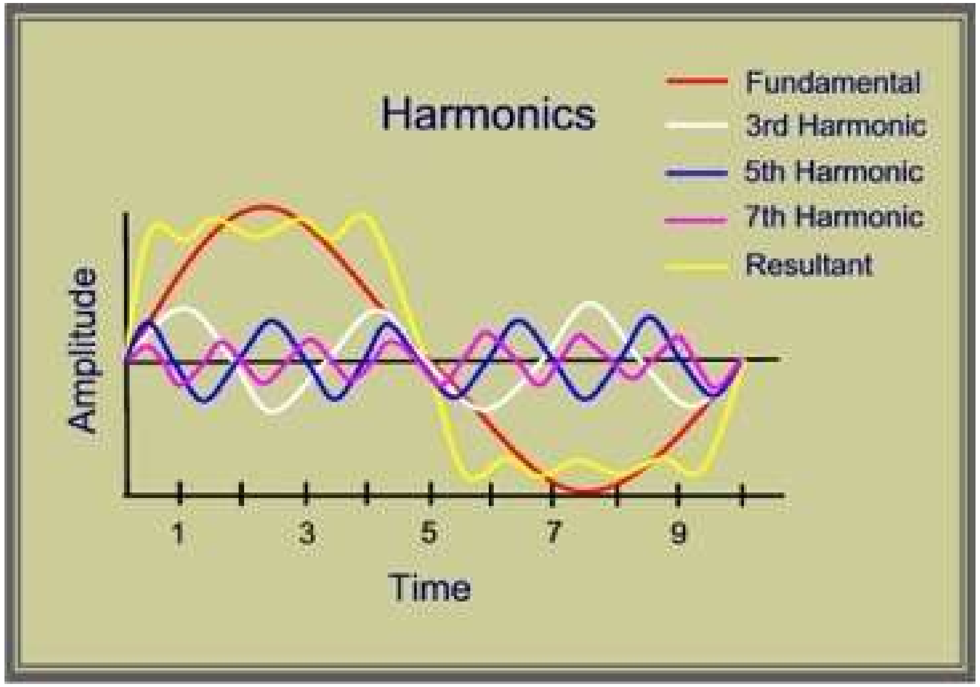
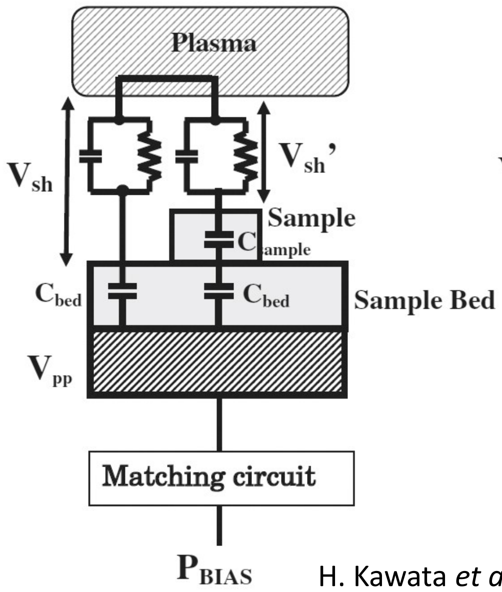
RF V-I Probe

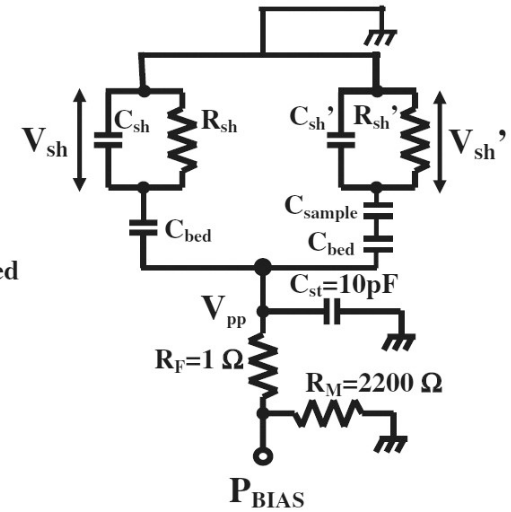
- Measurement of RF voltage, current and phase
- Harmonics can be monitored



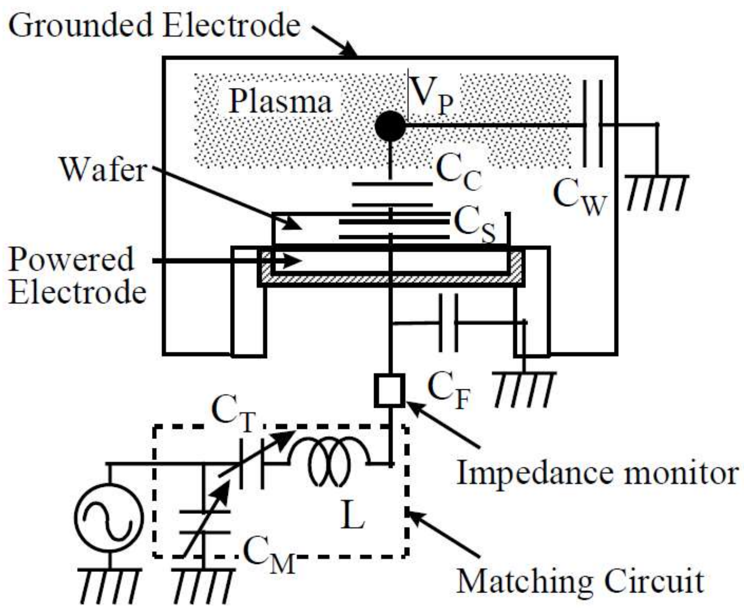
Impedance and Equivalent Circuits

- Impedance contains physical information of plasmas





H. Kawata *et al.*, *Jpn. J. Appl. Phys.*, 47 (2008) 6914



H. Takada et al, *Jpn. J. Appl. Phys.* 40 (2001) 1457

	PIM	OES
Viewport Cleaning	unnecessary	necessary
Small Exposed Area	possible	impossible

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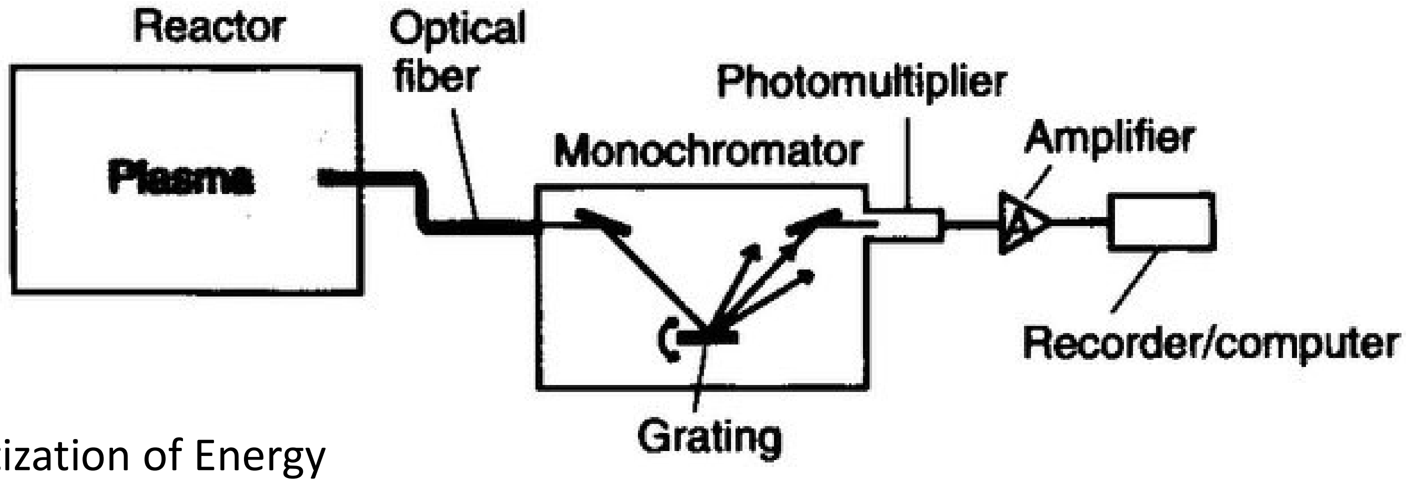
Chemical Diagnostics

Optical Emission Spectroscopy (OES)

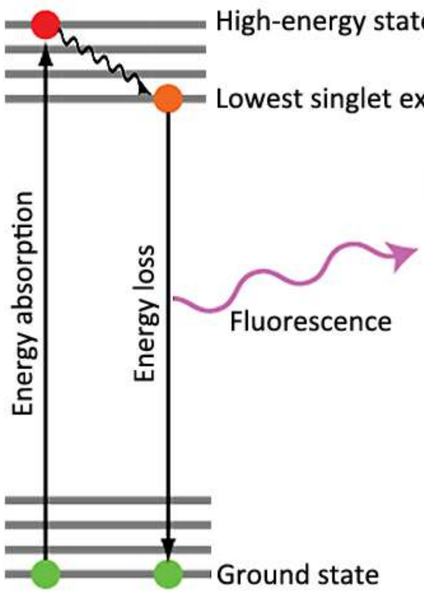


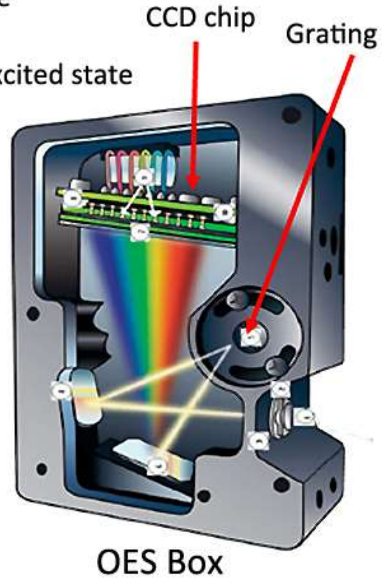
Quantization of Energy

- Quantum number
  Principal(n),
  Azimuthal(ℓ),
  Magnetic(m_ℓ),
  Spin(m_s)
- Energy States

$$\nu = \frac{1}{h}(E_f - E_i)$$

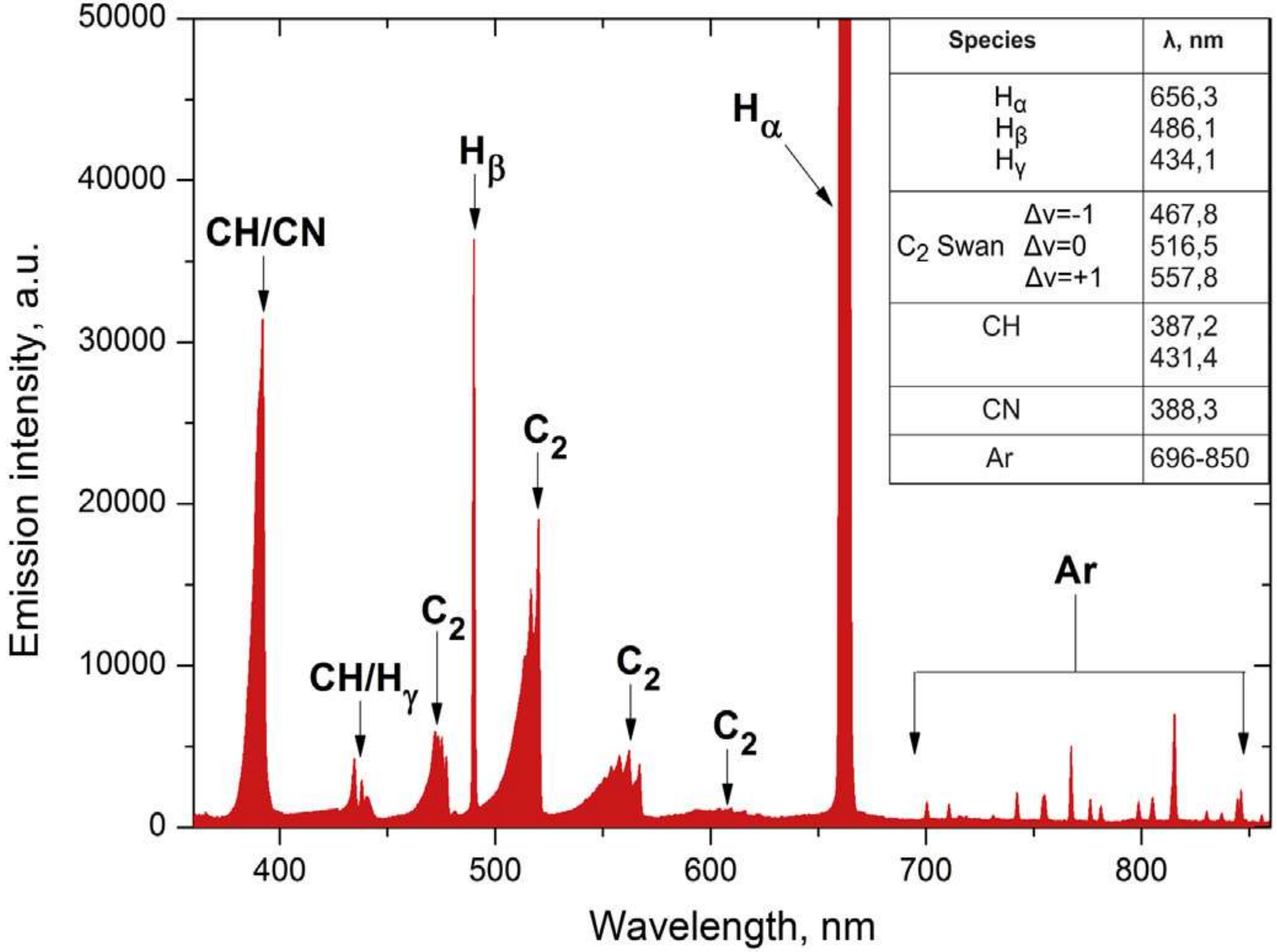
$$\lambda = \frac{c}{\nu}$$





Optical Emission Spectroscopy (OES)

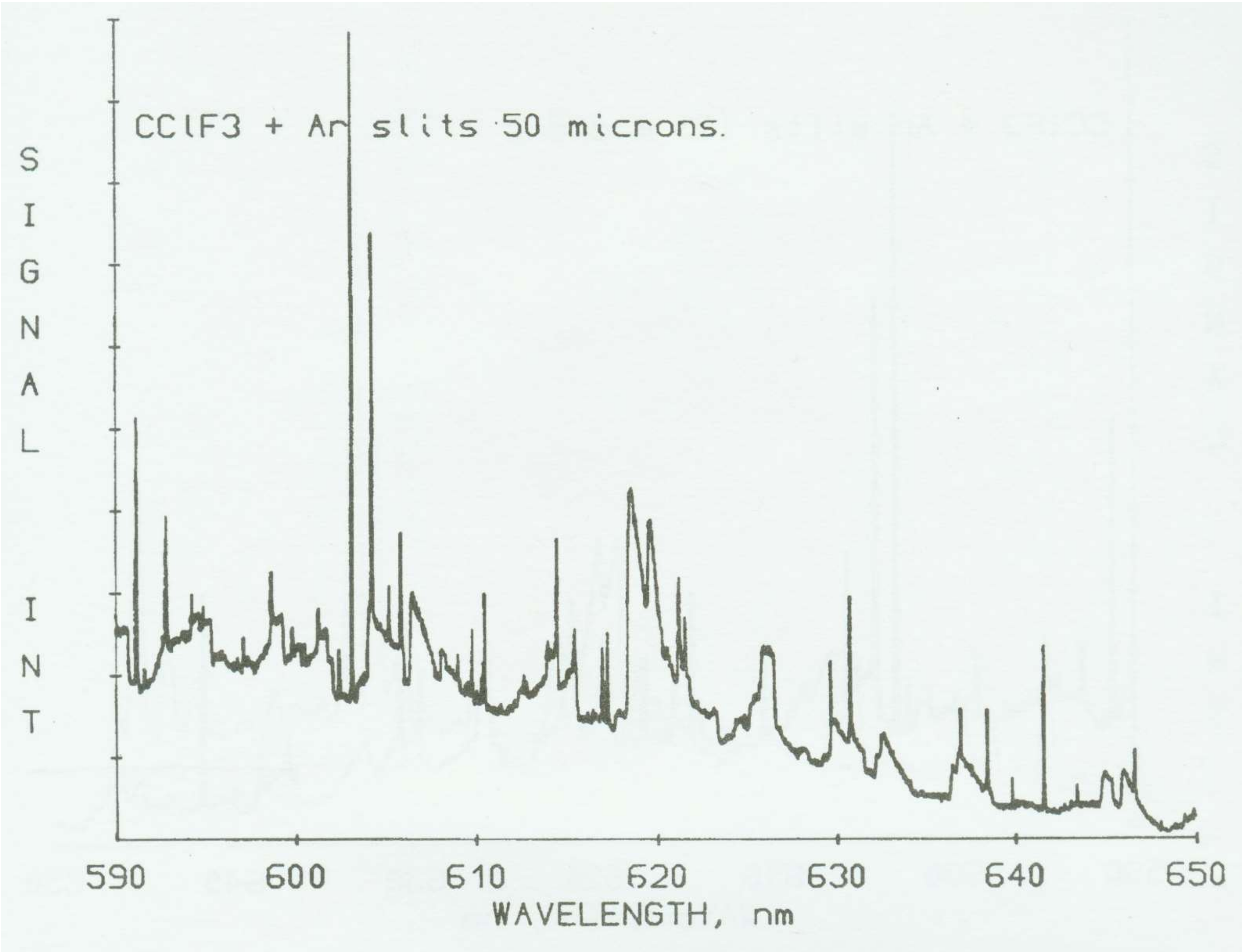
$H_2/Ar/CH_4$ plasma



Species		λ, nm
H_α H_β H_γ		656,3 486,1 434,1
C_2 Swan	Δv=-1 Δv=0 Δv=+1	467,8 516,5 557,8
CH		387,2 431,4
CN		388,3
Ar		696-850

→ **Endpoint Detection**
→ **Fault Detection**

Optical Emission Spectroscopy (OES)



Optical Emission Spectroscopy (OES)

◆ Principle of OES: Quantization

Optical Emission: Quantization of Energy

Electron

- **Quantum number**

:Principal(n), Azimuthal(ℓ), Magnetic(m_ℓ), Spin(m_s)

$$\nu = \frac{1}{h}(E_f - E_i) \qquad \lambda = \frac{c}{\nu}$$

- **Selection Rule**

$$\Delta n = 0,1,2,....$$

$$\Delta \ell = \pm 1$$

$$\Delta m_s = 0$$

※ If electron ≥ 2

$$L = \Delta \sum \ell_i = 0 \;\; or \;\; \pm 1$$

$$\Delta J = \Delta L + \Delta m_s = 0 \;\; or \;\; \pm 1$$

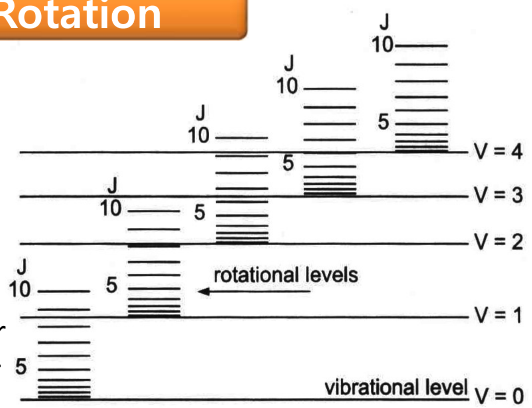
Vibartion & Rotation

$$E_v = k\nu_0\left(v + \frac{1}{2}\right)$$

$$E_r = B_0 N(N+1)$$

v: vibrational quantum number

N: rotational quantum number



Species	Wavelength (nm)
Al	308.2, 309.3, 396.1
AlCl	261.4
As	235.0
C_2	516.5
CF_2	251.9
Cl	741.4
CN	289.8, 304.2, 387.0
CO	292.5, 302.8, 313.8, 325.3, 482.5, 483.5, 519.8
F	703.7, 712.8
Ga	417.2
H	486.1, 656.5
In	325.6
N	674.0
N_2	315.9, 337.1
NO	247.9, 288.5, 289.3, 303.5, 304.3, 319.8, 320.7, 337.7, 338.6
O	777.2, 844.7
OH	281.1, 306.4, 308.9
S	469.5
Si	288.2
SiCl	287.1
SiF	440.1, 777.0

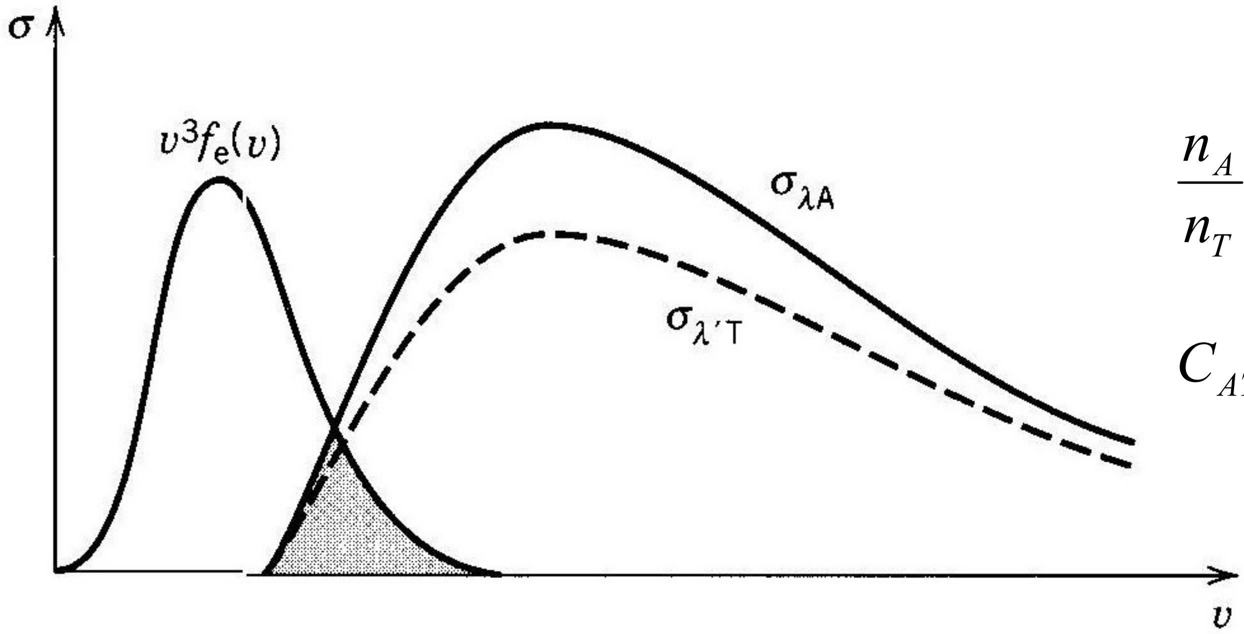
종말점 검출에 사용되는 OES 파장

[표 1.2-3-5] 종말점 검출에 사용되는 화학종 및 그에 해당하는 파장

Film	Etchant	Wavelength (Å)	Emitter
Al	Cl_2, BCl_3	2614	AlCl
		3962	Al
Poly Si	Cl_2	2882	Si
		6156	O
Si_3N_4	CF_4/O_2	3370	N_2
		3862	CN
		7037	F
		6740	N
SiO_2	CF_4 and CHF_3	7037	F
		4835	CO
		6156	O
PSG, BPSG	CF_4 and CHF_3	2535	P
W	SF_6	7037	F

Optical Actinometry with OES

Optical Actinometry

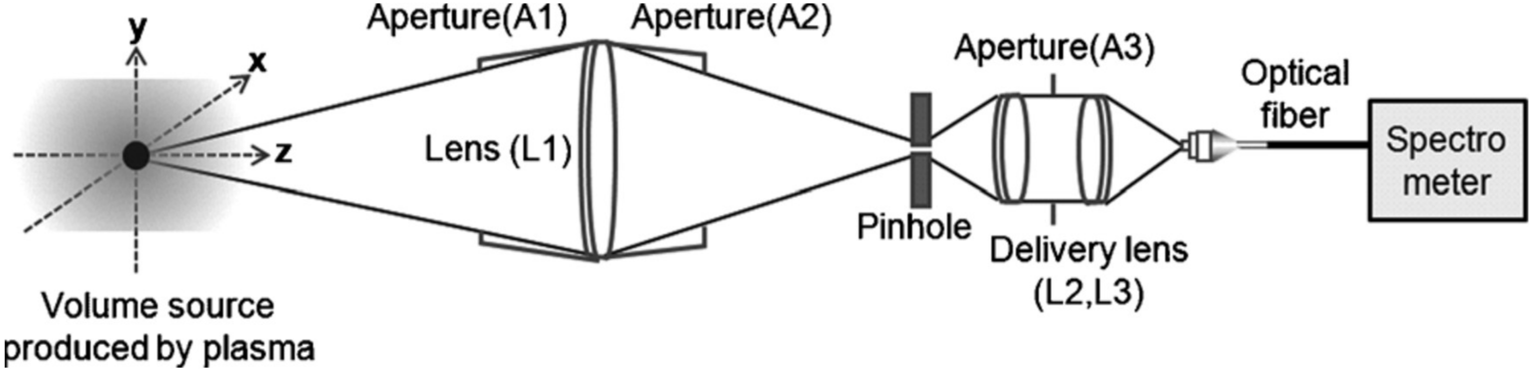


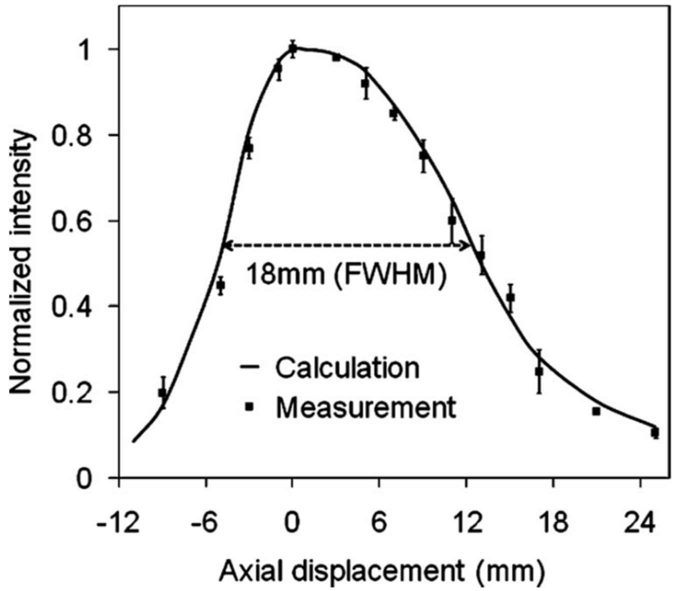
$$\frac{n_A}{n_T} = C_{AT}\frac{I_{\lambda}}{I_{\lambda'}}$$

$$C_{AT} = \frac{k_D(\lambda)}{k_D(\lambda')}\frac{Q_{A^*}}{Q_{T^*}}\frac{C_{\lambda A}}{C_{\lambda' T}}$$

M. A. Liberman & A. J. Lichtenberg (1994)

Spatially Resolved OES





Optical Emission Spectroscopy (OES)

Emission signal intensity of a species F is

$$In_S = \alpha_S^e [F]$$

where

$$\alpha_S^e = K \int_0^\infty Q(p, n_e) \delta_S^e(\varepsilon) N_e(\varepsilon) d\varepsilon$$

where

K = a constant depending on the sensitivity of the detector

δ_s^e (ε) = cross section for excitation of the emitting species to a given excited state caused by the impact of an electron of energy ε

N_e(ε) = number of electrons in the energy range dε present in the volume of the reactor viewed by the detector

Q(p,ne) = quantum yield for emission form the given excited state as a function of discharge pressure and electron density

Optical Emission Spectroscopy (OES)

TABLE 5-2 Spectra Observed in a Plasma (from [31], reprinted by permission of John Wiley & Sons, Inc.)

Particle	Degree of Freedom	Type of Spectrum	Spectral Region
Atom or ion	Electronic excitation	Line	UV-visible-IR
	Ionization	Continuum	UV-visible-IR
	Translation	Line profiles	
Electrons	Recombination	Continuum	UV-visible
	Free-free transitions	Continuum	IR
Molecules	Rotation	Line	Far infrared
	Vibration-rotation	Band	IR
	Electronic excitation	Band systems	UV-visible-IR

Laser Induced Fluorescence (LIF)

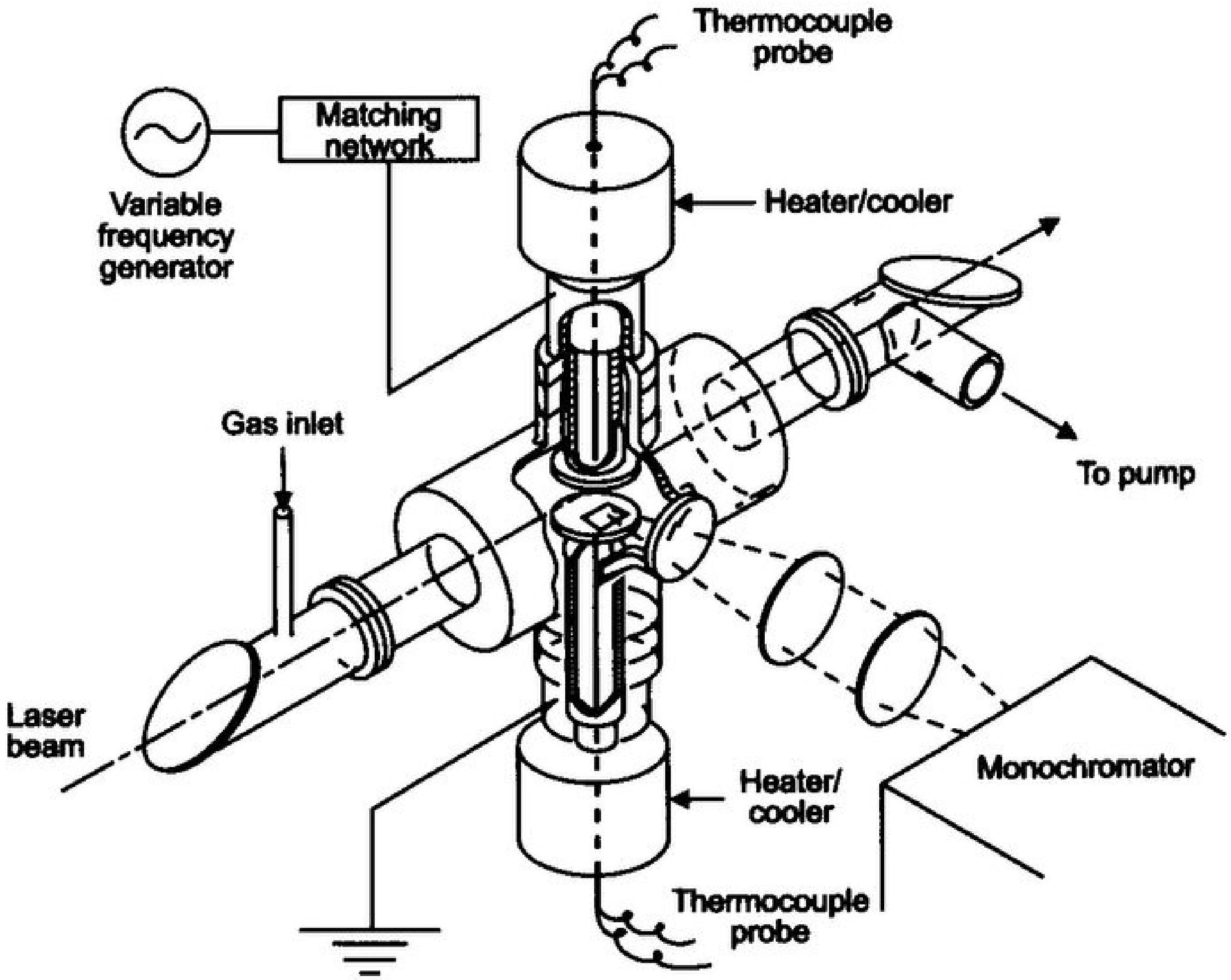
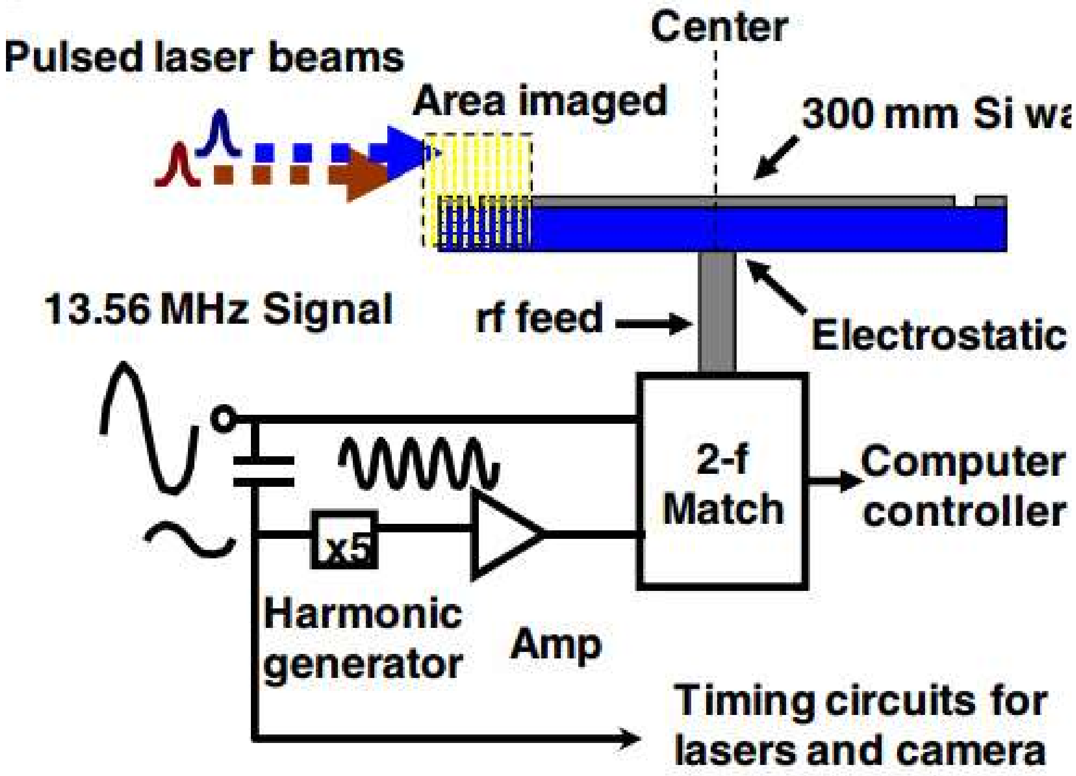
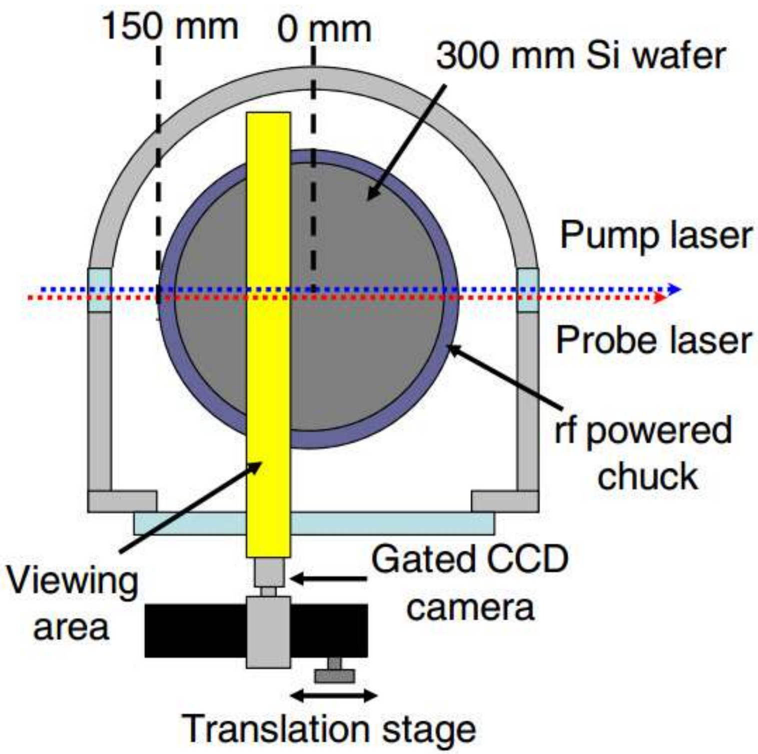


Fig. 5-13 Experimental setup for laser induced fluorescence in a parallel plate plasma reactor (from [32], reprinted with permission from *Plasma Diagnostics*, vol. 1, 1989).

Laser Induced Fluororescence

공간분해가 가능한 광학적 측정법

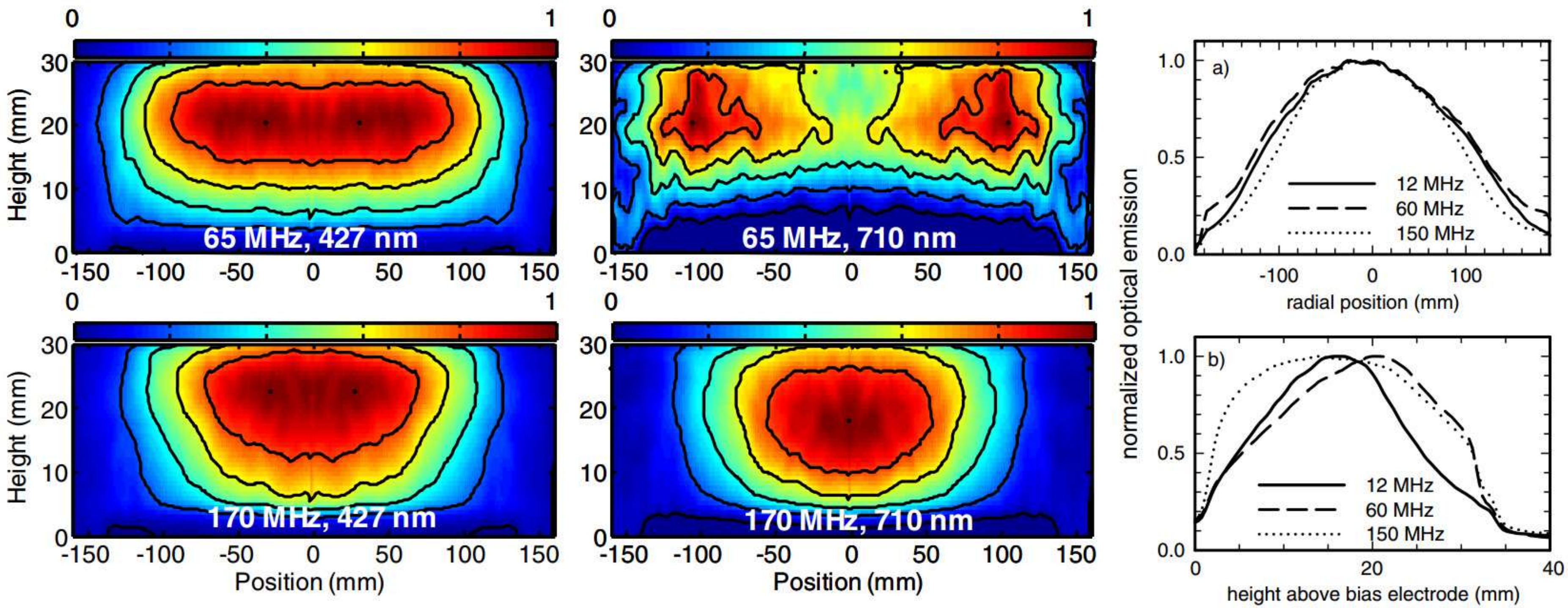




E. V. Barnat, *Plasma Sources Sci. Technol.* 20 (2011) 053001

Laser Induced Fluororescence

공간분해가 가능한 광학적 측정법



E. V. Barnat, *Plasma Sources Sci. Technol.* 20 (2011) 053001

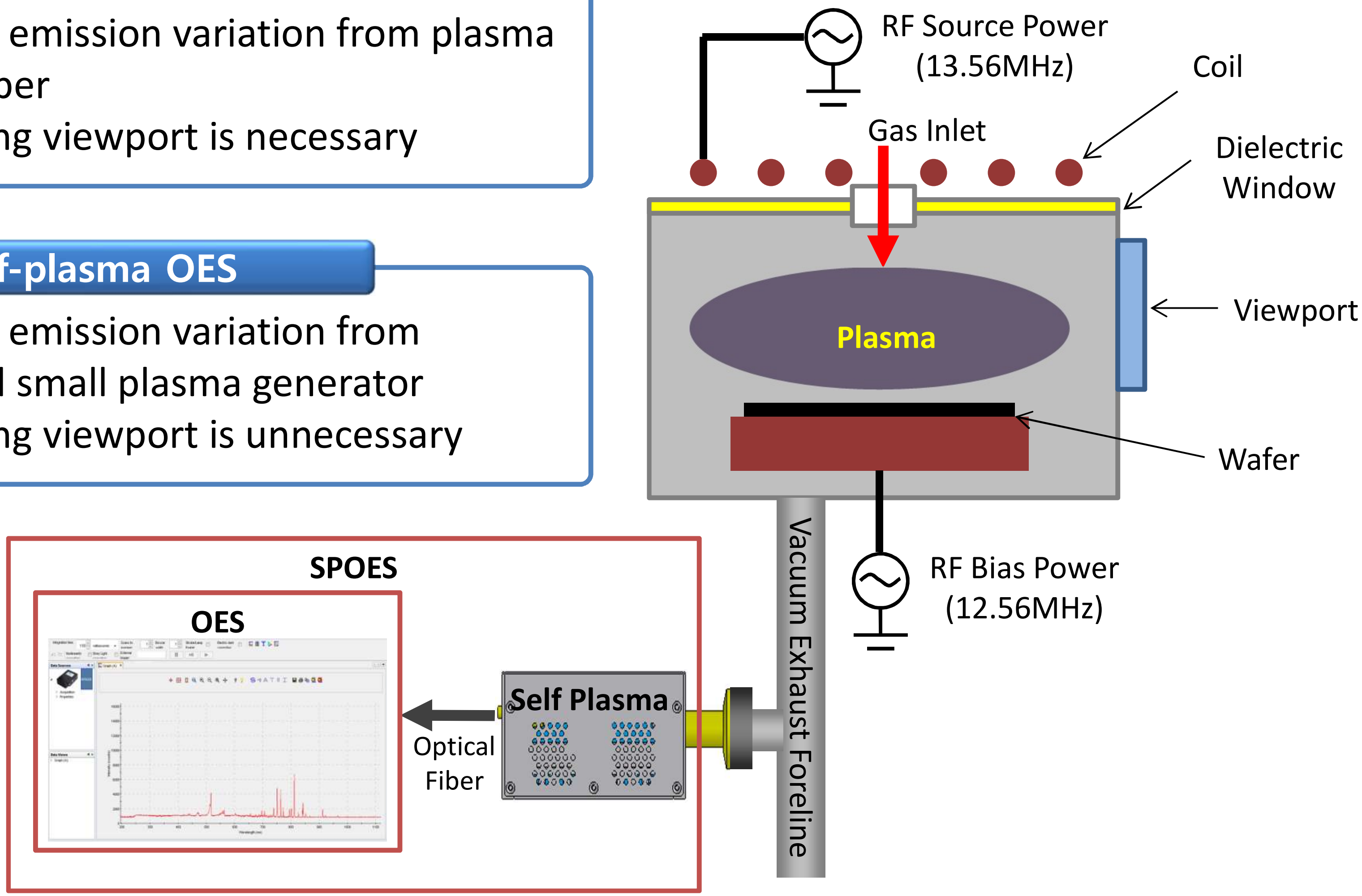
Self-Plasma OES

Conventional OES

- Detect emission variation from plasma in chamber
- Cleaning viewport is necessary

Self-plasma OES

- Detect emission variation from attached small plasma generator
- Cleaning viewport is unnecessary



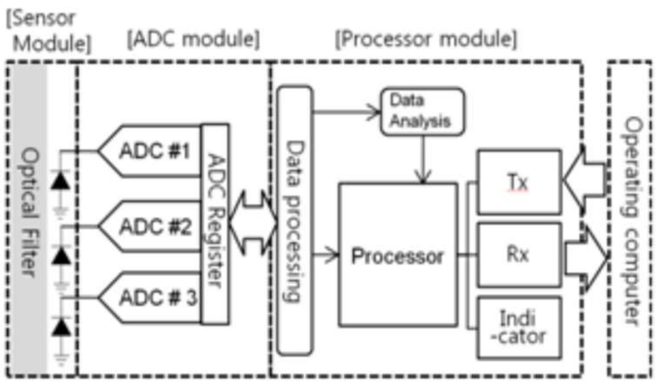
<Scheme of ICP with SPOES>

High Speed RGB monitor for Arc Detection

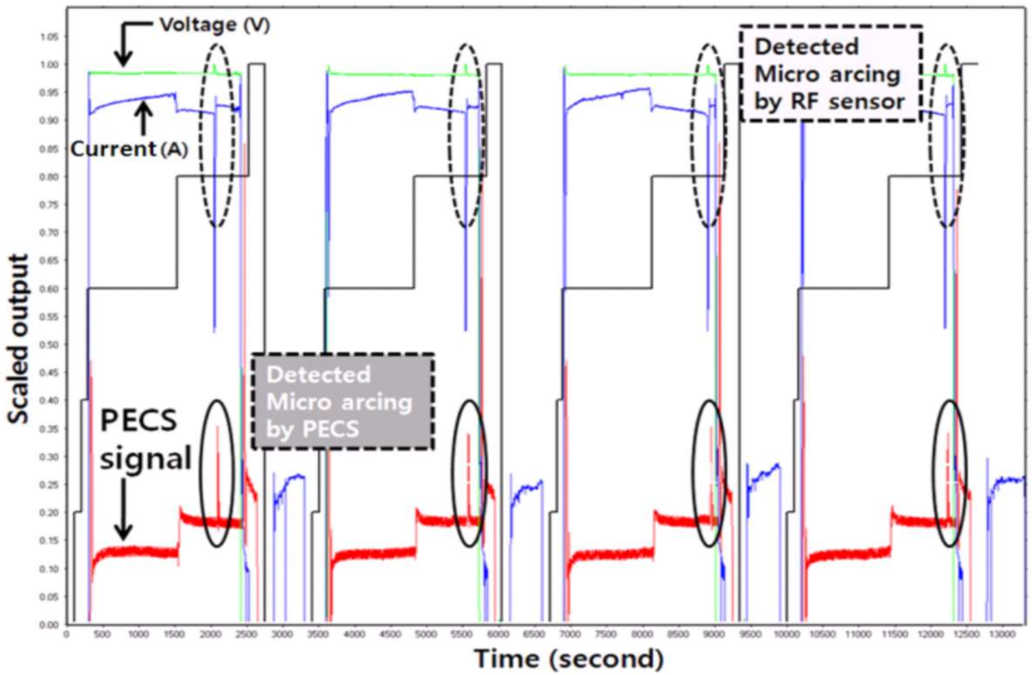
Plasma 진단으로 Particle , Arc 발생 모니터링

The Plasma Eyes Chromatic System (PECS)

- Observing the optical emission of a plasma glow discharge
- Measuring the intensity of Red-Green-Blue (RGB) values
- Red 590-720 nm, Green 480-600 nm, and Blue 400-540 nm
- the signals are transferred to a PC at up to 10 kHz,



Plasma Eyes Chromatic System (PECS)



Real-time plasma arcing detection inside the process chamber

S. J. Hong, *Transactions on Electrical and Electronic Materials,* 14 (2013) 71

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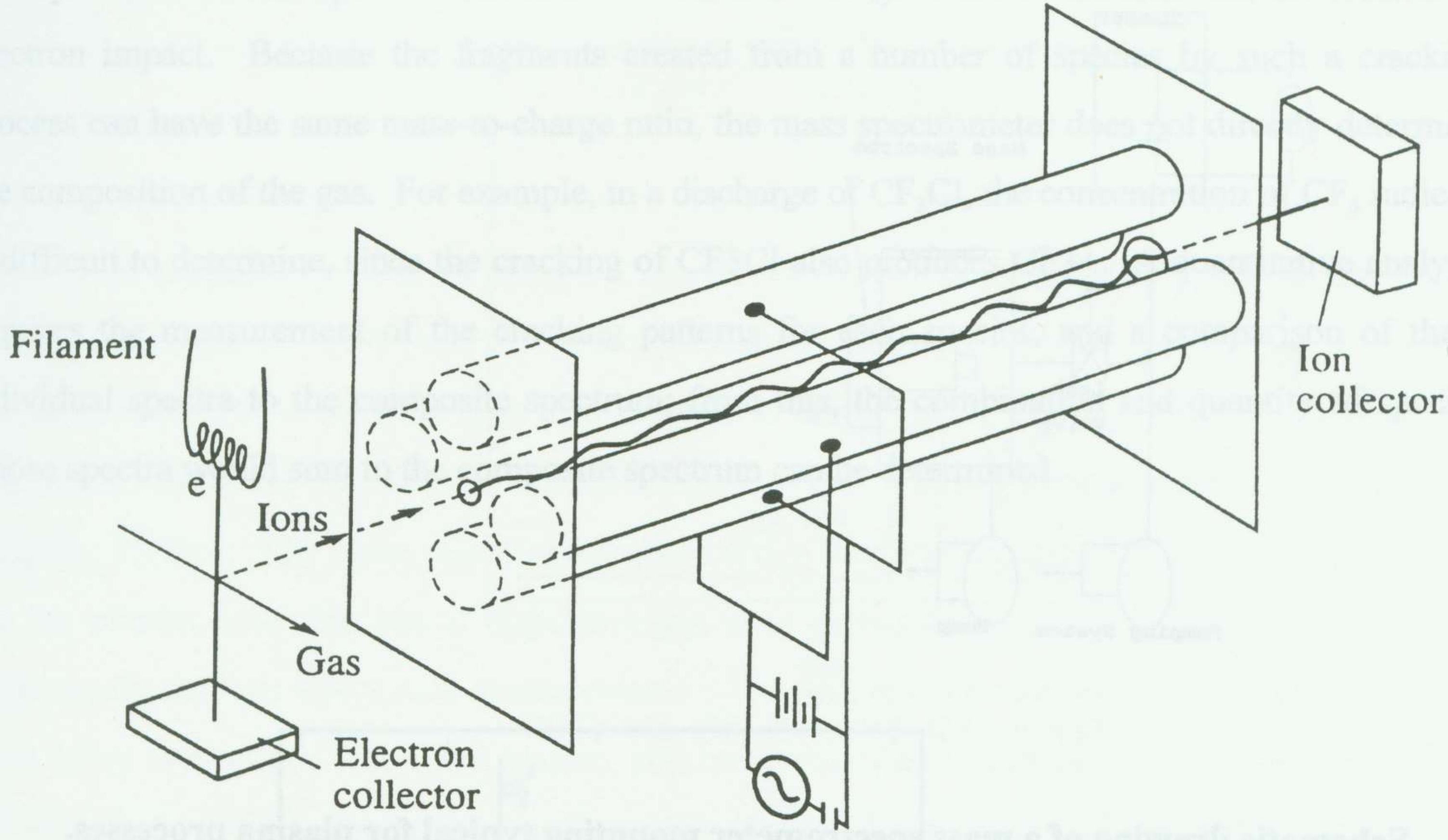
Mass Spectrometer

- For ion and neutral identification



Schematic drawing of a quadruple mass spectrometer.

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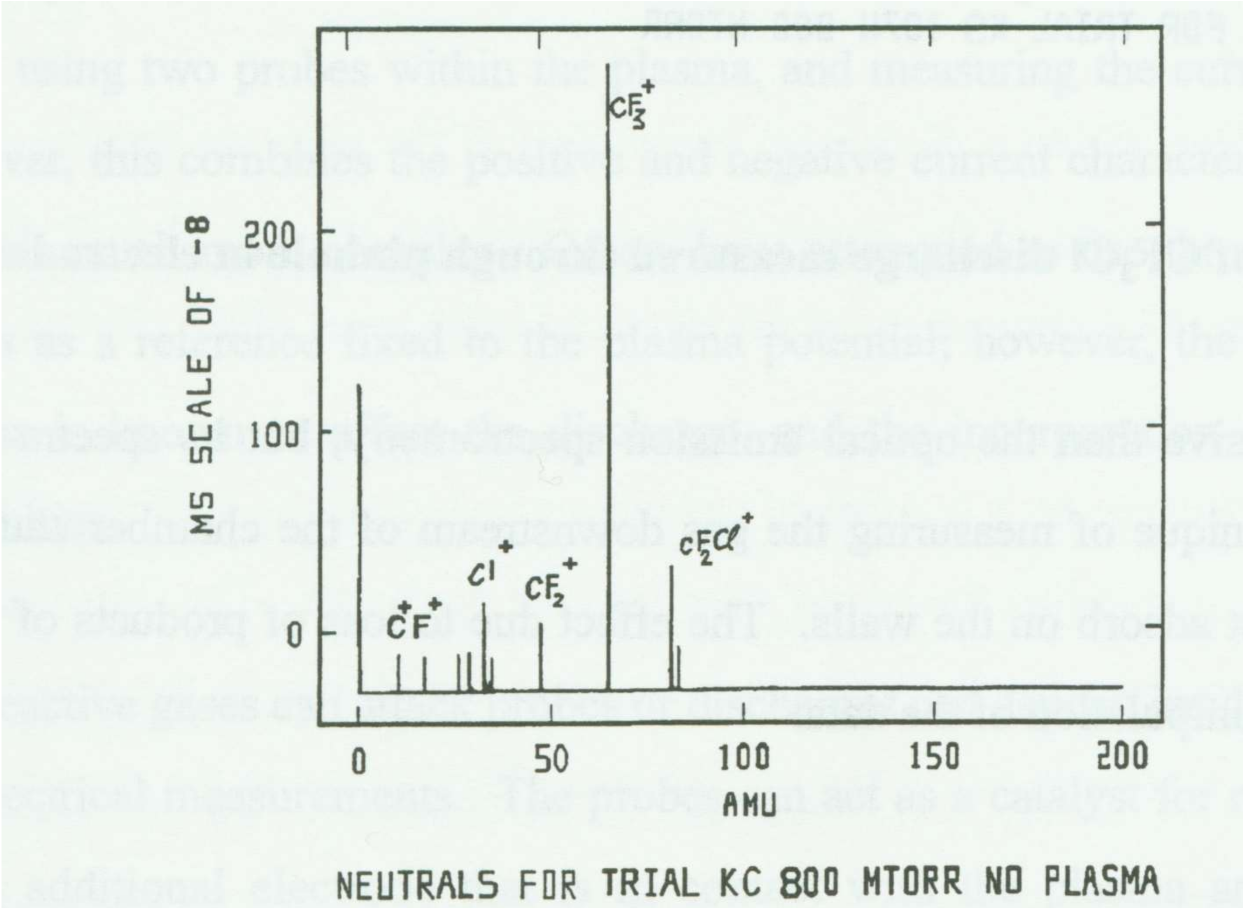
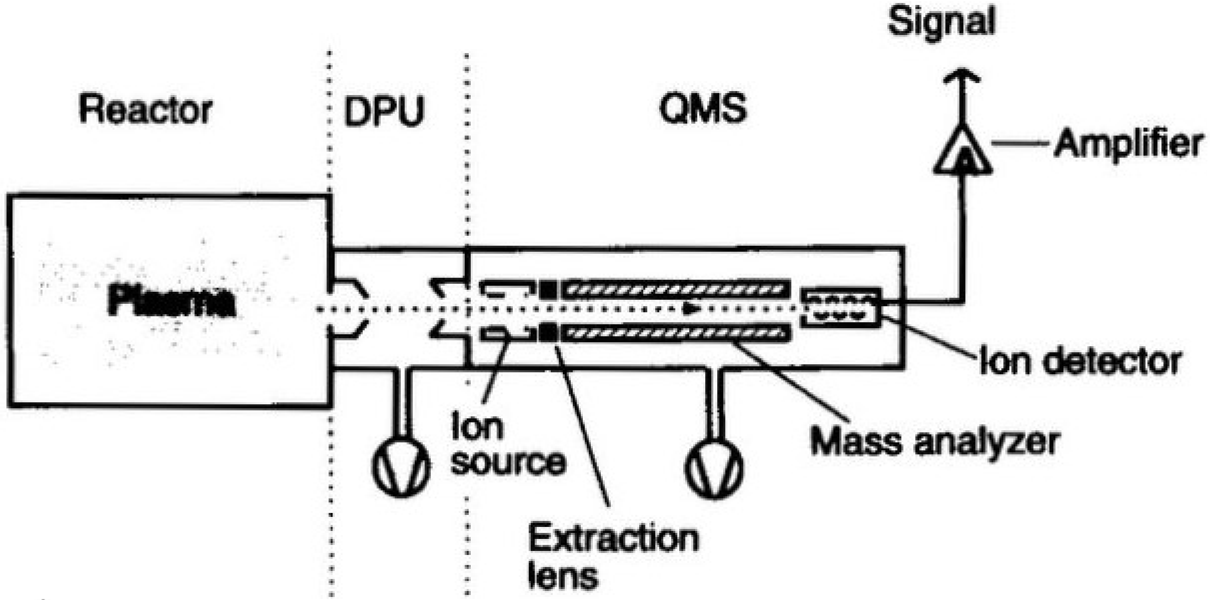
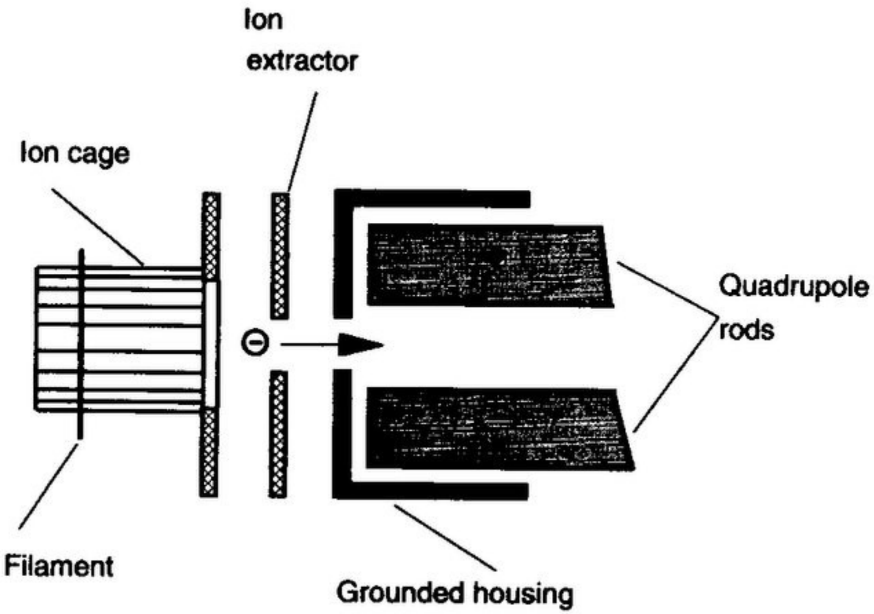
Mass Spectroscopy

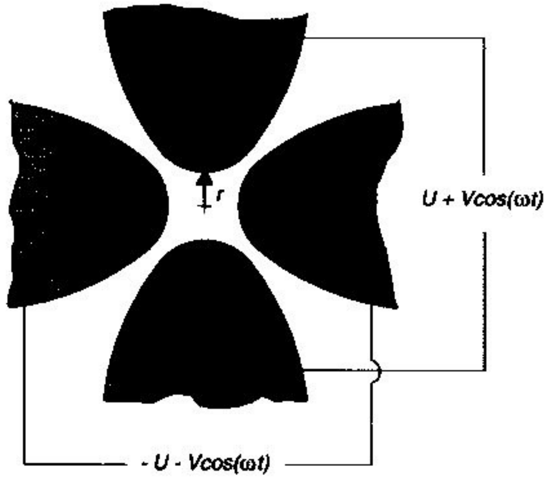
Spectrum of CF_3Cl



Quadruple Mass Spectrometer







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Quadruple Mass Spectrometer

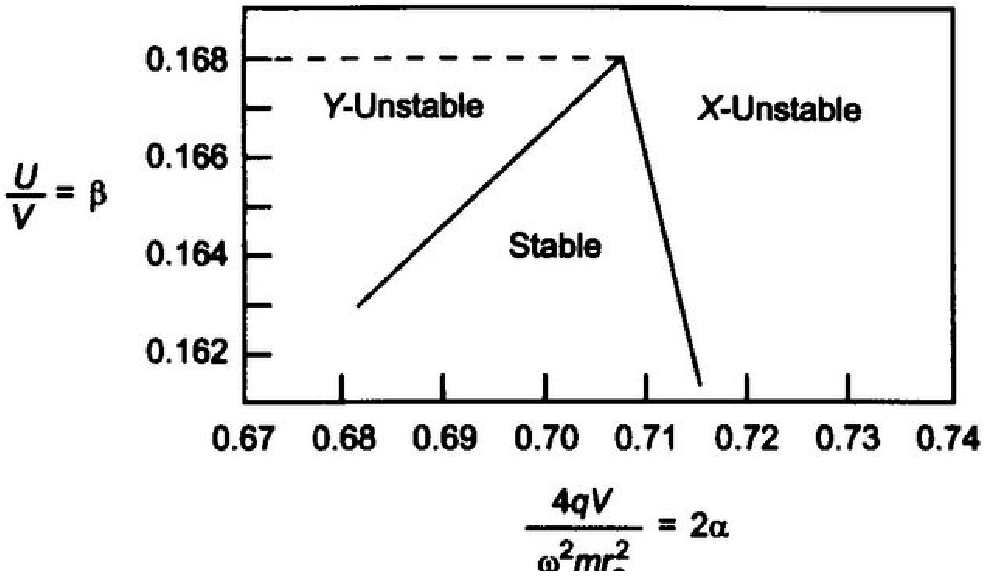


TABLE 5-1 Sensitivities of Quadrupole Mass Spectrometer for Determination of Pressure with 10% Accuracy (from [10], reprinted with permission from *Quadrupole Mass Spectrometry and Its Applications*, p. 138, 1976)

Pressure (torr)	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Current (amp)	10^{-12}	10^{-13}	10^{-14}	10^{-15}
Time electron multiplier (sec)	10^{-5}	10^{-4}	10^{-3}	10^{-2}
Time Faraday cup (sec)	0.02	0.2	2	

Quadruple Mass Spectrometer

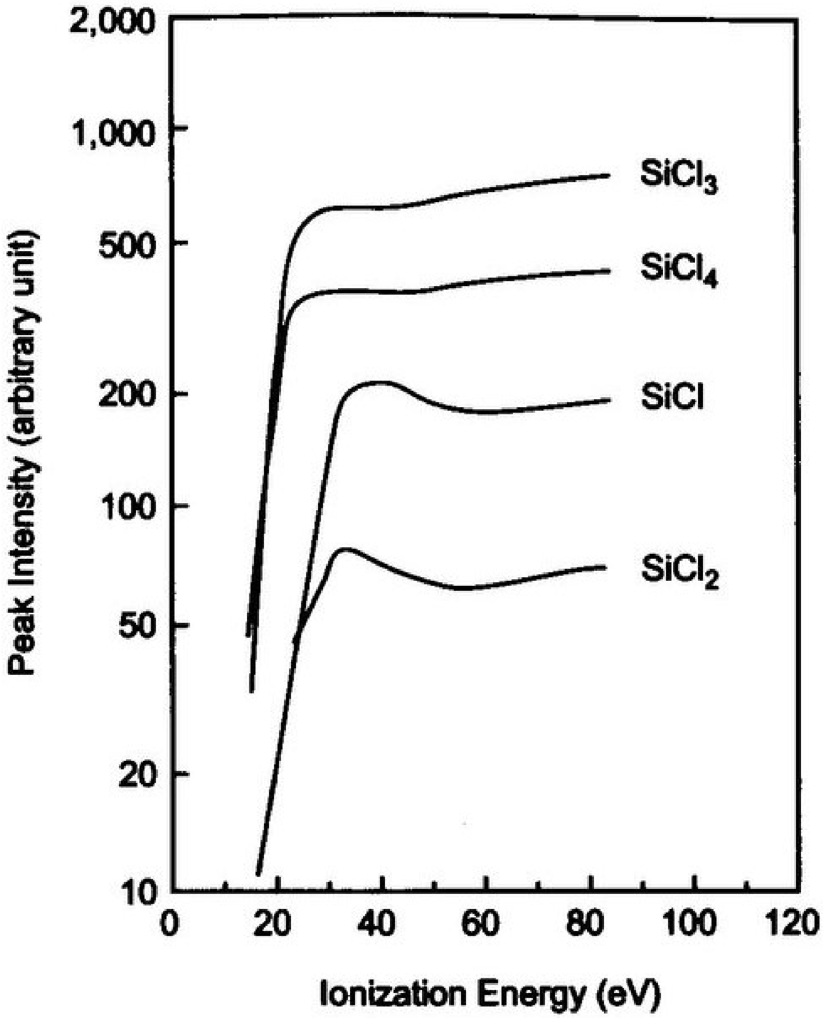
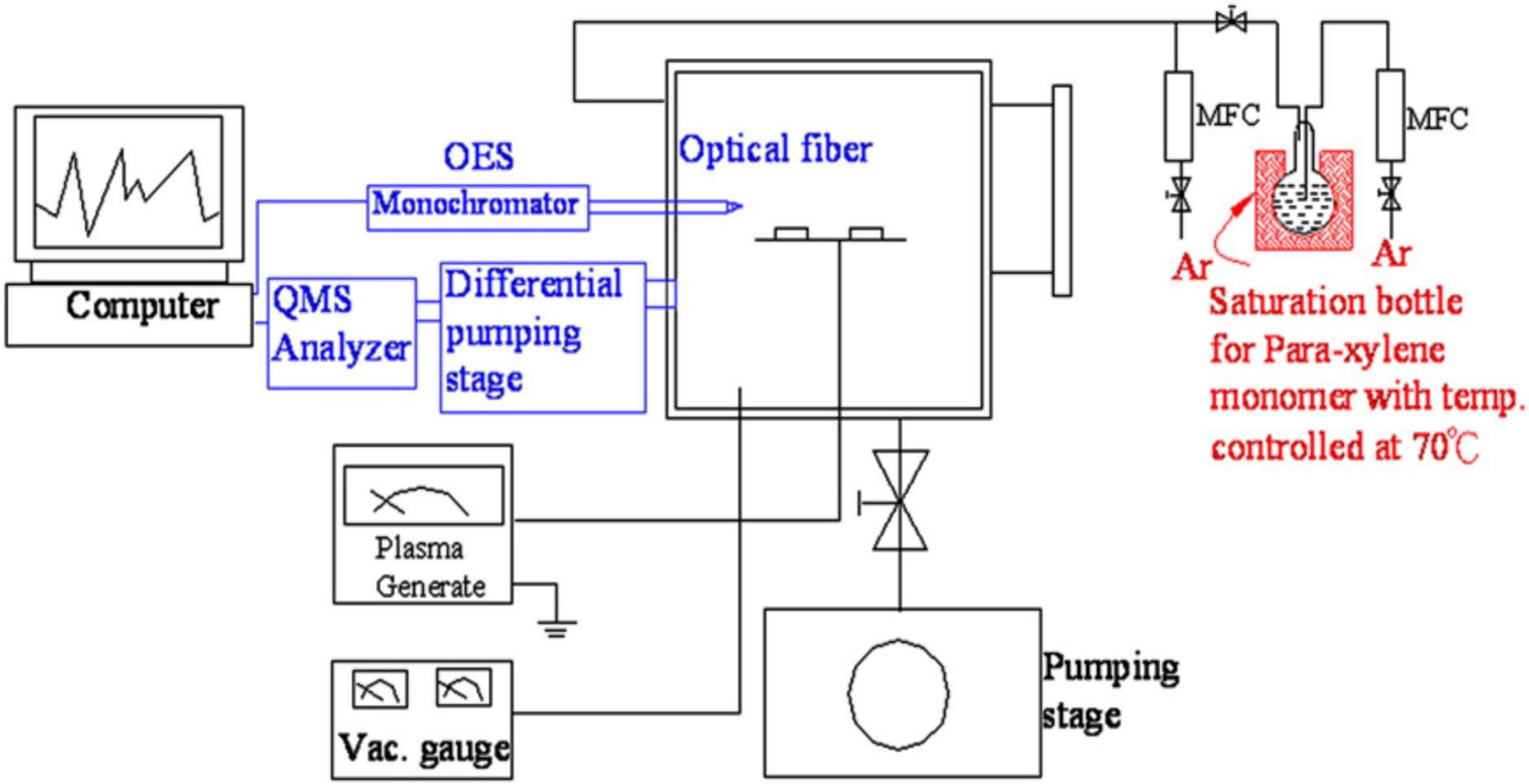


Fig. 5-5 Peak intensities versus ionization energy in ion source in an Ar + $SiCl_4$ plasma (from [16], reprinted with permission from *Plasma Chem. Plasma Process*, vol. 3, p. 235, 1983).

QMS/RGA

◆ **Principle of Quadruple Mass Spectrometer (QMS) / Residual Gas Analyzer (RGA)**



Scheme of QMS and OES installed plasma equipment

C-M Chou et al, *Surface & Coatings Technology,* 205 (2011) 4880

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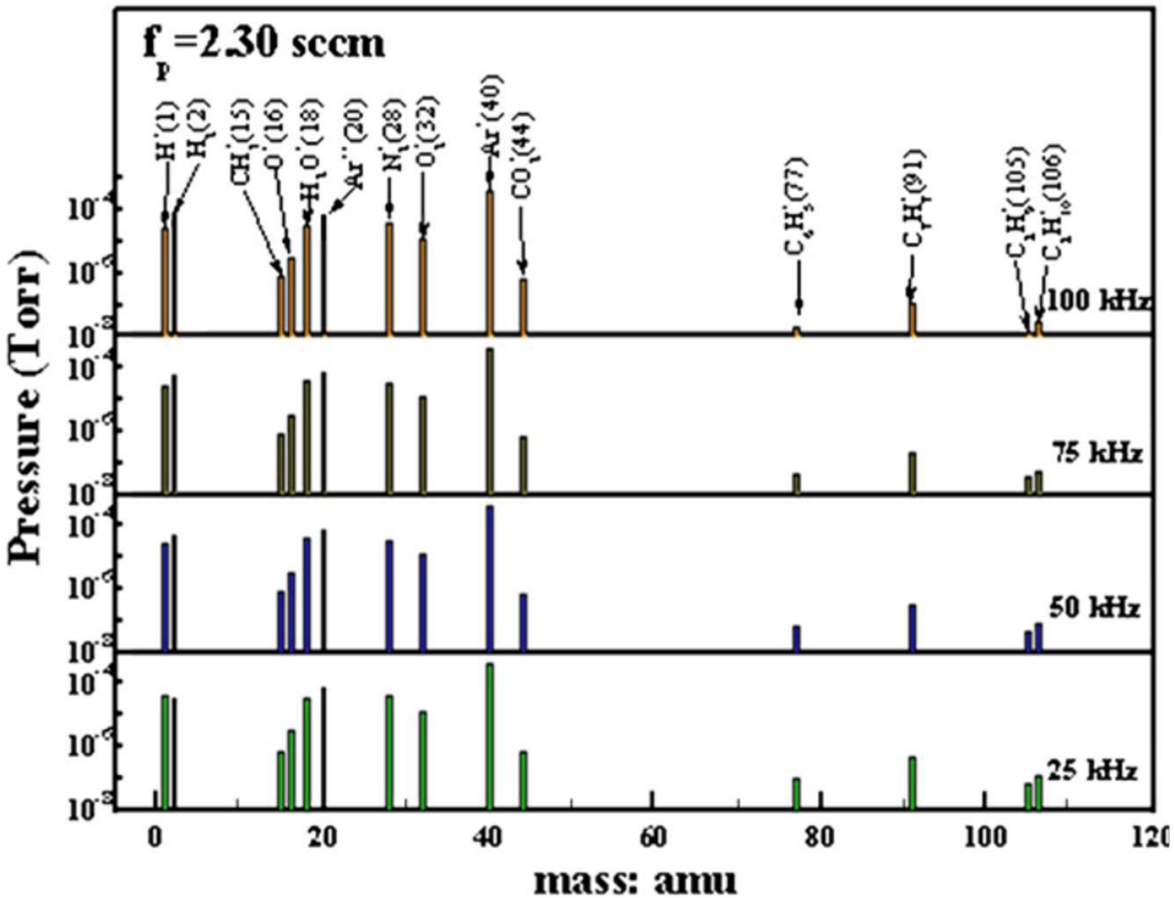
QMS/RGA

- **Principle of Quadruple Mass Spectrometer (QMS) / Residual Gas Analyzer (RGA)**



Example of analyzing para-xylene plasma by QMS

C-M Chou et al, *Surface & Coatings Technology,* 205 (2011) 4880

Chemical Monitoring Techniques

Review on Multivariate Analysis

History of Multivariate Analysis for Processes Control

Target	Methods	Monitoring Tool	Feature	Year
Fault Detection	PCA	Temperature	Steamed boiler monitoring	1996
Endpoint Detection	Artificial Neural Network	Plasma Impedance Monitoring	Etching SiO_2, TiN, poly-Si	1996
Fault Detection	Multi-way PCA	OES	Plasma etcher monitoring	2000
Endpoint Detection	PCA	OES	SiO_2 etching with selected-wavelength	2000
Process Monitoring / Fault Detection	Multi-scale PCA	Process variables	Tubular reactor monitoring	2002
Fault Detection	Time-lagged PCA	Sensor fault	Wastewater treatment monitoring	2004
Endpoint Detection	Multi-way PCA	OES	Metal etching with full-wavelength	2008
Endpoint Detection	Modified PCA	OES	SiO_2 etching with full-wavelength	2008
Fault Detection	Fuzzy decision tree	OES	Reactive ion etching modeling	2012
Fault Detection	Artificial Neural Network	Building energy consumption	Optimizing energy consumption	2015

PCA have been studied for applying OES with ex-situ analysis

⟹ New Approach & Real-time Analysis is needed

Data Analysis: Multivariate Analysis Based Method

Prediction

- Regression Analysis
- Principle Component Analysis
- Partially Least Square Regression

Clustering

- Nonhierarchical Clustering
  - •K-means
  - •K-medoids
  - •Fuzzy K-means
  - •Density Based
  - •....
- Hierarchical Clustering

Classification

- K-Nearest Neighbors
- Classification and Regression Trees
- Naive Bayes
- Logistic Regression
- Discriminant Analysis

Etc.

- Association Rules
- Artificial Neural Networks

Requirement

- Real-time Analysis : Computing time < Sampling time
- Index : End-user convenience

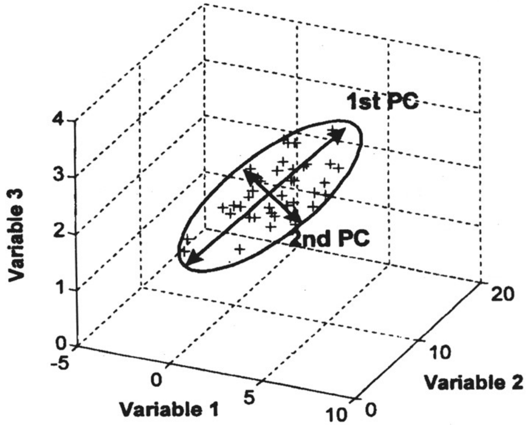
Data Analysis: Multivariate Analysis Based Method

Principal Component Analysis

Many variables
: Correlated

Loss of partial information

A few variables
: Uncorrelated

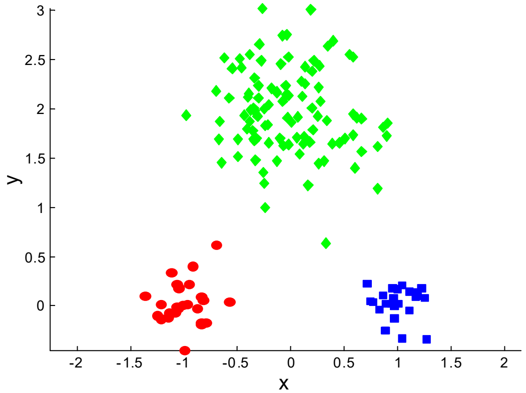


K-means Cluster Analysis

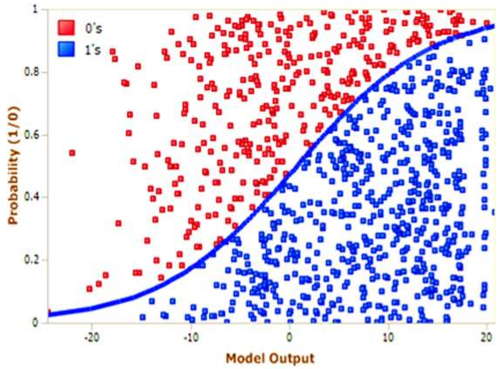
Nonhierarchical Method

Pre-determined Cluster Number

Class Discovery



Logistic Regression

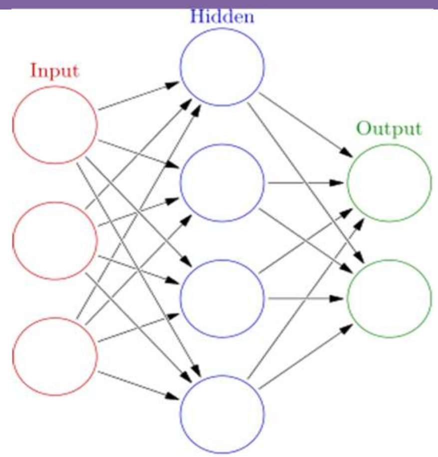


Many variables

Logistic Response Function

Classification (steady / fault)

Artificial Neural Networks



Interconnected Group of Nodes

Etch Model

Predict the Etching Process

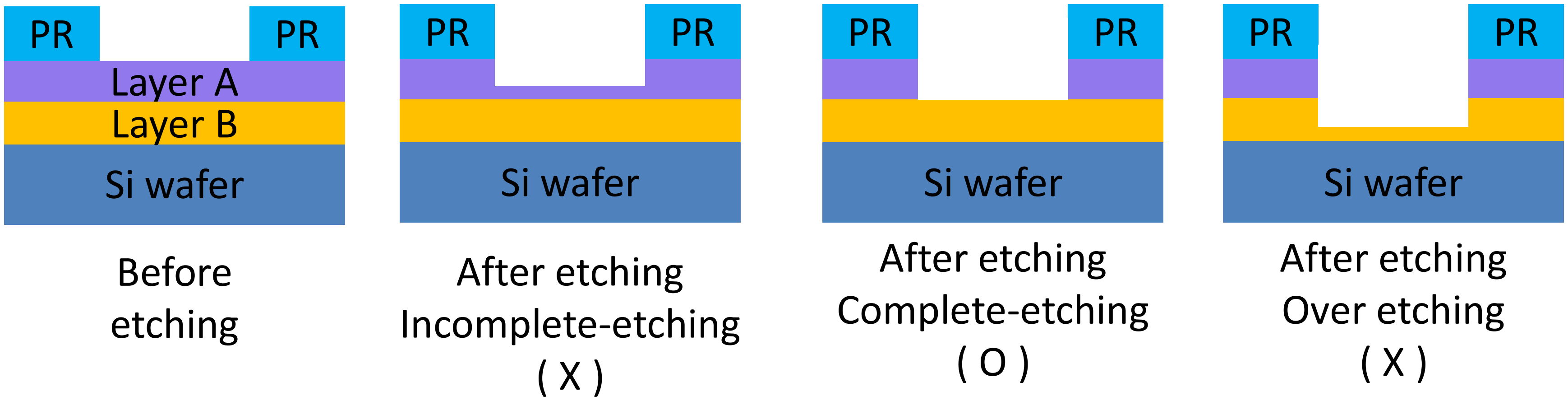
End Point Detection

Method	Measuring	Monitoring
Optical Emission Spectroscopy	Intensity of light emitted from discharge	Emission from reactive species and/or etch products
Optical reflection (Interferometery)	Interference phenomena or reflectivity differences	Changes in film thickness
Mass spectrometry	Gas composition	Etch products
Impedance Monitoring	Impedance/ Mismatch	Voltage/Phase change
Langmuir Probe	Changes in electron density or average energy	Current from probe energy
Pressure	Total pressure	Changes in total pressure

Plasma Monitoring: Endpoint Detection

- To control etching rate is important for IC manufacturing.
- It is necessary to avoid incomplete-etching & over-etching.
- Decreasing feature size, it becomes more and more challenging to detect endpoint.

$$SiN_x + CF_4 + O_2 \rightarrow \underbrace{SiF_x + F + CF_x}_{\text{표면}} + \underbrace{CN + FCN + C_2N_2 + N}_{\text{플라즈마 내부}}$$



- **It is critical to end the plasma etching process at target depth.**
- **Sensitive plasma monitoring required.**

Plasma Monitoring: Principal Component Analysis (PCA)

Measured variable ‘x, y, z’

measuring	x	y	z
1	x_1	y_1	z_1
2	x_2	y_2	z_2
. .		Data	
n	x_n	y_n	z_n

t_i : new independent variables

$$t_1 = p_{11}x + p_{12}y + p_{13}z$$
$$t_2 = p_{21}x + p_{22}y + p_{23}z$$
$$t_3 = p_{31}x + p_{32}y + p_{33}z$$

(Matrix) $t_i = Xp_i$

Contribution ratio

measuring	t_1	t_2	t_3
1			
2		Principal Component Score	
. .			
n			

Increasing information intensity of t_i

Maximizing s_{t_i}(variance of t_i)

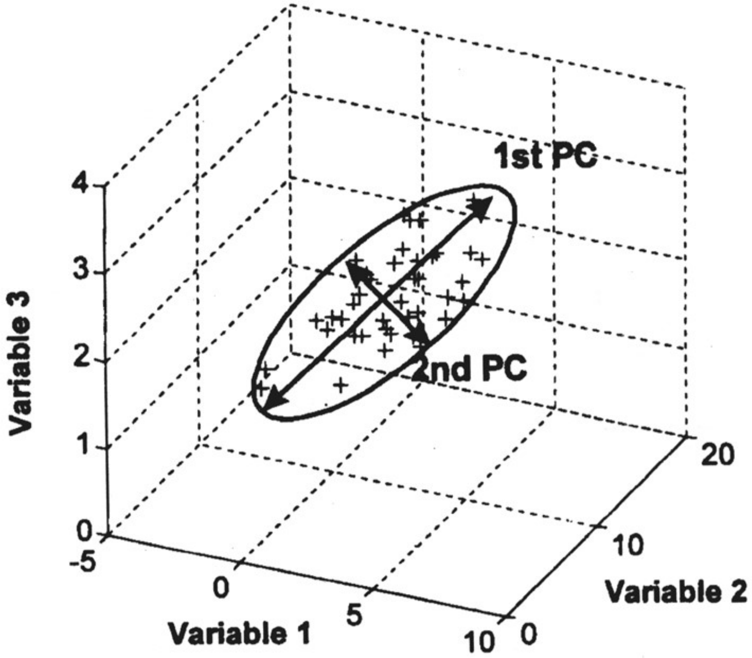
Constraint : $p_{i1}^2 + p_{i2}^2 + p_{i3}^2 = 1$

$$Sp_i = \lambda p_i \qquad S = \left(\frac{1}{n-1}\right)X^T X$$

Finding λ & p from S(variance-covariance matrix)

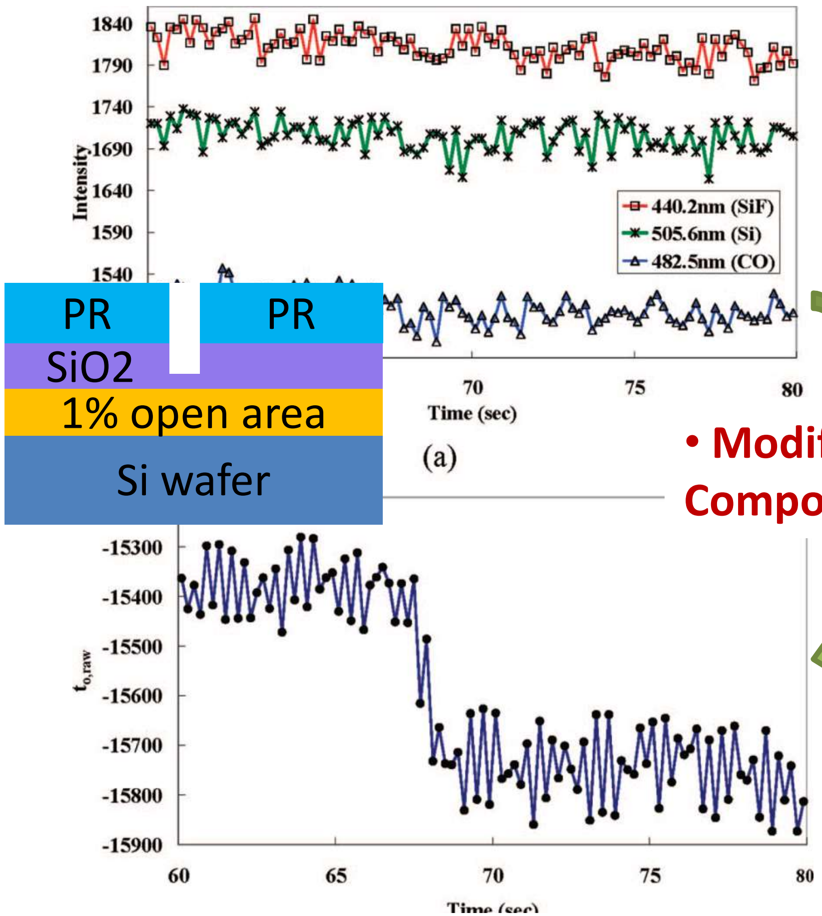
$$|S - \lambda I| = 0$$

- λ (eigenvalue) = Relative information intensity
- p_i (eigenvector) = loading vector = coefficient of principal components
- t_i = score vector

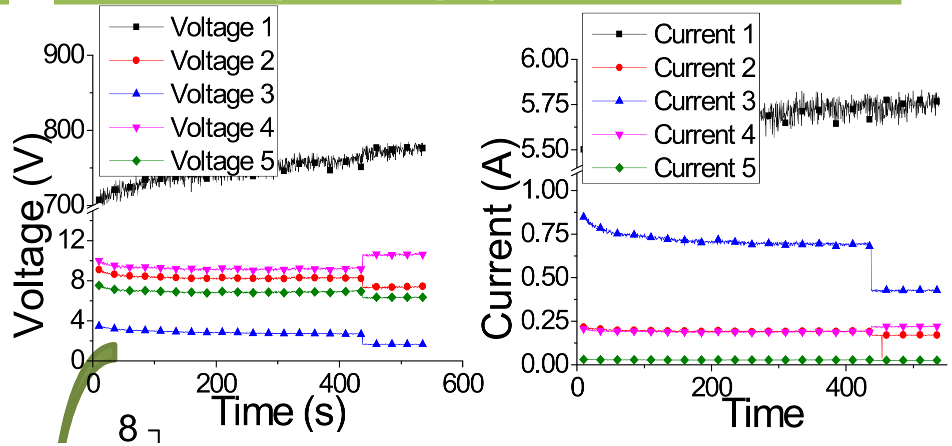


Plasma Monitoring: VI Probe & PCA

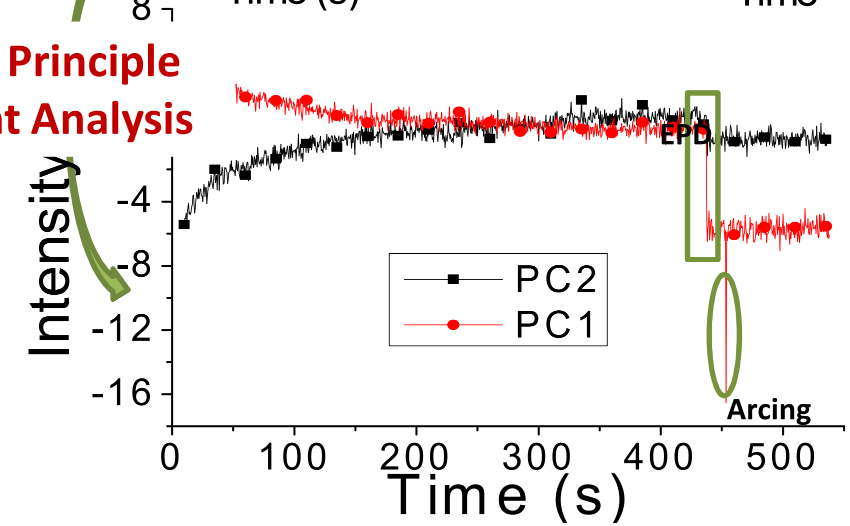
EPD (OES) : chemical information



EPD (VI probe): physical information



- **Modified Principle Component Analysis**



Ind. Eng. Chem. Res, 47, 11, (2008)   Plasma process polym. 10, 850 (2013)

- **Endpoint detection sensitivity improved by PCA algorithm**

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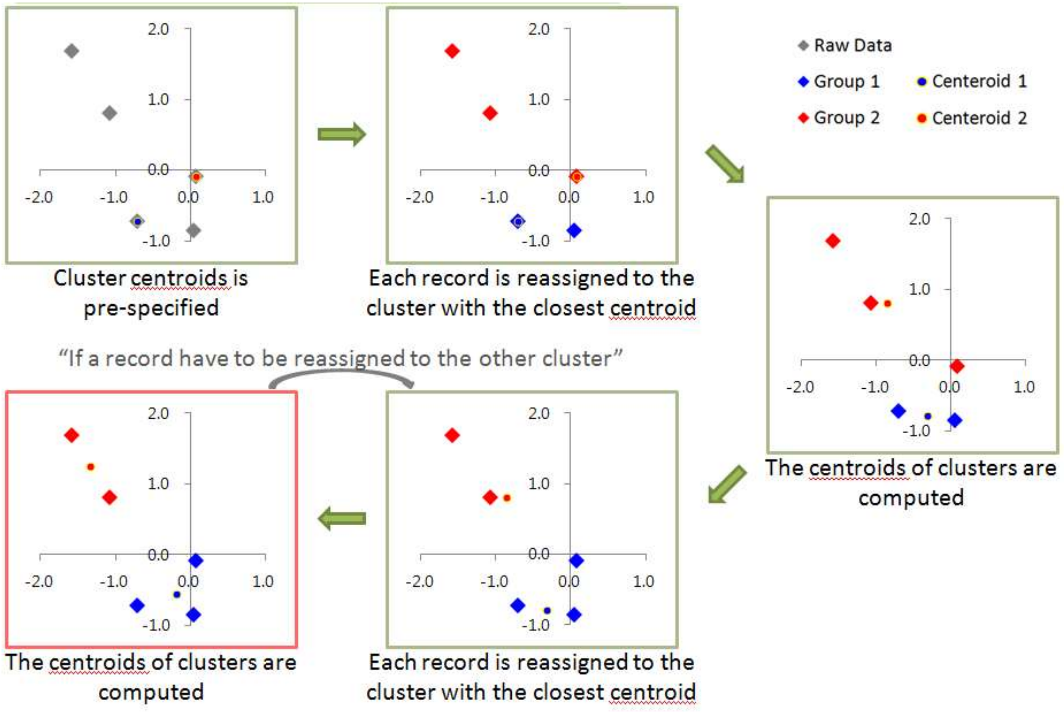
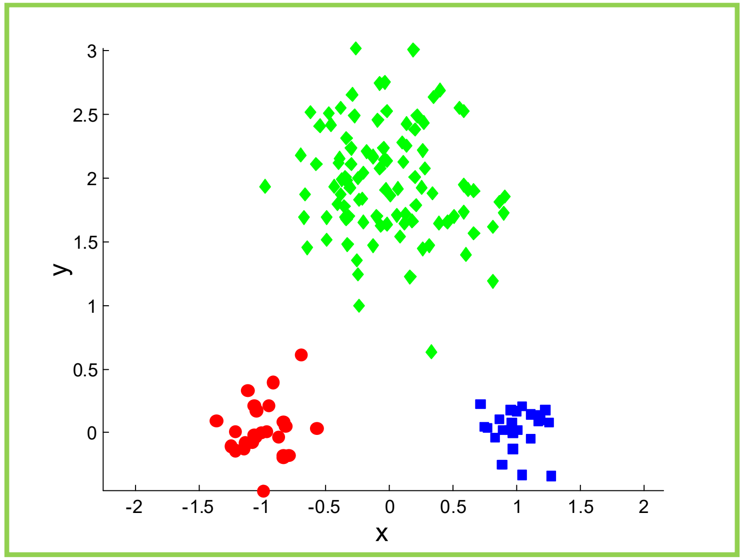
Plasma Monitoring: Cluster Analysis



Cluster analysis



$$R = \frac{\sum_{i=1}^{n}\sum_{j=1}^{2}(x_i - \bar{x}_j)(x_i - \bar{x}_j)^T a_{ij}}{\sum_{i=1}^{n}(x_i - \bar{x}_0)(x_i - \bar{x}_0)^T}$$

$\bar{x}_0$: Centeroid of all records

$\bar{x}_1$: Centeroid of cluster 1

$\bar{x}_2$: Centeroid of cluster 2

$$a_{ij} = \begin{cases} 1 & \text{if cluster } j \text{ includes record } i \\ 0 & \text{else} \end{cases}$$

- **Cluster analysis is suitable for fault identification in complex systems**

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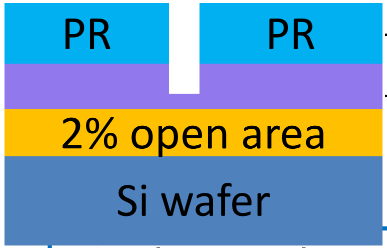
Plasma Monitoring with OES & Cluster Analysis

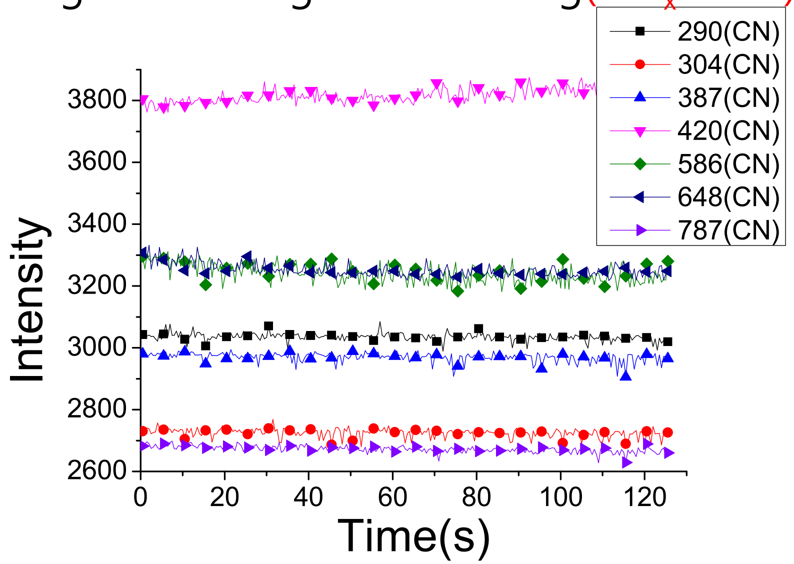
❖ Self Plasma OES/ Real time K-means Cluster Analysis Algorithm for the end point detection of SiN_x films



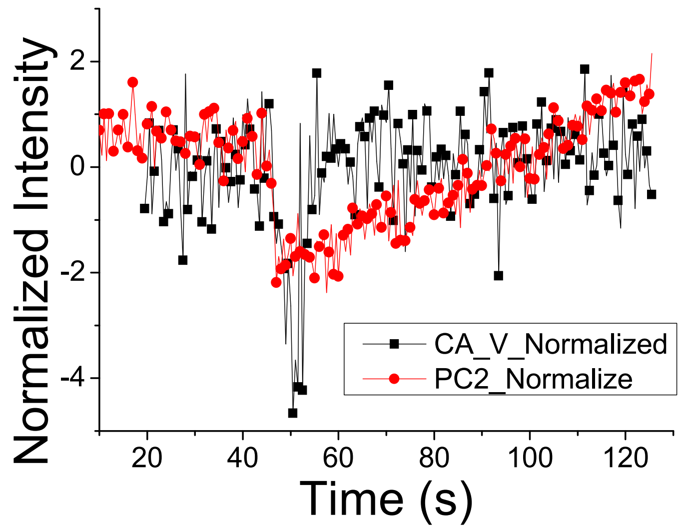
- 50mTorr / 250Ws / 250Wb / CF4 40sccm / Ar 40sccm / O2 10sccm
- Surface reactions $SiN_x + CF_4 + O_2 \rightarrow SiF_x + F + CF_x + CN + FCN + C_2N_2 + N$

표면 / 플라즈마 내부

Single wavelength monitoring (SiN_x 2.0%)



- Algorithm 적용 결과 (SiN_x 2.0%)



▪ EDP cannot be determined with single wavelength monitoring.

- **Cluster analysis improved sensitivity of endpoint detection.**

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Summary

- Plasma processing is a key technology in IC fabrication
- Plasma diagnostics and monitoring is essential for control and monitoring
- Physical and electrical sensors
  - For electron and ions density and energy distribution
  - Langmuir Probe and VI probes with equivalent circuit models
- Chemical sensors
  - Mass Spectroscopy (MS) for ions and radicals
  - Optical Emission Spectroscopy (OES) for radicals
  - Laser induced fluorescence
- Plasma monitoring algorithms
  - For endpoint detection and chamber matching
  - Algorithms can improve sensitivity