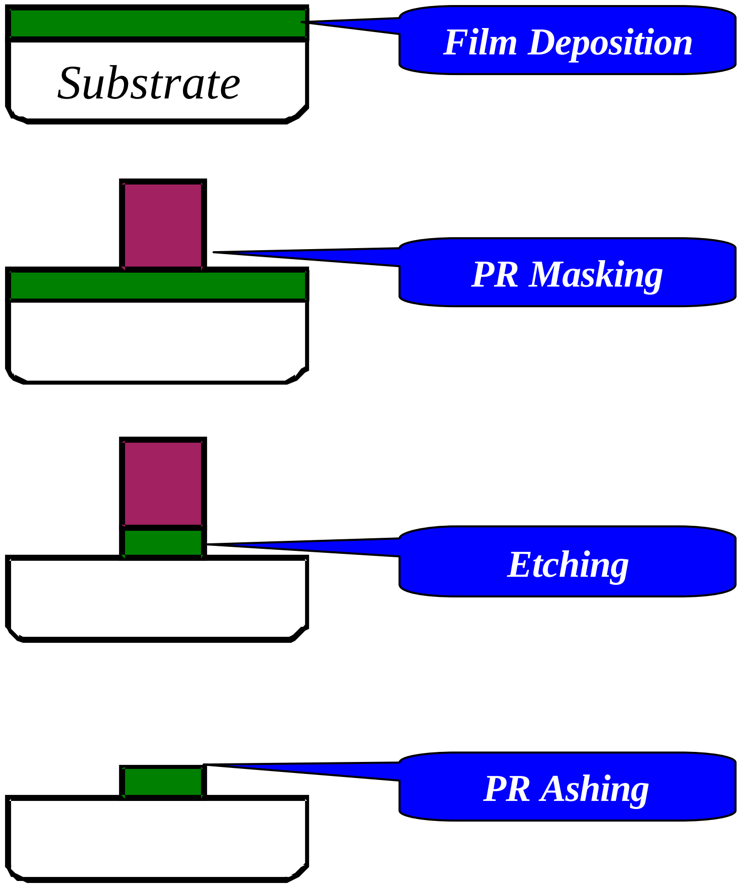
Etch Process 기초

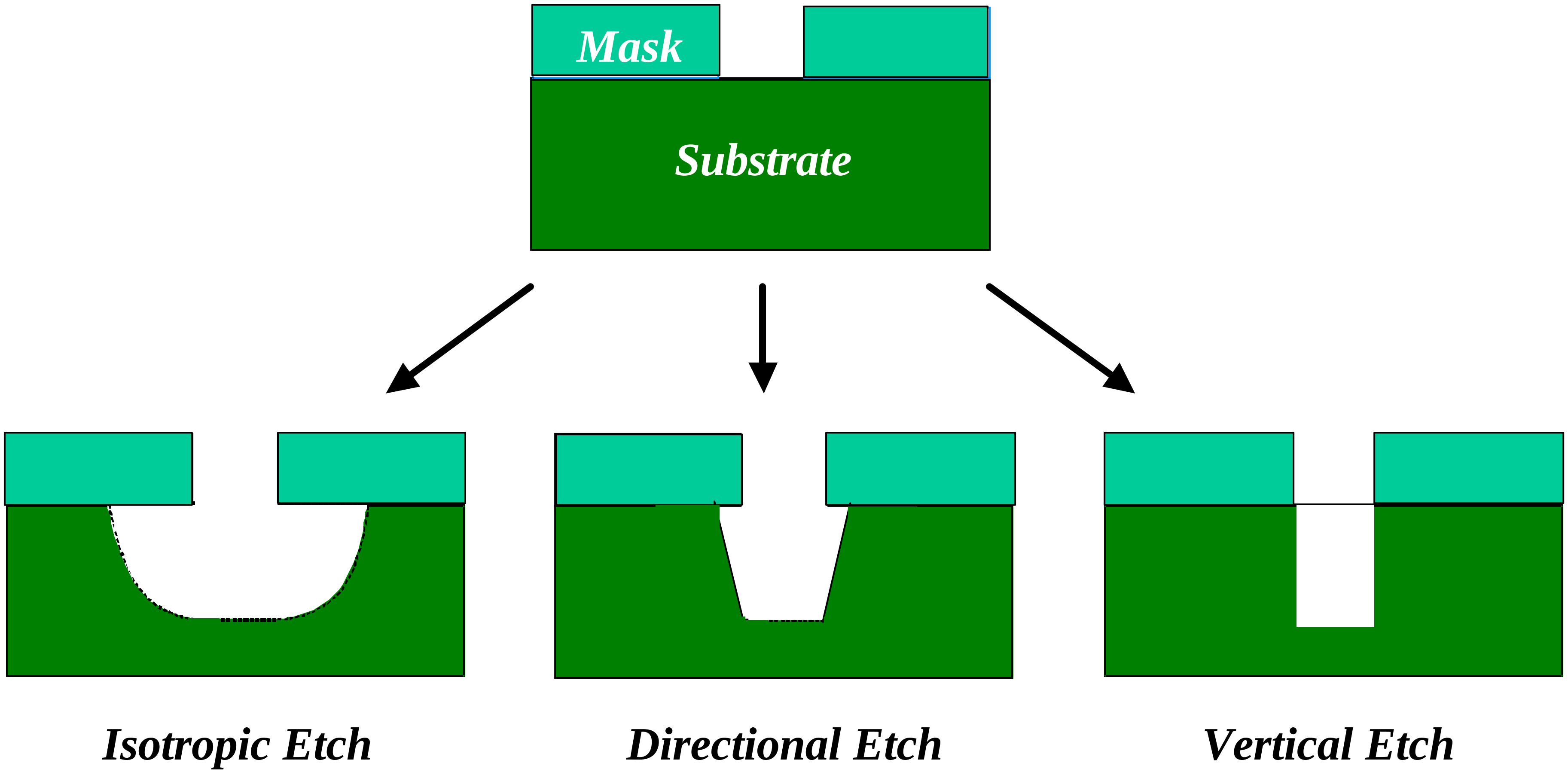
Contents

- ***Introduction to Etch Processes***
- Inside the Plasmas
- Plasma Etch Equipment
- Examples (DRAM Etch Process)

Pattern Transfer Method



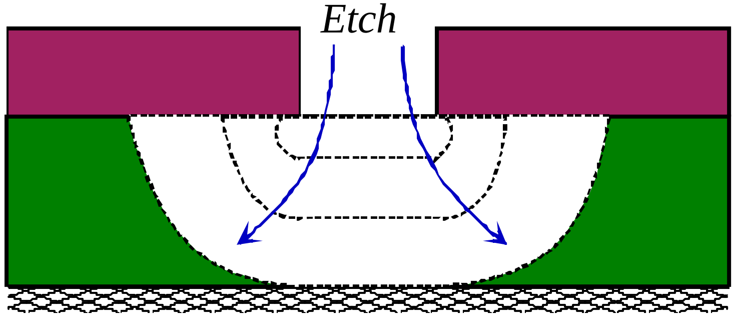
Directionality of Etching Processes



Etching Technology

Wet Etching

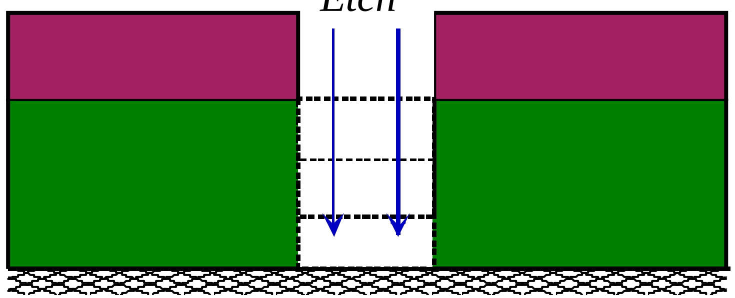
- by Wet chemical solution
- Isotropic etching



Vertical E/R = Horizontal E/R
Pure Chemical Reaction
High Selectivity
CD Loss or Gain

Dry Etching

- by Plasma
- Anisotropic etching



Vertical E/R >> Horizontal E/R
Ion assisted
Relatively low Selectivity
No CD bias

Wet Etching

- *Advantage*
  - *Low Cost*
  - *High Throughput*
  - *Reliability*
  - *Excellent Selectivity*
- *Disadvantage*
  - *Very hard to control Critical feature Dimension*
  - *Difficult to control the degree of over-etching due to undercut*
  - *Decrease in Etch rate as Reagent solutions are consumed*
  - *Hazardous and Difficult to handle*
  - *Toxic Fume*
- ***Current Status***
  - *Wet Cleaning for Polymer & PR removal*
  - *Pre-cleaning before Deposition*

Etch Process
기초

Definition of Dry Etching (Plasma Etching)

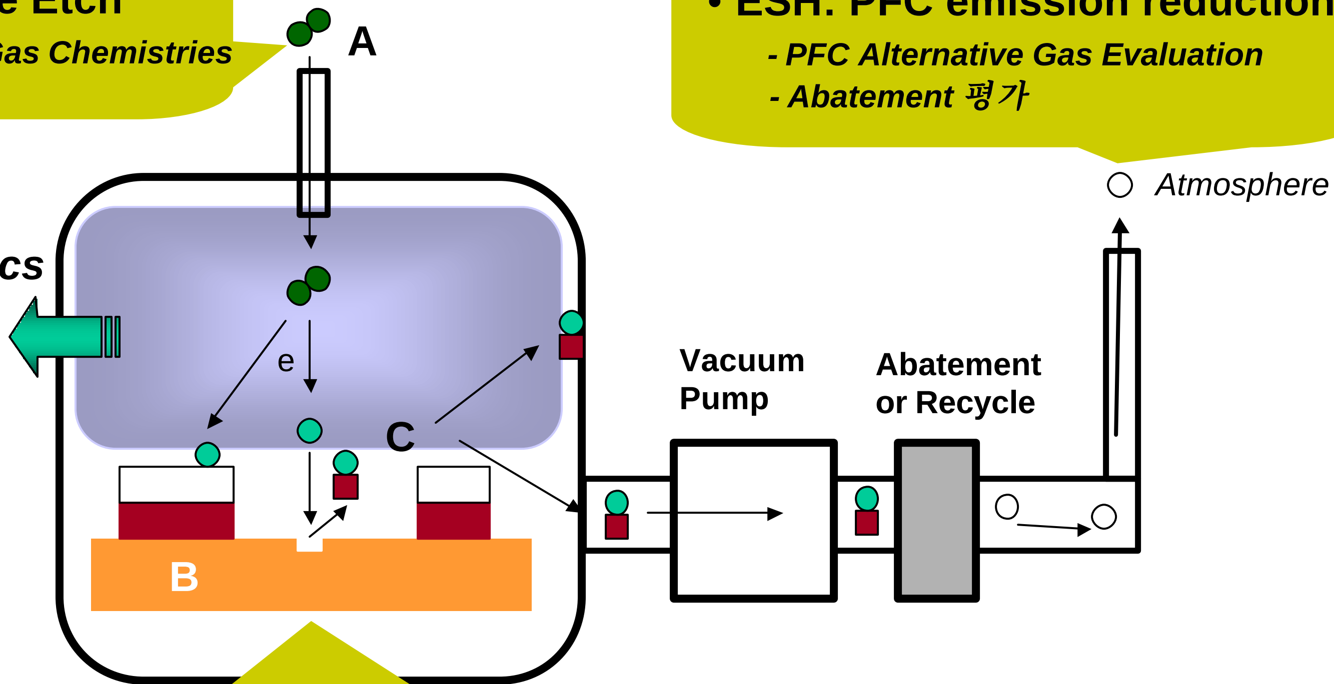
Plasma Etching º A + B ® C

- **Highly Selective Etch**
  - *PEC Test for New Gas Chemistries*

- **ESH: PFC emission reduction**
  - *PFC Alternative Gas Evaluation*
  - *Abatement 평가*

Plasma Diagnostics

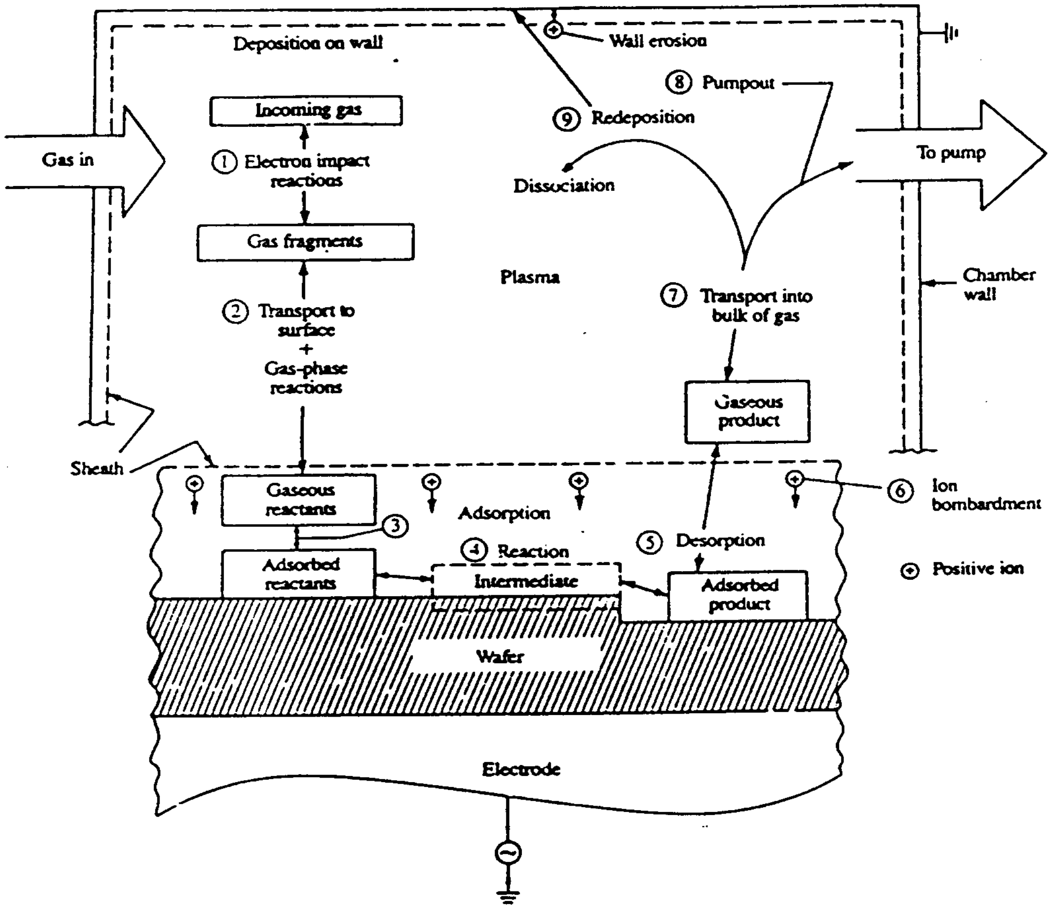
Electrostatic probe
Mass Spectrometer
Optical emission Spec.



- **Low Damage Etch**
  - *Pulsed Plasma Etch & New Source Evaluation*
  - *Damage Characterization*

참고

Plasma Etching Mechanism



- ✶ *Glow Discharge*
- ✸ *Transport*
- ✹ *Adsorption*
- ✼ *Etching Reaction*
- ⌖ *Desorption*
- ⌖ *Ion Bombardment*
- ✧ *Bulk Gas Stream*
- ⌑ *Pumping Out*
- ◈ *Redeposition*

What is Plasma Etching?

Take a Molecular Gas
(Usually Relatively Inert) — $Cl_{2(gas)}$

Establish a Glow Discharge &
(Ion and Electron Formation) — $e + Cl_2$ ® $Cl_2^+ + 2e$

Create Reactive Species — $e + Cl_2$ ® $2Cl + e$

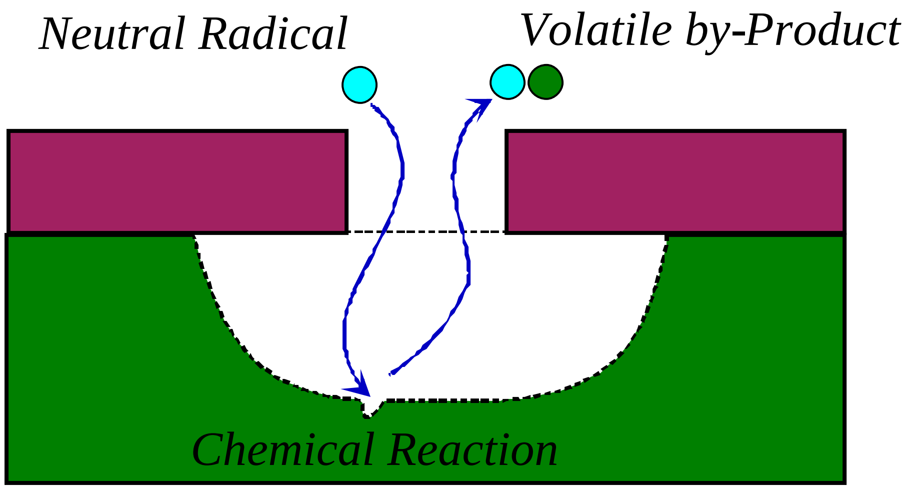
Chemical Reaction to form
a VOLATILE product — $Si + 4Cl$ ® $SiCl_4$

Product Desorption &
Pumping Away Volatile Product — $SiCl_{4(ads)}$ ® $SiCl_{4(gas)}$

Basic Method of Plasma Etching

Chemical

Thermalized neutral radicals chemically combine with substrate material forming volatile products

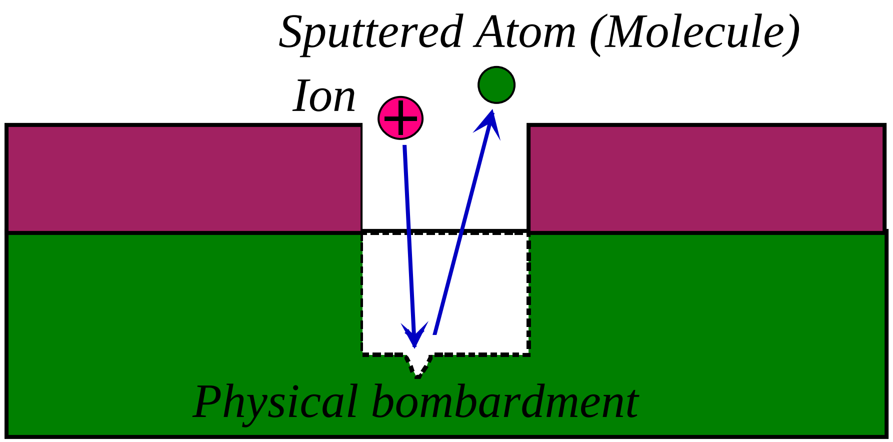


- *Isotropic*
- *Purely Chemical Reaction*
- *High Pressure*
- *Batch Wafer Type*
- *Less Electrical Damage*

Basic Method of Plasma Etching

Sputtering

The ion energy mechanically ejects substrate material

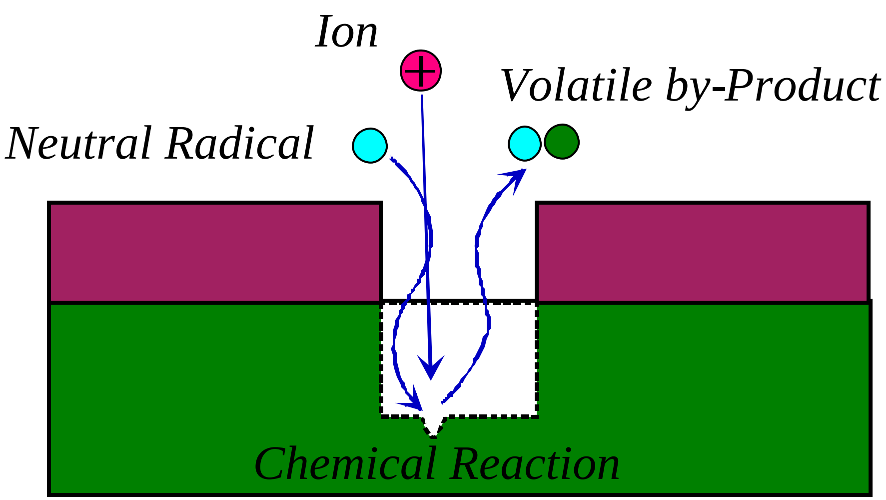


- *Anisotropic*
- *by Purely Physical Process*
- *High Directionality*
- *Low Pressure*
  : long mean free path
- *Single Wafer Type*
- *Low Etch rate*

Basic Method of Plasma Etching

Energetic Ion Enhanced

Ion bombardment enhances or promotes the reaction between an active species and the substrate material

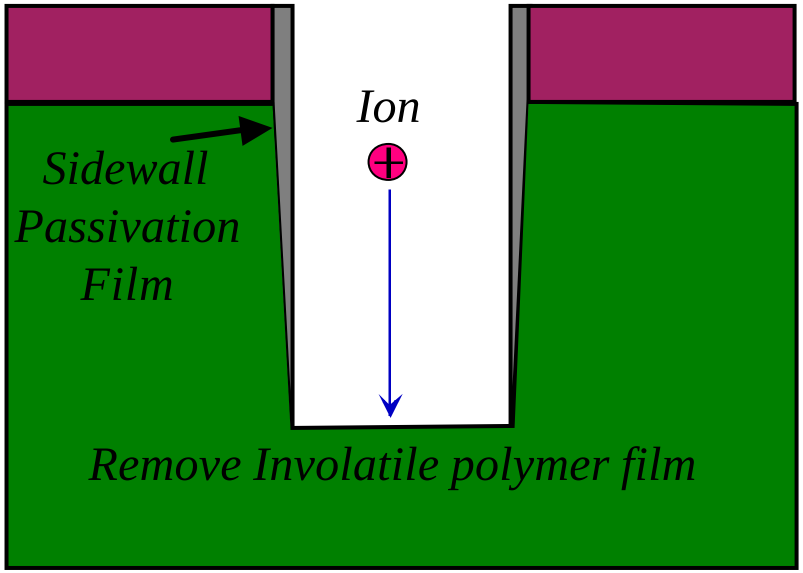


- *Damage Enhanced Chemical Reactivity*
- *Chemical Sputtering*
- *Chemically Enhanced Physical Sputtering*
- *Ion Reaction*

Basic Method of Plasma Etching

Protective Ion Enhanced

An inhibitor film coats the surface forming a protective barrier which excludes the neutral etchant



- *Sidewall Passivation*
- *Stopping lateral attack by neutral radical*
- *Ion directionality*
- *Involatile polymer film*
- *Additive film former (N_2, HBr, BCl_3, CH_3F)*

Solid - Etch Gas Systems

Solid	Etch Gas	Etch Products
Si, SiO_2, Si_3N_4	CF_4, SF_6, NF_3	SiF_4, Si_2F_6,..
Si	Cl_2, CCl_2F_2	$SiCl_4$, $SiCl_2$,..
Al	BCl_3, CCl_4,..	Al_2Cl_6, $AlCl_3$
Refractory Metals (W, Ta, Nb, Mo)	CF_4, Cl_2	WF_6, WCl_6
Organic Solids	O_2, O_2+CF_4	CO, CO_2, HF, H_2O,..
III-V (GaAs, InP)	Cl_2, CCl_2F_2	Ga_2Cl_6, $GaCl_3$, $AsCl_3$
II-VI (HgCdTe, ZnS,..)	CH_4 + H_2	$Zn(CH_3)_2$, H_2S

Difficult Materials

- *Fe, Ni, Co*
  - → *Halides are not volatile*
  - → *Carbonyls do not form readily*
- *Cu*
  - → *Chloride is volatile above 200℃*
- *Al2O3*
  - → *2Al2O3 + 12Cl => 2Al2Cl6 + 3O2*
  - → *Volatile products can be formed but the reaction is uphill thermodynamically*
- *Alkali Metals and Alkaline Earths (Groups I and II) Tend to Form Involatile Halides*
  - → *LiNbO3*
  - → *Pyrex (contains Na)*

- Introduction into Etch Processes

- ***<u>Inside the Plasmas</u>***

- Plasma Etch Equipment

- Examples (DRAM Etch Process)

Definitions

- ***Electron (e)***

  → *mass* (m_e) = 9.1 x 10^{-28} *g*

  → *charge* = -1.6 x 10^{-19} *coulomb*

- ***Proton*** (H^+)

  → *mass* = 1.67 x 10^{-24} *g*

  → *charge* = +1.6 x 10^{-19} *coulomb*

- ***Stable Molecule***

  → *a collection of 2 or more atoms with fully satisfied bonding*

  → *can be chemically active*

  → *eg.* Cl_2, F_2, *HF*, CF_4, SiF_4, ...

참고

Definitions

- ***Radical***
  - → *1 or more atoms with unsatisfied chemical bonding*
  - → *uncharged*
  - → *eg. F, O, OH, CFx (x = 1,2,3), ...*

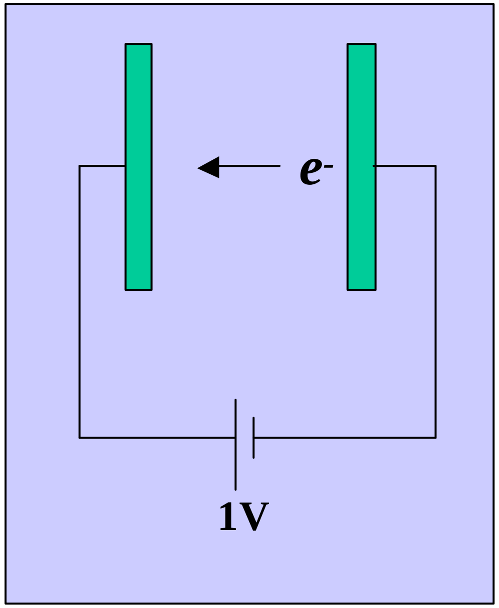
- ***Positive Ion***
  - → *an atom, radical, or stable molecule which has lost an electrons(s) leaving the particle with a positive charge*
  - → *eg. Cl+, Cl2+, CF3+, HF+, SiF4+, …*

- ***Negative Ion***
  - → *an atom, radical, or stable molecule which has captured an electron leaving the particle with a negative charge*
  - → *eg. Cl-, Cl2-, CF3-, SF5-, F-, ...*

참고

Electron Temperature

- 기체입자의 평균운동에너지 $E = 1/2\ mv_{th}^2 = 3/2\ kT$, v_{th} : 열속도
  k : Boltzman constant (온도 - 에너지)
  $= 1.3\text{x}10^{-23}$ J/K
- 두 전극 양 끝단에 1V를 가했을 때 전자가 가속되어 Anode 끝단에서의 최대에너지
  1 eV = 1.6 X 10^{-19} Coulomb• V
  → Joule
- 1 eV = $1/2\ mv^2$ ($e = 1.6\text{x}10^{-19}$ C , V = 1 Volt, $m = 9.1\text{x}10^{-31}$ kg)
  v @ 10^6 m/s : 1V 주어졌을 때 전자의 속도
- 전자가 1000 km/sec 를 갖도록 열에너지를 가해줄 수 있다면
  그때의 온도 T = 1eV/k (k = $1.3\text{x}10^{-23}$ J/K)
  = 11,600 K
- 1 V 가할 때, 전자의 에너지는 1 eV , 그때의 속도 1000km/sec ,
  등가의 에너지를 갖는데 필요한 온도는 11,600K
  1 eV º 11,600K
- A convenient unit for the electron temperature is the electron volt (eV)
- Average Electron Energy of the Glow Discharge Plasmas : 1~ 10 eV



General Information

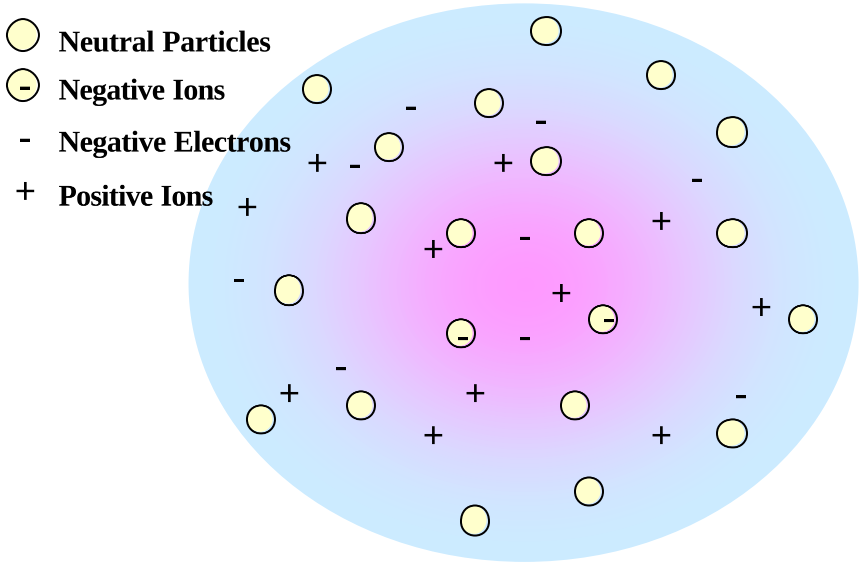
- ***Units of Pressure***
  - → *1 Atmosphere = 760 Torr = 1013 millibars = 1.013 x 10^5 Parscals*
  - → *1 Torr = 133 Pa*
  - → *1 Pa = 7.52 x 10^{-3}Torr*
  - → *1 millibar = 100 Pa = 0.75 Torr*

- ***Gas Density***
  - → *1 Torr = 3.2 x 10^{16} molecules/cm3*

- ***Mean Free Path***
  - → λ*(cm) = 5/P(millitorr) : very dependent on species*

- ***Charged Particle Fluxes***
  - → *1 milliamp = 6.25 x 10^{15} particles/sec*

What is Plasma ?



- Partially ionized gas containing about equal concentrations of positive and negative particles and chemically activated radicals
- Degree of ionization (*fi*)

  = No. of charged ions / original atoms and/or molecules

  Normally, $fi = 10^{-2} \sim 10^{-5}$
- Processing plasmas are described by the term "Glow Discharge"
- Electrically neutral

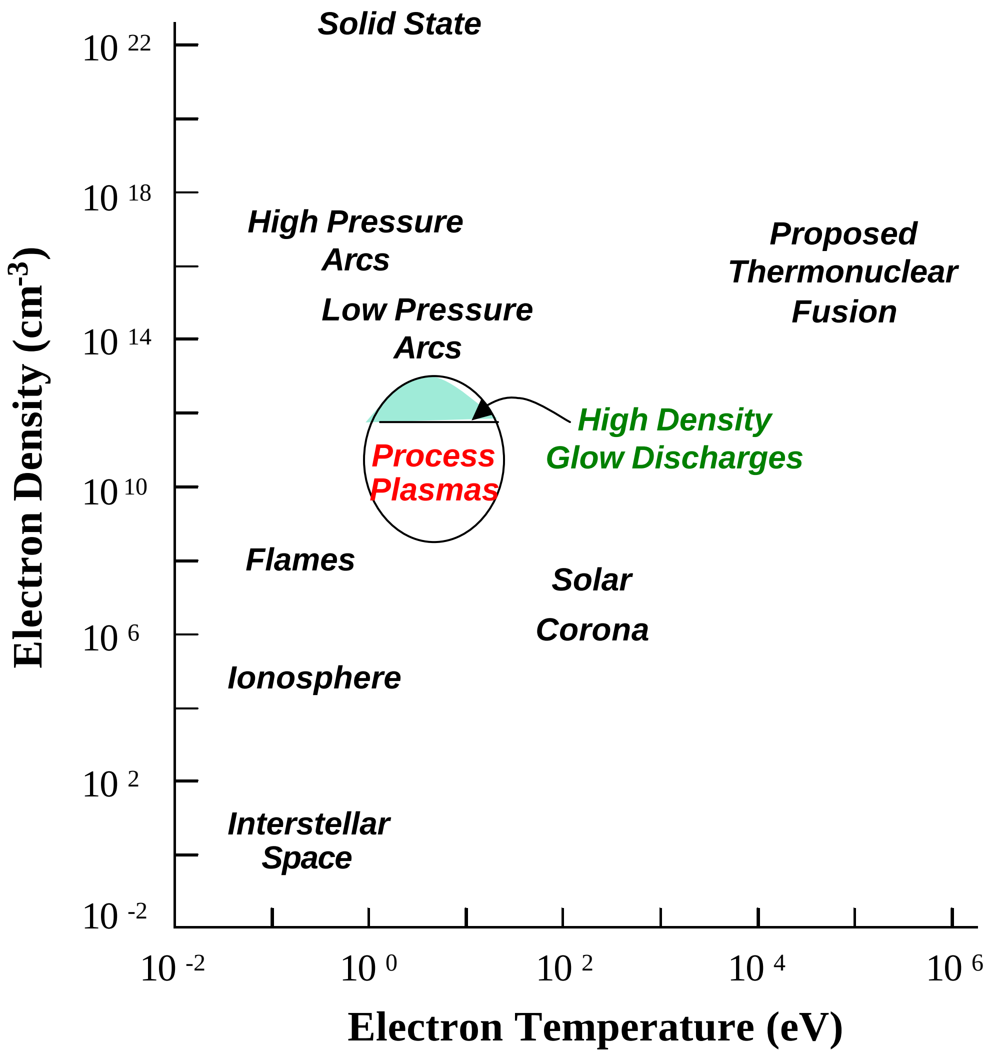
  density of electrons + negative ions

  = density of positive ions

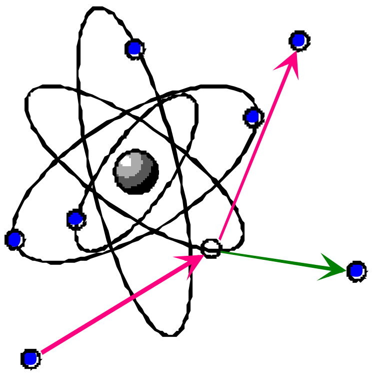
<u>Typical parameter values for a glow discharge plasma</u>

Neutrals	$m = 6.6 \times 10^{-23}$ g T = 20℃ = 293K ° 1/40eV $c = 4.0 \times 10^{4}$ cm/sec
Ions	$m_i = 6.6 \times 10^{-23}$ g T_i = 500K ° 0.04eV $c_i = 5.2 \times 10^{4}$ cm/sec
Electrons	$m_e = 9.1 \times 10^{-28}$ g T_e = 23000K ° 2eV $c_e = 9.5 \times 10^{7}$ cm/sec

A Variety of Plasmas

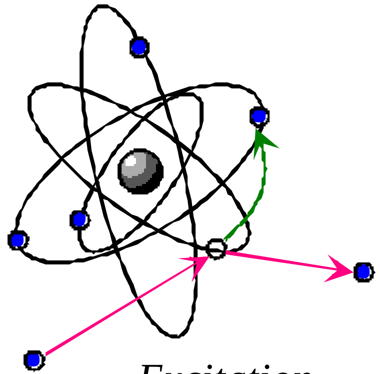


Electron Reactions in Plasma



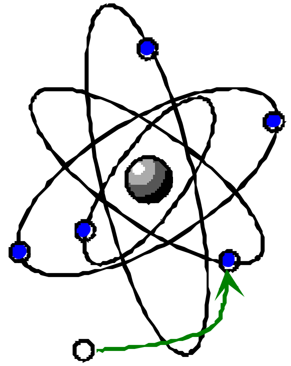
Positive Ionization

A + e ® A^+ + 2e

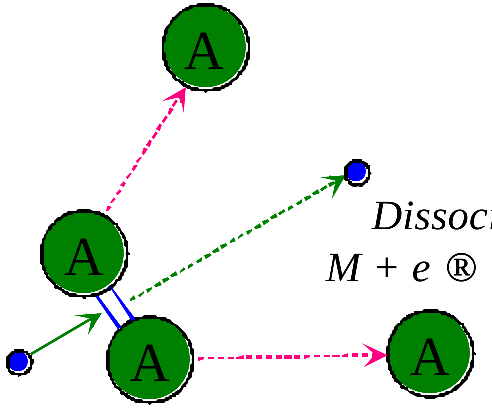


Excitation

A + e ® A + e*

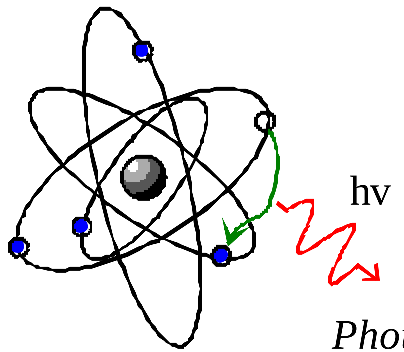


Recombination



Dissociation

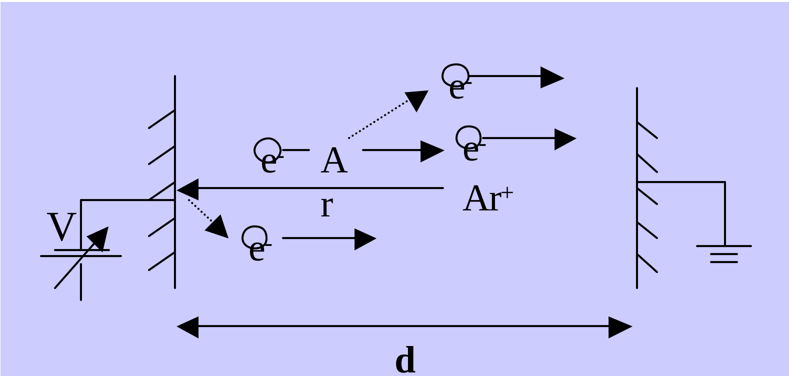
M + e ® 2A + e*

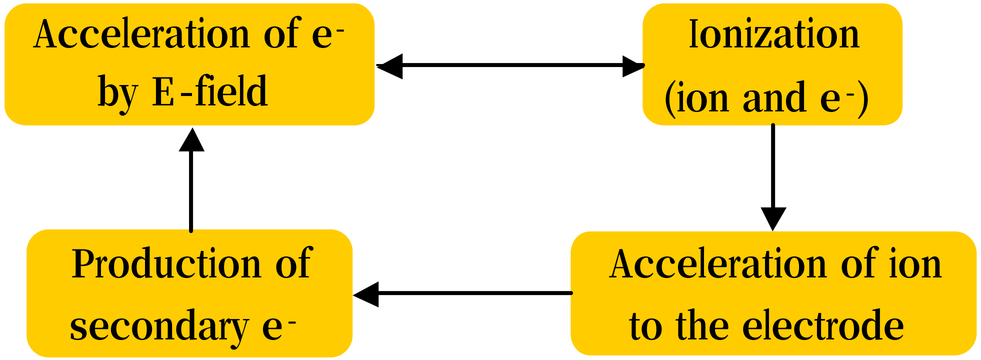


Photoemission

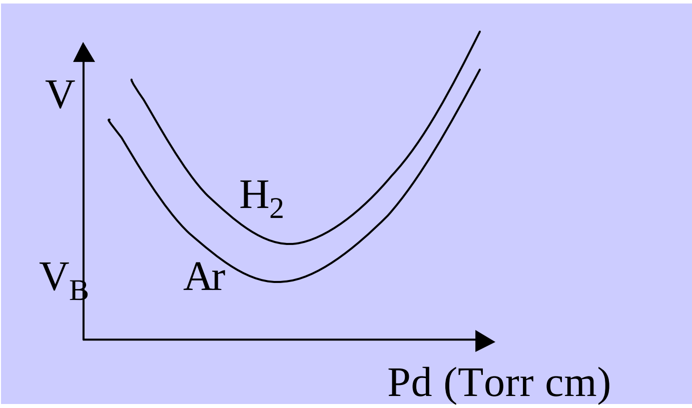
Ignition of Plasmas

• Ignition of plasma





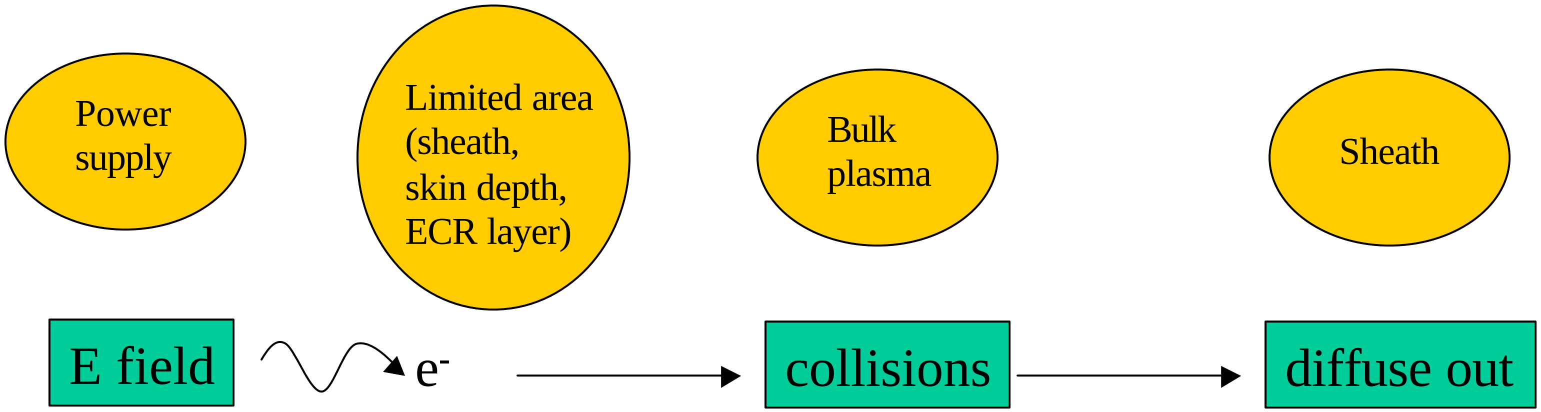
• **Paschen curve (plasma turn on voltage)**



Plasma의 발생(ignition) 요건

→ 충분한 에너지의 전자 + 충분한 충돌 횟수

Sustaining of Plasmas



- **Energy absorbed by e-** **=** **Collisional energy loss** **+** **Diffusional energy loss**

  - Capacitively coupled plasma
  - Inductively coupled plasma
  - Wave heated plasma

  Collisional energy loss:
  - ionization
  - dissociation
  - excitation
  - elastic collision
  - recombination

  Diffusional energy loss:
  - ions and electrons to the wall

- **Charges created in the plasma = charges lost to the wall + charges lost by recombination**

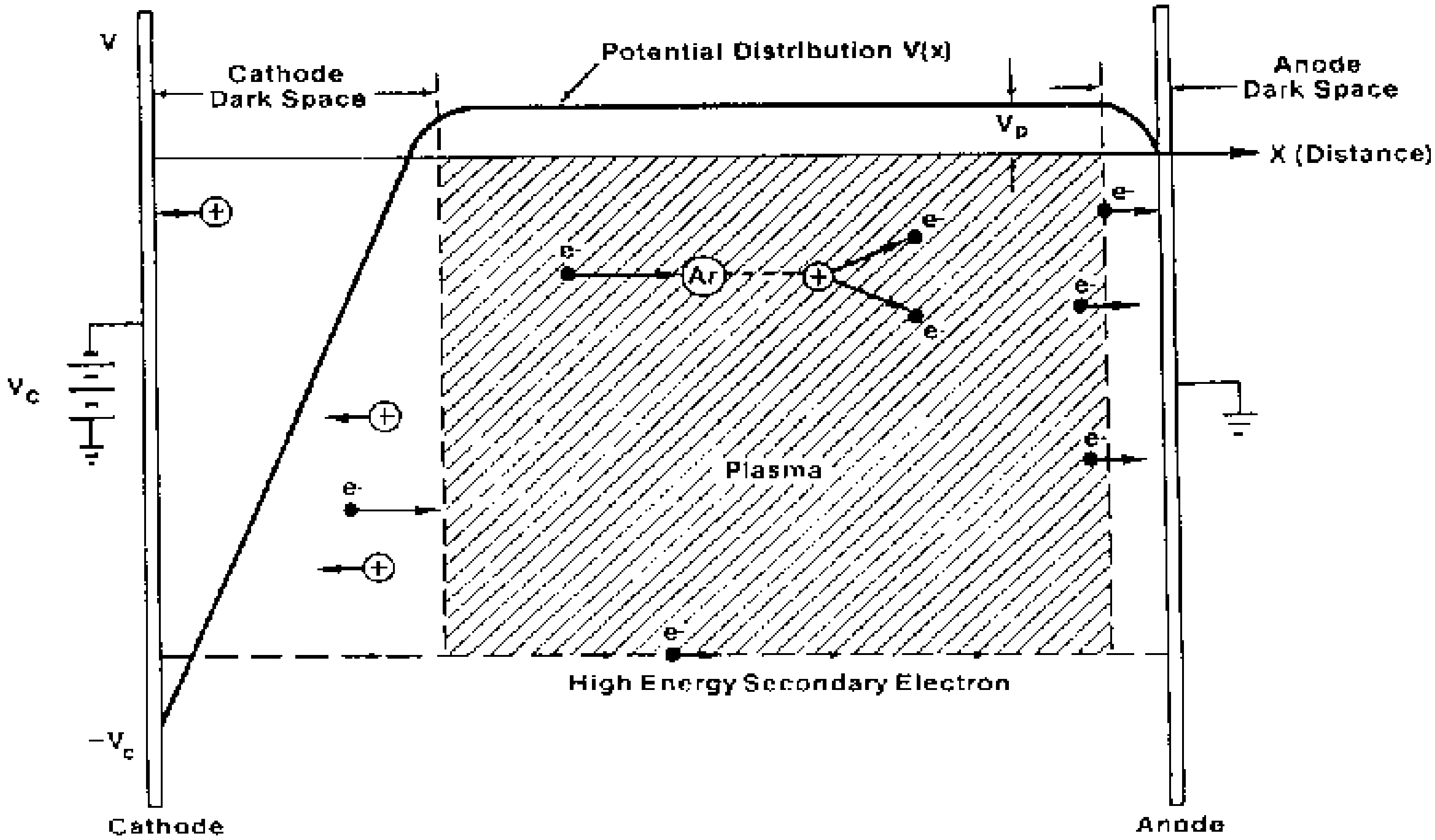
참고

Classification of Plasmas

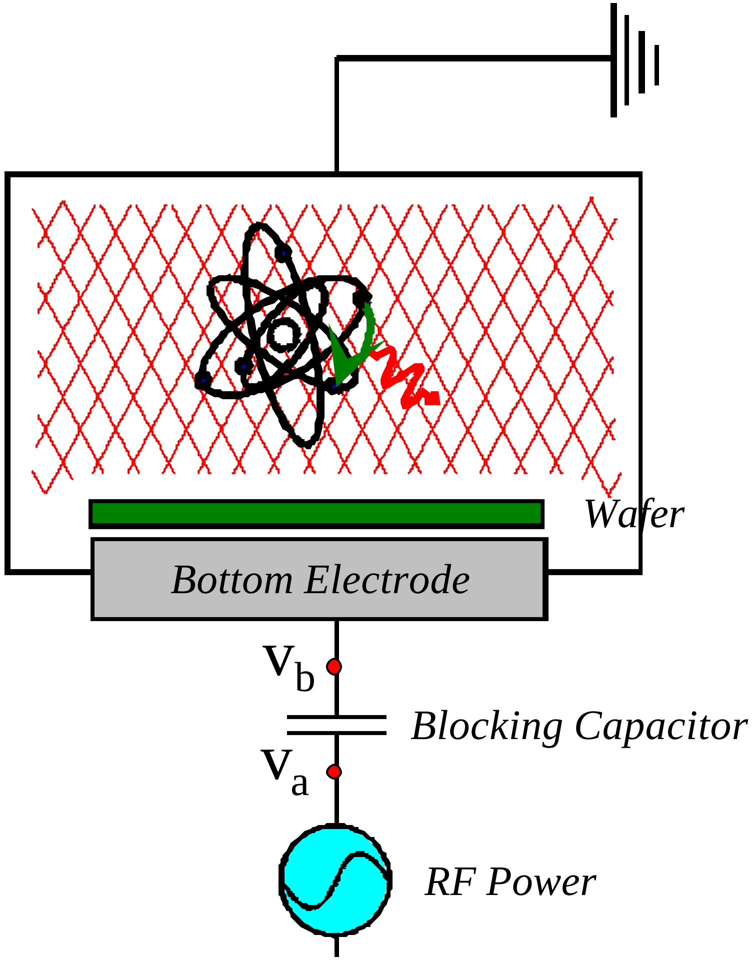
- by the energy transfer mechanism

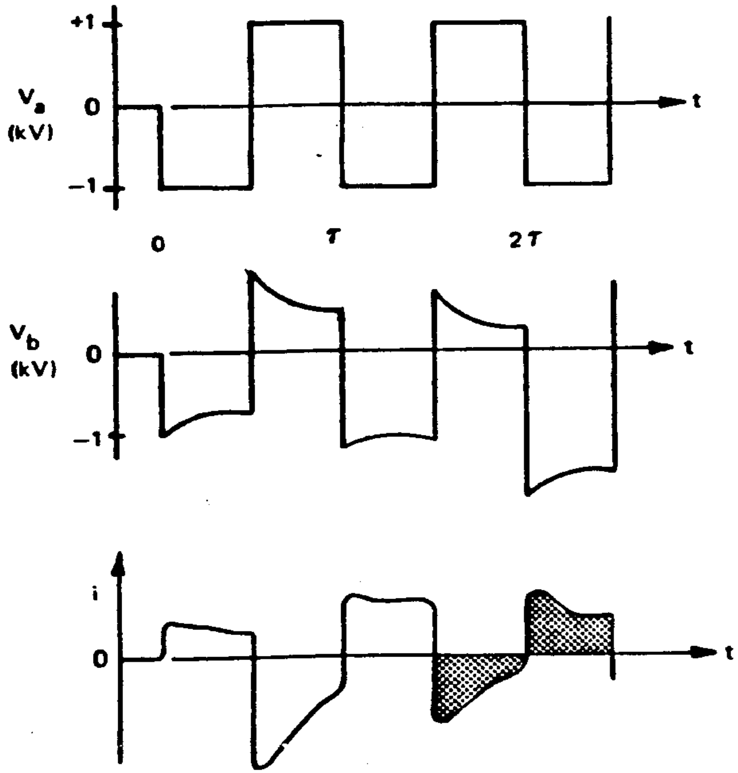
- CCP (capacitively coupled plasma)
  - powered electrode is directly coupled to the plasma
  - high electric field is formed near the powered electrode
  - power transfer efficiency is relatively low but very uniform plasma can be generated
  - e.g.) DC, RF(13.56MHz), VHF(>30MHz), UHF(~수100MHz), MF(~수100KHz)
- ICP (inductively coupled plasma)
  - power is transferred to the plasma by the induction, like transformer
  - no electrode exists inside the plasma
  - power transfer efficiency is high
  - substrate bias can be controlled independently
- Wave heated plasmas
  - power is transferred from the propagating EM wave
  - power transfer efficiency is very high
  - e.g.) Microwave plasma, ECR (microwave + B-Field), Helicon and helical plasma(RF + B-Field), Surface Wave (10MHz ~ 10GHz)

Principles of DC Plasma



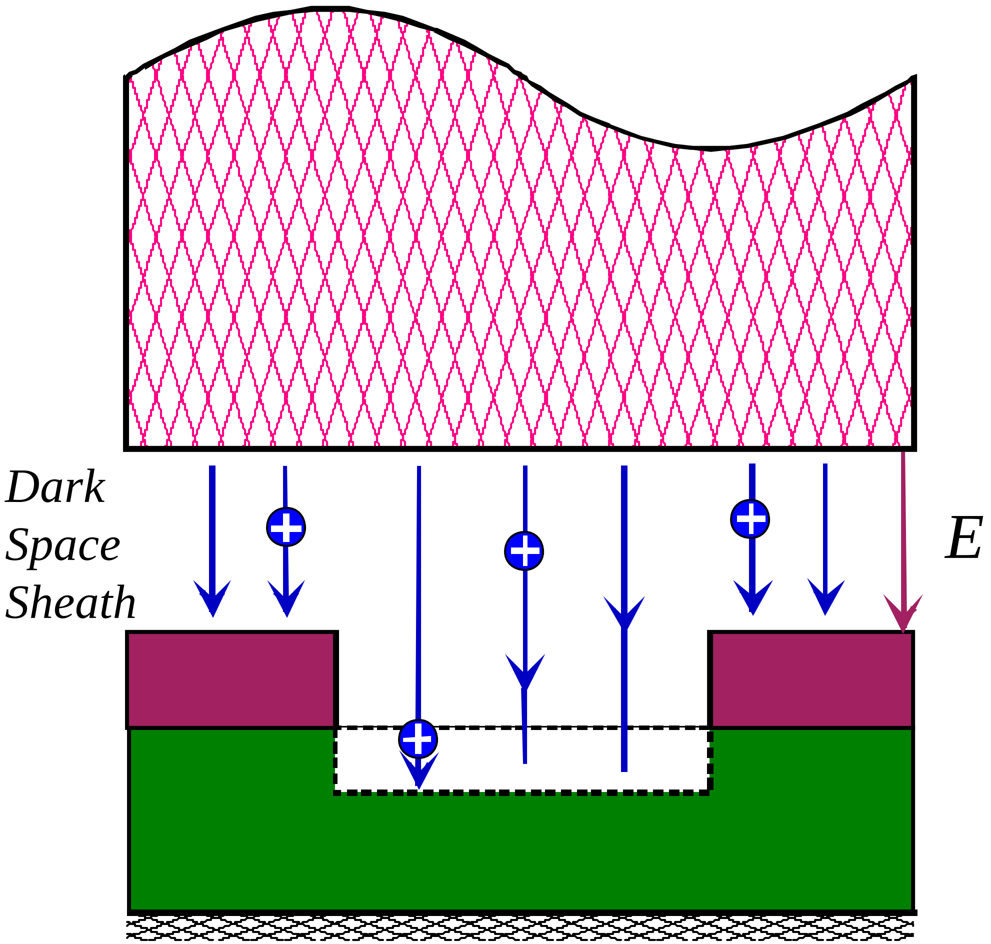
Generation of DC Self-bias Voltage

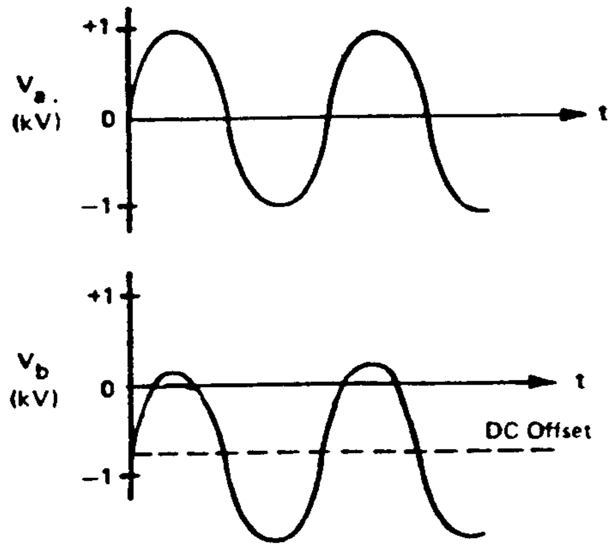




Equal areas = Zero net current

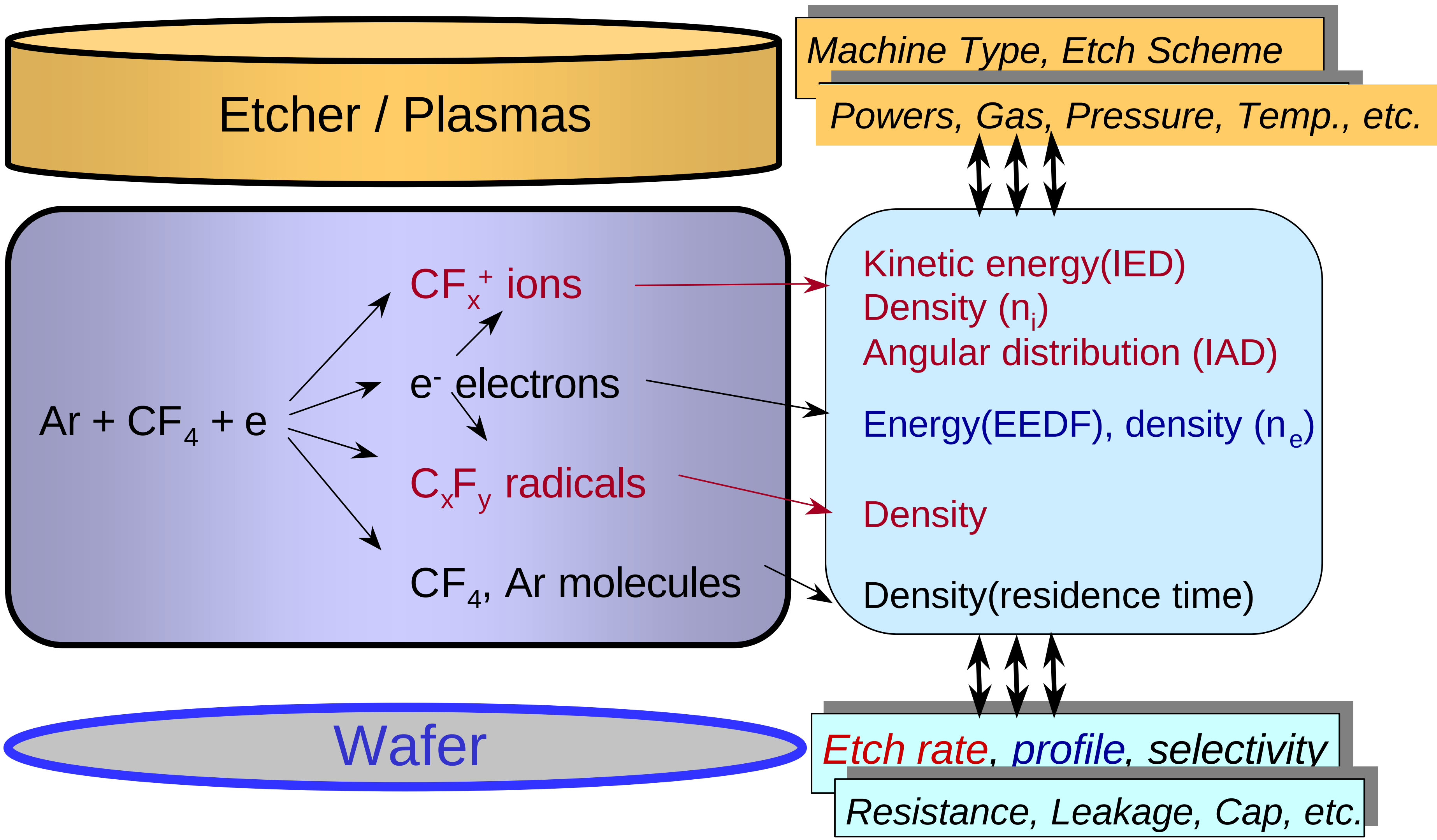
Directional Etching by DC Self-bias





E field is formed by DC Self-bias

Needs for Plasma Diagnostics



Plasma Gas Chemistries

- ***Fluorine 계 Plasma***

  CF_4, C_2F_6, C_3F_8, C_4F_8, C_4F_6, C_5F_8, etc.
  CF_3H, CF_2H_2, CFH_3, C_2HF_5, etc.
  NF_3, SF_6
  CF_3Cl, etc.

- ***Chlorine 계 Plasma***

  Cl_2, HCl, $CHCl_3$, BCl_3, CCl_4, etc.

- ***Bromine 계 Plasma***

  HBr

- ***Iodine 계 Plasma***

  HI

- ***Other Reactive Gases or Buffer/Inert/Additives***

  O_2, N_2, Ar, CO, H_2O, SO_2, H_2, NH_3, C_2H_4, etc.

Additive Gases in Ion Enhanced Etching

Materials	Etching Species	Source Gas	Additive Gas	Mechanism
Si	F	CF_4 C_2F_6 SF_6 NF_3 ClF_3 F_2	O_2 O_2 O_2 None None None	Chemical
SiO_2/ Si_3N_4	CF_x	CF_4 C_2F_6 CHF_3	H_2 H_2 None or O_2	Ion-energetic
Undoped Si n-type Si	Cl	Cl_2 Cl_2 CF_3Cl	None C_2F_6 None	Ion-energetic Ion-inhibitor
Al	Cl	Cl_2	BCl_3 CCl_4 $CHCl_3$	Ion-inhibitor

- Introduction into Etch Processes
- Inside the Plasmas
- ***Plasma Etch Equipment***
- Examples (DRAM Etch Process)

Plasma Etch Equipment Classification

- **By Plasma Ignition Mechanism**

  - Plasma Etch
  - RIE (Reactive Ion Etch) ⇒ MERIE (Magnetically Enhanced RIE)
  - ECR (Electron Cyclotron Resonance)

- **By Pressure Level**

  - Low / Medium (~수 10 mTorr) / High

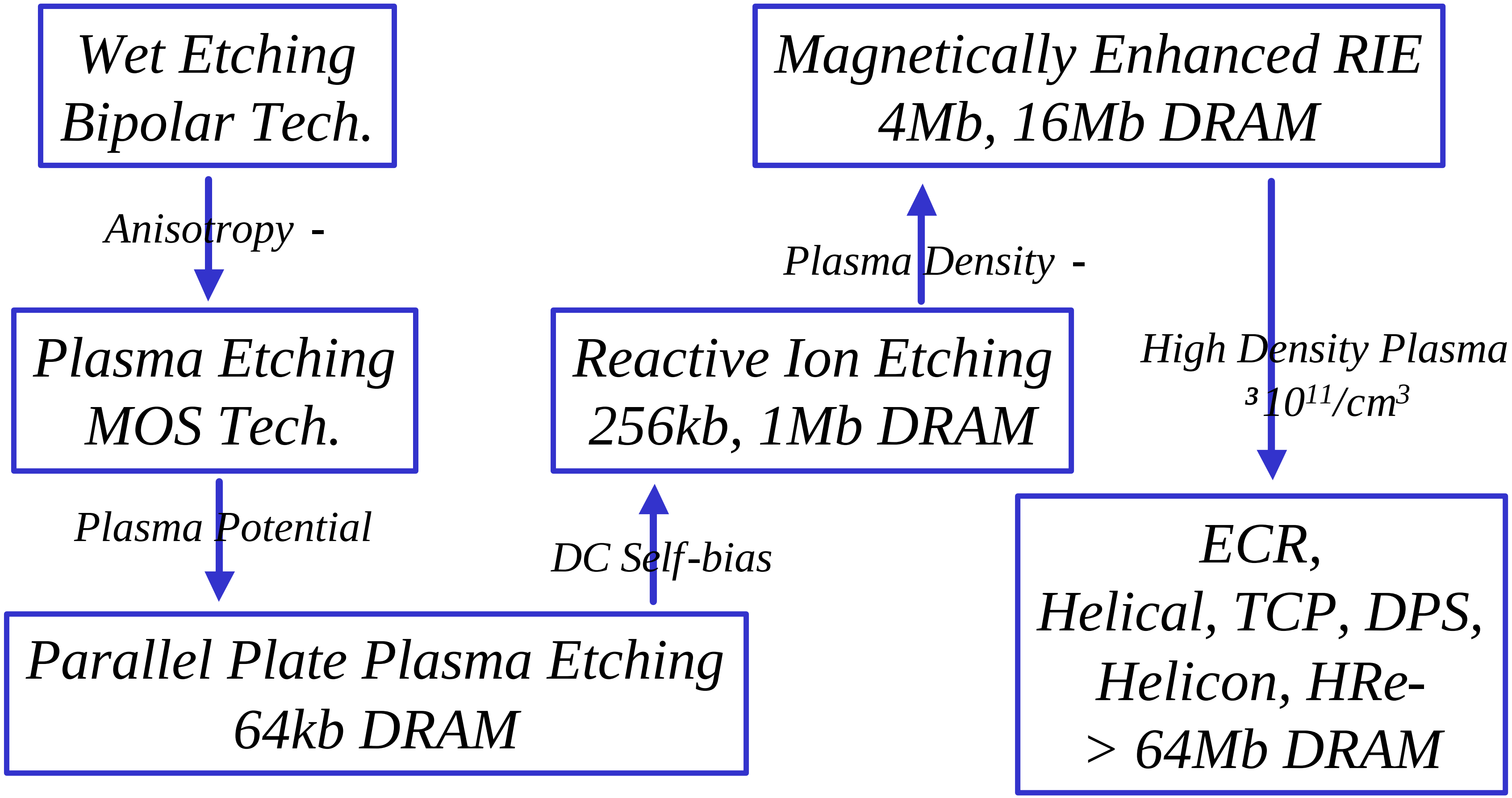
- **By Plasma Density**

  - Low / Medium (~10E+11/㎤) / High

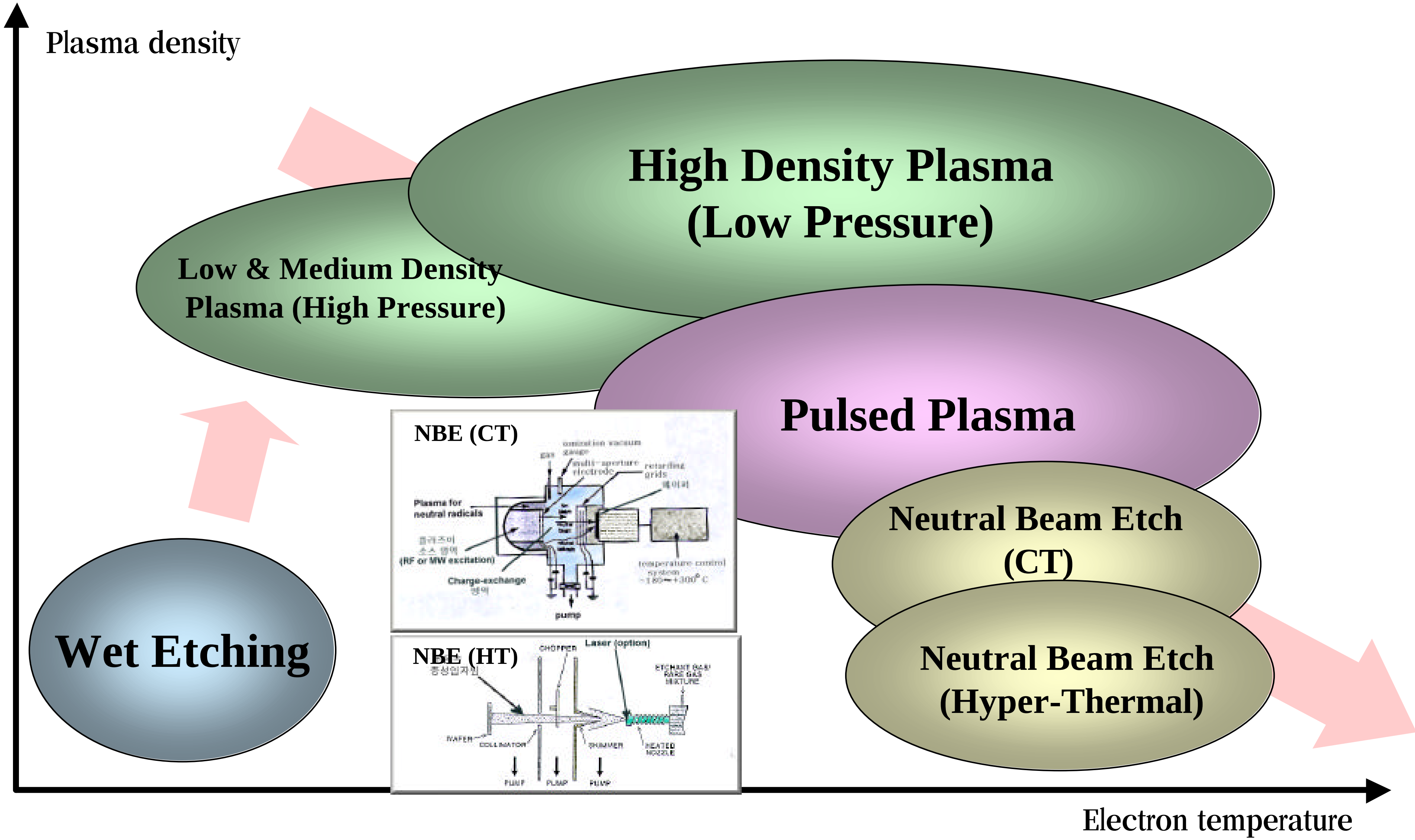
- **By Chamber Construction Type**

  - ICP / TCP / MΦRI / HRe- / DRM, etc

Trend of Etch Equipment

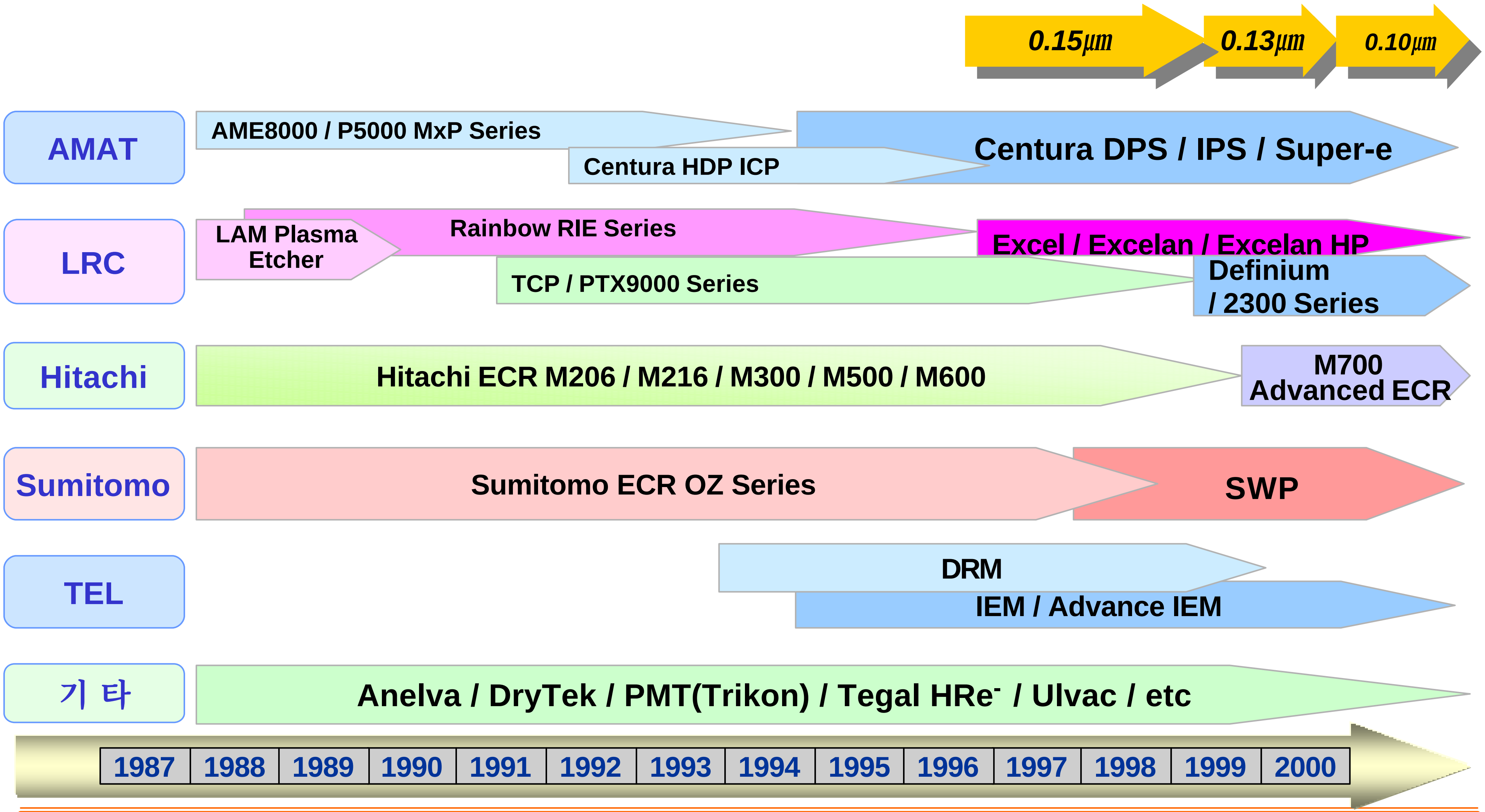


Trend of Etching Tools Development



참고

Dry Etch System의 최근 동향



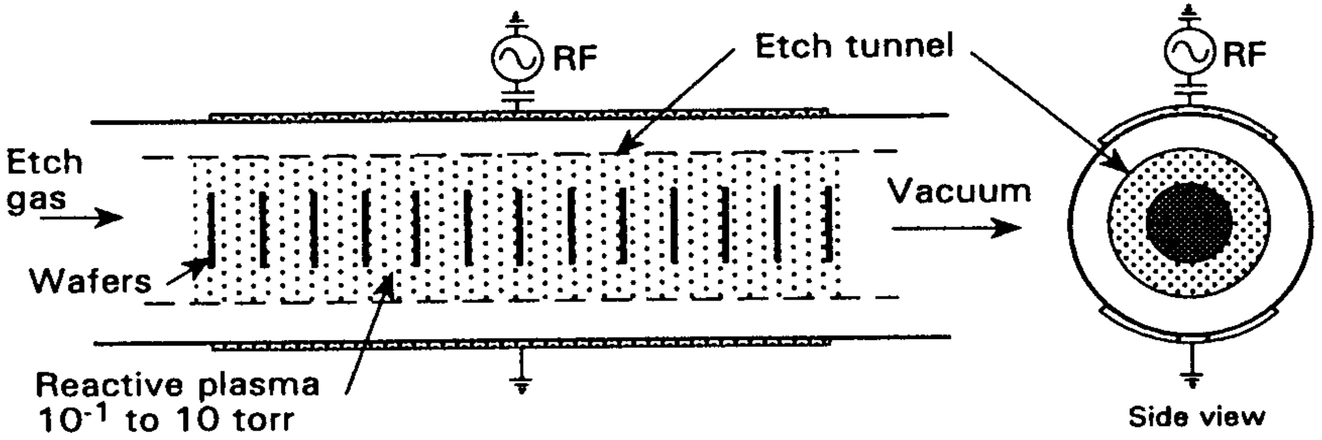
Plasma Reactors

Barrel Etcher

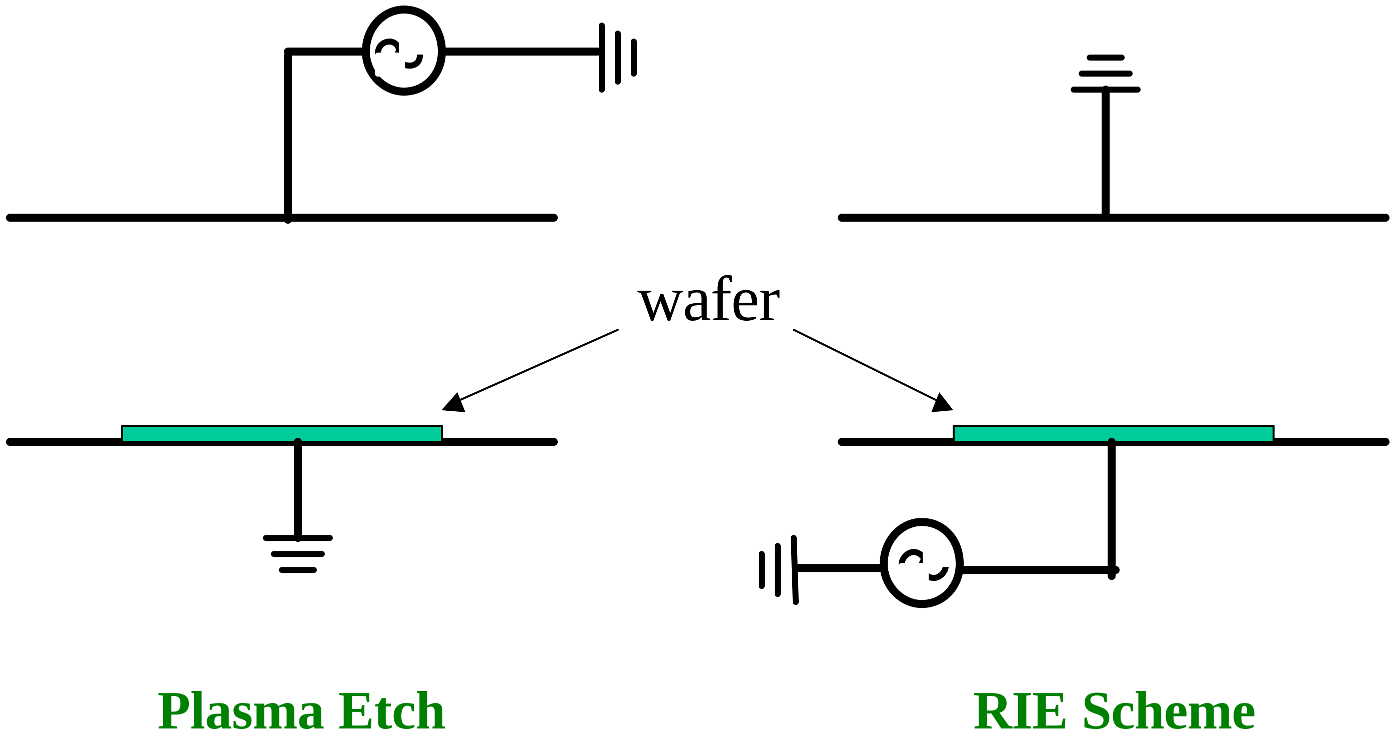
- *Isotropic Etching*
- *Batch Wafer Type*
- *Dielectric Vessel (Quartz, Floating)*
- *PR Ashing*

- *High Throughput*
- *Inexpensive*
- *Low Electrical Damage (Etch Tunnel - Cyl. Mesh)*

- *No Temp Control*
- *Non Uniformity*
- *Undercutting*



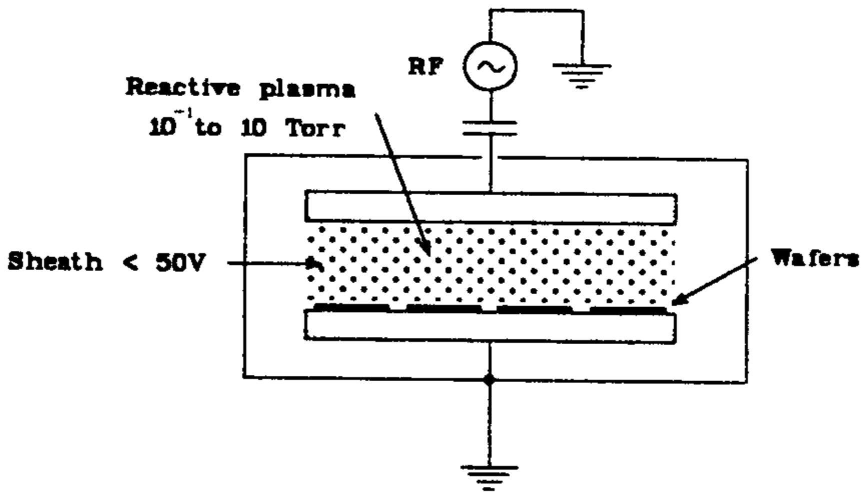
Plasma Etch & RIE



Plasma Reactors

Plasma Etcher

- *Plasma Etching Mode in Parallel Plate or Planar Reactor*
- *Wafer placed on the Grounded Electrode*
- *Capacitively Coupled Plasma*

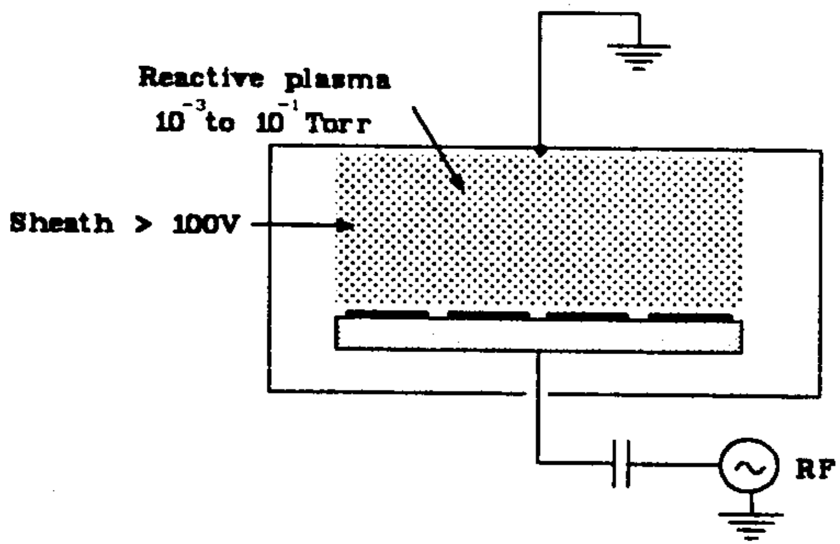


- *Isotropic by Radical*
- *Plasma Potential*
  (Low Ion Energy)
- *High Pressure*
- *Single Wafer Type*
- *Less Electrical Damage*
- *Reinberg Reactor*

Plasma Reactors

RIE Etcher

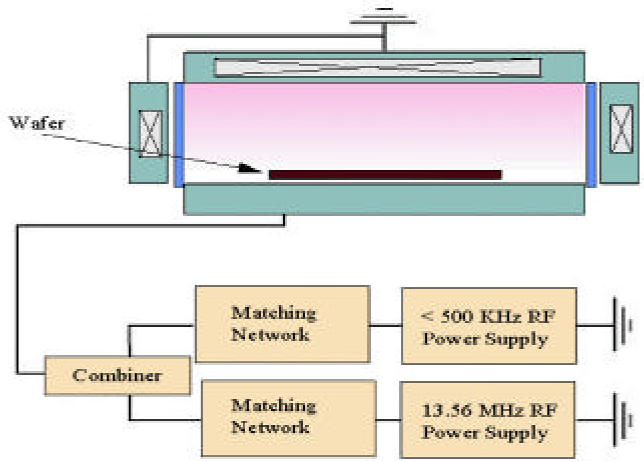
- *Reactive Ion Etching (RIE) = Plasma Etching + Energetic Ion Bombardment*
- *Reactive Ion Etching (RIE) ≡ Reactive Sputter Etching (RSE)*
- *Wafer placed on the RF-driven Electrode*
- *Capacitively Coupled Plasma*



- *Anisotropic by Ion*
- *DC Self-bias (High Ion Energy)*
- *Middle Pressure*
- *Single Wafer Type*
- *Electrical Damage*

Medium Pressure & Medium Density Plasma 1

: Modified RIE, HRe- 6540 (Tegal社)



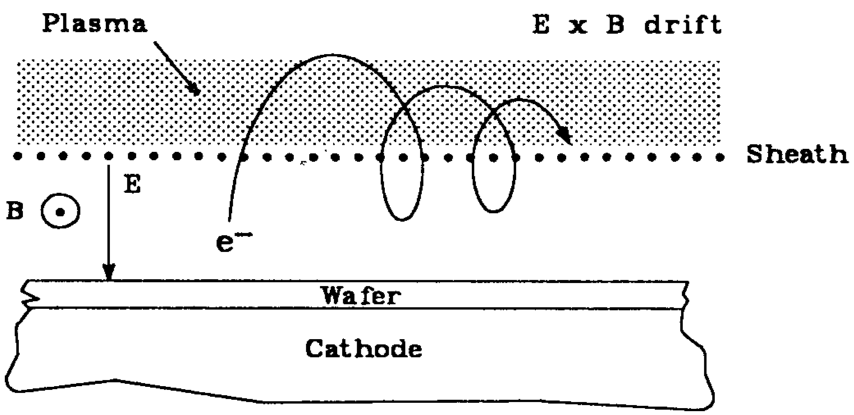
<Characteristics>

- Medium Pressure Control $\geq$ 10mT
- RIE Base Modified
- Confined Plasma by Magnets
  - Medium Density Plasma ~ 10^{11}
- Highly Uniform Plasma Density
- Lower Etch Damage

Plasma Reactors

MERIE Etcher

- *Magnetic field is above and Parallel to the cathode surface*
- *Keep the Secondary Electron by Cycloidal Motion in **ExB** Field*
- *Probability for electron-neutral collisions can be increased*
- *Ionization efficiency in Dark Sheath Region is increased*



- *B field is rotated electrically*
- *Anisotropic by Ion*
- *Low Pressure*
- *Single Wafer Type*
- *Lower Electrical Damage*

Plasma Reactors

MERIE Etcher

- *In the electric field* $\vec{E}$

$$\vec{F}_e = e\vec{E}$$

- *In the magnetic field* $\vec{B}$

$$\vec{F}_m = e\vec{v} \times \vec{B}$$

$$\vec{F}_{m,x} = eB_z v_y = eB_z \frac{dy}{dt}$$

$$\vec{F}_{m,y} = -eB_z v_x = -eB_z \frac{dx}{dt}$$

- *In the* $\vec{E}_y$, $\vec{B}_z$ *field*

$$\frac{d^2x}{dt^2} = A_{m,x} = \frac{eB_z}{M}\frac{dy}{dt}$$

$$\frac{d^2y}{dt^2} = A_{e,y} + A_{m,y} = \frac{eE_y}{M} - \frac{eB_z}{M}\frac{dx}{dt}$$

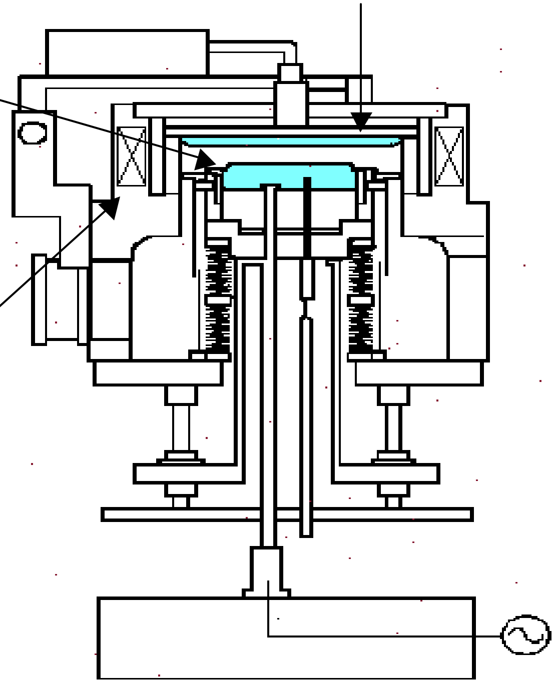
Therfore,

$$\frac{dx}{dt} = \frac{eB_z}{M} y = v_x,$$

$$\frac{dy}{dt} = \frac{eE_y}{M} t - \frac{e^2 B_z^{\ 2}}{2M^2} y^2 = v_y$$

Medium Pressure & Medium Density Plasma 2

: DRM (Tokyo Electron Lab.)



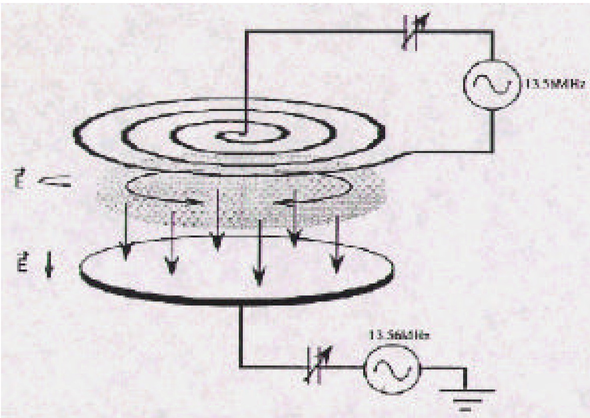
<Characteristics>

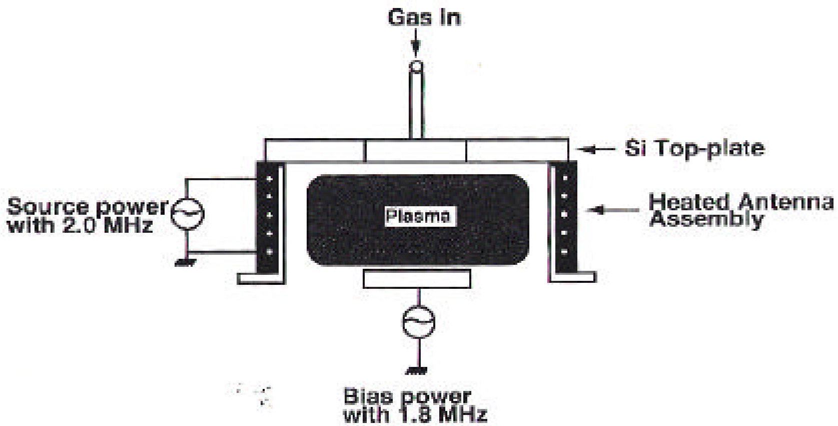
- Medium Pressure Control ≥ 10mT
- RIE Base
- Confined Plasma by Dipole Ring Magnet
  - Medium Density Plasma ~ 10^{11}
- Highly Uniform Plasma Density
- Lower Etch Damage

HDP Plasma Reactors

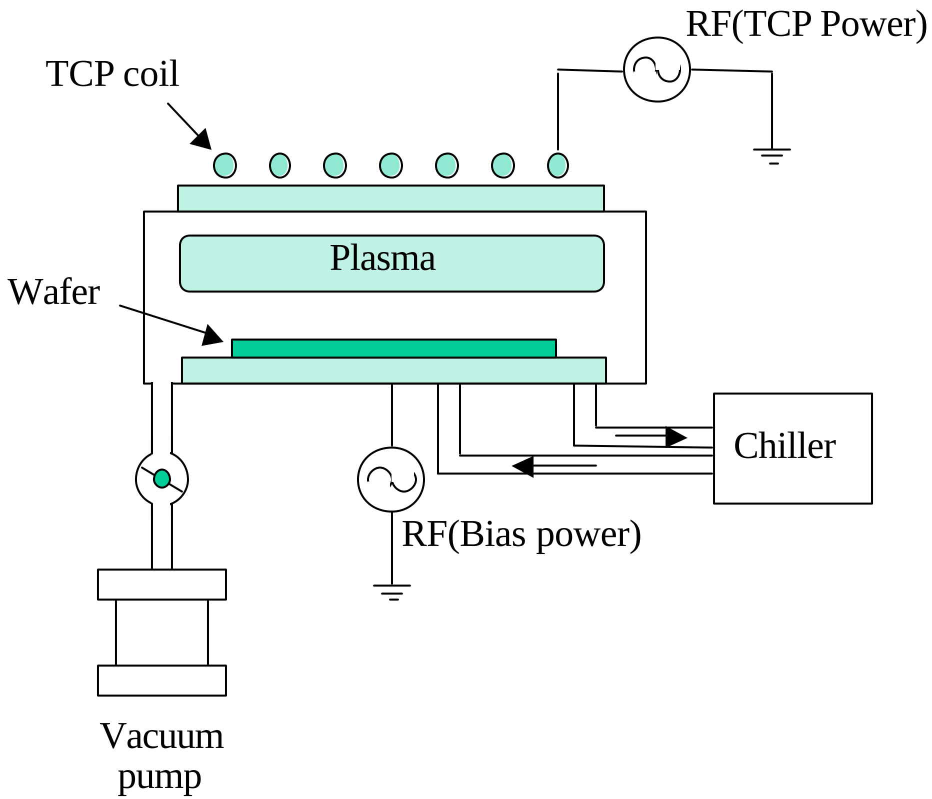
ICP (Inductively Coupled Plasma)

- *Planar, Cylindrical, Dome Type*
- *Capacitively Initiation & Inductively Breakdown (r ¯)*
  Dim mode, Bright mode
- *Lenz Law, Faraday's Induction Law*





ICP (TCP : Lam Research社)

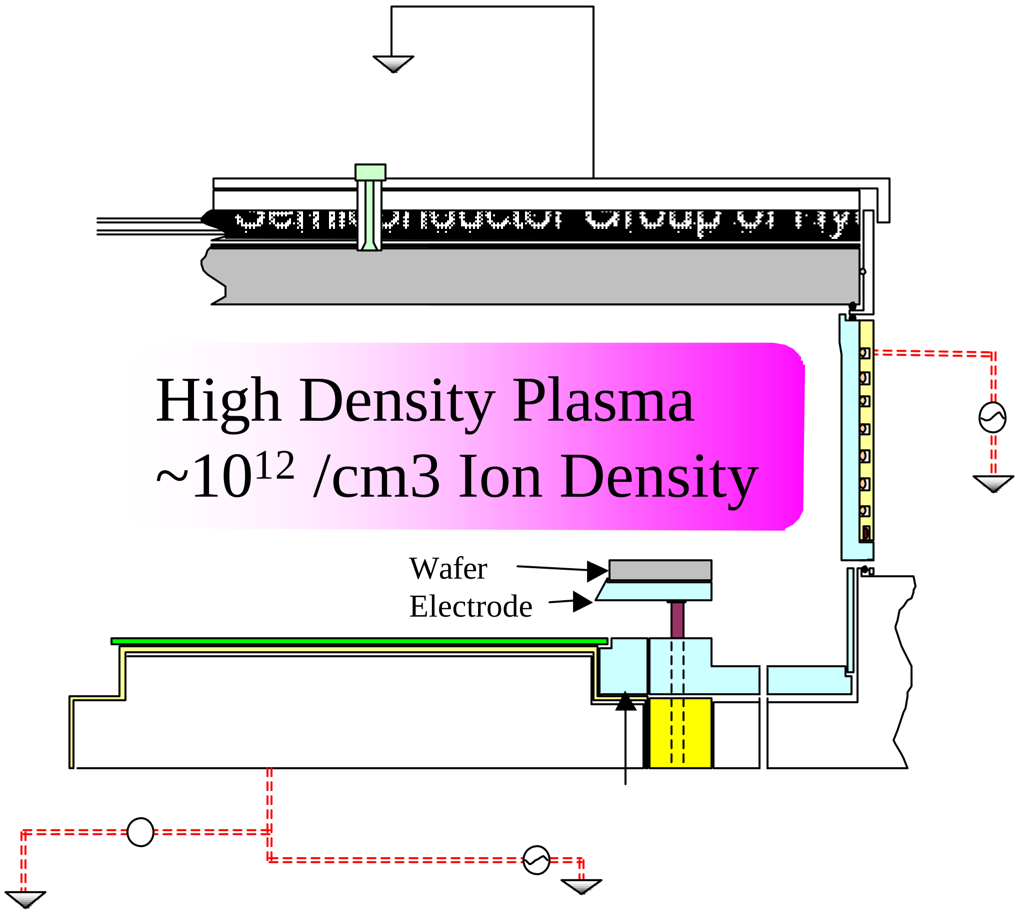


<Characteristics>

- **Low Pressure Control £ 5mT**
- **Independent Power Control**
  - **Plasma Source = TCP power**
  - **High Density Plasma ~ 10^{12}**
  - **Ion DC Bias = Bias Power**
- **Low Temperature Etching**
  : -50°C ~ +50°C
- **Improved Plasma Uniformity**

참고

ICP (HDP ICP : Applied Materials社)

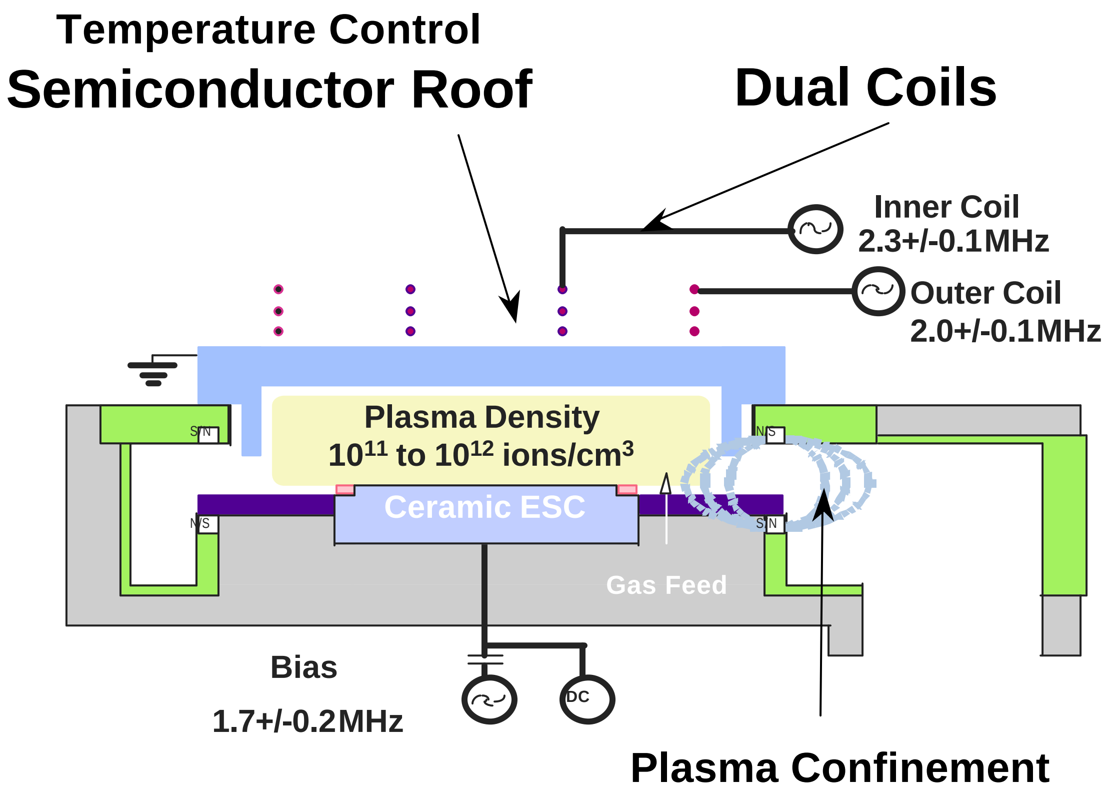


<Characteristics>

- **Low Pressure Control £ 5mT**
- **Power Transfer by ICP Coil**
  - **High Density Plasma ~ 10^{12}**
  - **Ion DC Bias = Bias Power**
- **Polymer Control by Roof-Si**
- **Improved Plasma Uniformity**

IPS (Applied Materials社)

: Inductively-Coupled Parallel Plate Semiconducting Chamber



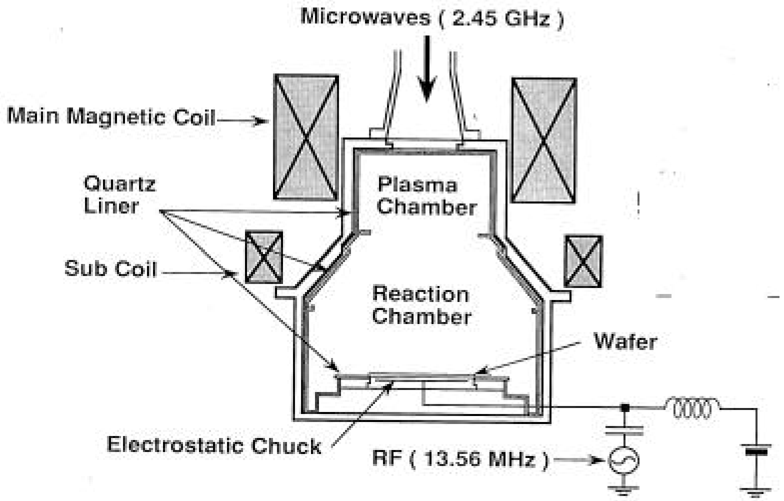
<Characteristics>

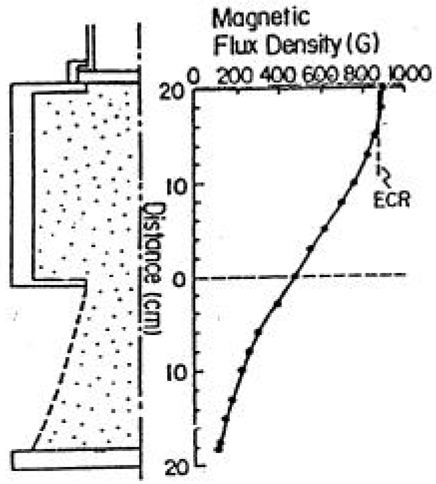
- Low Pressure Control
- Power Transfer by Dual Coil
  - High Density Plasma ~ 10^{12}
- Polymer & Temp. Control by Roof-Si
- Improved Plasma Uniformity w.r.t. HDP ICP for 12 inch

HDP Plasma Reactors

ECR (Electron Cyclotron Resonance)

Cyclotron Resonance = Maximum Electron Energy
Angular Frequency in B field (875G) =
Microwave Frequency (2.45GHz)

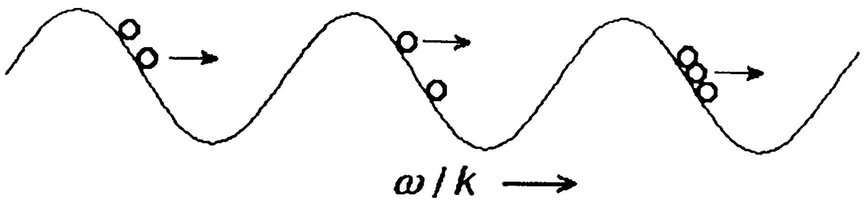


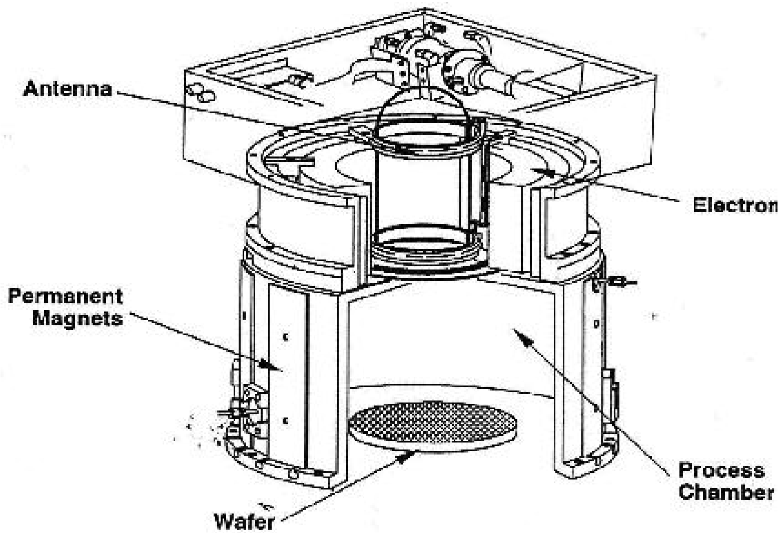


HDP Plasma Reactors

Helicon (M0RI)

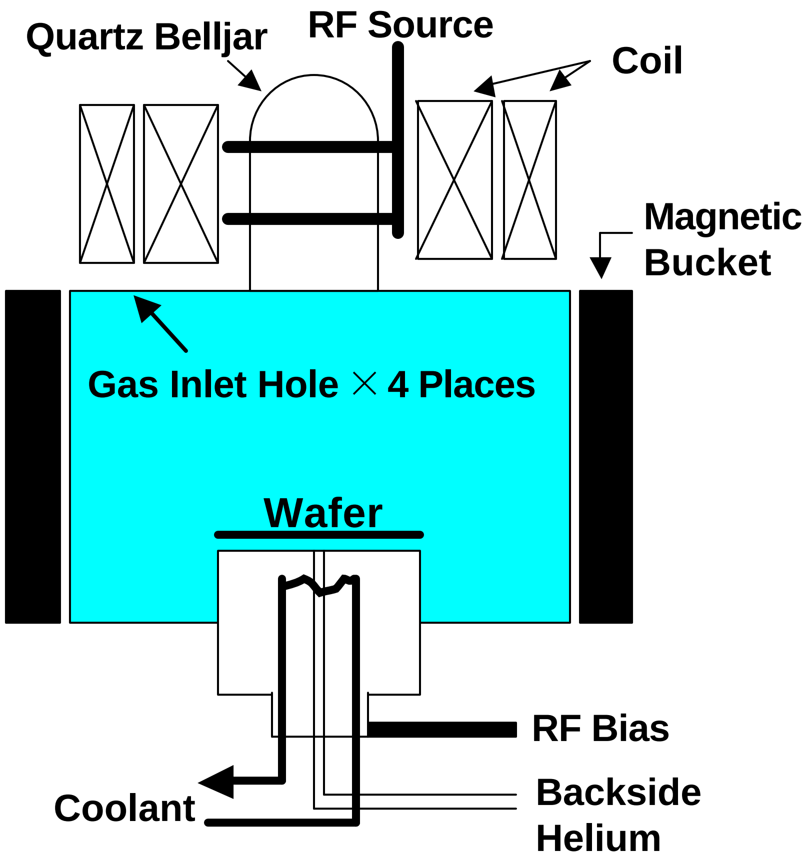
- *Helicon Wave : Power Transfer >1000 than Collision Process*
- *Landau Damping : Collisionless Mechanism*





참고

MΦRI Helicon (Trikon社)



<Characteristics>

- Low Pressure Control £ 3mT
- Independent Power Control
  - Plasma Source = MΦRI Coil
  - High Density Plasma ~ $10^{12\sim13}$
- Low Temperature Etching
  : -50°C ~ +50°C
- Highly Uniform Plasma Density
- Lower Etch Damage

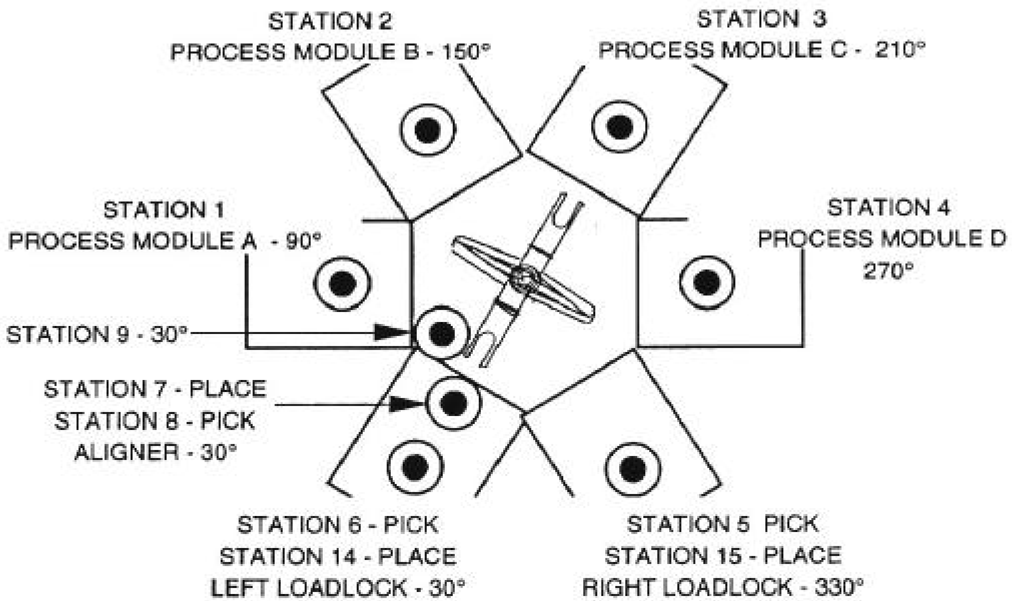
참고

Trends of HDP Reactors

- *Low Temperature Process : Low Activity of Radical*
  Anisotropic, Less Polymer Clean Process
- *Low Pressure Process : Long Mean Free Path, Fine Patterning*

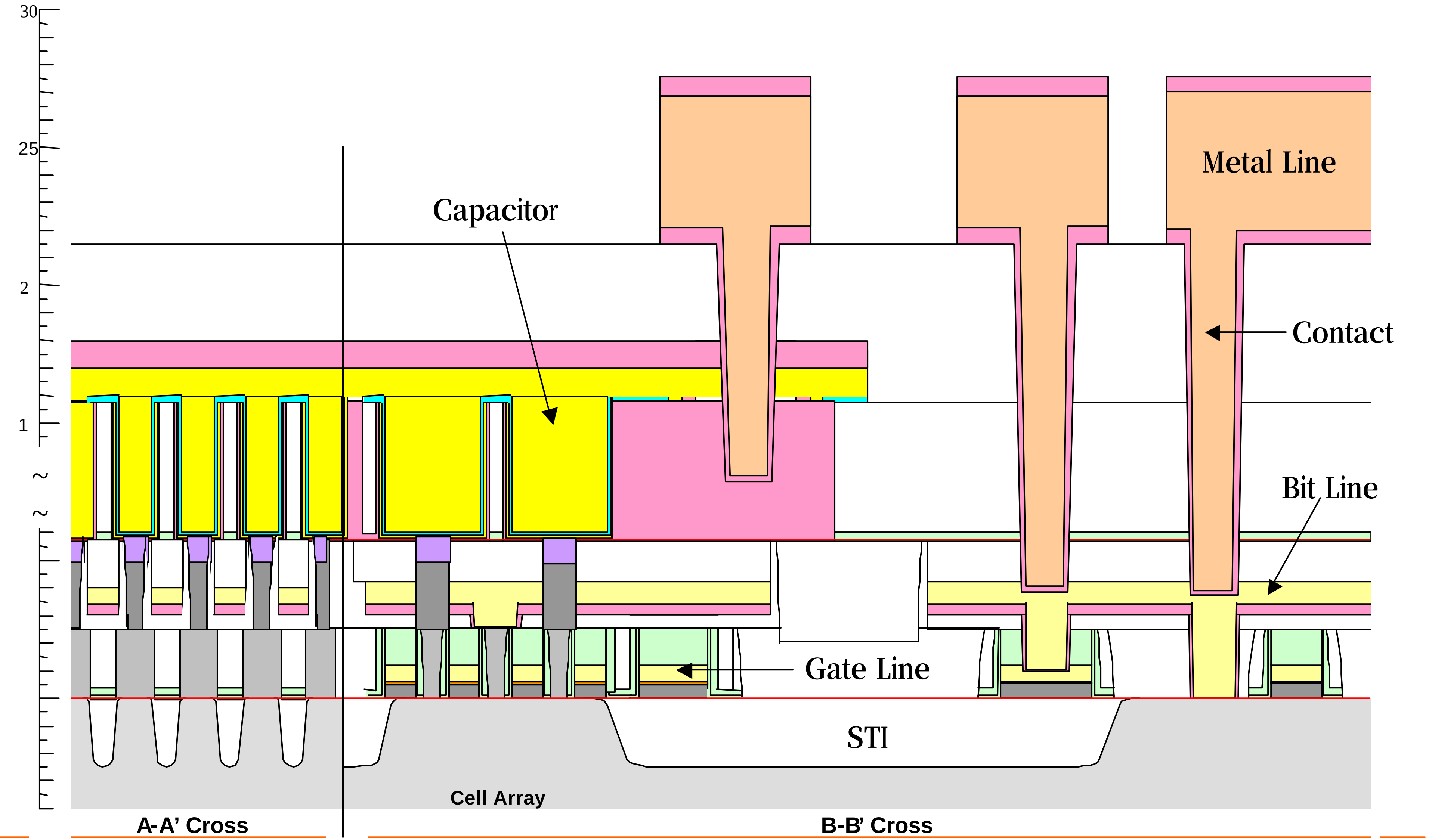
- *In-situ Process*
  : Single Wafer
  : Multi-chamber

- *High Density Plasma*
  : High Etch Rate

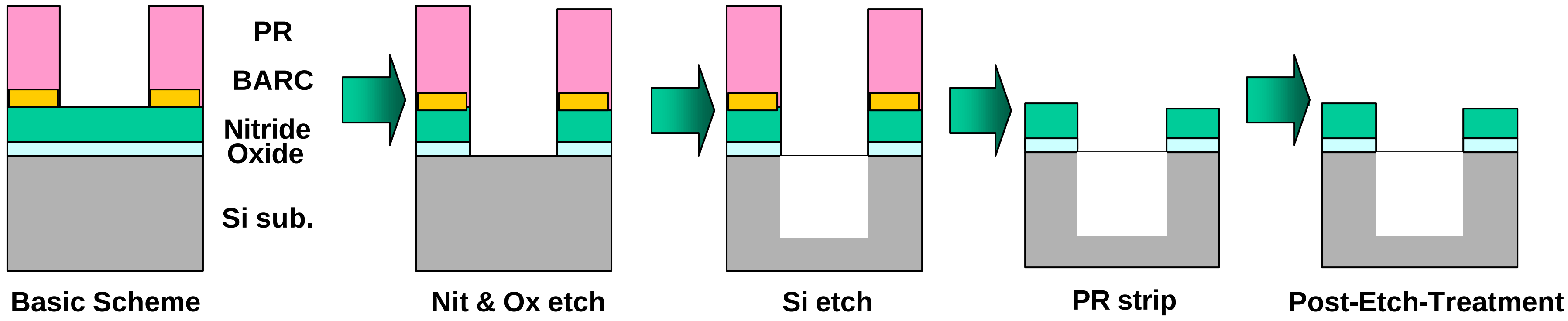


- Introduction into Etch Processes
- Inside the Plasmas
- Plasma Etch Equipment
- ***Examples (DRAM Etch Process)***

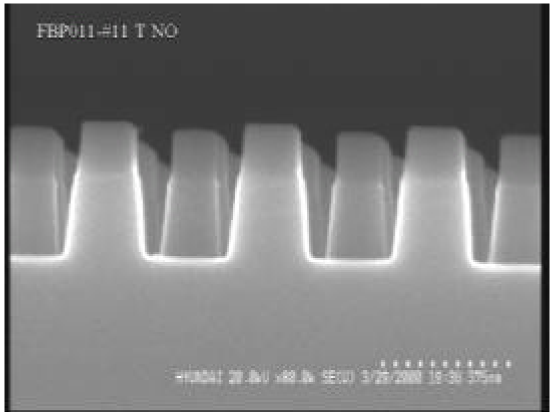
General DRAM Structure



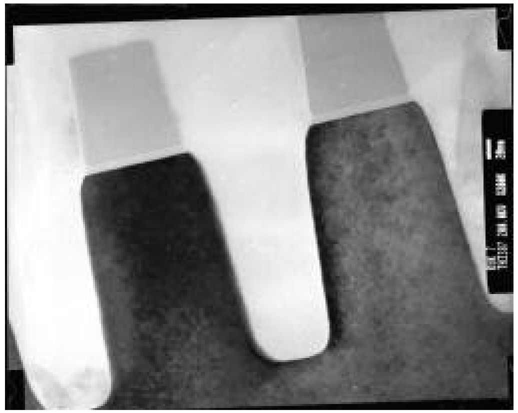
Introduction to STI Etch Process



SEM 단면 profile

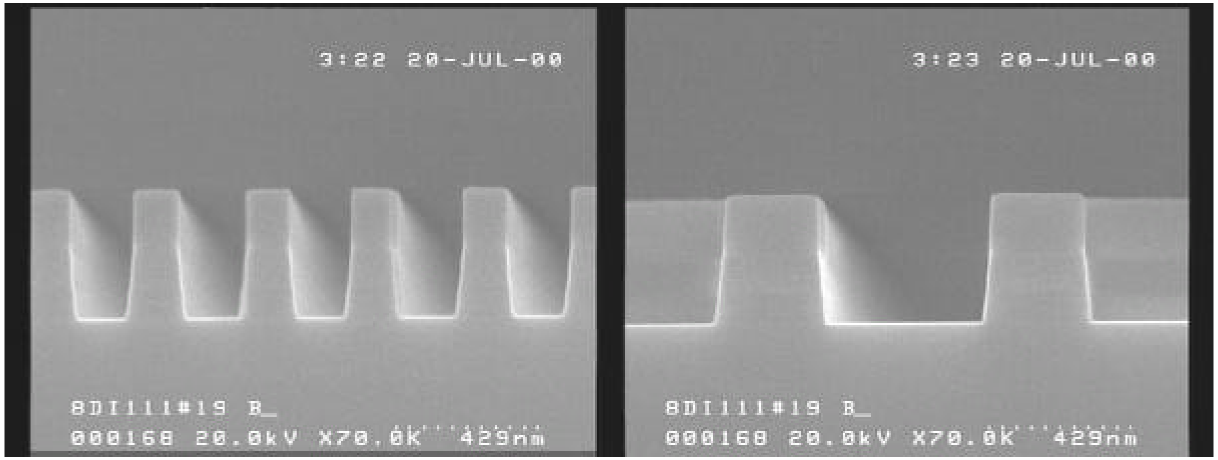


TEM 단면 profile

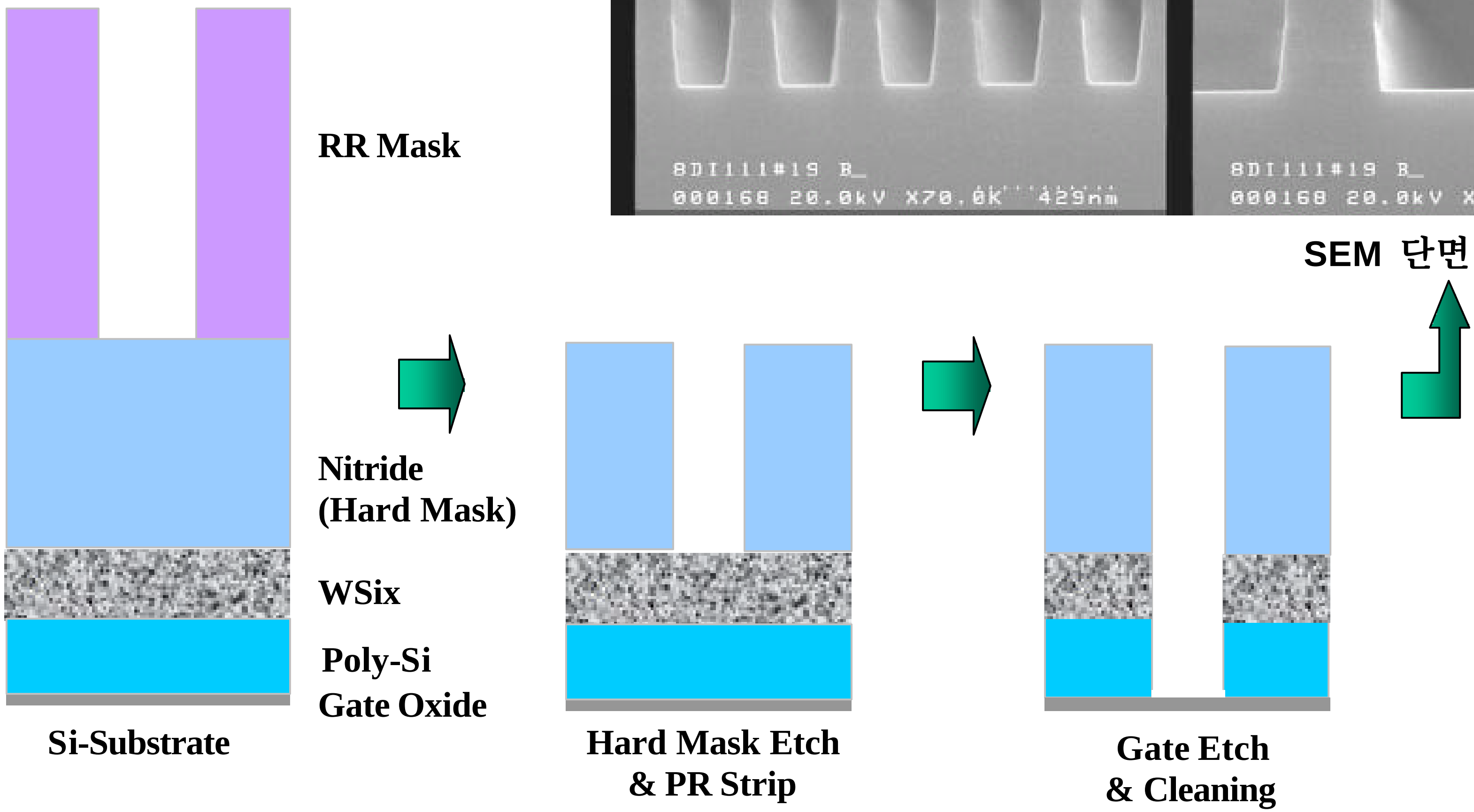


Etch Process 기초

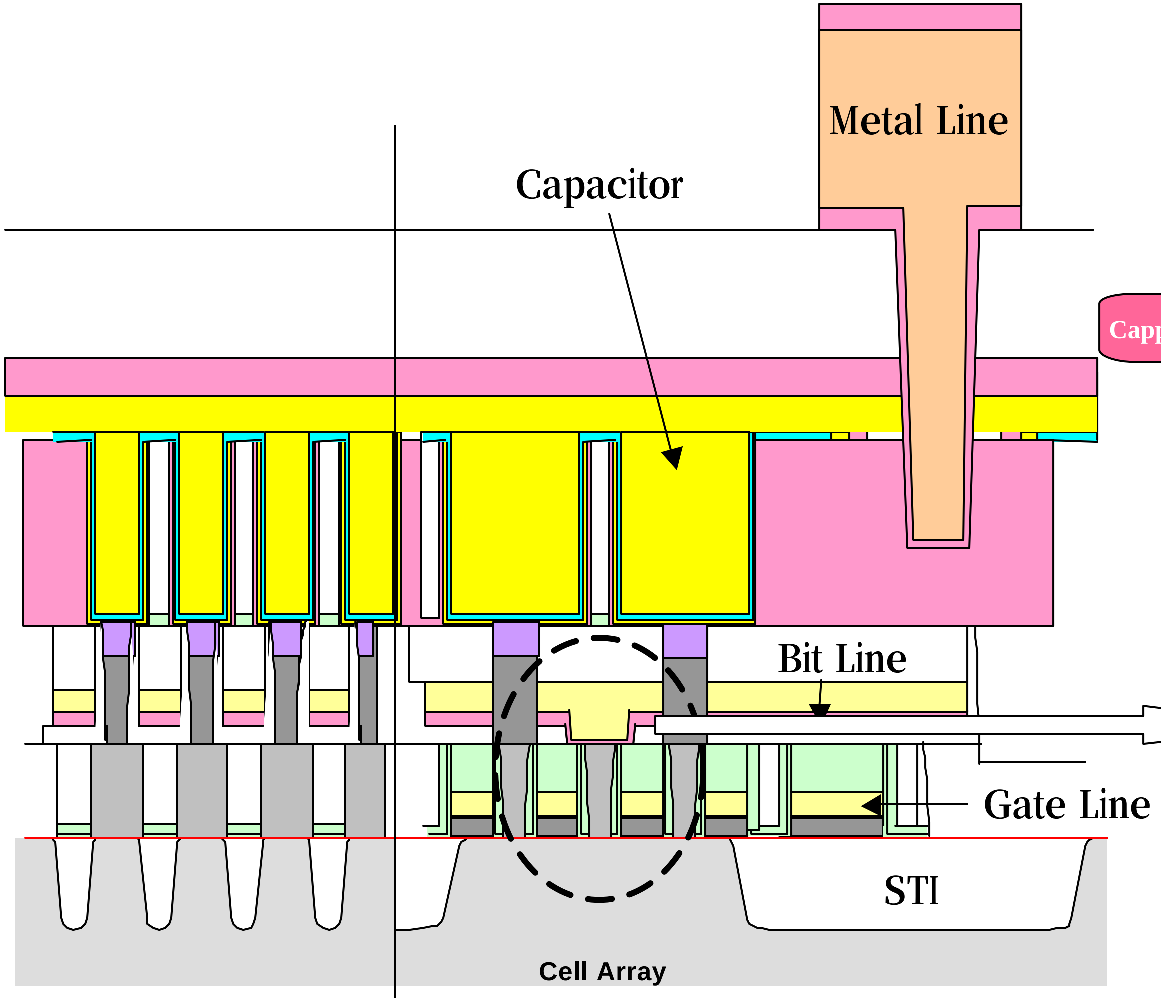
Introduction to WSix/Poly-Si Gate Etch Process

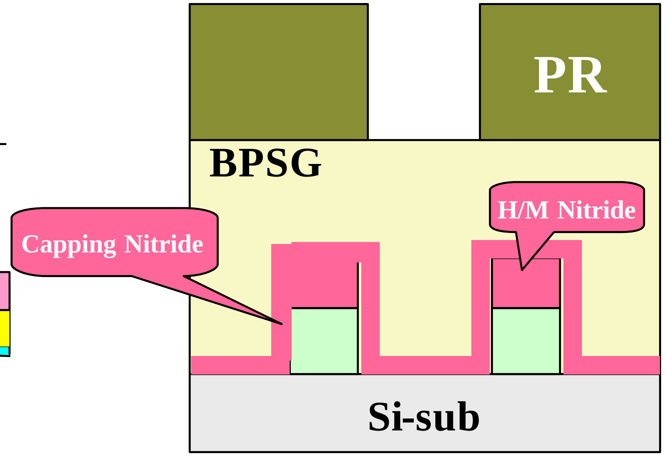


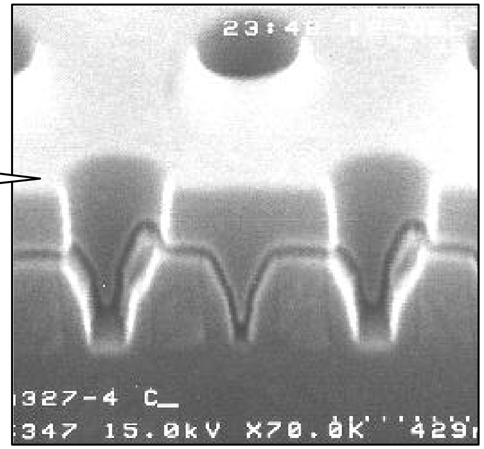
SEM 단면 profile



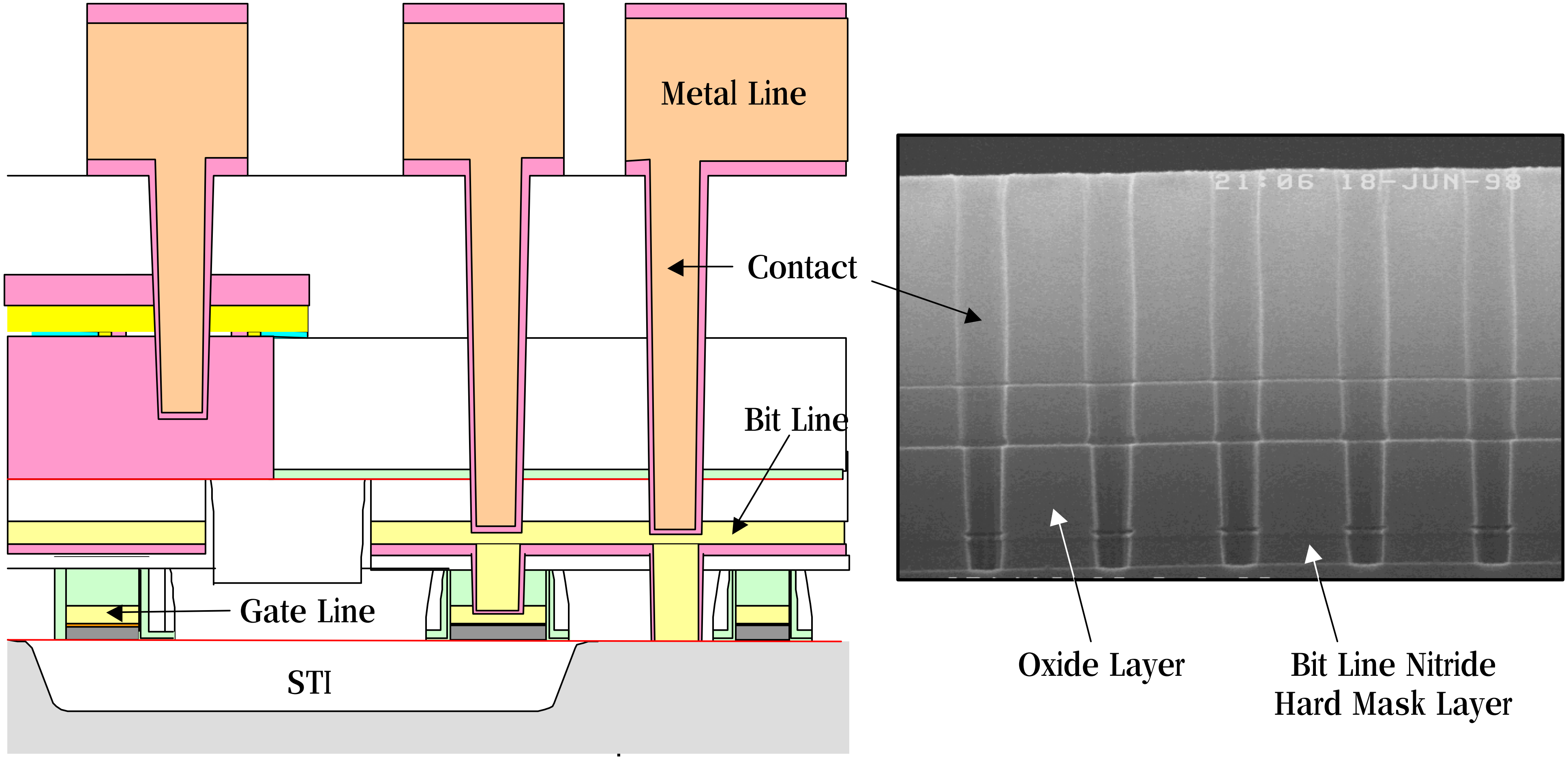
Introduction to SAC(Self-Align-Contact) Etch







Introduction to Contact Etch Process



Introduction to Al Metal Etch Process