PVD & Plasma Etching

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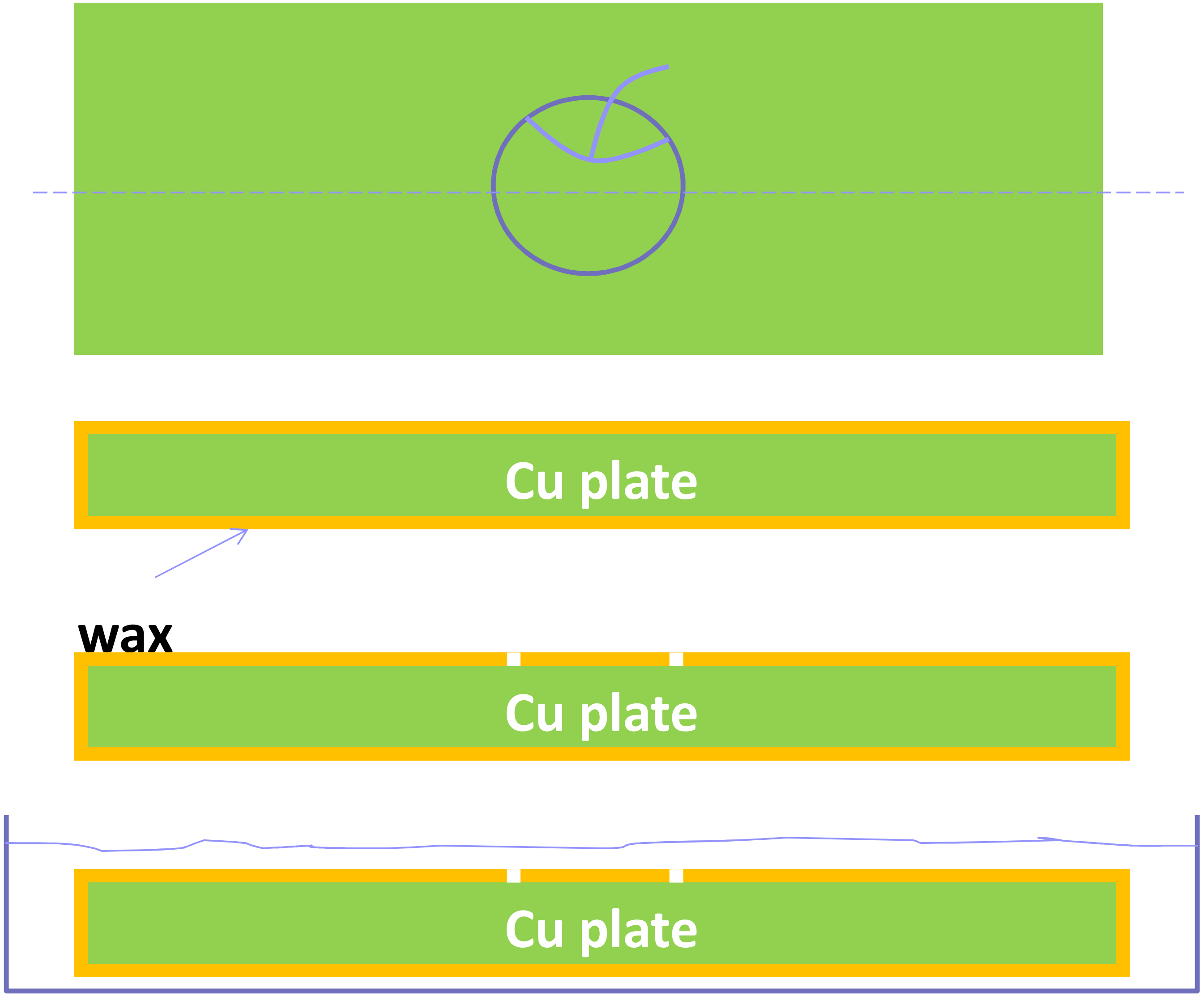
진공기술현장교육: 삼성SDI

강의 순서

- Semiconductor Processing & Etching
- Plasma Fundamentals
- PVD: Plasma Sputtering
- PVD: Evaporation
- Plasma Etching: Chemistry and Surface Reactions
- Plasma Etcher
- Plasma Diagnostics
- Summary
- 참고자료: Issues of Plasma Etching

Semiconductor Processing & Etching

Etching (동판화)



Etching

- 에칭:
  - 먼저 동판화에서 쓰이는 금속판 위에 밀랍을 주성분으로 한 그라운드를 바른 후 에칭니들이나 그 밖의 날카로운 도구로 그라운드 위를 긁으면 긁힌 부분은 그라운드가 벗겨져 판이 노출된다. 이 판을 산 속에 일정 시간 부식시키면 긁힌 부분, 즉 선을 그린 부분만 부식 정도에 따라 움푹 들어가게 되고 이곳에 잉크가 괴며 찍힌다.
- 산과 금속 부식제
  - 질산과 철, 과염화물이 가장 많이 사용된다. 동, 아연, 철에 질산 사용한 금속을 사용한 것에 다른 금속을 사용하면 좋지 않다. 사용전에 물과 희석하여 원하는대로 섞는다.(산:물=1:3) 질산은 매우 빨리 작용하고 에칭라인의 가장자리는 매우 가볍게 침식된다. 철, 과염화물은 특히 동에 적합하다. 천천히 작용하지만 에칭 라인에 해 없이 깊이 작용한다.
  - 이것은 희석하지 않고 46℃ B나 물과 희석해서 사용한다. 30℃ B를 올리면 작용이 빨라지고 희석하지 않은 산은 위험하다. 마스크, 장갑 착용등이 꼭 요구되며 적당히 환기도 해야한다. 처음 만든 질산과 철, 과염화물은 이미 사용된 것 5%를 첨가해서 사용하기 전에 오래 나눠야한다.

출처:네이버 백과사전

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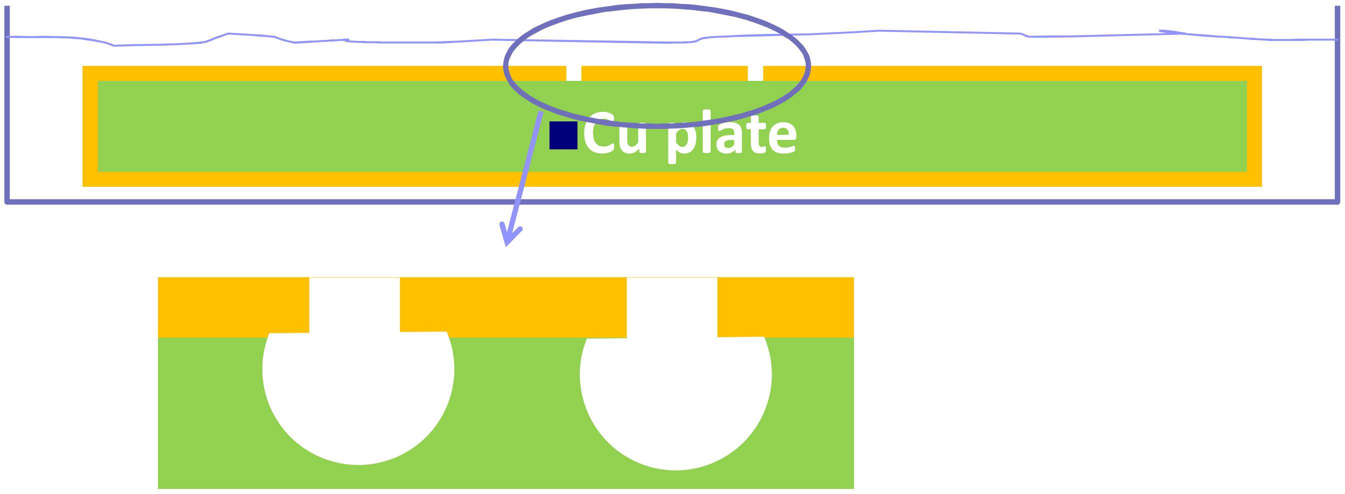
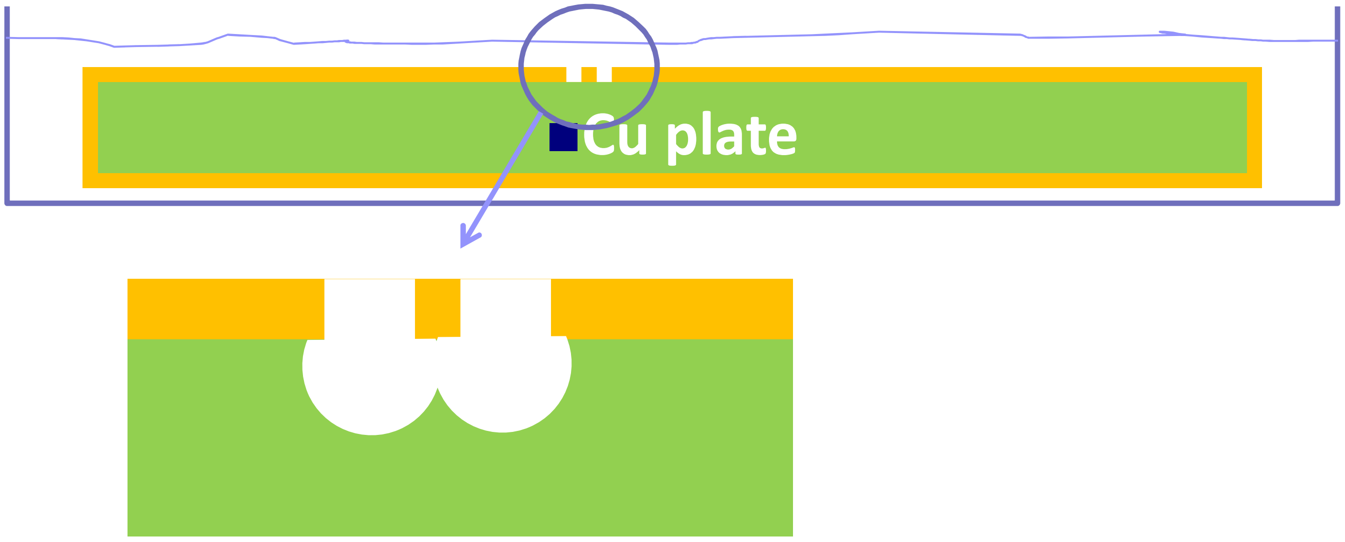
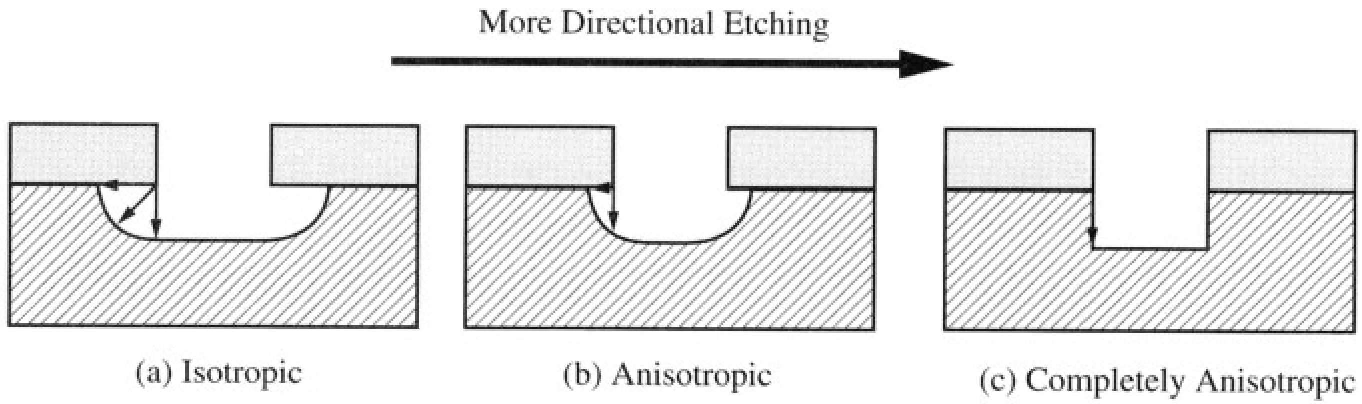




Isotropic vs. Anisotropic Etching



- Wet Etching
- Chemical Etching

- Dry Etching
- Plasma Etching
- Physical Etching
- Physical/Chemical Etching

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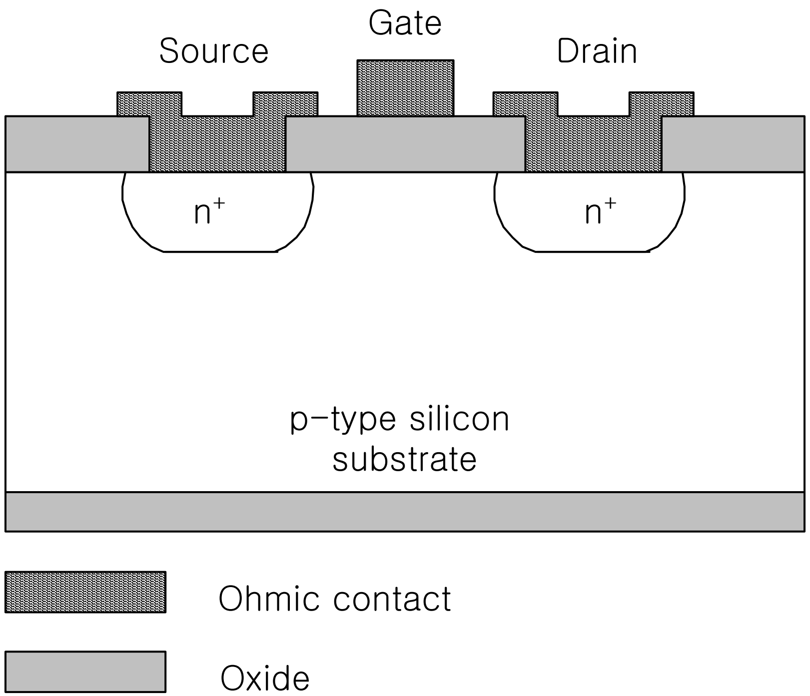
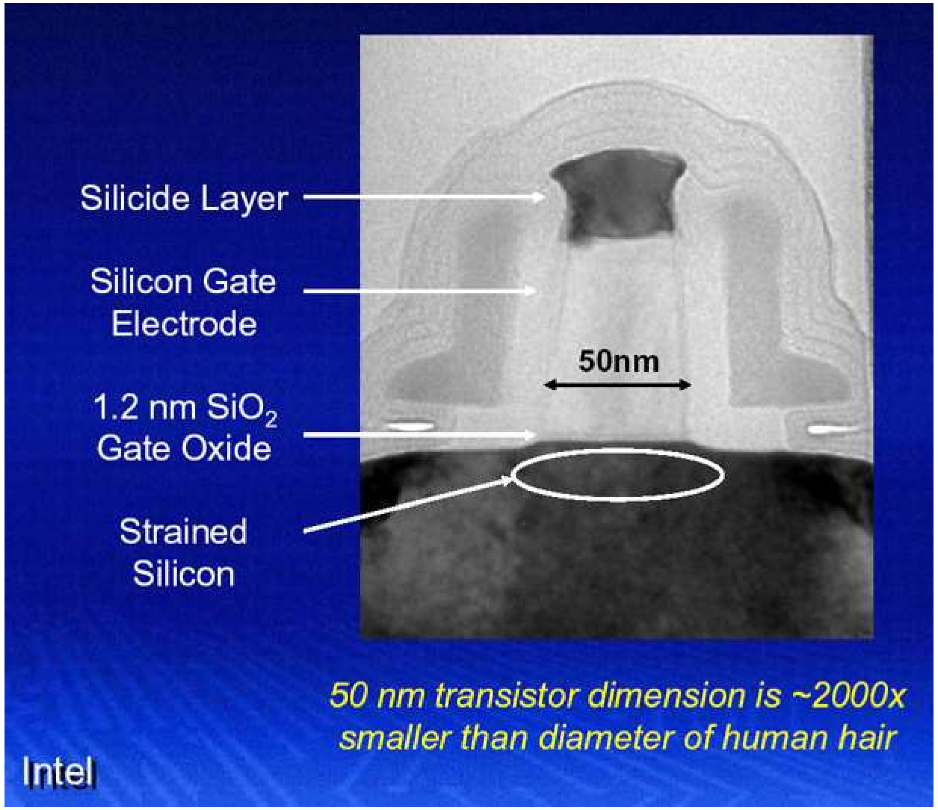
Transistor

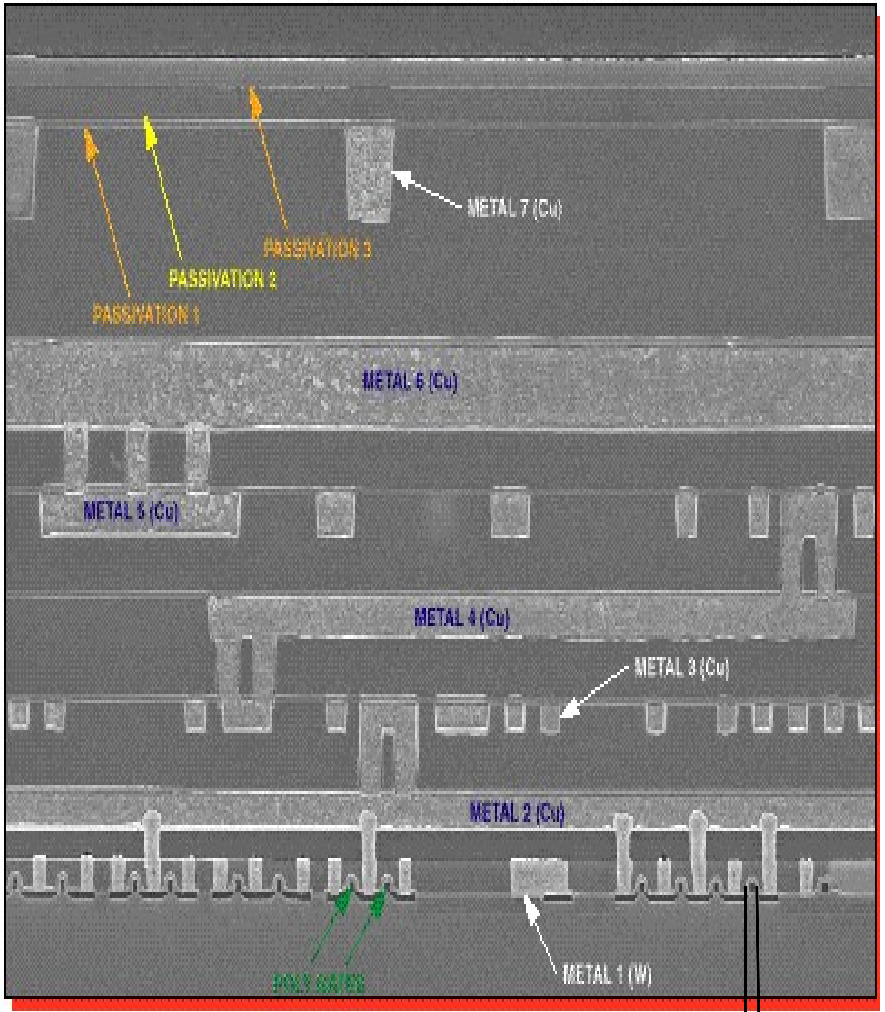
- MOSFET (metal-oxide-semiconductor field effect transistor)





Plasma Applications to Nano-Chip Processing

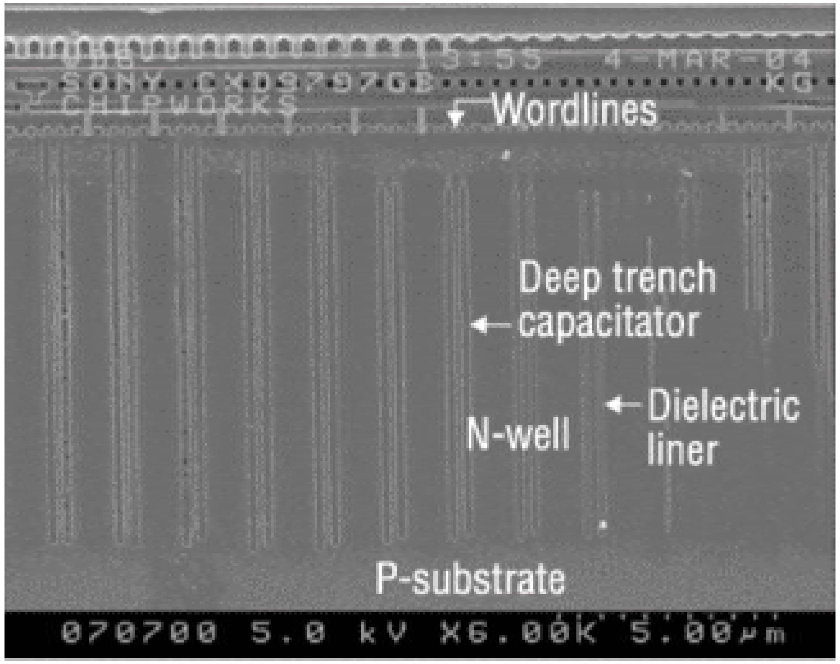
- About 40% of semiconductor process steps are plasma related

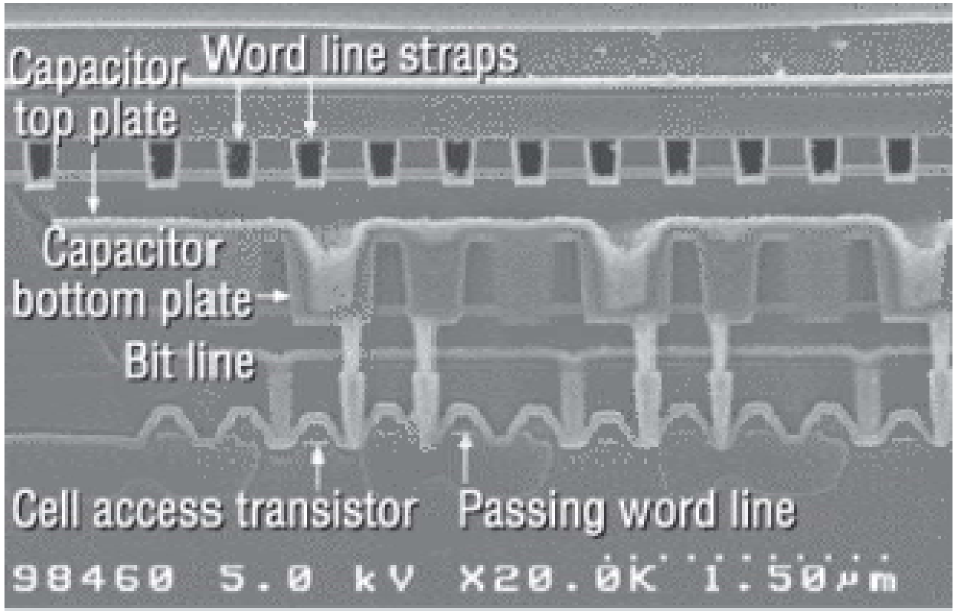


System IC

< 100nm @ 2008

DRAM Cross-section





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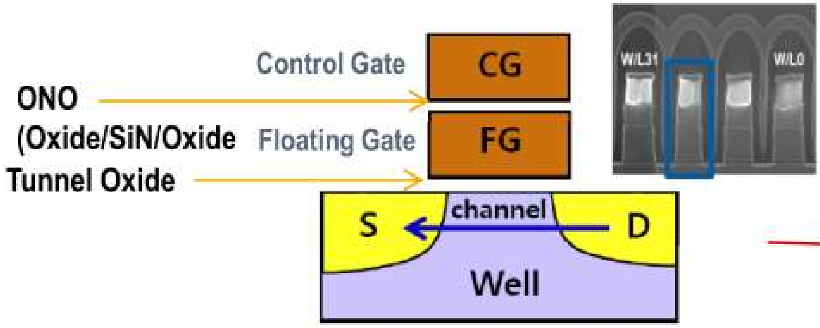
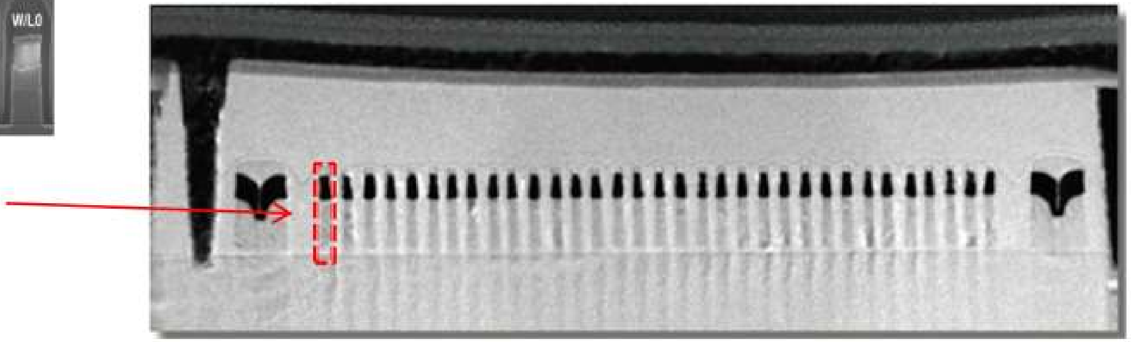
3D NAND cells require high aspect ratio plasma etching

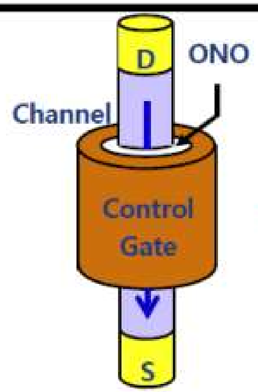
2D cell



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

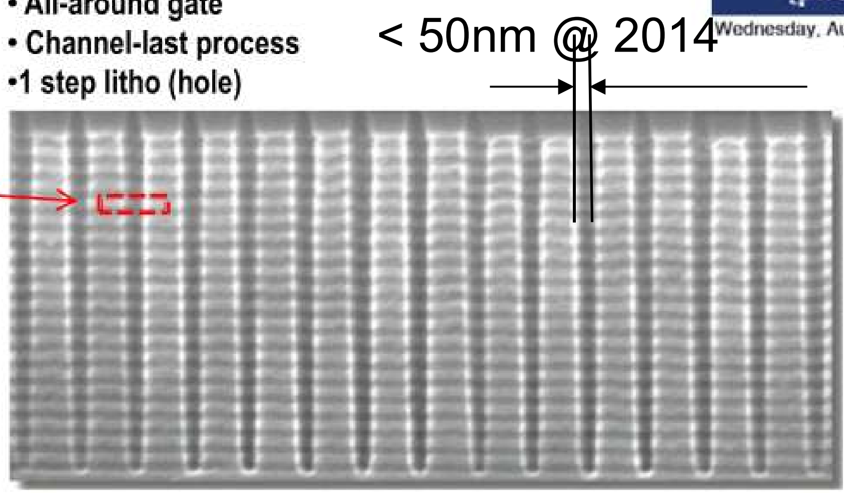


3D cell (Vertical String)



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)



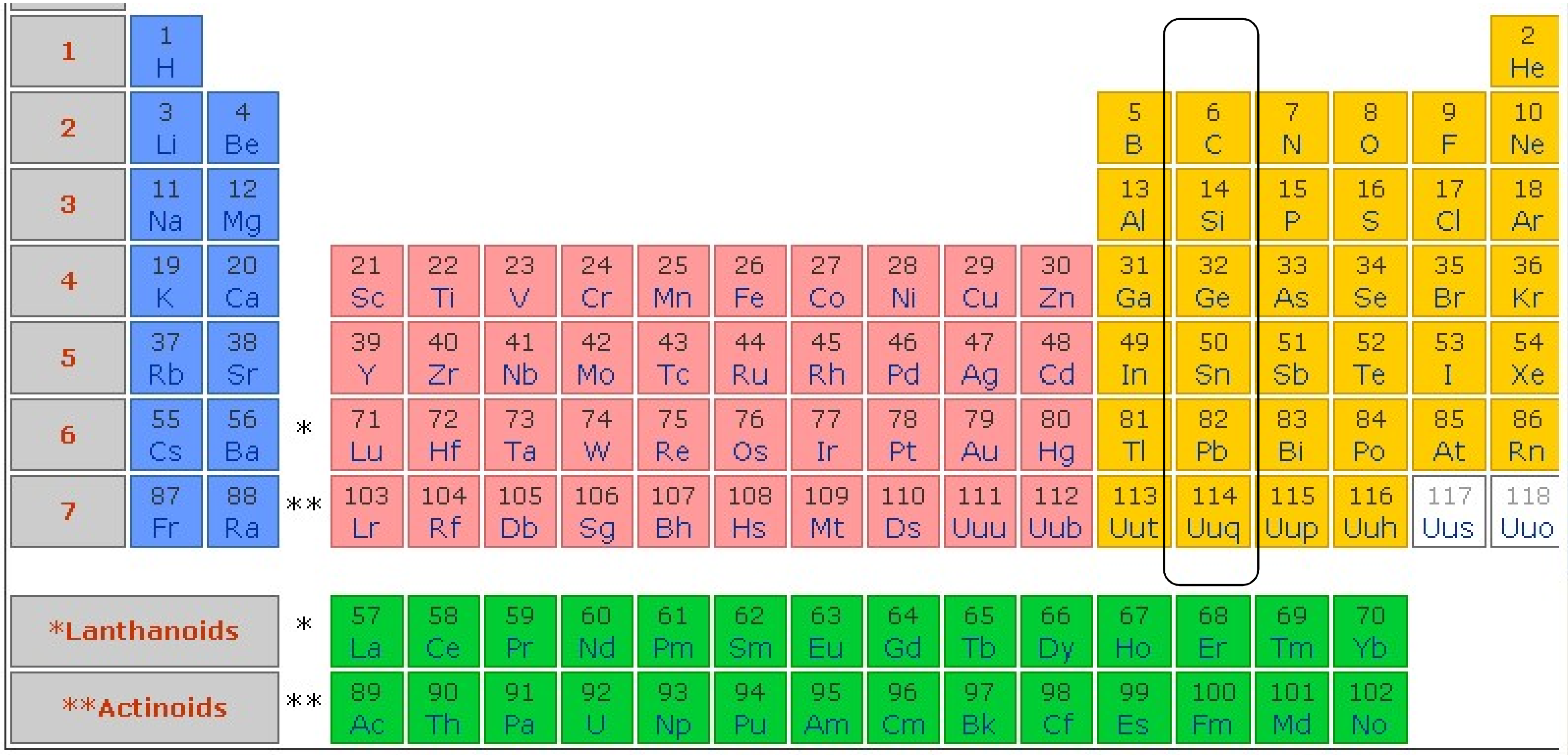
http://gigglehd.com/zbxe/613729(

Micron
Wednesday, August 10, 2011

Materials in Semiconductor Processing

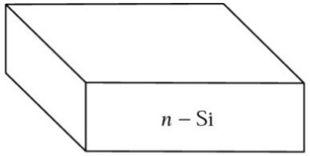
	Traditional Materials	New Materials
Semiconductor	Si, Ga-As, In-P	Si-Ge
Dielectric	Thermal SiO_2 for gate PECVD SiO_2, Si_3N_4	High-k for gate oxide Carbon doped oxide Organic low-k
Metal	Al, W	Cu, TiN, TaN
Organic	G-line photoresist I-line photoresist 248nm photoresist	193nm photoresist Si-containing photoresist

Periodic Table

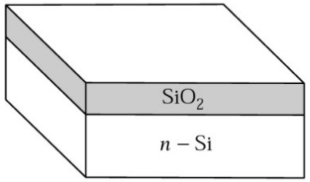


Element	IV-IV	III-V	II-VI	IV-VI
Si Ge	SiC SiGe	GaAs, GaP InAs, InP InSb	GdS, CdSe CdTe, ZnS ZnSe, ZnTe	PdS PbTe

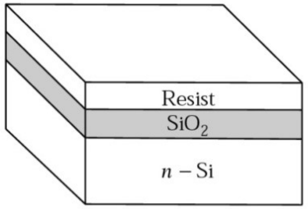
Process Overview



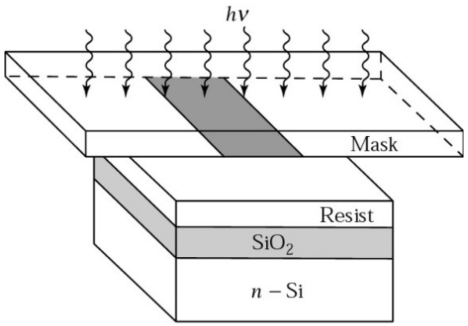
(a)

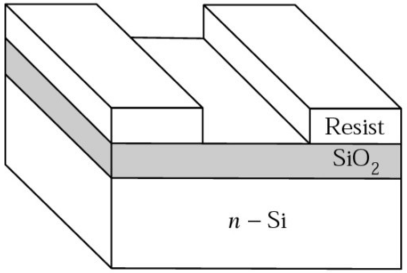


(b)



(c)





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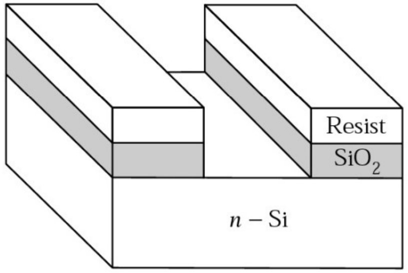

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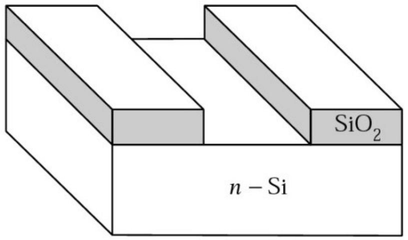

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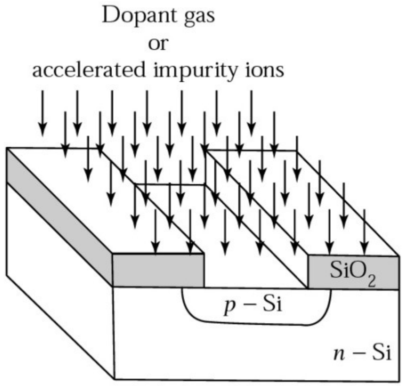
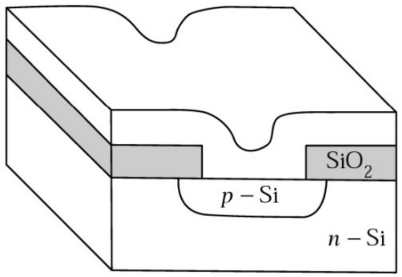
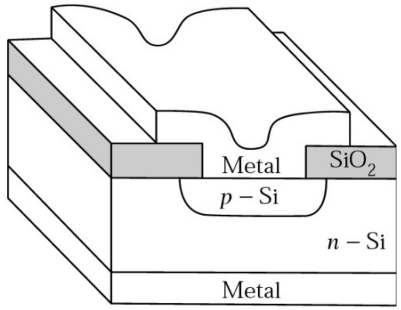


(d)

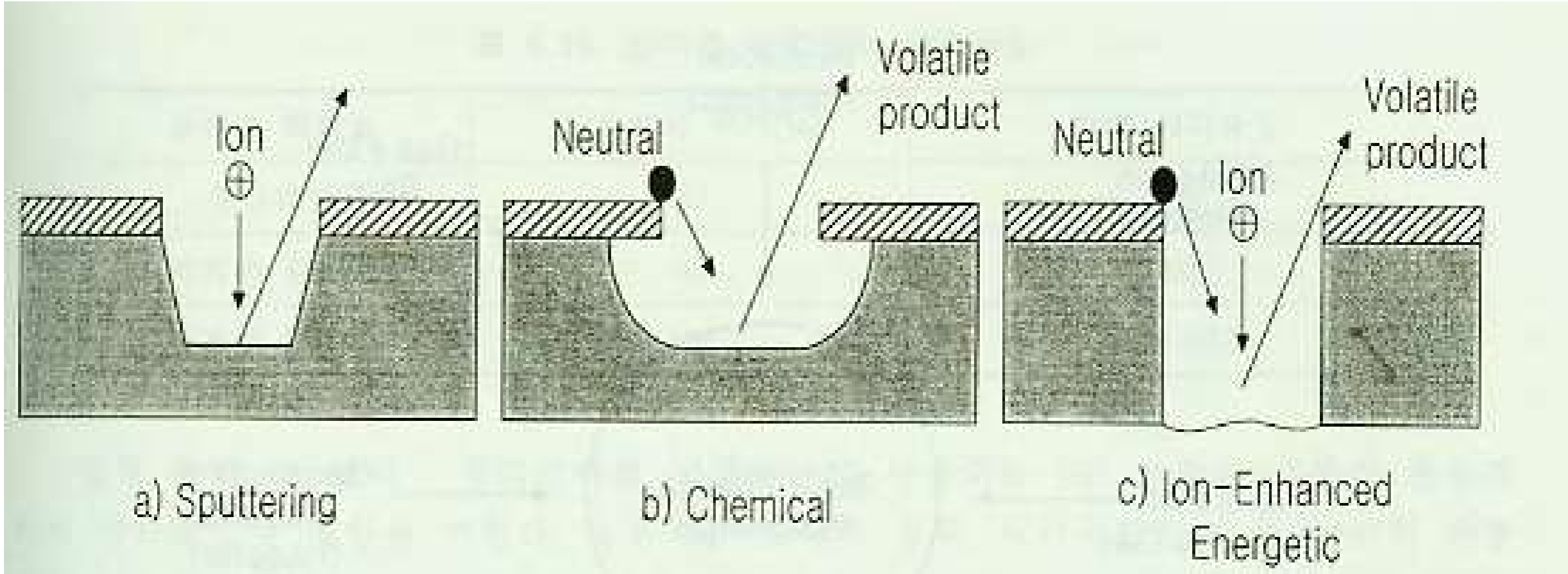


(e)



Dry (Plasma) Etching Types

Physical Process | Chemical Process | Physical + Chemical Process



Physical Process (a) Sputtering)

- anisotropic
- low selectivity
- low etch rate

Chemical Process (b) Chemical)

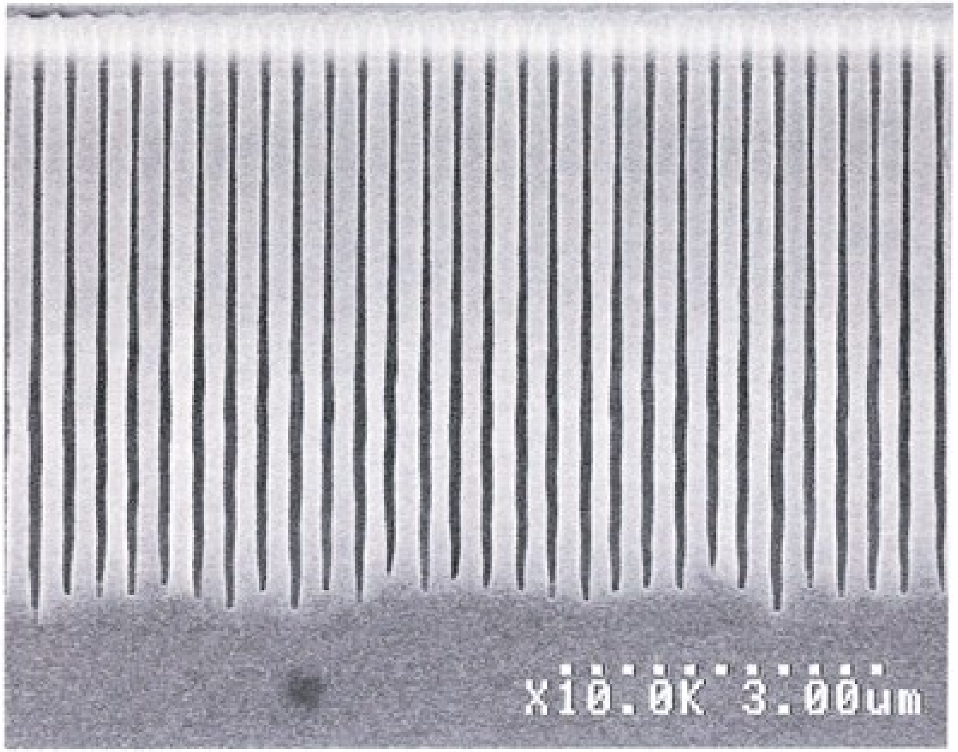
- isotropic
- high selectivity
- low etch rate

Physical + Chemical Process (c) Ion-Enhanced Energetic)

- anisotropic
- high selectivity
- high etch rate

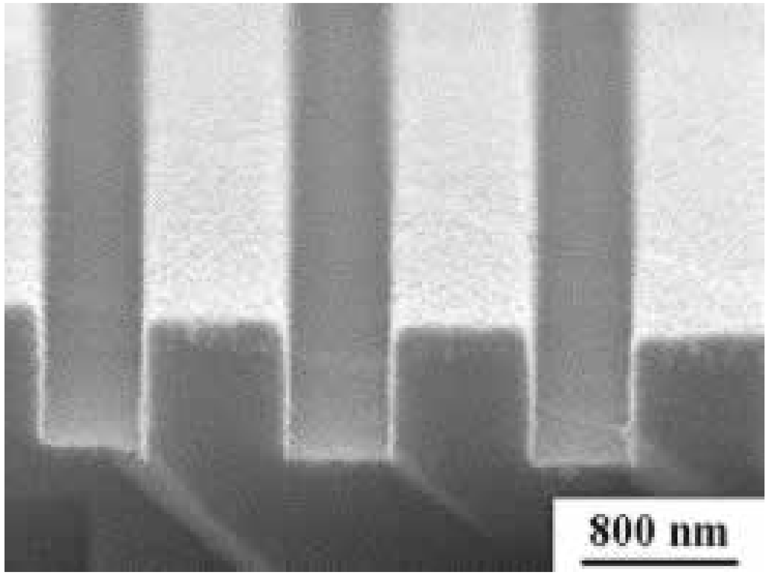
Plasma Etching

High Aspect Ratio Si Etching



■http://www.future-fab.com/assets/images/FFI11E1123F8b.htm

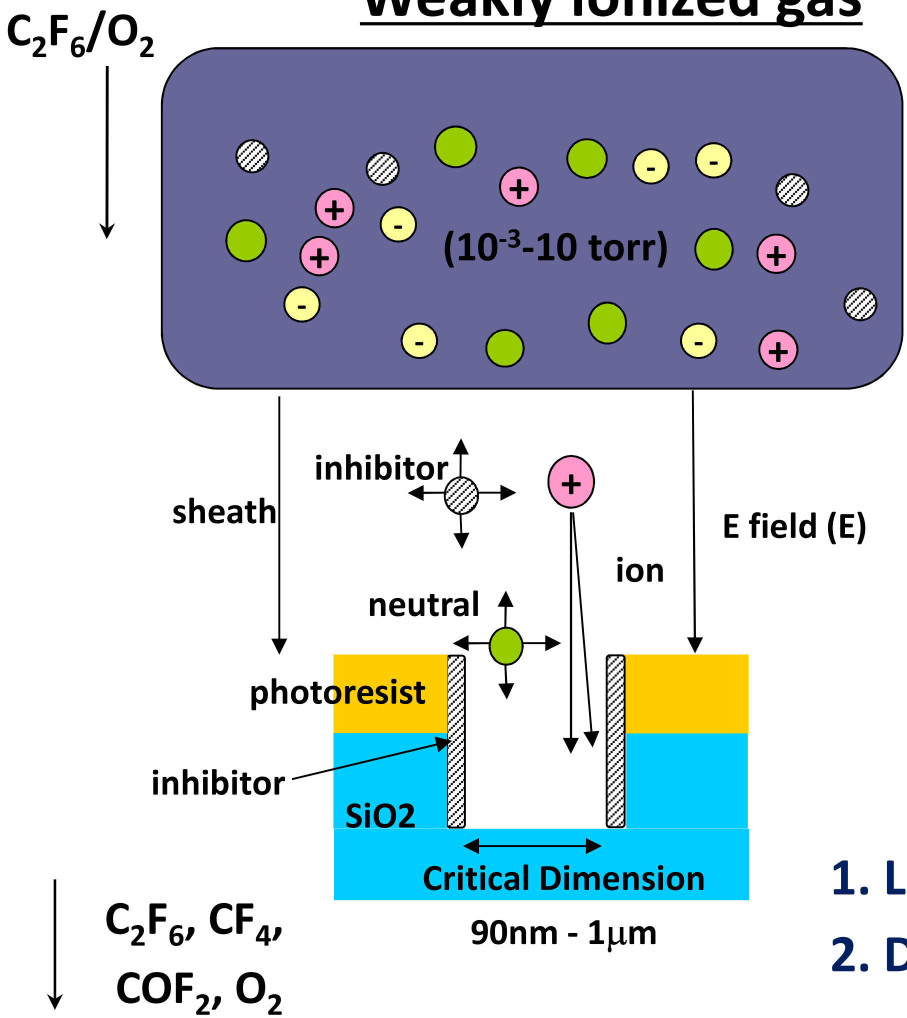
Squared Etch Profile



■http://www.iom-leipzig.de/pic_schw/caibe1.jpg

Plasma – Reaction Example

Weakly ionized gas



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 by reactive radicals & ions
2. Directionality due to ion and electric field

Wet Etching vs. Dry Etching

	Wet Etching	Dry (Plasma) Etching
Process/ Reaction	Solid + Liquid → Soluble Prod. $Si(s) + 2OH^{-} + 2H_2O \rightarrow Si(OH)_2(O^{-})_2\ (aq) + 2H_2\ (g)$	Solid + Gas → Volatile Prod. $SiO_2(s) + CF_4 \rightarrow SiF_4(g) + CO_2(g)$
Advantage	- Relatively simple - Easy to get high selectivity	-Anisotropic etching (suitable for the feature smaller than 1μm) -Ease to automate the process -Less toxic
Disadvantage	- Isotropic process (not suitable for the feature smaller than 3μm) -High cost in etchant -Toxic/Explosive -Bubble -Non-uniform	-Complex system -Difficulty to control -Device damage by energetic ions -Less selective than wet process

Merits and Demerits of Plasma Processing

- Merits
  - Low temperature processing
  - Micro- and nano-scale patterning
  - Dry processes and <u>less waste generation</u> than wet processes
  - Chemistry control is possible

- Demerits
  - Requires RF or DC power generators.
  - Requires vacuum in typical cold plasma processing
  - Chemistry is complex and difficult to control.

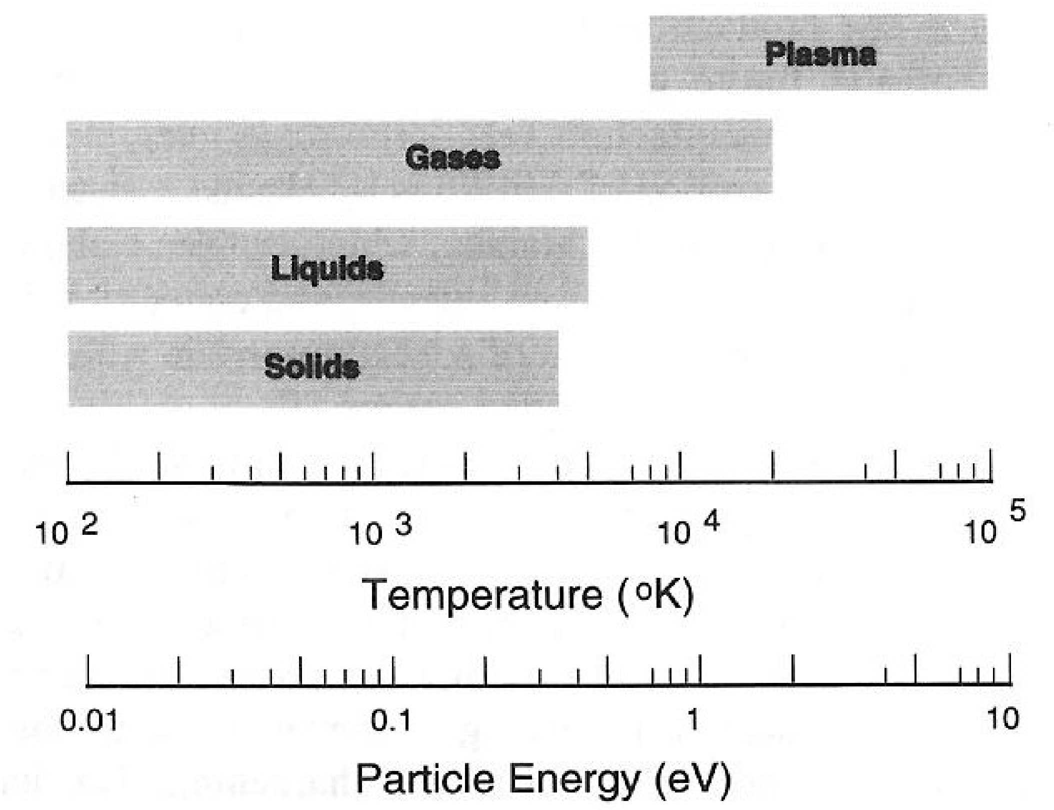
Plasma

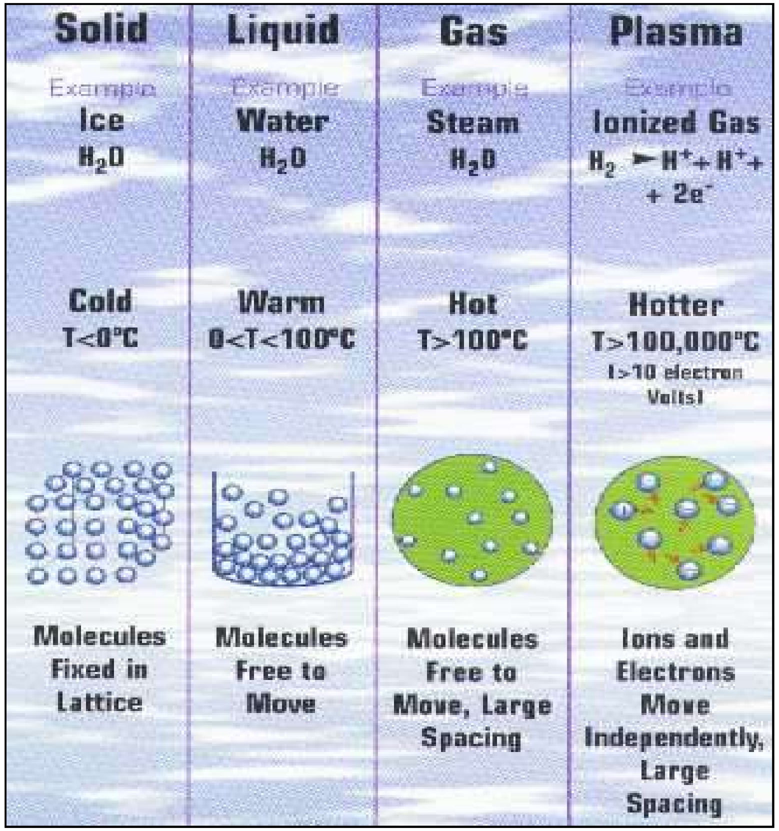
	Electron	Ion	Radical	Molecules
Mass				
Fraction				
Density				
Energy				
Function				

Plasma Fundamentals

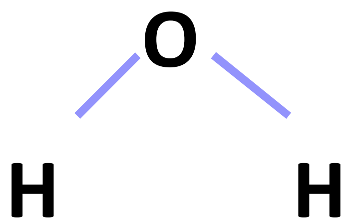
Plasma

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





Breakdown of H_2O molecules



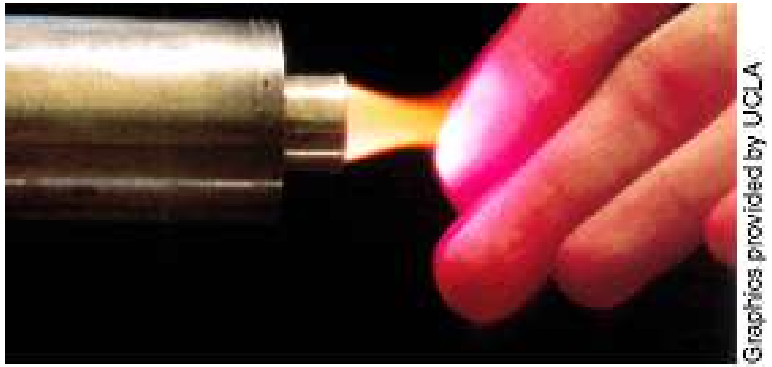
$$H \longrightarrow H^+ + e^-$$

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

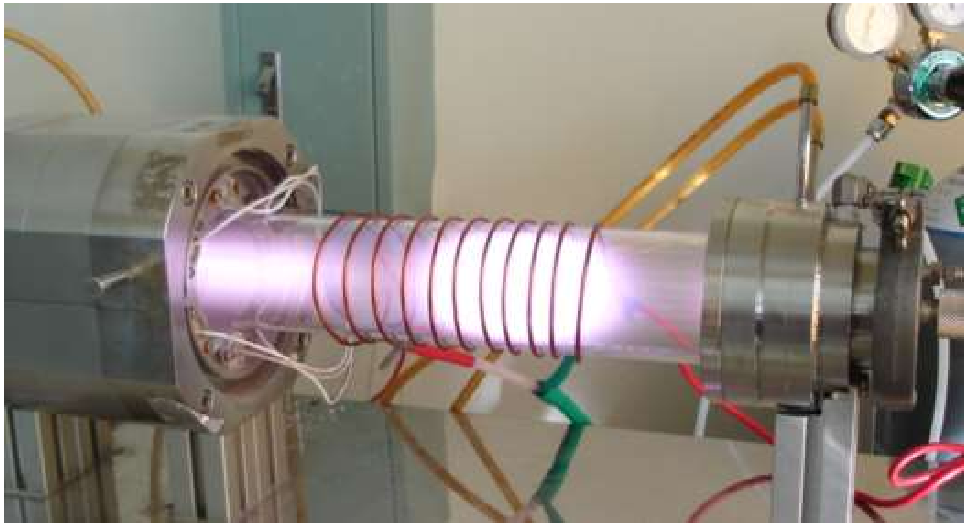
$$O - H \longrightarrow OH^+ + e^-$$

Radicals | Ions | Electrons

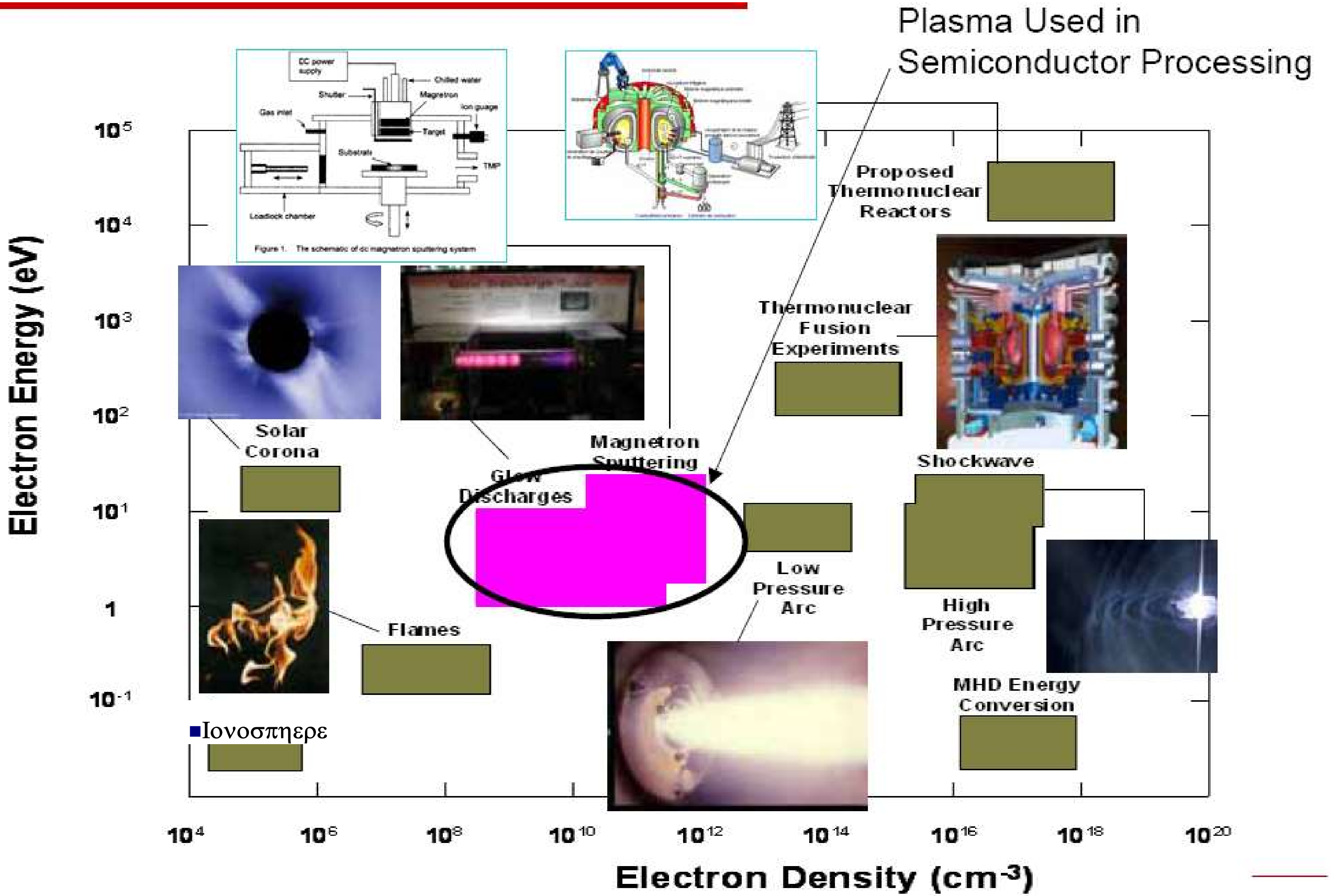
Plasmas in Material Processing



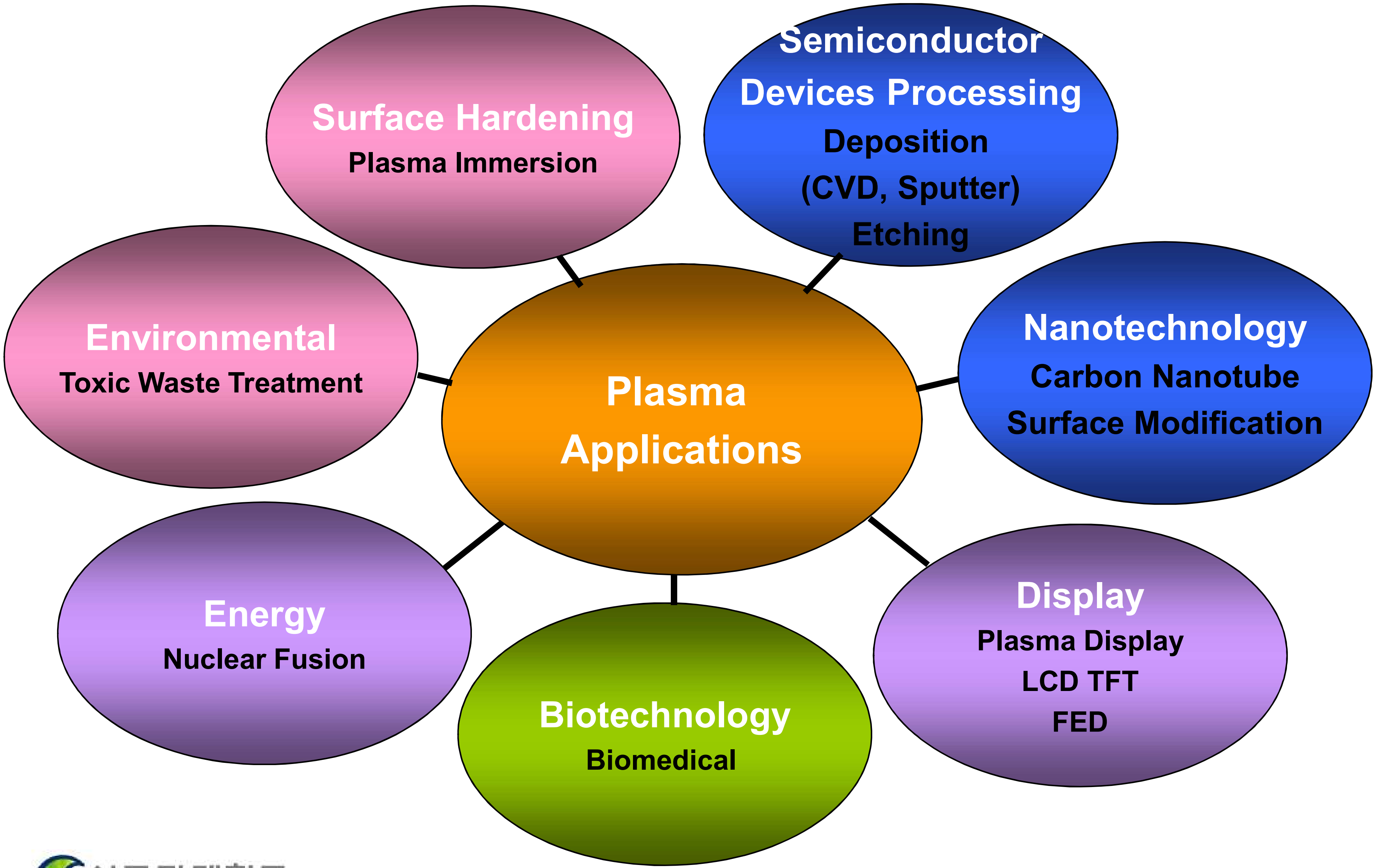
The low effluent temperature of atmospheric-pressure plasma makes the device ideal for several decontamination applications.



Plasmas as Function of Electron Energy & Density

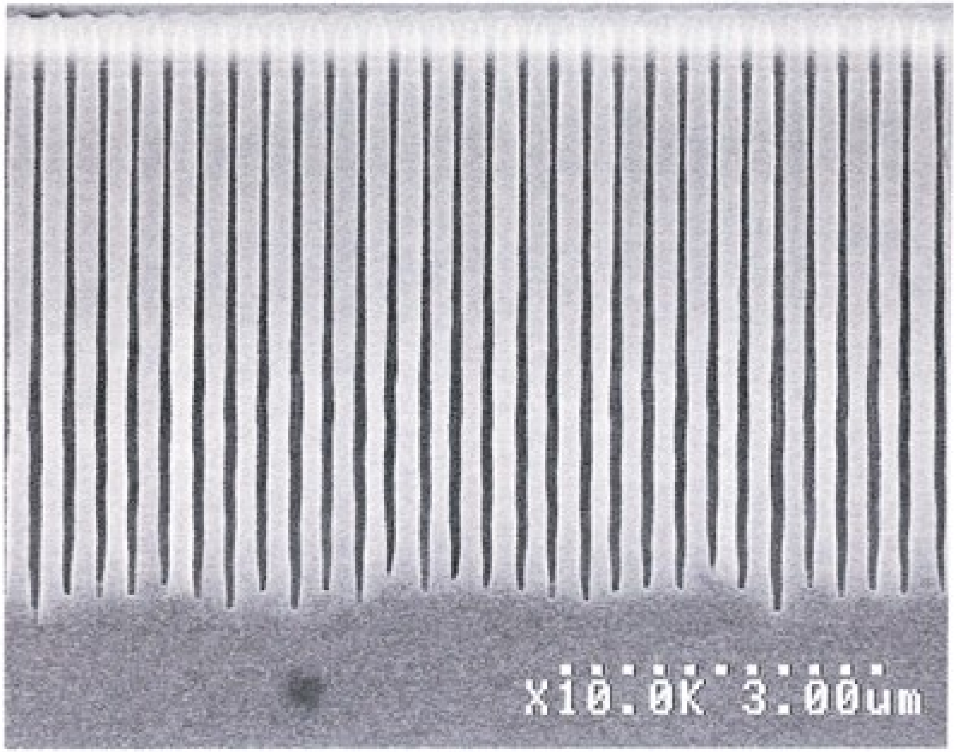


Plasma Application Areas



Plasma Etching

High Aspect Ratio Si Etching



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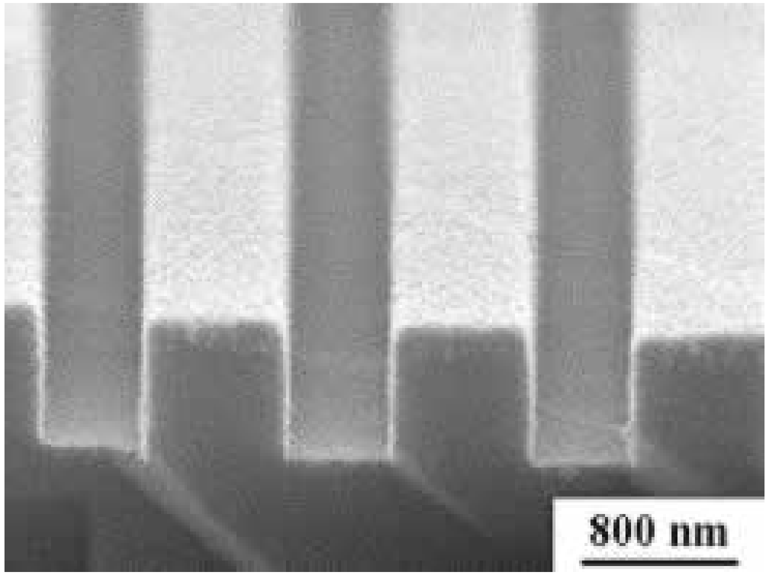
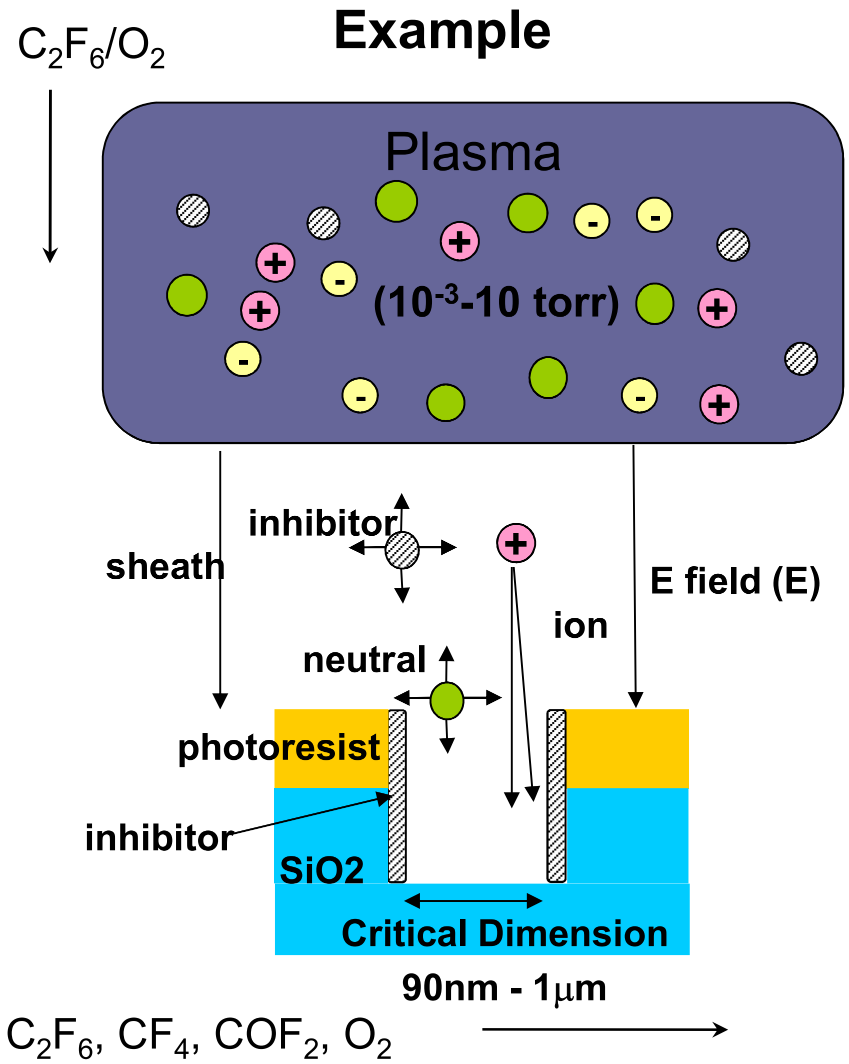


http://www.iom-leipzig.de/pic_schw/caibe1.jpg

Plasma – Generation Process



Plasma = Ionized Gas

Plasma (Soup of electrons, ions, radicals and molecules)

- Electric energy transferred to electron (1-5eV)
- Electron collides with molecules to generate ions and neutrals

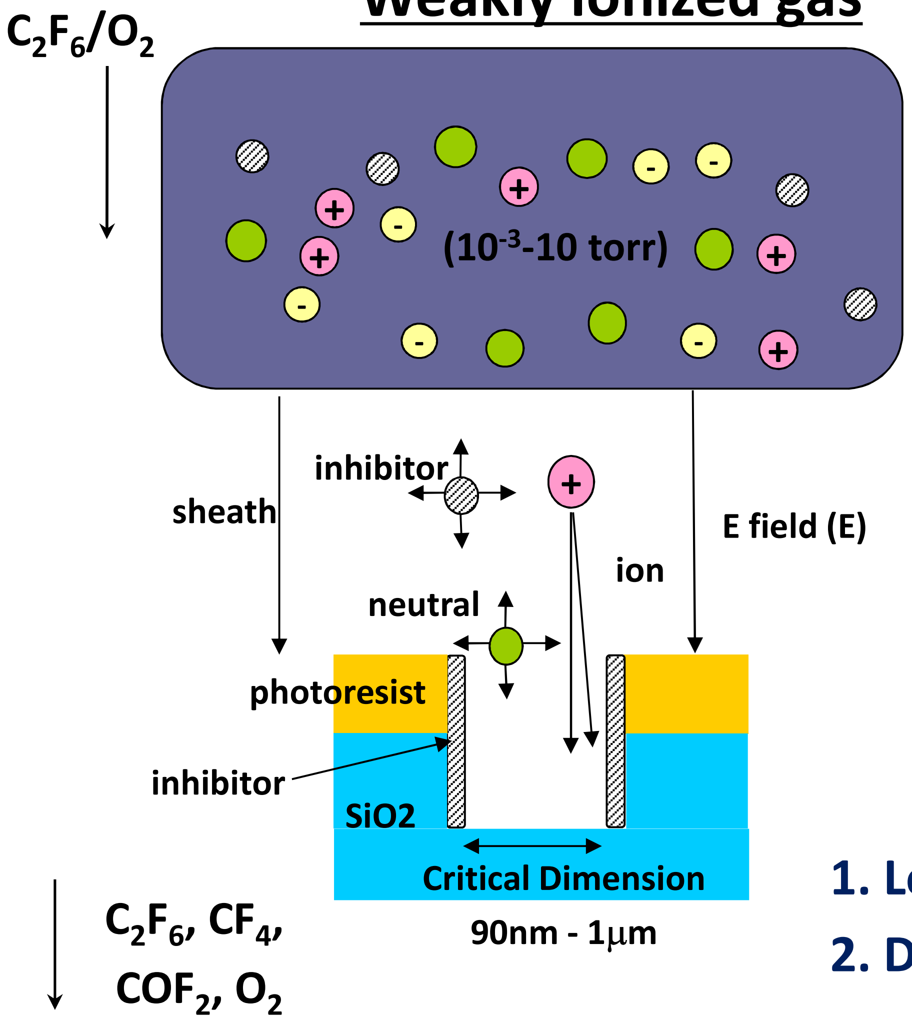
- Ions and electrons are in balance (quasi-neutral)
- Ions are accelerated in sheath (high energy ions)
- Surface reacts with ions and neutrals

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.
- Ions
  - 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 – Reaction Example

Weakly ionized gas



Example

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

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Plasma

	Electron	Ion	Radical	Molecules
Mass				
Fraction				
Density				
Energy				
Function				

Plasma in IC Processing

Property	Range
Pressure	0.001 – 10 torr
Electron density - Low density - High density	 10^9 – 10^{11} cm^{-3} 10^{11} – 10^{13} cm^{-3}
Average electron energy	1 – 10 eV
Average neutral and ion energy, k_BT	0.025 – 0.05 eV
Free radical density	5 – 90 %
Ionized fraction of gas - Low density - High density	 10^{-5} – 10^{-7} 10^{-3} – 10^{-1}
Neutral diffusivity	20 – 20,000 cm^2/s
Power dissipation	0.1 – 10 W/cm^2 (or W/cm^3)

Plasma Potential in DC Glow Discharge

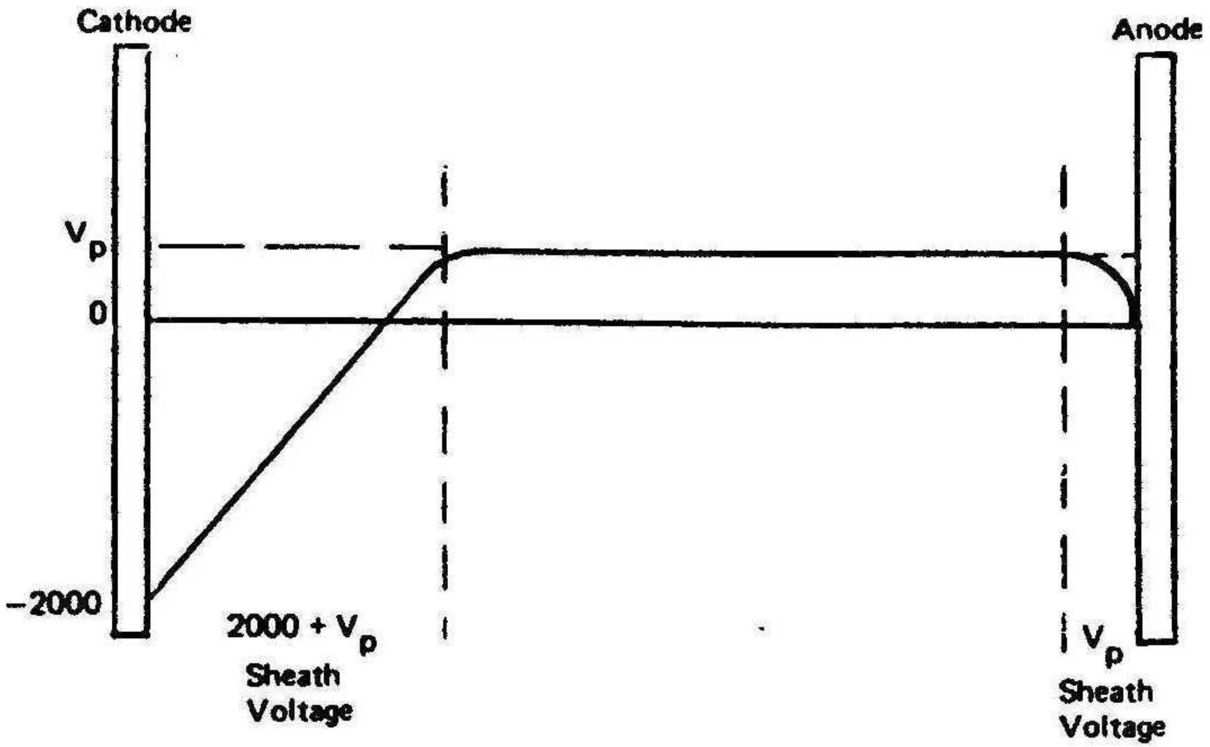
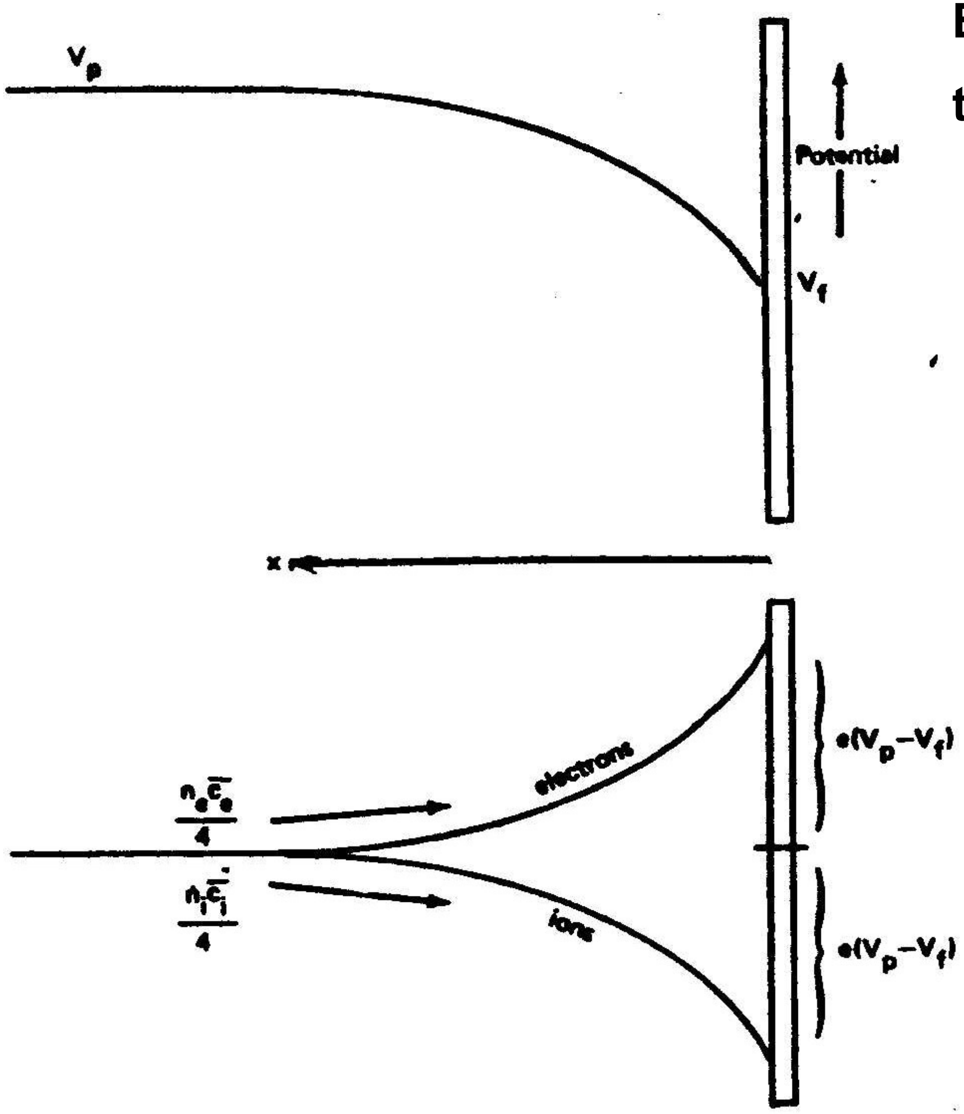
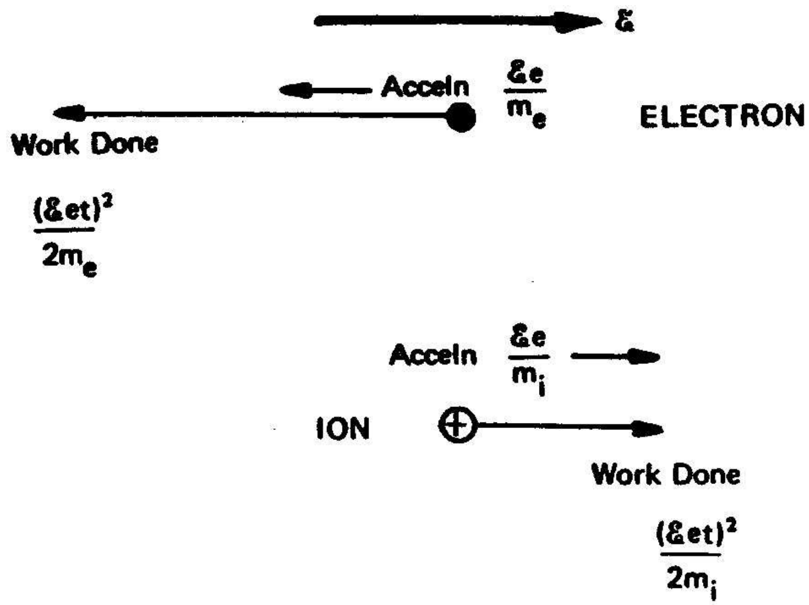


Figure 4-4. Voltage distribution in a dc glow discharge process

Energy Transfer from the Electric Field in Sheath



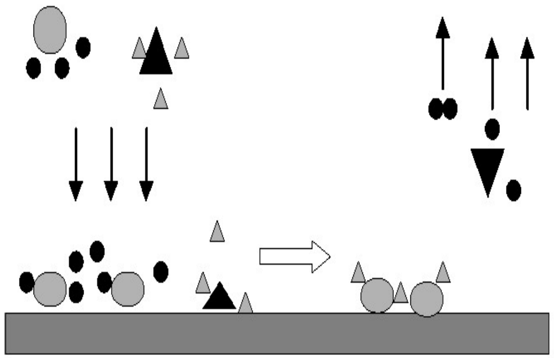
Energy Transfer from the Electric Field to electrons and ions



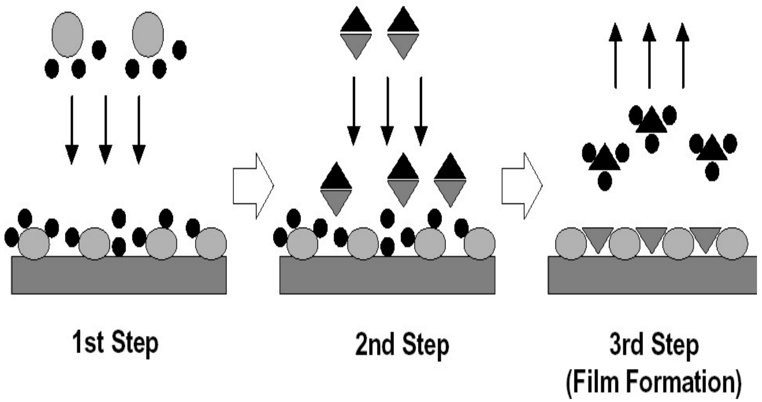
Physical Vapor Deposition:
Plasmas Sputtering & Evaporation

Models of Thin Film Deposition

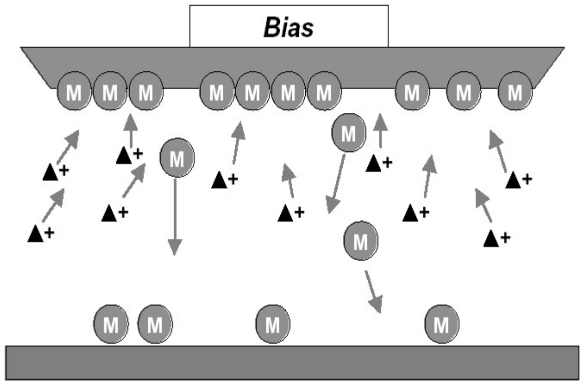
CVD Model



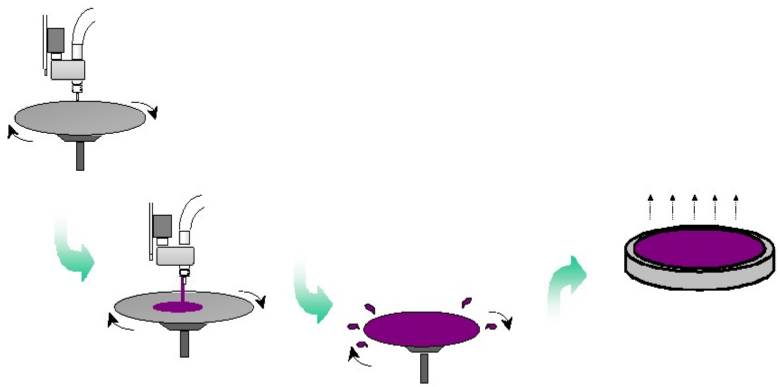
ALD Model



PVD Model



SOD Model



Physical Vapor Deposition (PVD)

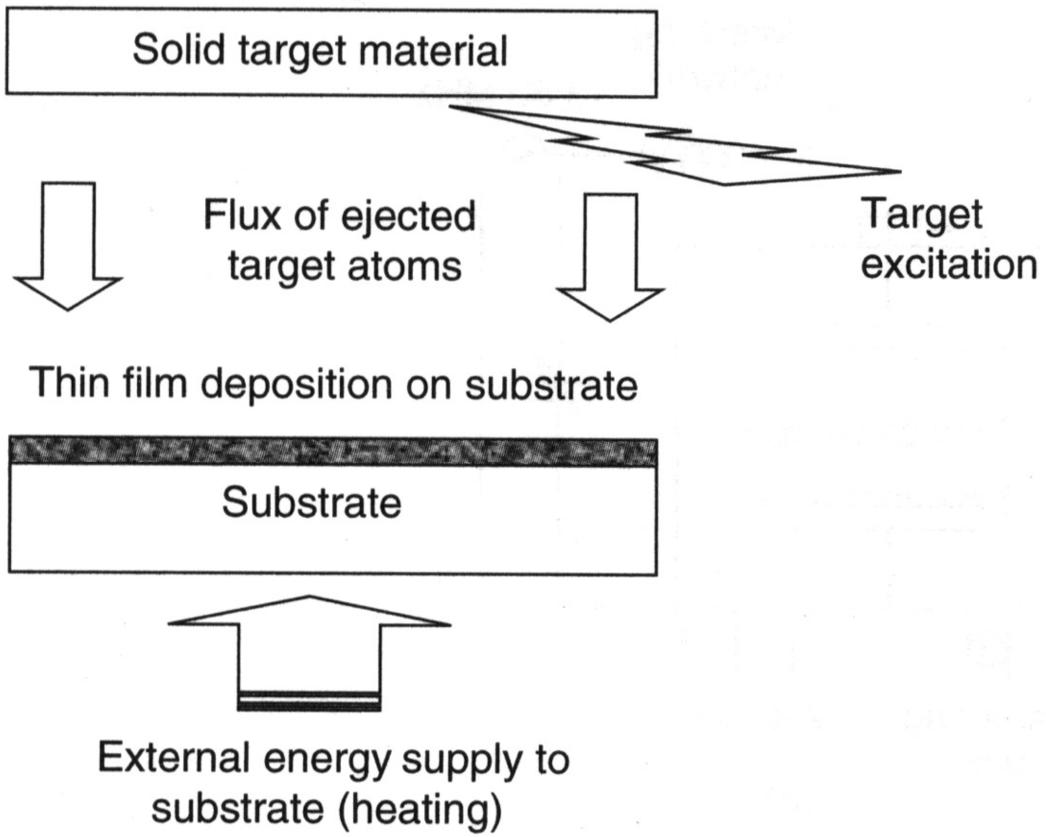
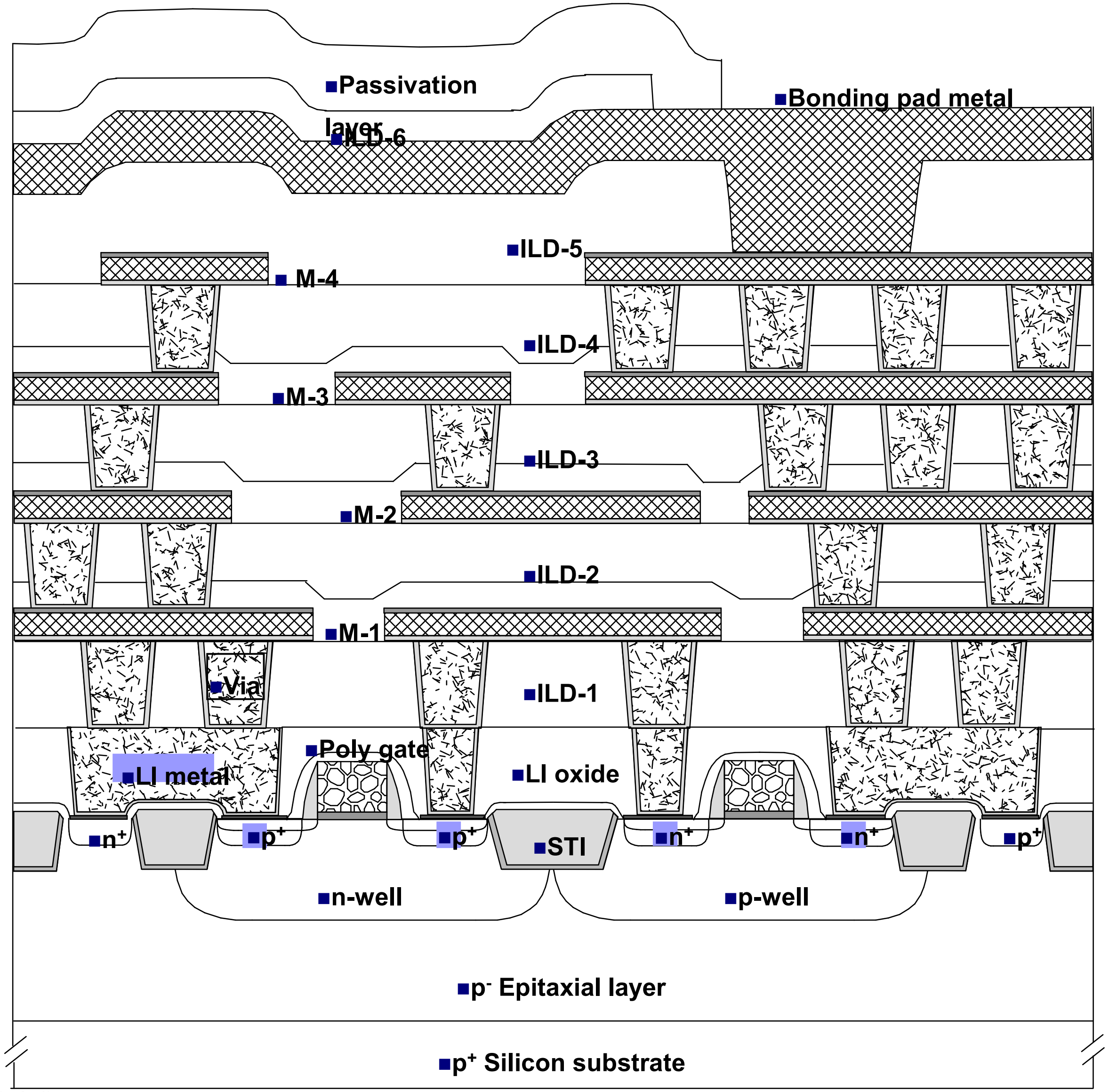


Figure 5.2 The principle of physical vapour deposition in a vacuum system

Characteristics of Deposition Processes

	PE-CVD	LP-CVD AP-CVD	PVD	ALD	SOD
Fine THK Control	bad	good	bad	Excellent	Good
Step Coverage	bad	Very good	bad	Excellent	Excellent
Throughput	high	low	high	Very low	high
Pin Hole Density	Not bad	Not bad	high	low	high
Film	SiO_2, SiN, SiC, SiOC, a-C	Si, SiO_2, SiN, W, WSix	Ti, TiN, Al, Cu, TaN, W	SiN, TiN, Al_2O_3, TaO, HfO	SiO_2, SiOC, a-C:H

Multilevel Metallization on a ULSI Wafer



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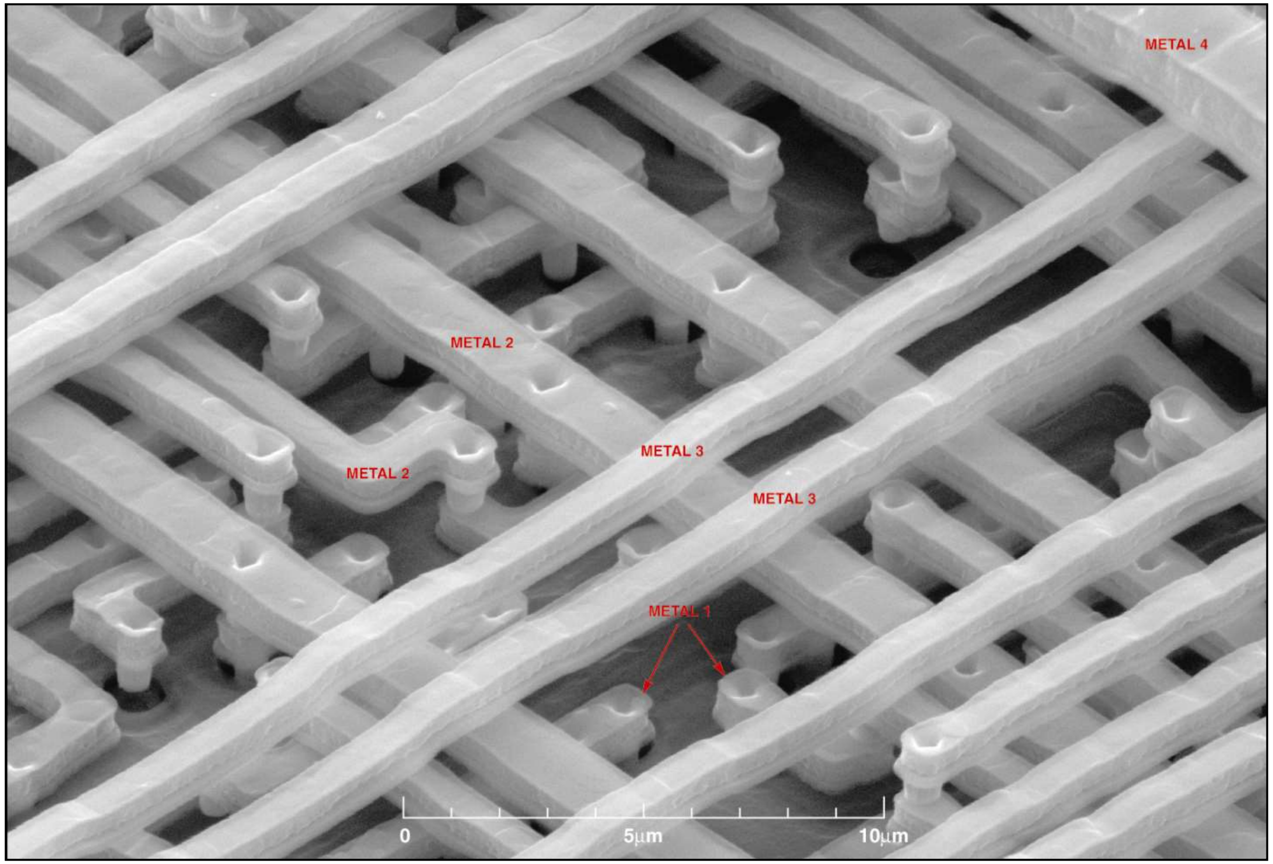
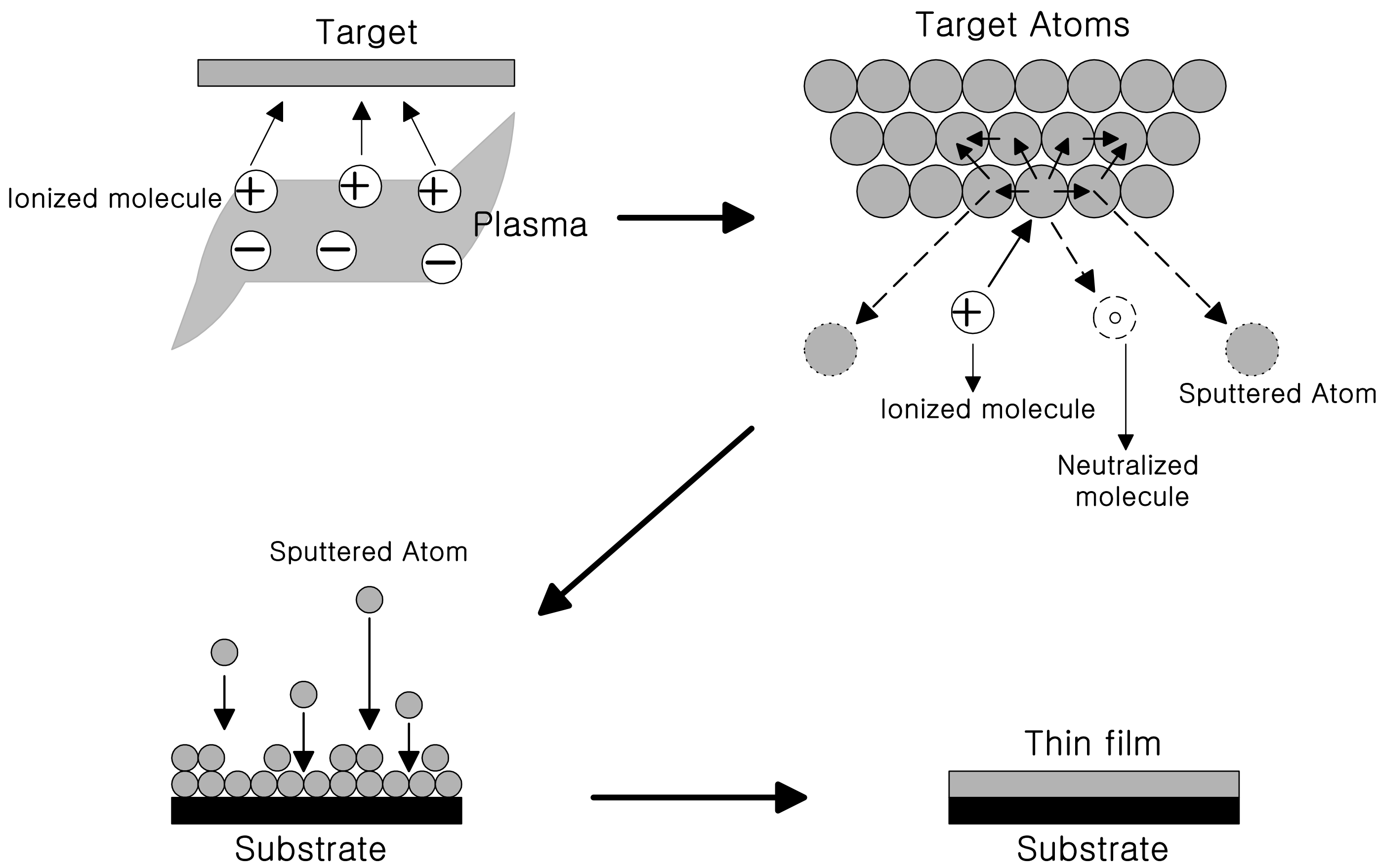
Metal Layers in a Chip



■Micrograph courtesy of Integrated Circuit Engineering

■M. Quirk, J. Serda, Semiconductor Manufacturing Technology

PVD: Sputtering



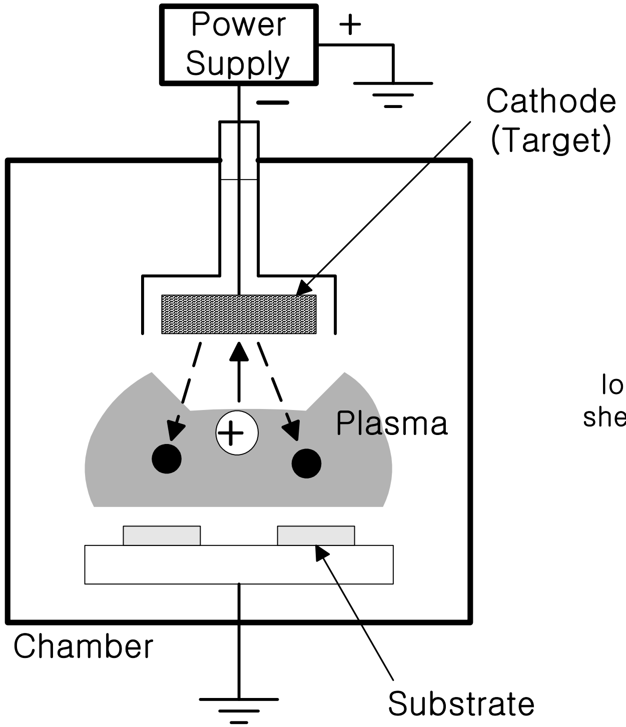
- High energy ions generated by plasma strike target materials and target material is deposited on substrate

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

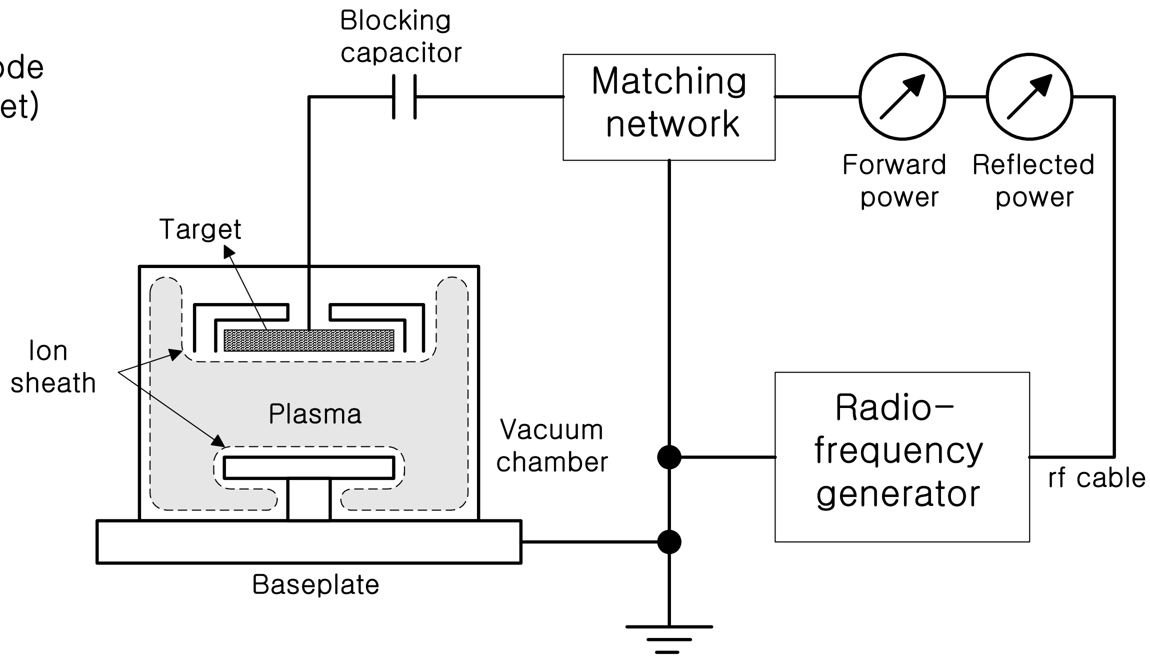
PVD: Sputtering Types

■ DC powered plasma



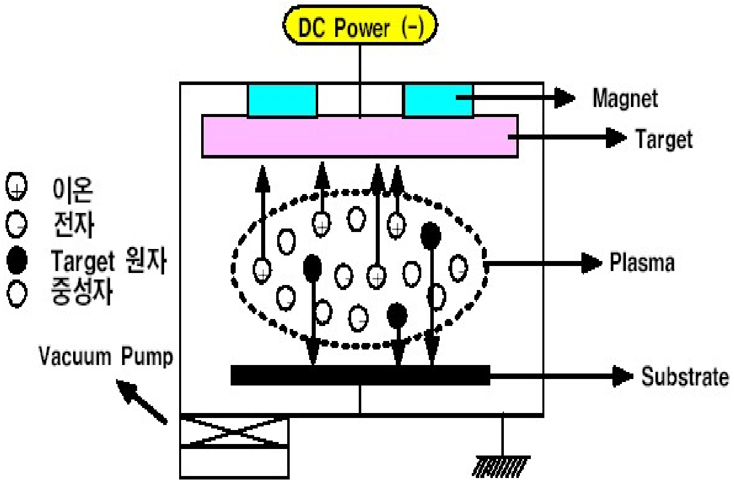
- Relatively simple
- Dielectric materials cannot be sputtered due to charge build-up

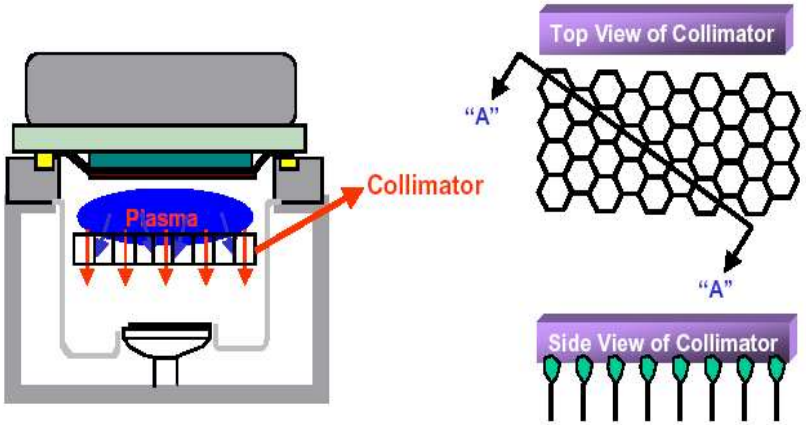
□ RF powered plasma

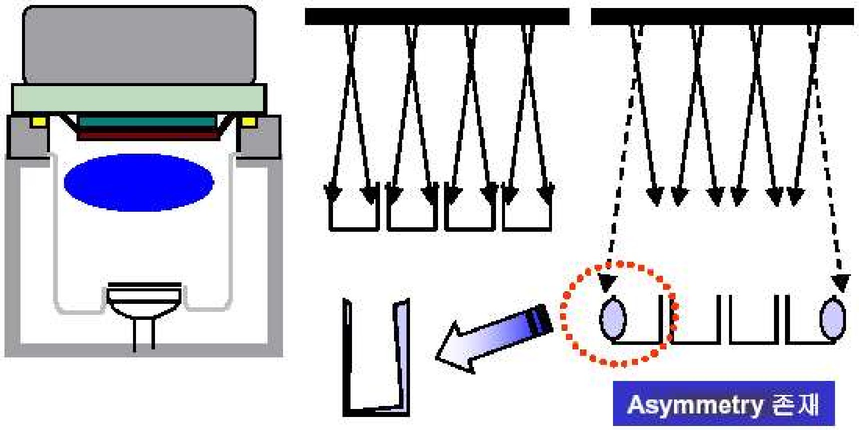


- Radio-frequency power used
- Dielectric material can be sputtered

PVD 장비







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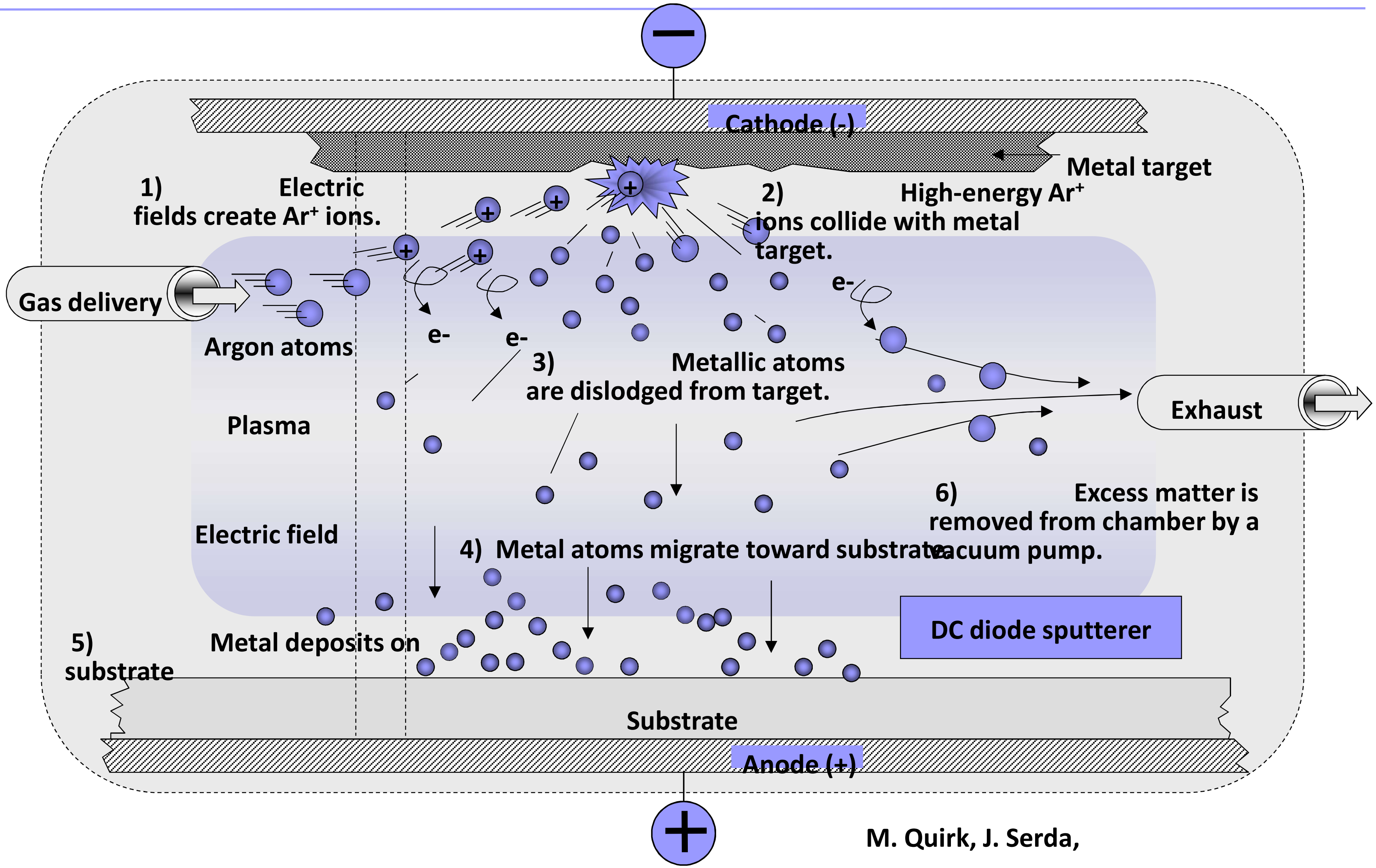
Some Advantages of Sputtering

1. Ability to deposit and maintain complex alloys.
2. Ability to deposit high-temperature and refractory metals.
3. Ability to deposit controlled, uniform films on large wafers (200 mm and larger).
4. Ability of multichamber cluster tools to clean the wafer surface for contamination and native oxides before depositing metal (referred to as in situ sputter etch).

Simple Parallel Plate DC Diode Sputtering System



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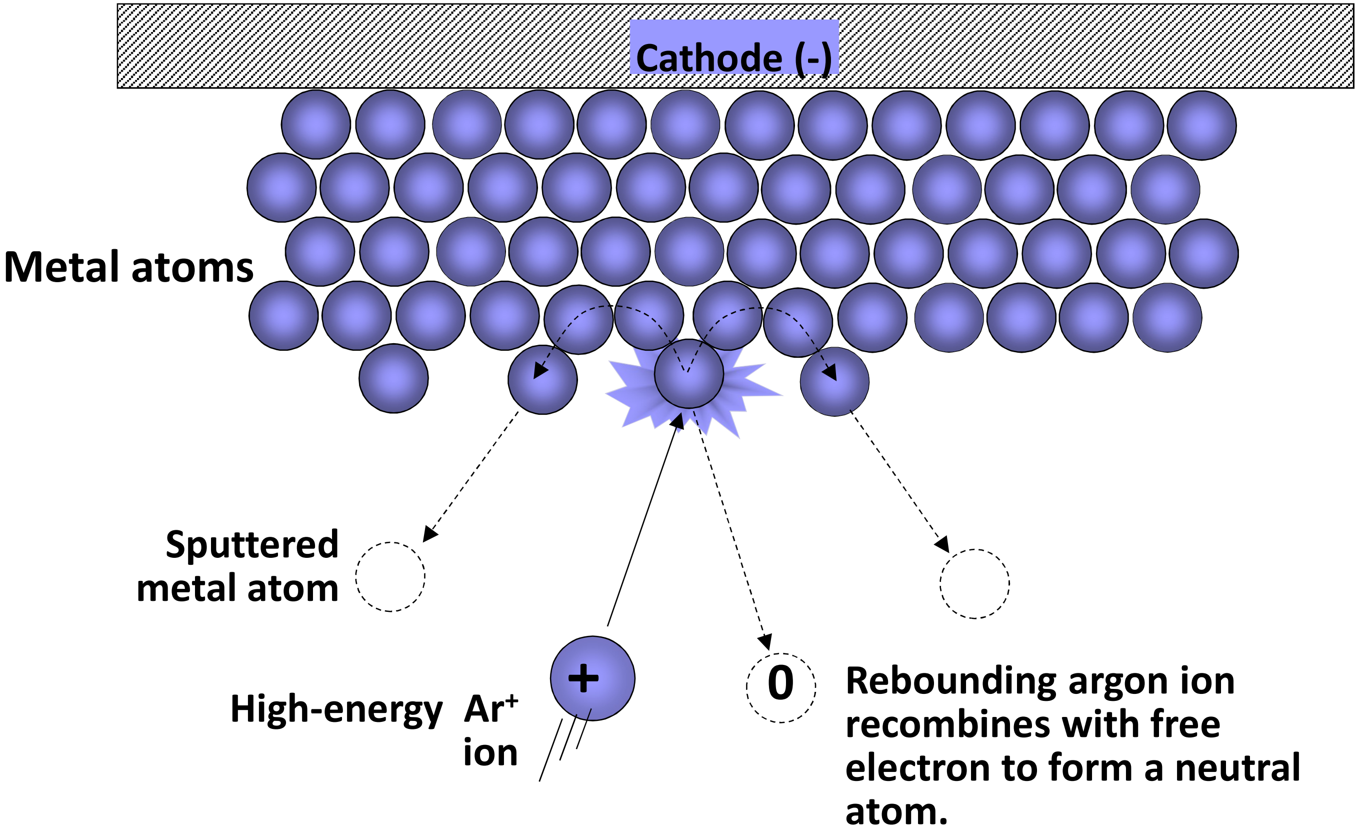
Dislodging Metal Atoms from Sputtering Target



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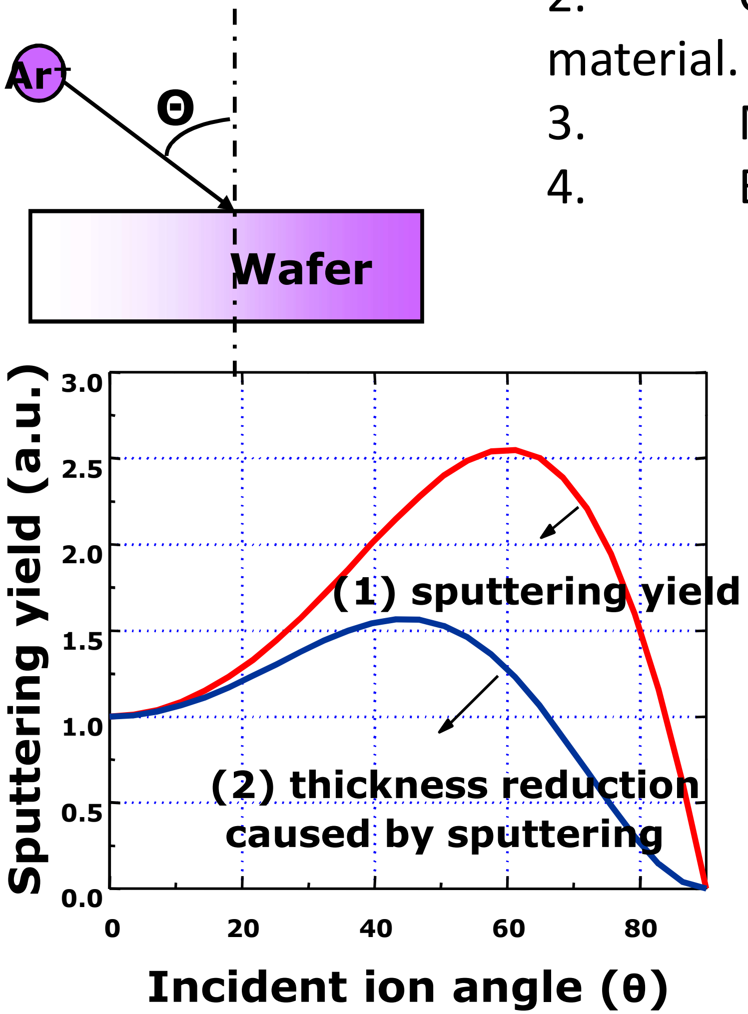
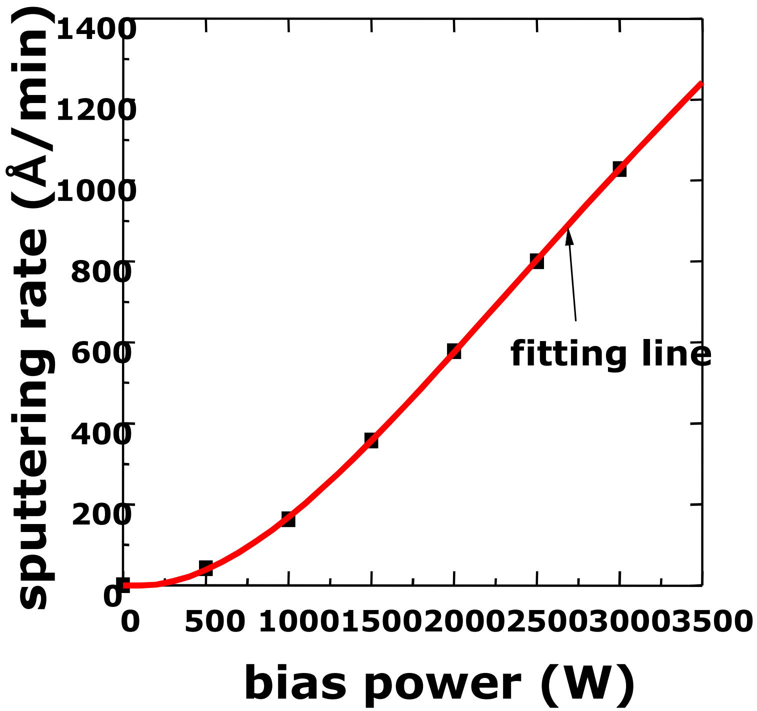
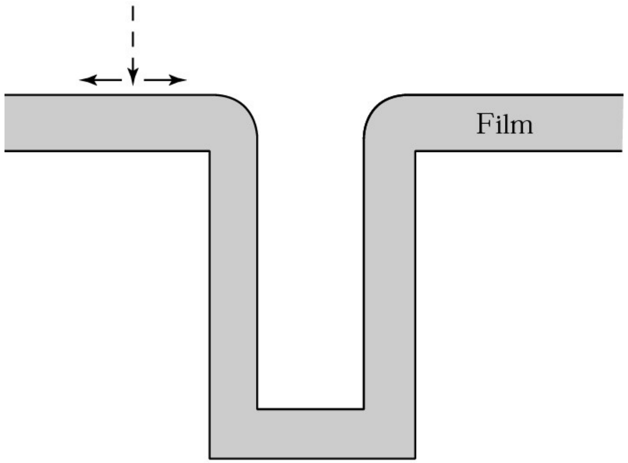
Factors affecting sputtering yield

1. Incident angle of the bombarding ions.
2. Composition and geometry of the target material.
3. Mass of bombarding ions.
4. Energy of the bombarding ions.

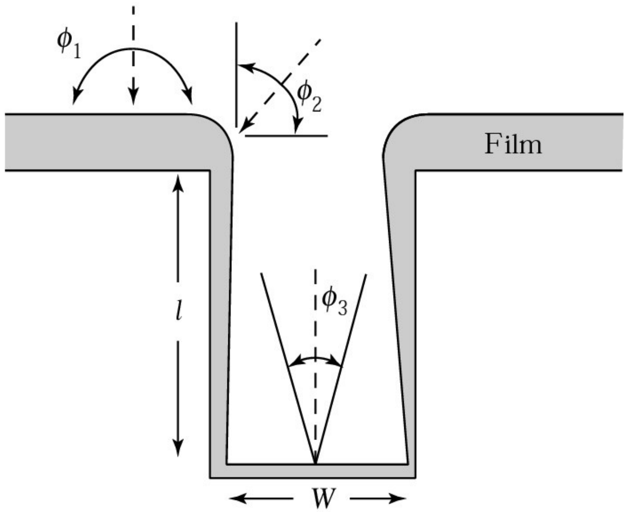




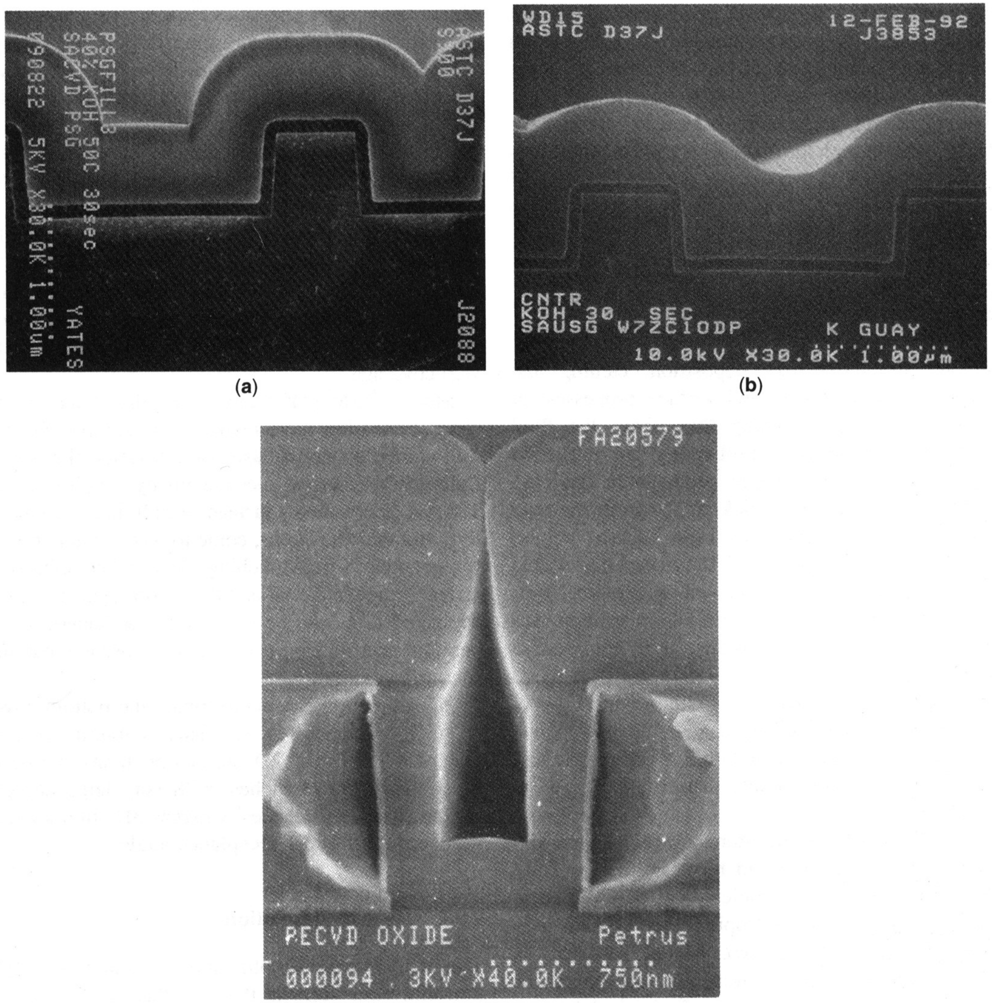
Step Coverage



(a)



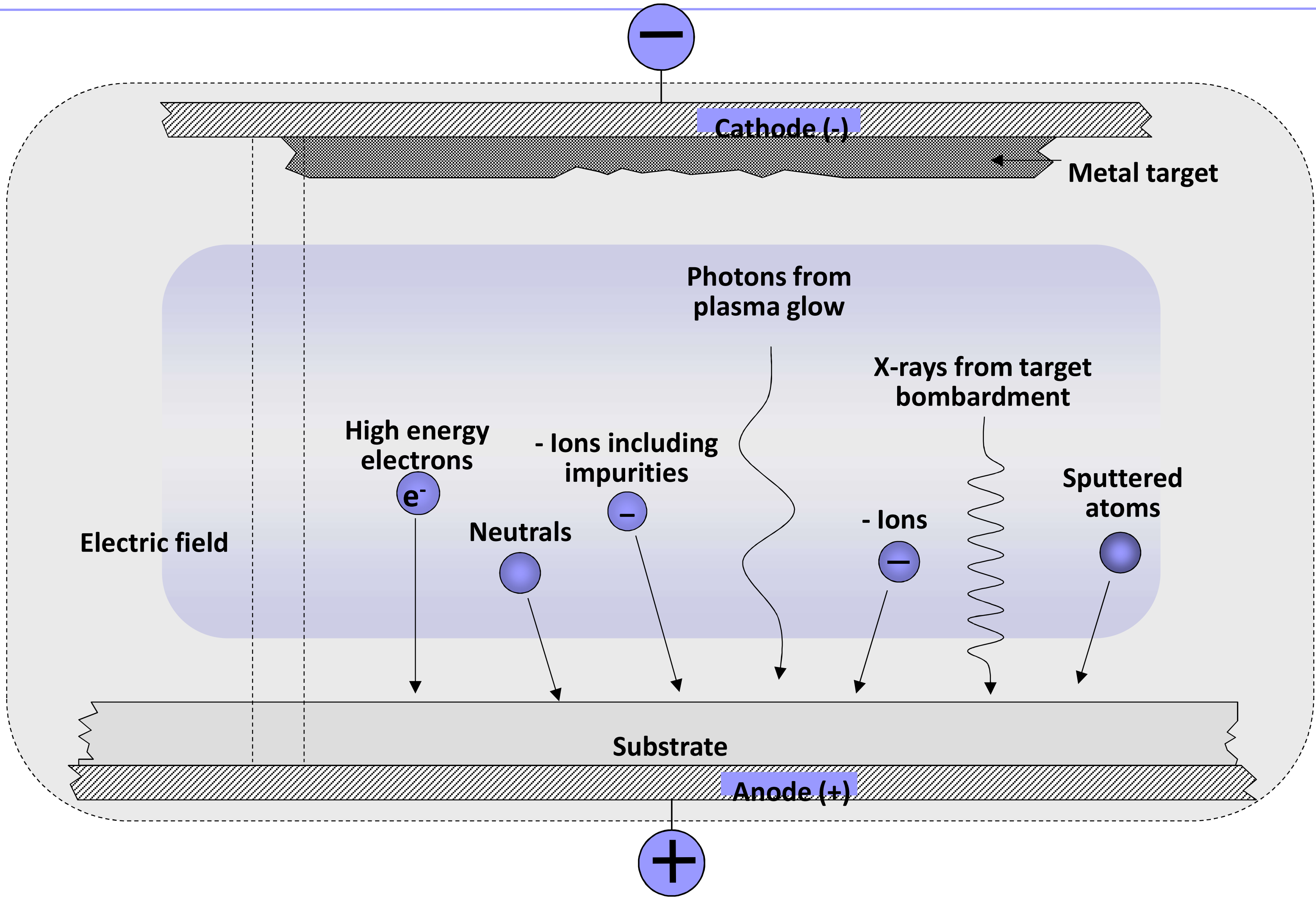
(b)



(a) (b) (c)

Figure 7.16 Step coverage in different CVD processes: (**a**) phosphorus doped CVD oxide with conformal (100%) step coverage, (**b**) undoped CVD oxide with flow-like profiles and (**c**) PECVD oxide from silane/nitrous oxide reaction leads to a void formation. Reproduced from Cote, D.R. *et al.* (1995), by permission of IBM

Different Species Landing on Substrate



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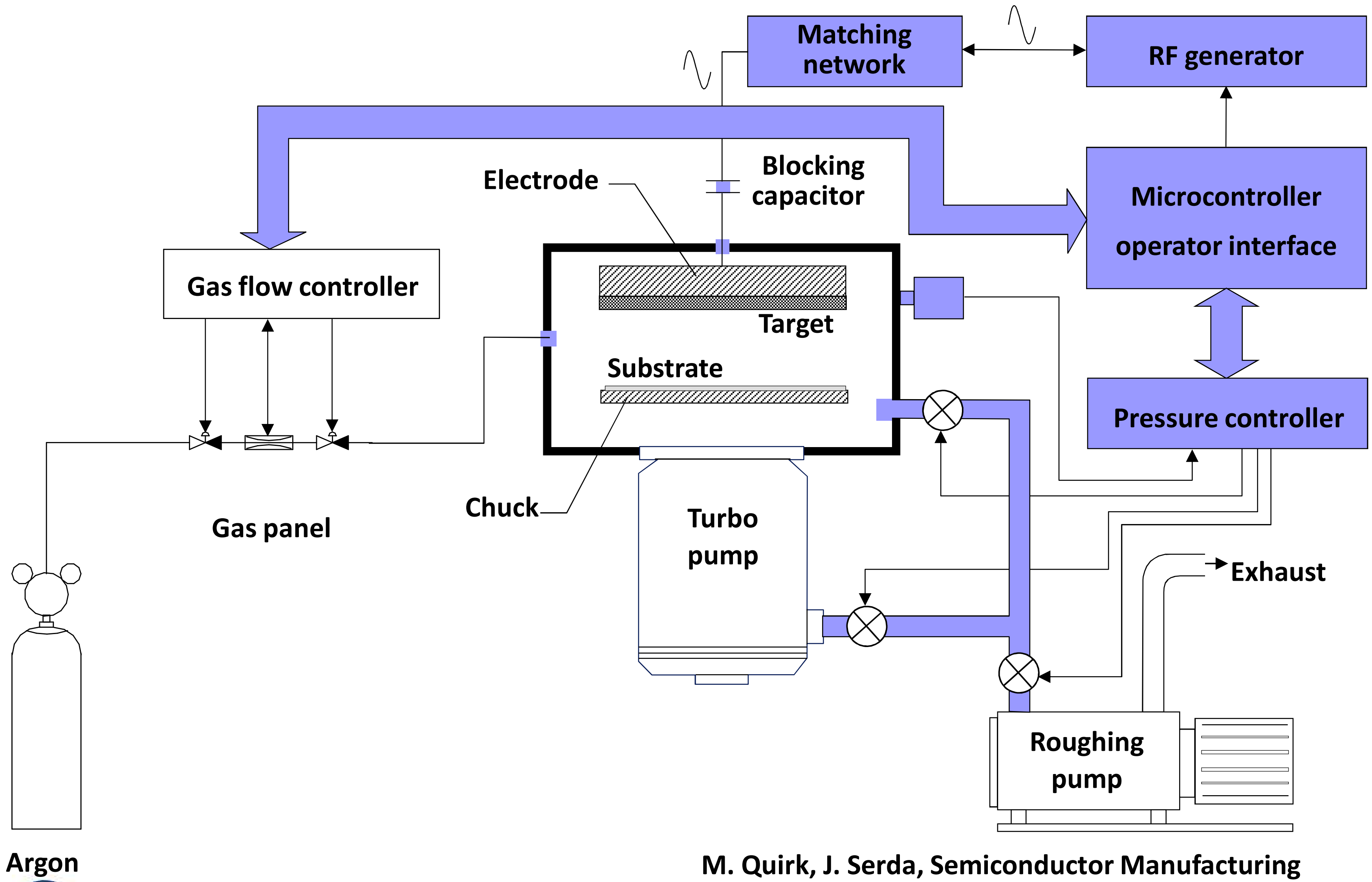
RF Sputtering System



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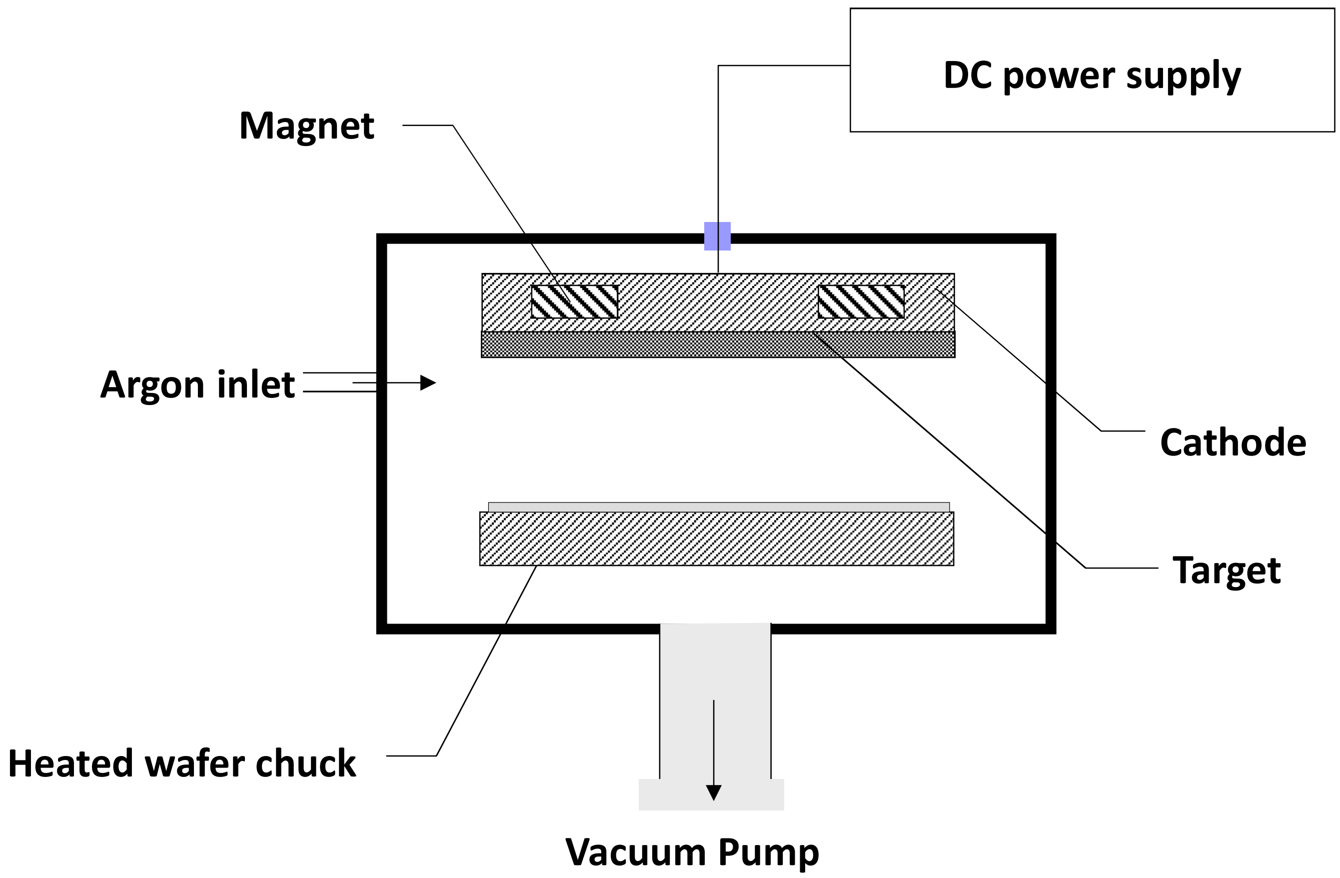
Magnetron Sputtering



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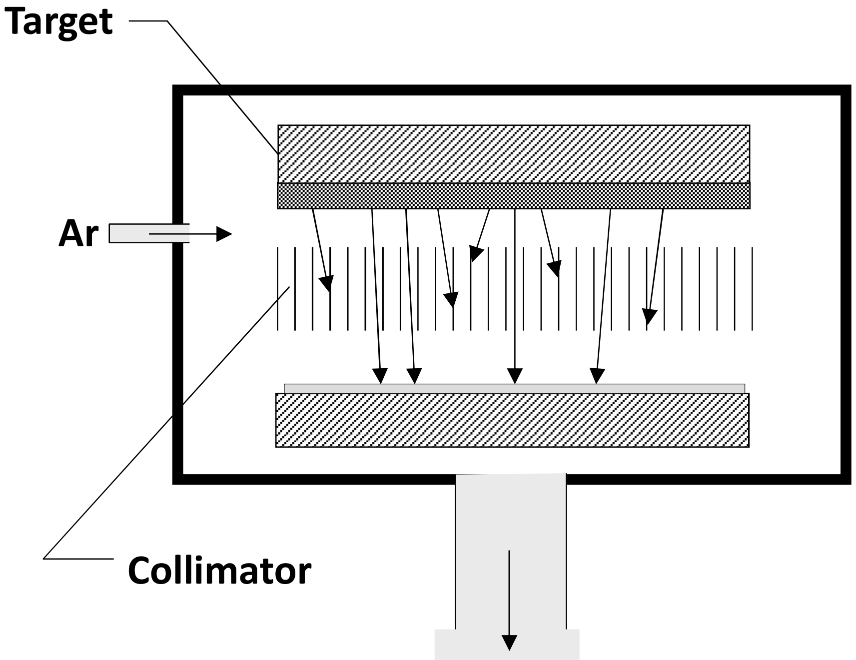
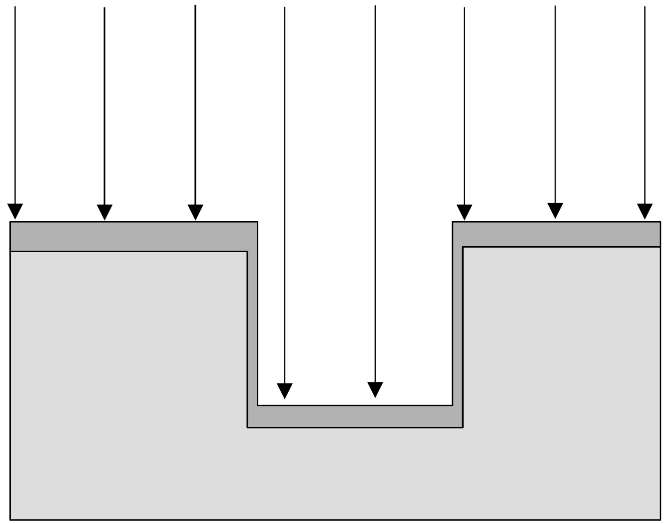
Collimated Sputtering

Collimated Sputtering System





Cross section of via showing coverage of resulting sputtered film.

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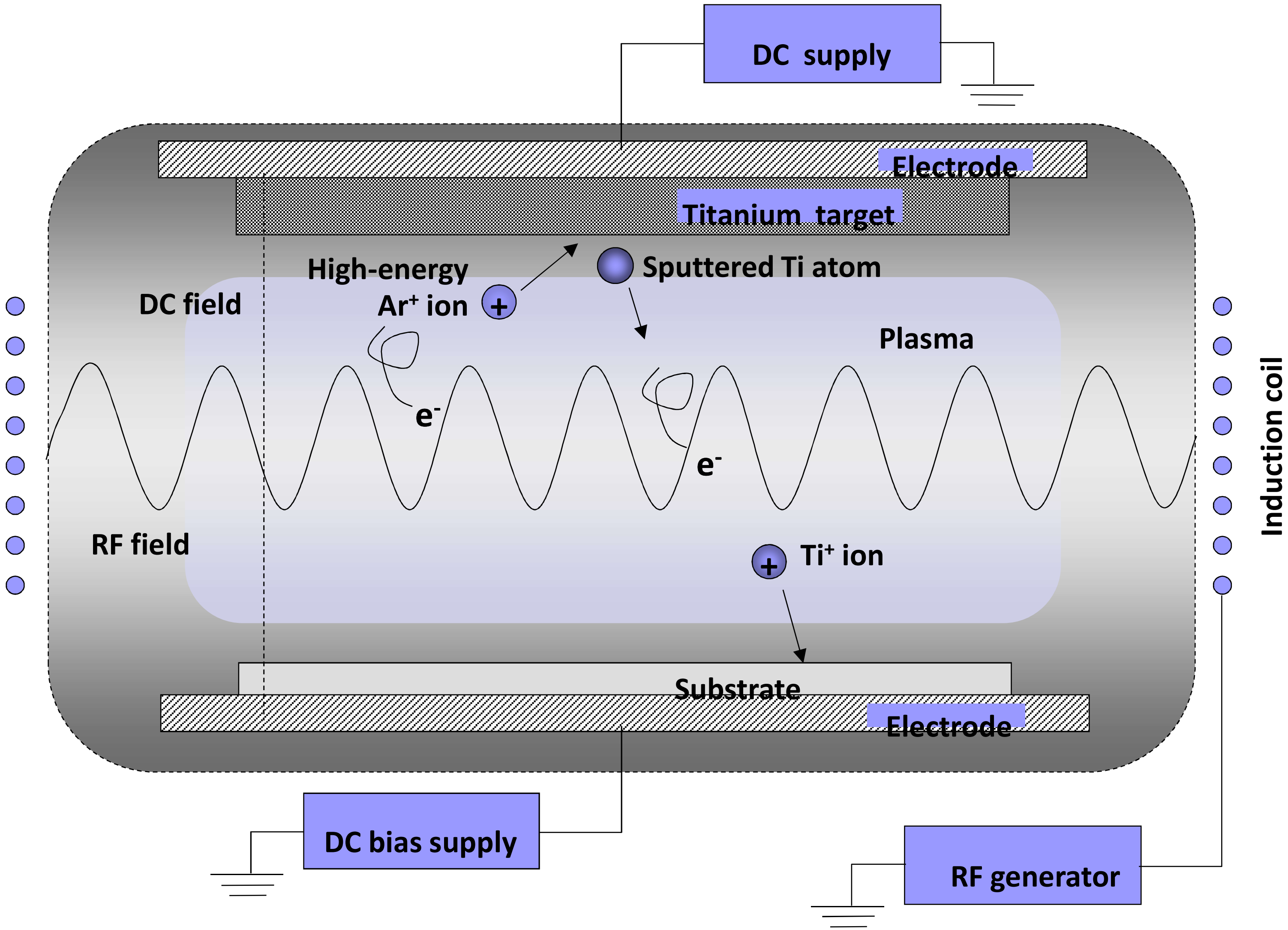
Concept of Ionized Metal Plasma PVD



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PVD Cluster Tool

Applied Materials

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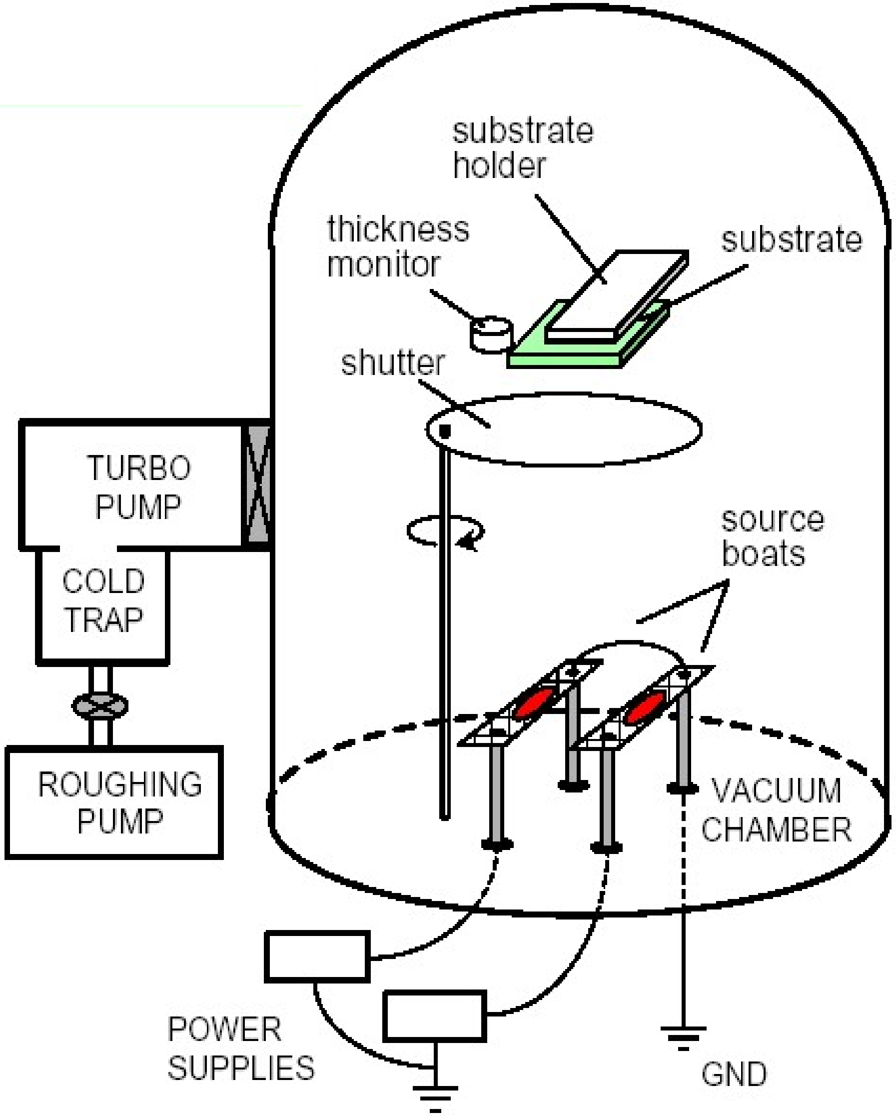
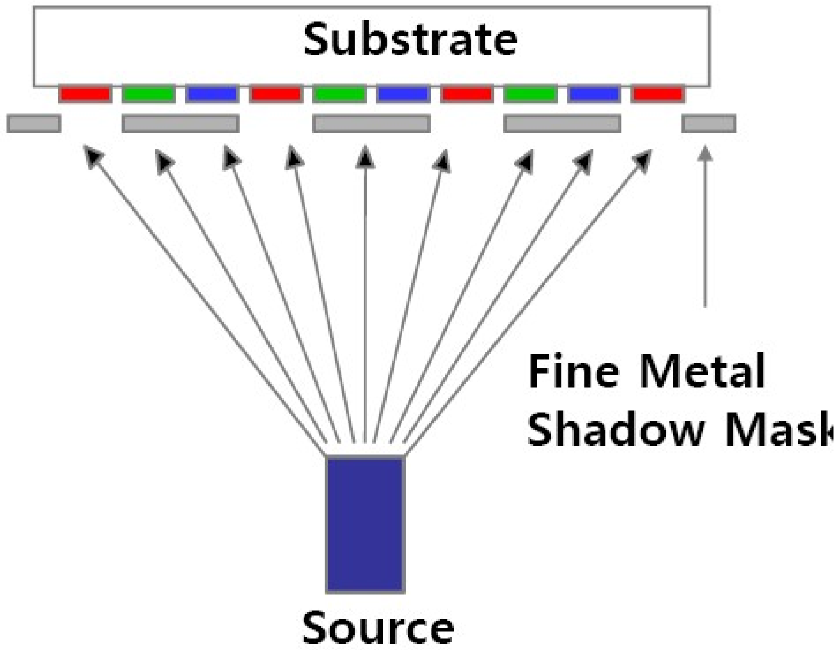
Evaporation Process



Thin film deposition for small molecules



+ Established technology

- Non-uniformity

- Waste of materials

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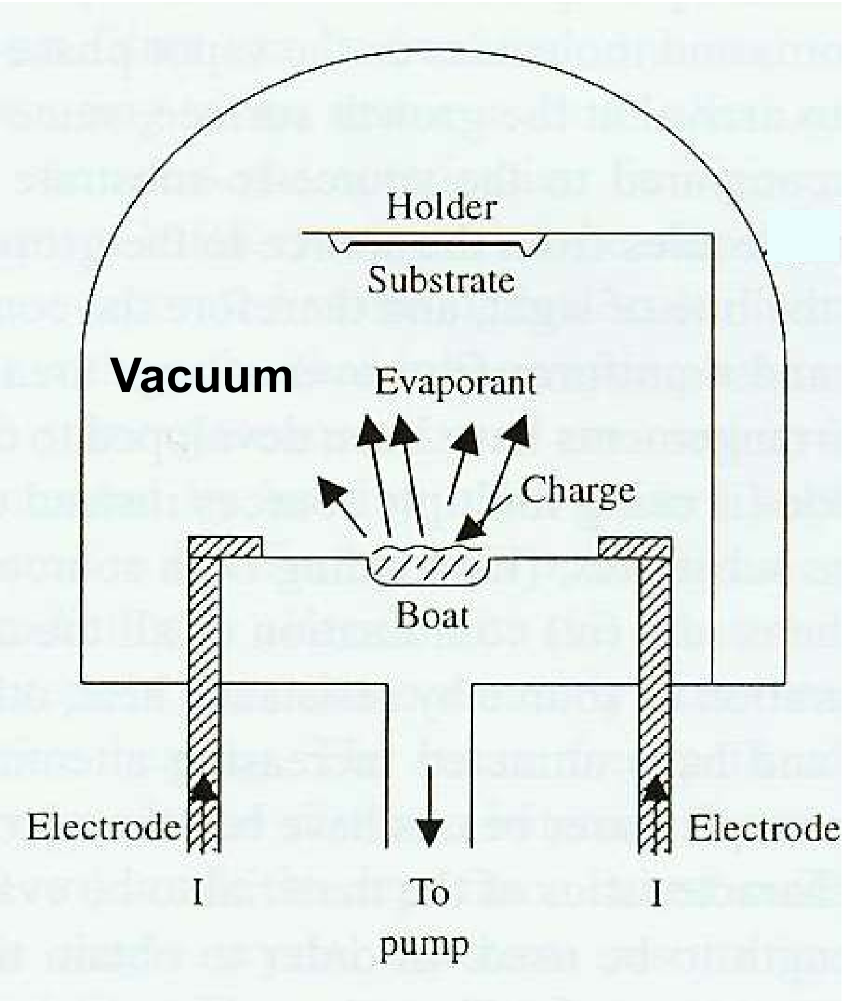
PVD: Evaporation



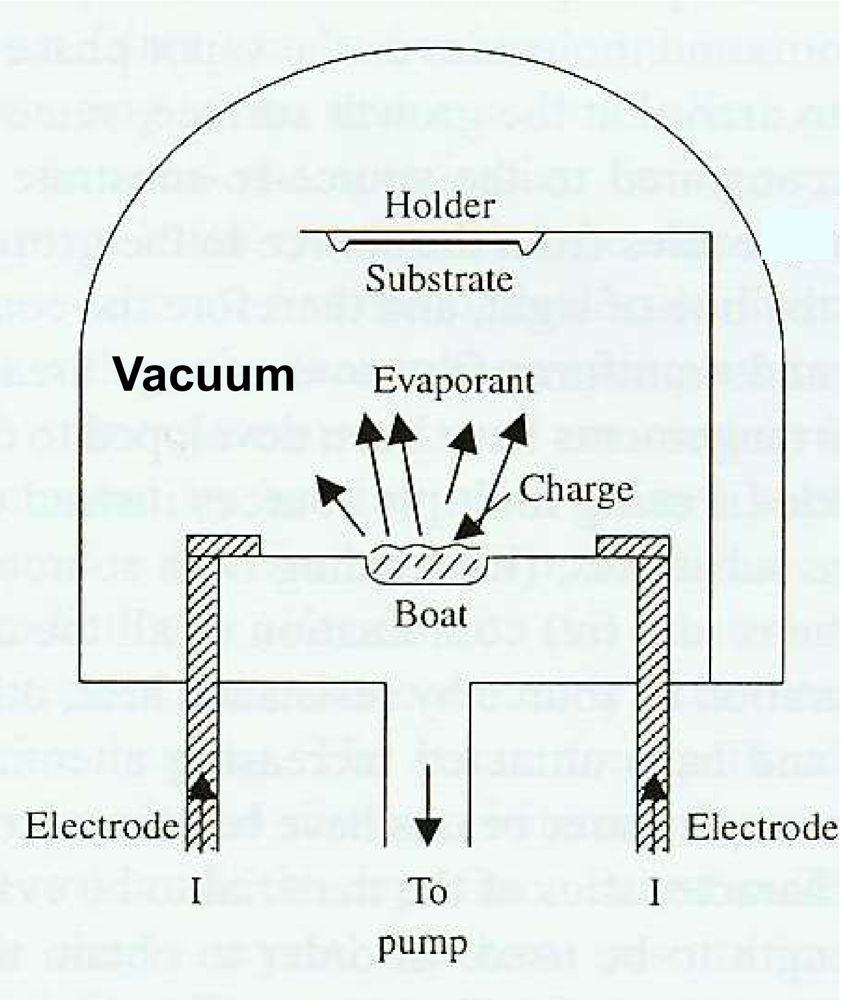
- Simple deposition technique
- Operated in 10^{-3} ~ 10^{-10} torr
- Vapor phase do not collide with each other since m.f.p. is large
- Line of sight deposition

- Relatively poor uniformity over a wafer
- For better uniformity
  - Multiple sources
  - Rotating the substrates
  - Loading both source & substrate on the surface of a sphere

- Source heating techniques
  - Resistive heating
  - Laser beams
  - Electron beams
  - Arc evaporation

PVD: Evaporation

- Evaporation is operated at vacuum to increase mean free path



$$\Gamma = \frac{nc}{4}$$

$$n = \frac{N}{V} = \frac{p}{k_B T}$$

$$c = \sqrt{\frac{8k_B T}{\pi m}}$$

$$\Gamma = \frac{nc}{4} = \frac{1}{4}\frac{p}{k_B T}\cdot\sqrt{\frac{8k_B T}{\pi m}} = \frac{p}{\sqrt{2\pi m k_B T}}$$

Deposition Rate by Hertz – Knudsen eq.

$$R_{evaporation} = \frac{a(p'' - p)}{\sqrt{2\pi m k_B T}}$$

a : evaporation coefficient

p": vapor pressure at evaporation surface

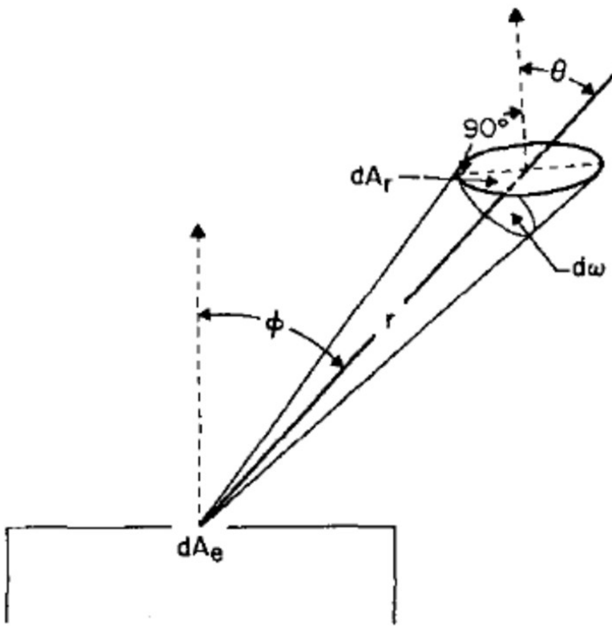
p: hydrostatic pressure

Vapor Pressure as a function of temperature

Cosine law of deposition

mass deposited per unit area

$$R_D = \frac{M_e}{\pi r^2} \cos\phi \cos\theta$$



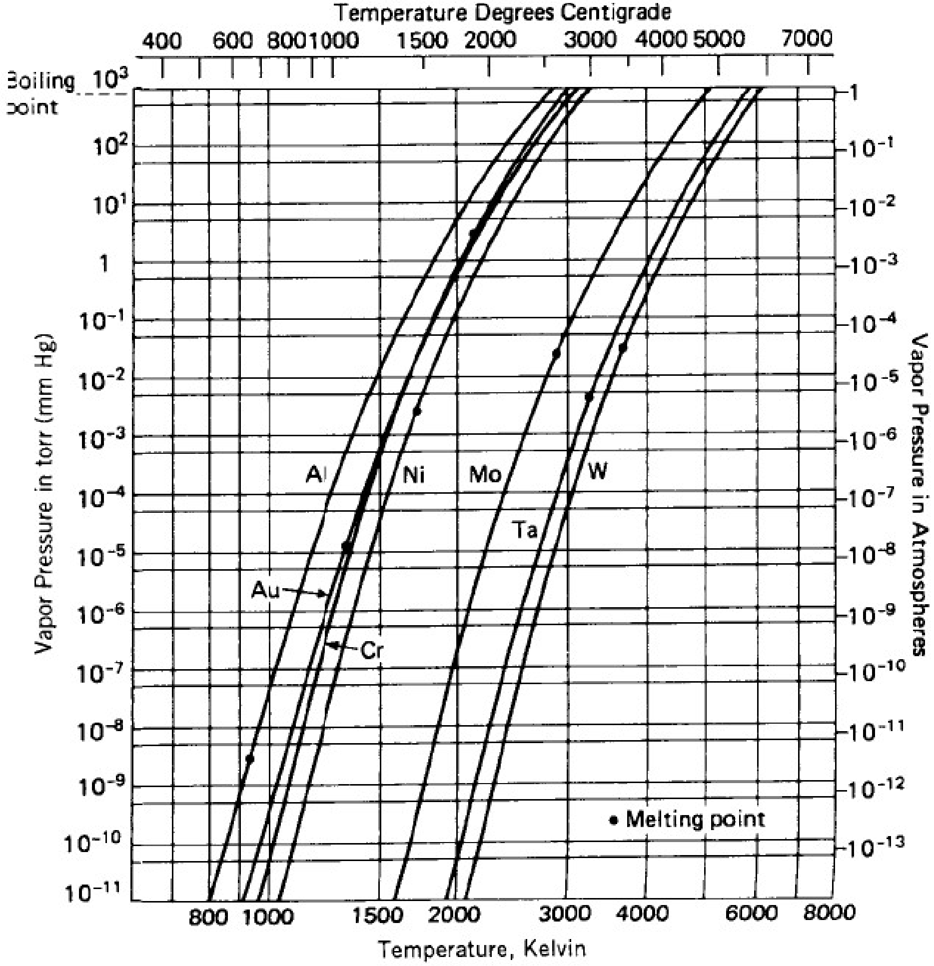
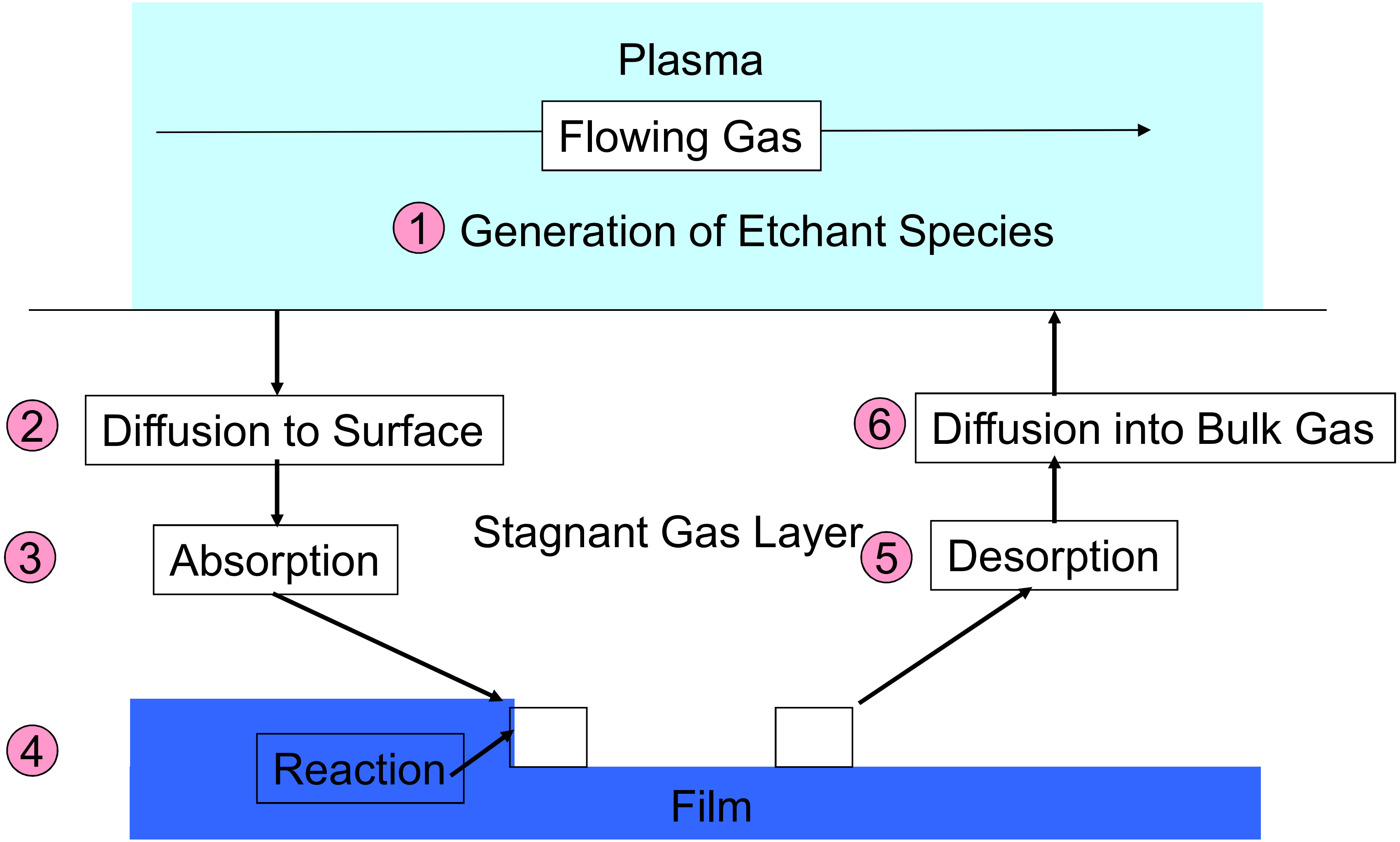


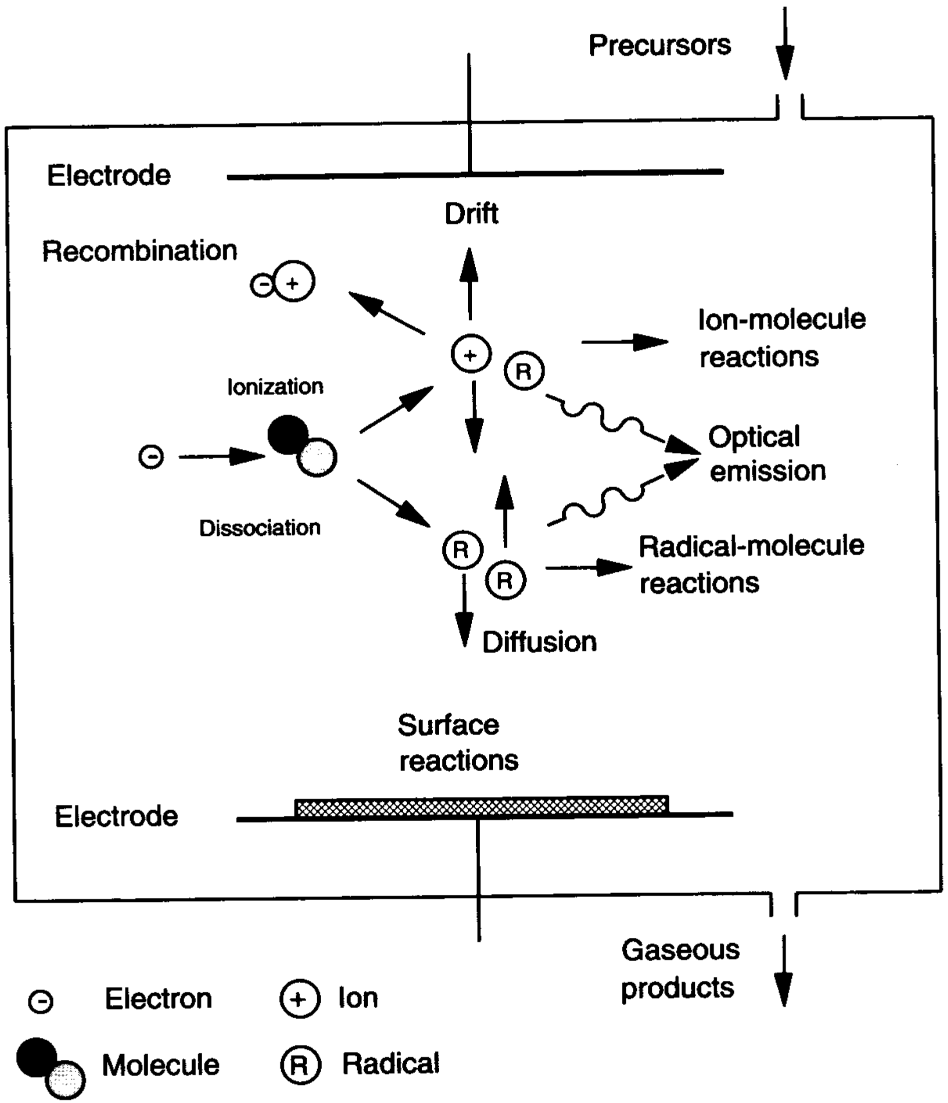
Fig. 8.1 Vapor pressure curves for selected materials. Adapted from [2].

Plasma Etching Chemistry & Surface Reactions

The 6 Steps of Plasma Chemical Etching



Reactions in Plasma



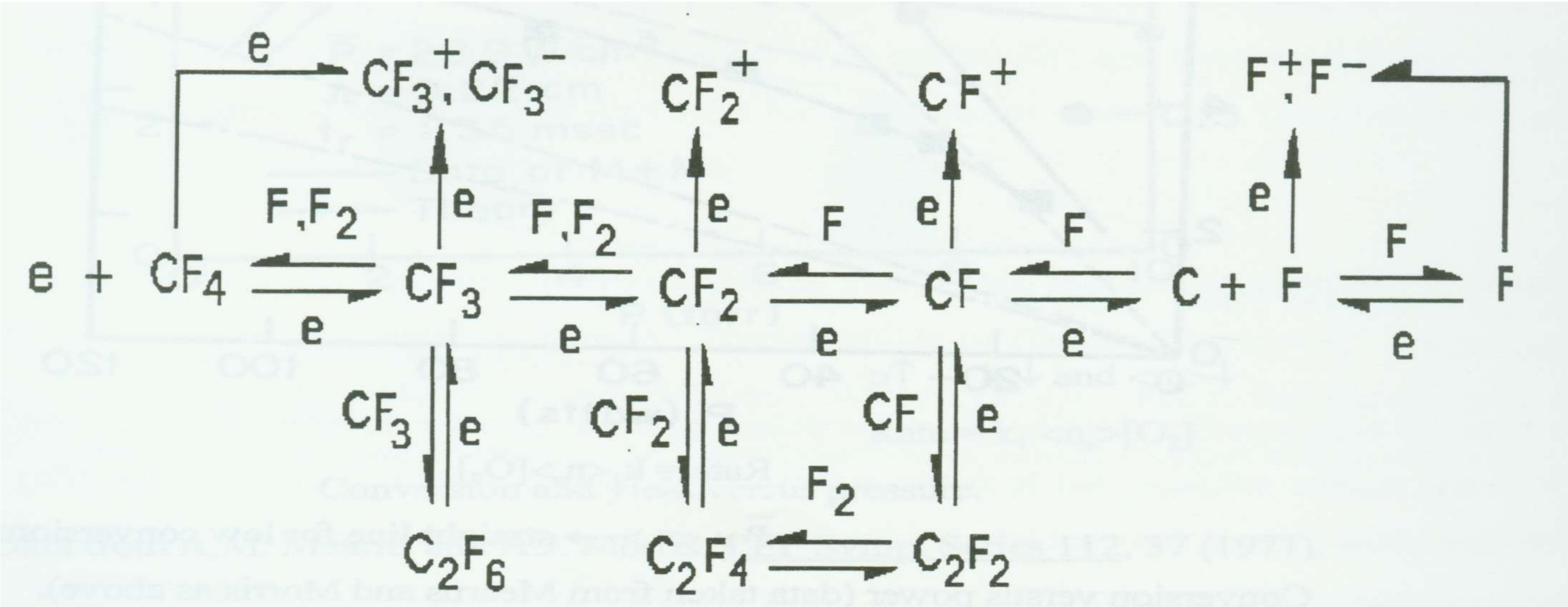
Reactions with Electrons in Plasma Discharge

- Excitation: $O_2 + e^- \rightarrow O_2^* + e^-$
- Dissociation: $SF_6 + e^- \rightarrow SF_5^* + F^* + e^-$
- Ionization: $Ar + e^- \rightarrow Ar^+ + 2e^-$
- Recombination: $e + Ar^+ \rightarrow Ar + h\nu$
- Dissociative attachement: $O_2 + e \rightarrow 2O + e \rightarrow O + O^-$

Table 11.5 Bond energies (kJ/mol)

C–O	1080	Si–F	550
Si–O	470	Si–Cl	403
Si–Si	227	Si–Br	370

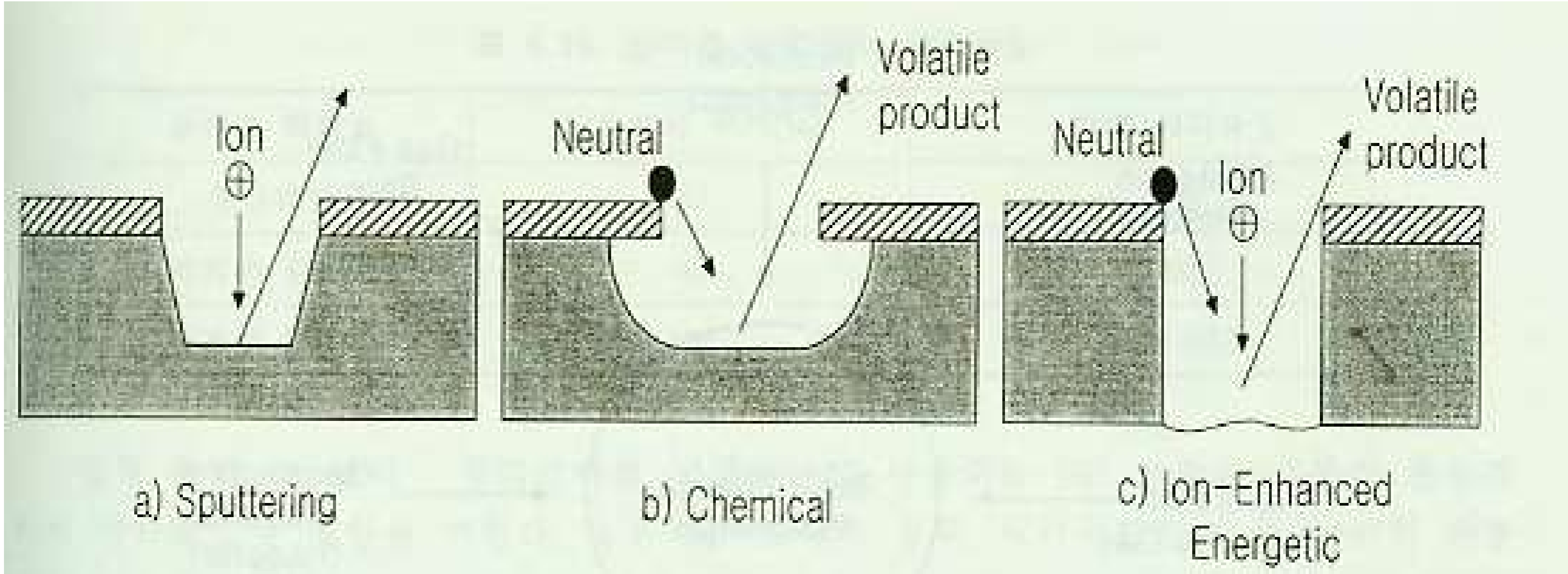
Reactions in CF_4 Discharge



■M.J.Kusher, J.Appl.Phys.53, 2923 (1982)

Dry (Plasma) Etching Types

Physical Process | Chemical Process | Physical + Chemical Process



- anisotropic
- low selectivity
- low etch rate

- isotropic
- high selectivity
- low etch rate

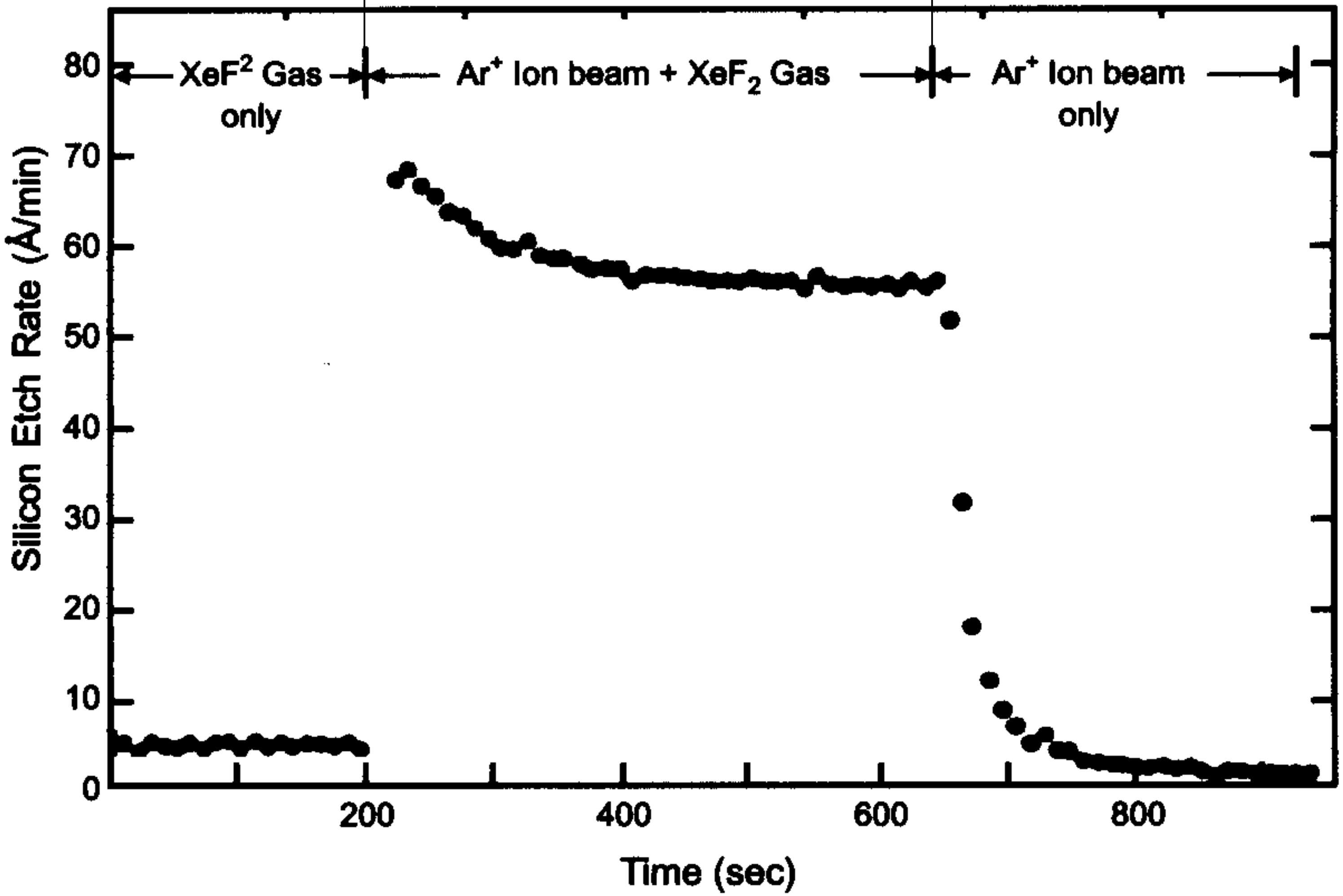
- anisotropic
- high selectivity
- high etch rate

Reactive Ion Etching

Etching by Neutral only

Etching by Ion(Ar^+) + Neutral (F)

Etching by Ion(Ar^+) only



Typical Etch Gases

Table 11.4 Typical etch gases

Fluorine	Chlorine	Bromine	Stabilizers	Scavengers/ others
CF_4	Cl_2	HBr	He	O_2
SF_6	BCl_3		Ar	
CHF_3	$SiCl_4$		N_2	
NF_3	$CHCl_3$			
C_2F_6				
C_4F_8				
XeF_2				

Etch Products

Table 11.6 Etch product boiling points (T_{bp}, °C)

SiF_4	−90	$SiCl_4$	−70	CO_2	−56
NF_3	−206	$AlCl_3$	190	PH_3	−133
WF_6	2.5	$GaCl_3$	78	AsH_3	−116
WOF_4	110	$TiCl_4$	−25		
TaF_5	96.8	$WOCl_4$	211	$SiBr_2$	5.4
MoF_6	17.5	WCl_6	275		
$MoOF_4$	98	$InCl_2$	235		
NbF_5	72	$MoCl_5$	194		
	$PtCl_4$	370d			
	PbCl4	−15			
	$Cr(CO)_6$	110d			

Note: d – decomposition

Table 11.7 Non-etchable reaction products (T_{bp}, °C)

$CuCl_2$	620	TiF_4	>400
CuF_2	950d	PbF_2	855
$CrCl_2$	824	CrF_2	1100
AlF_3	1290s	TiF_3	1200

Note: d – decomposition; s – sublimation

Gases used in Dry Etching Processes

- Solid(SiO_2) + Gas(4F) → Gas(SiF_4) + Gas(O_2)

Etch target		Gases for etching
Si	F containing	CF_4, SF_4, NF_3, SiF_4, BF_3, $CBrF_3$, XeF_2
	Cl-F containing	CClF, CCl_2F_2, CCl_3F, C_2ClF, $C_2Cl_2F_4$
	Cl containing	CCl_4, $SiCl_4$, PCl_3, BCl_3, Cl_2, HCl
	Br containing	HBr, Br_2
SiO_2	F-H containing	CHF_3, CF_4+H_2
	F/C < 4	C_2F_6, C_3F_8, C_4F_8
Al	Cl containing	CCl_4, BCl_3, $SiCl_4$, Cl_2, CCl_2F_2, CCl_3F
	Br containing	Br_2BBr_3

Gases for Plasma Etching

TABLE 8-2 Plasma Gases Used for Etching of Different Materials (from [26])

Material	Gases
Silicon	CF_4/O_2, CF_2Cl_2, CF_3Cl, $SF_6/O_2/Cl_2$, $Cl_2/H_2/C_2F_6/CCl_4$, C_2ClF_5/O_2, SiF_4/O_2, NF_3, ClF_3, CCl_4, CCl_3F_5, C_2ClF_5/SF_6, C_2F_6/CF_3Cl, Br_2, CF_3Cl/Br_2
SiO_2	CF_4/H_2, C_2F_6, C_3F_8, CHF_3/O_2
Si_3N_4	$CF_4/O_2/H_2$, C_2F_6, C_3F_8, CHF_3
Organics	O_2, CF_4/O_2, SF_6/O_2
Silicides	CF_4/O_2, NF_3, SF_6/Cl_2, CF_4/Cl_2
Al	BCl_3, BCl_3/Cl_2, $CCl_4/Cl_2/BCl_3$, $SiCl_4/Cl_2$
Cr	Cl_2, CCl_4/Cl_2
Mo, Nb, Ta, Ti, W	CF_4/O_2, SF_6/O_2, NF_3/H_2
Au	$C_2Cl_2F_4$, Cl_2, $CClF_3$
GaAs	BCl_3/Ar, $Cl_2/O_2/H_2$, $CCl_2F_2/O_2/Ar/He$, CCl_4
InP	CH_4/H_2, C_2H_6/H_2, Cl_2/Ar

Sidewall Formation in Si Etch

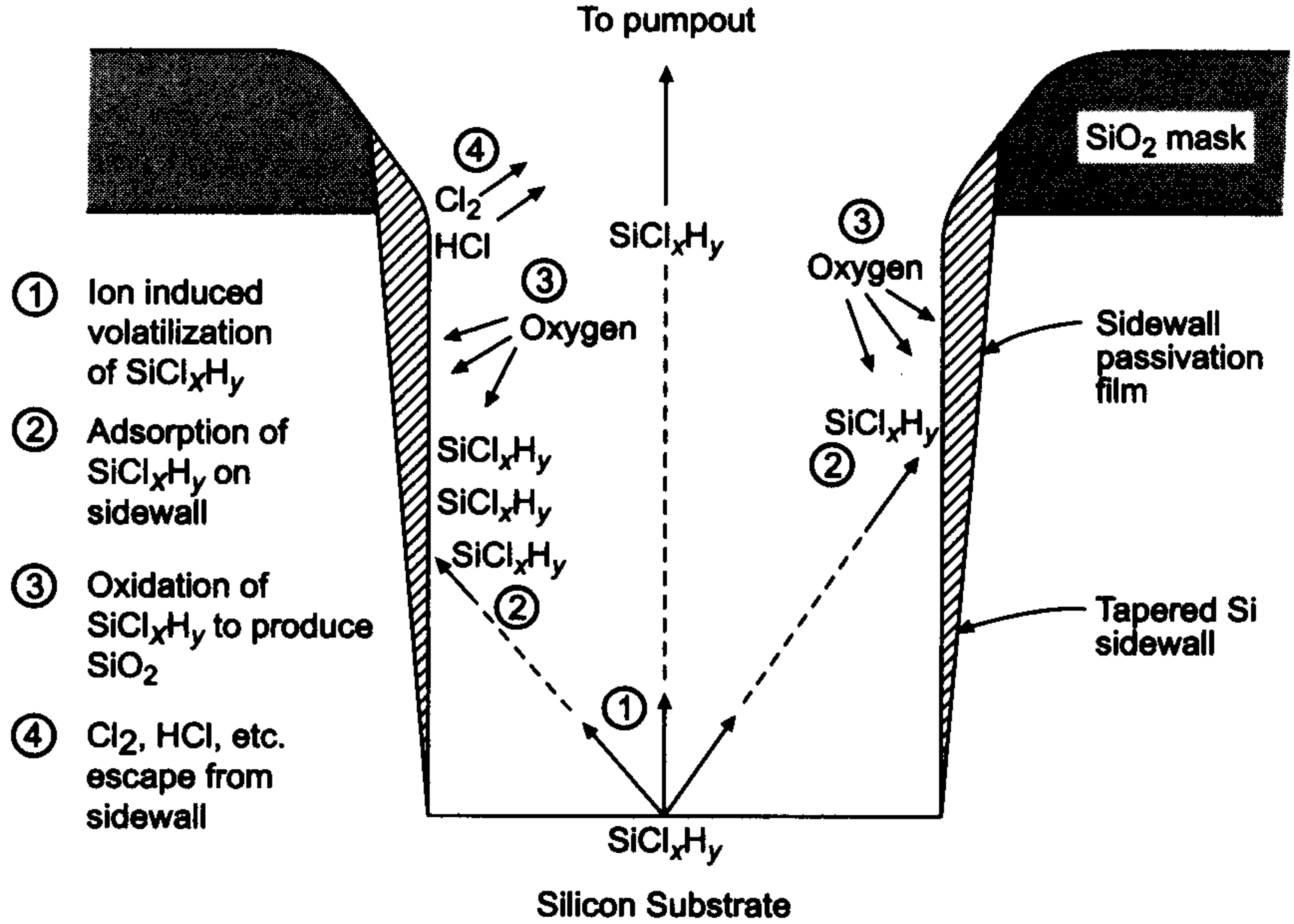
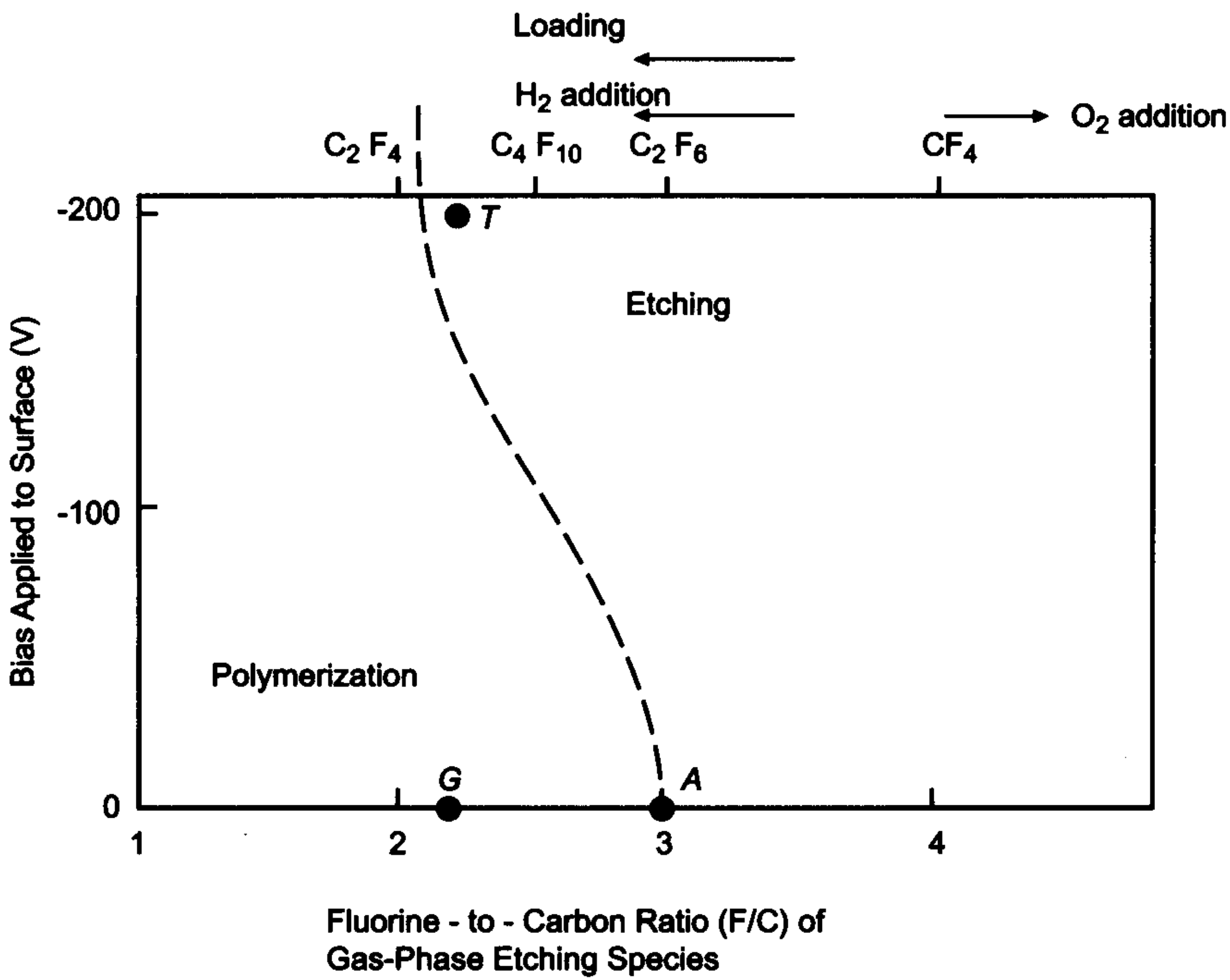


Fig. 8-7 A model for sidewall film formation in a $HCl/O_2/BCl_3$ RIE (from [20],

Fluorocarbon Plasma Chemistry



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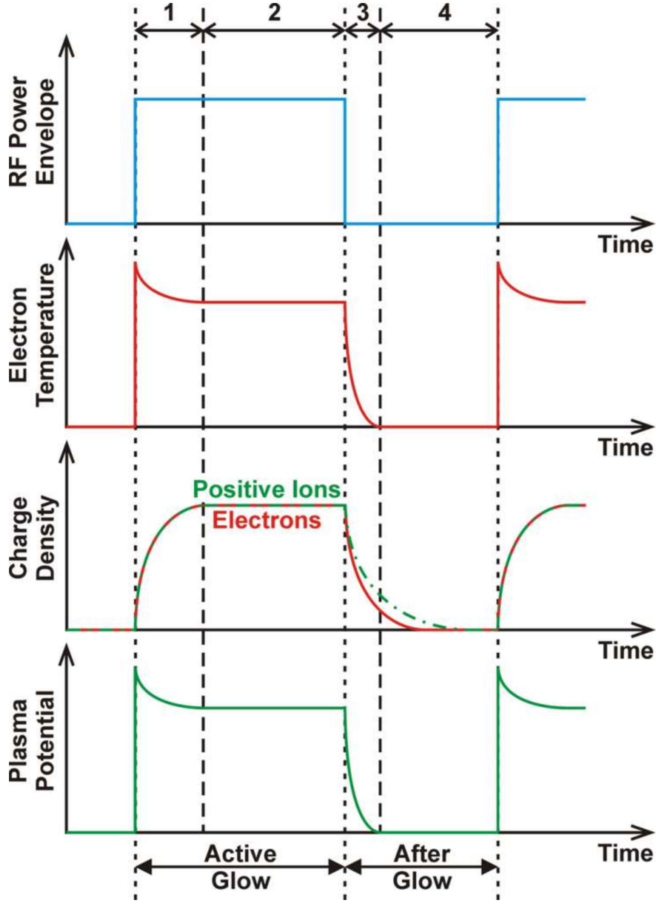
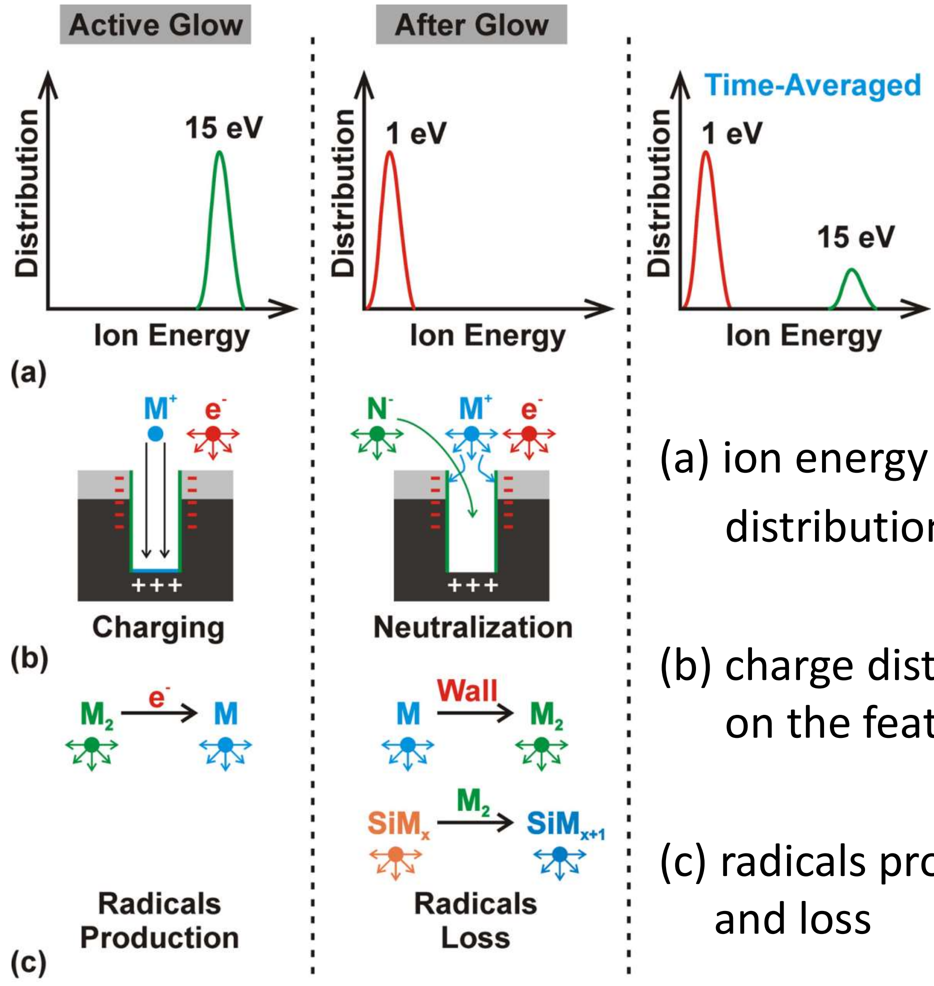
Pulsed Plasma Source

- Mechanisms





(a) ion energy distribution

(b) charge distribution on the feature

(c) radicals production and loss

■S. Banna et al., J. Vac. Sci. Technol. A 30, 040801 (2012)

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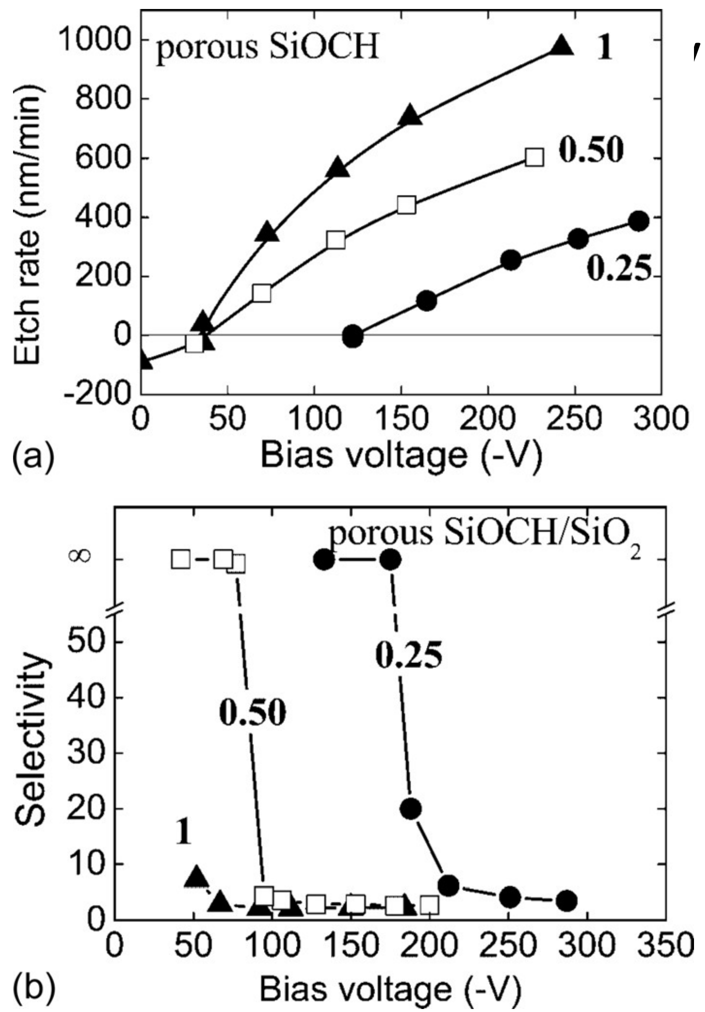
Pulsed Plasma Source



(a)

- Impact of the pulsed bias voltage duty cycle (1, 0.50, 0.25) on the porous SiOCH etch rate in CHF_3 plasma.

- The modulation frequency was fixed at 1 kHz.

- Decreasing the duty cycle led to a decrease of etch rates and to a shift of the etching/depositi on threshold to higher bias voltage.

(b) - Impact of the pulsed bias voltage duty cycl e (1, 0.5, 0.25) on the selectivity between poro us SiOCH and SiO_2 in CHF_3 plasma

▪ **V. Raballand et al., Plasma Processes Polym. 4, 563 (2 007)**

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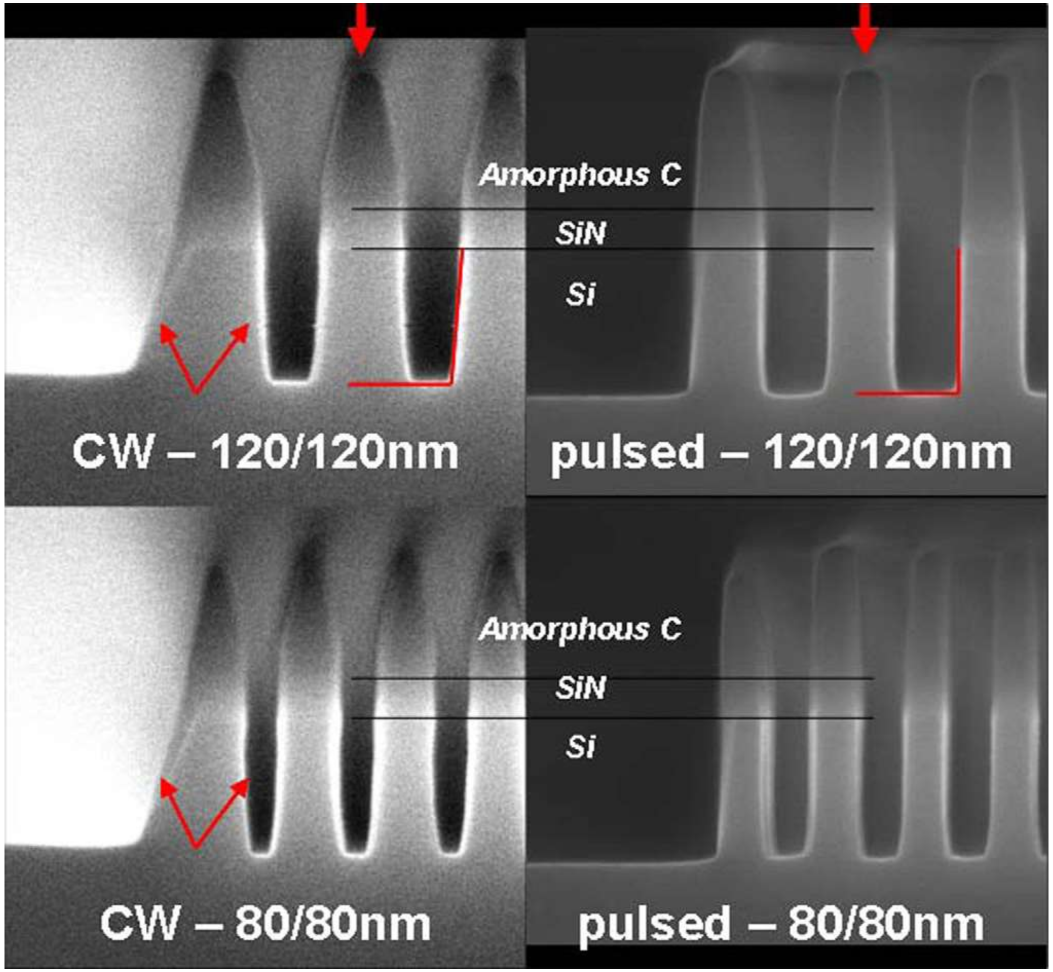
Pulsed Plasma Source

- Etch Profiles

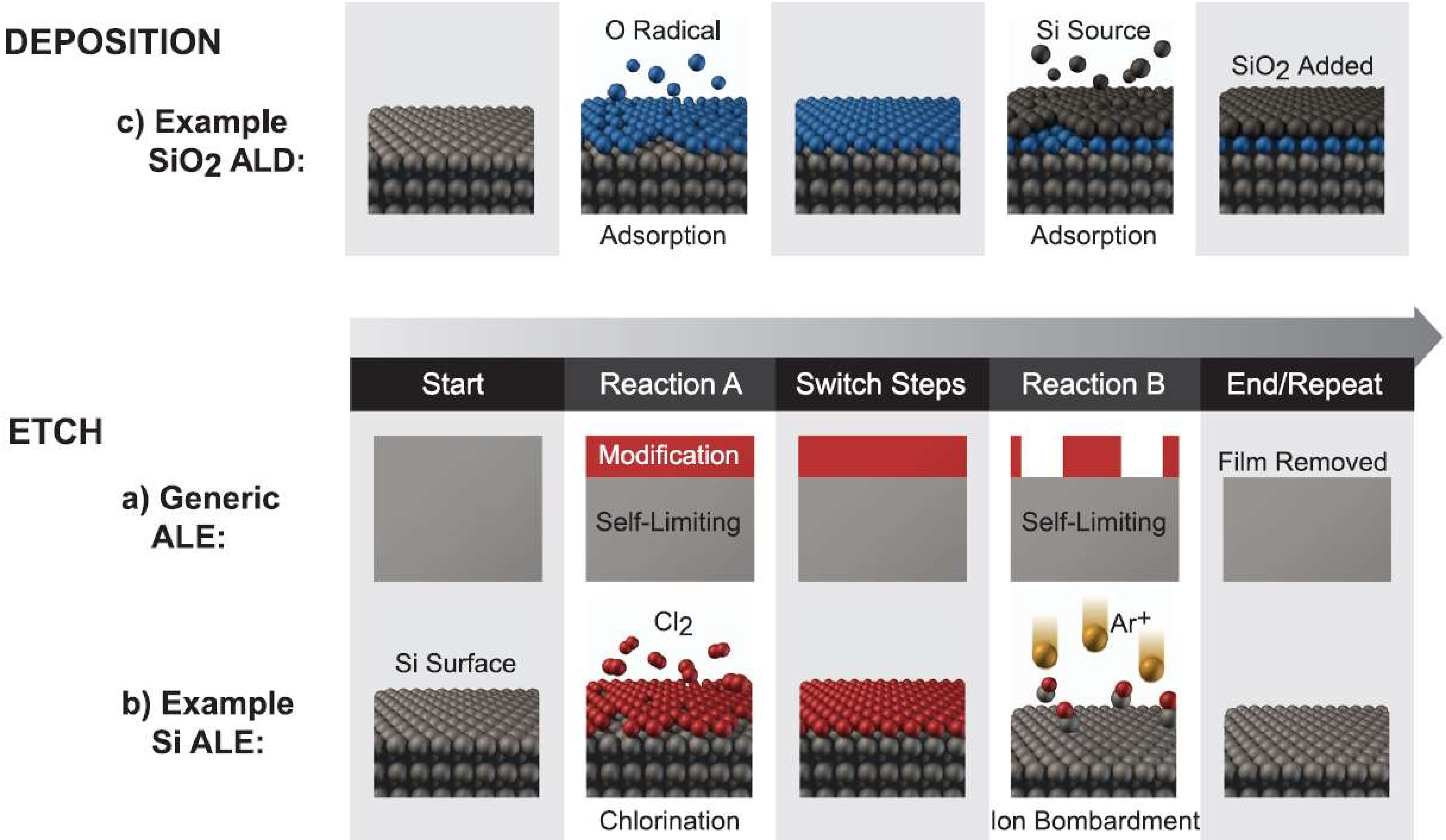


HBr/O_2 plasma etching in Si
Continuous wave (CW)
and Synchronous pulsing

1. 120 nm-wide with
   space of 120 nm trenches
2. 80 nm-wide with
   space of 80 nm trenches.

S. Banna et al., J. Vac. Sci. Technol. A 30, 040801 (2012)

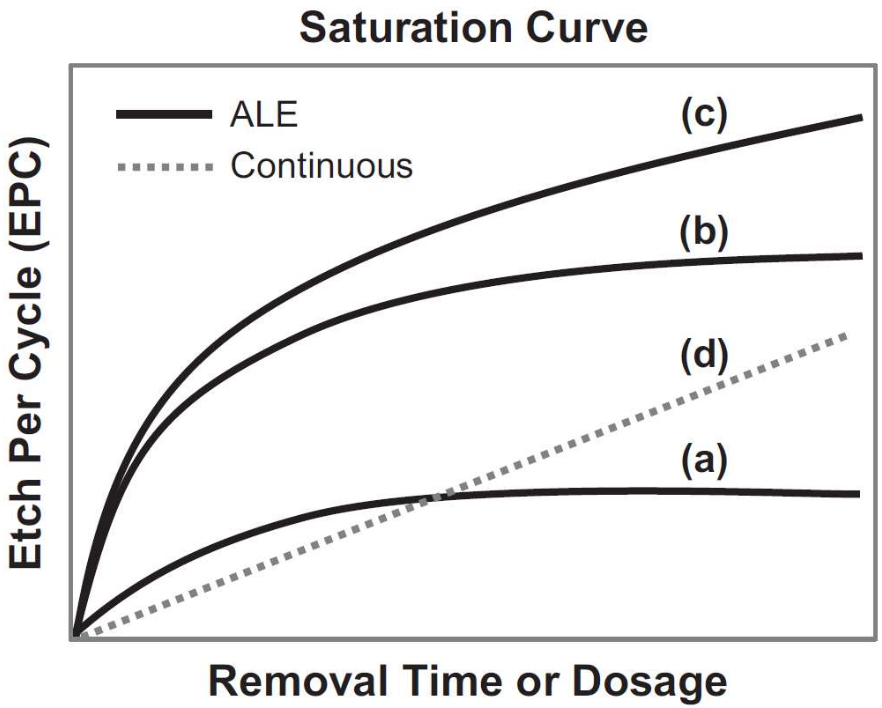
ALD and ALE

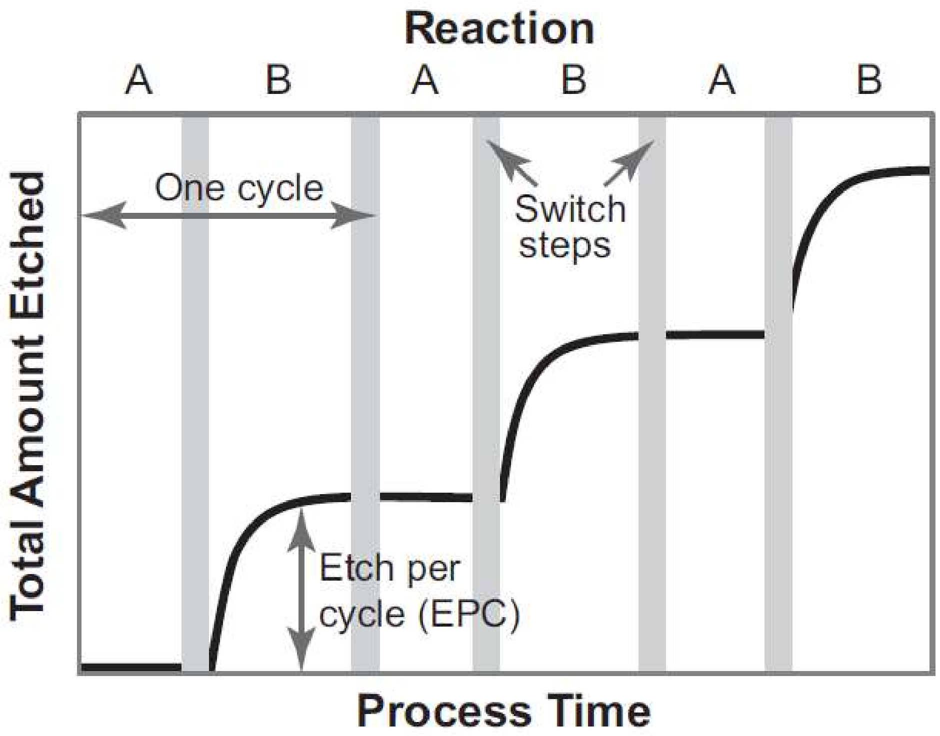


DEPOSITION
c) Example SiO_2 ALD:
O Radical
Adsorption
Si Source
Adsorption
SiO_2 Added
ETCH
a) Generic ALE:
b) Example Si ALE:
Start
Reaction A
Switch Steps
Reaction B
End/Repeat
Modification
Self-Limiting
Self-Limiting
Film Removed
Si Surface
Cl_2
Chlorination
Ar^+
Ion Bombardment

Atomic Layer Etching

◆ Self-limited Reaction





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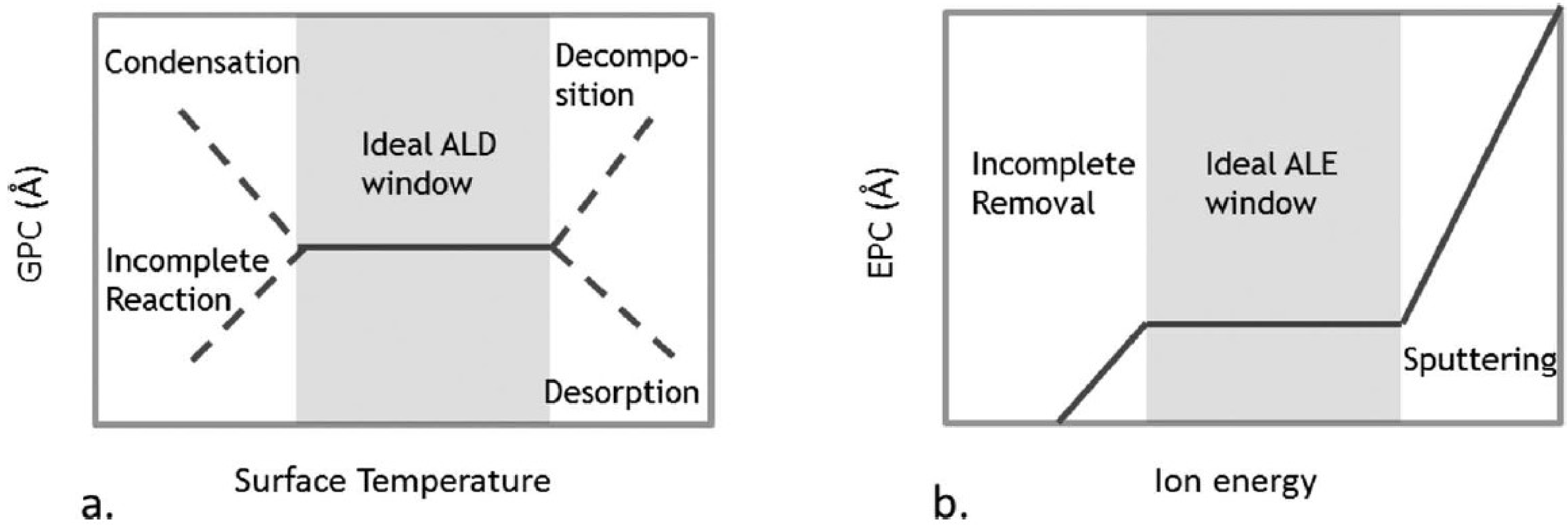
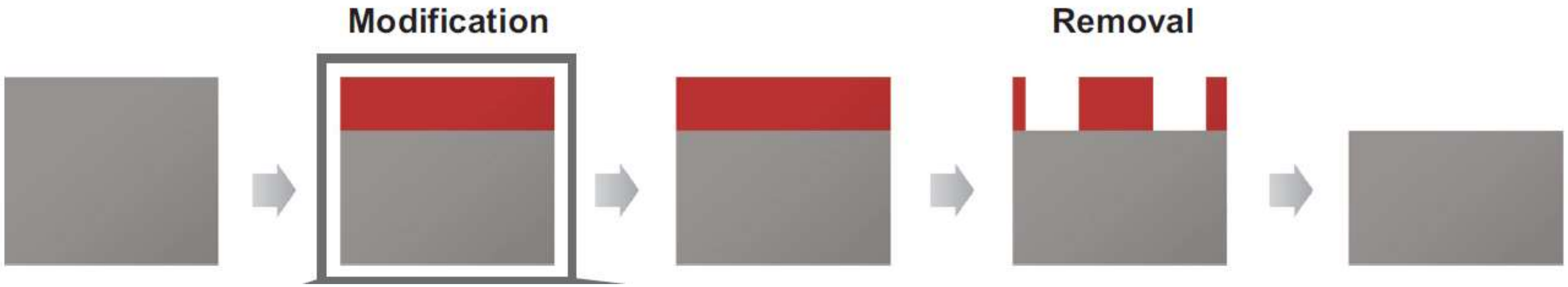
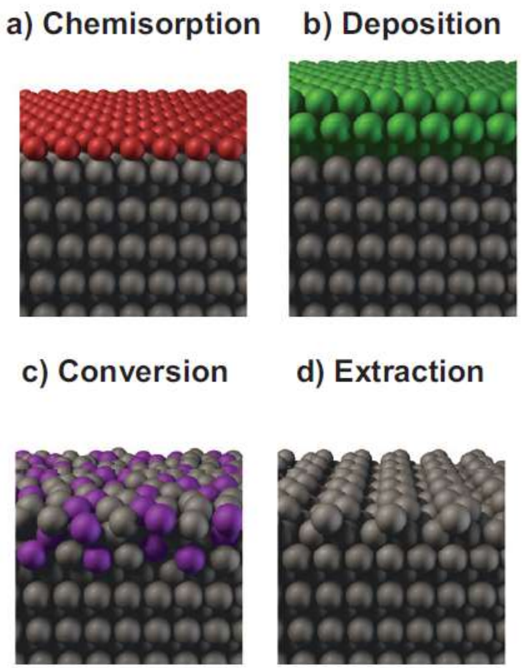
ALD and ALE

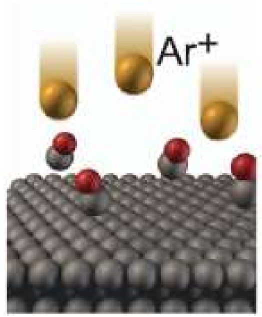


Condensation
Decompo-
sition
Ideal ALD
window
Incomplete
Reaction
Desorption
GPC (Å)
Surface Temperature
a.
Incomplete
Removal
Ideal ALE
window
Sputtering
EPC (Å)
Ion energy
b.

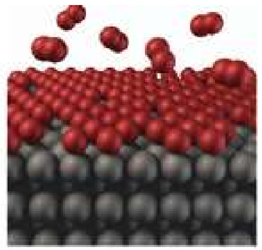
Atomic Layer Etching







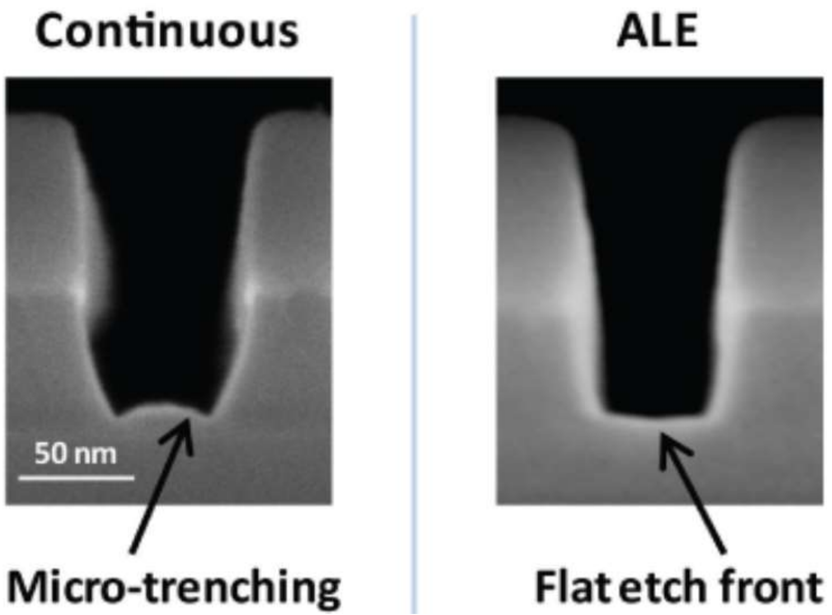
■Ion bombardment

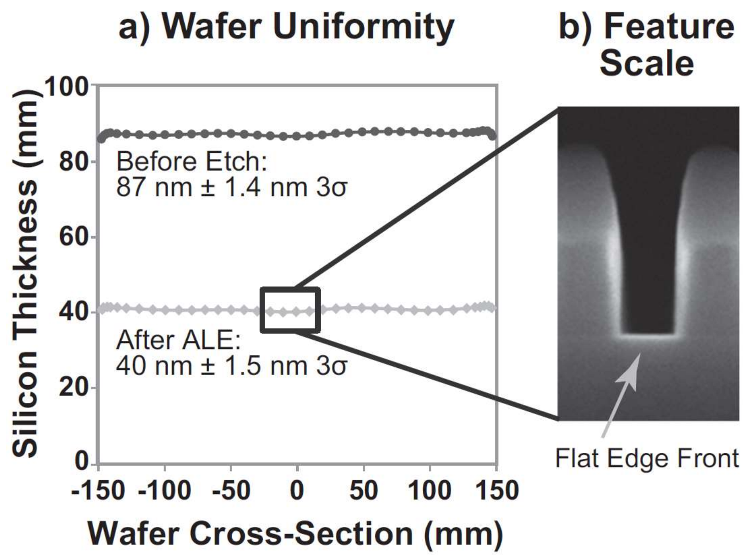


■Thermal desorption

Αδσορπτιον $\theta(t) = 1 - \exp(-K \cdot P \cdot t)$

Advantages of Atomic Layer Etching





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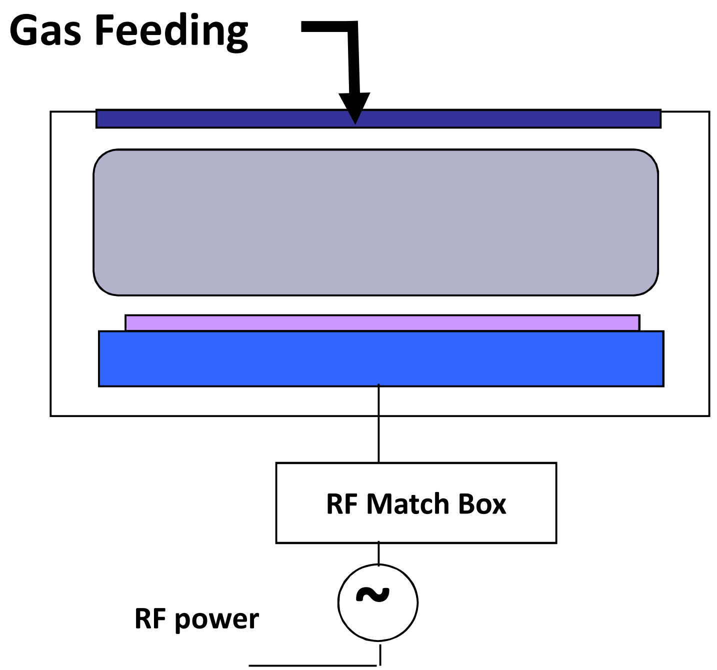
Plasma Etchers

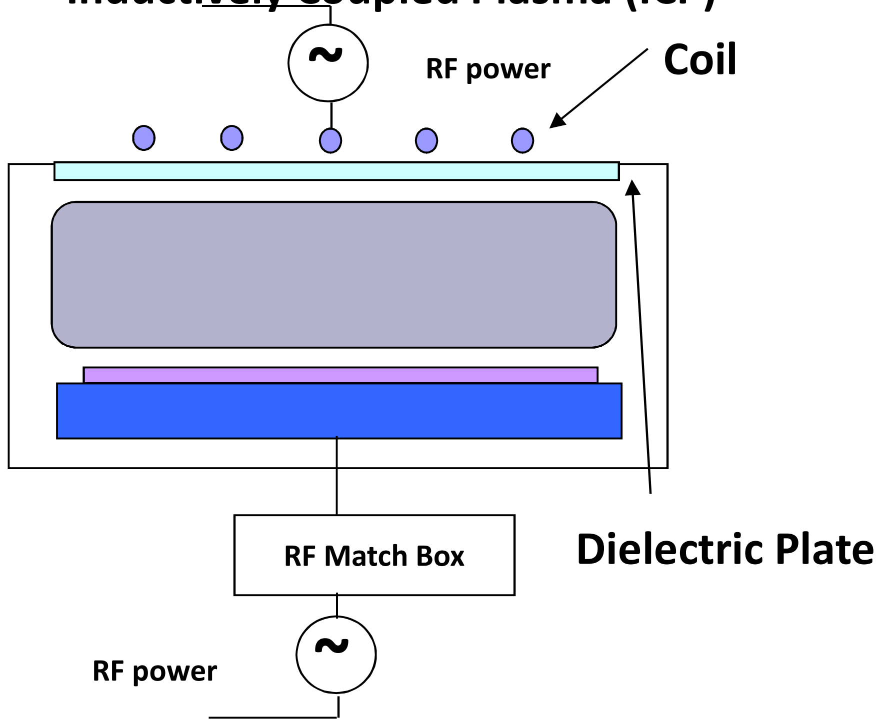
CCP and ICP

Capacitively Coupled Plasma (CCP)



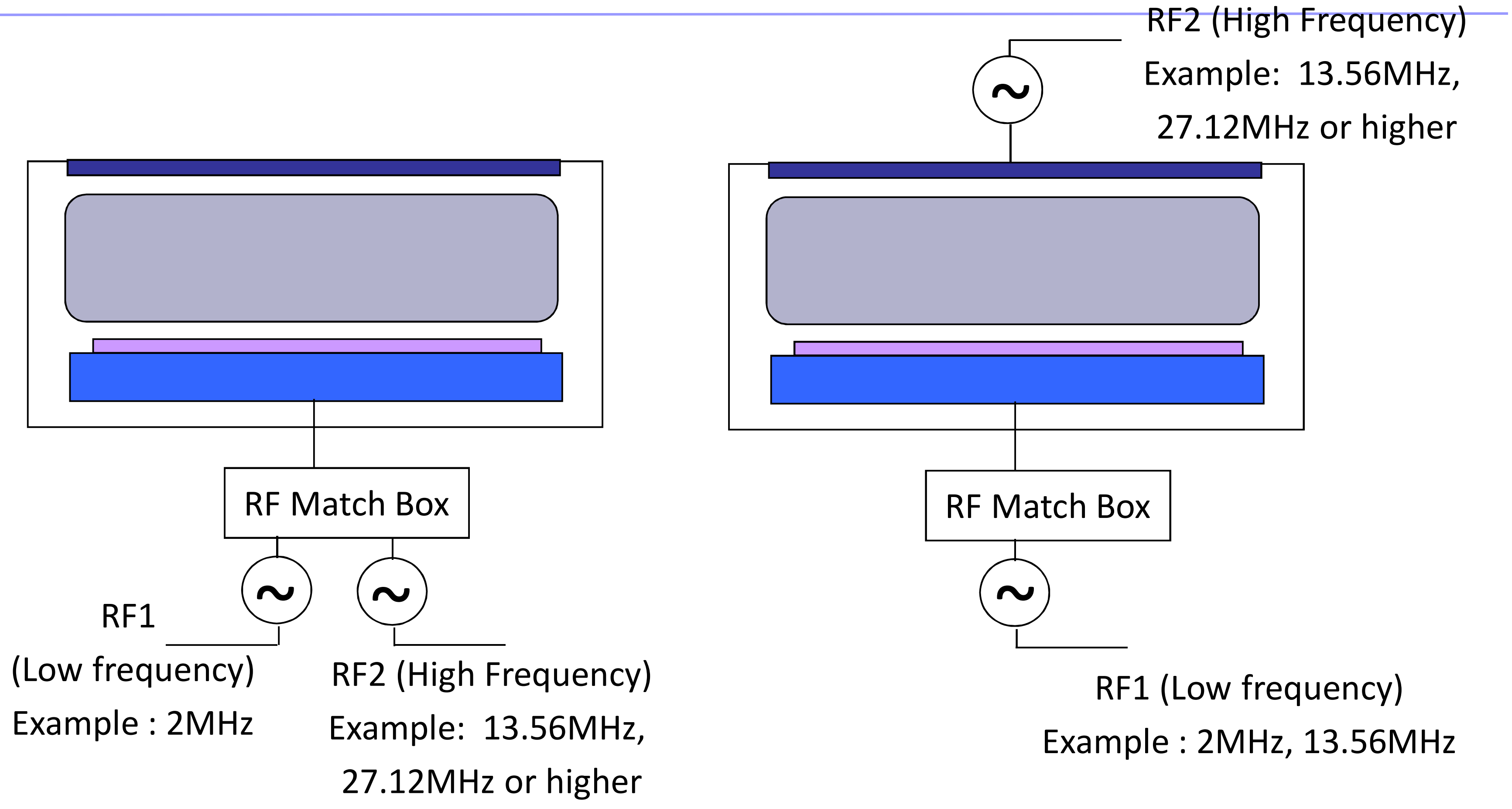
- Power delivered through parallel plates
- Relatively uniform plasma
- Low-to-medium density plasma : $10^8 \sim 10^{11}$ cm^{-3}
- High energy ion acceleration

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

Dual Frequency CCP



Decoupled plasma control

- Low frequency RF : ion energy control
- High frequency RF: plasma density control

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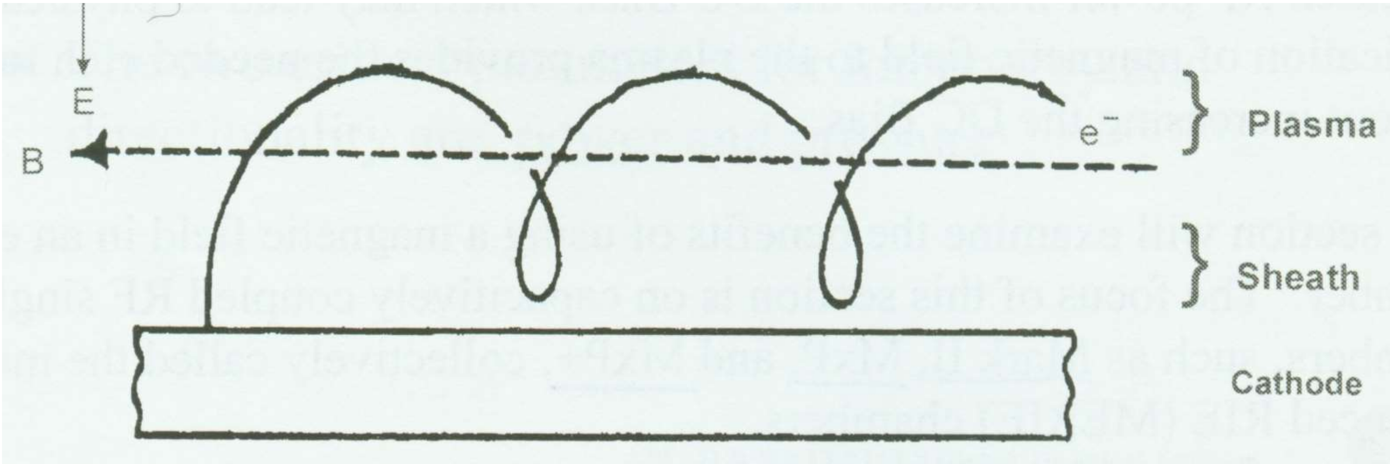
Effect of Magnetic Field



- Magnetic field makes the electron moving path longer
- Magnetic field increases plasma density
- Magnetically Enhanced Reactive Ion Etcher (MERIE)

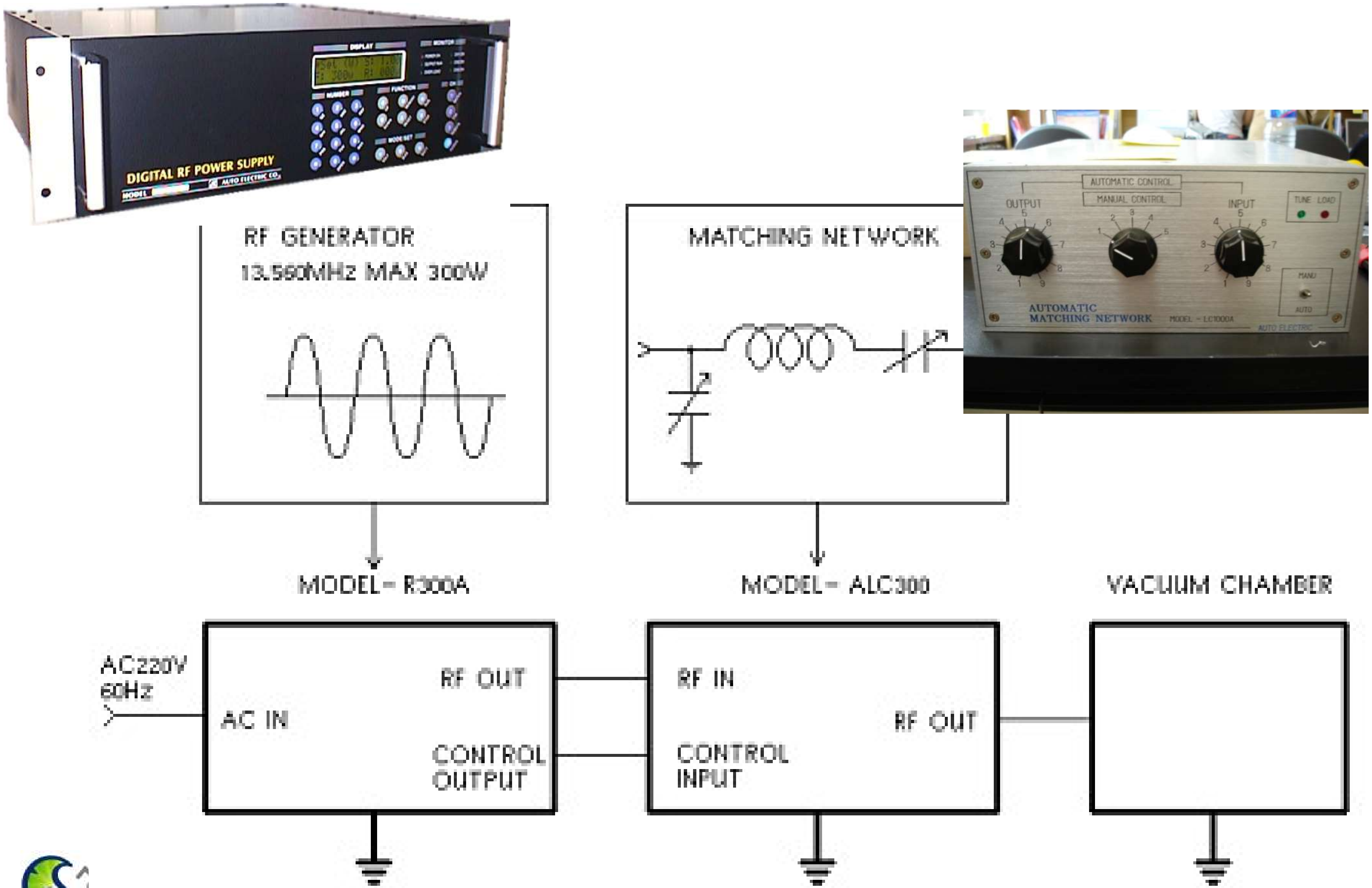
Plasma Reactors

Parameters	ICP	ECR	Helium	SPRP	MERIE	RIE	PE
Frequency	13.56 MHz	2.45 GHz	13.56 MHz	400 kHz	13.56 MHz	13.56 MHz	13.56 MHz
Gas pressure (torr) *	$\sim 1^{-3}$	$\sim 4^{-4}$	$\sim 1^{-3}$	$\sim 1^{-1}$	$\sim 1^{-2}$	$\sim 7^{-2}$	$\sim 1^{-1}$
Electron temperature (eV)	~ 4	~ 4	~ 4	~ 10	~ 5	~ 8	~ 8
Plasma density (cm^3) *	$\sim 5^{11}$	$\sim 3^{11}$	$\sim 5^{11}$	$\sim 8^{10}$	$\sim 5^{10}$	$\sim 1^{10}$	$\sim 3^{8}$
Ion current density (mA/cm^2)	~ 10	~ 10	~ 10	~ 2	~ 1	~ 0.1	~ 0.1
Ion energy (eV)	Controllable	Controllable	Controllable	30–150	~ 200	200–1000	~ 20

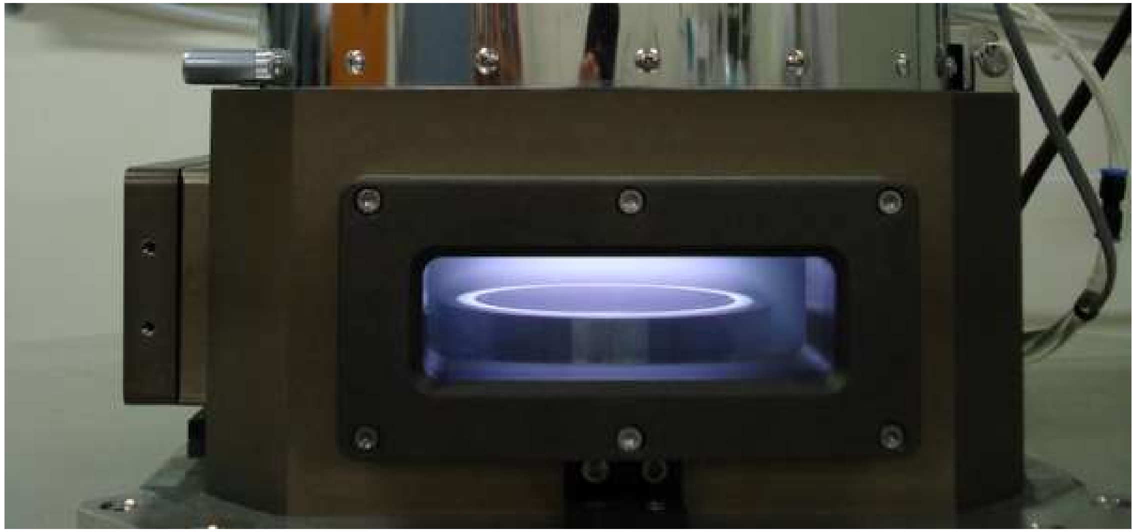
ICP – inductively coupled plasma
ECR – electron cyclotron resonance
SPRP – split power reverse phase/rainbow 4500
* indicates $\sim \times 10^x$

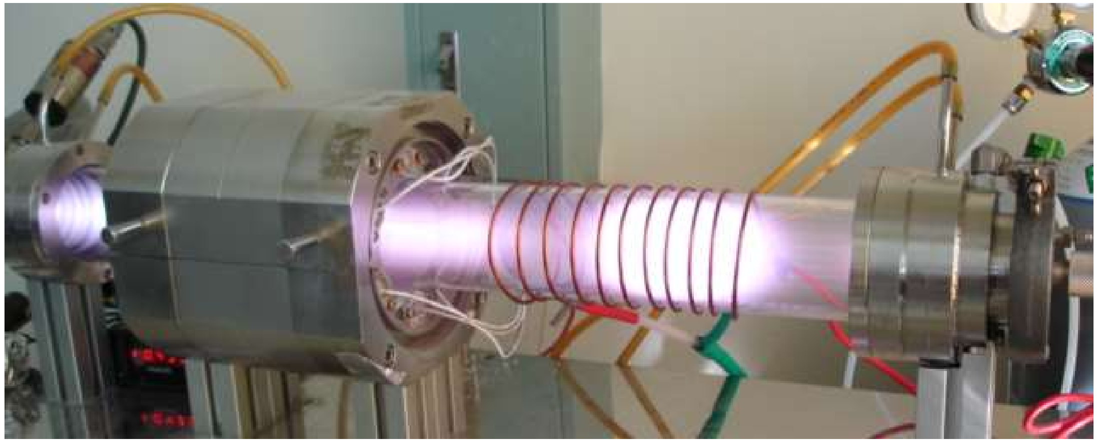
MERIE – magnetically enhanced RIE
RIE – reactive ion etching
PE – plasma etching

RF Power Supply and Matching Network



Plasma Reactors





Commercial Plasma Etchers

MERIE

ICP

VHF Dual Frequency CCP

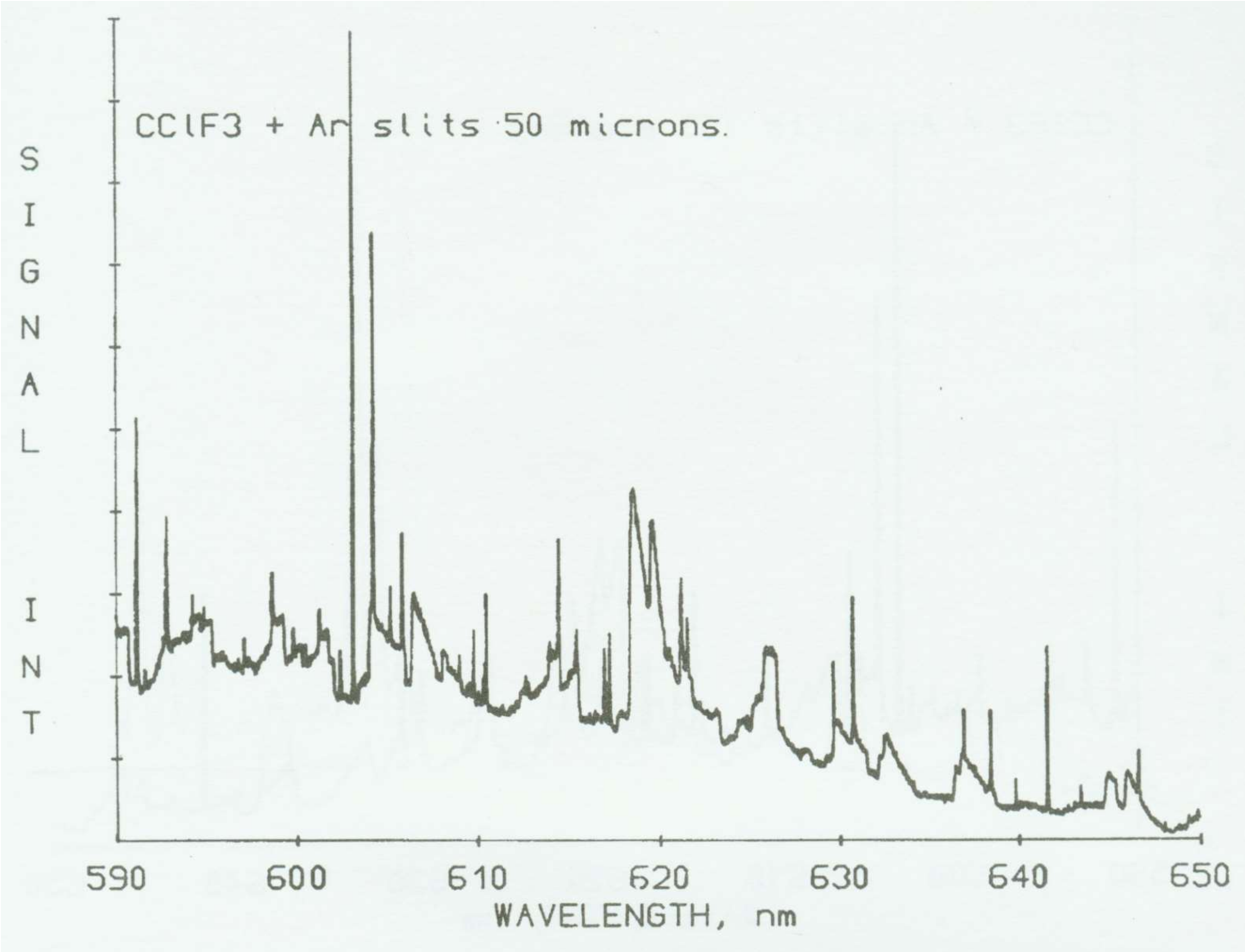
http://www.appliedmaterials.com/products/assets/brochures/etch_english_1204.pdf

Plasma Diagnostics

Plasma Diagnostics

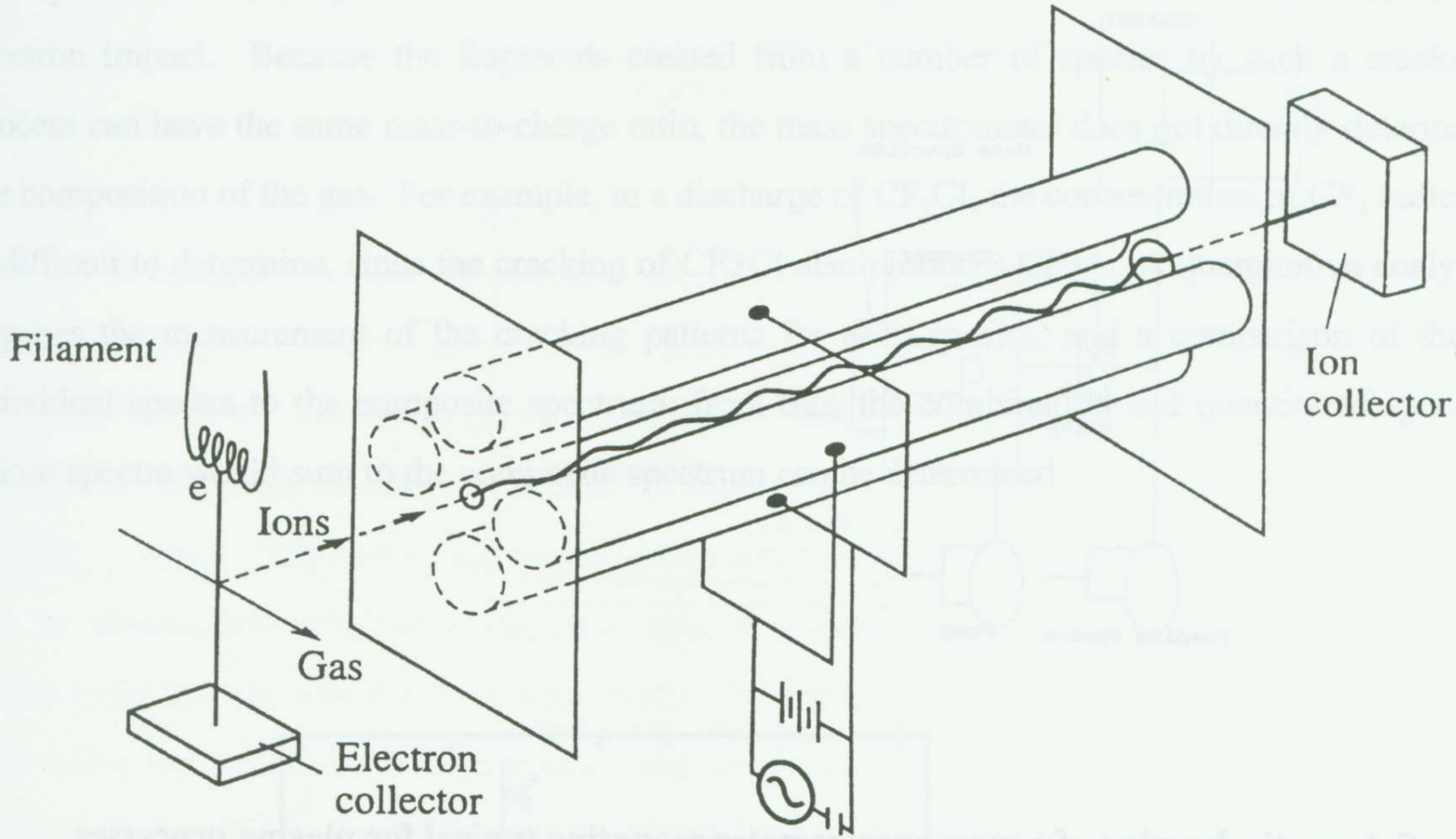
- Optical Emission Spectroscopy (OES)
- Mass Spectroscopy (MS)
- Langmuir Probe
- Endpoint Detection for Plasma Etching

Optical Emission Spectroscopy (OES)



Mass Spectrometer

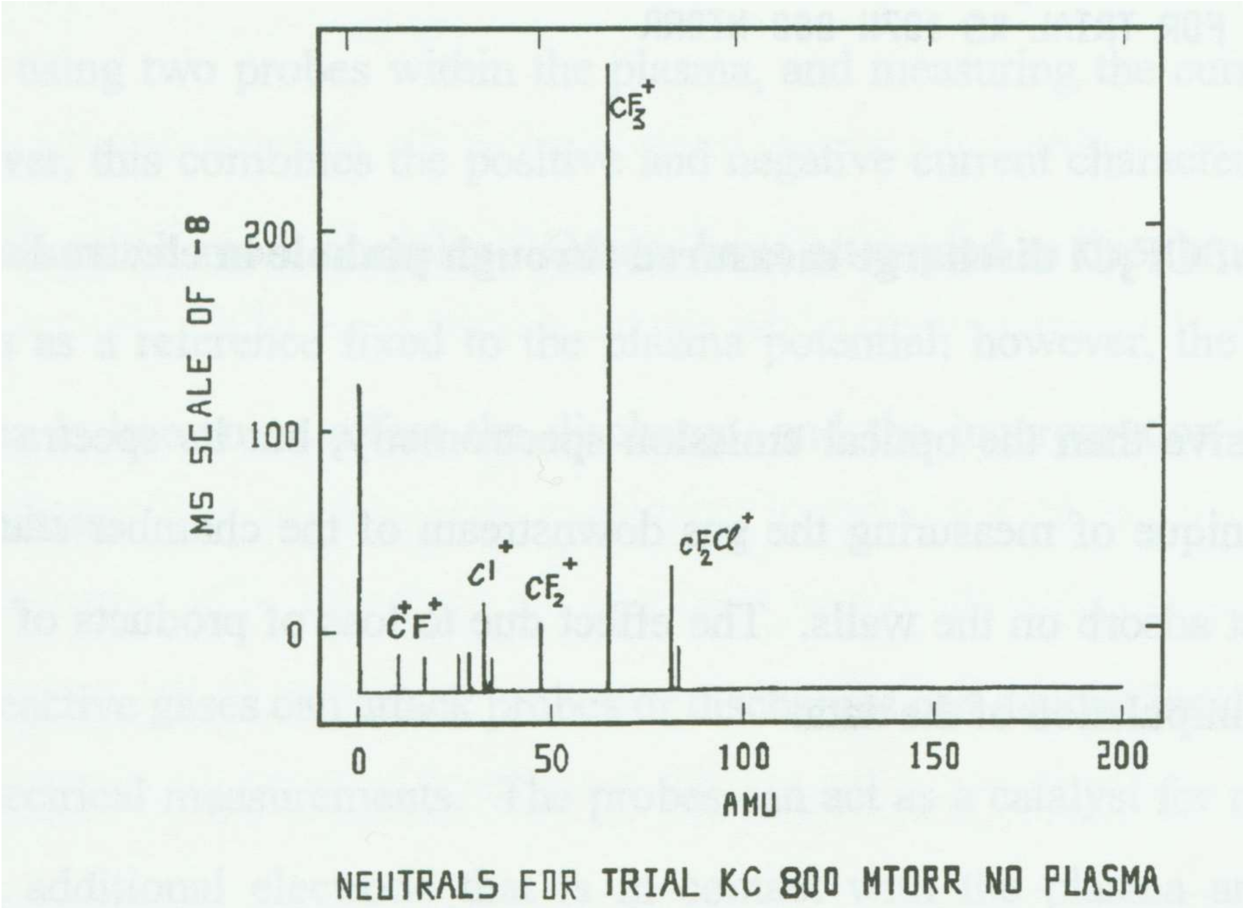
- For ion and neutral identification



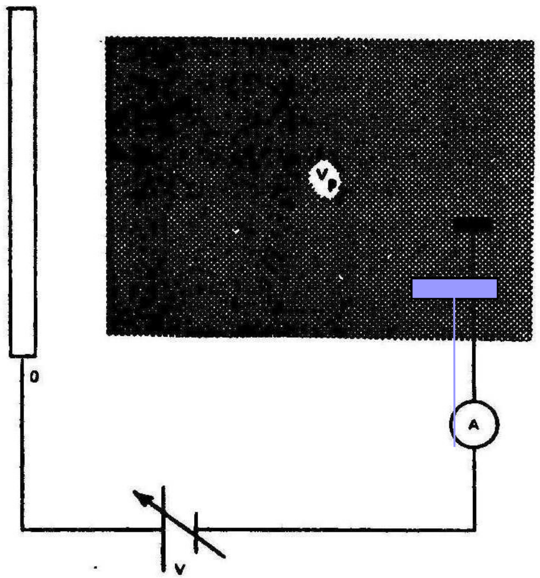
Schematic drawing of a quadruple mass spectrometer.

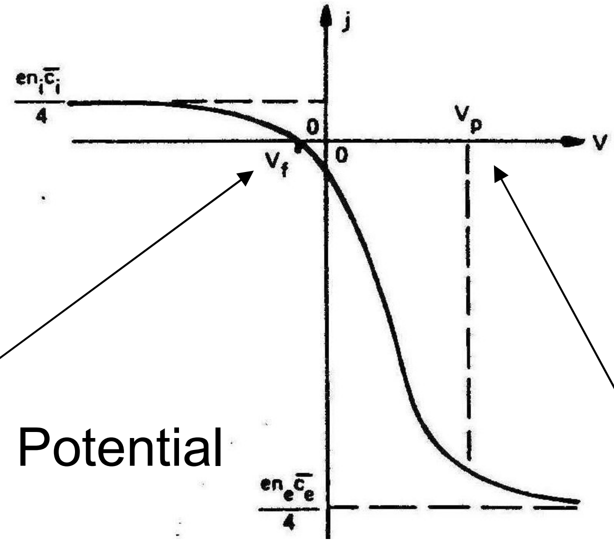
Mass Spectroscopy

- Spectrum of CF_3Cl



Langmuir Probe and IV Curve

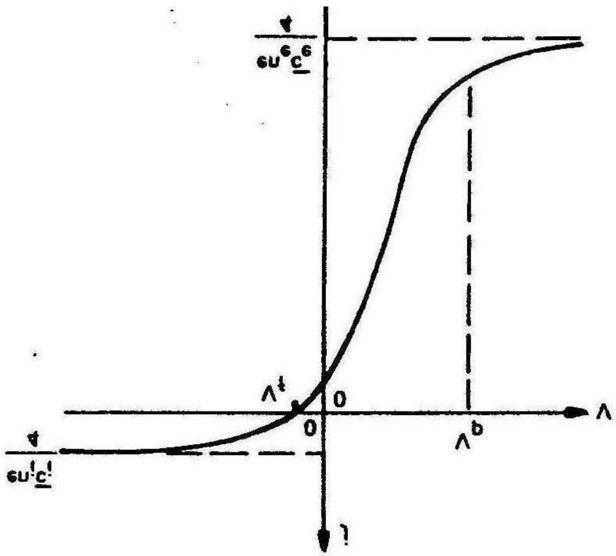




■Floating Potential

■상하대칭

■Plasma Potenti

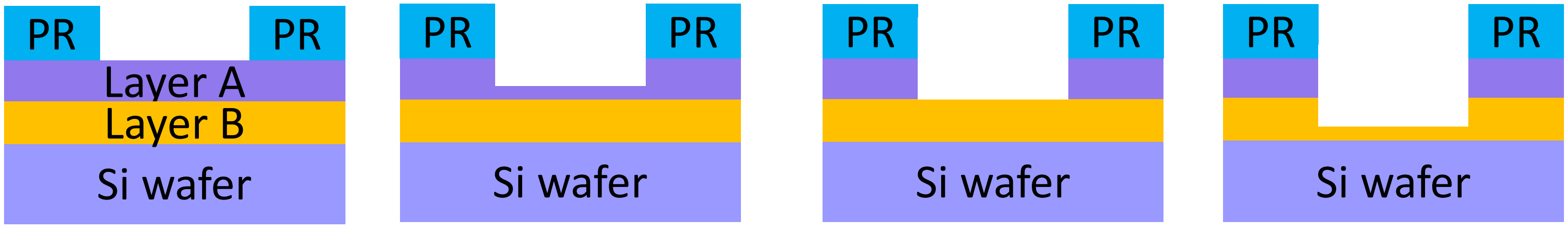


$$V_f = -\frac{kT_e}{2e}\ln\left(\frac{m_i}{2.3m_e}\right)$$

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.

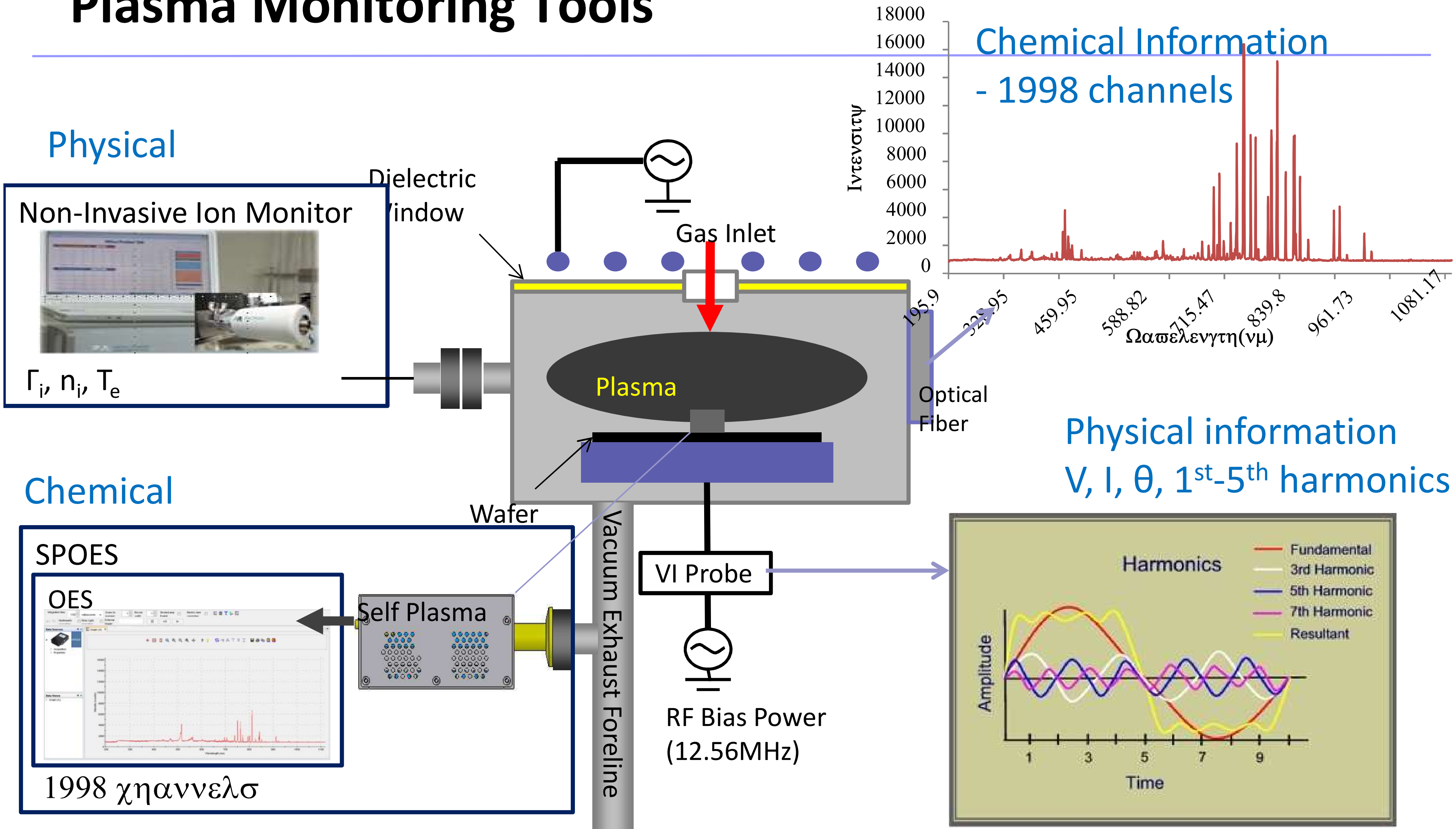
$$SiN_x + CF_4 + O_2 \rightarrow \underbrace{SiF_x + F + CF_x}_{\text{표면}} + \underbrace{CN + FCN + C_2N_2 + N}_{\text{플라즈마 내부}}$$



Before etching | After etching Incomplete-etching (X) | After etching Complete-etching (O) | After etching Over etching (X)

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

Plasma Monitoring Tools



- Chemical and physical sensors are required for plasma analysis
- Big data mining techniques applied to increase sensitivity of sensors

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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: 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

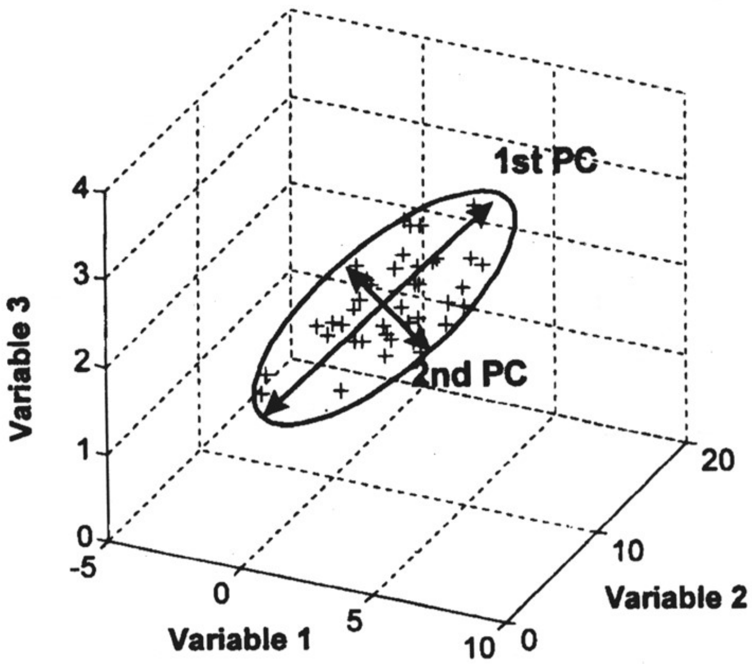
Maximizing s_{t_i}(variance of t_i)
Constraint : $p_{i1}^2 + p_{i2}^2 + p_{i3}^2 = 1$

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

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

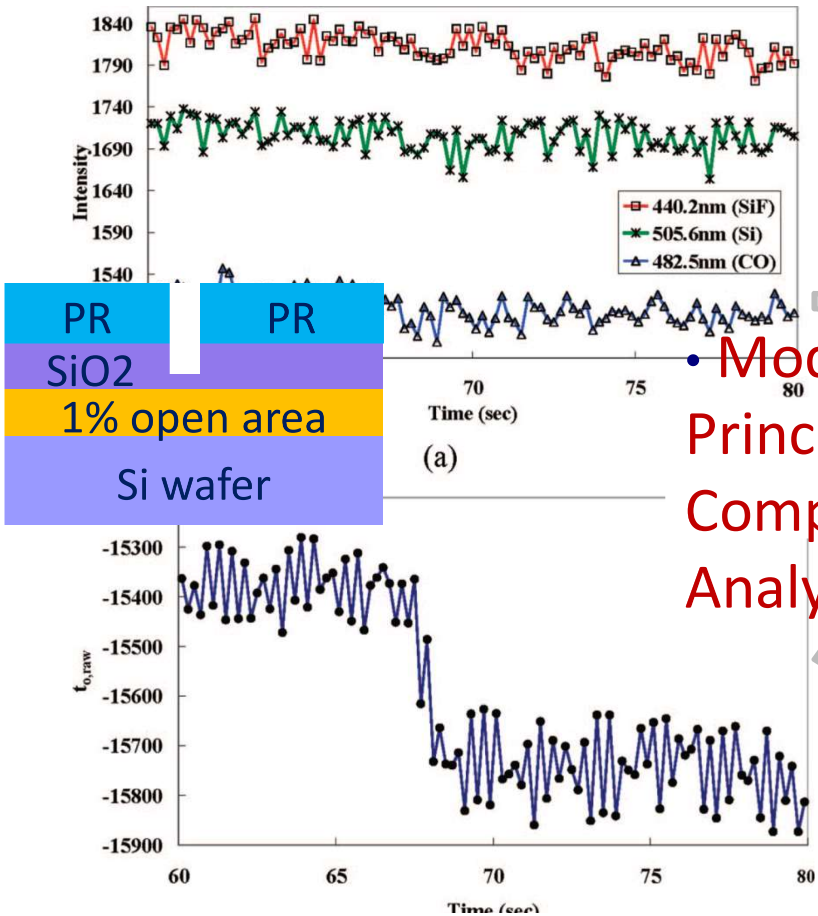
$$|S - \lambda I| = 0$$

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

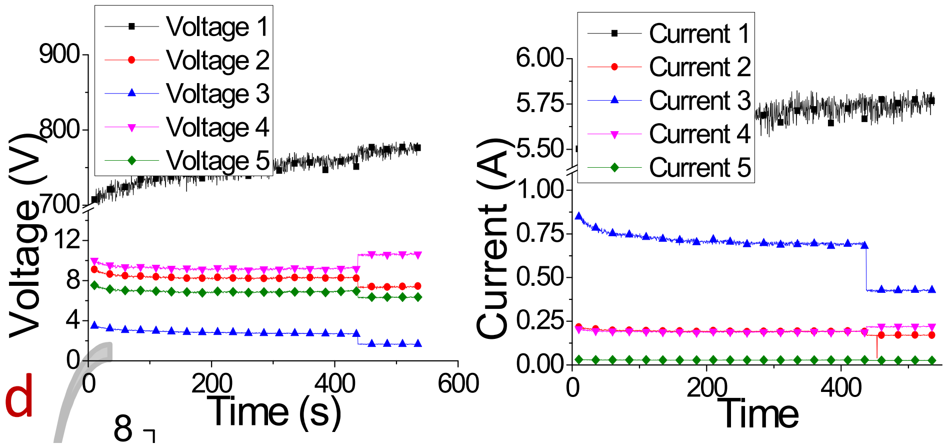


Plasma Monitoring @ SKKU

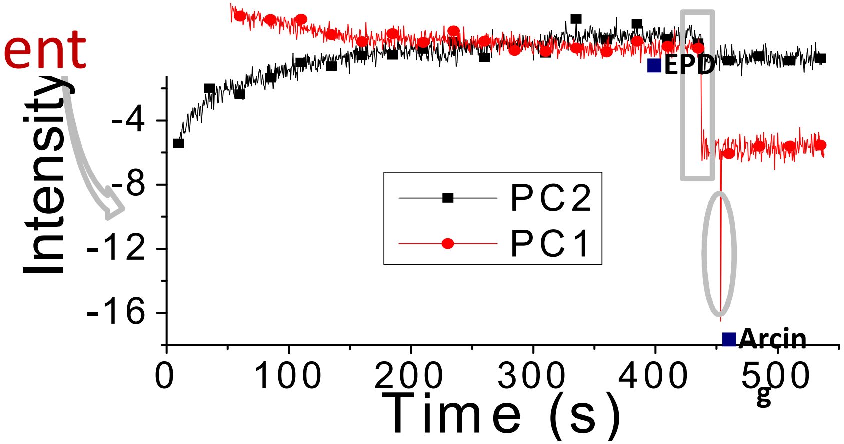
EPD (OES) : chemical information



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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Summary

- Plasma Etching by Radicals and Ions
- Plasma Etching Chemistry
  - F, Cl, and Br containing compounds for Si etching
  - F containing compounds for SiO2 etching
  - Cl, and Br containing compounds for Al etching
- Plasma Diagnostics
  - Physical: Langmuir Probe, Impedance
  - Chemical: OES, Mass Spectroscopy
- Issues of plasma etching
  - Process: Profile, Uniformity, Selectivity, Striations
  - Productivity: Etch rate, Cleaning

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- B. Chapman, “Glow Discharge”, Academic Press, 1980
- M. A. Liberman & A. L. Lichtenberg, “Principles of Plasma Discharges and Materials Processing”, Wiley Interscience, 1994
- 특허청, 한국발명진흥회, “반도체 제조용 식각기술, PM보고서”, 2004
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