國立交通大學
電子工程學系暨電子研究所
National Chiao-Tung University
Department of Electronics Engineering &
Institute of electronics

Etching Process
- Plasma Fundamentals

Outline

- Introduction to etching process
- Wet etching technique
- Plasma Fundamentals
  - Introduction to Plasma
  - Collision process in plasma
  - Plasma dynamics and sheath
  - Plasma reactors
  - High density plasma sources
- Plasma etching techniques
  - Plasma etching
  - Adverse effects
  - Dielectric etching
  - Poly-Si and bulk Si etching
  - Metal etching
  - End-point detection

Etching History

- In 1959, Robert Noyce at Fairchild Semiconductor invented the first planar silicon IC.
- In mid-1970, employed photo lithography Novolak-based resist to pattern device with critical linewidth < 3μm.
- Wet etching was used for manufacturing devices with critical line width > 3 μm.
- Since 1960's, pioneering work on gaseous free radical etching by J. Ligenza at Bell Lab.
- Since 1980's, progressing to 1 μm generation, plasma etching became dominant process.

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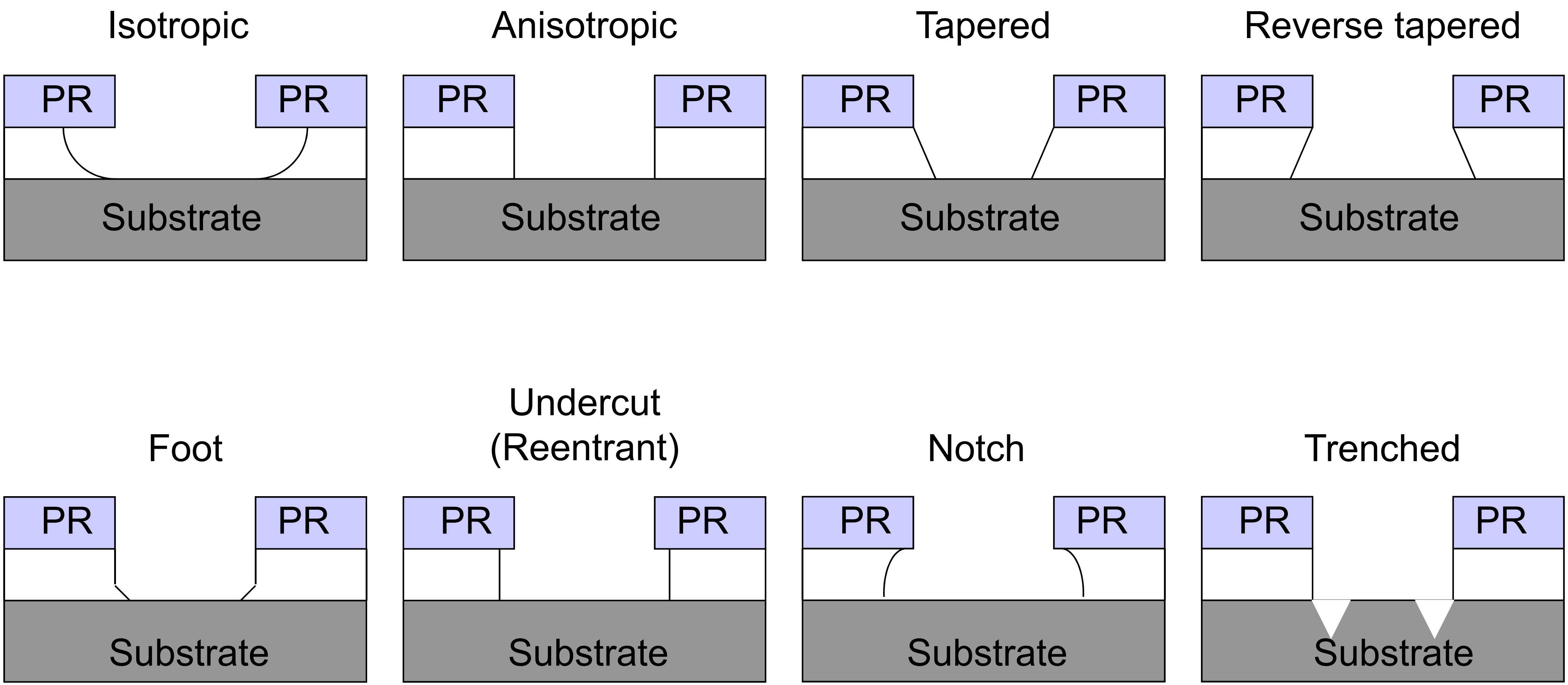
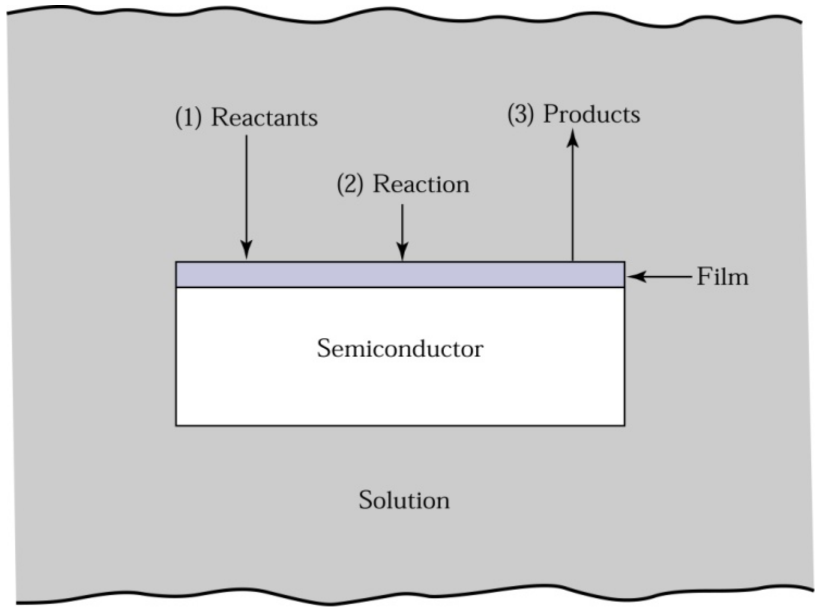
Etching Profile



Wet Etching

Application of Wet Etching

- Film stripping
- Pre-metal deposition, pre-poly-Si deposition, pre-diffusion, and pre-oxidation clean.
- Damage removal after dry etching.
- Polymer removal
- Selective etching between metal and metal silicides



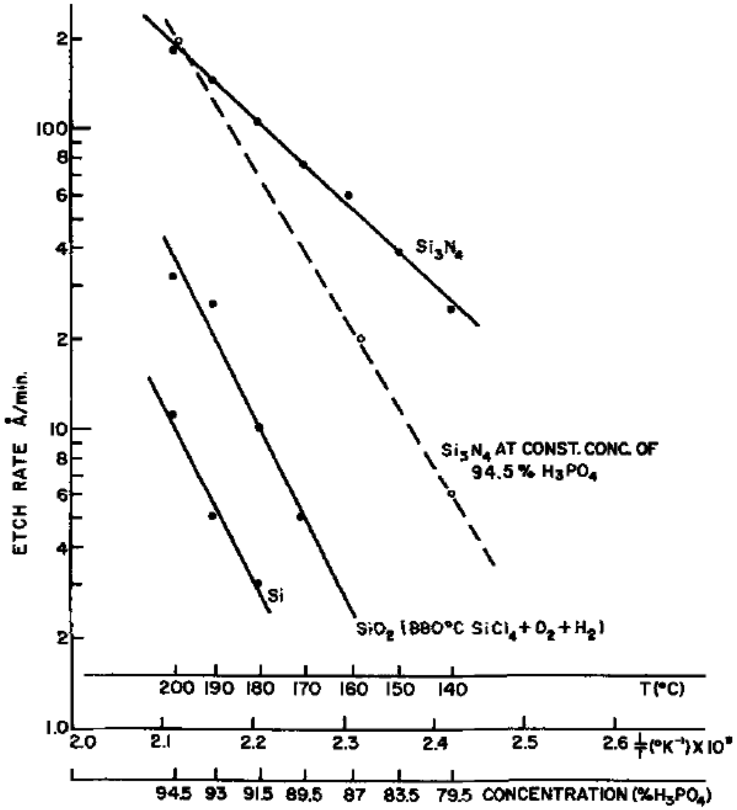
SiO_2 Wet Etching

- Diluted HF
  - HF : H_2O=1:10 ~ 1:1000
  - The overall reaction is $SiO_2+6HF \rightarrow H_2SiF_6+2H_2O$
  - The detailed reaction is very complex.
- Buffered HF or Buffered Oxide Etchant (BOE)
  - NH_4F + HF + H_2O
  - The addition of NH_4F forms buffered solution.
  - NH_4F controls pH value and provides sufficient F to maintain constant etching rate.

Property	Thermally grown at 1000°C	SiH_4+O_2 at 450°C	TEOS at 700°C	$SiCl_2H_2$+N_2O at 900°C
Density (g/cm^3)	2.2	2.1	2.2	2.2
Etch rate (nm/min) (H_2O:HF=100:1)	3	6	3	3
Etch rate (nm/min) (Buffered HF))	44	120	45	45

Si_3N_4 Wet Etching

- Hot H_3PO_4
  - $Si_3N_4 + 4H_3PO_4 \rightarrow Si_3(PO_4)_4 + 4HN_3$
  - 91.5% H_3PO_4 boiling at 130-180 °C
  - LPCVD Si_3N_4 : 10 nm/min
  - CVD SiO_2 : 0.1~1 nm/min
  - Poly-Si or heavily doped Si : slightly faster than SiO_2
  - H_2O depletion will degrade etch rate selectivity.



- Hot HF or DHF
  - Etching rate higher than 1 μm/min of LPCVD Si_3N_4 in hot HF can be obtained.
  - Etching rate of PECVD Si_3N_4 in DHF is much higher than 1 μm/min at room temperature.

Si Wet Etching

- Si wet etching usually proceeds by oxidation followed by the dissolution of the oxide by a chemical reaction.
  - Commonly used etchants contain HNO_3, HF, and CH_3COOH with additives such as H_2SO_4 or H_3PO_4

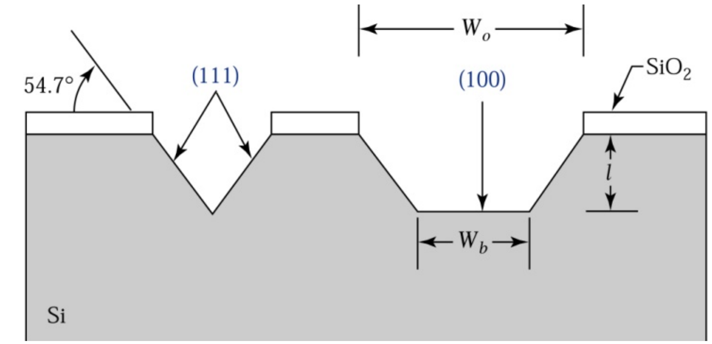
$$Si + 4HNO_3 \rightarrow SiO_2 + 2H_2O + 4NO_2$$

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$

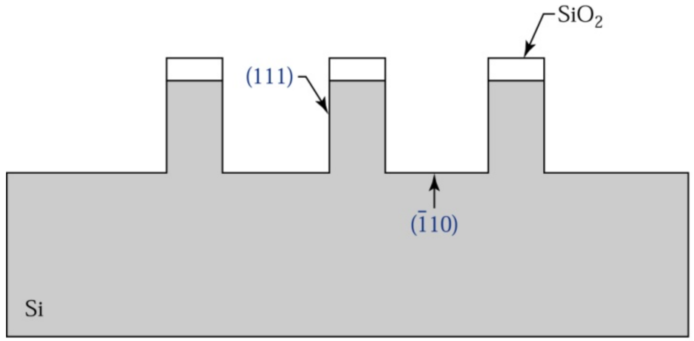
- CH_3COOH is used to reduce the dissolution of HNO_3.

Si Anisotropic Etching

- Si may be etched by direct dissolve Si atoms.
  - The (111)-plane has higher Si bonds density than the (110)- and (100)-plane. The etch rate in (111)-plane is expected to be the lowest.
  - Anisotropic etching or oriented dependent etching becomes possible.
- Etch (100)-oriented Si through a window creates V-groove.
  - 19 wt% KOH at 80°C, (100) : (110) : (111) = 100 : 16 : 1
  - 10 wt% KOH at 80°C, (100)-Si etch rate ~ 1.1 μm/min, selectivity to SiO_2 > 600.



$$W_b = W_0 - 2l\cot 54.7 = W_0 - \sqrt{2}l$$

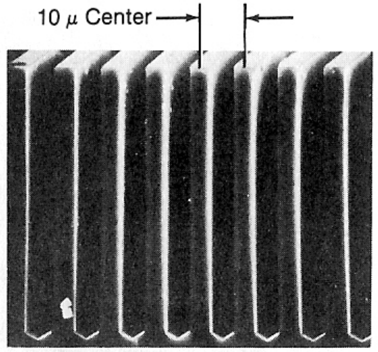


(b)

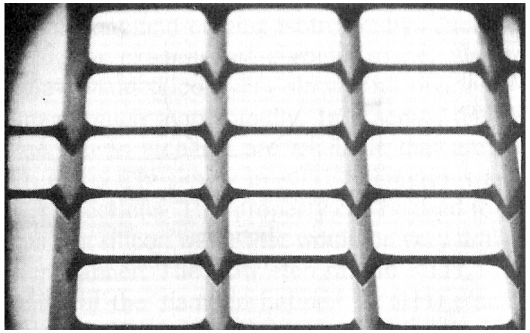
Etching Rate Selectivity of KOH

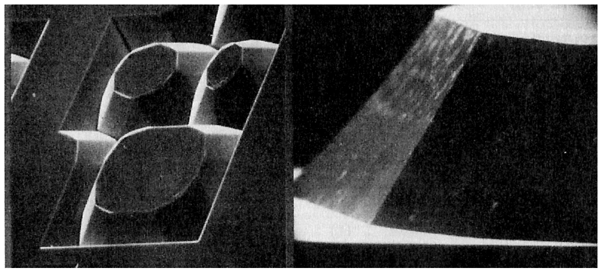
30 wt% KOH

Temperature(°C)	Film type	Time(min)	Etching rate(nm/min)
60	Tox	30	1.71
	USG	30	2.34
	Si_3N_4	30	-0.03
80	Tox	5	8.33
	USG	5	20.34
	Si_3N_4	5	0.02



(110) Silicon ODE 80 μ deep, 10 μ centers





(100)-Si/SiO_2 Etching Rate Selectivity

wt% KOH	Temperature(℃)								
	20	30	40	50	60	70	80	90	100
10	3725	2623	1914	1446	1096	852	667	526	423
15	2476	1780	1296	972	736	576	446	353	284
20	1784	1278	947	700	534	415	321	256	205
25	1342	954	704	523	398	305	241	191	153
30	1014	718	533	394	301	233	182	144	115
35	916	664	476	360	272	210	164	131	105
40	879	620	465	347	262	200	158	126	101
45	834	599	442	327	248	190	149	119	95
50	777	549	409	305	229	178	139	111	88
55	694	488	370	273	207	164	125	99	81
60	617	449	319	239	183	137	110	88	71

Anisotropic TMAH Etching Rates

Orientation	Etching rate (μm min^{-1})	Etching rate ratio	
		(i j k)/(100)	(i j k)/(111)
100	0.603	1.000	37
110	1.114	1.847	68
210	1.154	1.914	70
211	1.132	1.877	69
221	1.142	1.894	69
310	1.184	1.964	72
311	1.223	2.028	74
320	1.211	2.008	73
331	1.099	1.823	67
530	1.097	1.819	66
540	1.135	1.882	69
111	0.017	0.027	1

TMAH (20.0wt%, 79.8°C)

Anisotropic Etchants for Si

Etchant/Diluent/Additives/ Temperature	Etch Stop	Etch Rate (100) (μm/min)	Etch Rate Ratio (100)/(111)	Remarks	Mask (Etch Rate)
KOH/water, isopropyl alcohol additive, 85°C	B > 10^{20} cm^{-3} reduces etch rate by 20	1.4	400 and 600 for (110)/(111)	IC incompatible, avoid eye contact, etches oxide fast, lots of H_2 bubbles	Photoresist (shallow etch at room temperature); Si_3N_4 (not attacked); SiO_2 (28 Å/min)
Ethylene diamine pyrocatechol (water), pyrazine additive, 115°C	≥5 × 10^{19} cm^{-3} reduces the etch rate by 50	1.25	35	Toxic, ages fast, O_2 must be excluded, few H_2 bubbles, silicates may precipitate	SiO_2 (2–5 Å/min); Si_3N_4 (1 Å/min); Ta, Au, Cr, Ag, Cu
Tetramethyl ammonium hydroxide (TMAH) (water), 90°C	>4 × 10^{20} cm^{-3} reduces etch rate by 40	1	From 12.5 to 50	IC compatible, easy to handle, smooth surface finish, few studies	SiO_2 etch rate is 4 orders of magnitude lower than (100) Si LPCVD Si_3N_4
N_2H_4/(water), isopropyl alcohol, 115°C	>1.5 × 10^{20} cm^{-3} practically stops the etch	3.0	10	Toxic and explosive, okay at 50% water	SiO_2 (<2 Å/min) and most metallic films; does not attack Al according to some authors[104]

[a] Given the many possible variables, the data in the table are only typical examples.

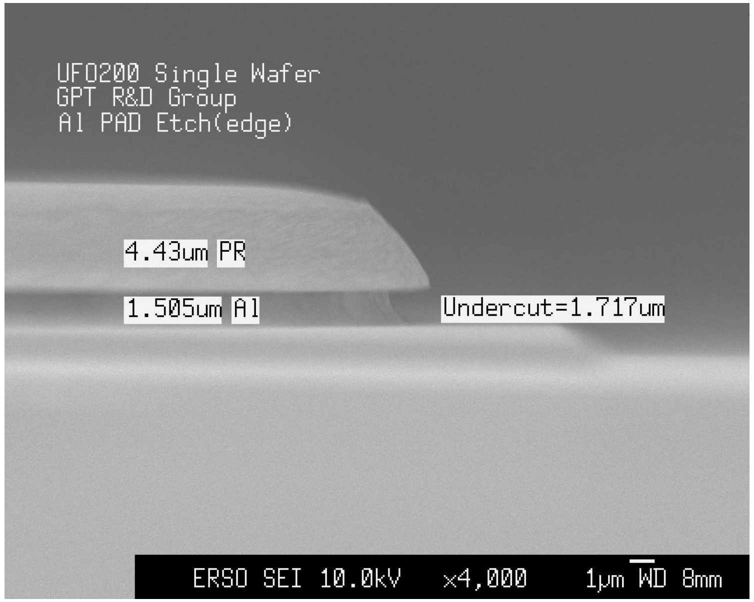
Fundamentals of Microfabrication, M. Madou, CRC Press, 1997

Wet Etching of SiGe

- Selective etching of SiGe (crystalline or polycrystalline) over both Si and SiO_2 has been reported with the following solutions:
  - $NH_4OH : H_2O_2 : H_2O$ (SC-1)
    - J. Electronic Materials, V.21, p.805 (1992).
  - $HF : H_2O_2 : CH_3COOH$
    - J. Electrochem. Soc., V. 138, p.202 (1991); J. Electrochem. Soc., V.142, p.1260 (1995).
  - $HF : HNO_3 : H_2O$
    - J. Electrochem. Soc., V.139, p.2943 (1992); App. Phys. Lett., V.58, p.1899 (1991).
  - $HF : HNO_3 : CH_3COOH$
    - App. Phys. Lett., V.65, p.1700 (1994).
- Etching rate increases with increasing Ge fraction in the film.

Al Wet Etching

- Typical etchants are hot H_3PO_4 or H_3PO_4 + HNO_3 + CH_3COOH + DI water.
  - HNO_3 : CH_3COOH : H_3PO_4 : H_2O = 4 : 3.5 : 73 : 19.5
  - HNO_3 oxidizes Al and then H_3PO_4 dissolves Al-O.
  - Process temperature : 30-80°C
  - Etching rate: 30~200 nm/min



Wet Etching of Titanium

- 1:1 mixture of hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4)
- H_2O_2 oxidizes titanium to form TiO_2
- H_2SO_4 reacts with TiO_2 and removes it simultaneously
- H_2O_2 oxidizes silicon and silicide to form SiO_2
- H_2SO_4 doesn’t react with SiO_2

Common Wet Chemical Etchants

Material	Etchant	Comments
SiO_2	HF (49% in water) "straight HF"	Selective over Si (i.e., will etch Si very slowly in comparison). Etch rate depends on film density, doping.
	NH_4F:HF (6:1) "Buffered HF" or "BOE"	About $^1/_{20}$ th the etch rate of straight HF. Etch rate depends on film density, doping. Will not lift up photoresist like straight HF.
Si_3N_4	HF (49%)	Etch rate depends strongly on film density, O, H in film.
	H_3PO_4:H_2O (boiling @ 130–150ºC)	Selective over SiO_2. Requires oxide mask.
Al	H_3PO_4:H_2O:HNO_3:CH_3COOH (16:2:1:1)	Selective over Si, SiO_2, and photoresist.
Polysilicon	HNO_3:H_2O:HF (+ CH_3COOH) (50:20:1)	Etch rate depends on etchant composition.
Single crystal Si	HNO_3:H_2O:HF (+ CH_3COOH) (50:20:1)	Etch rate depends on etchant composition.
	KOH:H_2O:IPA (23 wt. % KOH, 13 wt. % IPA)	Crystallographically selective; relative etch rates: (100): 100 (111): 1
Ti	NH_4OH:H_2O_2:H_2O (1:1:5)	Selective over $TiSi_2$.
TiN	NH_4OH:H_2O_2:H_2O (1:1:5)	Selective over $TiSi_2$.
$TiSi_2$	NH_4F:HF (6:1)	
Photoresist	H_2SO_4:H_2O_2 (125ºC)	For wafers without metal.
	Organic strippers	For wafers with metal.

Etching Rate (Å/min)

J. Microelectromechanical Systems, p.256, 1996.

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL SC Si <100>	Poly n^+	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/ 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HntPR
Concentrated HF (49%) Wet Sink Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k	140	52 30 52	42 0 42	<50	F	-	P 0	P 0
10:1 HF Wet Sink Room Temperature	Silicon oxides	-	7	0	230	230	340	15k	4700	11	3	2500 2500 12k	0	11k	<70	0	0
25:1 HF Wet Sink Room Temperature	Silicon oxides	-	0	0	97	95	150	W	1500	6	1	W	0	-	-	0	0
5:1 BHF Wet Sink Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9	4 3 4	1400	<20 0.25 20	F	1000	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7	0.8	<1	37	24 9 24	28 28 42	19 19 42	9800	-	-	-	550	390
Silicon Etchant (126 HNO_3 : 60 H_2O : 5 NH_4F) Wet Sink Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	130	3000	-	0	0
KOH (1 KOH : 2 H_2O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W	380	0	0	F	0	-	-	F	F
Aluminum Etchant Type A (16 H_3PO_4 : 1 HNO_3 : 1 HAc : 2 H_2O) Heated Bath 50°C	Alumnium	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H_2O : 1 H_2O_2 : 1 HF) Wet Sink Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 <10	8800	-	0	0
H_2O_2 (30%) Wet Sink Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0	60 60 150	<2	0
Piranha (~50 H_2SO_4 : 1 H_2O_2) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Sink Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>44k	>39k

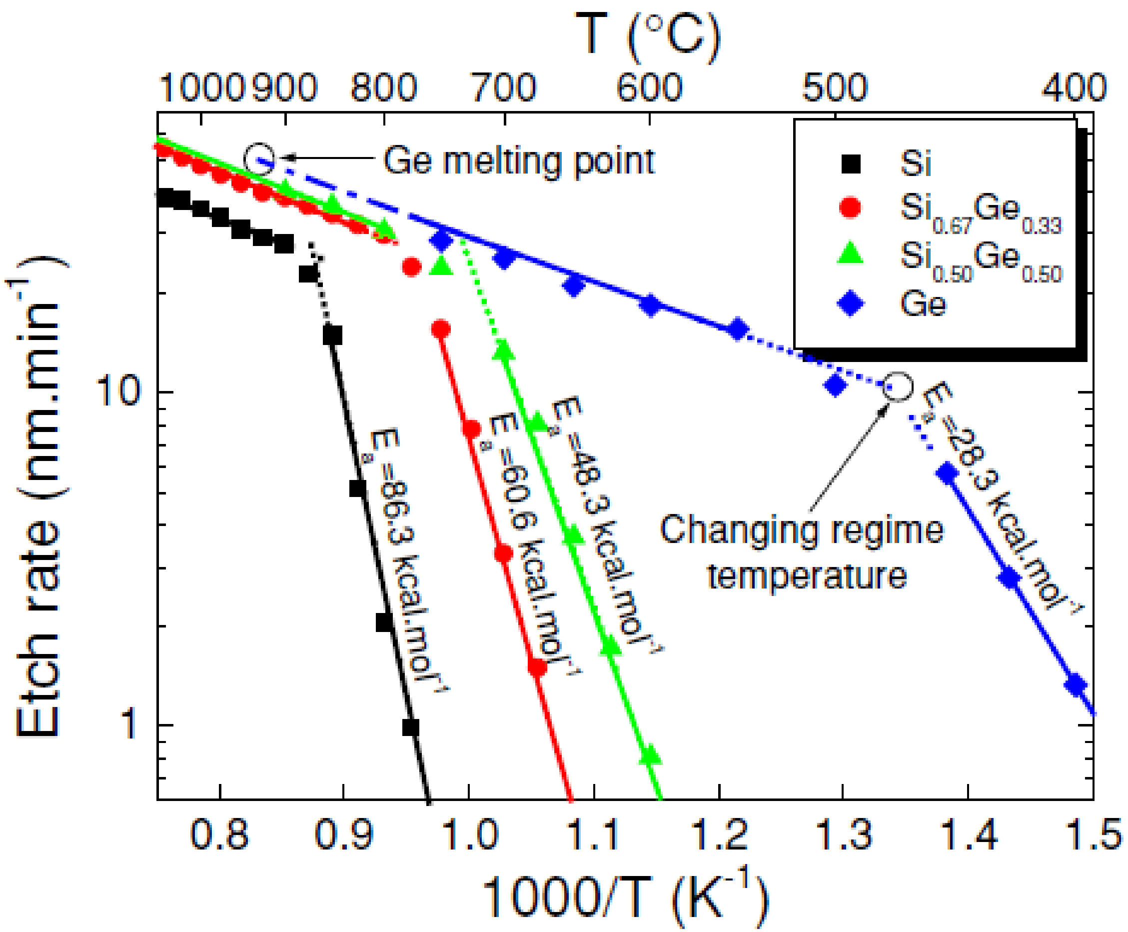
Chemical Vapor Etching

- Chemical vapor etching is a non-plasma mode dry etching.
  - Purely chemical reactions with gaseous byproducts.
  - Isotropic etched profile and high selectivity.
  - Processing usually done at an elevated temperature.

Applications and Etch Chemistry

Materials to be etched	Chemical vapor etching	Plasma chemical etching
Si/SiGe	HCl	F- or Cl-based chemistry
SiO_2	HF	F-based chemistry
Photoresist	O_3, H_2SO_4/H_2O_2 (SPM)	O_2
Chamber coating		NF_3

Si and SiGe Chemical Vapor Etching

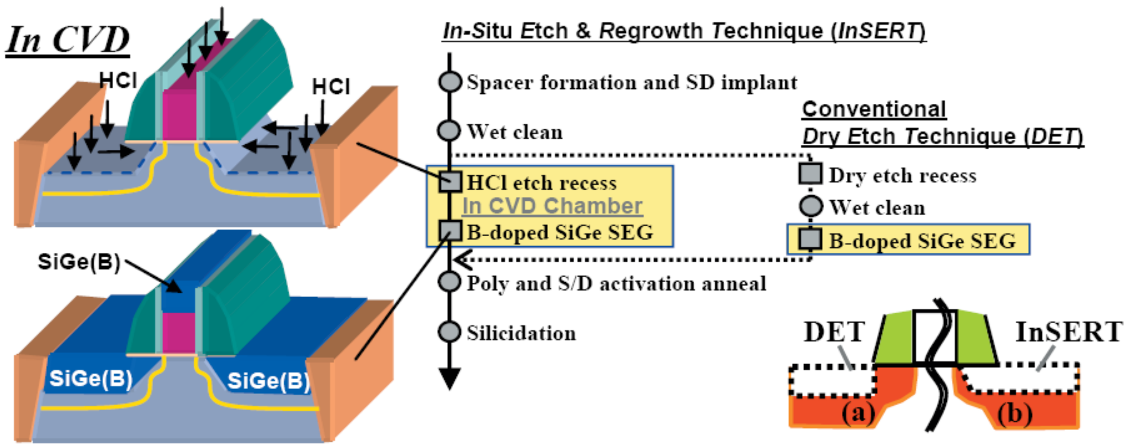


Semicond. Sci. Technol. V. 20, p.127 (2005).

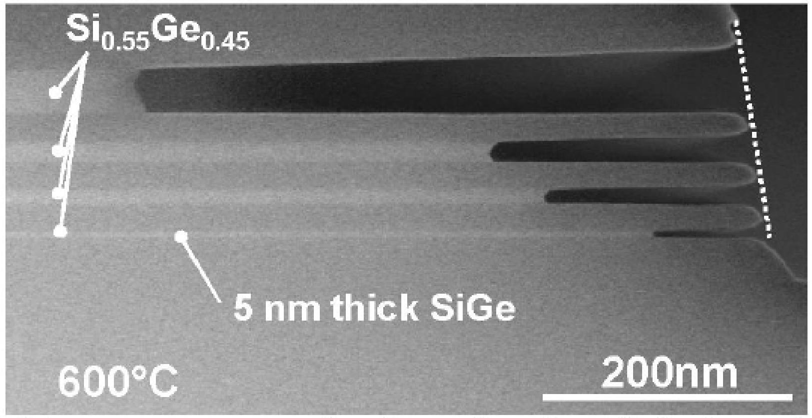
- HCl partial pressure: 0.208 torr.
- High selectivity to SiO_2.
- Etch rate increases dramatically with increasing Ge fraction in the SiGe film.

Applications of Chemical Vapor Etching

VLSI 2005, S.3A.2, p.24.



IEDM 2007, S.27.4, p.689.



➢PMOS with embedded SiGe source/drain formed with an integrated *in-situ* selective etching/epitaxy process in a CVD reactor.

➢Selective etch of SiGe over Si.

➢Potential applications:
- Si-on-nothing (SON). VLSI'99, p.29.
- Si nanowire devices. IEDM'05, p.735.
- Localized FD/SOI. IEDM'07, p.689.

Defect Delineation

Name	Composition	Comments	Reference
Dash	1HF, $3HNO_3$, 10 CH_3COOH	Delineates defects in (111) silicon; requires long etch times; is concentration dependent.	W. C. Dash, JAP., vol-27, p.1193, 1956.
Sirtl	1HF, 1(5M-CrO_3)	Delineates defects in (111); needs agitation; does not reveal etch pits in (100) very well.	E. Sirtl and A. Adler, Z. Metallk., vol-52, p.529, 1961.
Secco	2HF, 1(0.15M-$K_2Cr_2O_3$)	Delineates OSF in (100) silicon very well; agitation reduces etch times.	F. Secco, JECS, vol-119, p.948, 1972.
Wright-Jenkins	60ml HF, 30 ml HNO_3, 30 ml(5M-CrO_3), 2g $Cu(NO_3)_2$, 60ml CH_3COOH, 60 ml H_2O	Delineates defects in (100) and (111) silicon; requires agitation.	M. Wright Jenkins, JECS, vol-124, p.757, 1977.
Schimmel	2HF, 1(1M-CrO_3)	Delineates defects in (100) silicon without agitation; works well on resistivities 0.6-15 Ω-cm n- and p-types.	D. G. Schimmel, JECS, vol.126, p.479, 1979.
Modified Schimmel	2HF, 1(M-CrO_3), 1.5H_2O	Works well on heavily doped (100) silicon.	D. G. Schimmel, JECS, vol.126, p.479, 1979.
Yang	1HF, 1(1.5M-CrO_3)	Delineates defects on (111), (100) and (110) silicon without agitation.	K. H. Yang, JECS, vol-131, p.1140, 1984.

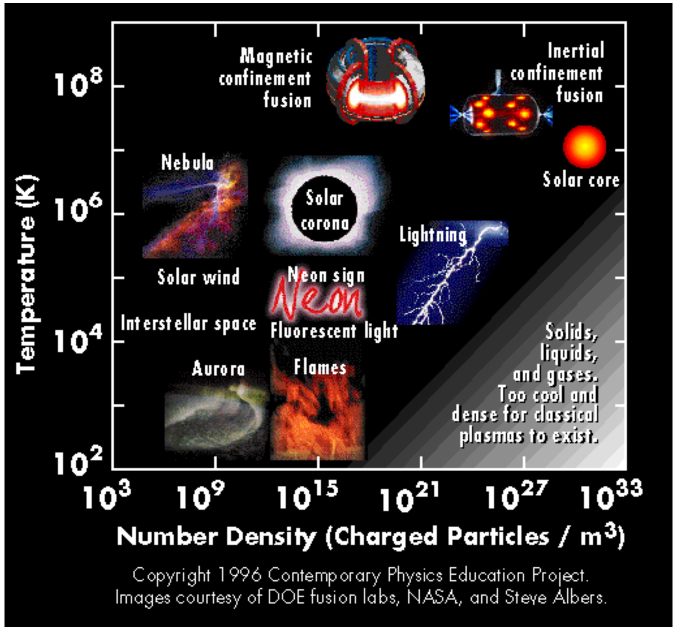
Plasma Fundamentals

Outline

- Introduction to Plasma
- Collision process in plasma
- Plasma dynamics
- Sheath and Glow discharge
- Plasma Reactors
- High density plasma sources

What Is a Plasma?

- A plasma is an ionized gas with equal numbers of positive and negative charges.
- A more precise definition: *A plasma is a quasi-neutral gas consisting of charged and neutral particles which exhibits collective behavior.*
- Ex: Sun, flame, neon light, etc.



http://fusedweb.pppl.gov/CPEP/Chart_Pages/5.Plasma4StateMatter.html

Fourth State of Matter

Solid	Liquid	Gas	Plasma

Temperature increases

Components of Plasma and Ionization

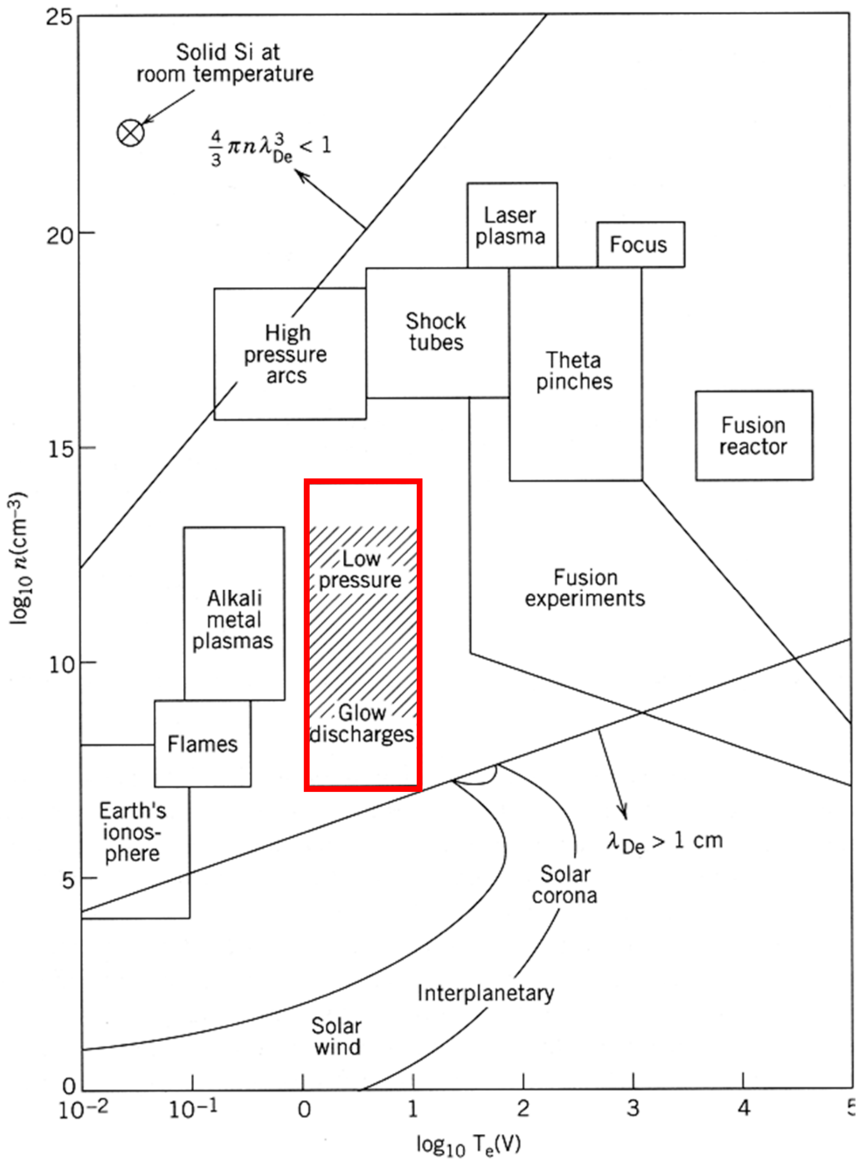
- A plasma consists of neutral atoms or molecules (including radicals), negative charges (mostly electrons) and positive charges (ions).
- Quasi-neutral
  - Assuming negative ion density = 0, $n_i \approx n_e$ (positive ion density = electron density = plasma density)
- To form and sustain a plasma it requires energy input to ionize the gas continuously.
- Ionization rate: $h \approx n_e/(n_n+n_e)$, where n_n is the neutral gas density.
  - Weakly ionized plasmas: $h \approx n_e /(n_n+n_e) \approx n_e/n_n << 1$
  - Fully ionized plasmas: $h \approx 1$

Glow Discharges and Ionization Rate

- Ideal gas
  - 1 mole = 6.02×10^{23} molecules, volume of 1 mole gas = 22.4 L = 2.24×10^{4} cm^{-3}
  - At 1 atm, gas density is 2.6×10^{19} cm^{-3}
  - At 1 torr, gas density is 3.54×10^{16} cm^{-3}
- Ionization rate is mainly determined by electron energy (temperature) in plasma.
  - In most plasma processing chambers, the ionization rate is less than 0.001%.
  - The ionization rate of high density plasma (HDP) sources is much higher, typically about 0.01 ~ 0.1%.
  - Ionization rate in the core of sun is ~100%.
- Plasmas initiated and sustained by electric fields which are produced by either dc or ac power supplies.
  - Typical pressure range: 0.1 to 1000 mtorr
  - Typical electron temperature: 1 to 10 eV
  - Typical plasma density: 10^{9} to 10^{12} cm^{-3}

Plasma Density

- Plasma density and electron temperature ranges for a variety of natural and man-made plasmas.
- In a low pressure glow discharges, electrons are not in thermal equilibrium with ions and neutrals and $T_e >> T_i > T_n$.

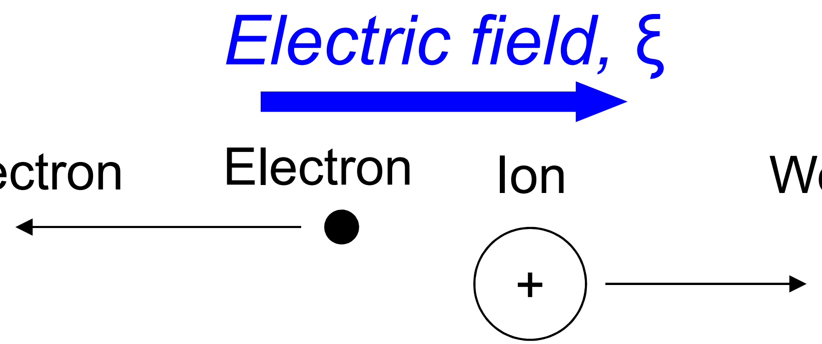


Applications in Semiconductor Process

- Etching
  - Reactive ion etching, dry chemical etching, dry cleaning (PR Strip)
- Thin-film deposition
  - Sputtering deposition, PECVD/HDP CVD, etc.
- Doping
  - Ion implantation, Plasma immersion ion implantation (PIII), etc.
- Lithography
  - Light source (High pressure Hg lamp, excimer laser, EUV)
- Annealing/Re-crystallization
  - Excimer Laser
- Surface treatment
  - Plasma nitridation/oxidation/hydrogenation
- Material analysis
  - Inductively coupled plasma mass spectroscopy (ICP-MS), etc.

Movement of Charged Particles

- Electron is much lighter than ion
  - $m_e << m_i$ (m_e: $m_{Hydrogen}$ =1:1836)
- Electric forces on electrons and ions are the same so that electron has much higher acceleration than ion.
  - $F = q\mathscr{E}$, where q is charge and $\mathscr{E}$ is electric field. $\Rightarrow a = \dfrac{q\mathscr{E}}{m}$
- Energy is transferred from electric field to electrons and ions.
  - Electrons absorb energy much more efficiently than ions due to light mass.
  - Energetic electrons impact neutral species and thus initiate the plasma



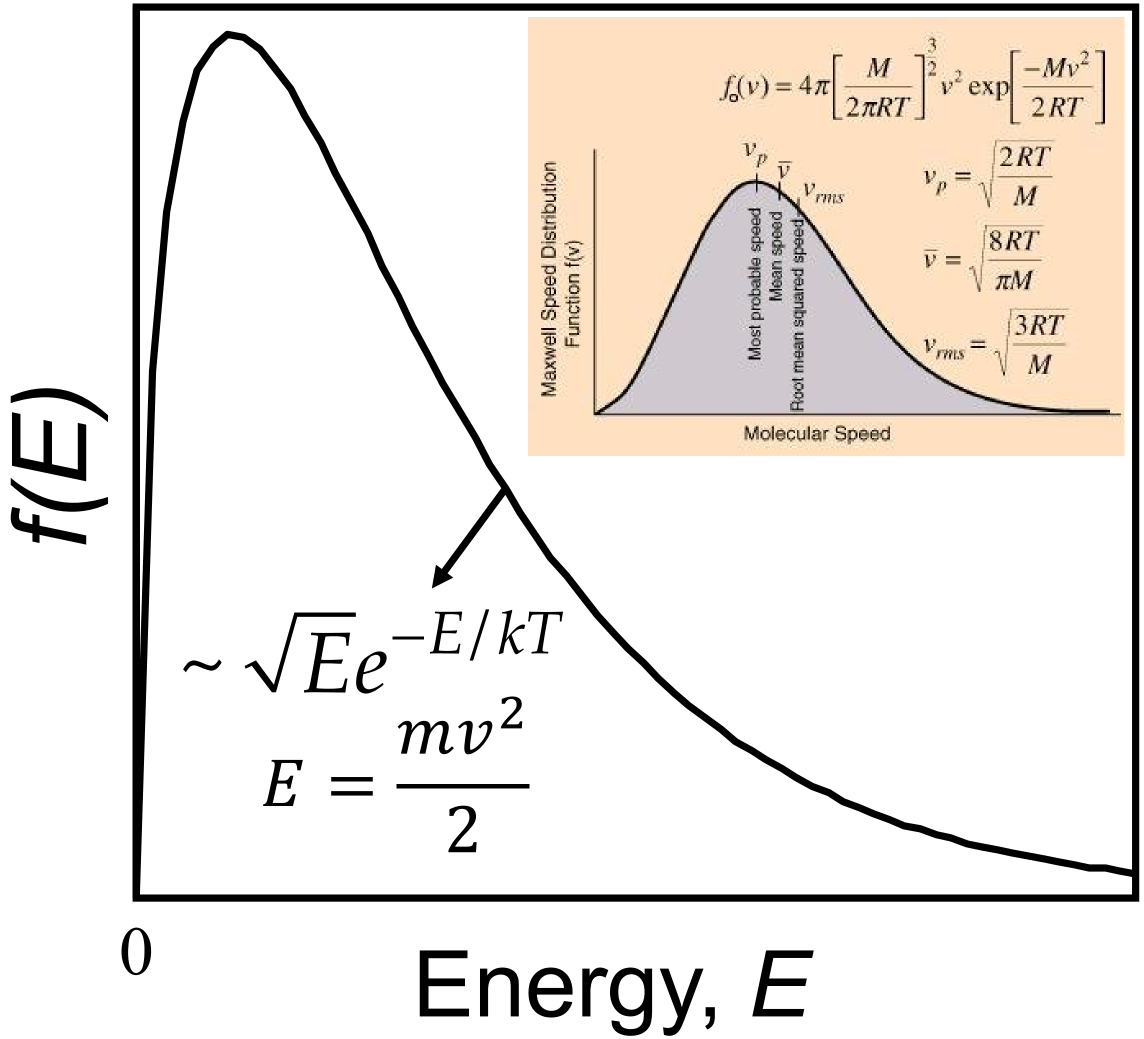
Work done on electron

$$W_e = \frac{(q\mathscr{E}t)^2}{2m_e}$$

Work done on positive ion

$$W_i = \frac{(q\mathscr{E}t)^2}{2m_i}$$

Maxwell-Boltzmann Distribution



- When a gas species is in thermal equilibrium, it is usually described by the Maxwell-Boltzmann (or Maxwellian) distribution.

$$f(E) = \frac{2}{kT}\sqrt{\frac{E}{\pi kT}}e^{-E/kT} \text{ and } \int_0^\infty f(E)dE = 1$$

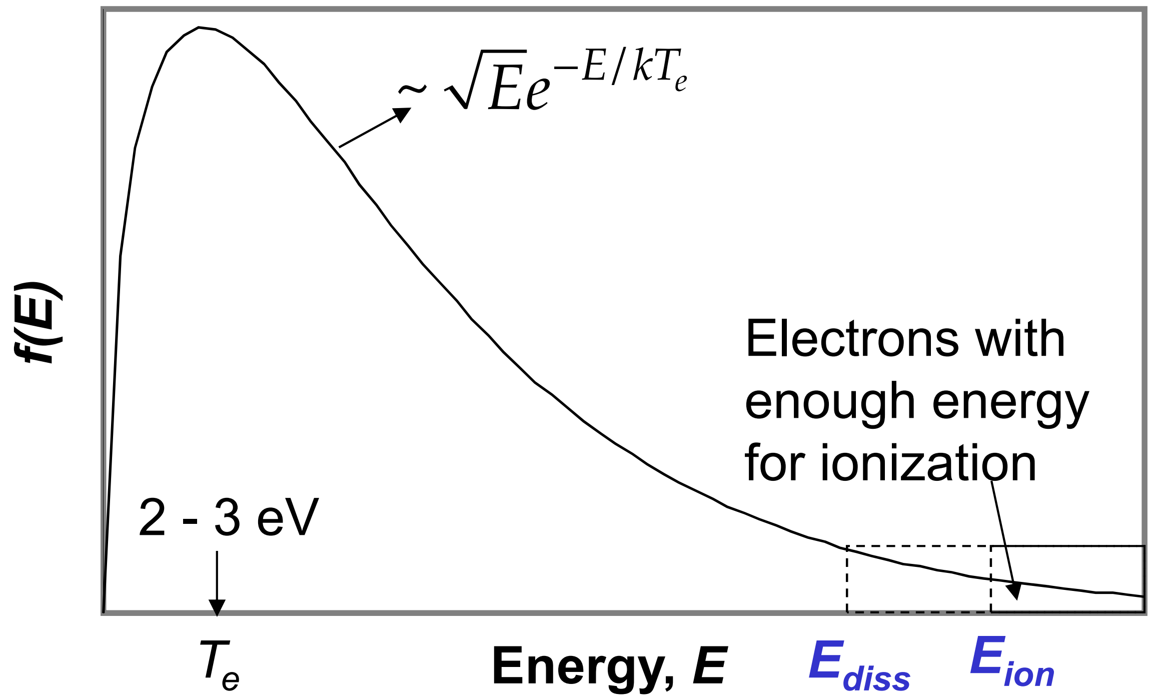
$$\overline{E} = \int_0^\infty Ef(E)dE = \frac{3kT}{2}$$

Flux of particles passing a unit area in a unit time

$$\Gamma = \frac{n\bar{v}}{4}, \text{ where n is the particle density}$$

Maxwellian Distribution

- In a number of cases, especially weakly ionized plasmas, f(E) for electrons is not Maxwellian.
  - It is still quite common to speak of electron temperature when referring to the average electron energy.
  - Sometimes two-temperature distribution is used to describe the electrons in a glow. Typical electron temperature in glow discharges: 1 to 10 eV.

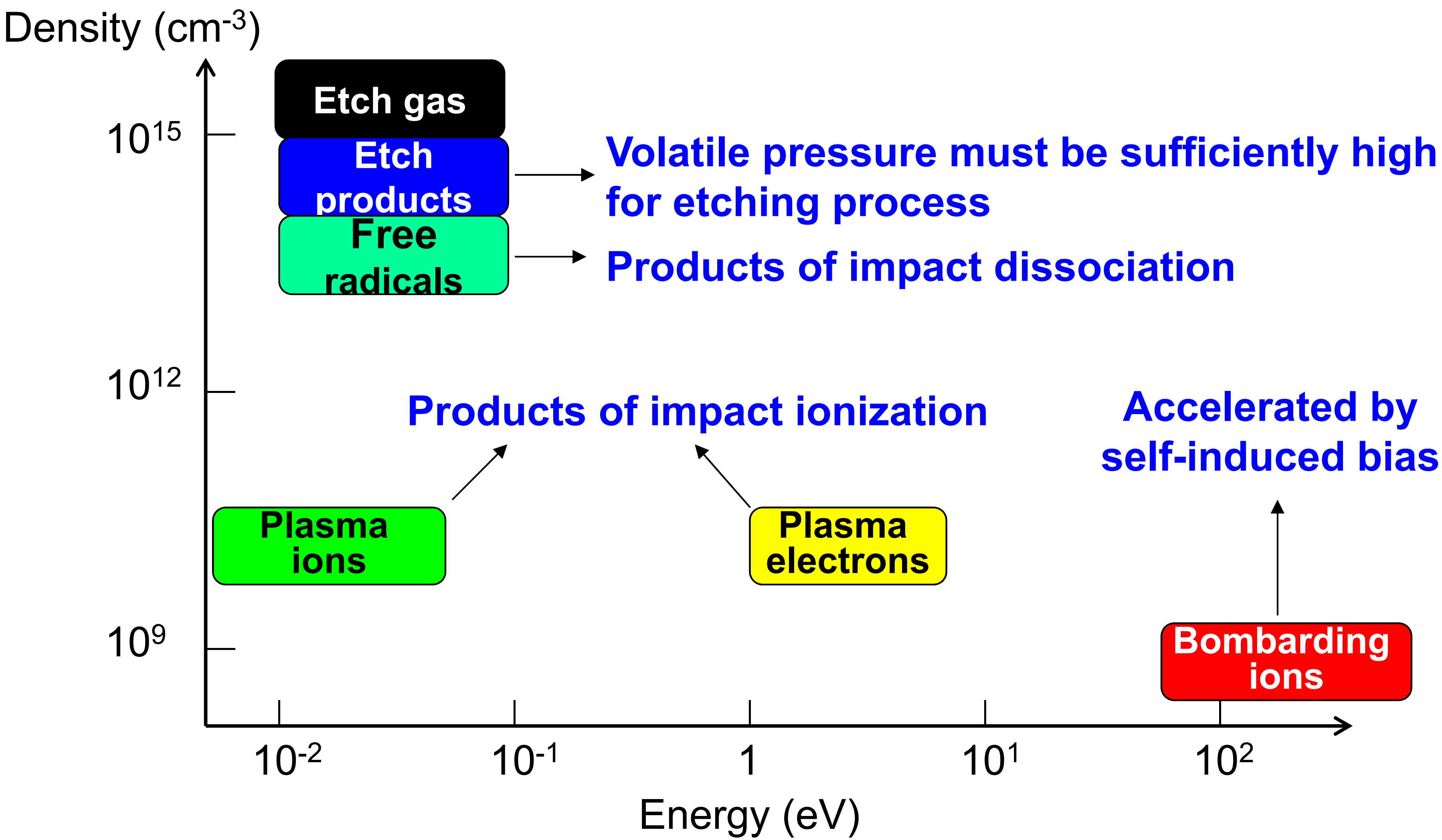


T_e: 1eV = 11,600 K

E_{ion}: ionization energy
E_{diss}: dissociation energy

Density and Energy for Various Species

Low-Pressure Capacitive RF Discharge (RIE)



Collision Process in Plasma

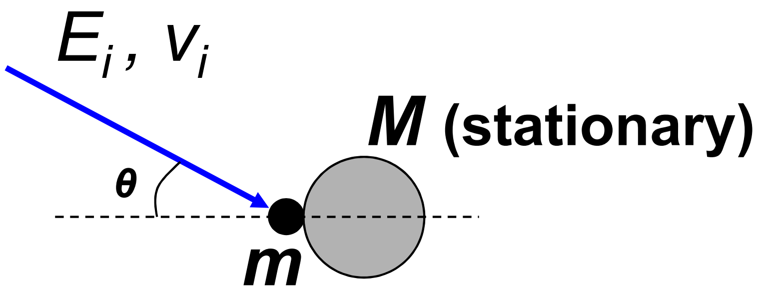
Elastic and Inelastic Collisions

- Elastic collisions: the total kinetic energy is conserved.
- Inelastic collisions : the total kinetic energy is not conserved.
- Main elastic collisions in glow discharge:
  - Hard sphere collision, Coulomb collision (Rutherford scattering), and Polarization scattering.
  - Affect the transport of particles significantly.
- Main inelastic collisions in glow discharge:
  - Ionization
  - Excitation
  - Relaxation
  - Dissociation
  - Recombination
  - Electron attachment
  - Charge transfer

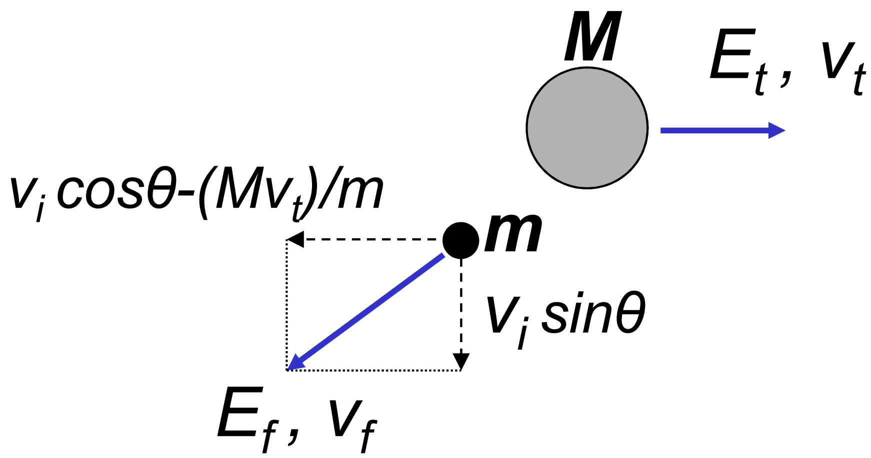
Hard Sphere Collision

- Energy transfer of hard sphere collision

Before collision



After collision



θ *: the angle between v_i and the line joining the centers of m and M.*

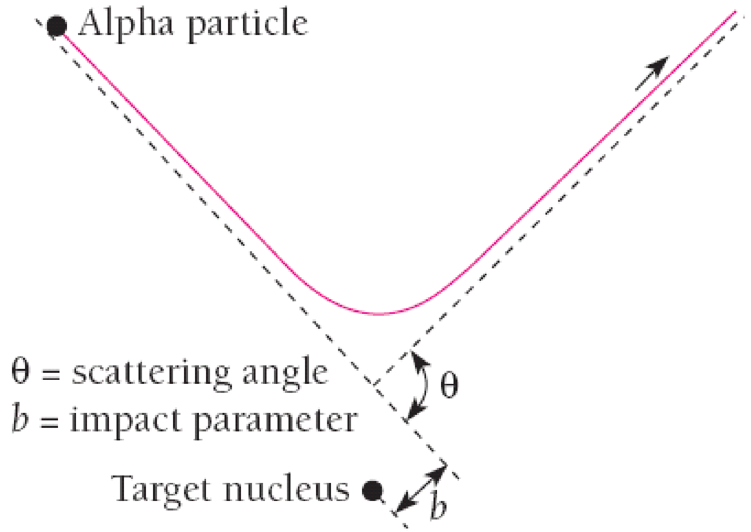
$$\frac{E_t}{E_i}=\frac{E_i-E_f}{E_i}=\frac{4mM\cos^2\theta}{(m+M)^2}\le\frac{4mM}{(m+M)^2}\approx 0 \text{ as } m << M$$

Hence electrons transfer little energy to heavy particles during elastic collisions, therefore $T_e >> T_i$ in a low - pressure discharge.

Coulomb Collision

Rutherford scattering model

$$N(\theta) = \frac{N_i n t Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 KE^2 \sin^4(\theta/2)}$$



N(θ): number of α particles per unit area that reach the screen at a scattering angle of θ

N_i: total number of α particles that reach the screen

n: number of atoms per unit volume in the foil

Z: atomic number of the foil atoms

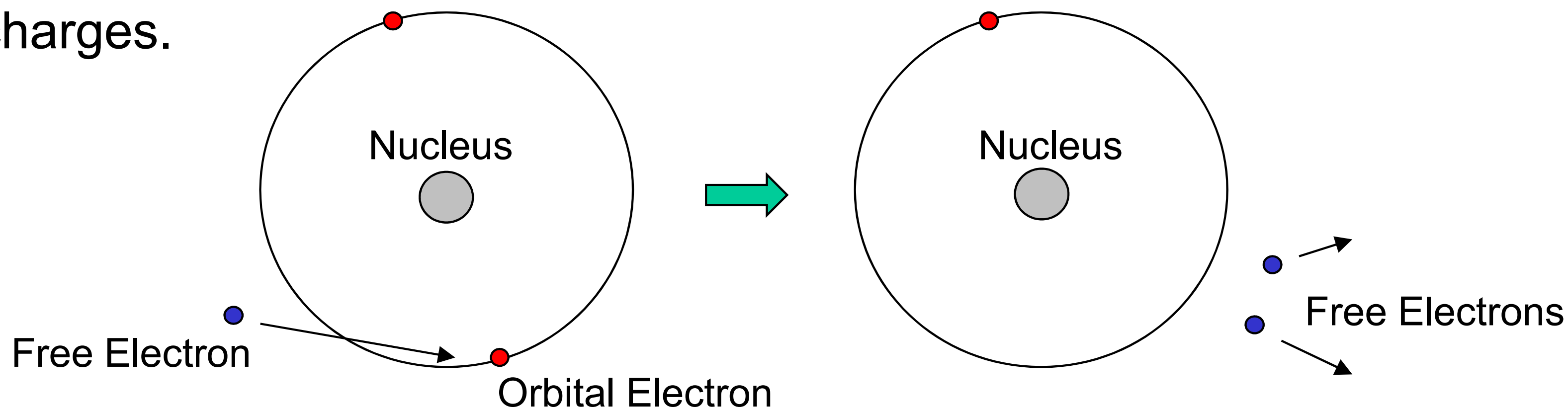
r: distance of the screen from the foil

KE: kinetic energy of the α particles

t: foil thickness

Impact Ionization

- An inelastic process that ionizes neutral atoms or molecules.
- Needs energy input to carry out the process.
- Examples:
  - Electron impact ionization: $e^- + A \rightarrow 2e^- + A^+$
  - Photo-ionization: $h\nu + A \rightarrow A^+ + e^-$
- Impact ionization
  - An energetic electron collides with neutral atom or molecule and knocks out at least one of orbital electrons (when $E > E_{ion}$).
  - Ionization collisions generate electrons and ions
  - It sustains the plasma and represents a major ionization process in glow discharges.



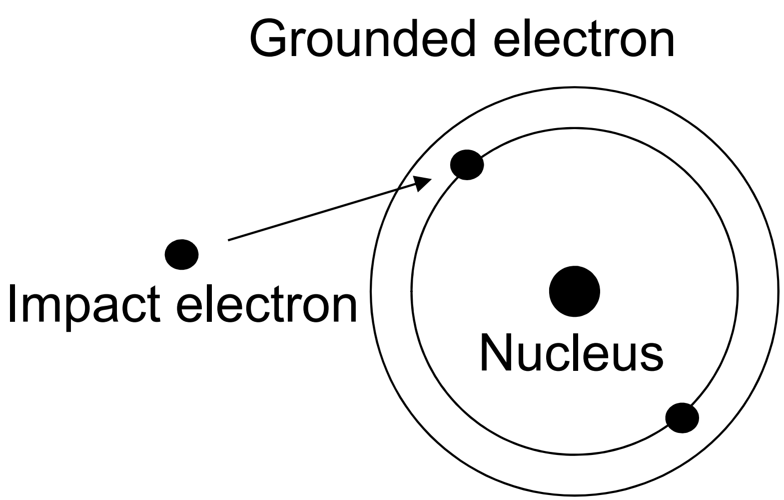
Ionization Energy (in eV)

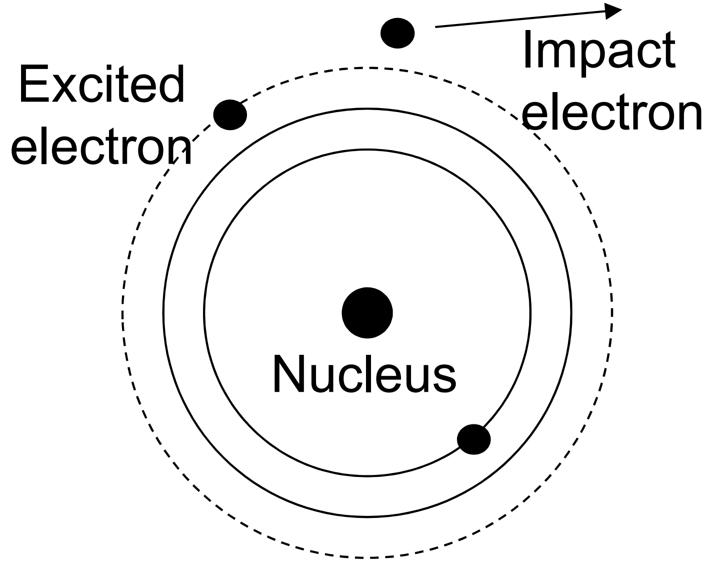
H	13.5	H_2	15.4
He	24.6	N_2	15.5
N	14.5	O_2	12.2
O	13.5	Cl_2	12
F	17.4	Br_2	11
Cl	13	BCl_3	11
Ar	15.7		

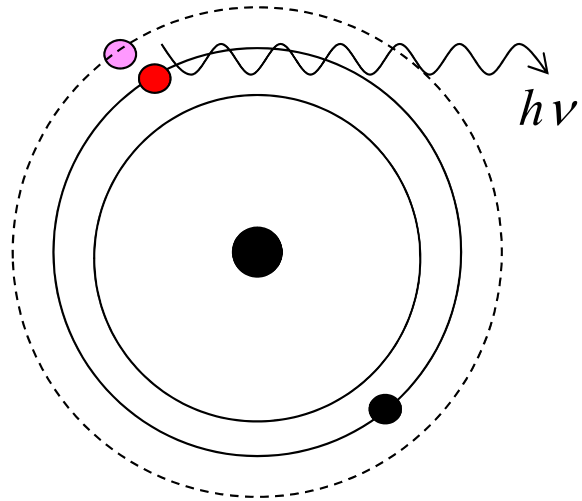
Excitation and Relaxation

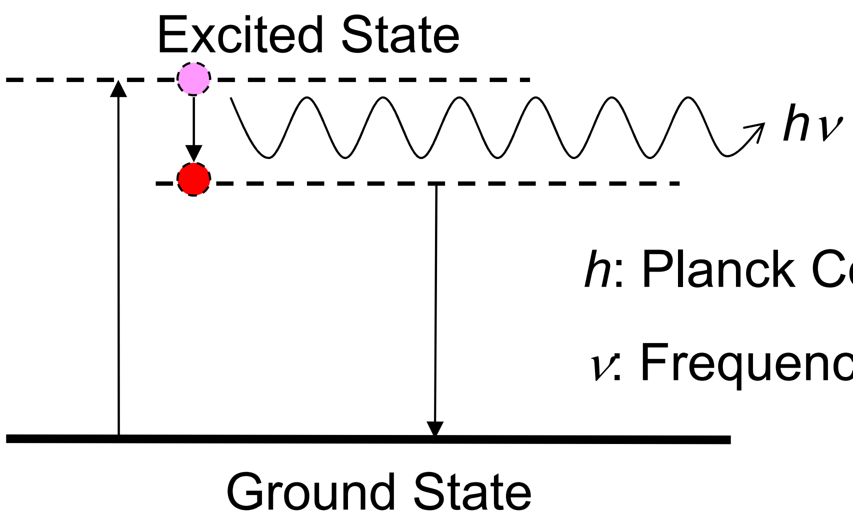
- Excitation $e^- + A \rightarrow A^* + e^-$ (* denotes the excited state)
- Relaxation $A^* \rightarrow A + h\nu$ (Photons)
- Frequencies (ν) of emitted photons are determined by the ingredients of the discharges, the reason why different gases have different glow colors.
- Glow discharge can be used as light source:
  - High-pressure Hg lamp, excimer laser
- Change of the glow colors during processing is used for endpoint detection (EPD) in etching processes.

Excitation Collision and Relaxation



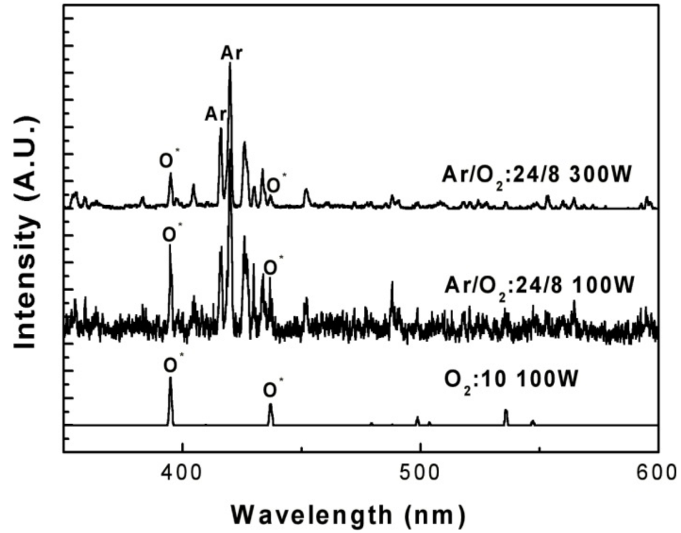






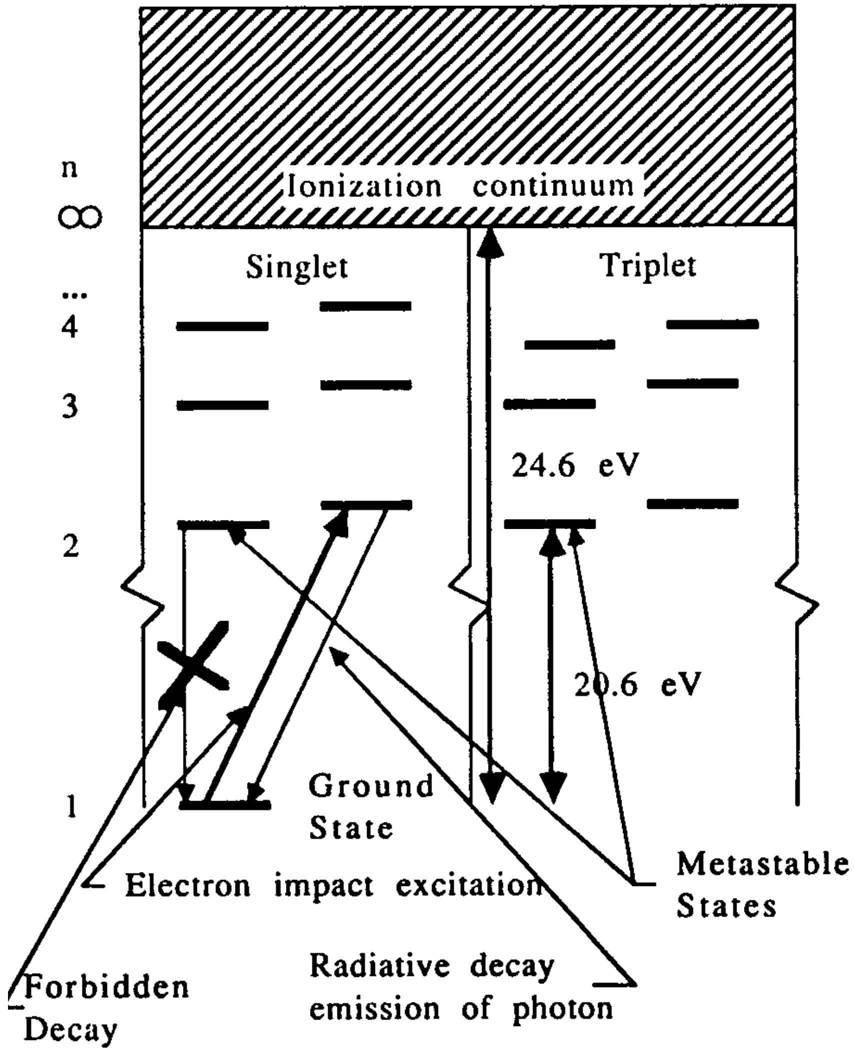
h: Planck Constant

ν: Frequency of Light



Metastable States

- Typical lifetime for excited atom is short (~ 100 ns or less).
- Excited atoms or molecular are said to be in metastable state when their lifetime is long (1 ms ~ 1 s).
  - Metastable species arises because the selection rules forbid relaxation to the ground state.
  - Atomic energy levels for He, showing the singlet and triplet series.
  - The energy necessary to ionize is 24.6 eV, while the energy for the first electronic excitation is 20.6 eV.
  - States which are forbidden to decay to the ground state have long lifetime and are called metastable states.

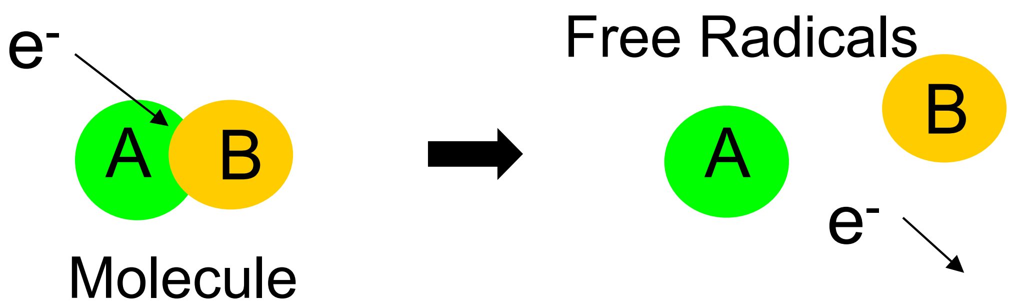


Penning Processes

- The metastable states have considerable energy (e.g., 20.6 eV for He) and may cause excitation or ionization when they collide with ground state neutrals.
  - Penning excitation: $A^* + B \rightarrow A + B^*$
  - Penning ionization: $A^* + B \rightarrow A + B^+ + e^-$
- These processes increase the excitation and ionization rates in plasmas, one of the reasons why rare gases like He or Ar are often added in glow discharges.

Dissociation

- Electron collides with a molecule (with kinetic energy E), it can break the chemical bonds and generate free radicals when $E > E_{diss}$:
  - $e^- + AB \longrightarrow A + B + e^-$
- Free radicals (A and B) have at least one unpaired electron and are chemically very reactive.
- Increasing chemical reaction rate.
- Very important for both etch and CVD.



Radical

- An atom or a collection of atoms with incomplete chemical bonding, e.g., F, Cl, Br, O, H, OH, CF_x ($x = 1 \sim 3$).
  - Products of dissociation processes.
  - Usually very reactive. Often serve as etchant species in etch or deposition precursors in CVD.
  - Most important plasma-surface chemistry is accomplished by radicals.
- Radical density is typically orders of magnitude higher than plasma density (because $E_{diss} < E_{ion}$) in diode-type reactors.
- Radicals typically survive much longer than ions.
- The above two features are reasons why the down-stream (remote plasma) reactors can potentially be employed for isotropic etching processes such as PR ashing.

Recombination

- Direct recombination: positive ions collides with an electron or negative ions.
  - $e^- + A^+ \longrightarrow A$
- Recombination by three-body collision:
  - $e^- + A^+ + B \longrightarrow A + B$
  - B can be a gas atom, electrode, or the chamber wall.
- Radiative recombination:
  - $e^- + A^+ \longrightarrow A + h\nu$ (photons)
- Among the aforementioned processes the three-body collision is far more important.
- Recombination rate = Ionization rate as the plasma becomes stable.
- Minimizing recombination rate is useful for promoting plasma density.

Cross-section of Electron Attachment

$$e^- + A \rightarrow A^-$$

Process gas	Total electron attachment cross section* (10^{-16} cm^2 eV)	Attachment rate constant (10^{-8} cm^{-3} s^{-1})
CCl_4	24.9	23.7
SF_6	11.1	24.9
$CFCl_3$	6.4	1.2
Cl_2	~3.0	~20.0
CF_2Cl_2	0.66	0.012
CF_4	<0.1	$<10^{-4}$
N_2	0	0
Ar	0	0

* Integrated between 0.04 to 2.5 eV

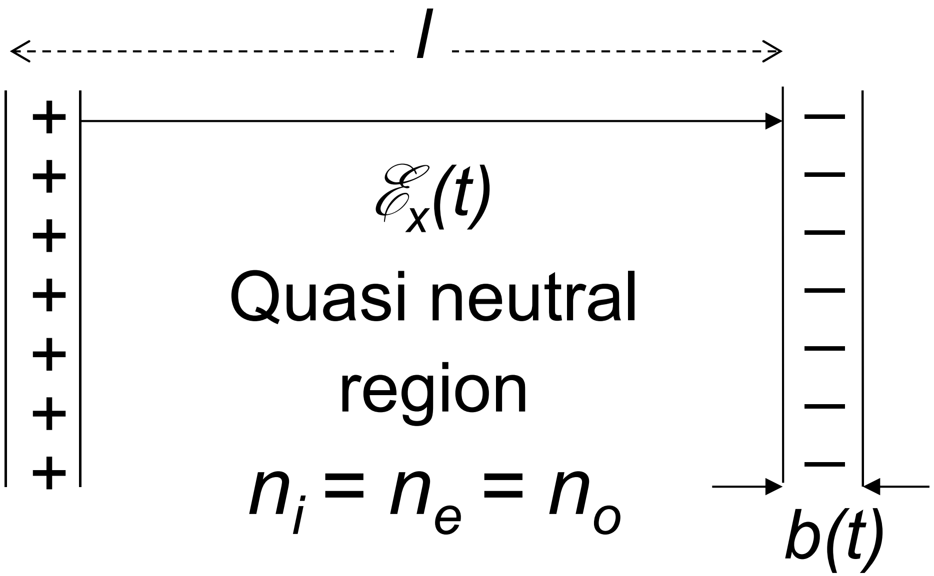
Data from Christophoorou I. G.., ed., “Electron-molecule interaction and their applications, Vol.2 (Academic press, London, 1984)

Electronegative Plasmas

- Electronegative (EN) plasmas such as oxygen plasma, contain a significant number of species which have positive electron affinity and electrons are likely to attach to.
- As a consequence, the number of free electrons is dramatically reduced, resulting in less efficient energy transfer into the discharge from the power supply.
- The EN plasmas are thus more difficult to initiate as compared with electropositive (EP) ones and need a higher power to ignite and sustain.
- EP gases such as Ar or N_2 are often added into the EN plasmas to help reduce the power and stabilize the plasmas.

Plasma Dynamics and Sheath

Plasma Oscillation-1



- Assume a slab of electrons in a plasma displaces to the right (+x direction) with respect to the positive ions by a small distance b(t) ($b \ll l$).
- Using Gauss's Law, an electric field develops in the quasi neutral region:
  $\mathscr{E}_x(t) = e n_o b(t)/\varepsilon_o$

Plasma Oscillation-2

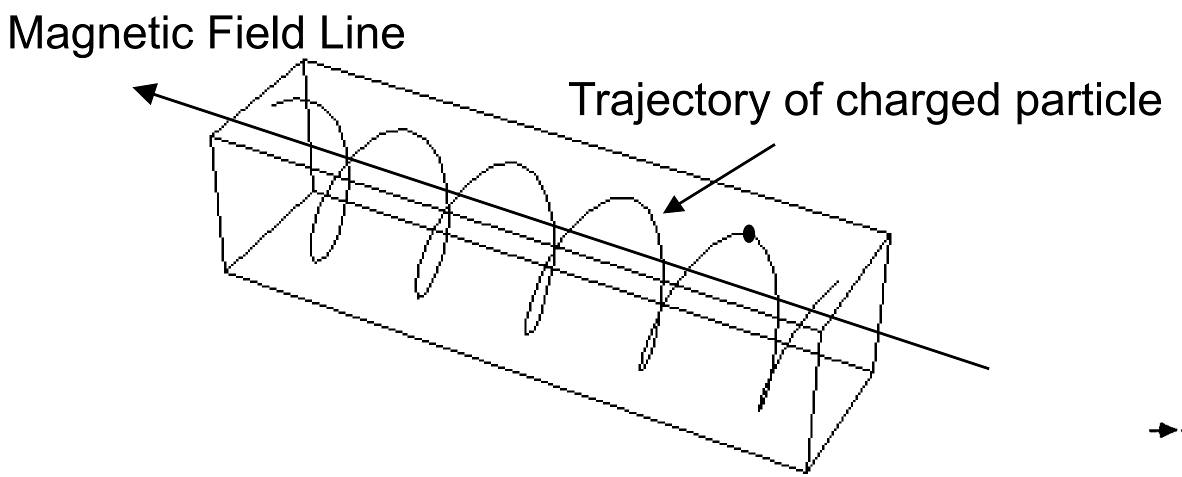
- The force equation for the electrons is
  - $m_e \dfrac{d^2 b}{dt^2} = -e\mathscr{E}_x(t) \Rightarrow \dfrac{d^2 b}{dt^2} = -\omega_e^2 b$, where $\omega_e = \sqrt{\dfrac{e^2 n_o}{m_e \varepsilon_o}} \approx 8980\sqrt{n_o}$ Hz (n_o in cm^{-3})

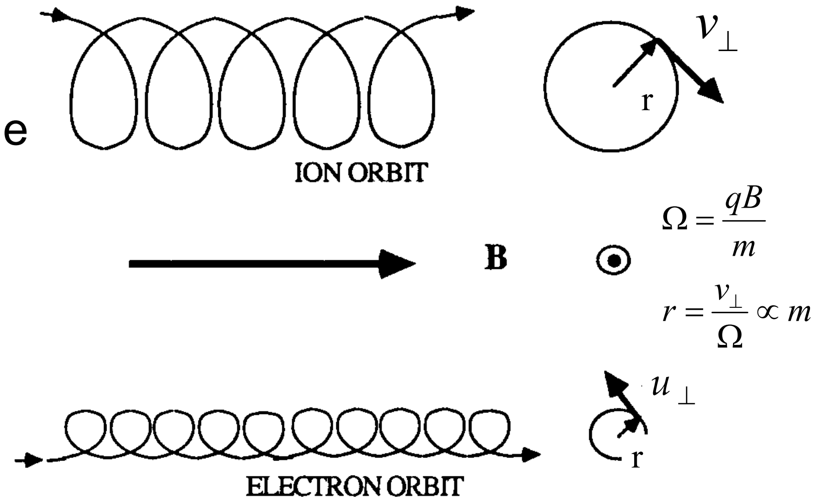
    is known as the electron plasma frequency.
  - And $b(t) = B_o \cos(\omega t + \varphi_o)$ indicating that the electron slab exhibits a simple harmonic motion.
- When ion's motion is also taken into account,
  - $\omega_p = (\omega_i^2 + \omega_e^2)^{1/2}$, where $\omega_i = \sqrt{\dfrac{e^2 n_o}{m_i \varepsilon_o}}$ is the ion plasma frequency.
  - ω_e is related to the Debye length by

    $\lambda_D = \dfrac{v_{th}}{\omega_e} = \sqrt{\dfrac{\varepsilon_o T_e}{e n_o}} \approx 743\sqrt{\dfrac{T_e}{n_o}}$, where $kT = m_e v_{th}^2$, T_e in volts, and n_e in cm^{-3}.
  - The plasma typically used in material processing have a Debye length in the range of 0.01 to 1.0 mm.
  - Let T_e=4 V and $n_e=10^{10}$ cm^{-3}, the Debye length is 0.14 mm.

Magnetic Force and Gyro-motion

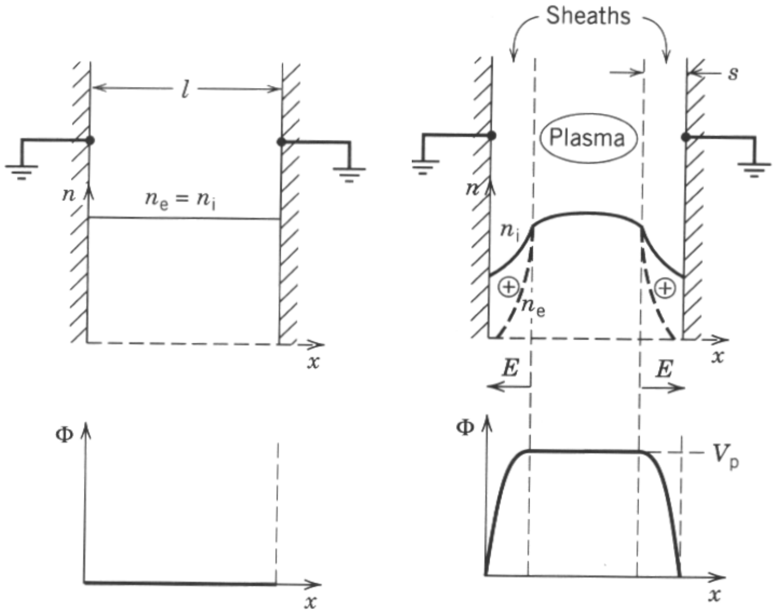
- Magnetic force on a charged particle: $F = q\vec{v} \times \vec{B}$
  - Magnetic force is always perpendicular to the particle velocity, v.
  - Charged particle will spiral around the magnetic field line (Gyro-motion).
- A charged particle in gyro-motion in magnetic field having a angular frequency $\Omega = \dfrac{qB}{m}$
- Gyro-radius of charged particle in a magnetic field, *r,* can be expressed as: $r = \dfrac{v_\perp}{\Omega} \propto m$





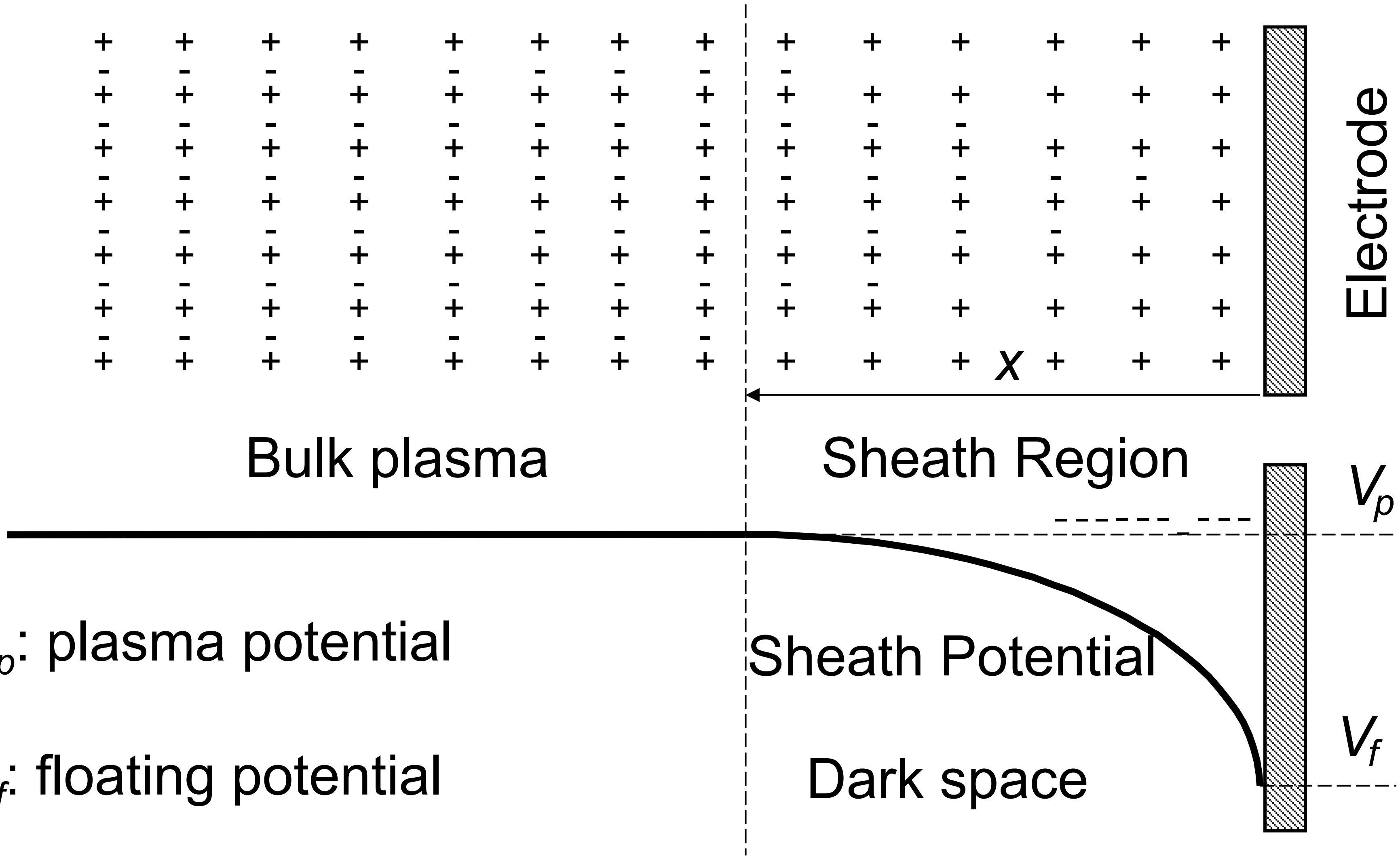
Sheath and Sheath Voltage

- What is a sheath ?
  - Plasmas, which are quasi neutral (n_i~n_e), are joined to wall surfaces across thin positively charged layers called sheaths.
  - Electron thermal velocity is at least 100 times the ion thermal velocity
  - Initially the charge density is zero and the electrical field is zero everywhere.
  - On a very short timescale, some electrons near the wall are lost due to its fast moving speed.
  - Positive ion sheaths form near each wall in which n_i>>n_e.
  - This forms a electric fields within the sheaths point from the plasma to the wall.



initial after sheath formation

Sheath Potential

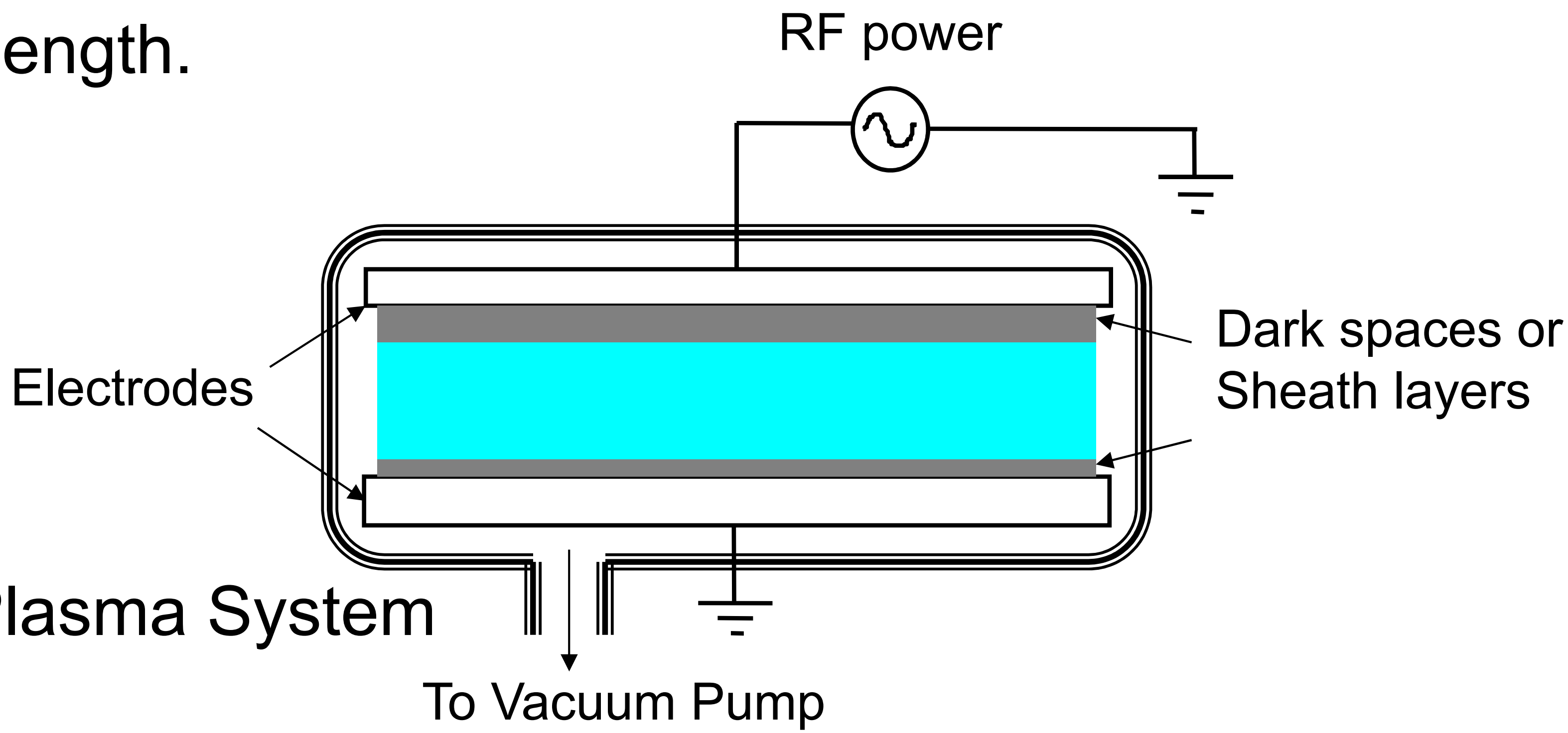


V_p: plasma potential

V_f: floating potential

Sheath Thickness

- The sheath thickness is close to the Debye length when the electrode is floating or grounded.
- When a power supply (dc or ac) is connected to the electrode, the sheath thickness could be much thicker than the Debye length.

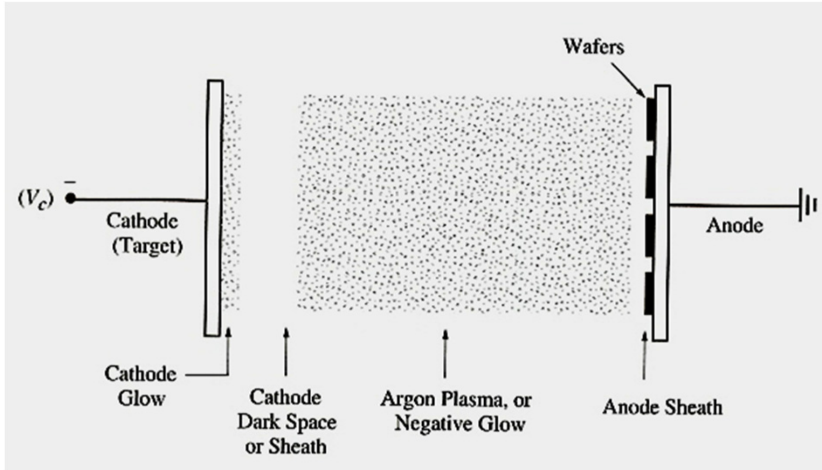


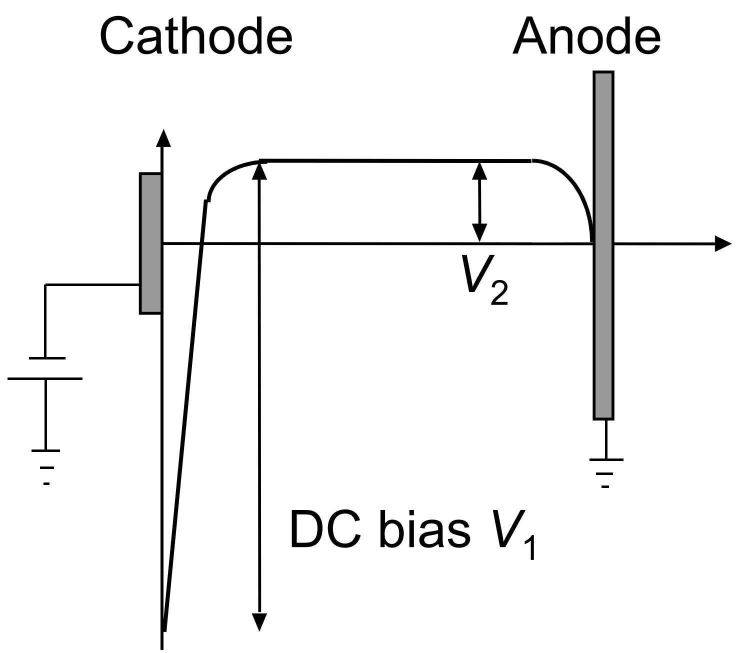
Parallel Plate Plasma System

Low and Medium Density Plasma Reactors

DC Glow Discharges

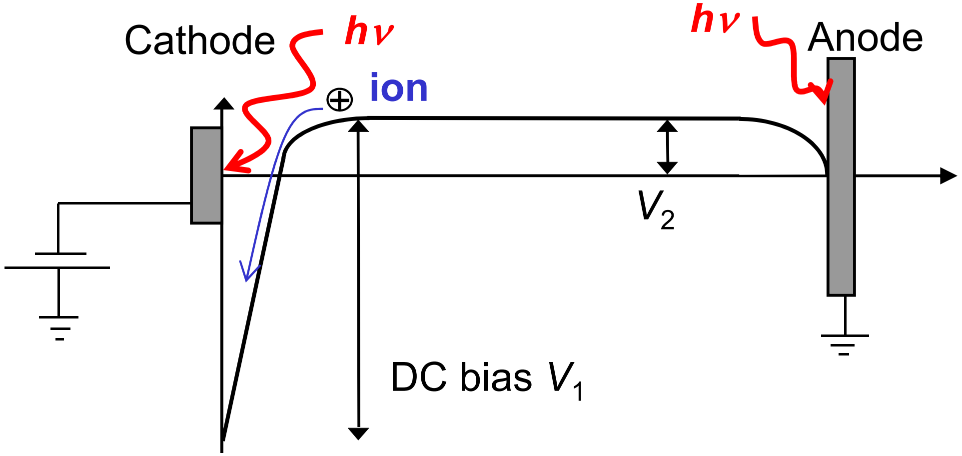
- Ar plasma example
  - Most of the space between the electrode is made up of the Ar plasma, called the negative glow. The voltage is fairly constant through out this region due to low resistance.
  - Near the cathode, where there is an excess of positive ions and a shortage of electrons. This is called the cathode dark space or cathode sheath and is on the order of 0.1 to 10 mm.
  - Right next to the cathode, where there is a thin cathode glow region due to the interaction between the incoming ions and the cathode material.
  - Additional glow regions and dark spaces can form closer to the anode, the anode sheath.
  - It finds little applications in the field of reactive plasma etching due to the charging effect on insulator surfaces.

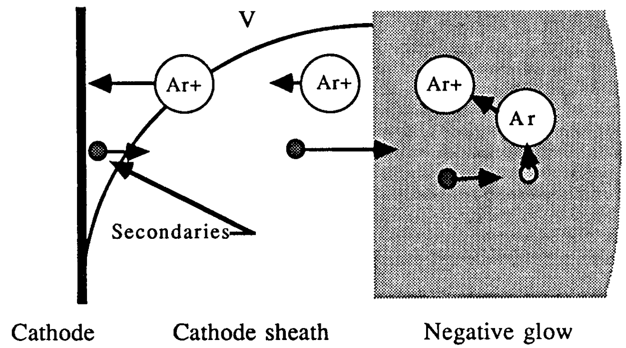




Bombardment Effects

- Products after bombardment: secondary electrons, sputtered target species, and photons
- Secondary electron emission
  - The number of electrons ejected per incident particle is called the secondary electron yield or coefficient, denoted by.
  - Secondary electrons produced at electrodes will be accelerated by the sheath voltage and flow into the plasma, and then release of energy in the glow via collisions, including ionization, excitation, and dissociation.
  - Some secondary electrons collide directly with the anode.



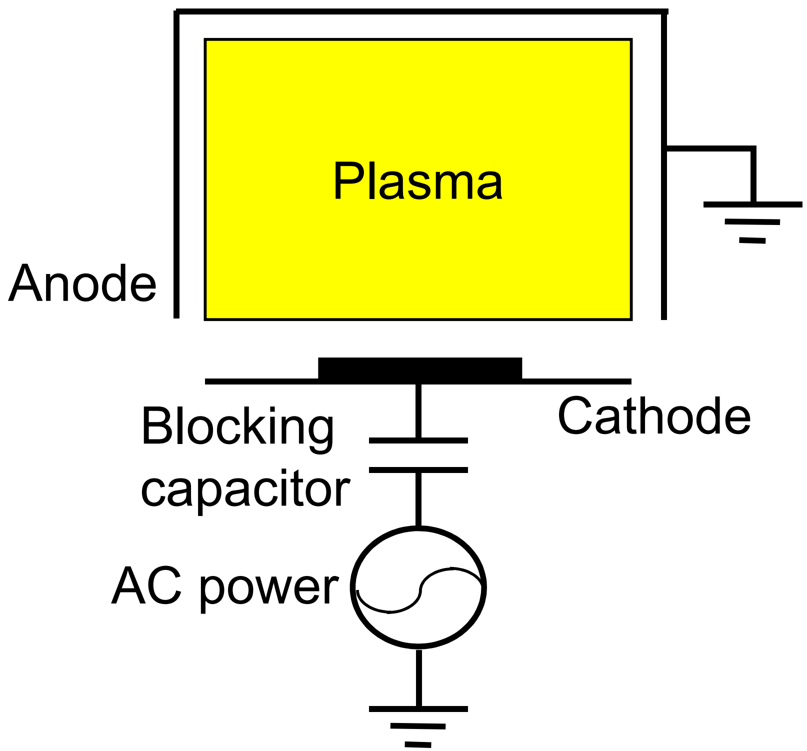


Issues for DC Glow Discharges

- Inefficient plasma generation
  - Most input power is used to accelerate the ions through the sheath. Sustaining of plasma generation depends on the secondary electron emission by ion bombardment which is typically with low efficiency. A magnet placed behind the target is usually used to confine the secondary electrons and increase the efficiency.
- Charging of insulator electrodes
  - Making the sheath voltage not stable and thus not suitable for etching applications.
  - This is the main reason why DC glow discharges are not suitable for reactive plasma etching applications.

Diode Reactor

- Advantages
  - Very simple configuration
  - Capacitive coupling plasma
  - Widely used in RIE and PECVD.
  - Charging effect on insulating surface could be solved.
- A blocking capacitor is inserted between the RF power and the cathode.
- Blocking capacitors may come from the matching network and the surface capping insulator on wafer at cathode.



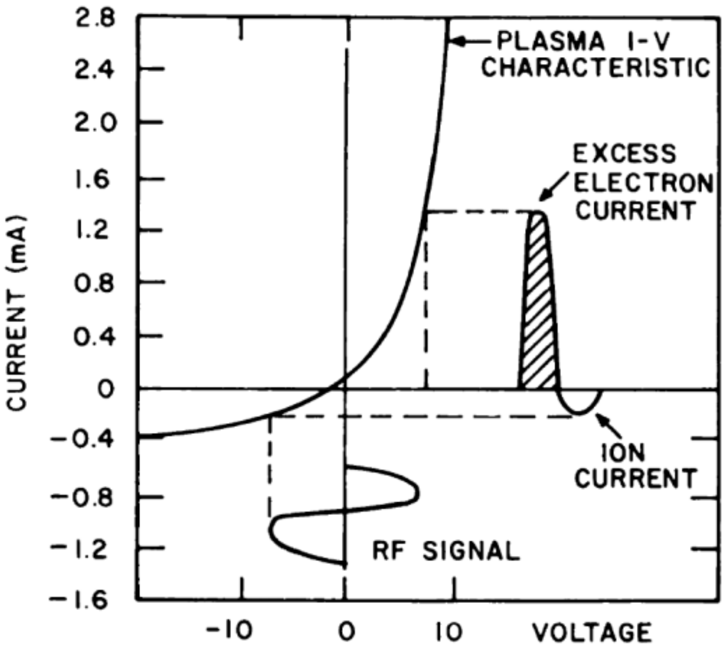
Power Supply Frequency

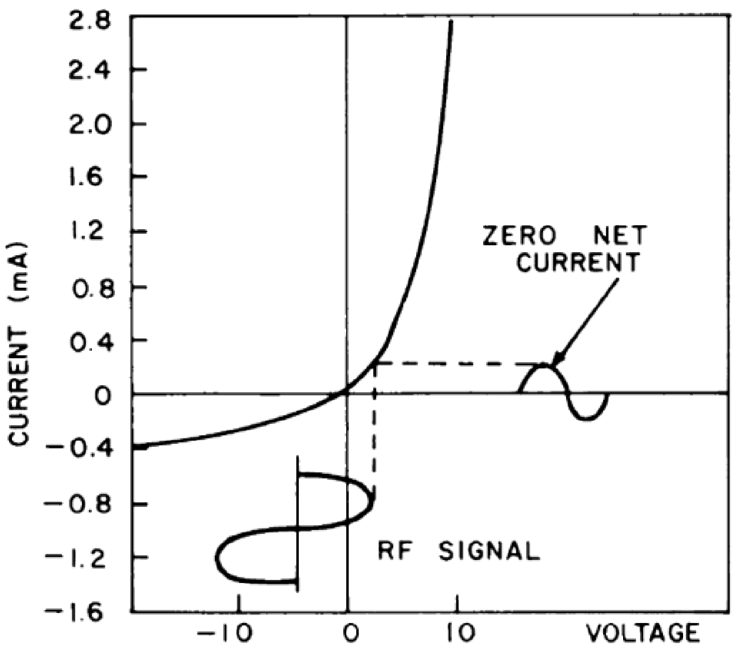
- The positive charges accumulated during one half-cycle can be neutralized by electron bombardment during the next half cycle.
- Typical electron oscillation frequency ω_e ~ 1 GHz.
- Typical ion oscillation frequency ω_i < 10 MHz.
- The power frequency used for diode is usually set in the range between ω_i and ω_e, so that only electrons in the glow are responsible for the ac signal.
- 13.56 MHz (allotted by the International Communication Authorities) RF is usually used.

Development of Self-bias - 1

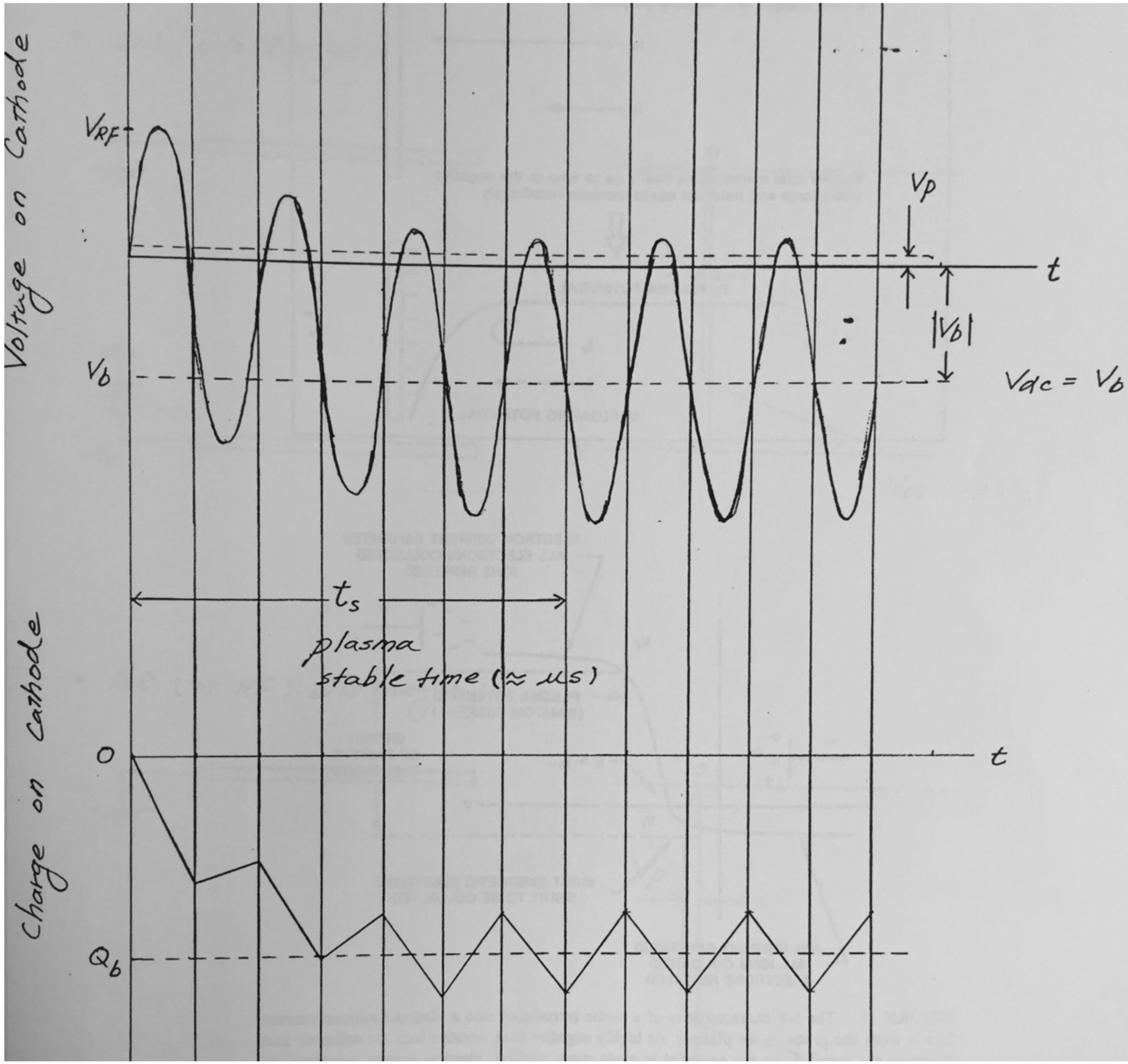
John L. Vossen, Thin Film Processes, p.29, 2012

- Formation of self-bias
  - Electron velocity is much higher than ion velocity.
  - The electron current in the positive half-cycle is higher than the ion current in the negative half-cycle.
  - The accumulated electrons reduce the electrode potential until the electron current equals to the ion current. A steady self-bias is setup.

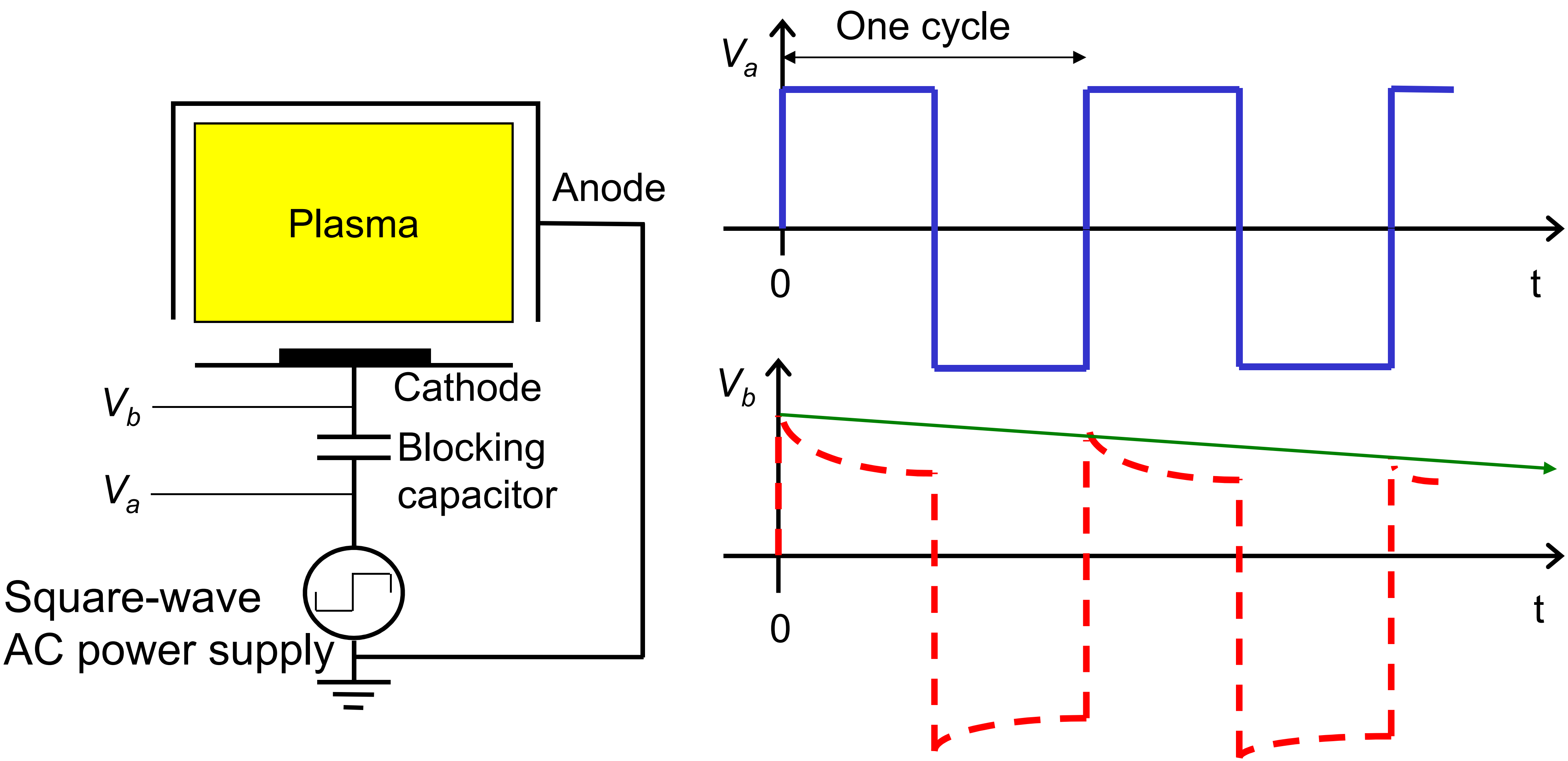




Development of Self-bias - 2

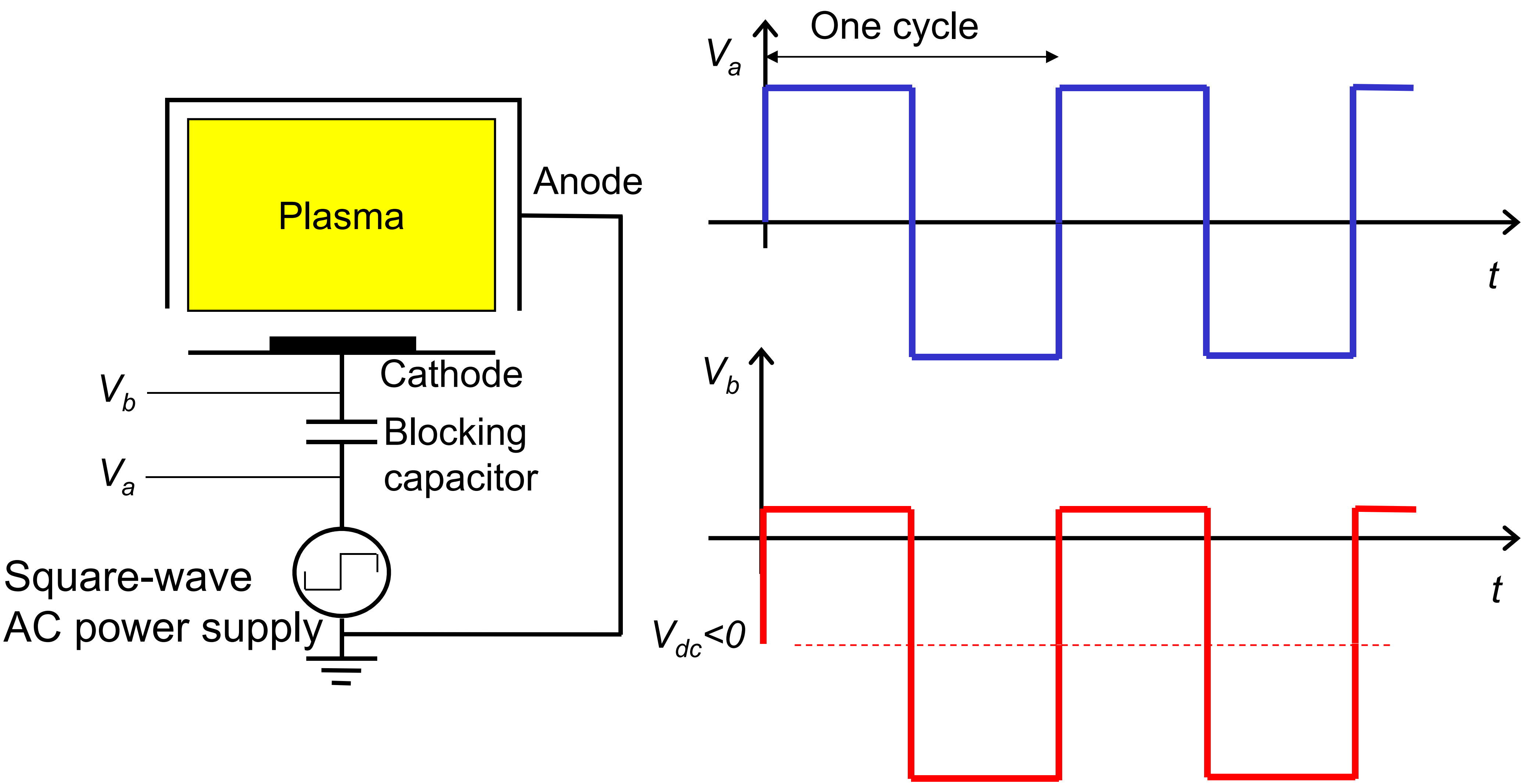


Development of Self-bias - 2



Before steady-state is reached.

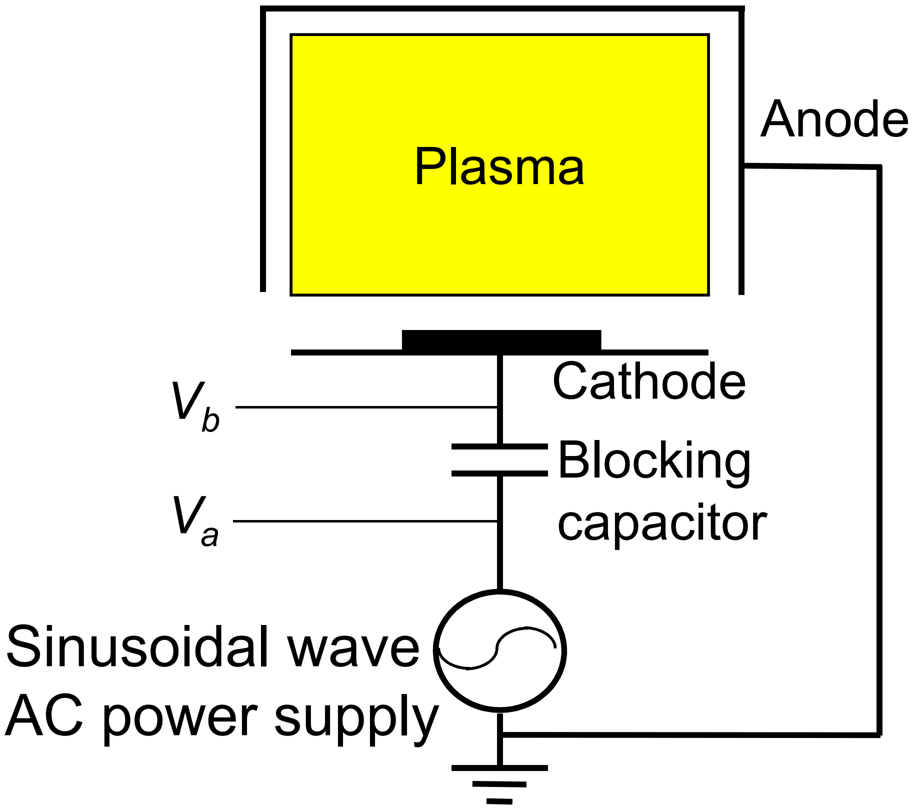
Development of Self-bias - 3

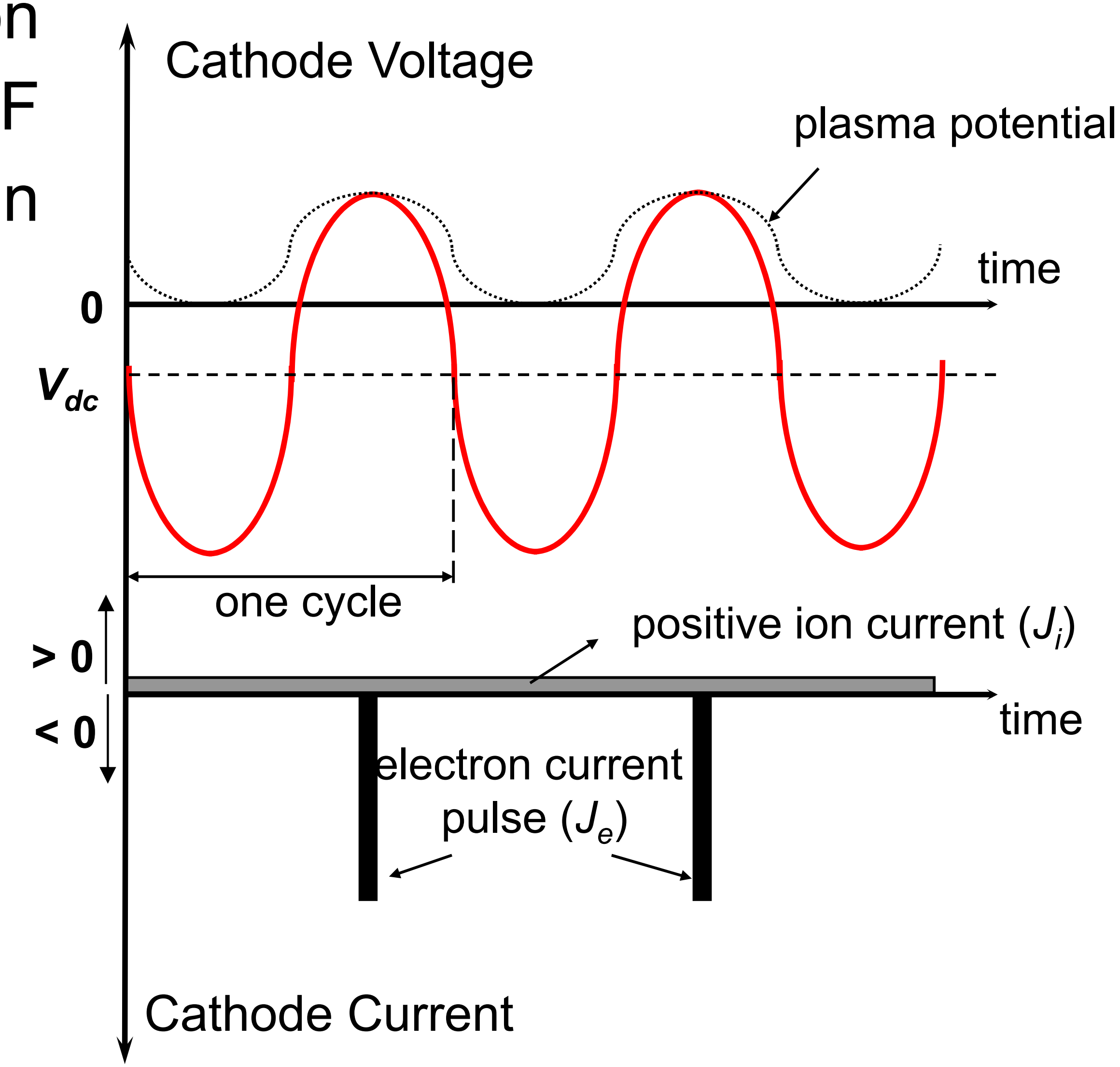


After steady-state is established

Development of Self-bias - 4

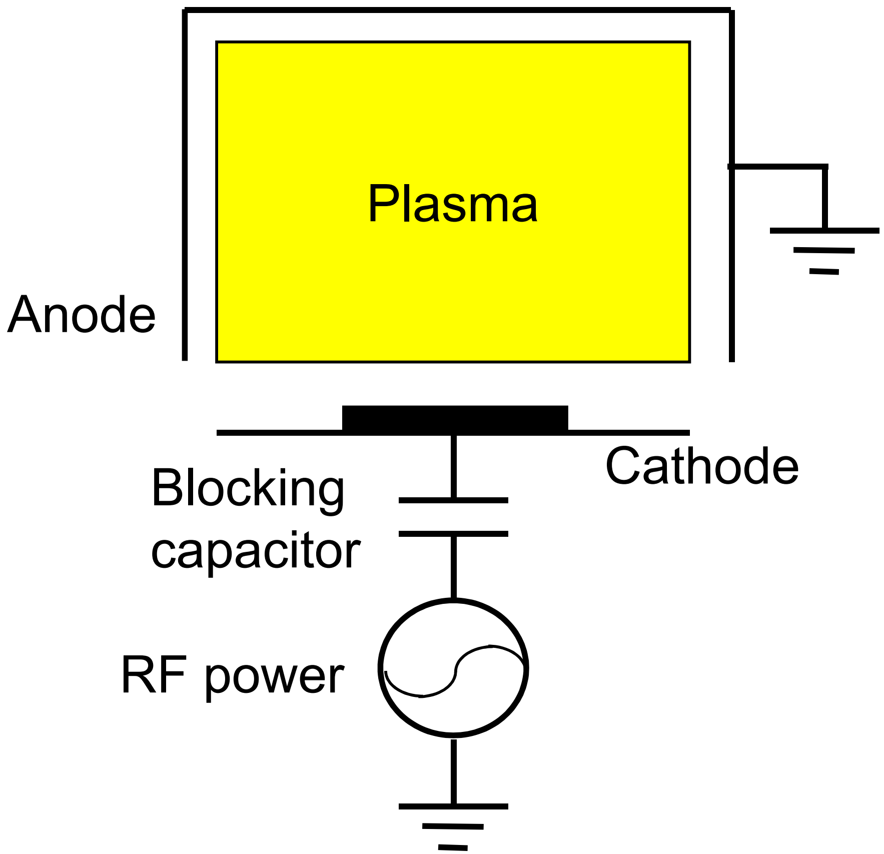
- In steady sate, positive ion charges collected in one RF cycle are neutralized by an electron current pulse.



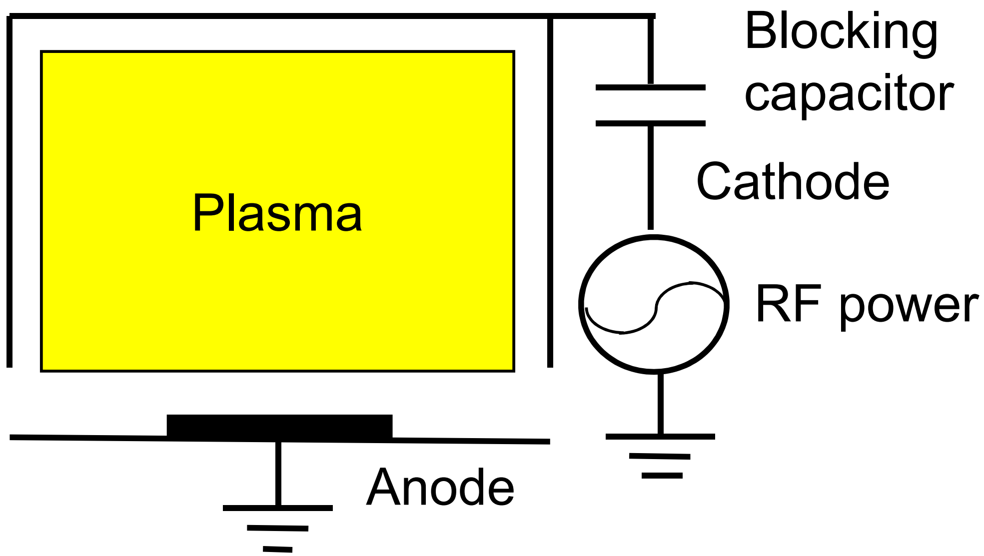


RIE-mode and Plasma-mode Operations

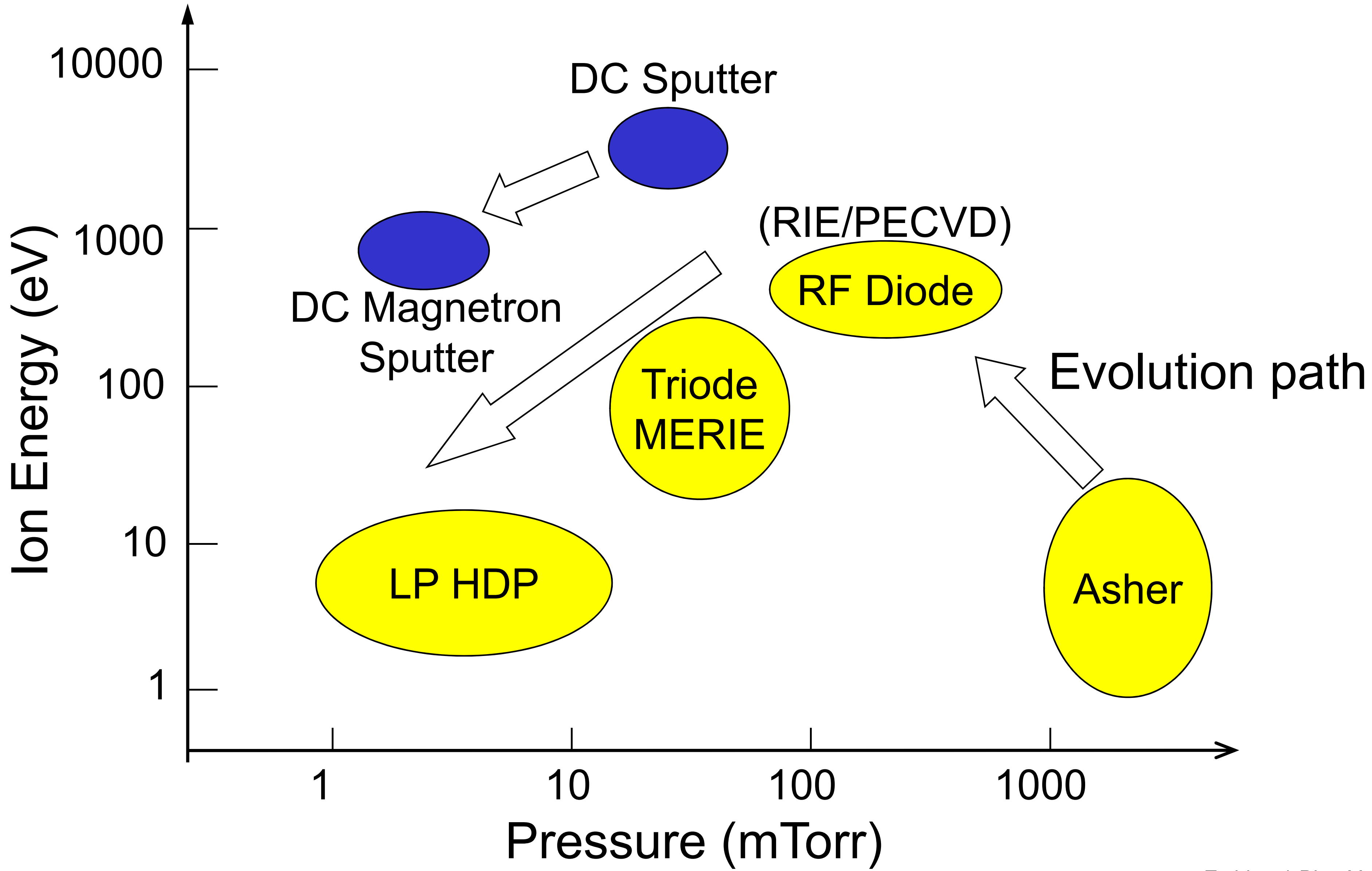
RIE-mode Operations



Plasma-mode Operations

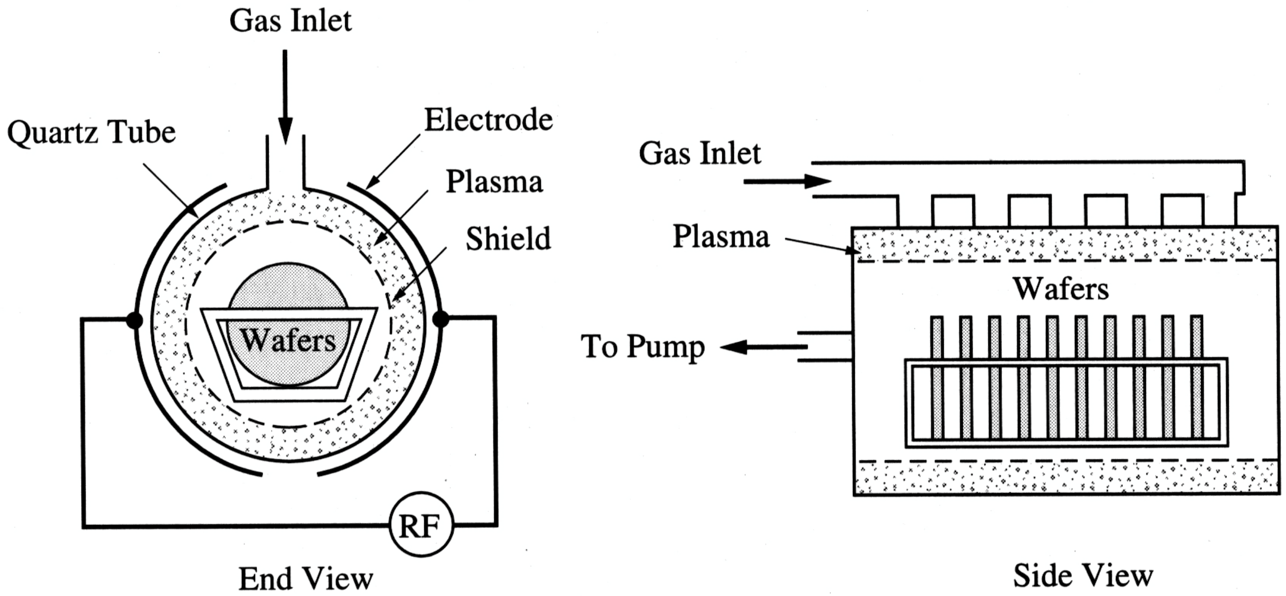


Evolution of Plasma Reactor Technology



Barrel Reactors

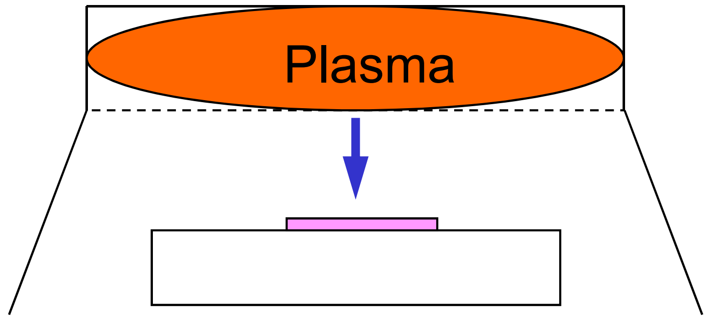
- Batch-type processing, high throughput.
- Pressure: 0.1 ~ 5 torr.
- Isotropic etch process (pure chemical etch).
- Poor process uniformity.
- Older systems for smaller size wafer (<150 mm).
- Suitable for PR stripping.



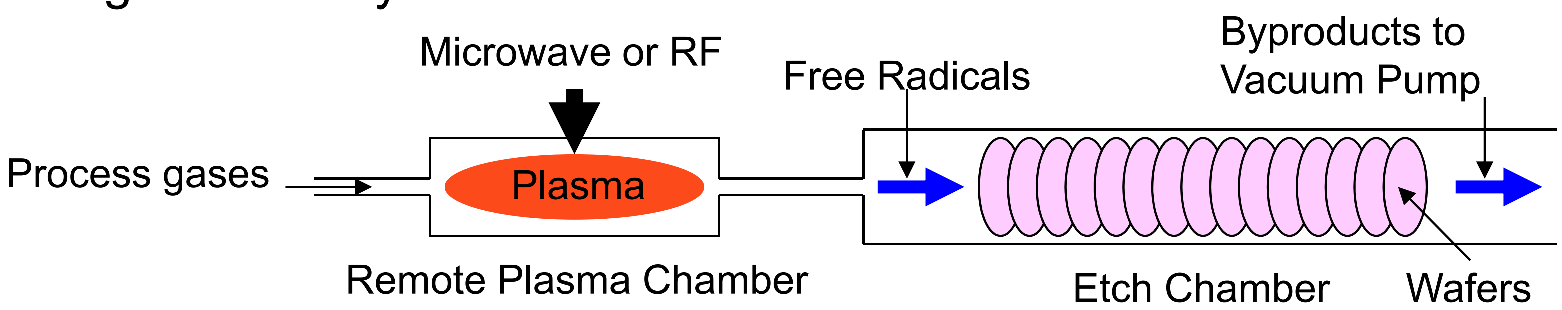
Downstream Reactors

- Ion bombardment and photon radiation could be eliminated.
- Pressure: 0.1 ~ 5 torr.
- Isotropic process for etch applications.
- Single-wafer reactors are widely used in manufacturing.
- Requirement
  - Pure chemical etching
  - Charge free
  - Radiation free
  - Contamination free
  - High etching rate
  - High selectivity

Single-wafer type



Batch type



Limitations for Diode Reactors

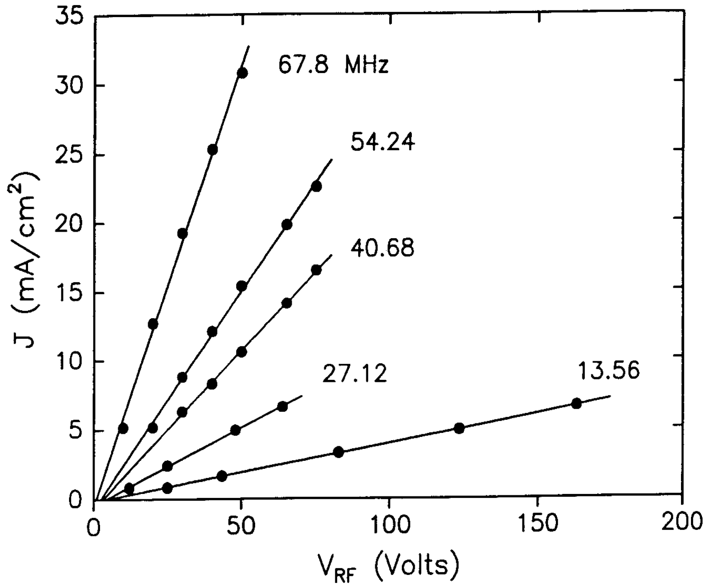
- Diodes usually use 13.56 MHz power supply.
- Main limitations:
  - High operation pressure (typically P > 100 mtorr)
  - Low plasma density (typically $\leq 10^{10}$ cm^{-3} as P ~ 100 mtorr)
  - High cathode V_{dc} for RIE (typically several hundreds of eV)
- Reasons:
  - Only one power source used for both plasma generation and V_{dc} control.
  - Poor capacitively coupled plasma (CCP) generation efficiency.
  - At pressures of 1 - 300 mtorr, and RF power density > 0.1 W/cm^2, only 3 - 10 % of the total RF power dissipated in the 13.56 MHz discharge is absorbed by plasma electrons and "spent" partially in ionization.

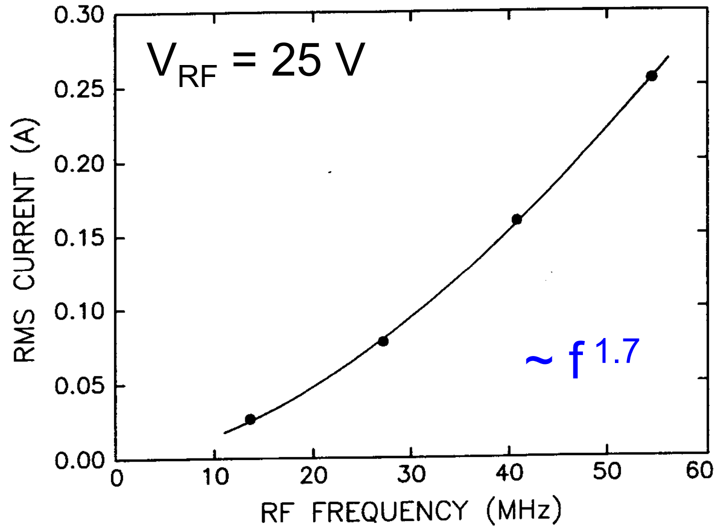
Ways for Resolving Diode's Issues

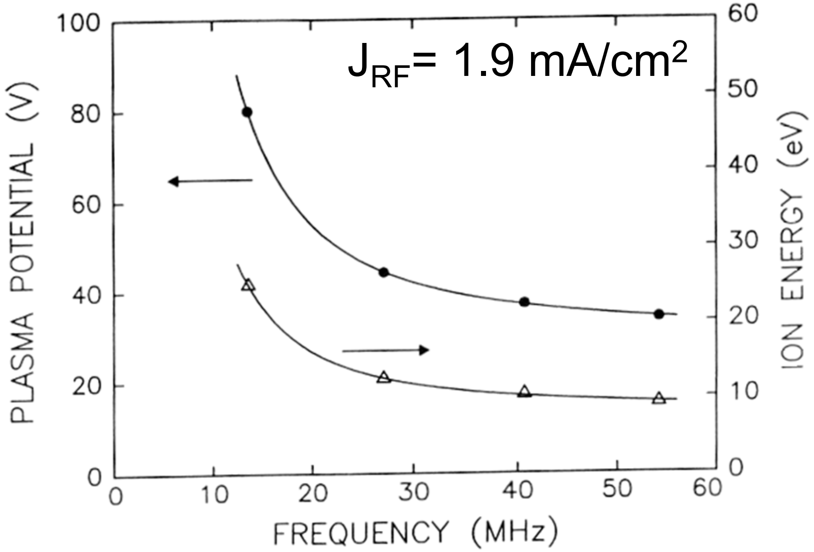
- Equipped with very-high-frequency (VHF >> 13.56 MHz)
- Triodes
- Magnetically enhanced diodes
- High-density plasma (HDP) reactors (non-capacitive plasma triodes)
    - Exs: ICP, ECR, Helicon wave, etc.

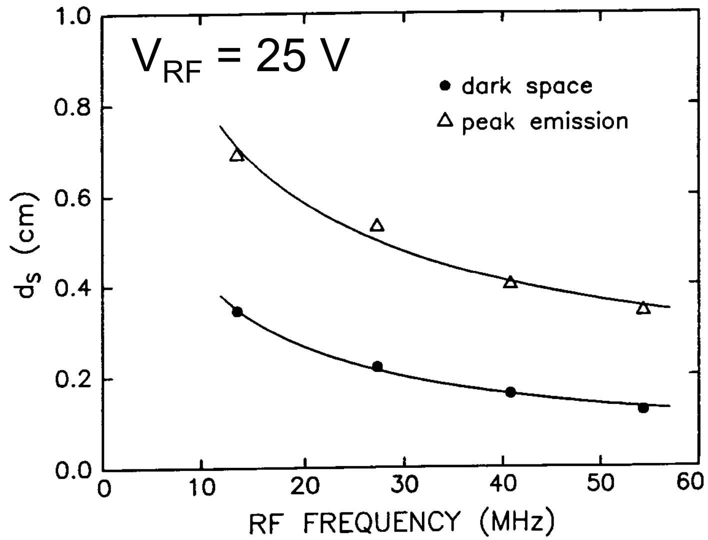
Effects of VHF

Ar plasma, RF power = 50 W, P = 250 mtorr, Electrode gap L = 2 cm

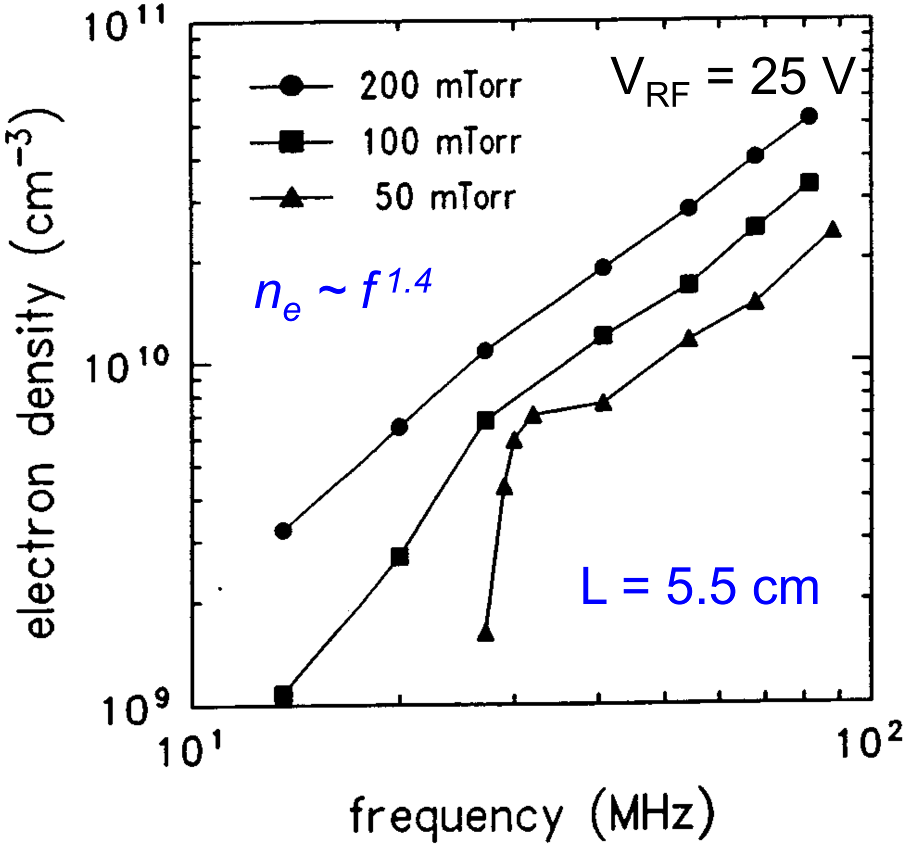


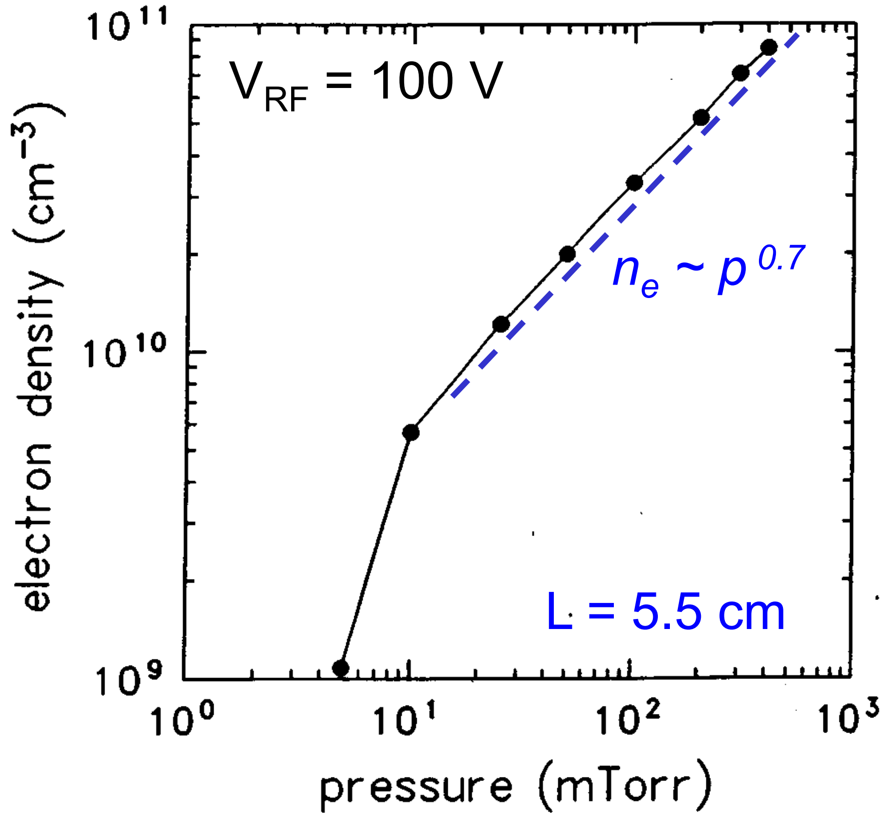






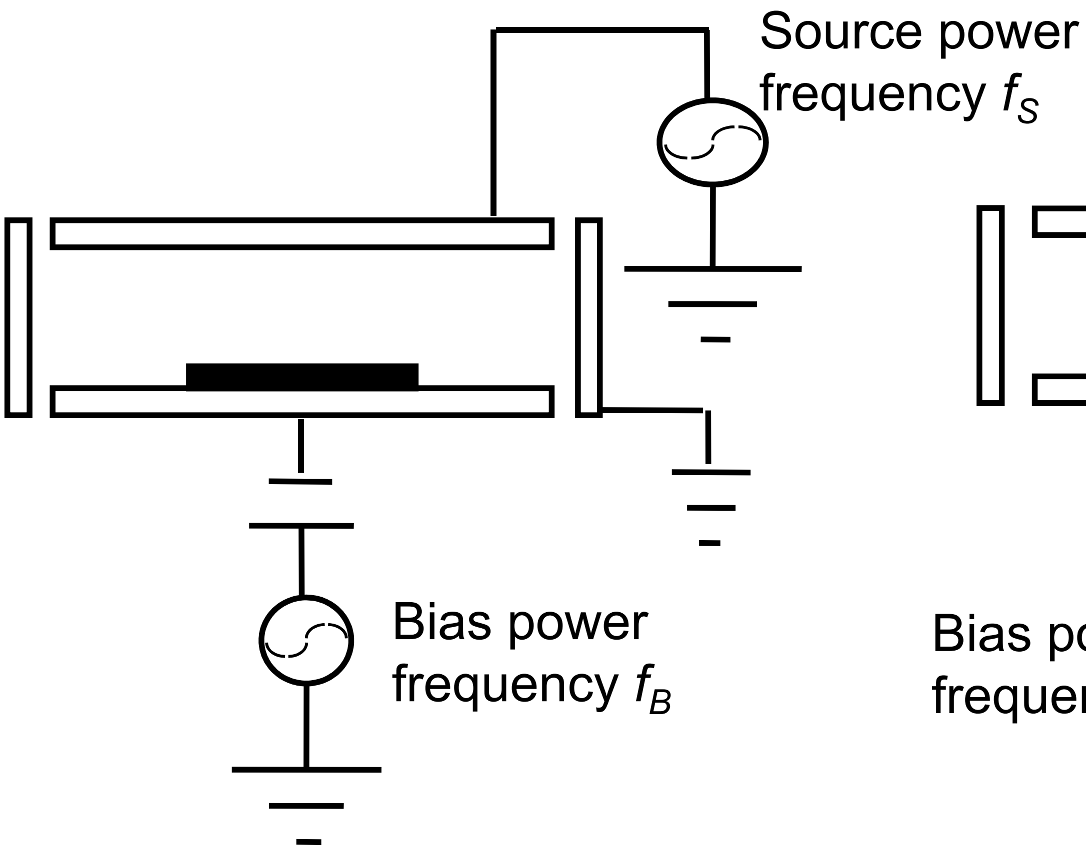
Effects of VHF

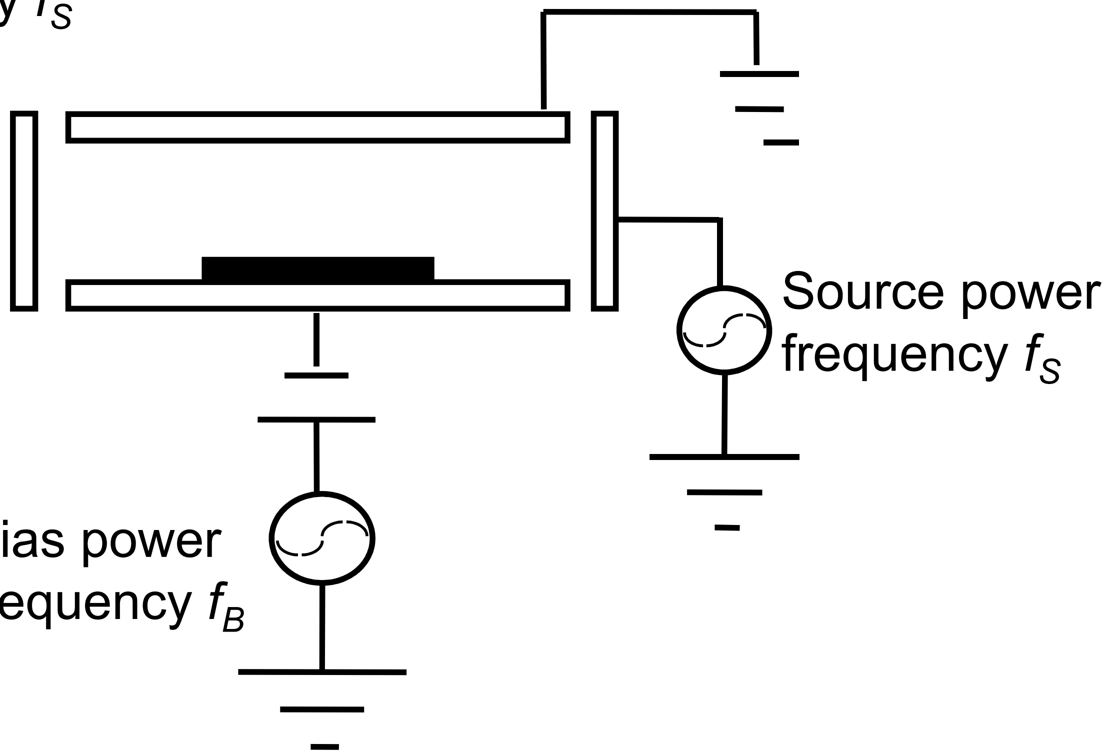




Triode Reactor

- Configurations
  - Independent control of plasma generation and V_{dc}. (actually not true for most conditions)

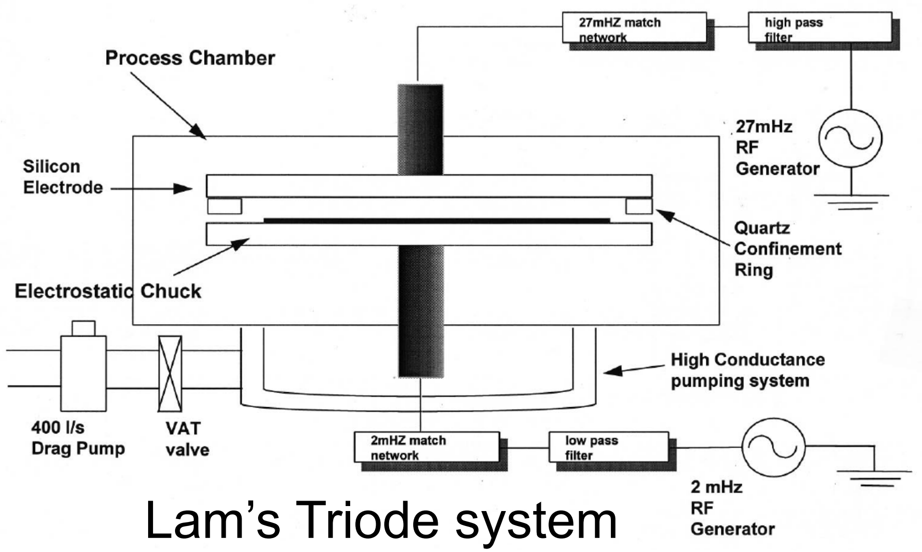




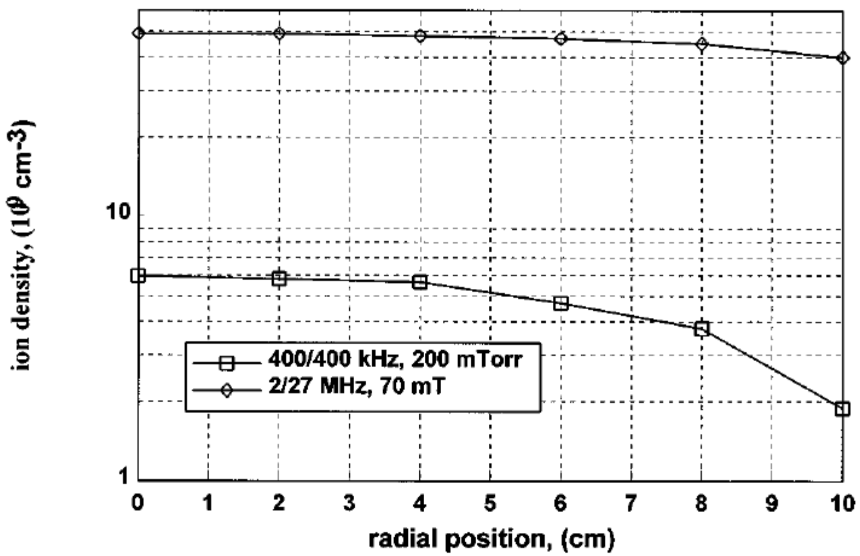
Dual Frequency Triode

(J. Vac. Sci. Technol., B14, p.3276, 1996)

- Good dual-frequency design increases plasma density, improves plasma, and reduces operation pressure.



Lam's Triode system

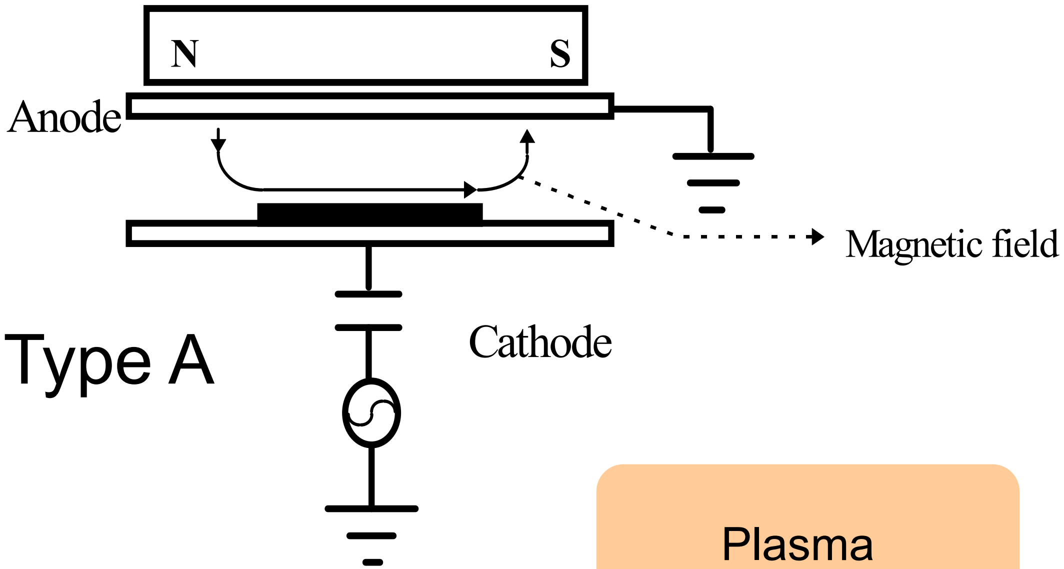


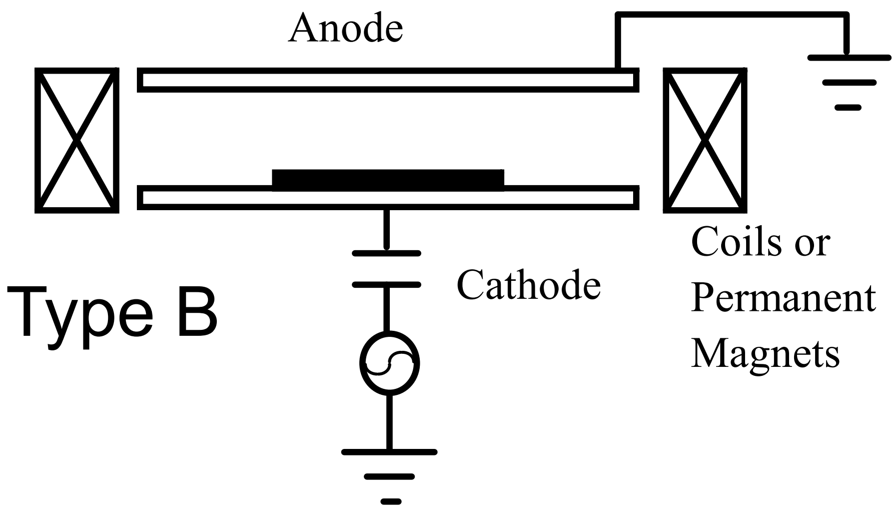
- Issues
  - Correct concept and simple idea. However, limited progress is made over conventional diode reactors due to the fact that the low CCP generation efficiency at low pressures as most of the power is dissipated in the sheath. In addition, the rf source and bias powers may interact with each other and lead to a non-stable plasma operation.

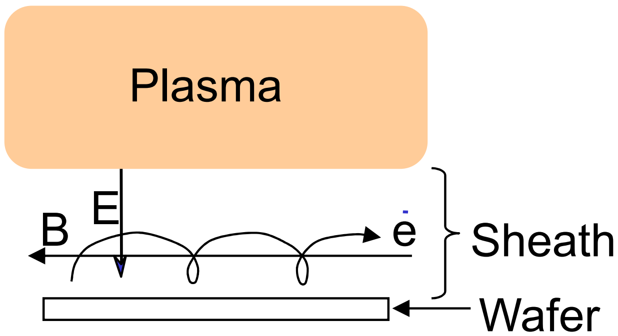
Magnetic-enhanced (ME) RIE

➢ Configurations

- Typical dc magnetic field: 50 ~ 80 G
- The magnetic field is parallel to the wafer surface and confines electrons to a circular trajectory near the cathode.

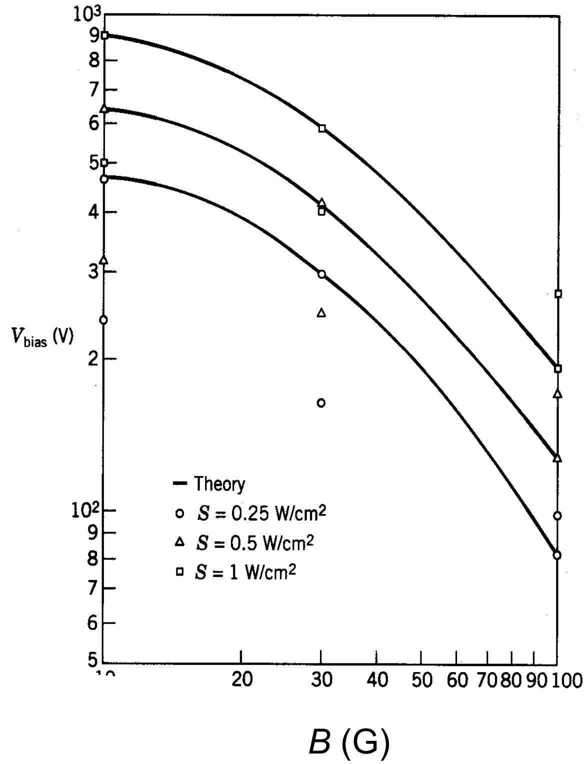


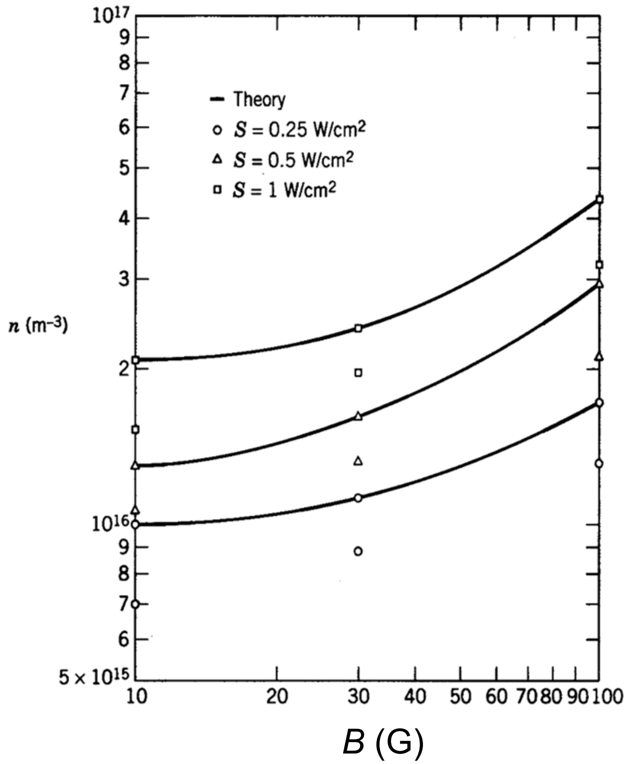




Effect of Magnetic Field

- Magnetic field increases electron density in sheath layer.
  - Less charge difference in sheath region.
  - Lower DC bias.
  - Enhanced stochastic heating.
- Effects on ion bombardment
  - Increasing ion density
  - Reducing ion energy (V_{dc})





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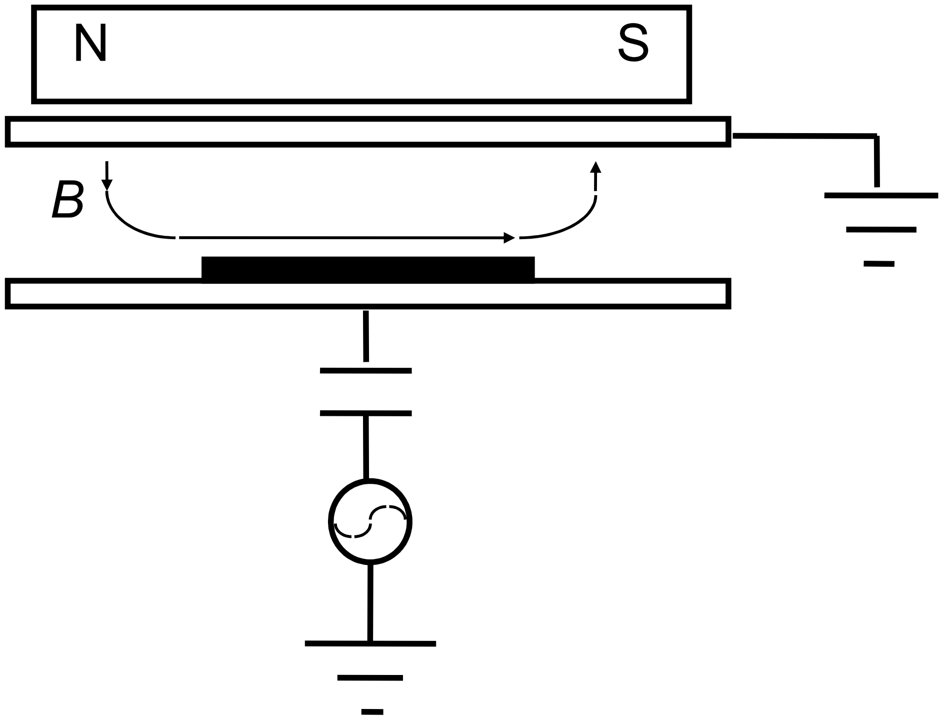
Department of Electronics Engineering &
Institute of electronics

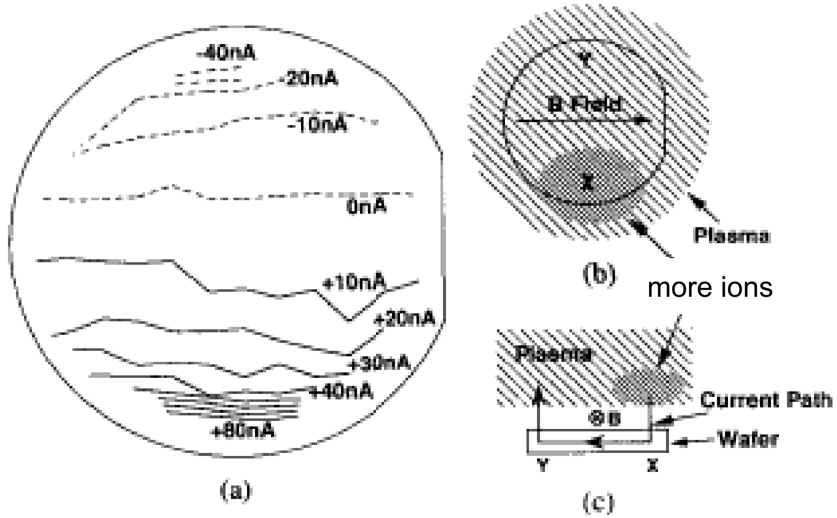
Non-uniform Plasma Due to Magnetic Field

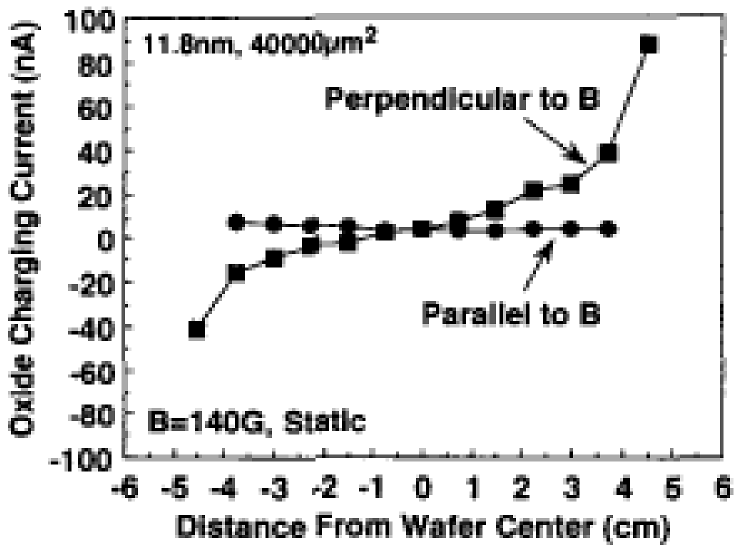
IEEE EDL, Vol.14, p.88, 1993

➢ Origins

- Due to the larger normal B-field component at the wafer edge (Type A)
- Due to the E x B electron drift in the sheath
- Often the applied B field is rotated to improve the uniformity

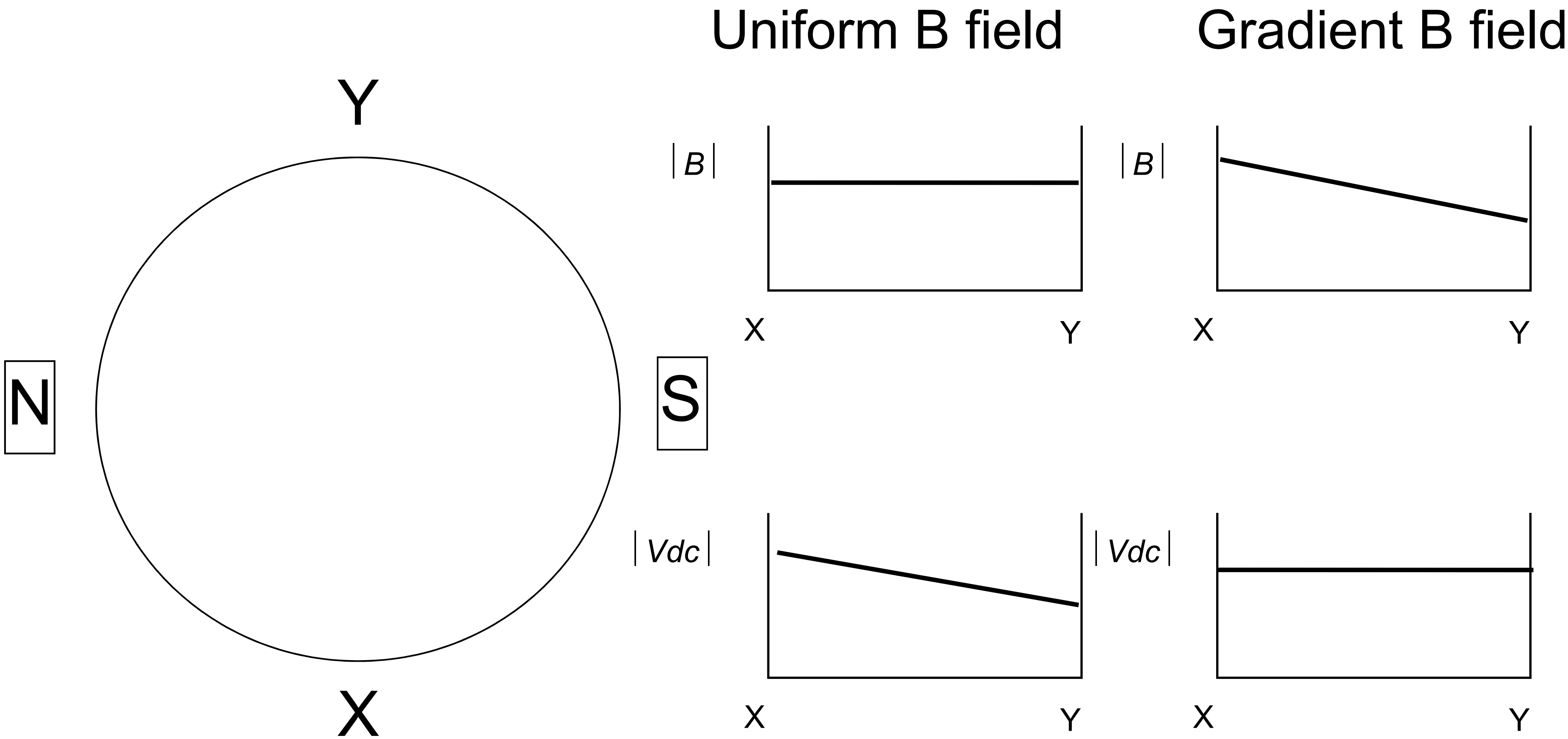






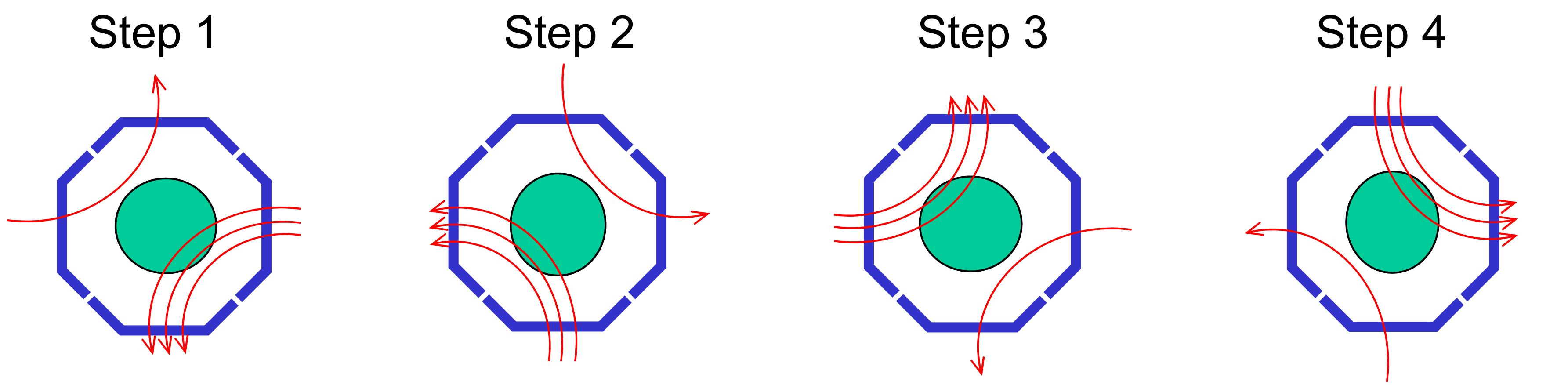
Improvement of Plasma Uniformity

Using Optimized Gradient Field



MERIE with Time-varied Magnetic Field

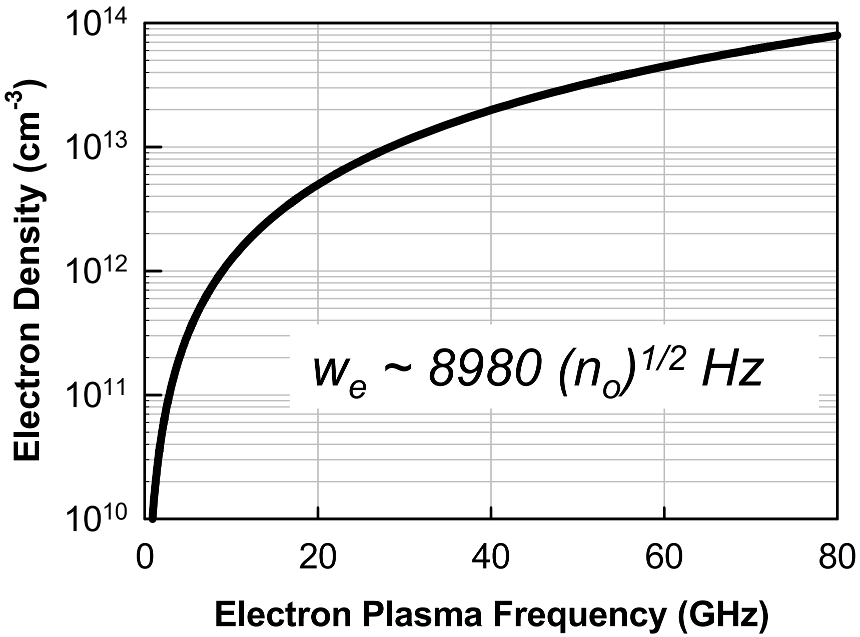
- Adjacent coils are powered at one B-field strength while the opposite coils are powered at a different strength, which is operator selectable (step 1).
- The sequence continues by switching to the next pair of coils, as illustrated by steps 2-4. The rotation creates a gradient B-field, which results in a highly uniform electron distribution across the wafer.



High Density Plasma Sources

HDP Source

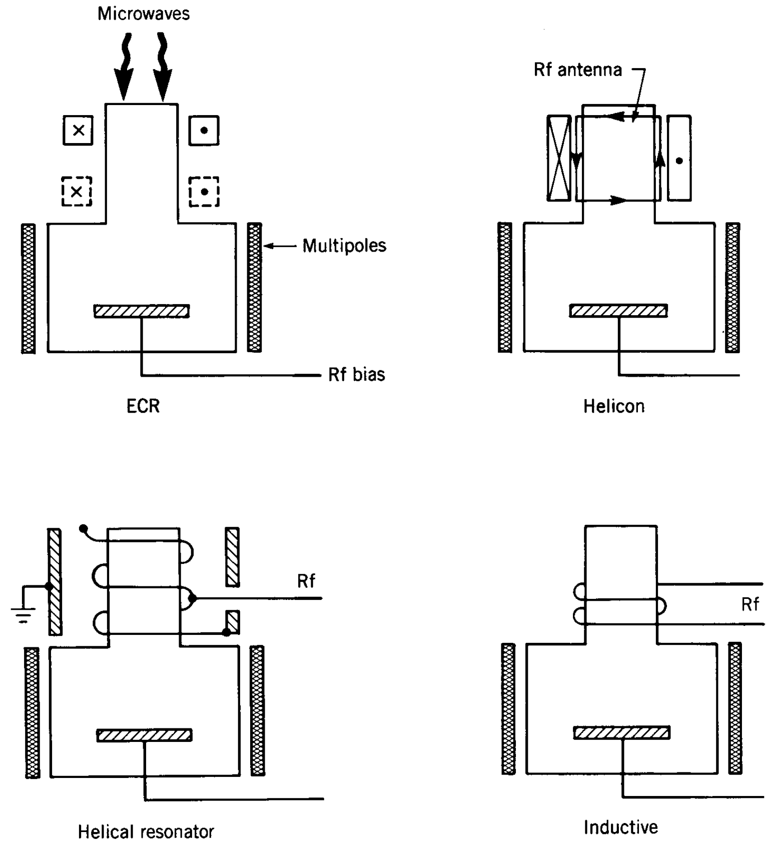
- Source types other than capacitive coupling mode are usually employed.
- In a non-magnetized plasma, EM wave with frequency lower than the electron plasma frequency cannot propagate through the plasma.
- Mechanisms involving resonant wave-particle interactions in magnetized plasmas (e.g., ECR and helicon wave resonance) are efficient ways for electron heating.



Types of HDP Reactors

➢ HDP reactors

- Magnetic confinement (High Density Reflected Electron or HRe)
- Inductive (or transformer) couple plasma (ICP or TCP)
- Electron cyclotron resonance (ECR)
- Helicon wave plasma (HWP)
- Surface wave plasma (SWP)
- Others



➢ General properties

- Low-pressure operation (typically < 50 mtorr).
- Independent control of plasma generation and ion energy (V_{dc}).
- High plasma density (typically $10^{11} \sim 10^{12}$ cm^{-3}).
- Low ion energy (typically < 100 eV).

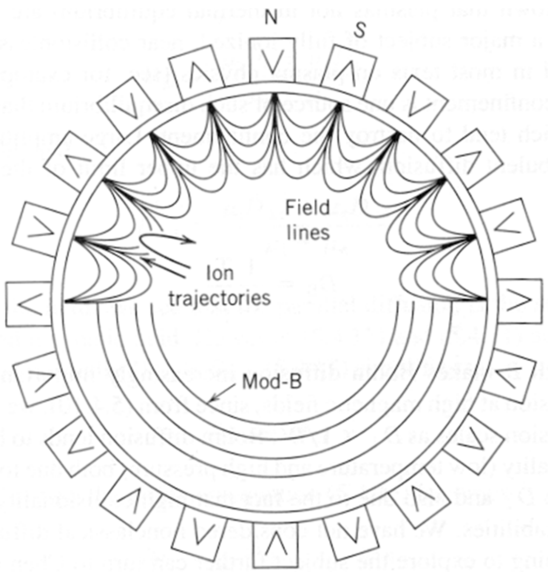
Commercial HDP Reactors

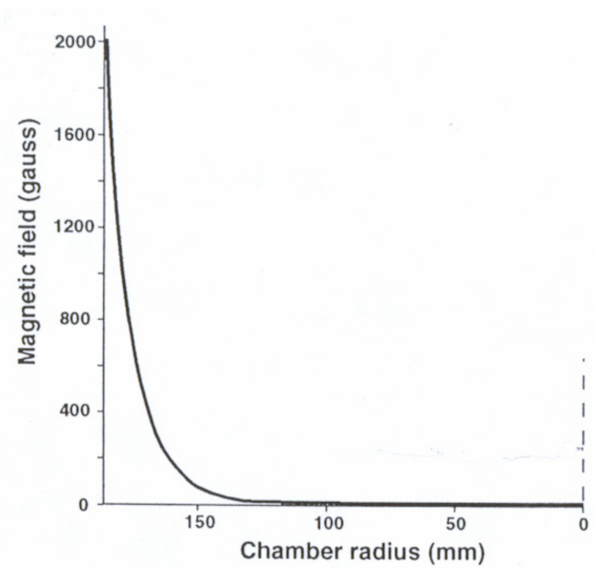
	PMT MORI	Lucas Lab. Helicon	Prototech Helical Res.	Drytech Hollow Cathode	Tegal HRe	**Lam TCP**	**Applied Materials DPS**	Hitachi ECR	Sumitomo ECR	Anevela ECR	Sumitomo SWP
Source freq. (MHz)	13.56	13.56	13.56	13.56	13.56	13.56	2	2450	2450	2450	2450
Bias freq. (MHz)	1.6/13.56	13.56	13.56	13.56	< 0.5	13.56	1.8	2/13.56	13.56	0.4	0.4
Source B field (gauss)	50-120	50-400	NA	NA	NA	NA	NA	875	875	875	NA
Plasma density (cm^{-3})	**$3x10^{12}$**	$3x10^{11}$	$1x10^{12}$	$1x10^{12}$	$3x10^{11}$	$1x10^{12}$	$1x10^{12}$	**$1x10^{11}$**	**$1x10^{11}$**	**$1x10^{11}$**	$1x10^{12}$
Pressure (mTorr)	0.5~10	1-10	0.05~ 300	10-180	1-20	1-25	1-10	0.4~10	0.5~1	0.5~10	10~50

Magnetic Multipole Confinement (MMC)

➢ MMC plasma reactors

- It uses permanent-magnet pole pieces and arrange them alternately around the process chamber to create a magnetic-field-free region around the wafer.
- A high density of ions is achieved through the reflection of electrons back into the plasma from the surface magnetic-field buck.
- This greatly increases the effective path of electrons, and higher ion density is generated from the higher frequency of electron-neutral collisions.
- Magnetic field in the center of an MMC reactor is very low and may not result in plasma non-uniformity.



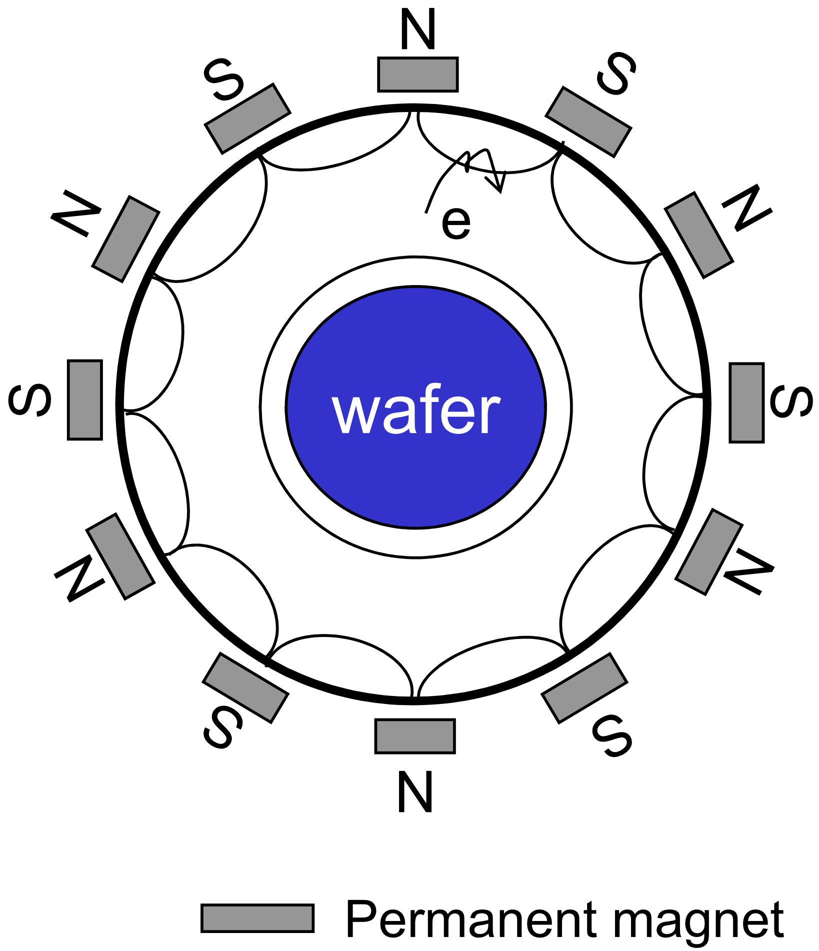


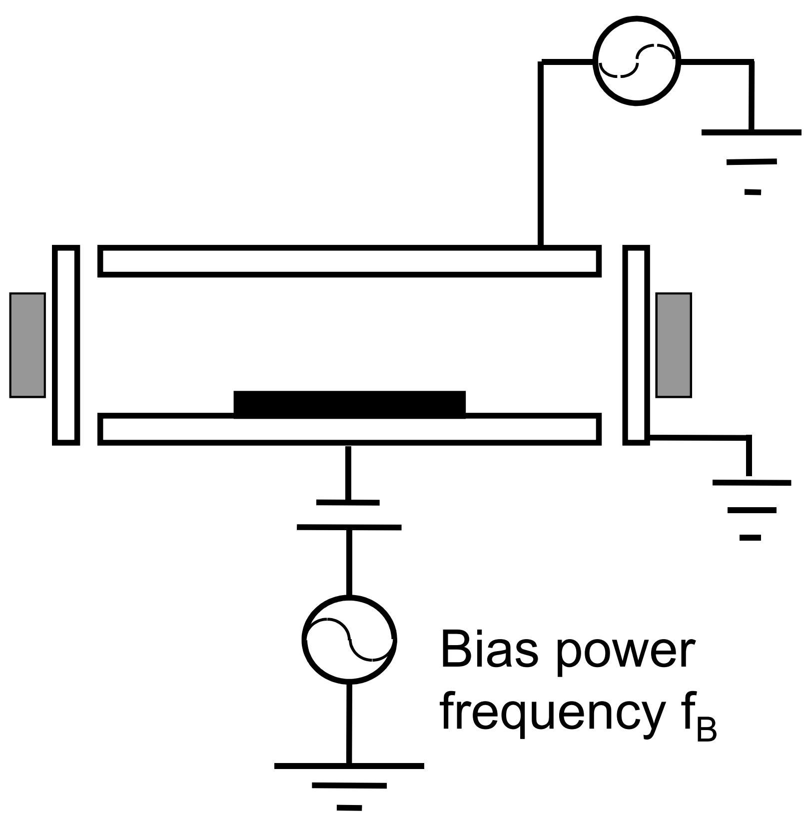
Magnetic Multipole Confinement (MMC)

- Hot electrons, having energy higher than the DC sheath potential, can be effectively confined. These electrons, if created and trapped at low pressures, can be the main ionization source for a discharge.
  - Significant (but not large) improvements in plasma density can be obtained in the confinement of the bulk (low-temperature) plasma in a discharge.
  - Significant improvements in radial plasma uniformity can be obtained.
- Applications of MMC in HDP reactors
  - HRe (Tegal, Triode)
  - MORI (PMT, helicon wave source)
  - ICP (experimental tools)
  - ECR (experimental tools)

HRe Reactor

Tegal Corp.



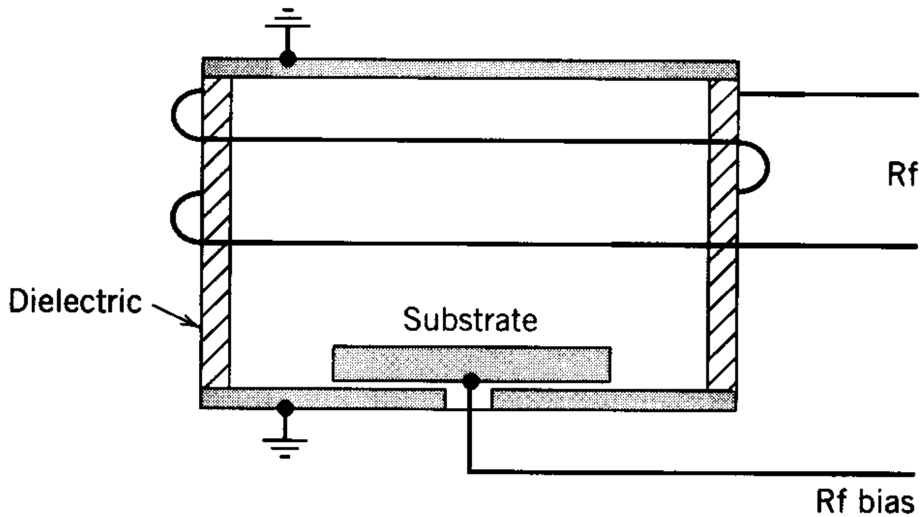


Inductive Discharges

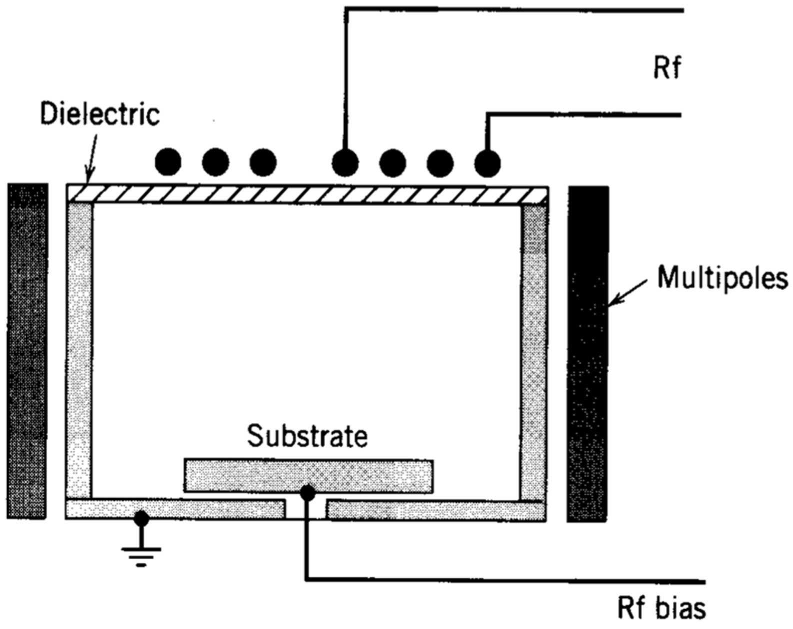
- An inductive discharge source generates high density, low pressure plasma that is decoupled from the wafer, and it allows independent control of ion flux and ion energy.
- Plasma is generated by a spiral coil that is typically separated from the plasma by a dielectric plate (quartz plate in general) on the top of the reactor, though in some applications it is placed inside the plasma reactor.
- The wafer is located several skin depths away from the coil, so it is not affected by the electromagnetic field generated by the coil.

Inductive Discharges

- The coils may be applied to the sides of a cylindrical tool or to the top (e.g.. TCP). These non-resonant RF inductive sources are perhaps the simplest in design of all the enhanced sourced to date.



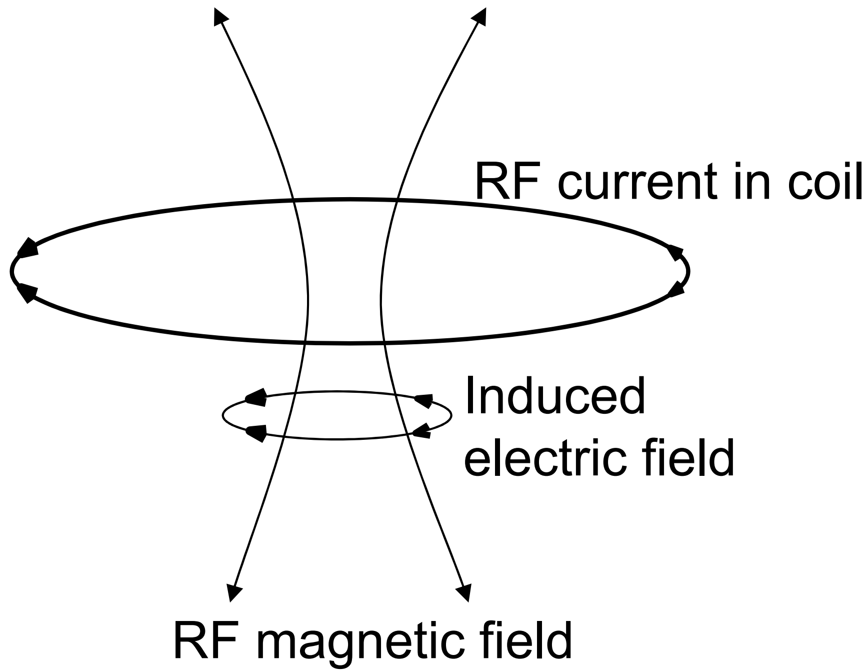
Cylindrical geometry



Planar geometry

Inductively Coupled Plasma (ICP)

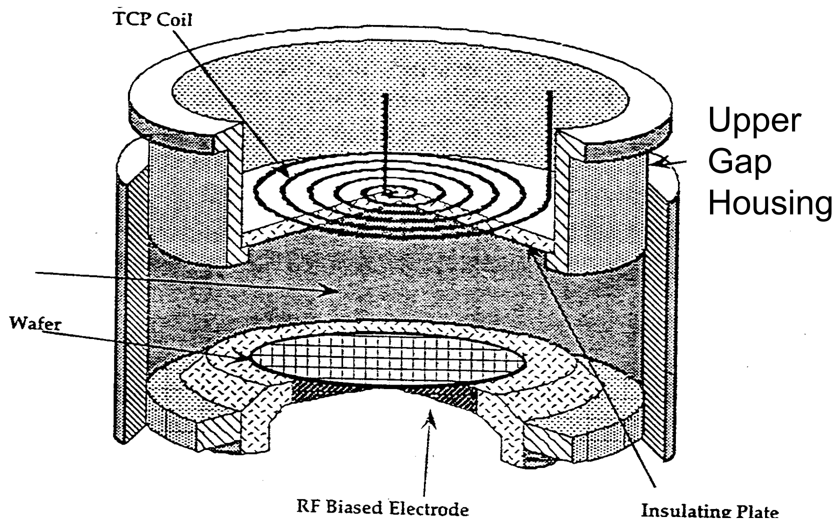
- Inductively couple RF power to plasma.
- Like a transformer, also called TCP
- Changing magnetic field cause electric field.
- Electrons are accelerated in angular direction.
- Could achieve high plasma density at low pressure.

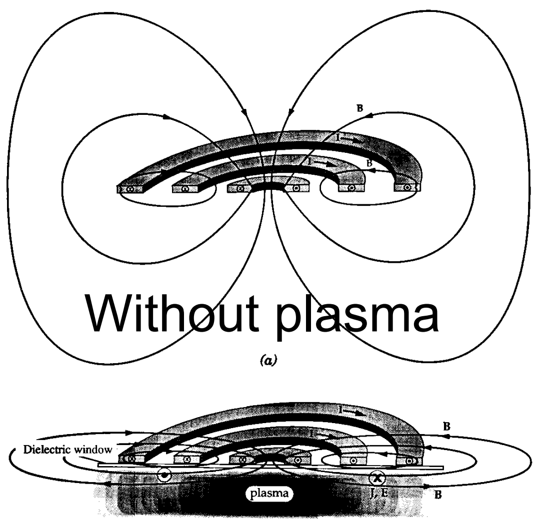


Example of ICP Chamber

- Upper part of chamber: ceramic or quartz.
- Source RF inductively couples with plasma.
- Source RF generates plasma and controls ion density.
- Bias RF controls ion bombardment energy.
- Ion energy and density are independently controlled.

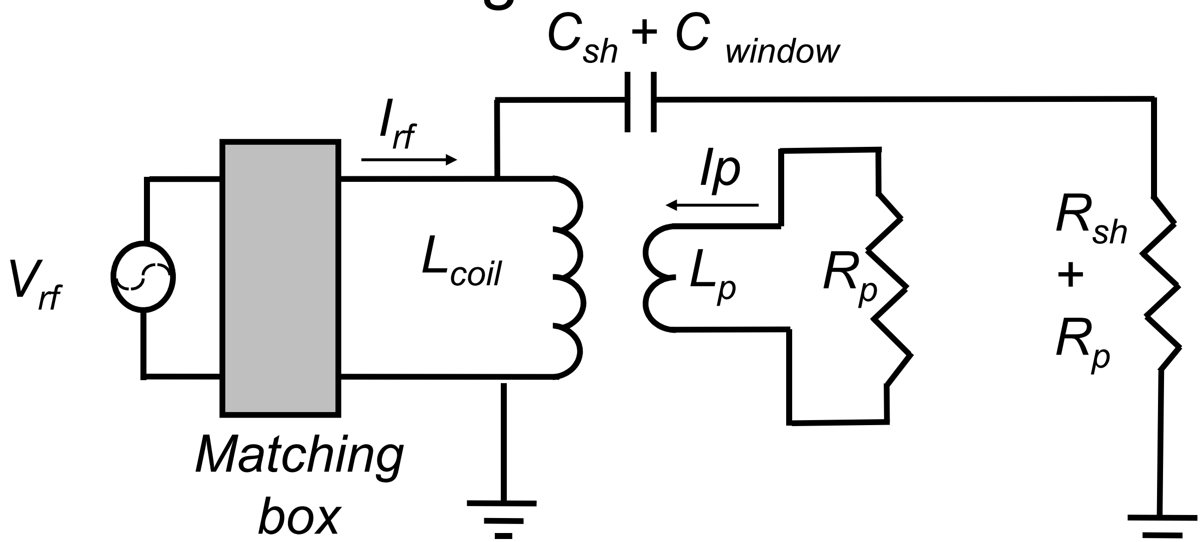
LAM TCP system





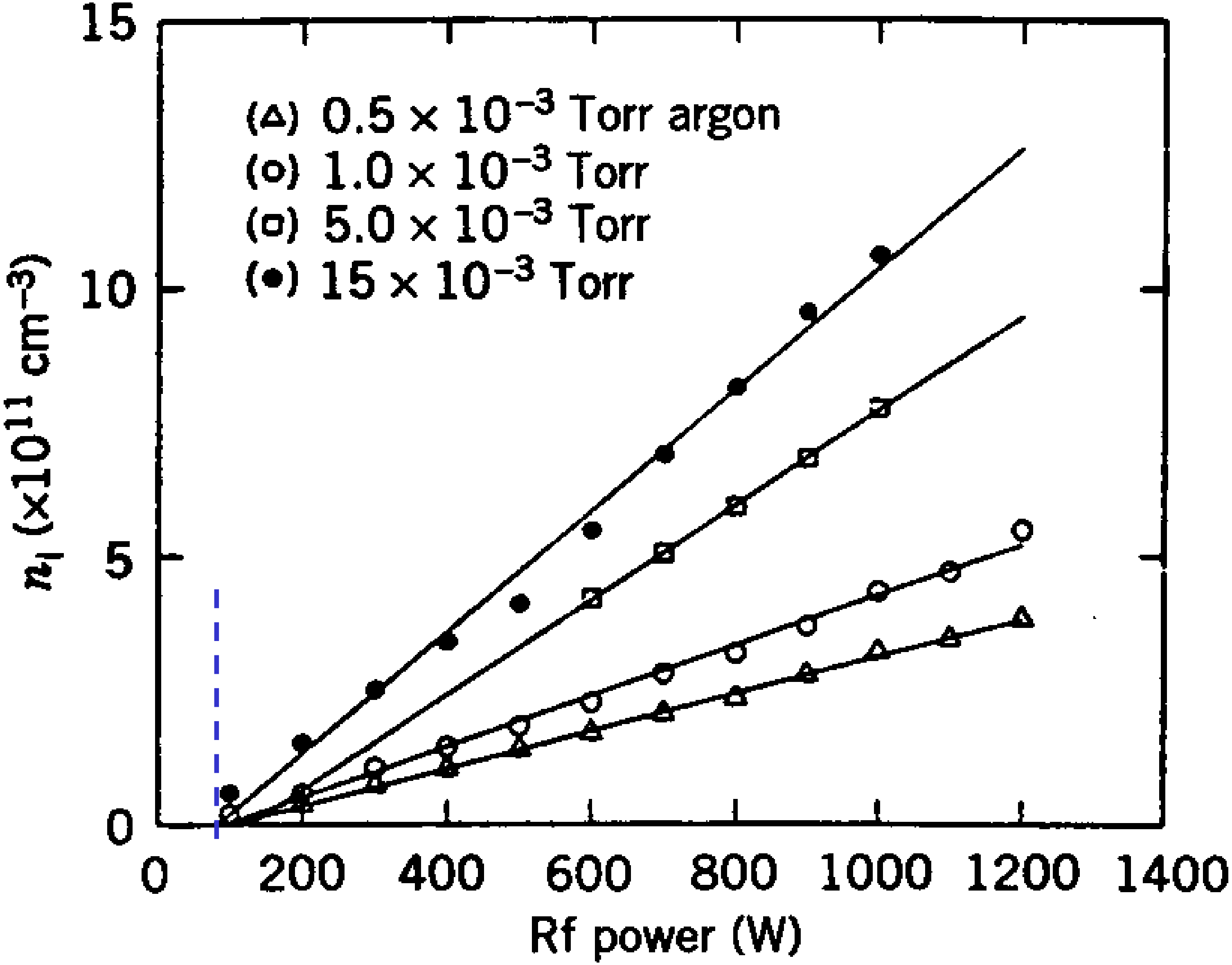
Power Dissipation in ICP

- Based on the equivalent circuit, the expression of induction power can be derived as $P_{ind} = B\sqrt{I_{rf}^2 - I_{th}^2}$, where B and I_{th} (threshold current) are parameters of the system.
- Thus, except for some interaction with capacitive power, an RF induction system does not run in the inductive mode until the coil current exceeds I_{th}. Values of B and I_{th} depend on the reactor design.



R_p: plasma resistance;
R_{sh}: sheath resistance;
L_p: plasma inductance;
L_{coil}: coil inductance;
C_{sh}: sheath capacitance;
C_{window}: dielectric window capacitance

Effect of RF Power



Power Coupling in ICP

- The source frequency typically used in inductively driven plasmas is much lower than the plasma frequency, so that no electromagnetic wave propagation occurs within the plasma.
- Instead, all RF fields are attenuated by the plasma and most power is dissipated within a skin depth (δ_s) of the plasma boundary.
- To simplify the analysis, the RF current in the plasma is often assumed to flow within a skin depth of the plasma boundary closest to the induction coil. The skin depth is

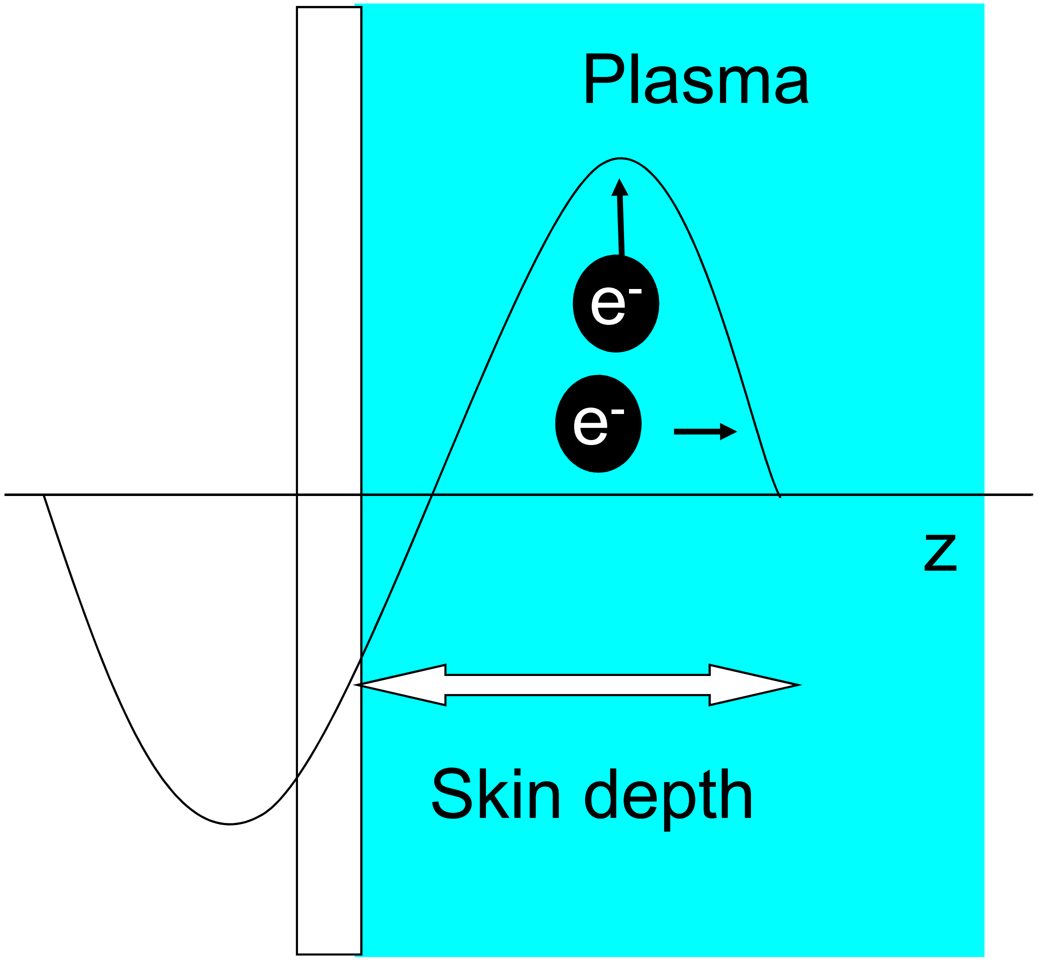
$\delta_s = \sqrt{\dfrac{2}{\omega\sigma\mu_o}}$, where μ_o is the permeability of the medium and σ is the AC plasma conductivity.

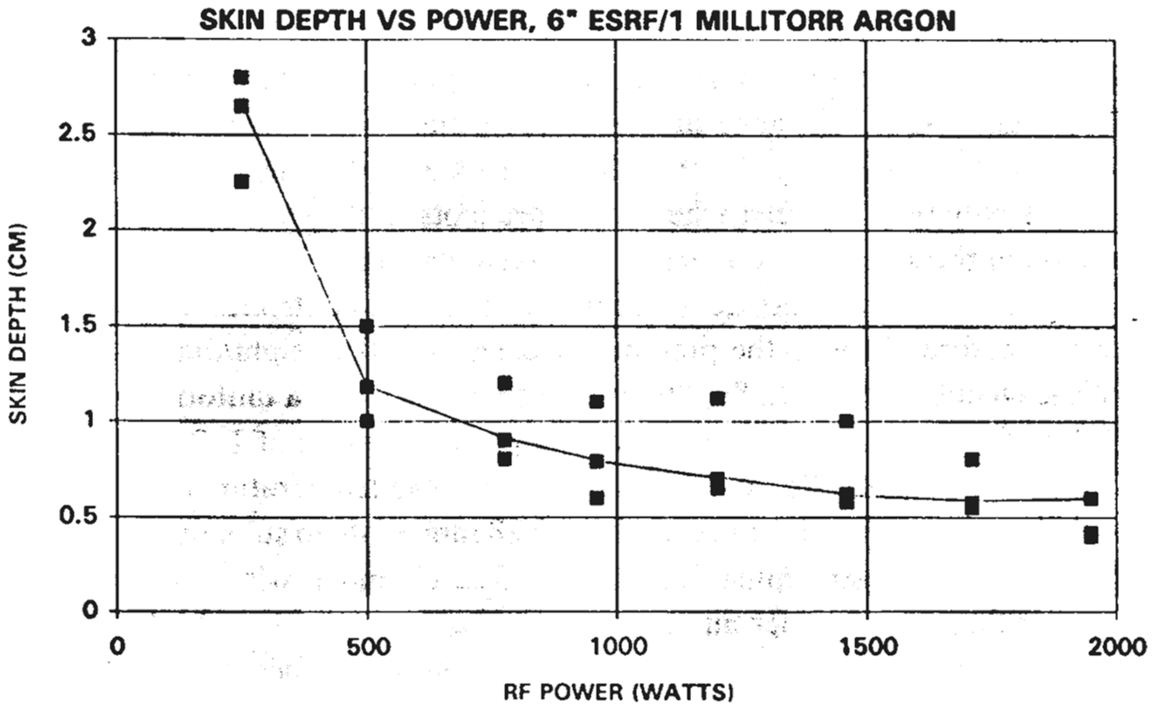
Power Coupling in ICP

- For weakly ionized plasma, σ is given by
  - $\sigma = \dfrac{\omega_e^2 \varepsilon_0}{\nu_m + j\omega}$, where ν_m is the electron-neutral momentum transfer frequency (collision rate).
- As ν_m << ω(collisionless regime), $\delta_s = \sqrt{\dfrac{2m}{e^2 n_e \mu_o}}$, which is independent of ω;
- As ν_m >> ω (collision regime), $\delta_s = \dfrac{c}{\omega_{pe}}\sqrt{\dfrac{2\nu_m}{\omega}} = \sqrt{\dfrac{2}{\omega \mu_o \sigma_{dc}}}$, where *c* is the speed of light.

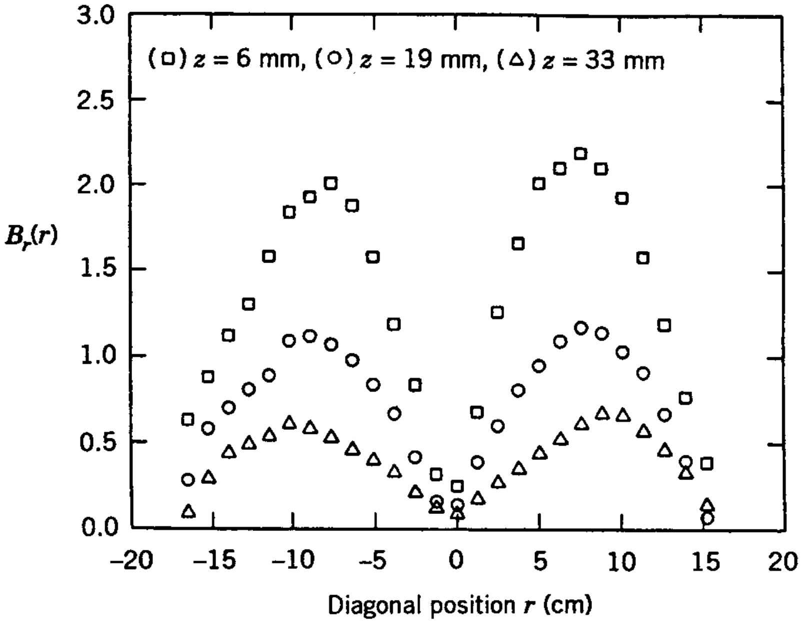
Generation of ICP and Skin Depth

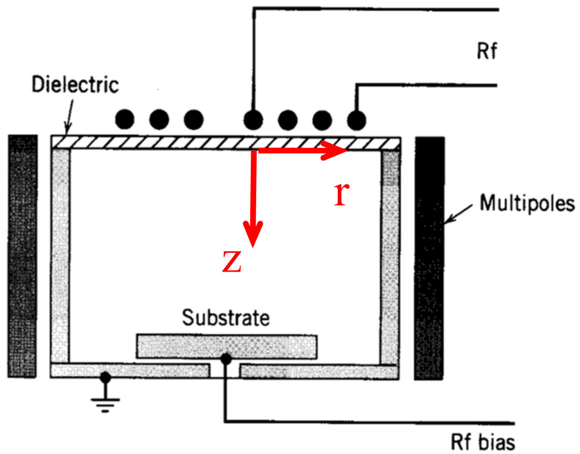
$\omega < \omega_e$

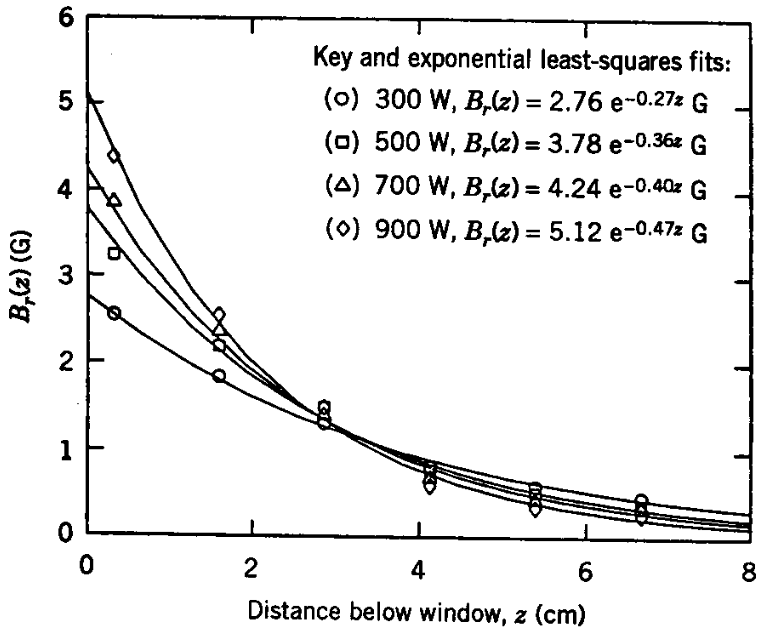




Magnetic Induction







RF magnetic induction amplitude versus diagonal radius at three different distances below the window (2.54 cm-thick) as measured in a 5 mTorr oxygen discharge.

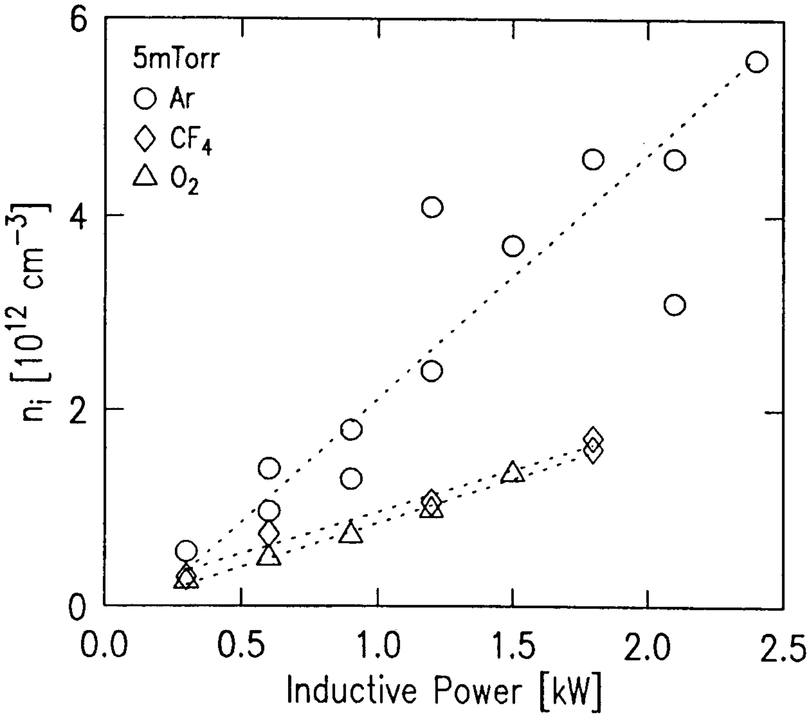
RF magnetic induction amplitude versus z at r = 6.3 cm in a 5 mTorr oxygen discharge. The solid line are a least-squares fit ($\sim e^{-z/\delta s}$) to the data. Skin depth (δ_s) values varying from 2.1 to 3.7 cm are determined from this plot.

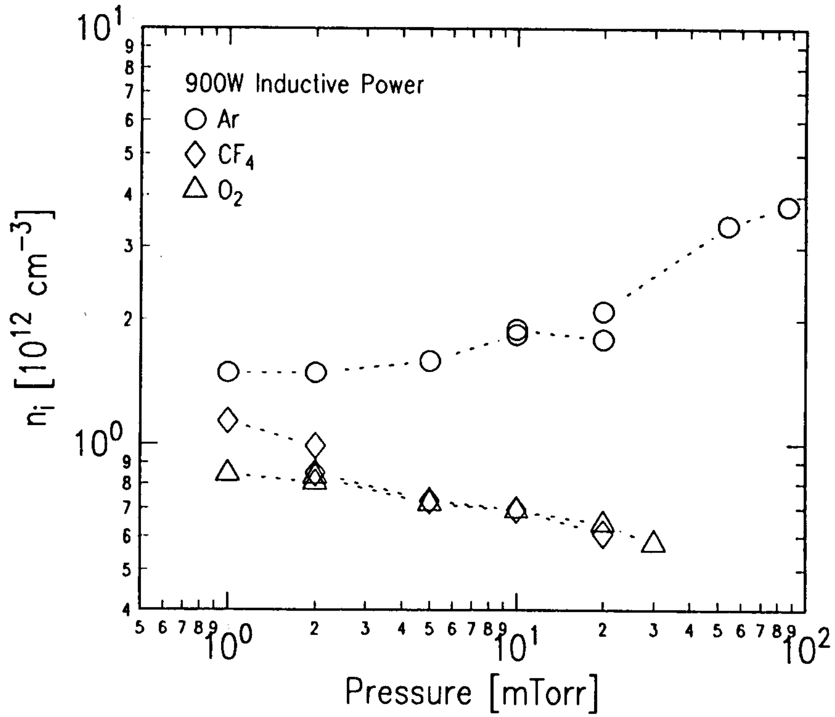
Concern for Electronegative Plasmas

- The plasma density of electronegative (EN) plasmas (e.g., O_2, CF_4 discharges) generated by most HDP sources are usually lower than that of the electropositive (EP) plasmas under identical power and pressure conditions.
- In some reactor configurations, such as the LAM TCP system, and the Hitachi and Anelva ECR sources, the workpiece is placed as close to the ion generation region as possible for maximum efficiency of ion usage.

Concern for Electronegative Plasmas

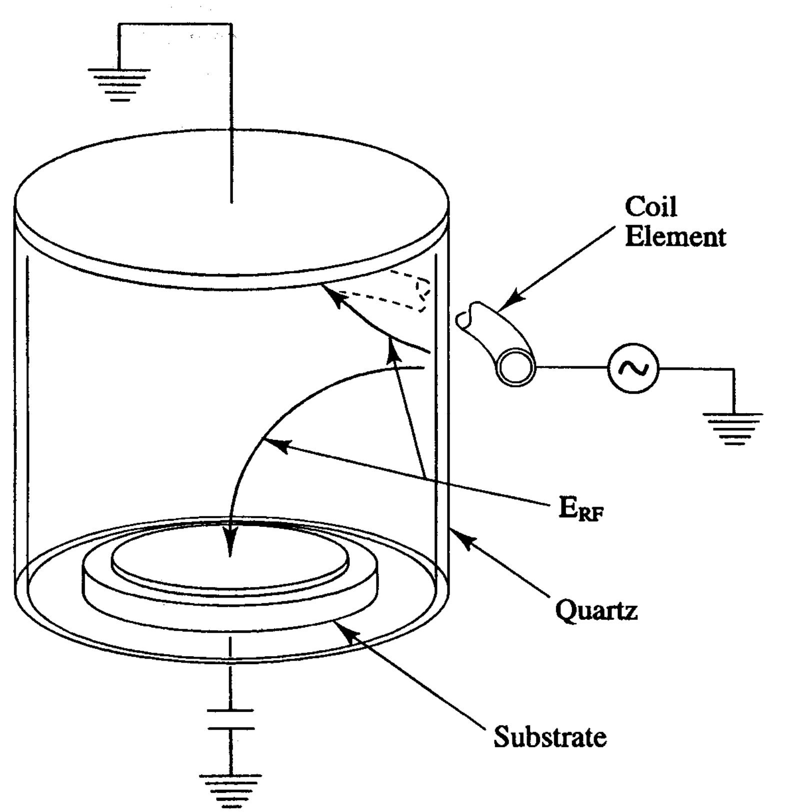
- Though less ion density, the threshold power for ICP EN plasmas is the same as that of the EP plasmas
- Difference in ion density between EP and EN plasmas increases with increasing pressure.





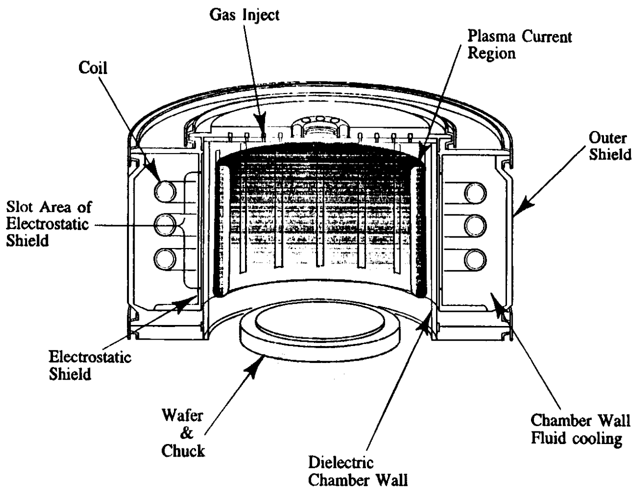
Pros and Cons of Basic ICP

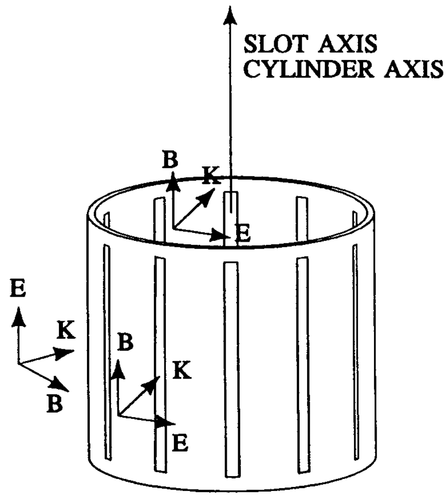
- Advantages
  - Simple concept
  - No requirement of dc magnetic field
  - RF rather than the microwave source power
- Major issues
  - Unshielded plasma is an inductive plasma with a capacitive component that is the integration of the coil electrodes.
  - Chamber sputtering due to capacitive coupling mechanism.
  - Plasma uniformity control.



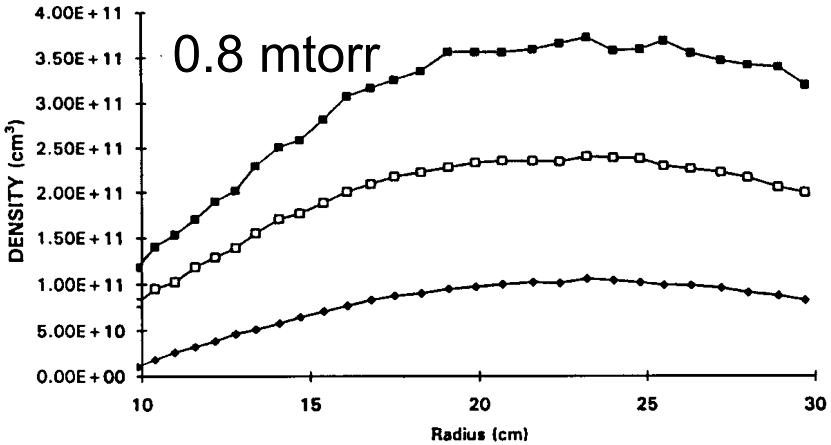
Electrostatic Shielding

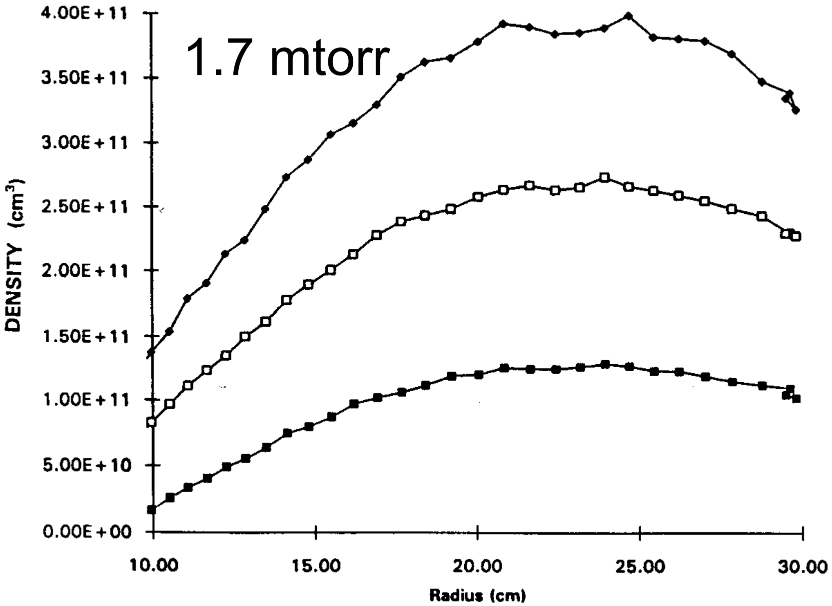
- Electrostatic shielding with a conductive metal plate or box can reduce the capacitive coupling effect in ICP sources.
- For efficient plasma generation, some slots are cut on the conductive element along the direction perpendicular to the electric field (or parallel to the magnetic field) of the electromagnetic wave.
  - Electric field perpendicular to the conductive bar -> EM waves pass
  - Electric field parallel to the conductive bar -> EM waves are stopped

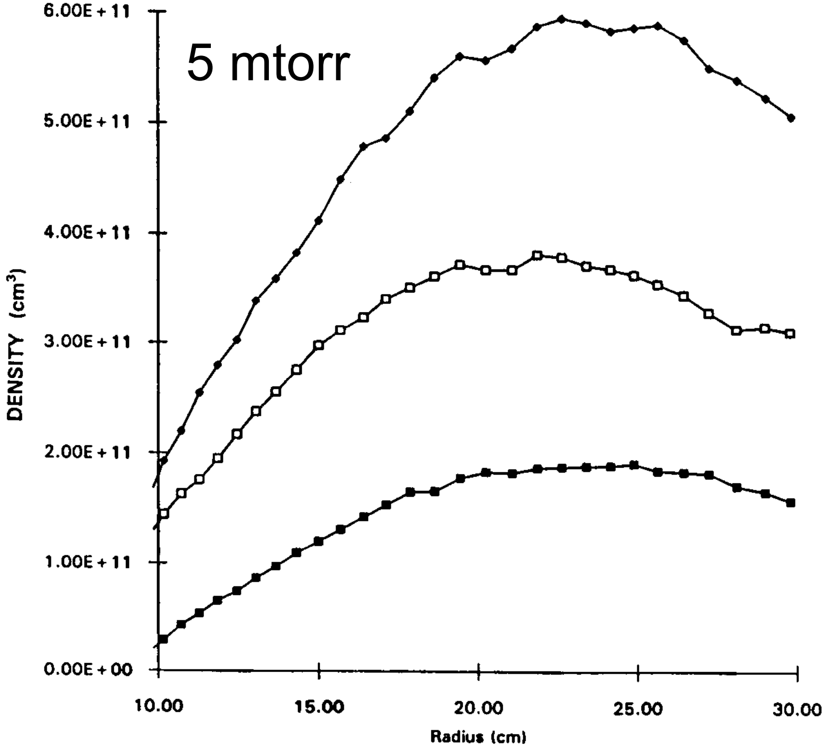




Plasma Uniformity in ICP Ar Discharges



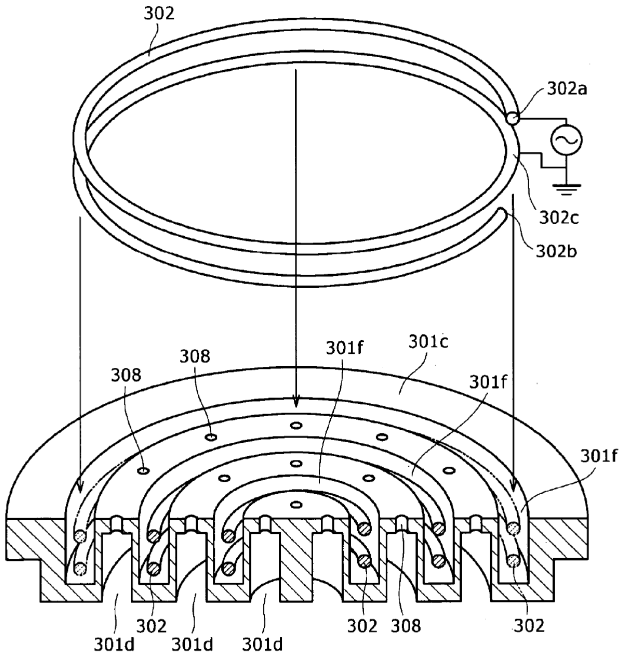




Power: 1000, 2000, 3000 W

Methods for Improving Plasma Uniformity

- Magnetic multi-pole confinement
  - J. Vac. Sci. Tech.., A11, p.147 (1993)
- Modified coil design (unequal space)
  - LAM TCP systems
- Modified dielectric plate shape (dome) and position
  - JJAP, 34, p.2089 (1995)
- Flexible coil design
  - JJAP, 38, p.4268 (1999)
- Modified gas injection
  - FOI Groove ICP



Groove ICP

Electron Cyclotron Resonance (ECR)

- ECR discharges use microwave excitation in the presence of magnetic field to generate a high-density discharge.
  - The Lorentz force causes the electrons to circulate around the magnetic field lines in circular orbits, with a characteristic cyclotron frequency of

$$\Omega = \frac{qB}{m}$$

  - When this frequency equals the applied microwave frequency, resonance coupling may occur between the electron energy and the applied electric field, which results in a high degree of dissociation and ionization (10^{-2} for ECR compared to 10^{-6} for RIE).
  - With a microwave frequency of 2.45 GHz, the required magnetic field is 875 gauss.

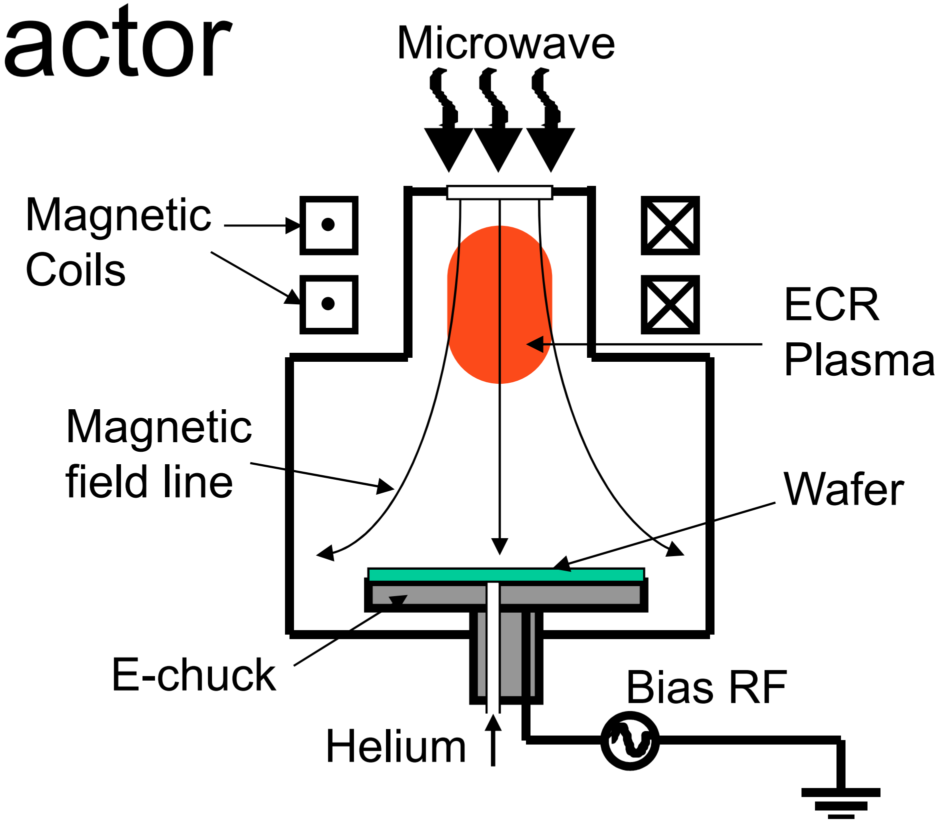
ECR Reactor

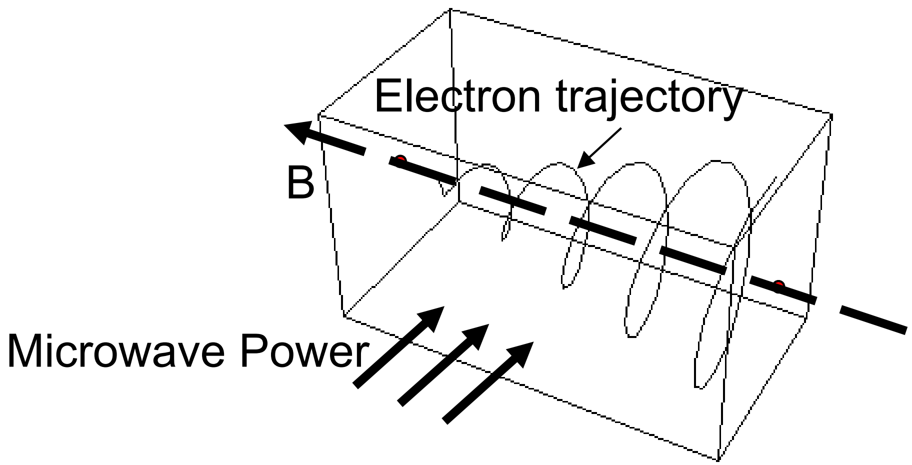
- In magnetic field, electron gyro-frequency

  $\Omega_e(MHz) = 2.80B$(in Gauss),

  e.g. 2.45 GHz vs. 875 Gauss.
- Resonance occurs if incident microwave frequency equals to Ω_e

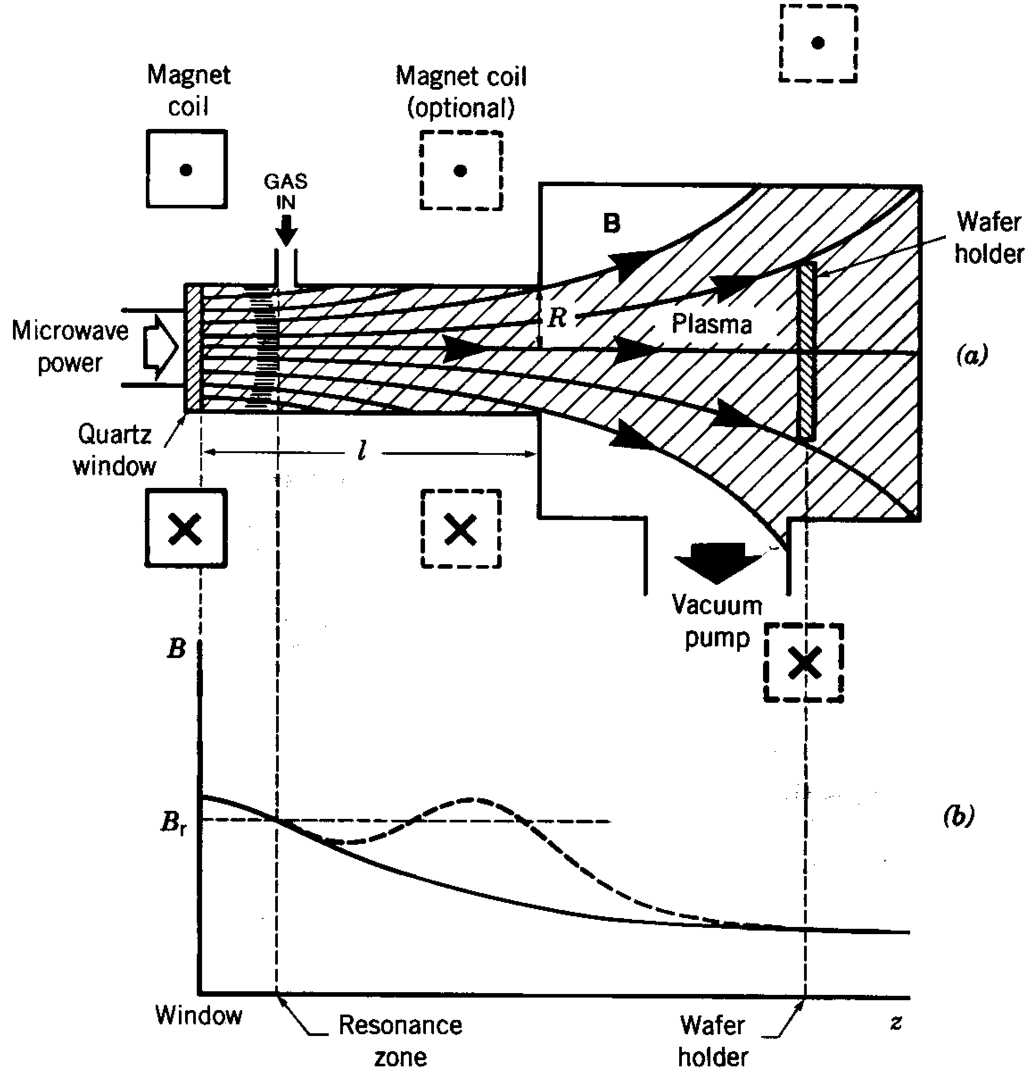
  $\omega_{MW} = \Omega_e$
- Electrons get energy from microwave.





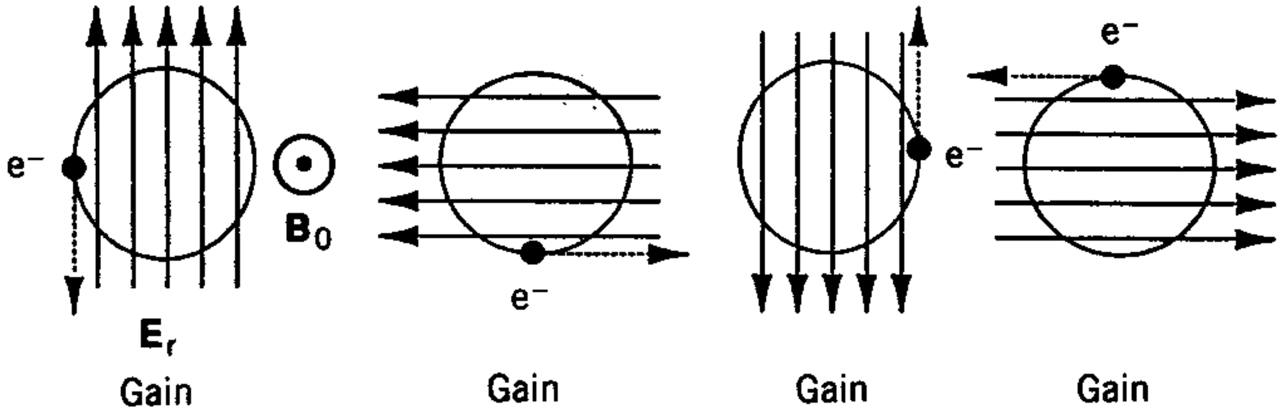
ECR Zone

- The magnetic field in the reactor is not uniform. ECR Zone is the region where resonance occurs (i.e., the magnetic field strength meets the ECR condition).
- ECR zone could have a disk- or ring- shape, depending on the currents applied to the magnetic coils.



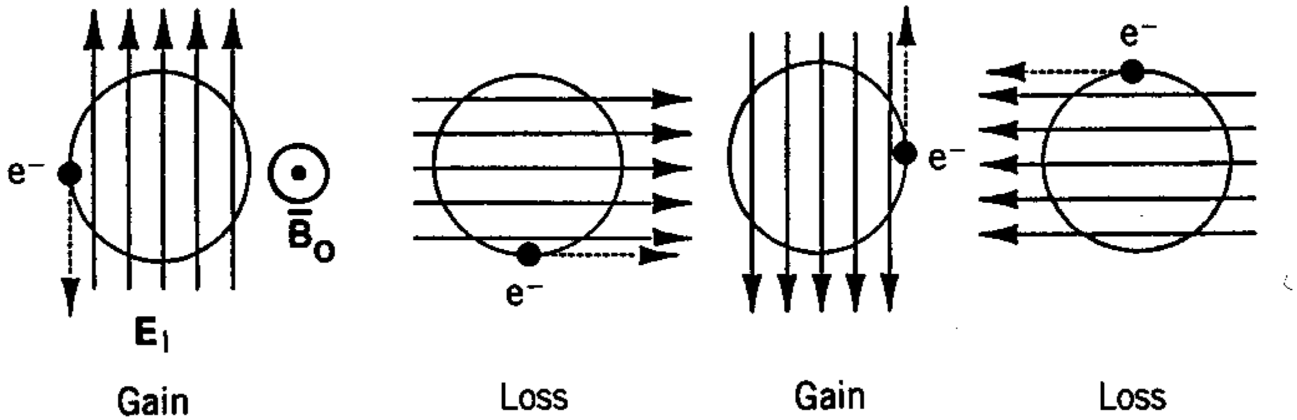
Basic Principle of ECR Heating

RH μ-wave



- Continuous energy gain for right-hand (RH) polarization wave

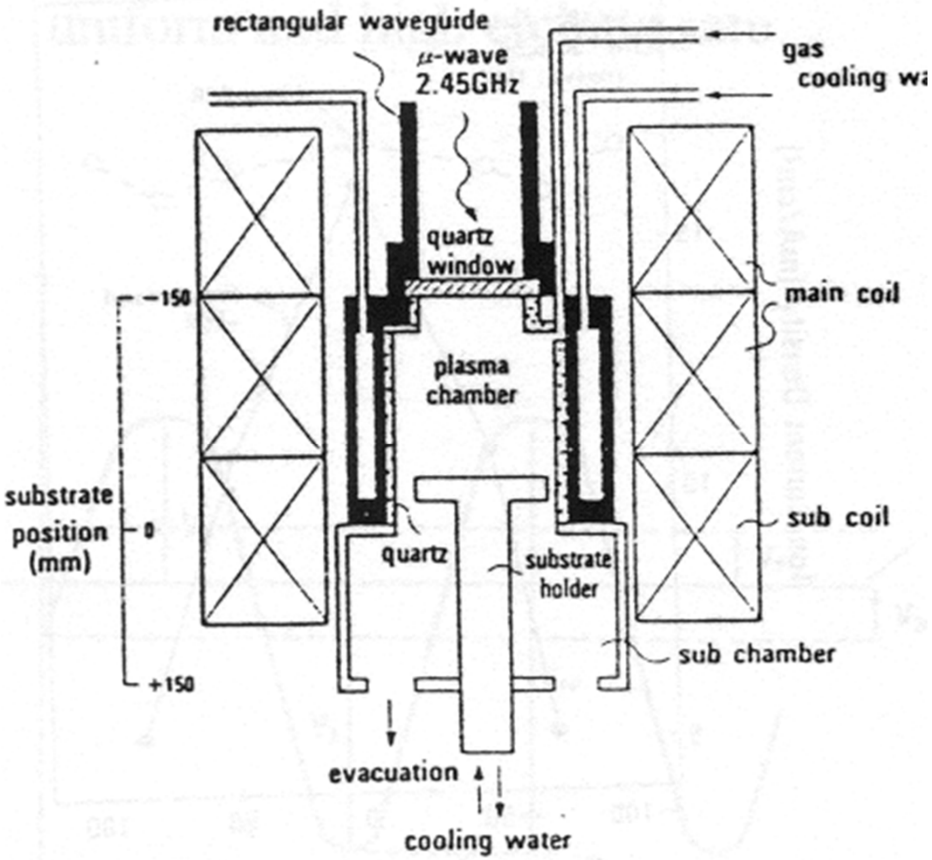
LH μ-wave

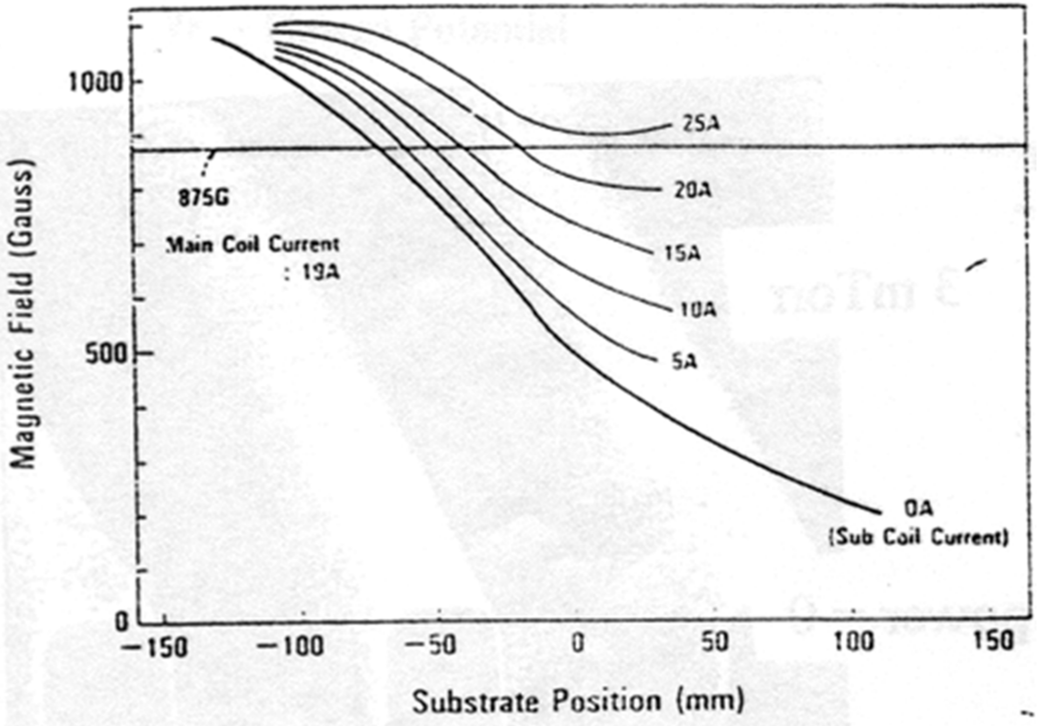


- Oscillating force on the electron produced by left-hand (LH) polarization wave resulting in no net energy gain.

B-field Gradient vs. Sub-coil Current

- Use of a supplementary coil around the wafer can improve the process uniformity.





Brief History of Helicon Wave Plasma

- In 1965, Lehane and Thonemann discovered that helicons can exist in a gaseous plasma.

- In 1984, Boswell found that helicon wave were unusually efficient in producing plasmas (~1000 times higher than the theoretical rate due to collisions).

- In 1985, Chen proposed Landau damping as the reason for this discrepancy. He also completed a detailed theory of helicon propagation and absorption in 1991.

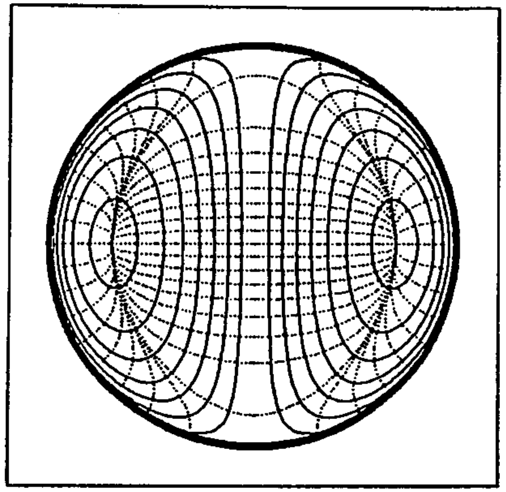
Helicon Discharges

➢ Helicon modes

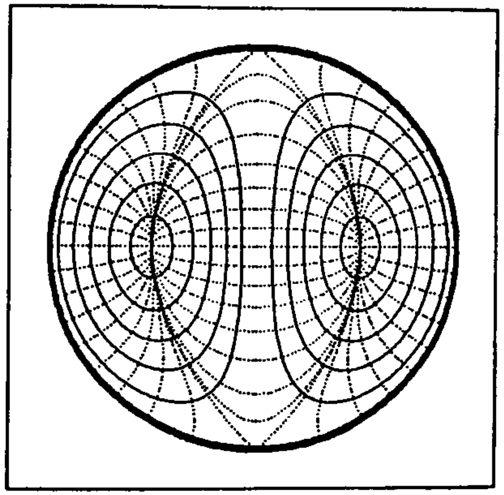
- Superposition of low-frequency bounded whistler waves propagating at a common (fixed) angle to the dc magnetic field (B_o). (whistler wave: the right-hand polarized wave in the frequency range $\omega_{ci} << \omega << \omega_{ce}$).
- Fields of the helicon modes have the form:

$\mathscr{E}, H \propto e^{j(\omega t - k_z z - m\theta)}$, where the integer m specifies the azimuthal mode.

- Pattern of magnetic (solid) and electric (dashed) field lines in the *m* = +*1* and –*1* modes of the helicon wave in a uniform plasma in a plane perpendicular to the DC magnetic field.



m = +1

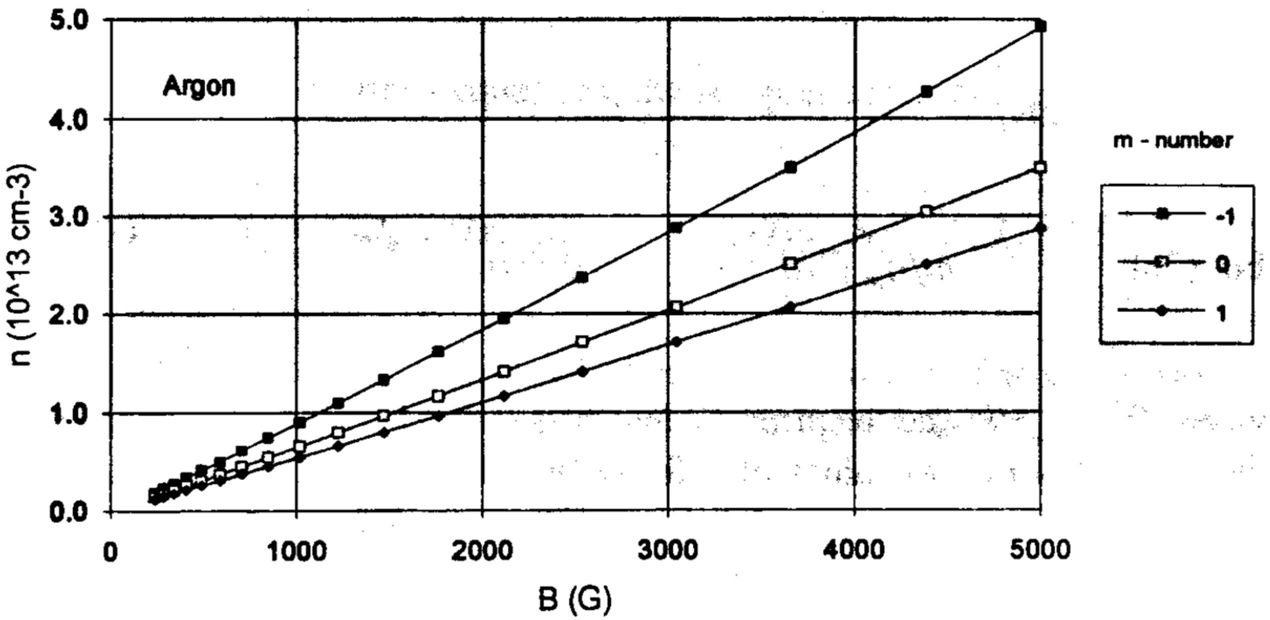


m = -1

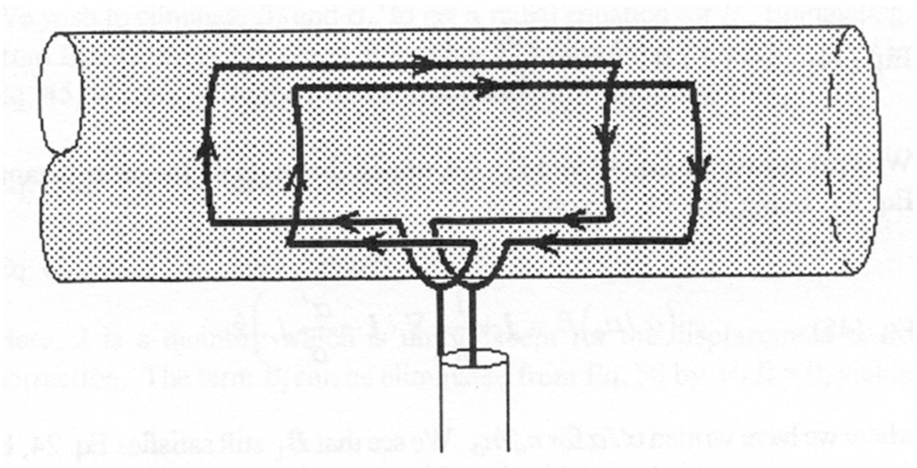
Plasma Production via Resonantly Excited Waves

- Apply B-field (B_o) in source
- Estimate desired density
- From dispersion relation find frequency & wavelengths
- Design appropriate antenna to excite desired wavelengths

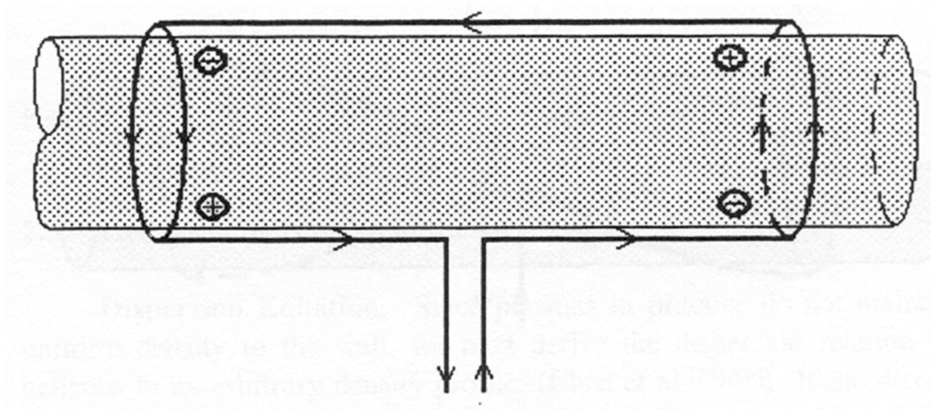
Cylinder radius : 5 cm
RF: 13.56 MHz



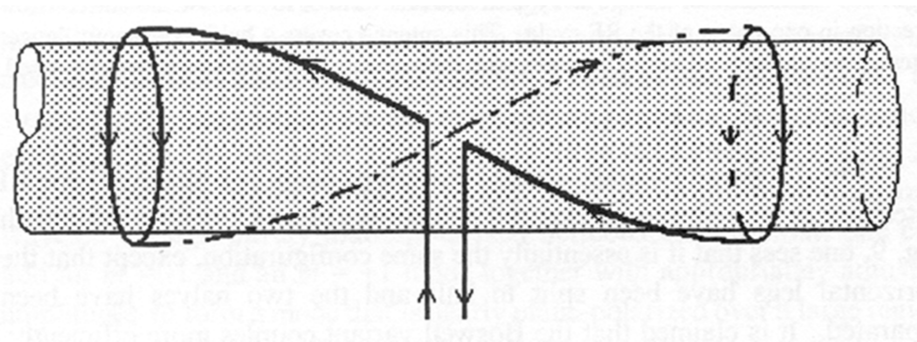
Antenna Types



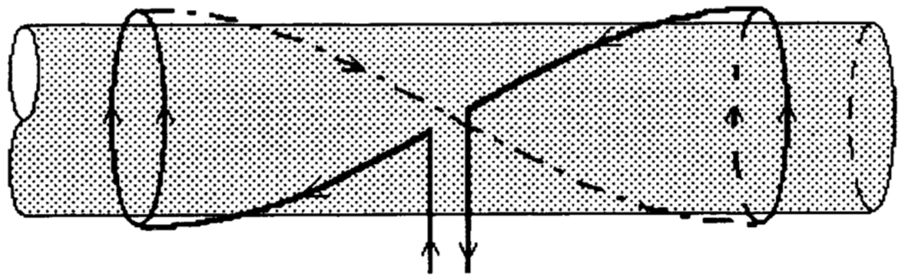
Boswell-type paddle-shaped antenna



Nagoya Type III helical antenna

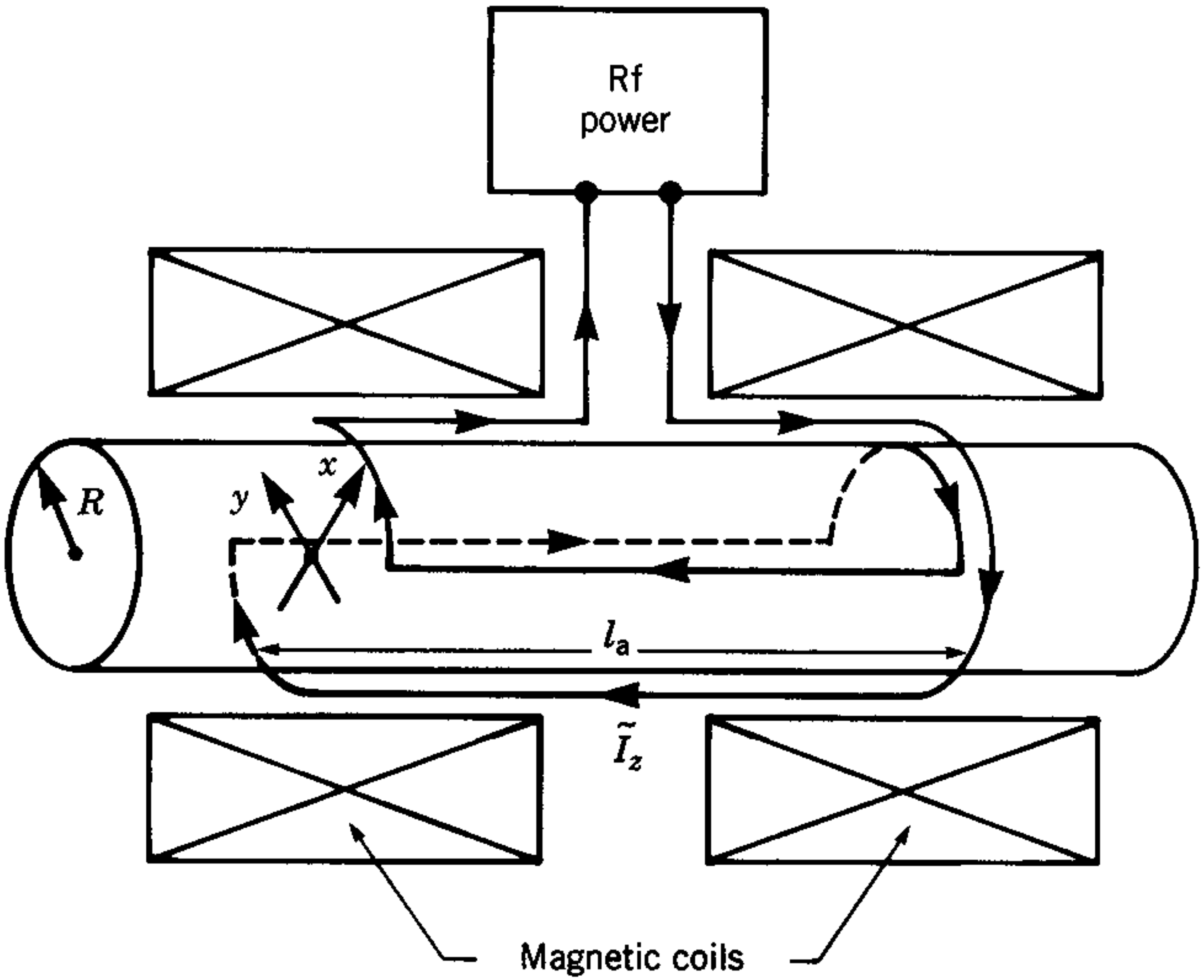


Left-hand helical antenna



Right-hand helical antenna

Antenna for m = 1 Helicon Mode Excitation

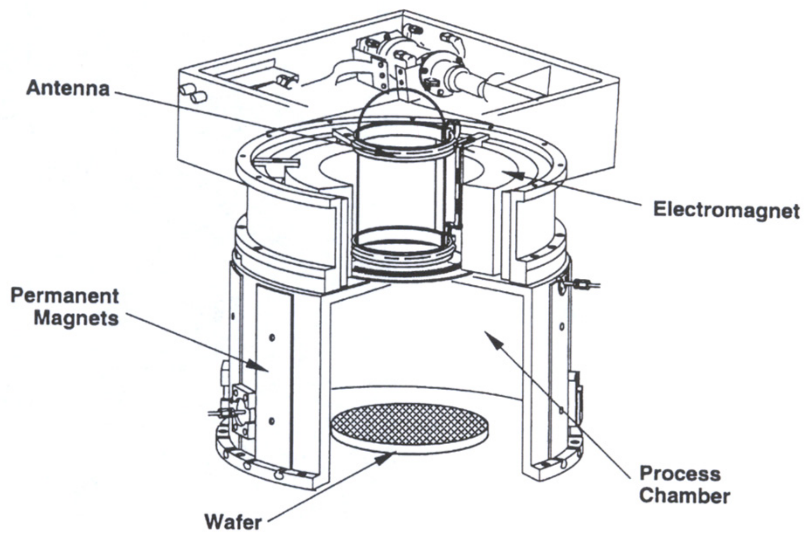


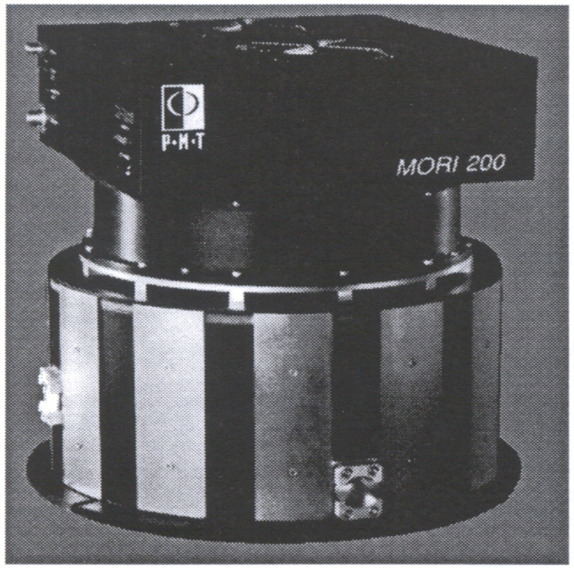
Helicon Plasma Sources

- The driving frequency is typically 1 ~ 50 MHz, with 13.56 MHz commonly used for processing.
- The magnetic fields vary from 20 to 200 G for processing discharges, while fields up to 1000 G have been employed for some fundamental plasma studies.
- Plasma densities range from 10^{11} ~ 10^{14} cm^{-3}, and typically 10^{11} ~ 10^{12} cm^{-3} for processing.
- Helicons are excited by an RF-driven antenna that couples the transverse mode structure across an insulating chamber wall.
- The mode then propagates along the column, and the mode energy is absorbed by plasma electrons due to collisional (ohmic) or collisionless (Landau) damping.

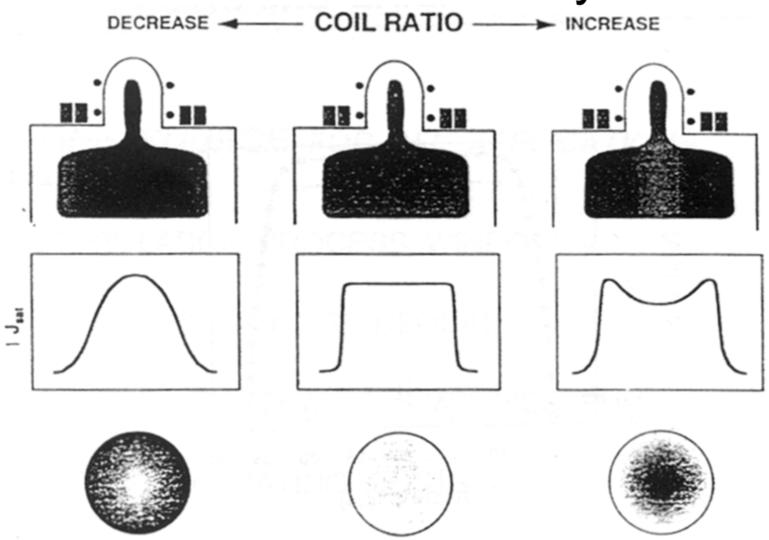
Commercial Helicon Reactors

- Vortex helicon sources - Lucas Signatone Corp.
  - m = 1 excitation; 13.56 MHz RF power
  - B: 50 ~ 150 G; P: 1 ~ 10 mTorr
  - References: SPIE, Vol.1392, p.95 (1990);J. Vac. Sci. Technol. B12, p.2310, p.2322, p.2333, p.1340 (1994)
- MORI-200 sources - Trikon/PMT Corp.
  - m = 0 excitation; MORI: M = O Resonant Inductive





Plasma Uniformity

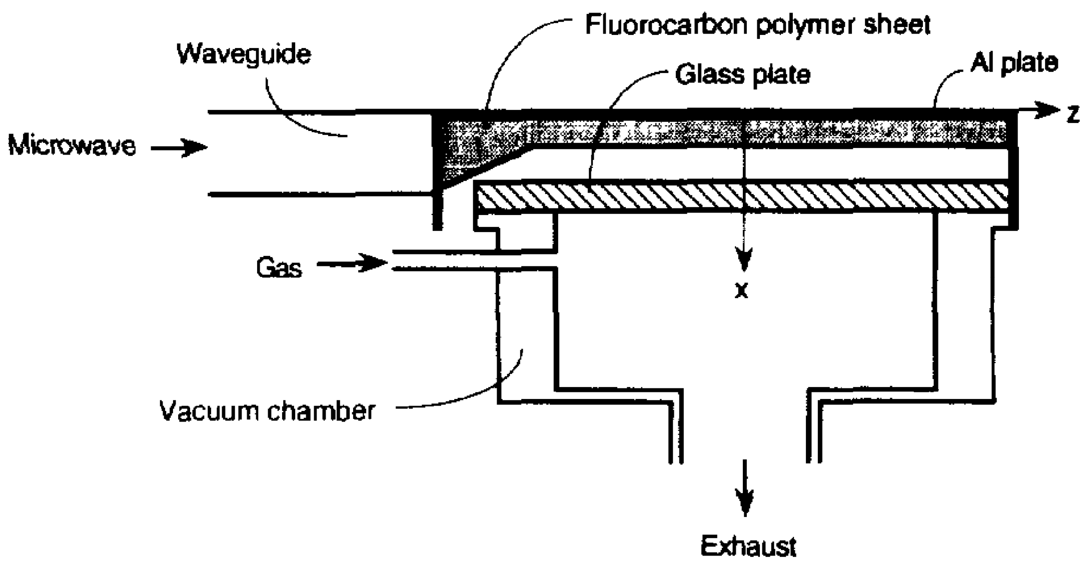


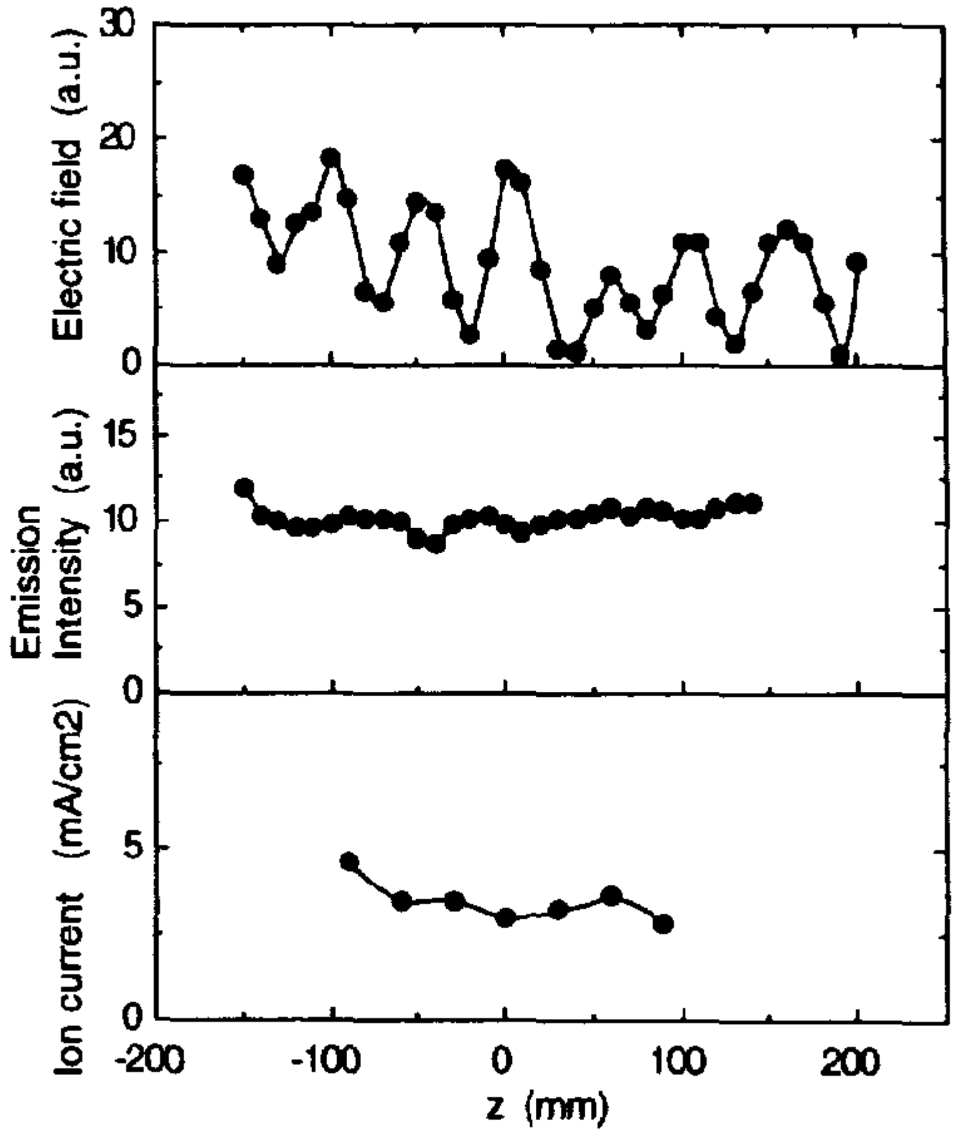
Surface Wave Plasma

- Surface wave plasma is typically generated by microwave (e.g., 2.45 GHz) excitation without a static magnetic field.
- Cylindrical and planar (rectangular) configurations have been developed, though the latter form is more suitable for large-area processing applications.
  - JJAP, Vol.33, p.7037 (1994)
  - J. Vac. Sci. Technol. A11, p.164 (1993)
- In the planar configuration, microwave is introduced through a dielectric sheet, and the plasma is generated in the chamber underneath the dielectric sheath.
- An ion density of 1×10^{12} cm^{-3} was recorded using an Ar plasma at 30 mTorr.

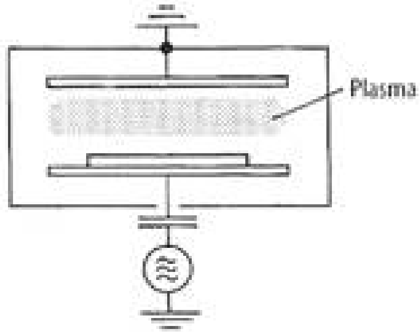
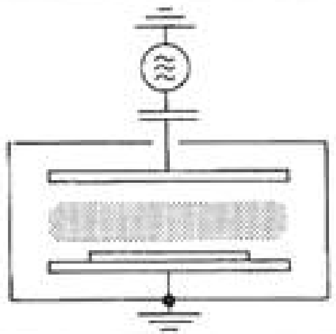
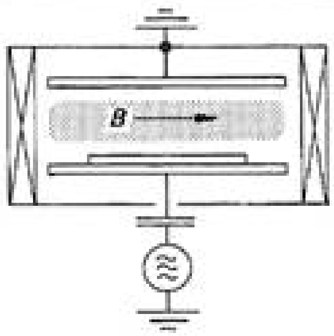
SWP Configuration and Characteristics

J. Vac. Sci. Technol. A11, p.164, 1993

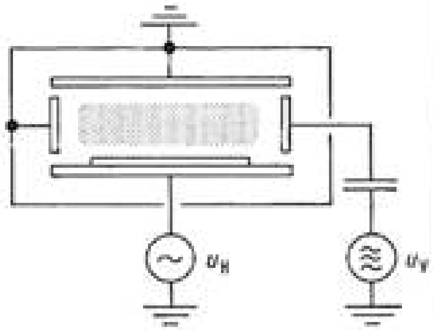
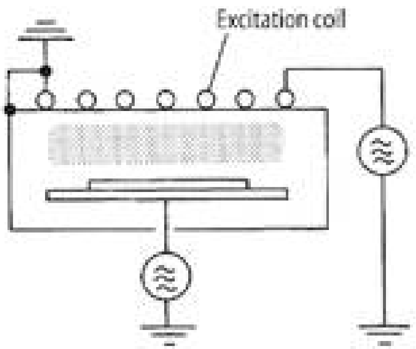




Summary of Plasma Reactors - I

Etch process	Configuration	Advantages	Disadvantages
Reactive ion etching (RIE) Reactive sputter etching (RSE)		• High degree of anisotropy • Pattern transferred accurately to size	• Low selectivity • Low etch rate • Damage to surface
Anodically coupled plasma etching in the parallel plate reactor		• High selectivity • High etch rate • Little damage to surface	• Undercutting of etch mask
Magnetically enhanced reactive ion etching (MERIE)		• High degree of anisotropy • High etch rate • Little damage to surface • Low loading effect	• Low homogeneity

Summary of Plasma Reactors - II

Triode reactive etching (TRIE)		• High degree of aniso-tropy • Two voltage supplies provide greater flexibility for process optimization	• Additional electro-des
Inductive-coupled plasma etching Transmission coupled plasma etching (TCP)		• Low loading effect • High etch rate because of high plasma density	• There must be no ferromagnetic material between the excitation coil and the plasma because of the inductive coupling

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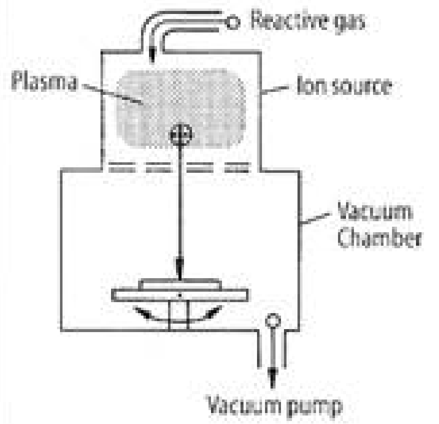
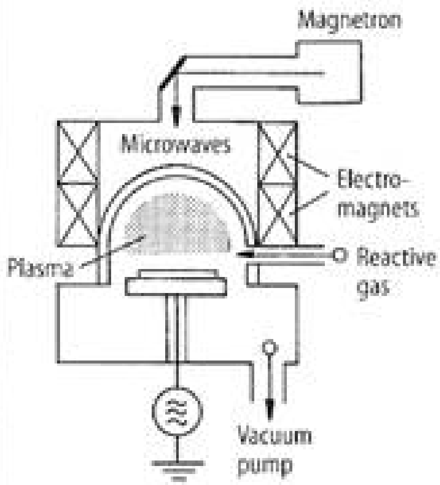
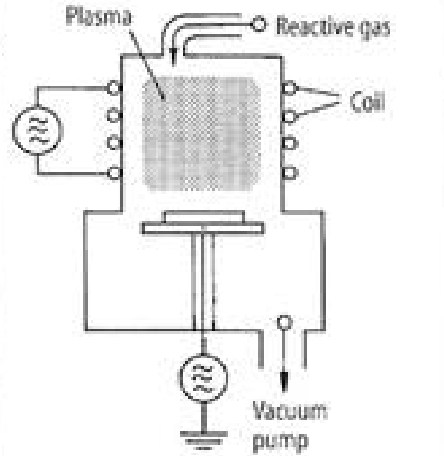
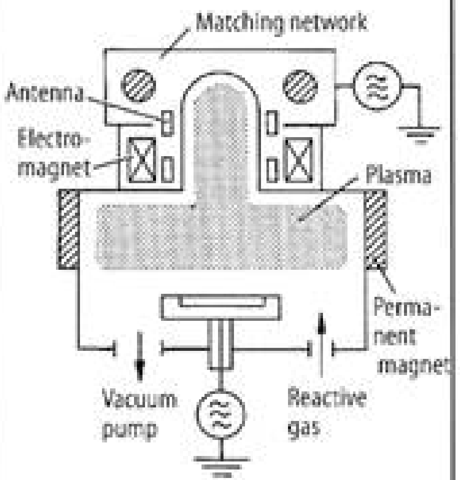
Department of Electronics Engineering &
Institute of electronics

Summary of Plasma Reactors - III

Etching technique	Etching reactor design	Source	Advantages	Disadvantages
Reactive ion beam etching (RIBE) Chemically assisted ion beam etching (CAIBE)	 	• Kauf-mann source	• Low gas pressure • High degree of anisotropy • Etch profile adjustable by setting table angle	• Low etch rate • Source sensitive to reactive gases • Inhomogeneous etch rate • Complex reactor compared with parallel plate reactor
Electron cyclotron resonance (ECR) etching Reactive ion stream etching (RISE)	 	• ECR source	• Low gas pressure • High plasma density • Little surface damage • High degree of anisotropy	• Complex reactor compared with parallel plate reactor

Summary of Plasma Reactors - IV

Etching with inductively coupled plasma source (ICP) High density plasma (HDP)		• Inductively coupled source	• High etch rate because of high plasma density • Low gas pressure • High degree of anisotropy	• Complex reactor compared with parallel plate reactor
Etching with helicon source Mode M = 0 resonant induction (MORI) Resonant inductive plasma etching (RIPE)		• Helicon source	• Low gas pressure • High plasma density • Little surface damage • High degree of anisotropy • Uniform etch rate	• Complex reactor compared with parallel plate reactor