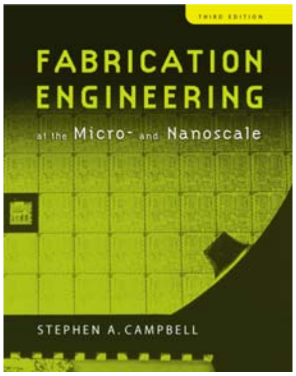
ECE 416/516
IC Technologies

Lecture 10:
Vacuum & Plasmas

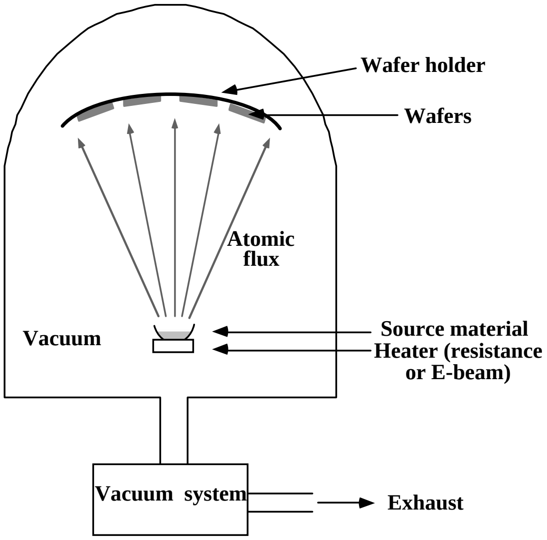
Professor James E. Morris
Spring 2012

Chapter 10

Vacuum Science and Plasmas



Vacuum for Etching & Physical Vapor Deposition (PVD)



Mean free path in vacuum

Lecture Topics: Vacuum

- Gas Kinetic Theory
  - Evaporation / Impingement
- Pumping Speeds
  - Gas flow conductance
- Vacuum Pumps
  - Vacuum systems
  - Pump down sequence
- Vacuum measurement

Lecture Topics: Plasmas

- **Glow Discharge**
- **Cathode Sheath**
  - **Ionization**
  - **Electron Emission**
  - **Space Charge Current**
- **Glow Region**
  - **Electrons & Ions**
  - **Energies & Currents**
- **Plasma Sheath**
  - **Anode/Cathode potentials**
- **Debye Shielding**
- **Langmuir Probe**
- **RF Discharge**
  - **Self-bias**
  - **Matching**
  - **Potential distribution**
- **Plasma Applications**

Lecture Objectives

- Can calculate evaporation/impingement rates at P,T
- Can design vacuum systems to pump-down specifications
- Can describe physical operation of vacuum pumps and measurement devices
- Can describe plasma physics
- Can calculate characteristic parameters of cathode sheath and plasma
- Can calculate plasma potential distribution (DC & RF)
- Can interpret Langmuir probe data

Vacuum: Kinetic theory of gases

Probability distribution of molecular velocities:

$$p(v) = 4\pi\left[\frac{m}{2\pi kT}\right]^{3/2} v^2 e^{-mv^2/2kT}$$

Average velocity magnitude (speed):

$$|v| = \bar{c} = \int_0^\infty v\,p(v)\,dv = \sqrt{\frac{8kT}{\pi m}}$$

Average velocities:

$$\overline{v_x} = \overline{v_y} = \overline{v_z} = \sqrt{\frac{2kT}{\pi m}}$$

RMS velocity:

$$v_{rms} = \sqrt{\frac{3kT}{\pi m}}$$

N_2 velocity at RT ~240m/s=530mph

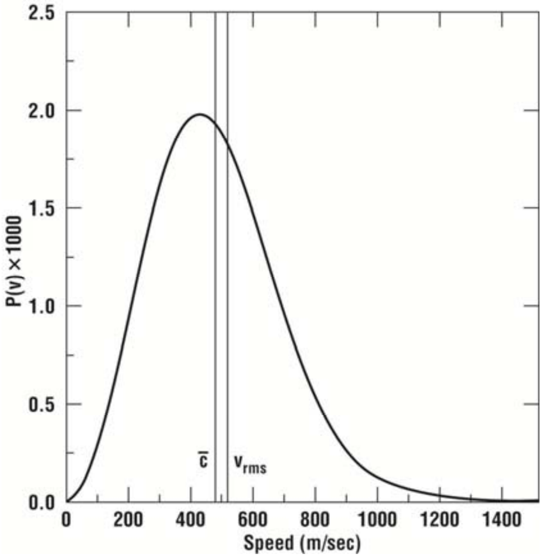


Figure 10.1 A Maxwellian speed distribution of particles; P(*v*) is the probability that a particular particle will have the target magnitude of velocity.

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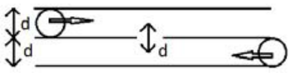
Collisions:



d~0.3nm
for N_2, O_2

$$\text{Collision c/s} = \pi d^2 = 4\pi r^2$$

$$\text{Probability of collision over length } \ell = p = \ell\pi d^2 n$$

for n molecules/unit vol.

$$\text{MFP} = \lambda = \ell = \frac{1}{\pi d^2 n} \text{ when } p = 1, \rightarrow \frac{1}{\sqrt{2}\pi d^2 n} \rightarrow \frac{kT}{\sqrt{2}\pi d^2 P}$$

$$\text{since } n = n/V = P/kT$$

Also:
See Table 10.1 for diffusivity, viscosity, thermal conductivity

And, flux/unit area impinging on surfaces per unit time,

$$J = n\overline{v_x}/2 = \sqrt{n^2 kT/2\pi m} = \sqrt{p^2/2\pi m\,kT}$$

For N_2,	1atmos (760τ)	7.6mτ	$7.6\text{x}10^{-6}$τ	$7.6\text{x}10^{-9}$τ
Flux (molecules/cm^2.s)	$3\text{x}10^{23}$	$3\text{x}10^{18}$	$3\text{x}10^{15}$	$3\text{x}10^{12}$ $3\text{x}10^4/\mu\text{m}^2$.s 3/(10nmx10nm).s

Maxwell-Boltzmann & Molecular Velocities

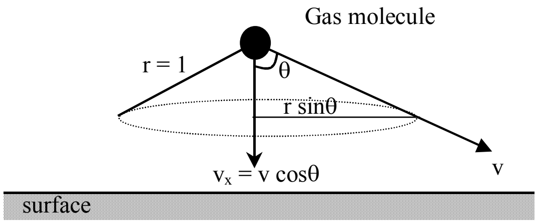
- Distribution of gas velocities v
- $P(v) = (1/N)\,(dN/dv) = 4\pi v^2\,(m/2\pi kT)^{3/2} \exp -(\tfrac{1}{2}mv^2/kT)$
- where
  - $P(v)$ = probability of molecular velocity v to v+dv
  - N = total number of gas molecules
  - m = molecular mass
  - k = Boltzmann's constant = 1.38×10^{-23} J/K
  - T = absolute temperature
- Average speed (velocity magnitude)

$$v = |v| = {}_0\!\int^{\infty} v\,P(v)\,dv = 4\pi\,(m/2\,\pi kT)^{3/2}\;{}_0\!\int^{\infty} v^3 \exp -av^2\,dv$$

where $a = m/2kT$

ie. $|v| = 4\pi\,(m/2\pi kT)^{3/2} / 2a^2 = (8kT/\pi m)^{1/2}$

Molecular Impingement Flux



$J_i = \tfrac{1}{2}\,n\,\overline{v_x}$, $n = (N / vol)$

since half molecules move +x, half -x

$$\overline{v_x} = \int v_x(\theta)\,dA / \int dA$$
$$= {}_0\!\int^{\pi/2} (v\cos\theta)\,(2\pi\sin\theta)\,d\theta \,/\, {}_0\!\int^{\pi/2} 2\pi\sin\theta\,d\theta$$
$$= v.2\pi\,[\tfrac{1}{2}\cos{}^2\theta]_0^{\pi/2} / (-2\pi) = v/2$$

$Av = v/2 = (2kT/\pi m)^{1/2}$ & $J_i = n\overline{v_x}/2 = \tfrac{1}{4}\,nv = n(kT/2\pi m)^{1/2}$

Impingement Rate (Ideal Gas Law)

Relate to pressure

Force = rate of momentum change

$F/A = J_i\,(2m\bar{v}_x) = (\tfrac{1}{2}n\bar{v}_x)(2m\bar{v}_x) = nm\bar{v}_x^2$

$= 1/3\ nmv^2\ \ =$ pressure p

Average by using v_{rms}

$p = 1/3\ nm(3kT/m) = nkT = NkT/V$

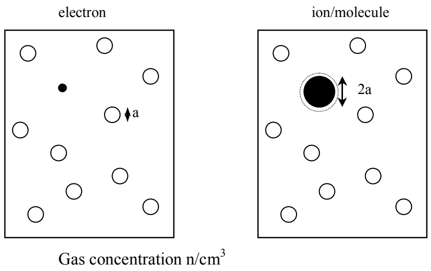
∴ Molecular impingement rate

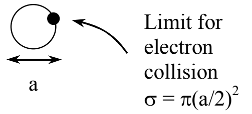
$J_i\ =\ \tfrac{1}{2}nv_x\ = \tfrac{1}{2}n(2kT/\pi m)^{1/2}$

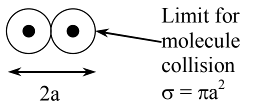
$= (p/kT)(kT/2\pi m)^{1/2}$

$= p/(2\pi mkT)^{1/2}$

Mean Free Path







Gas concentration n/cm^3

Total projected area
gas molecules/cm^2 c/s and /cm traveled = $n\pi a^2/4$

∴ electron mfp $\lambda_e = 1/(n\pi a^2/4)$ &
ion/molecule mfp $\lambda_I = 1/n\pi a^2$

Knudsen Number

- Define Knudsen number $K_n = \lambda/L$
  where L physical dimensions
  characteristic of process
- For $K_n > 1$ --> high vacuum
  - (Molecular flow regime)
- For $K_n < 0.01$ --> fluid flow
  - (Viscous flow regime)

Gas Transport: Mass

- Mass
  - Fick's Law --> Diffusing flux $J_A = -D_{AB}\,(dn_A/dx)$
  - Diffusivity D_{AB} (m^2/s) $= \frac{1}{4}\, v\, \lambda \approx T^{7/4}(M_A^{-1}+M_B^{-1})^{1/2}/p(a_A+a_B)^2$
    from Kinetic Theory
- Momentum
  - Shear Stress τ (N/m^2) $= \eta(du/dx)$
    where viscosity η (Poise) $\eta = \frac{1}{4}\, nmv\lambda \approx (MT)^{1/2}/a^2$
- Energy (heat)
  - Conductive heat flux: Φ (w/m^2) $= -K_T(dT/dx)$ (Fourier's Law)
  - Thermal conduction : K_T (W/mK) $= \frac{1}{2}n(c_v/N_A)v\lambda \approx (T/M)^{1/2}c_v/a^2$

Low Pressure Properties of Air (22°C)

Pressure (torr)	Pressure (Pa)	Ptle Density /m^3	Av Ptle spacing	mfp	Ptle flux (/nm^2s)
760 τ	101 Kpa	2.48×10^{25}	3.43nm	65nm	2.86×10^{9}
0.75τ	100	2.45×10^{22}	34.4nm	66um	2.83×10^{6}
7.5 mτ	1	2.45×10^{20}	160nm	6.6mm	2.83×10^{4}
7.5×10^{-6}	10^{-3}	2.45×10^{17}	1.6um	6.64m	28.3
7.5×10^{-8}	10^{-5}	2.45×10^{15}	7.4um	664m	28.3/10nm^2
7.5×10^{-10}	10^{-7}	2.45×10^{13}	34.4um	66Km	28.3/100nm^2

$$\text{Mass } G = \rho V = nmV, \therefore \text{ mass flow rate } q_m = dG/dt$$

$$\text{but "throughput" } Q = q_m \frac{P}{\rho} = Vm\frac{dn}{dt}\frac{P}{nm} = \frac{PV}{n}\frac{dn}{dt} = kT\frac{dn}{dt}$$

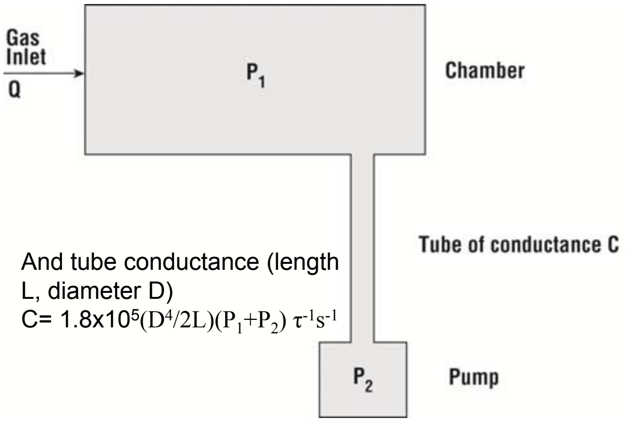
Standard liter: 1 liter gas
@ 1 atmosphere & 273K
=1/22.4 moles

1 std.l/min=760τ.l/min

Conductance: $C = \dfrac{Q}{P_1 - P_2}$

Parallel: $C = C_1 + C_2 + ...$

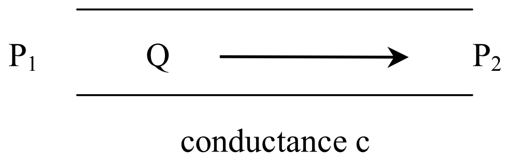
Series: $\dfrac{1}{C} = \dfrac{1}{C_1} + \dfrac{1}{C_2} + ...$



And tube conductance (length L, diameter D)
C= $1.8\times10^5(D^4/2L)(P_1+P_2)\ \tau^{-1}s^{-1}$

Figure 10.2 A simple vacuum system showing a uniform pressure chamber with inlet flow *Q*, a vacuum pump, and a tube of conductance *C.*

Gas Flow/Conductance

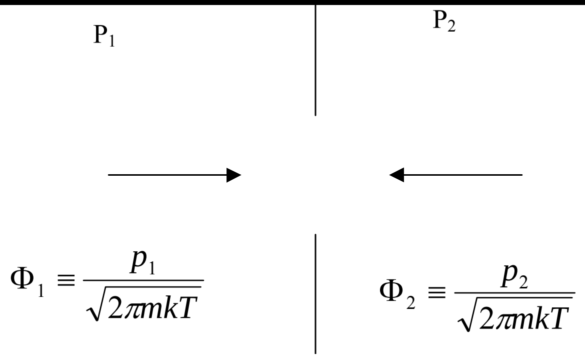


$Q = C(P_1 - P_2)$

Q units [pressure - volume/time]

C units [volume/time]

Conductance of Orifice



$$\Phi_1 \equiv \frac{p_1}{\sqrt{2\pi mkT}} \qquad \Phi_2 \equiv \frac{p_2}{\sqrt{2\pi mkT}}$$

Net flux = $(\Phi_1 - \Phi_2)A$

= 11.7A[l/sec] x $(P_1 - P_2)$ [Pa] for air, 298K

$\therefore$ C = 11.7A l/sec

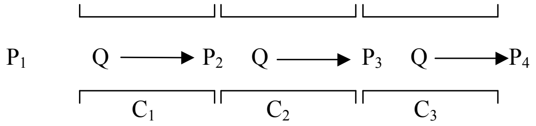
Note: valid for molecular flow ONLY

Series Conductances

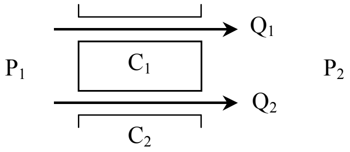
$P_1 - P_2 = Q/C_1$ $P_2 - P_3 = Q/C_2$ $P_3 - P_4 = Q/C_3$

Add --> $P_1 - P_4 = Q(1/C_1 + 1/C_2 + 1/C_3) = Q/C$

$\therefore\ C^{-1} = C_1^{-1} + C_2^{-1} + C_3^{-1} = \Sigma_i C_i^{-1}$



Parallel Conductances



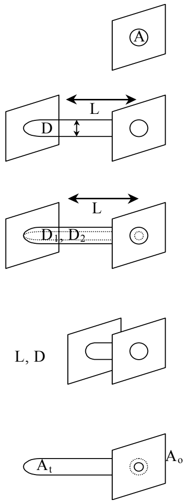
$Q_1 = C_1(P_1 - P_2)$ $Q_2 = C_2(P_1 - P_2)$

Add $Q = Q_1 + Q_2 = (C_1 + C_2)(P_1 - P_2)$
$= C\ (P_1 - P_2)$

$\therefore\ C = C_1 + C_2$

$C = \Sigma_i C_i$

Standard Conductance (C[l/s])



- $C=3.64A(T/M)^{1/2}$
- $=11.7A$
- $C=2.85(D^2/(1+3L/4D))(T/M)^{1/2}$
- $=9.14D^2/(1+3L/4D)$
- $C=3.81(D^3/L)(T/M)^{1/2}$
- $=12.2(D_1-D_2)^2(D_1+D_2)/L$
- $C=19.4(A^2/DL)(T/M)^{1/2}$
- $=12.2D^3/L$
- $C=3.64(A/(1-A/A_t))(T/M)^{1/2}$
- $=11.7A_o/(1-A_o/A_t)$

Variable conductance valves

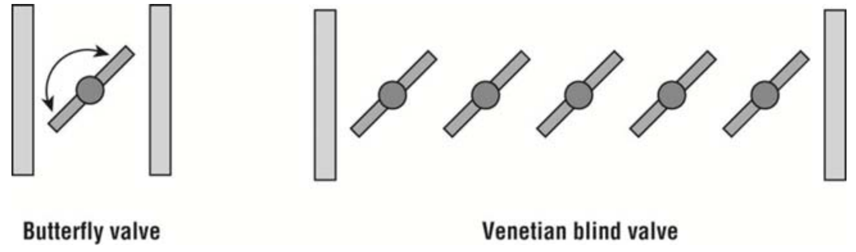


Figure 10.3 Variable conductance valves used in small- and large-diameter vacuum lines.

Ex. 10.2: 2m pumping line, 2.5cm diameter. Need chamber pressure $P_{ch}=P_1 = 1\tau$ and throughput Q=1std l/min. What is pumping speed required?

Eq'n 10.14 → $P_1-P_2 = Q/(1.8\times10^5 \text{torr}^{-1}\text{s}^{-1}(D^4/2L)(P_1+P_2))$

$P_1^2-P_2^2 = Q/(1.8\times10^5 \text{torr}^{-1}\text{s}^{-1}(D^4/2L))$

$= (760\text{torr } 1000\text{cc/min } 60^{-1}\text{min/s})/(9\times10^4 \text{torr}^{-1}.\text{s}^{-1}(2.5\text{cm})^4/200\text{cm})$

$= 0.72\text{torr}^2$

So $P_{pump}=P_2=(1\text{torr}^2-0.72\text{torr}^2)^{0.5}=0.53\text{torr}$, & $S=Q/P_{pump}=((760\text{torr} \times 1\text{l/min})/0.53\text{torr}=1440$ l/min

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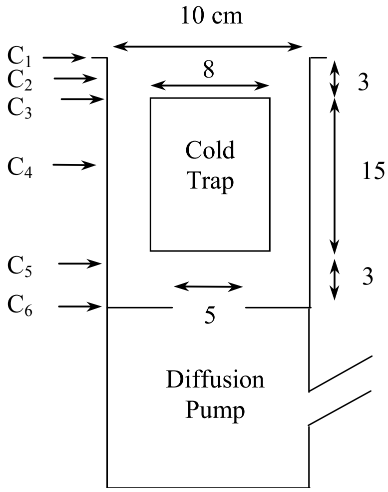
Pump Example



$C_1 = 11.7A = 11.7\pi\,(5)^2 = 919$ l/s

$C_2 = 12.2\,D^3/L = 12.2(10^3/s) = 4065$ l/s

$C_3 = 11.7A = 11.7\,\pi(5^2 - 4^2) = 331$ l/s

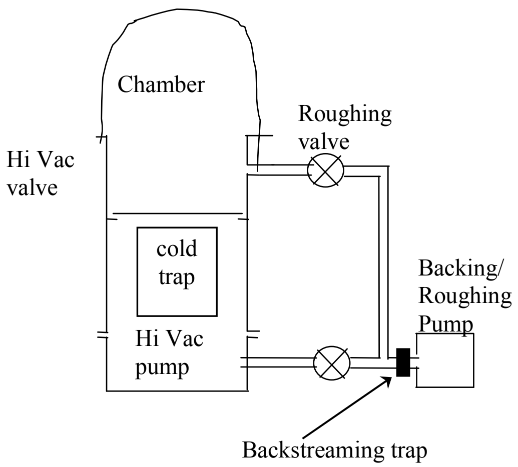
$C_4 = 12.2(D_2 - D_1)^2\,(D_1 + D_2)\,/L$
$= 12.2\,(10 - 8)^2\,(10 + 8)\,/15$
$= 58.6$ l/s

$C_5 = C_2 = 4065$ l/s

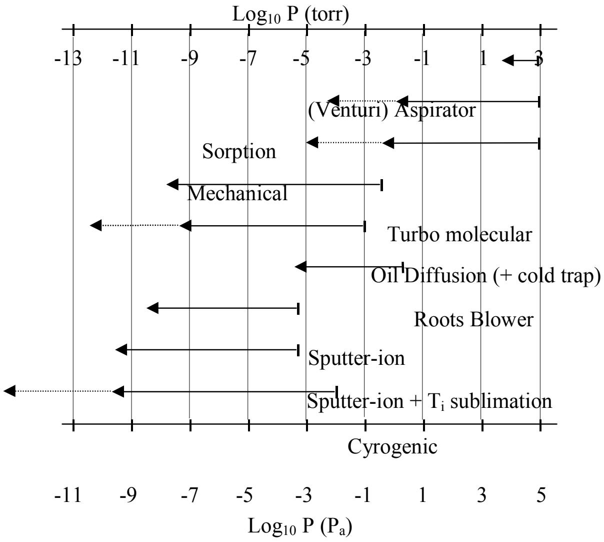
$C_6 = 11.7A_0\,/\,(1 - A_0/A_t)$
$= 11.7\,\pi(2.5)^2/(1 - (2.5/5)^2$
$= 303$ l/s

$C = (\,_{i=1}\Sigma^6\,C_i^{-1})^{-1} = 40$ l/s

Vacuum System



Vacuum Pumps



"Rough vacuum" pumping (760τ →0.1τ)
(Roughing pumps)

Mechanical

Pressure differential α compression ratio
100:1 →
1 atmosphere to 0.01 atmosphere (7.6τ)

Pumping speed:
$S_P = Q/P_P = dV_P/dt$

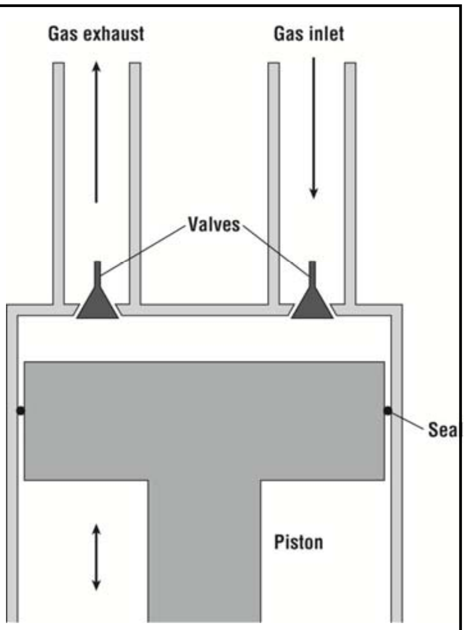
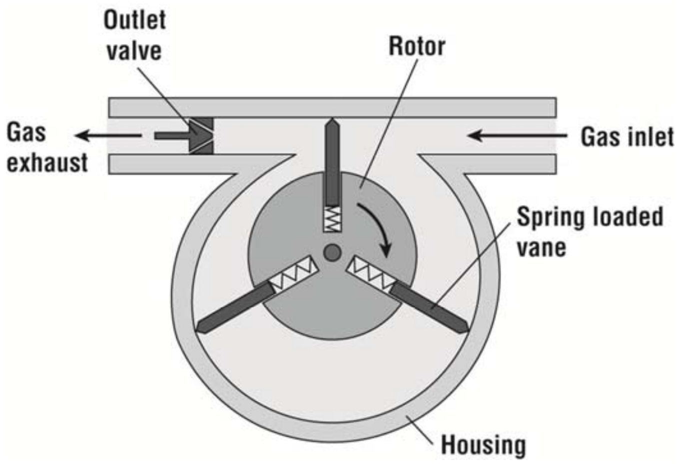


Figure 10.4 A schematic of a single-stage, two-valve piston pump.

More common



20mτ (2-stage→1mτ)

Figure 10.5 One of the most common types of pumps for microelectronic processing is the rotary vane vacuum pump.

Flow rate = $S_P \times P_{IN}$
= pumping speed x inlet pressure

See Ex 10.3 →

Condensation

e.g. H_2O vapor pressure 20τ

If 2mτ partial pressure in chamber and compression ratio = 10^4, H_2O condenses out as liquid

Problem with corrosive gases → liquids

Gas ballast valve:
Adds inert N_2
but slows pumping speed

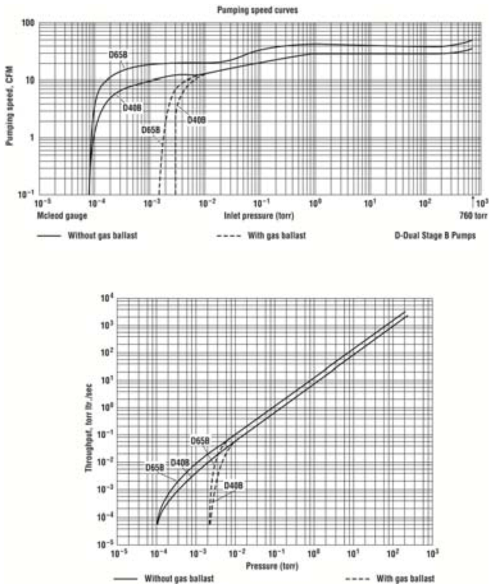


Figure 10.6 The pumping characteristics of Leybold D65® and D40® two-stage rotary vane vacuum pumps with and without gas ballasting *(courtesy Leybold)*.

Positive displacement pump

<0.1mm clearance
No seal, so compression only ~30:1

Typically used with (before) rotary pump to increase inlet pressure

Combination:

$$S_{eff} = S_{RB} S_{RV} \frac{k_0}{S_{RM} + k_0 S_{RV}}$$

See Ex 10.3 for increased pumping speed of combination

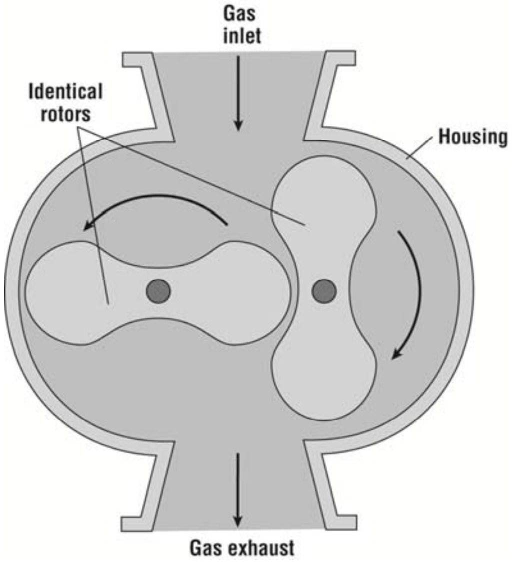


Figure 10.7 Schematic diagram of a Roots blower.

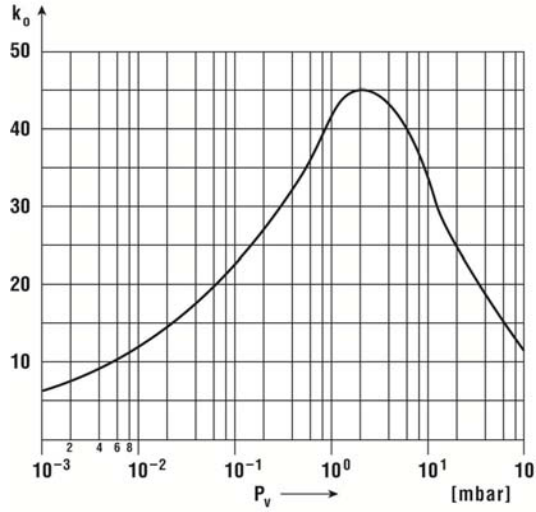


Figure 10.8 Compression ratio as a function of inlet pressure for a typical Roots blower (*courtesy Leybold*).

Backstreaming
Dry pumps

High vacuum

Medium 0.1torr to 10^{-4} torr
High 10^{-4}torr to 10^{-8} torr

Momentum transfer to gas particles

Limited range
Needs roughing pump

Compression ratio ~10^{8}

Figure 10.9 Cutaway view of a diffusion pump *(courtesy Varian).*

Rotor/stator spacings ~1mm

Overall multi-stage compression ratio ~10^{9}

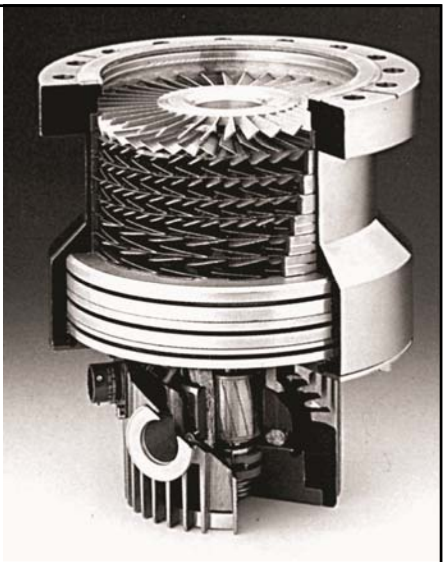


Figure 10.10 Cutaway view of a small turbomolecular pump. Notice the change in the blade angle and shape going from the high vacuum (top) to low vacuum (bottom) ends *(courtesy Varian).*

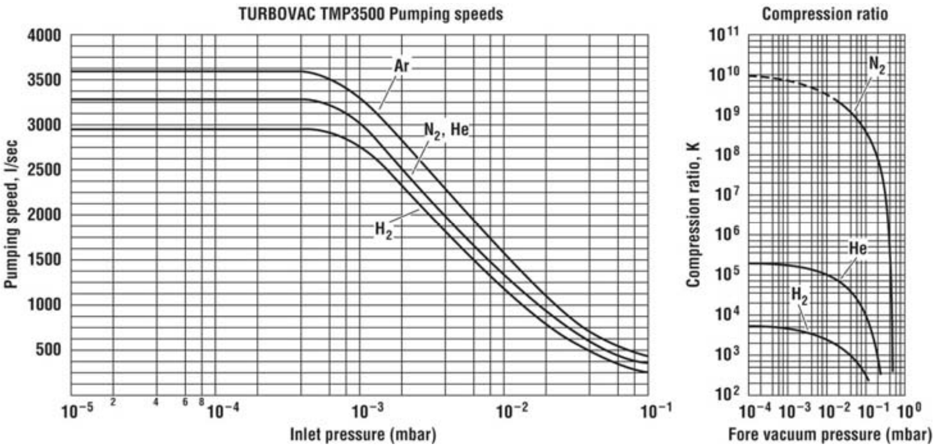


Figure 10.11 Pumping speed and compression ratio of a typical turbo pump as a function of inlet pressure for several representative gases (*courtesy Leybold*).

Gas entrapment pumps:

Cryopump

Ti sublimation pump
Ti sputter pump

LN2 sorption roughing
(molecular sieve)

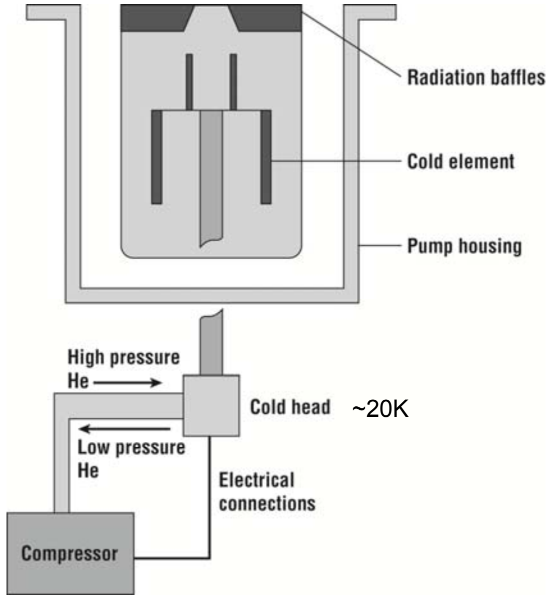
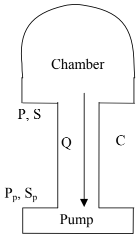


Figure 10.12 Schematic view of a typical cryopump.

Pumping Speed: Ideal



Ideal

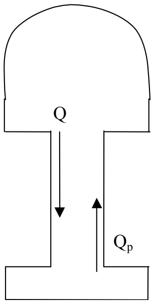
Pump speed defined as $S = Q/P$

ie. $S_p = Q/P_p$ at pump

Find effective pumping speed at chamber $S = Q/P$

$Q = (P - P_p)\,C = (Q/S - Q/S_p)\,C$

$\therefore\ 1/S = 1/S_p + 1/C$ ie. $S = S_p / (1 + S_p/C)$



Backstreaming/leak

$Q + Q_p = S_pP_p \quad \therefore\ Q = S_pP_p\,(1 - Q_p/S_pP_p)$

When $Q = 0$ at ultimate pump pressure P_0, then $Q_p = S_pP_0$

$\therefore$ Effective pump speed

$S_p' = Q/P_p = S_p(1 - P_0/P_p) \dashrightarrow 0$ as $P_p \dashrightarrow P_0$

Pump down: Ideal

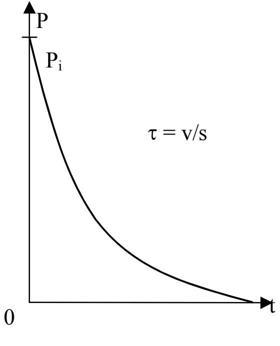
Gas load $Q = Q_L + Q_G - V(dP/dt)$

(Leaks & Outgassing)

For $Q \approx -V(dP/dt) = PS$

$dP/P = -\,(S/V)\,dt$

$P = P_i \exp -(S/V)t$



If $V = 200l$, $S = 20\ l/s$, $\tau = V/S = 10s$

ie. P decr. 1 decade / 23 secs

ie. 760 torr to 7.6 mtorr takes 2.5 min

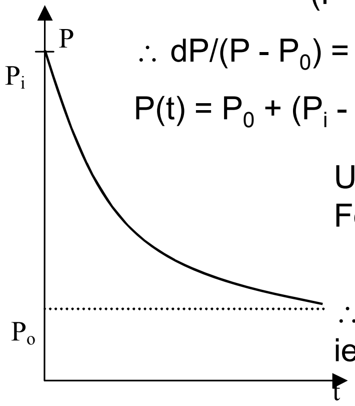
(more because S decr. as P decr.)

Pump down: Outgassing

If $Q_L + Q_G = Q_X \neq 0$

$-V(dP/dt) = PS - Q_X$ --> 0 when $Q_X = P_0S$

$= (P - P_0)S$

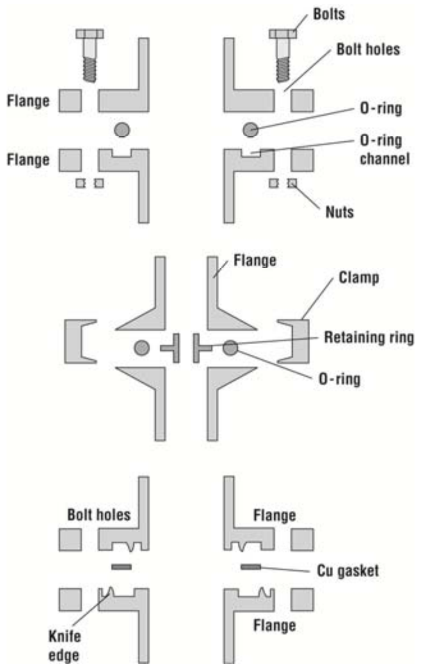


$\therefore dP/(P - P_0) = -(S/V)\, dt$

$P(t) = P_0 + (P_i - P_0) \exp - (S/V)\, t$

Ultimate pressure $P_0 = Q_X/S$
For hi-vac, if V = 200l, S = 200 l/s,
then τ = 1s

$\therefore$ P decreases 1 decade / 2.3 sec
ie. 10^{-2} torr --> 10^{-6} torr in 10 secs



Vacuum seals

Neoprene/Viton O-rings
Conflat flange

Pressure gauges

Capacitance manometer
Thermocouple
Ionization

Figure 10.13 Two types of O-ring seals for medium vacuums and the Conflat® flange used for sealing high vacuum systems.

Pressure Measurement:
Direct Gauges (Wall displacement)

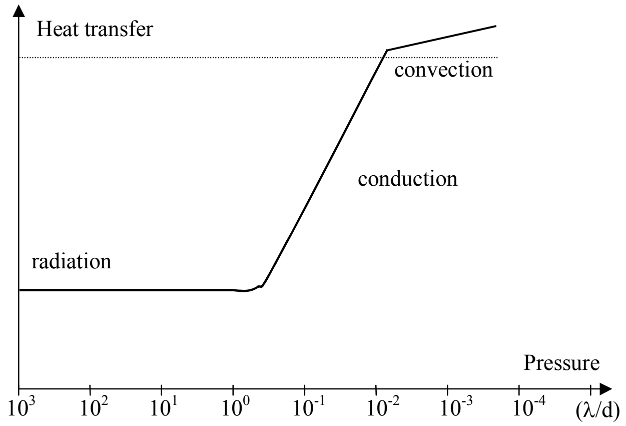
- Solid wall
  - Radiometer
  - Bourdon tube
  - Diaphragm
    - Capacitance manometer
- Liquid wall
  - U-tube manometer
  - McLeod

Pressure Measurement: Indirect gauges (Measurement of Gas Properties)

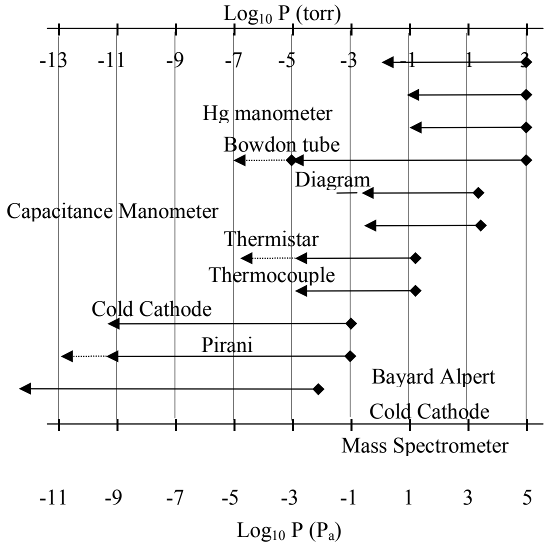
- Momentum transfer (viscosity)
  - Quartz fiber
  - Rotating disk
- Charge generation (ionization)
  - Hot cathode
    - Bayard Alpert & Schulz - Phelps
  - Cold cathode
    - Penning & Redhead
  - Radioactive
    - Alphatron
- Energy transfer (thermal conductivity)
  - Thermopile
  - Pirani

Example of Range Limits

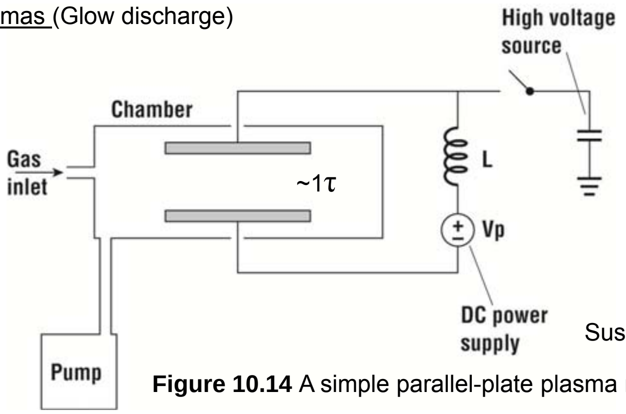
Pirani/thermocouple gauge



Pressure Gauges



DC Plasmas (Glow discharge)



Start plasma

L protects V_P from HV

Sustain plasma

Figure 10.14 A simple parallel-plate plasma reactor.

Gas normally insulating
High voltage initiates breakdown
Plasma : Dissociation, etc

Dissociation	$e^* + AB \leftrightarrow A + B + e$
Atom ionization	$e^* + A \leftrightarrow A^+ + B + e$
Molecular ionization	$e^* + AB \leftrightarrow AB^+ + e + e$
Atomic excitation	$e^* + A \leftrightarrow A^* + e$
Molecular excitation	$e^* + AB \leftrightarrow AB^* + e$

Fabrication Engineering at the Micro- and Nanoscale Campbell

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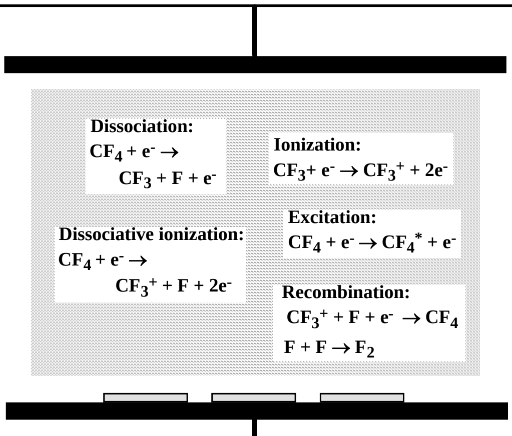
e.g. Plasma etching



Dissociation:
$CF_4 + e^- \rightarrow CF_3 + F + e^-$

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

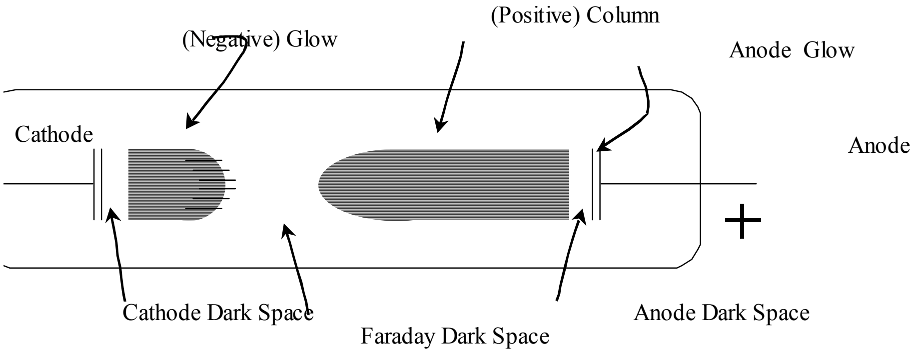
Dissociative ionization:
$CF_4 + e^- \rightarrow CF_3^+ + F + 2e^-$

Excitation:
$CF_4 + e^- \rightarrow CF_4^* + e^-$

Recombination:
$CF_3^+ + F + e^- \rightarrow CF_4$
$F + F \rightarrow F_2$

- **Etching gases include halide-containing species such as CF_4, SiF_6, Cl_2, and HBr, plus additives such as O_2, H_2 and Ar. O_2 by itself is used to etch photoresist. Pressure = 1 mtorr to 1 torr.**
- **Typical reactions and species present in a plasma used are shown above.**
- **Typically there are about 10^{15} cm^{-3} neutral species (1 to 10% of which may be free radicals) and 10^8-10^{12} cm^{-3} ions and electrons.**
- **In standard plasma systems, the plasma density is closely coupled to the ion energy (as determined by the sheath voltage). Increasing the power increases both.**

Glow Discharge: Basic



(Positive) Column

(Negative) Glow

Anode Glow

Cathode

Anode

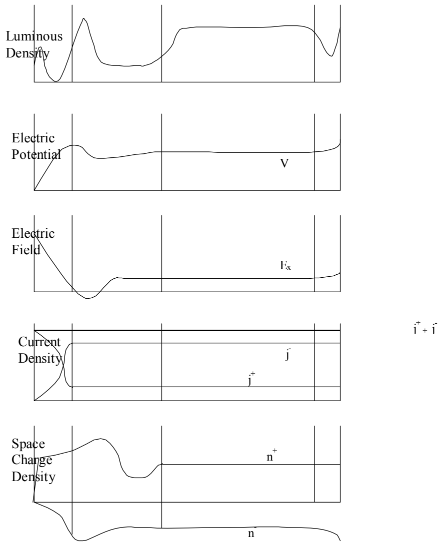
+

Cathode Dark Space

Faraday Dark Space

Anode Dark Space

Glow Discharge: Electrical/Optical



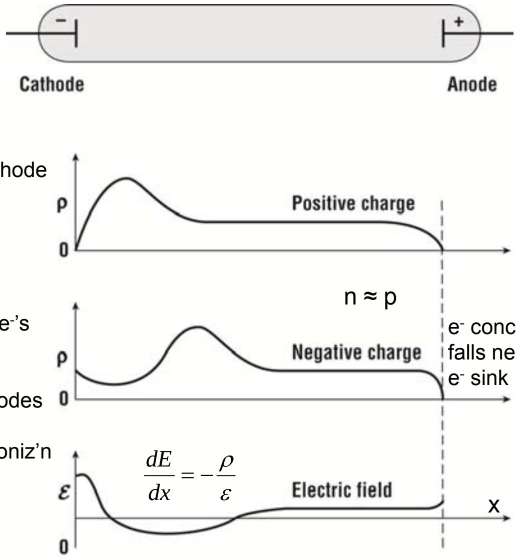
See p 274

e^-s move faster than ions in same field
- accel'd from cathode, so n<<p near cathode
- e^- energy creates ions, so p incr with x

This shields plasma to right, decr E ,
hence decr ioniz'n, so p decr

Optical emission:
Moderate energy e^- + atom → excite core e^-'s
return to ground state → photon
Higher energy e^-s ionize atoms instead
Low energy e^-s → no emission near electrodes

In Faraday dark space, e^-s lost energy to ioniz'n



n ≈ p

e^- conc'n
falls near
e^- sink

$$\frac{dE}{dx} = -\frac{\rho}{\varepsilon}$$

x

Figure 10.15 Positive and negative charge densities and electric field as a function of position in the plasma.

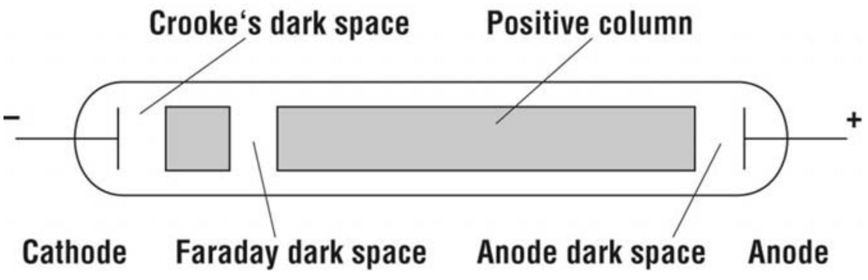
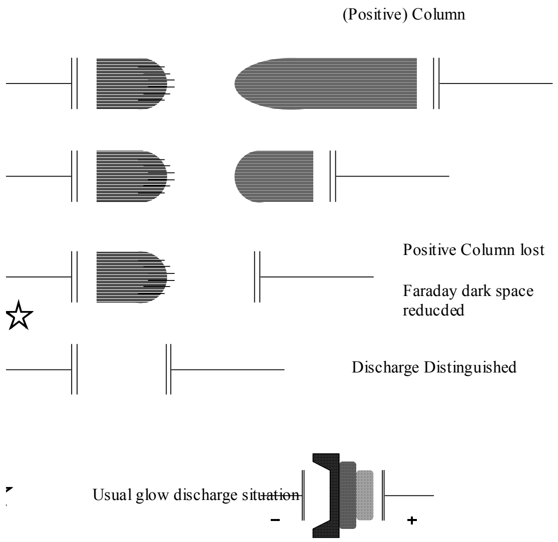


Figure 10.16 Structure of a dc plasma.

In Faraday dark space, e^-s lose energy to ionization
Low pressure → electron mfp increases
→ Faraday space increases
→ plasma extinguishes

Hence DC plasma pressure ≥ 1 mτ

Glow Discharge: Plate Separation



(Positive) Column

Positive Column lost

Faraday dark space reducded

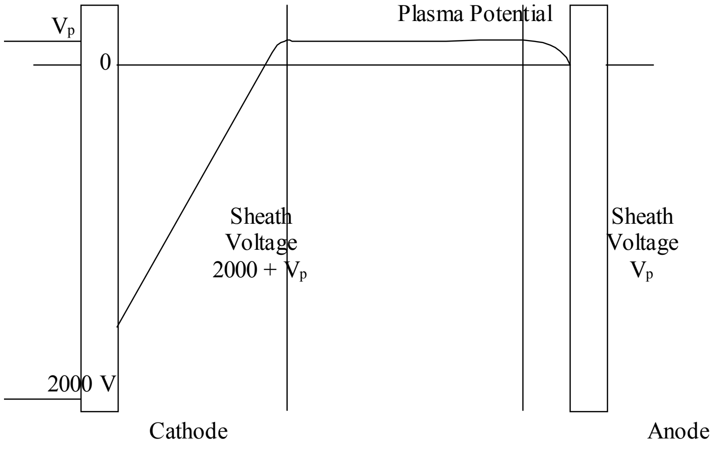
Discharge Distinguished

Usual glow discharge situation

−

+

Glow Discharge: Potential Distribution



V_p

0

Plasma Potential

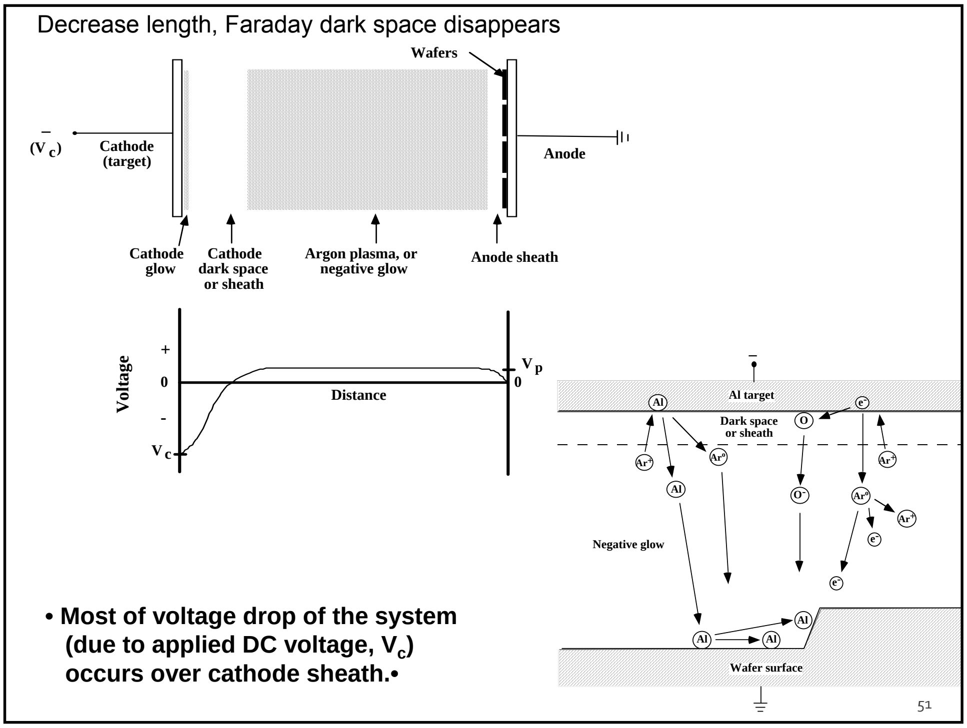
Sheath Voltage $2000 + V_p$

Sheath Voltage V_p

2000 V

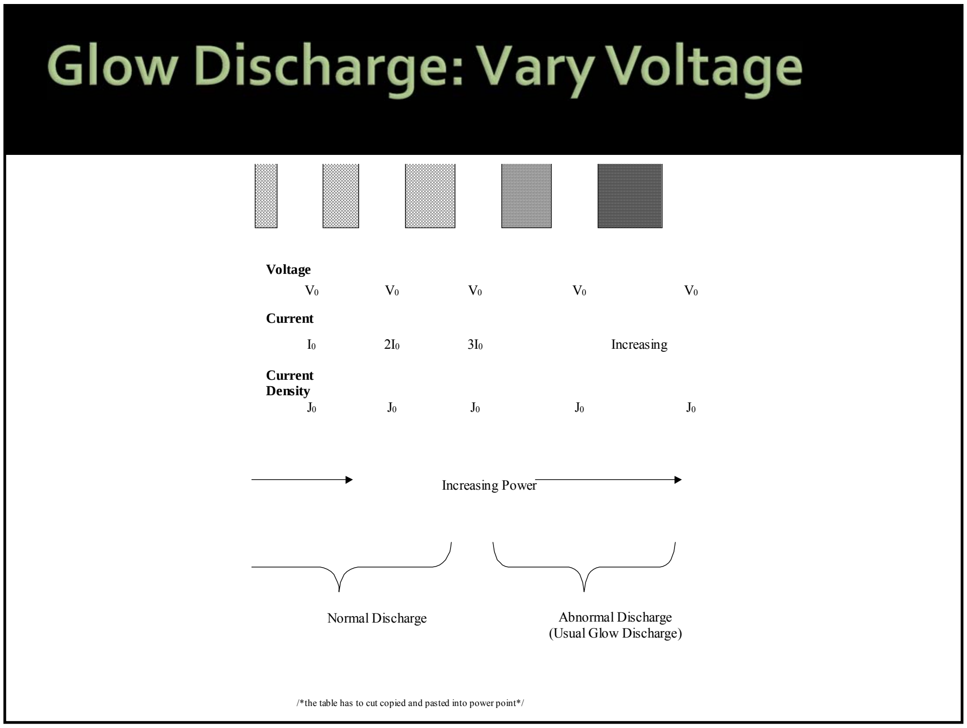
Cathode

Anode



Decrease length, Faraday dark space disappears

- Most of voltage drop of the system (due to applied DC voltage, V_c) occurs over cathode sheath.•



Glow Discharge: Vary Voltage

Voltage	V_0	V_0	V_0	V_0	V_0
Current	I_0	$2I_0$	$3I_0$	Increasing	
Current Density	J_0	J_0	J_0	J_0	J_0

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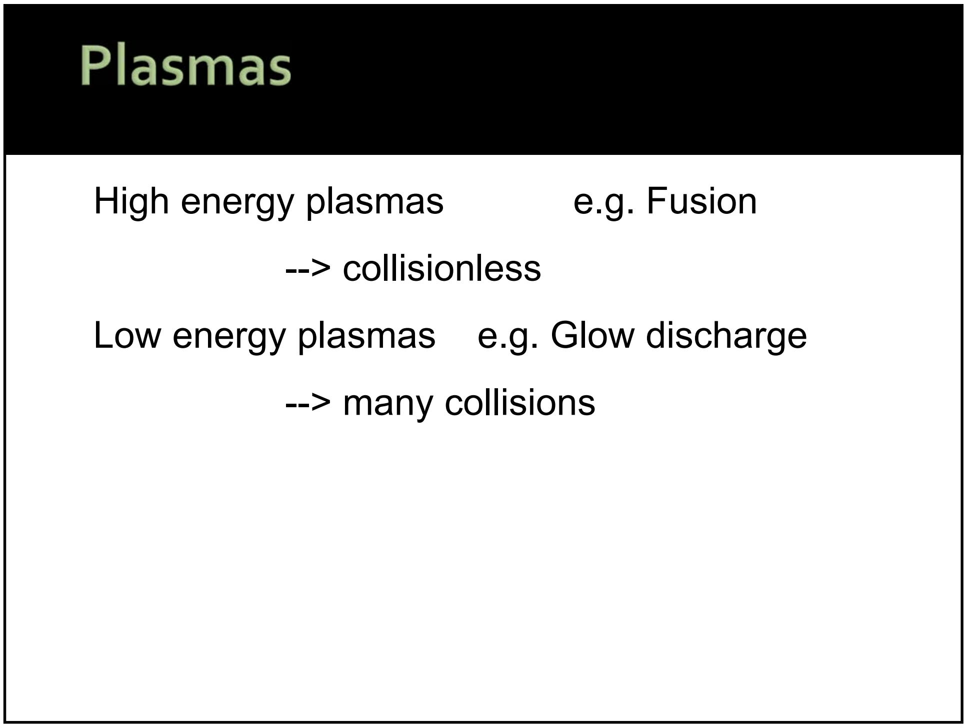


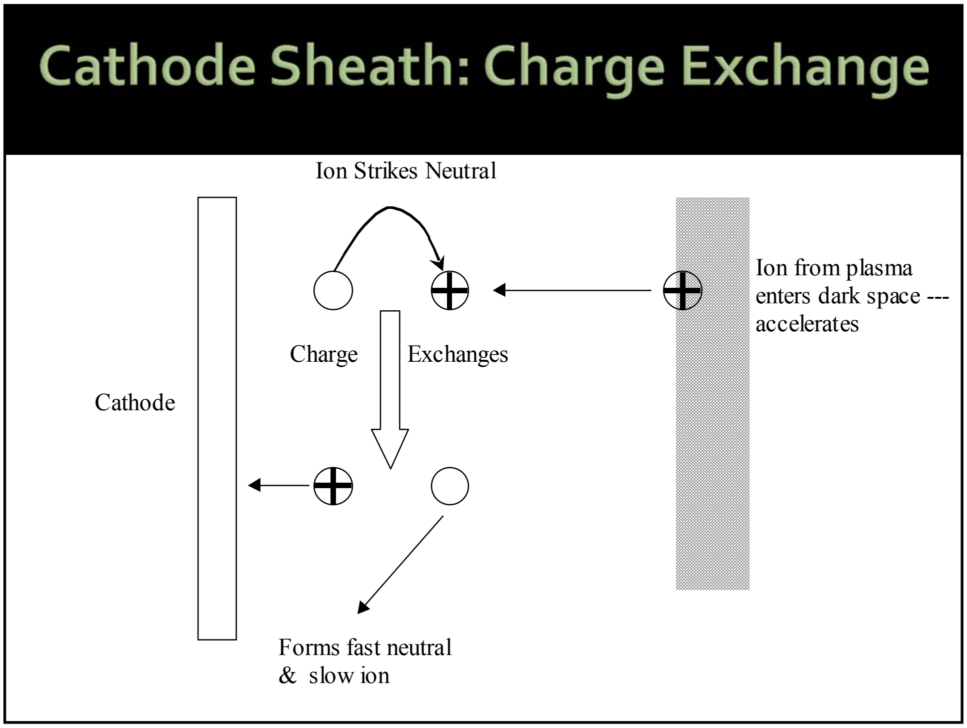
Plasmas

High energy plasmas e.g. Fusion

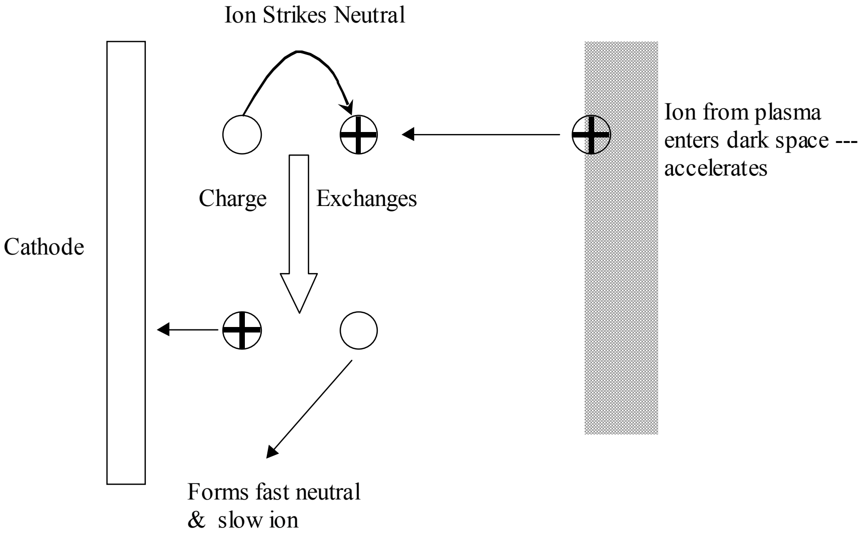
--> collisionless

Low energy plasmas e.g. Glow discharge

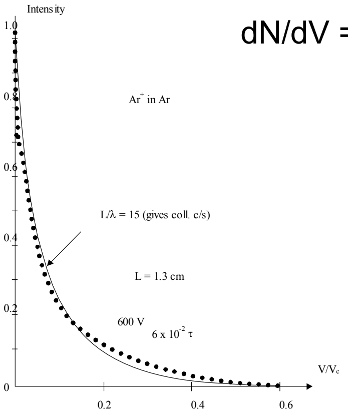
--> many collisions



Cathode Sheath: Charge Exchange



Cathode Sheath: ion energy



$$dN/dV = (N_0/V_C)(L/2\lambda)(1 - V/V_C)^{-1/2}$$

$$.\exp - L/\lambda\ [1 - (1 - V/V_C)^{1/2}]$$

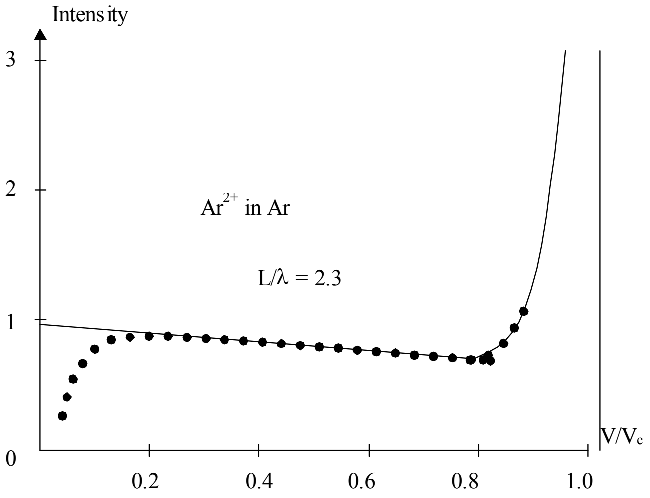
$$\Rightarrow (N_0/V_C)(L/2\lambda).\exp -(L/2\lambda)(V/V_C)$$

$$\lambda << L$$

dN = No of ions arriving at cathode with energy V to V+dV

V_C = cathode potential, λ = mfp, L = dark space width

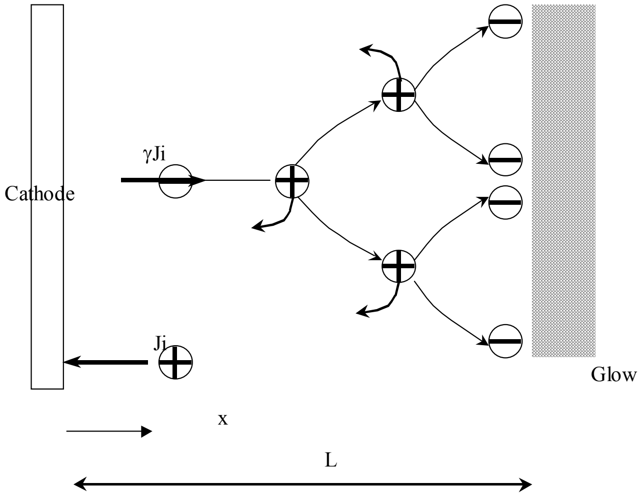
Cathode Sheath: Doubly Charged



Significant proportion reach cathode without collision.

Cathode Sheath: Ionization

Electron Ionization



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

Cathode Sheath: Electron Distribution

No. of ionizing collisions = $N_e(x).nq\Delta x$

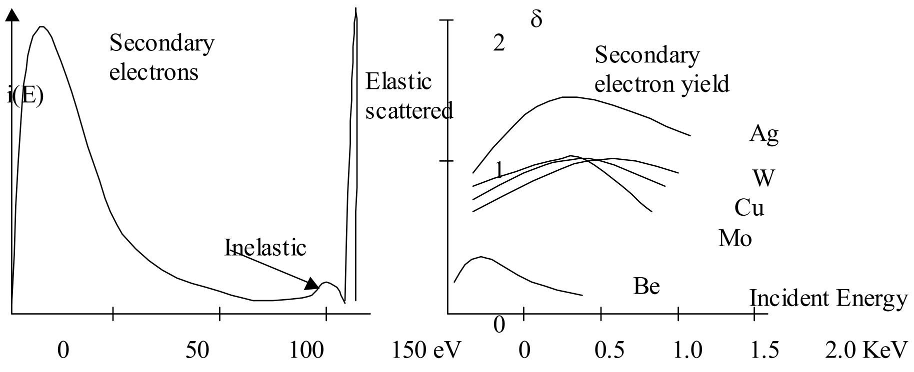
at point x to $x+\Delta x$

$N_e(x)$=electron density, n=neutral density,
q=collision cross section
ie. $\int dN_e(x) / N_e(x) = \int n\, q\, dx$
$\therefore N_e(x) = N_e(0) \exp n\, q\, x$

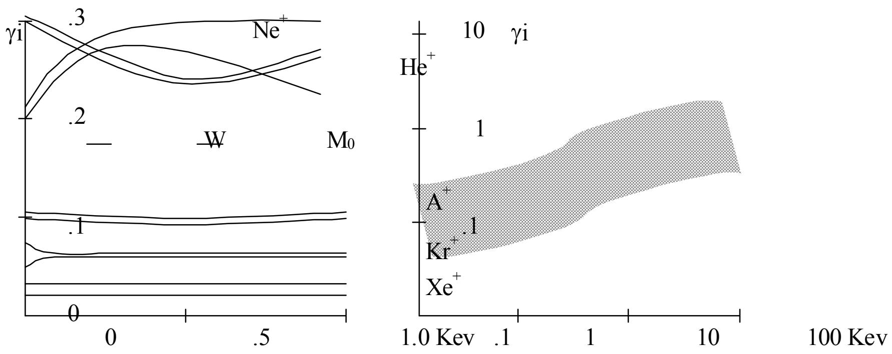
ie. electron multiplication & ionization across sheath so each ion at cathode produces $\gamma(\exp nqL - 1)$ other ions in dark space (typ. $\gamma \sim 0.25$).

Similarly Ion Impact ionization: est. rate ~ 0.15

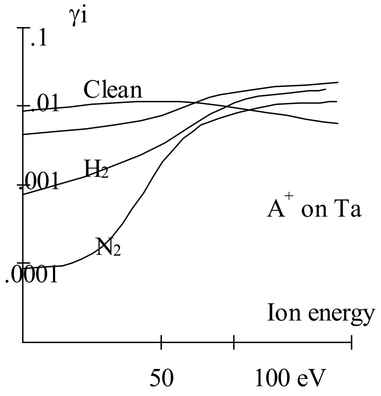
Secondary Electron Emission: Electron Bombardment

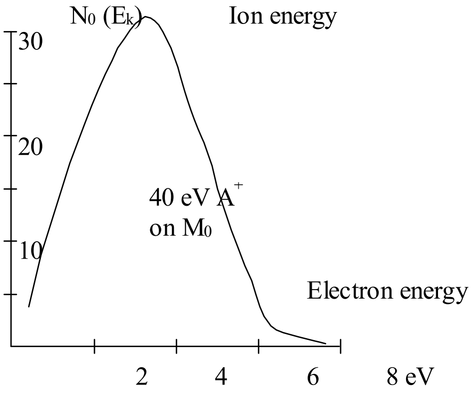


Secondary Electron Emission: Ion Bombardment

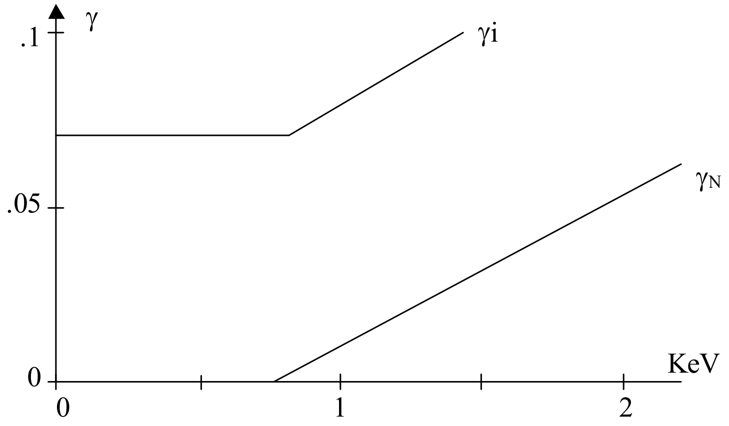


Secondary Electron Emission: Ion Energy



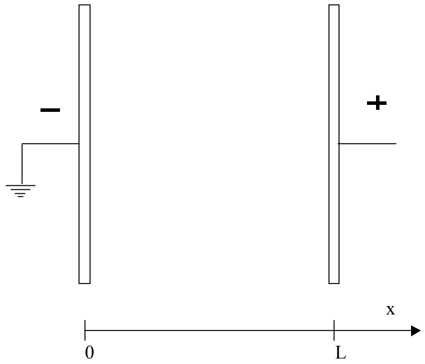


Secondary Electron Emission: Neutral Bombardment



Photon bombardment (Photo emission)

Cathode Sheath: Space Charge Limited Current #1



j = electron current density = $N_e e v$

$\& \ \frac{1}{2} m v^2 = eV$ $\qquad \therefore v = (2eV/m)^{1/2}$

For $d^2V/dx^2 = -\rho/\varepsilon_0 = N_e e/\varepsilon_0 = j/v\varepsilon_0$

$= (j/\varepsilon_0)(m/2e)^{1/2} V^{-1/2}$

Cathode Sheath: Space Charge Limited Current #2

Rewrite as $(dV/dx)(d^2V/dx^2) = (j/\varepsilon_0)(m/2e)^{1/2} V^{-1/2} dV/dx$

& integrate $\frac{1}{2}(dV/dx)^2 = (j/\varepsilon_0)(m/2e)^{1/2} 2V^{1/2}$

Rearrange $V^{-1/4} dV = (4j/\varepsilon_0)^{1/2} (m/2e)^{1/4} dx$

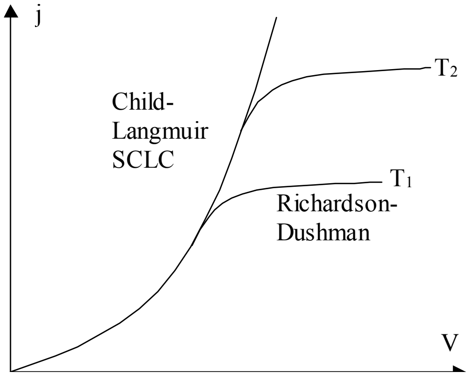
& integrate $4/3 \, V^{3/4} = (4j/\varepsilon_0)^{1/2} (m/2e)^{1/4} x$

gives:

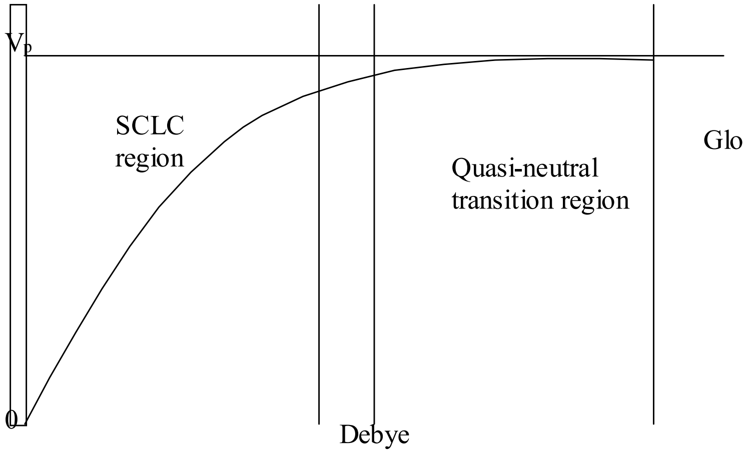
$j = (4\varepsilon_0/9)(2e/m)^{1/2} V^{3/2}/x^2$

$\& \ V \propto x^{4/3}$

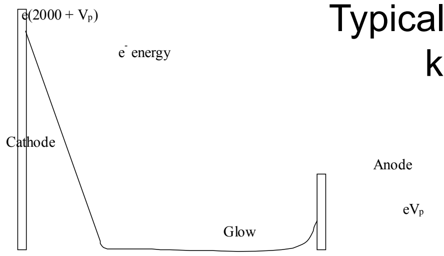
$dV/dx \propto x^{1/3}$



Cathode Sheath: Regions



Glow Region: Thermal electrons



Typical electron temperatures
$kT_e \sim$ 2eV to 8eV

For V_p~10v, neglig. probability of e^- reaching cathode,
small finite probability at anode (~ 0.1%)

Velocity distribution in electron gas

$$dn/n = 4\pi(m/2\pi kT)^{3/2} v^2 \exp -mv^2/2kT \, dv$$

gives energy distribution

$$dn/n = (2/\pi^{1/2})(E/kT)^{1/2} \exp -(E/kT) \, d(E/kT)$$

Glow Region: Electron Ionization

Proportion of e^-'s with energy $\geq E_0$,
distribution temperature T_e

$$f(E>E_0)=2\pi^{-1/2}\int_{E_0/kT_e}^{\infty}(E/kT_e)^{1/2}\exp -(E/kT_e)\,d(E/kT_e)$$

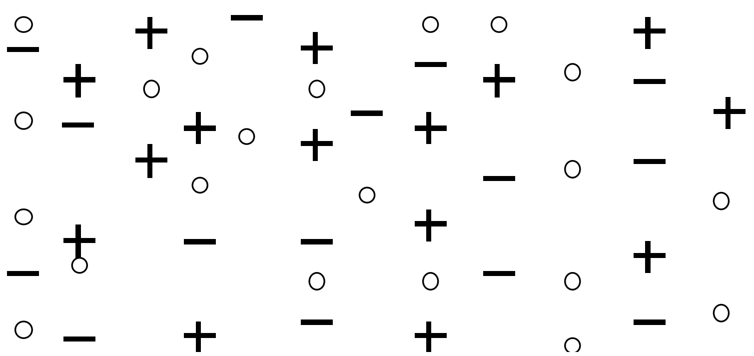
For E_0 = 15.76eV (Argon ionization threshold) :

kT_e =	1	2	4	8 eV
$f(E>E_0)$ =	$7\text{x}10^{-7}$	$1.3\text{x}10^{-3}$	0.05	0.28

For E_0 = 11.76eV (Argon excitation threshold):

kT_e =	1	2	4	8 eV
$f(E>E_0)$ =	$4\text{x}10^{-5}$	$9.5\text{x}10^{-3}$	0.13	0.42

Plasma



Electrically neutral

O Neutral atoms, + Positive ions, - Electrons

Collisions

1) Electron - atom elastic collision
- negligible energy transfer, electron changes direction

2) Electron impact ionization $e^- + Ar \dashrightarrow 2e^- + Ar^+$
- Multiplicative; threshold at ionization energy 15.8 eV

3) Electron impact excitation $e^- + Ar \dashrightarrow e^- + Ar^*$
- Excitation threshold 11.56 eV

4) Photo-excitation / ionization

5) Relaxation of excited atoms $Ar^* \dashrightarrow Ar + hv$
- Glow!

6) Recombination $Ar^+ + e^- \dashrightarrow Ar$??? - 3
body (wall, atom) - 2
stage $e^- + Ar \dashrightarrow Ar^-$, $Ar^- + Ar^+ \dashrightarrow 2Ar$ - Radiative
$e^- + Ar^+ \dashrightarrow Ar + h\upsilon$

7) Ion-neutral charge transfer

Also: Ion-impact ionization, dissociation, e^- attachment, etc

Plasmas: Ion energy, Ion/Electron Velocities, & Plasma Currents

Electric Field:
Acceleration = eE/m
Distance traveled = ½ (eE/m) t^2
Work done = eE. ½ (eE/m) $t^2 \propto m^{-1}$

Particle flux (kinetic theory) J = nv/4

$j_e = (en_e\, v_e) / 4 \sim 38$ mA/cm^2

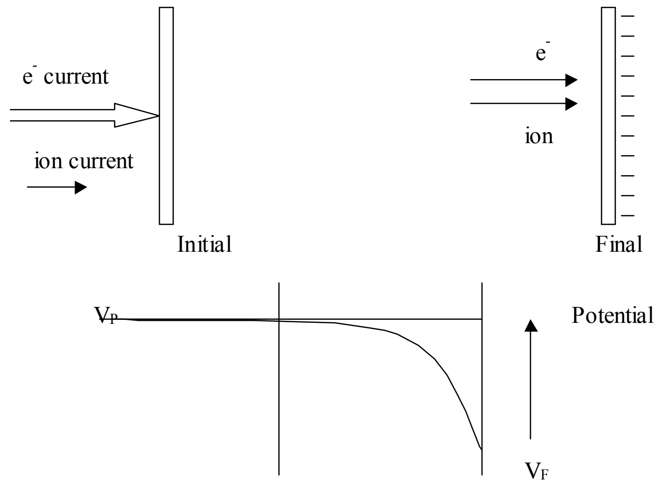
$j_I = (en_i\, v_i) / 4 \sim 21\mu$A/cm^2

Ions: Negligible energy from field
$m \sim 6.6 \times 10^{-26}$ Kg
Thermal energy $\frac{1}{2} m v_i^2 = 3/2\, kT_i \approx 3/2\, kT$
Ion $v_i \approx 5.2 \times 10^4$ cm/sec 0.04 eV $\Rightarrow T_i \approx 500$K

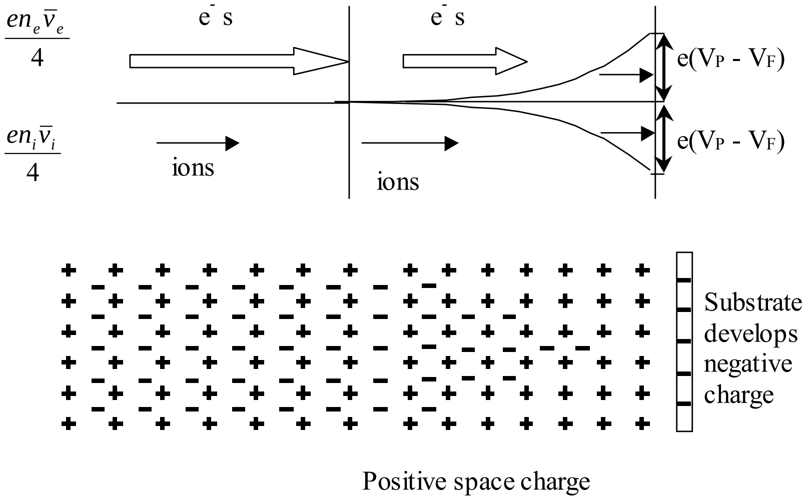
Neutral atoms:
T = 293K $\Rightarrow$ 0.026 eV, v = 4.0×10^4 cm/sec

Electrons:
$m \sim 9.1 \times 10^{-31}$ Kg, energy from field
$v_e \approx 9.5 \times 10^7$ cm/sec, 2eV $\Rightarrow T_e \approx 23{,}200$K

Plasma Sheath: Introduction



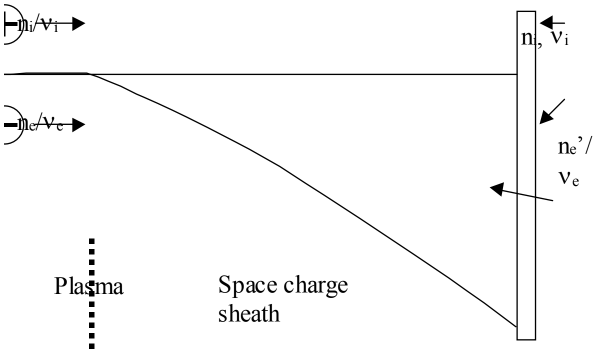
Plasma Sheath: Physics



$$\frac{e n_e \bar{v}_e}{4}$$

$$\frac{e n_i \bar{v}_i}{4}$$

Plasma Sheath/Substrate Potential #1



Ions accelerated

Electrons retarded

Why?

Velocities reduced by retarding field in sheath. But----those that reach the substrate had higher velocities in plasma.

$\nu_e' = \nu_e$

Plasma Sheath/Substrate Potential #2

Maxwell Boltzmann --> $n_e' = n_e \exp -[e(V_p - V_f)]/kT_e$

$\therefore\ n_e \,.\, \exp -e(V_p - V_f)/kT_e \,.\, v_e / 4 = (n_i v_i) / 4$

& $n_e = n_i$ (charge equality in plasma)

$\therefore\ V_p - V_f = (kT_e/e) \ln (v_e / v_i)$

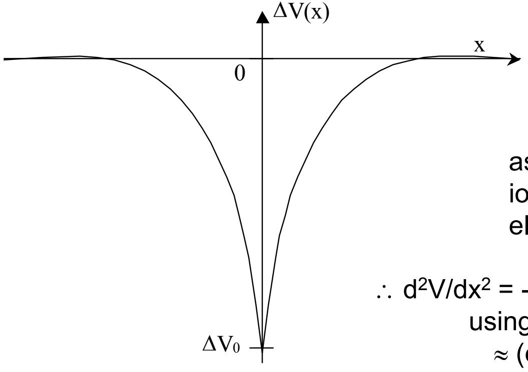
Also mean velocity $v = (8kT/\pi m)^{1/2}$

$\Rightarrow V_p - V_f = (kT_e/2e) \ln (m_i T_e / m_e T_i)$

Typ ~ 15v

Debye Shielding & Debye Length

Assume a potential perturbation $\Delta V(x)$



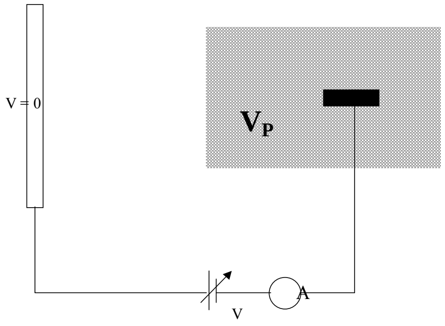
$d^2V/dx^2 = -\rho/\varepsilon_0 = -(e/\varepsilon_0)(n_i - n_e(x))$
assuming n_i constant due to mass of ions and that transient effects affect electrons only.

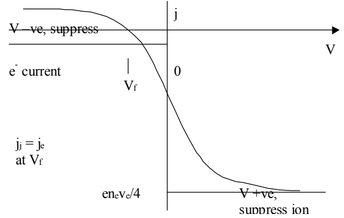
$\therefore\ d^2V/dx^2 = -(en_i/\varepsilon_0)(1 - \exp -(e\,\Delta V(x) / kT_e))$
using $n_e(x)/n_e = \exp -(e\,\Delta V/kT_e)$ & $n_e = n_i$
$\approx (en_i/\varepsilon_0)\, e\Delta V(x) / kT_e$, for $\Delta V(x) << kT_e$

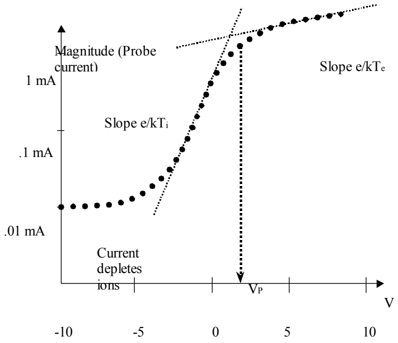
$\therefore$ Solution: $\Delta V(x) = \Delta V_o \exp - |x| / \lambda_D$
where $\lambda_D = (kT_e\, \varepsilon_0 / n_i e^2)^{1/2}$ = Debye length.

~ 100μm for $n_i \sim 10^{10}$/cc, $kT_e \sim$ 2eV

Langmuir Probe







$j_e = (en_e v_e /4) \exp -[(e(V_p - V))/kT_e]$

$\ln j_e = \ln (en_e v_e /4) - e(V_p - V) / kT_e$

& $\ln j_i = \ln (en_i v_i /4) - e(V_p - V) / kT_i$

Langmuir Probe Size

$j_e >> j_i$

Possible problem of depletion of plasma electrons by probe current

$\therefore$ Need VERY small probe.

Say $j_e \sim 38$ mA/cm^2 & draw 1 mA

--> probe area $2.6\text{x}10^{-2}$ cm^2

$\therefore$ for 0.25 cm probe, r = 166 μm

NB $\lambda_D \sim 100$ μm

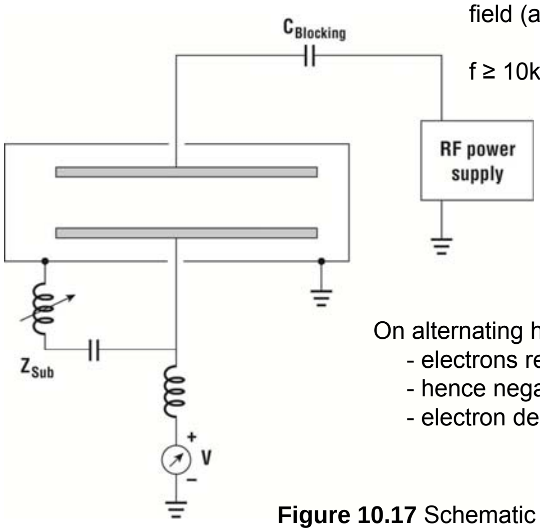
$\therefore$ ~ 120 μm diameter wire!!

RF Plasmas

(Includes possible insulating electrode surfaces)

At low frequencies, charges follow field (acts as varying dc)

f ≥ 10kHz, ions cannot follow field



On alternating half cycles:

- electrons reach both electrodes
- hence negative charges on electrodes
- electron depletion nearby (dark spaces)

Figure 10.17 Schematic of an RF plasma system.

Fabrication Engineering at the Micro- and Nanoscale Campbell

With DC blocking

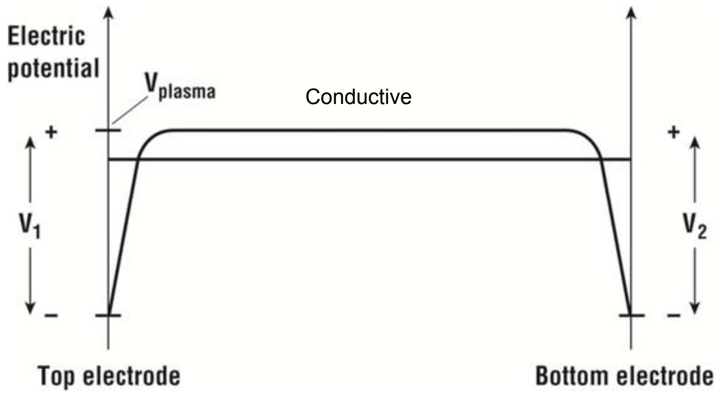
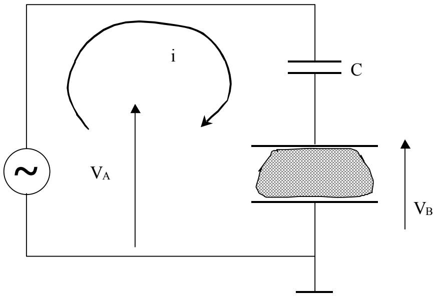
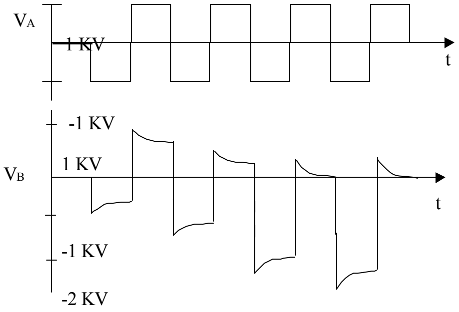


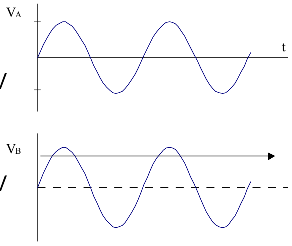
Figure 10.18 Typical plot of dc voltage as a function of position in an RF plasma.

RF Discharge: Circuit & Self-bias

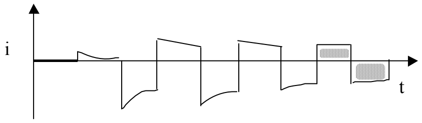




- 1kV
- -1kV
- -1kV



DC OFFSET



RF Discharge Frequency

Required frequency :-

Say C ~ 1 pF/cm^2 (1/8 inch SiO_2)

i ~ 1 mA/cm^2

(typical ion current sputtering rates)

Then time to charge capacitor to V_A~1000 volts

t ~ CV / i --> 1 μs

ie. maintain RF discharge with f ≥ 1 MHz

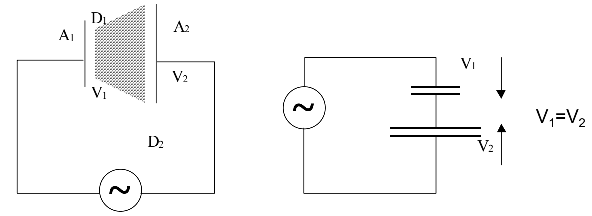
In practice ---> 100 KHz

---> 13.56 MHz

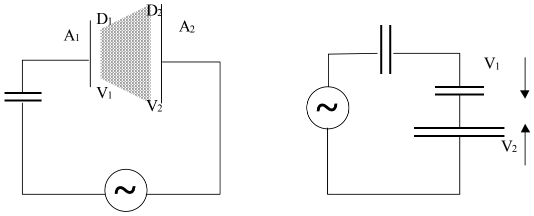
---> untuned

RF Blocking Capacitor

- Without blocking capacitor



- With blocking capacitor



RF Voltage Distribution

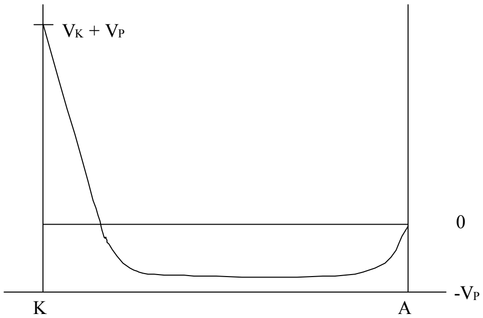
Assume space charge limited ion current density $j_i = KV^{3/2} / m_i^{1/2}D^2$ is equal at both electrodes

$$\therefore V_1^{3/2}/D_1^2 = V_2^{3/2}/D_2^2$$

Also: $C \propto A/D$ and $V_1/V_2 = C_2/C_1 \Rightarrow (A_2/A_1)(D_1/D_2)$

$$\therefore V_1^{3/2}/V_2^{3/2} = (D_1/D_2)^2 = (V_1A_1/V_2A_2)^2$$

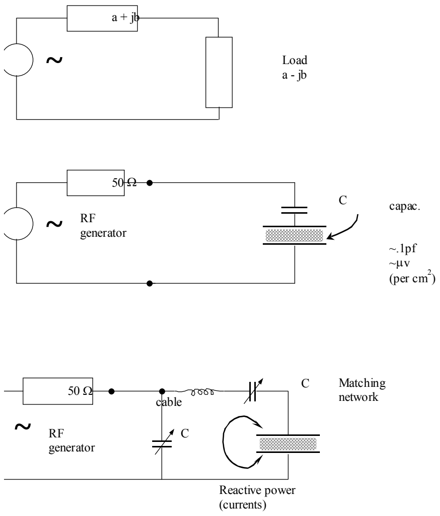
$$\therefore V_1/V_2 = (A_2/A_1)^4$$



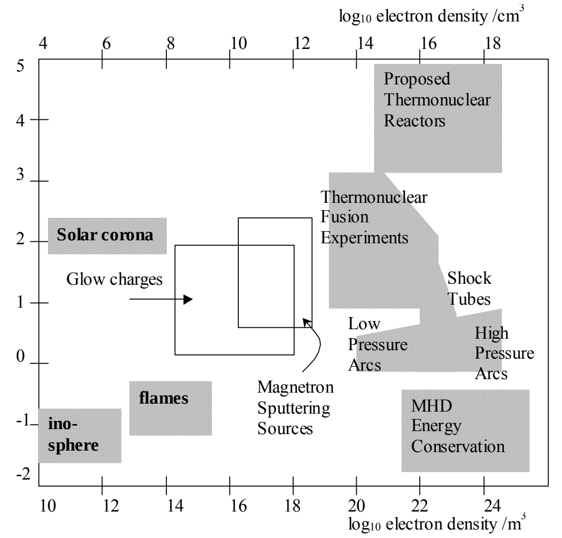
Small cathode A_K ,
Chamber anode A_A

$\therefore V_K + V_P = (A_A/A_K)^4V_P$
(large)

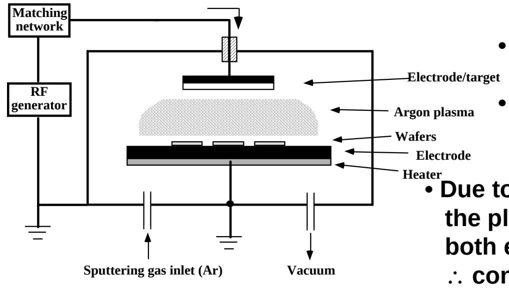
RF: Matching Network



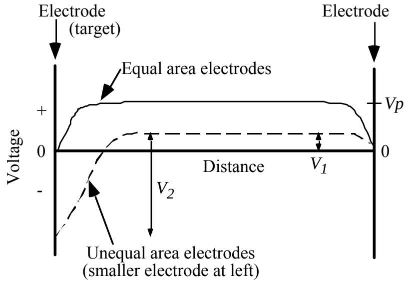
Plasma Applications



RF Sputter Deposition



- For DC sputtering, target electrode is conducting.
- To sputter dielectric materials use RF power source.



- Due to slower mobility of ions vs. electrons, the plasma biases positively with respect to both electrodes. (DC current = zero.) ∴ continuous sputtering.
- When the electrode areas are not equal, the field must be higher at the smaller electrode (higher current density), to maintain overall current continuity

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^m \quad \text{(m = 4 theoretically} \quad \text{= 1-2 experimentally)} \ (13)$$

- Thus by making the target electrode smaller, sputtering occurs "only" on the high voltage target. Wafer electrode can also be connected to chamber walls, further increasing V_2/V_1.

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Ex. 10.4 Ground bottom/RHS electrode

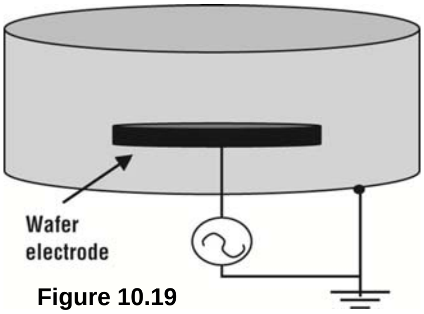


Figure 10.19

Wafer "platen" 200mm disk
in 350mm diameter chamber
of height 150mm.
Pressure 10mtorr and V_P=+0.1V.
What is electrode DC voltage?

Grounded chamber area is
$A_1 = 2\text{x}\pi(17.5\text{cm})^2 + \pi \text{ x } 35\text{cm x } 15\text{cm}$
= 3572 sq cm

Electrode area is $A_2 = 2 \text{ x } \pi(10\text{cm})^2$ = 628 sq cm

So V2/V1 = (3572/628)4 = 1047

And $V_{electrode} = -1047.V_1 + V_P = -1047 \text{ x } 0.1 + 0.1 = -104.6\text{V}$

So wafers bombarded with ions from cathode sheath voltage 104.6V

High density plasmas

Increase ion bombardment by increasing ion density by increasing efficiency of electron impact ionization by increasing acceleration path of electrons

e.g. Magnetron sputter source: $F = q.\bar{v}\text{x}\bar{B}$ $\quad r = mv/qB$

Ions large mass, so B has little effect
Electrons: Helical paths increase path lengths, and hence increase ionization
Therefore increase free radicals

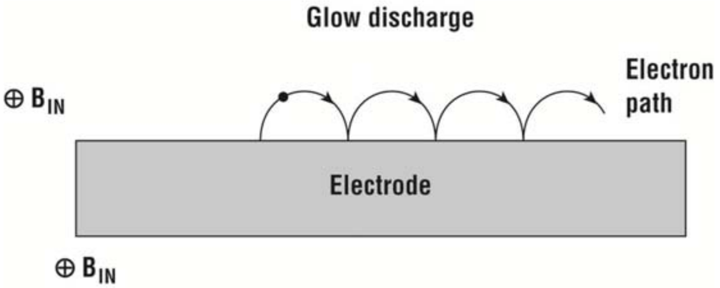
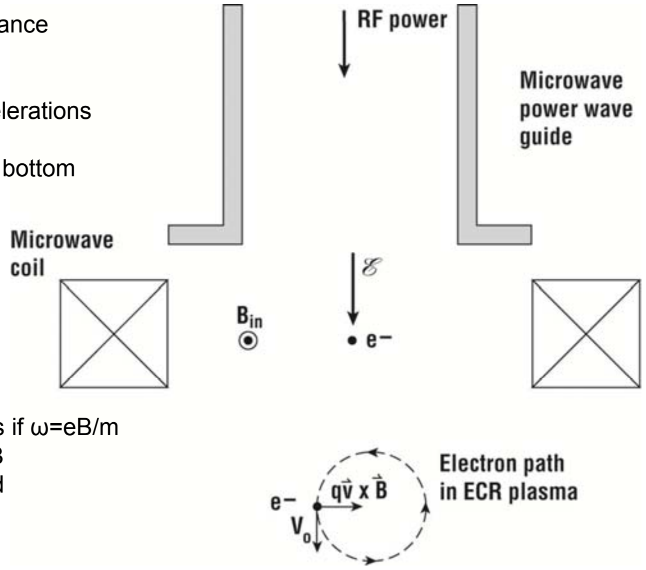


Figure 10.20 In a simple magnetically confined plasma, electrons ejected from the cathode are confined by the Lorentz force to stay in the cathode dark space.

Electron cyclotron resonance

$E=E_0\cos\omega t$ L ↔ R accelerations
B provides accelerations
top ↔ bottom



Electron travels in circles if $\omega = eB/m$
If mfp >> $2\pi r = 2\pi mv/qB$
then ionization increased

Figure 10.21 In an ECR plasma, an alternating field causes the electrons to move in circular orbits, dramatically increasing the ion density.

See p 279

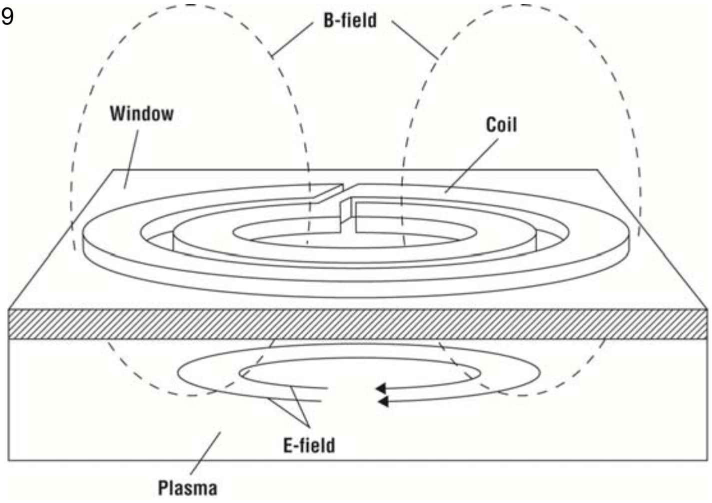


Figure 10.22 Schematic of ICP system showing the RF coil, the dielectric window, and the magnetic and electric fields *(From Hopwood [13], reprinted with permission from Plasma Sources Science and Technology. Copyright 1992, IOP Publishing).*

Summary

- Vacuum
  - Kinetic Theory --> vacuum, mfp, impingement
  - Gas Flow --> conductance, pump speeds
  - Vacuum Pumps and Gauges
- Plasmas
  - Glow discharge physics
  - Cathode sheath current
  - Plasma electron & ion energies
  - Plasma sheath & electrode potentials
  - Langmuir probe
  - RF self-bias & electrode potentials