Lecture 10

Vacuum Technology and Plasmas

Reading:

Chapter 10

Vacuum Science and Plasmas

In order to understand deposition techniques such as evaporation, sputtering, , plasma processing, chemical vapor deposition, molecular beam epitaxy, etc…, we must first have a grasp of the manner in which vacuum and gases flow. Thus, we will begin with a discussion of vacuum physics and vacuum techniques.

Definitions of Vacuum Regimes:

1.) Rough Vacuum: ~0.1-760 torr (atmospheric pressure is 760 torr)
2.) Medium Vacuum: ~ 0.1 to 10^{-4} torr
3.) High Vacuum: ~ 10^{-8} to 10^{-4} torr
4.) Ultrahigh Vacuum: < 10^{-8} torr

2 modes of gas flow:

1.) Viscous Flow regime: gas density (pressure) is high enough, many molecule-molecule collisions occur and dominate the flow process (one molecule "pushes" another). Collisions with walls play a secondary role in limiting the gas flow.
2.) Molecular flow regime: gas density (pressure) is very low, few molecule-molecule collisions occur and molecule-chamber wall collisions dominate the flow process (molecules are held back by walls)

The average distance between collisions (mean free path) is:

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n} = \frac{kT}{\sqrt{2}\pi d^2 P}$$

where d is the molecule diameter in meters, k=1.381e-23 J/K, and pressure, P, is in pascal (d~ 3 Angstroms for diatomic molecules).

At room temperature, λ is 78 um for 1 torr (typical plasma process pressure) and 7.8e6 meters for 1e-11 torr (typical Molecular Beam Epitaxy systems).

Knudsen Numbers and Pumping Technology

The Knudsen number (K_n) is used to distinguish between regimes. K_n (dimensionless number) is ratio of the mean free path to the characteristic dimension of the chamber (can be diameter of a pipe, or vacuum chamber). When $K_n>1$ then you are in the molecular flow regime. When $K_n<0.01$ you are in the viscous flow regime. In between, the flow characteristics are indeterminate.

Vacuum pump systems are characterized by throughput, Q, which is a measure of the mass flow through a system and pumping speed. Units are pressure-volume/time such as:

torr-liters/second
sccm=standard cubic centimeters per minute (or cubic centimeters @ 1 atmosphere (760 torr)/minute)
slm=standard liters per minute (or liters @ 1 atmosphere (760 torr)/minute)
Note: 1 standard liter is 1/22.4 moles of gas.

Conductance and Pumping Speed

Throughput, $Q=C(P_{upstream} - P_{downstream})$ where C is the conductance (we will use Liters/Sec unit) and…

For Molecular flow:

For a tube $C=11.6(D^3/L)$ where D is the tube diameter in cm, L is the tube length in cm and P is pressure in torr. Note for this case, C is independent of pressure. For an orifice (small hole with negligible length), $C=11.6\,\pi D^2/4$.

For Viscous Flow:

For a tube, $C=180(D^4/L)P_{average}$

A more accurate means of characterizing gas flow in this regime is $Q=K(P^2_{upstream} - P^2_{downstream})$ where K is a constant related to conductance, C by the relationship $K=C/(2 \text{ x } P_{average})$ where $P_{average}=(P_{upstream}-P_{downstream})$.

Proof:

$$Q = C\left(P_{upstream} - P_{downstream}\right)$$

$$P_{average}Q = C\left(P_{upstream} - P_{downstream}\right)P_{average}$$

$$P_{average}Q = C\left(P_{upstream} - P_{downstream}\right)\frac{\left(P_{upstream} + P_{downstream}\right)}{2}$$

$$P_{average}Q = C\left(P^2_{upstream} - P_{upstream}P_{downstream} + P_{upstream}P_{downstream} - P^2_{downstream}\right)\frac{1}{2}$$

$$Q = \left(\frac{C}{2P_{average}}\right)\left(P^2_{upstream} - P^2_{downstream}\right)$$

$$Q = K\left(P^2_{upstream} - P^2_{downstream}\right)$$

$$\therefore \qquad K = \left(\frac{C}{2P_{average}}\right)$$

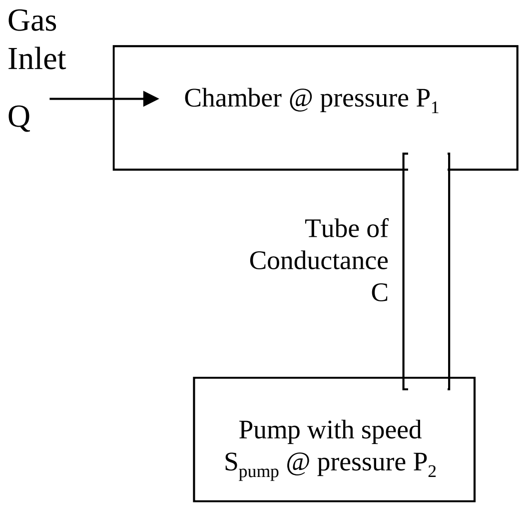
Conductance and Pumping Speed

Like electrical conductance, parallel conductance add while series conductance add in reciprocal form $1/C_t=1/C1 + 1/C2 + ...$ Pumps are specified in terms of pumping speed, S, (units volume/time) which is related to throughput as,

$S=Q/P_{\text{at the pump inlet}}$. (Note: S is a function of P)

A pump can be used with a tube to calculate the effective pumping speed at the end of the tube:

$$1/S_{eff} = 1/C + 1/S_{pump}$$



Gas Inlet

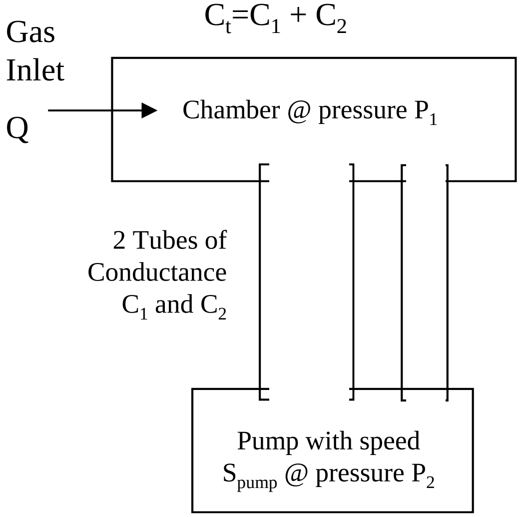
Q

Chamber @ pressure P_1

Tube of Conductance C

Pump with speed S_{pump} @ pressure P_2

$C_t=C_1 + C_2$



Gas Inlet

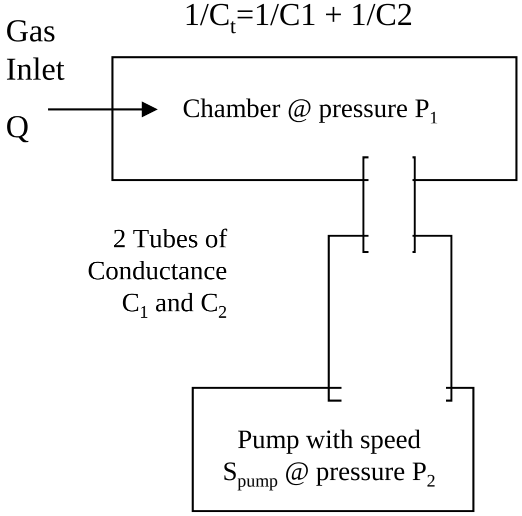
Q

Chamber @ pressure P_1

2 Tubes of Conductance C_1 and C_2

Pump with speed S_{pump} @ pressure P_2

$1/C_t=1/C1 + 1/C2$



Gas Inlet

Q

Chamber @ pressure P_1

2 Tubes of Conductance C_1 and C_2

Pump with speed S_{pump} @ pressure P_2

Conductance and Pumping Speed

Pump down time: (For Viscous Flow)
The pressure after a pump is turned on is:

$$P = P_o e^{-St/V}$$

Where P is pressure, Po is original pressure (for example 760 torr for atmospheric pressure), S is the pumping speed, V is the volume of the chamber and t is time.

Thus, the time to reach a particular vacuum is:

$$t = \frac{V}{S}\ln\left(\frac{P_o}{P}\right)$$

Example: How long does it take to pump down a 50 liter chamber from atmosphere (760 torr) to 60 mtorr directly using a mechanical pump with a speed of 9 L/sec verses through a 0.5” diameter, 8 foot long tube using a pump.
Directly:

$$\mathrm{t} = \frac{\mathrm{50L}}{\mathrm{9L/sec}}\ln\left(\frac{\mathrm{760\ torr}}{\mathrm{0.06\ torr}}\right) = 52\ \mathrm{seconds}$$

Through Tube:

$$\mathrm{S_{eff}} = \frac{1}{\frac{1}{\mathrm{C_{tubing}}}+\frac{1}{S}} = \frac{1}{\frac{1}{180\left(\frac{(0.5\mathrm{x}2.54)^4}{8x12*2.54}\right)x0.5(760+0.06)}+\frac{1}{9L/\sec}} \approx 9L/\sec \quad \Rightarrow \quad \mathrm{t} = \frac{\mathrm{50L}}{\mathrm{9L/sec}}\ln\left(\frac{\mathrm{760\ torr}}{\mathrm{0.06\ torr}}\right) = 52\ \mathrm{seconds}$$

In reality, the pumping speed of a pump and the conductance of the tube normally is not constant with pressure, resulting in a significant increase in the pump down time. You can see this by noticing the Conductance at 60 mTorr is 0.05 L/S While at 760 torr it is ~729 L/S. We can integrate or to simply get an estimate of the actual pump down time by breaking the calculation up into smaller pressure steps:

P_{top}	P_{bot}	C_{tubing}	S_{eff}	Pump down Time in step			
760	76	802.7101	8.900211	12.93557			
76	7.6	80.27101	8.092651	14.2264			
7.6	0.76	8.027101	4.242878	27.13471			
0.76	0.076	0.80271	0.736979	156.2178			
0.076	0.06	0.130584	0.128717	91.82513			
			Total:	302.3396	sec or	5.038994	minutes

Types of Pumps

1.) Rough/medium vacuum

a.) Piston pumps (not used much due to particle problems)

b.) Rotary vane pumps (majority of cheap applications)

c.) Dry pumps (no oil back streaming)

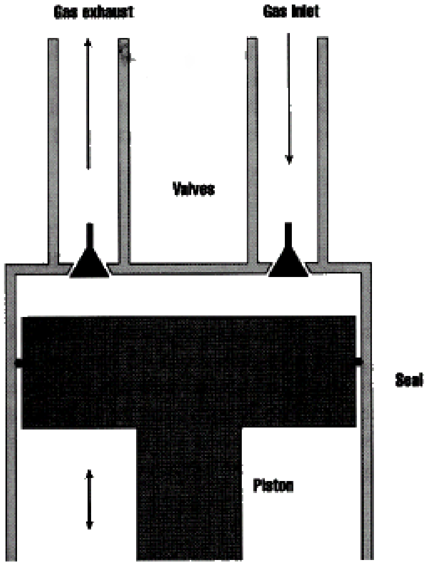
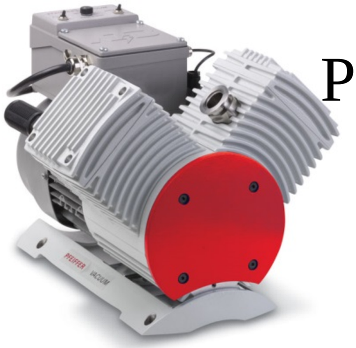


Figure 10-4 A schematic of a single stage two valve piston pump.



Pfeiffer Piston Pump

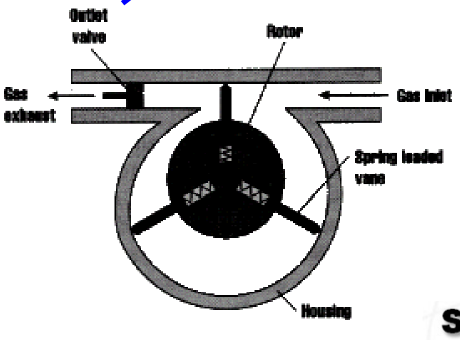
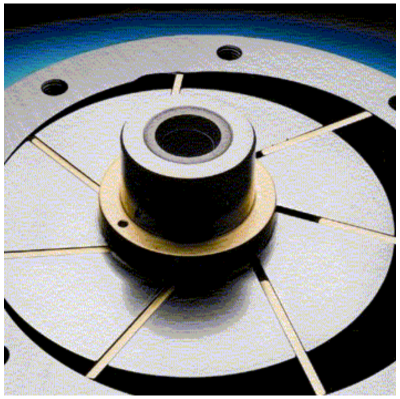
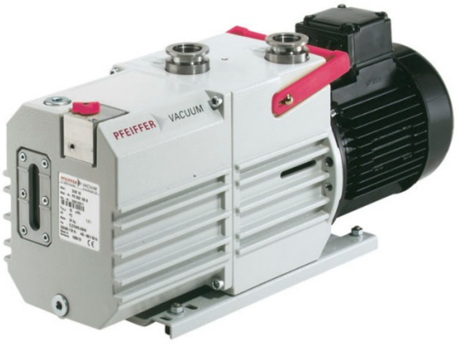


Figure 10-5 One of the most common types of pumps for microelectronic processing is the rotary vane vacuum pump.

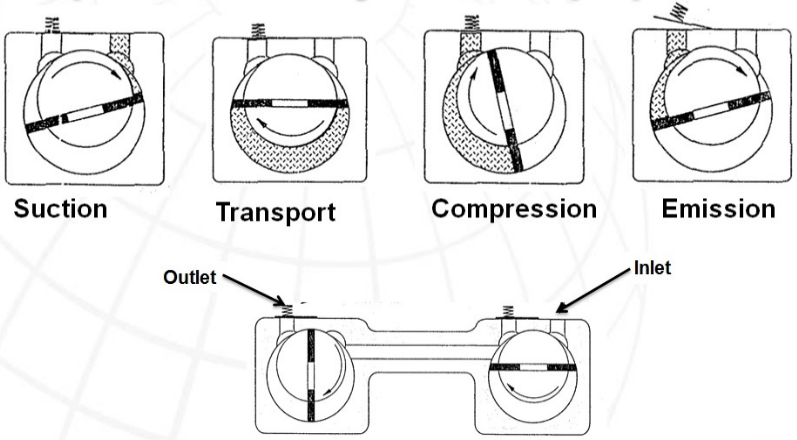




Pfeiffer Piston Pump

Sometimes an extra, added gas is inserted directly at the pump to prevent corrosion of the pump parts by dilution. This is called a ballast Gas or Purge Gas

Sequence of Rotary Vane Pump Operation



Types of Pumps

1.) Rough/medium vacuum

d.) Add a Roots blower (similar to a supercharger on a drag racer) Increases the pressure on the primary pumps inlet by "pre-compressing" the gases. If k_o is the compression ratio of the roots blower, S_{rb} is the pumping pumping speed of the RB, and S_p is the pumping speed of the pump, then the effective pumping speed of the combo is,

$$S_{eff} = \frac{S_{rb} S_p k_o}{S_{rb} + k_o S_p}$$

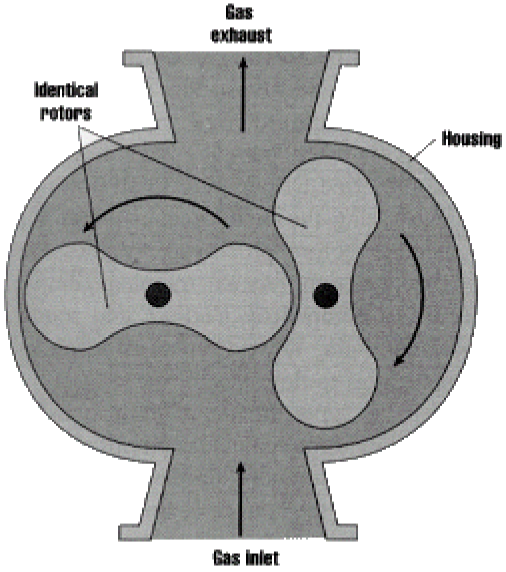
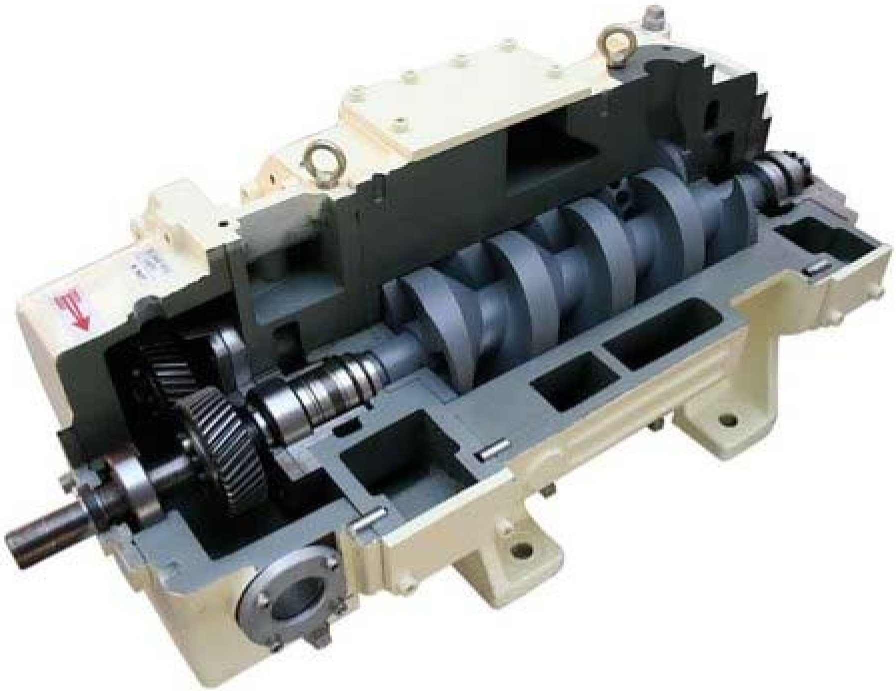
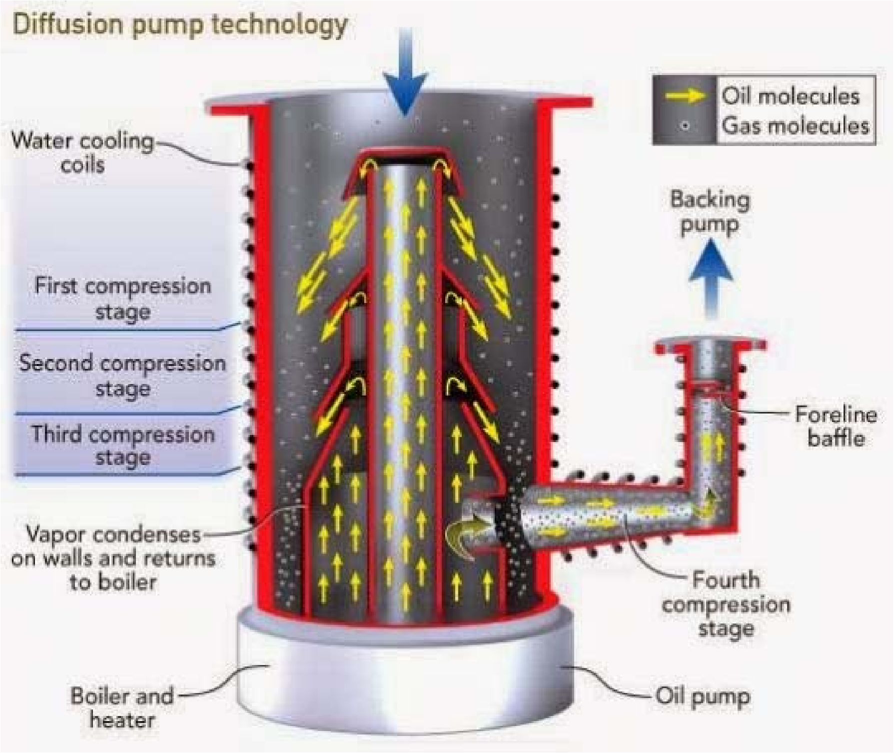


Figure 10-7 Schematic diagram of a Roots blower.



Types of Pumps

2.) High and Ultrahigh Vacuum
    a.) Diffusion pump (not used much due to oil contamination)
    b.) *Turbopump (oil, grease, ceramic, ceramic oil free bearings and magnetic levitation)
        Turbo and Turbomolecular Drag Variants



Turbo pumps can spin at 5,000 to 120,000 rpm

Bearings used are critical and avoiding mechanical shock (gas bursts, or vibration) are important

http://supervacindustries.blogspot.com/2013/12/q.html

Types of Pumps

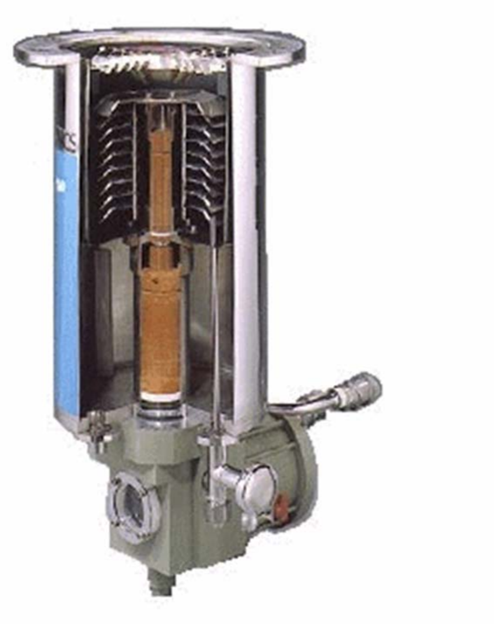
2.) High and Ultrahigh Vacuum

c.) *Cryopump (can be dangerous in certain processes)

Freezes gas molecules on fins cooled by a refrigeration cycle that typically uses He instead of Freon to reach inner array temperatures of ~10K.

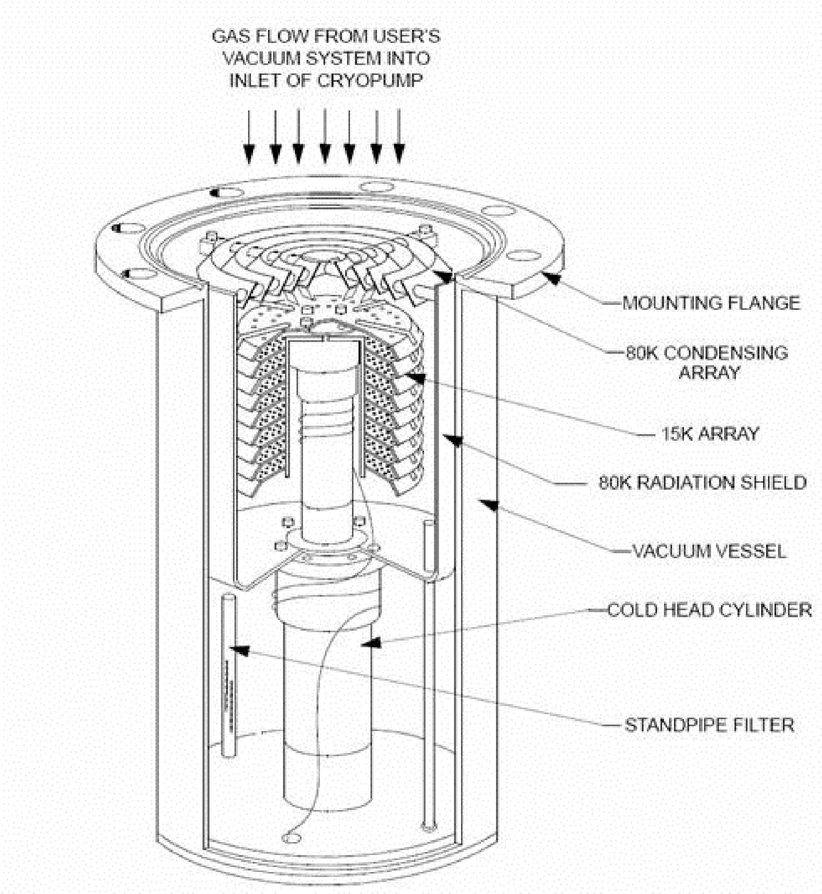
Uses an outer warmer array at ~65-77K.

CTI/Brooks
Automation
Cryopump Pump



Compressor Unit

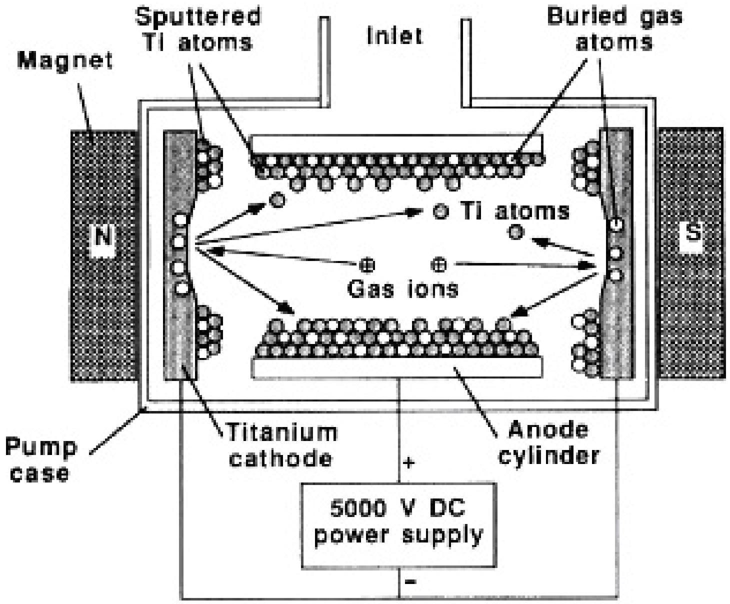
Refrigerator Unit



Types of Pumps

2.) High and Ultrahigh Vacuum
  d.) Ion pump (very clean but low pumping speed and capacity)
  Only good for ~<1e-6 Torr
  Overheats at higher pressures

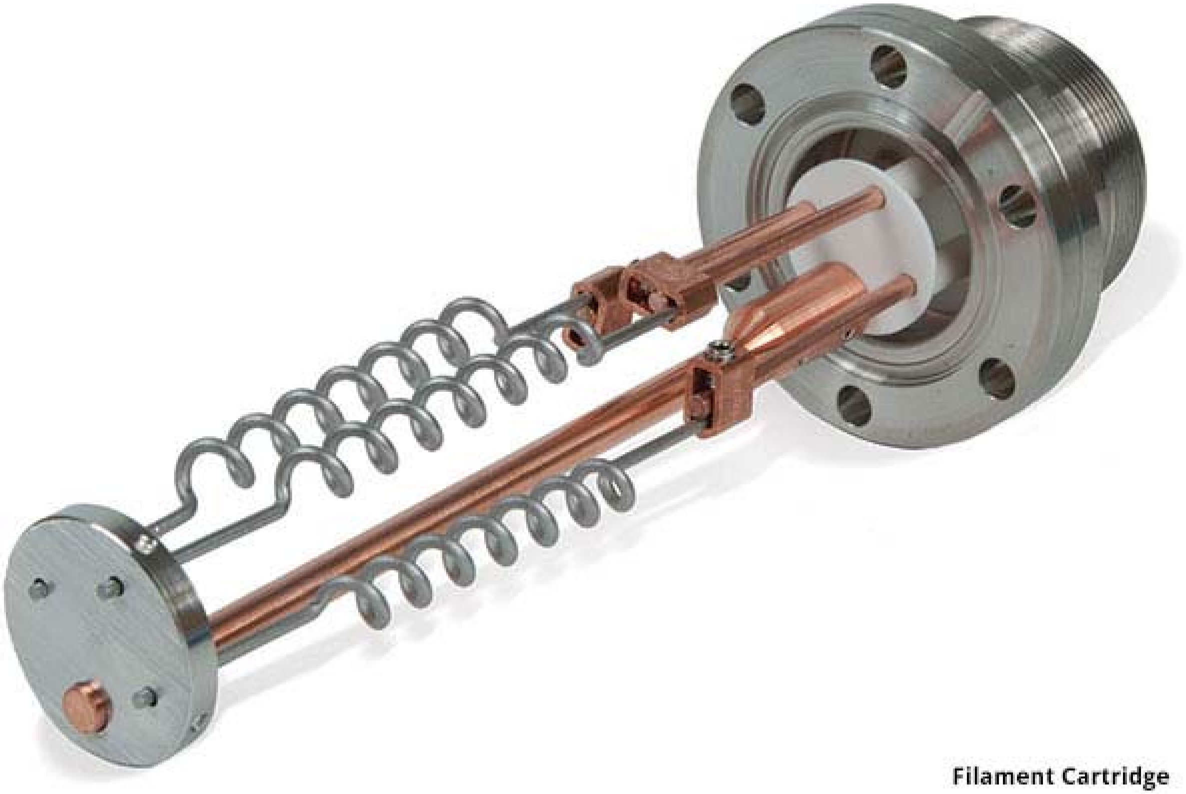
Agilent Ion Pump



http://blog.precisionplus.com/commercial-vacuum-pumps-a-summary-of-styles-applications/

Types of Pumps

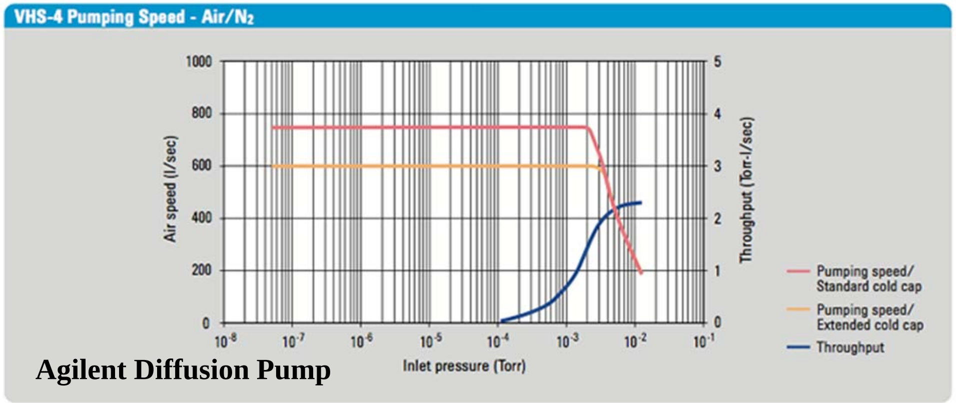
2.) High and Ultrahigh Vacuum
    e.) Titanium Sublimation Pump (evaporate Titanium to aid in pumping)
    Part of a family of “getter pumps” that use reactive chemistry to trap certain gases (and sometimes bury them)
    Has to be in a location where titanium will not contaminate the process
    Only good for ~<1e-8 Torr



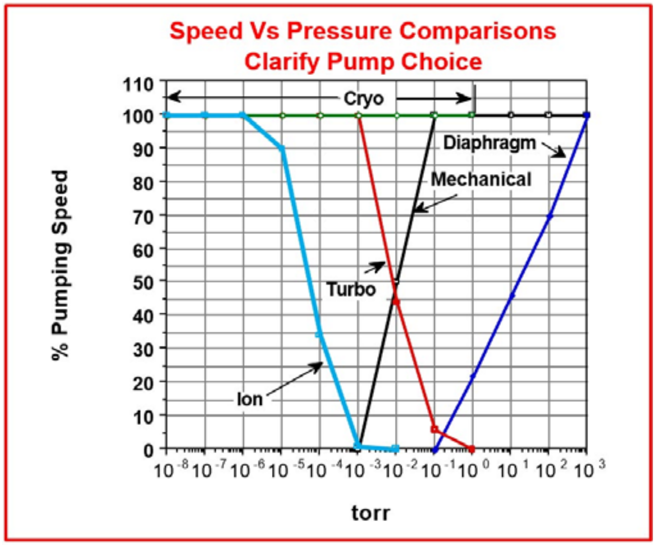
Kurt Leskar TSP Pump

Conductance and Pumping Speed

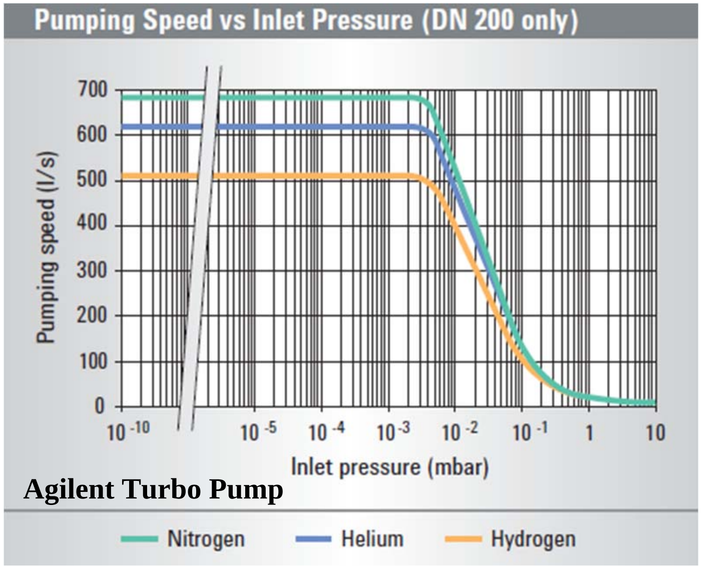
Pumping Speed is strongly dependent on pump style, pressure and gas species.



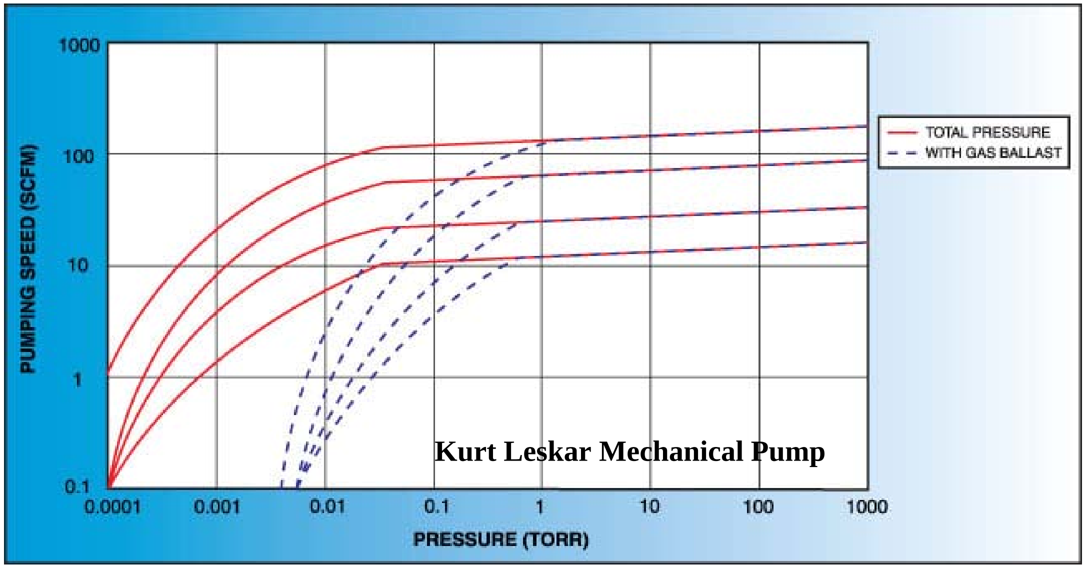
Agilent Diffusion Pump



The increase or decrease of pumping speed at various pressures can have important effects on your process. Roughing pumps tend to lose speed as the pressure drops and high-vacuum pumps tend to have an increase.



Agilent Turbo Pump



Kurt Leskar Mechanical Pump

Plasmas

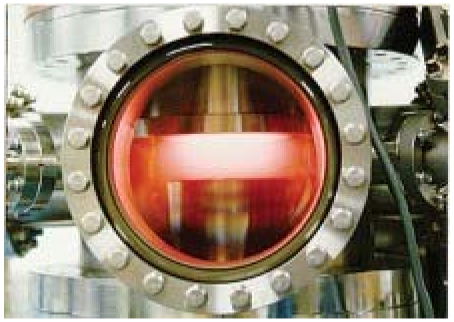
Consider the thermal energy required to break apart the nitrogen molecule. The bond energy is 9.7 eV =3kT/2 ==> T~75,000 degrees C! This is not possible by thermal means, but is possible by hyper thermal processes like plasmas. A plasma is a gaseous collection of ions, electrons, energetically excited molecules, and neutral gas species, normally created by the application of electromagnetic fields.

Plasmas can be used to drive reactions that would otherwise be thermally prohibited.
Plasmas can be used to deposit, chemically etch or sputter materials

Many reactions can occur in a plasma. If e* is an excited electron in a plasma:
Dissociation: $e^* + AB \leftrightarrow A + B + e$
Atomic Ionization: $e^* + A \leftrightarrow A^+ + 2e$
Molecular Ionization: $e^* + AB \leftrightarrow AB^+ + 2e$
Atomic Excitation: $e^* + A \leftrightarrow A^* + e$
Molecular Excitation: $e^* + AB \leftrightarrow AB^* + e$

Most modern plasmas are generated by either a DC current flowing through the gas or a radio frequency (RF) field exposed to the gas(RF plasmas do not require DC current flow, and thus, can be used to process insulating and conducting materials)

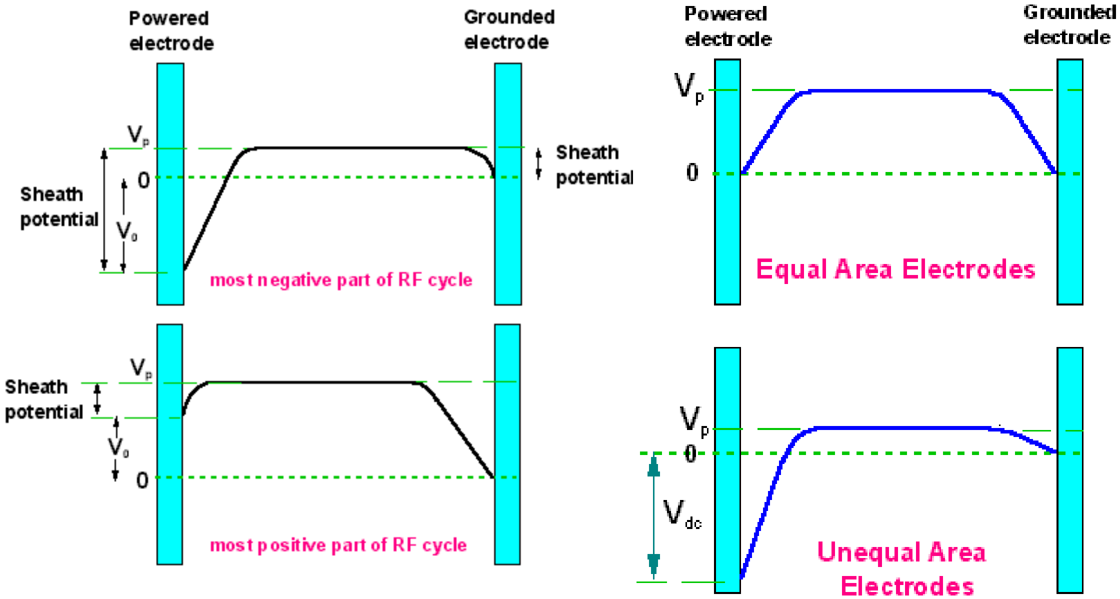
Types of Plasma Systems



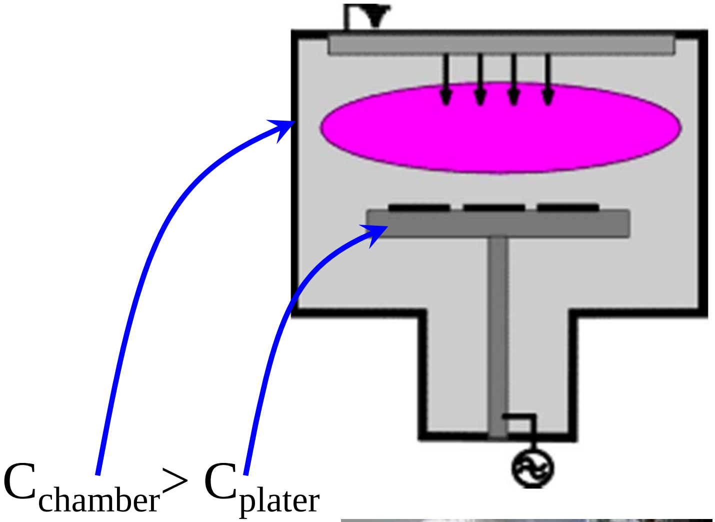
Parallel Plate Systems

Advantages: Cheaper

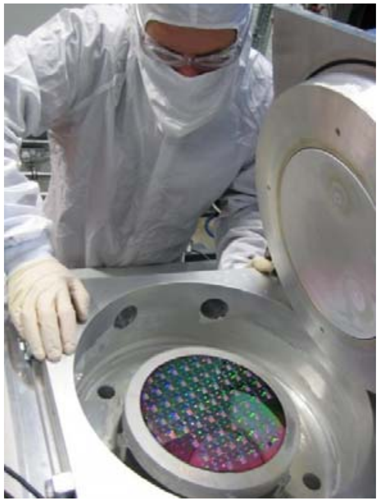
Disadvantages: Lower plasma density, difficult to keep clean in production due to particulates flaking off the upper plate.



Time averaged values for the potentials in different RF reactors



$C_{chamber} > C_{plater}$



Every half cycle, the electric field accelerates electrons into the plates causing them to become negatively charged. The atoms/molecules can not respond fast enough to the E-field to gain a net momentum. However, the induced negative charge on the plates causes an electric field to be created that drifts ions out of the “glow discharge region” toward the plates. By having plates with different capacitances (area changes or external capacitors) the voltage on the top plate can be made to be different from the bottom plate resulting in a net movement of ions. Note all uncharged species simply diffuse away from the glow discharge region where they are created.

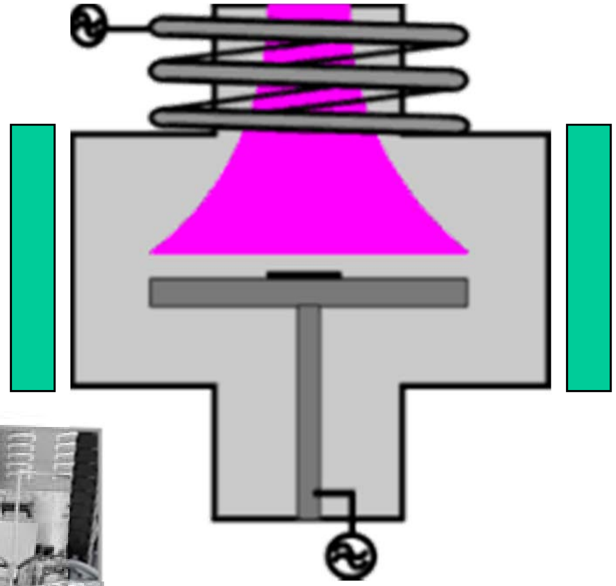
http://www.chm.bris.ac.uk/~paulmay/misc/msc/msc4.htm

Types of Plasma Systems

Inductively Coupled Systems

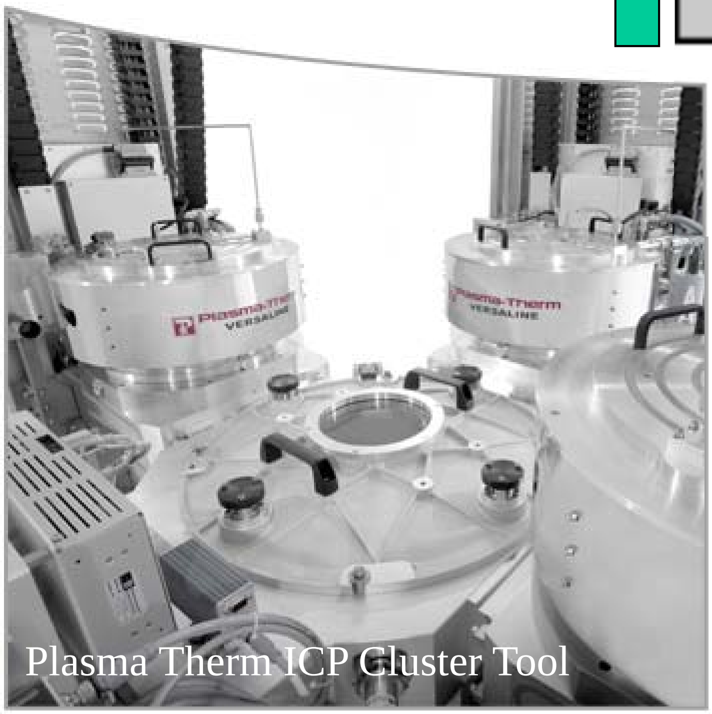
Advantages: Higher plasma density (~10-50 x), easier to clean (low particulate), better uniformity over large areas.

Disadvantages: Nearly 3 times the cost of a comparable parallel plate system.

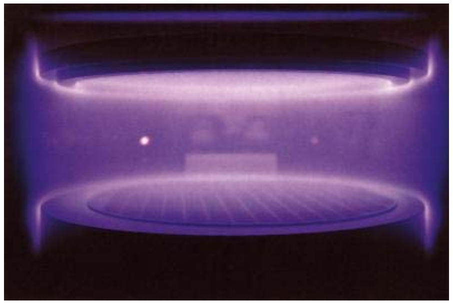


Optional Magnets

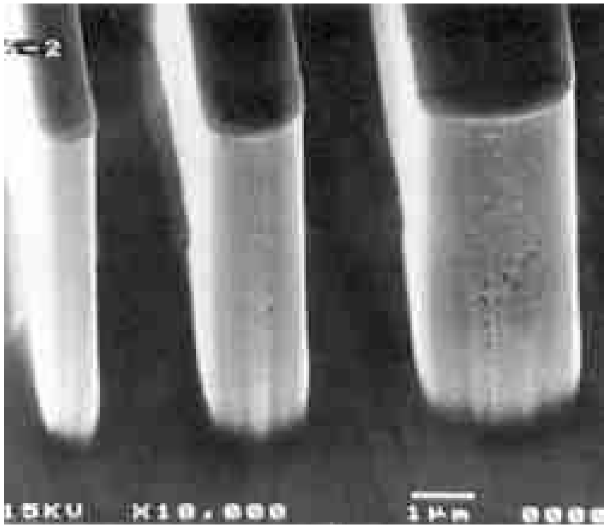
Electromagnetic fields are induced into the gas by one or more coils located on the periphery of the vacuum chamber. Magnets may be used to enhance confinement of the plasma and control recombination (ions and electrons annihilating each other) at the chamber walls.

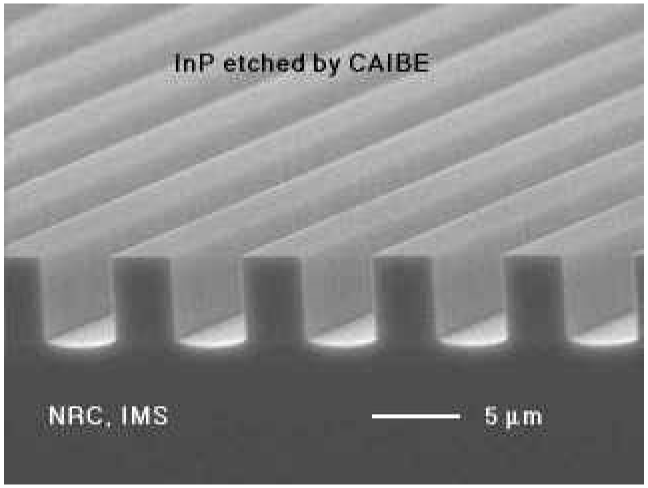


Plasma Therm ICP Cluster Tool



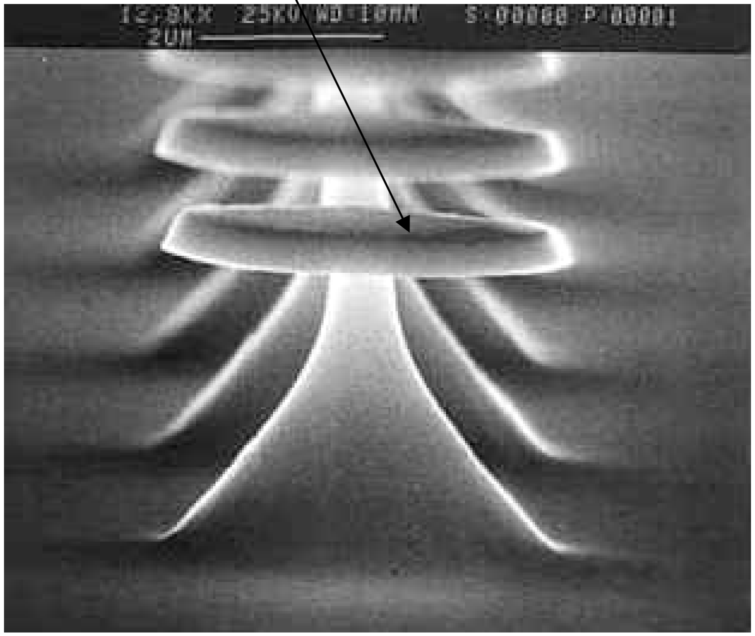
Examples of using Electric Fields for Enhanced Sidewall Abruptness (Anisotropy) in a Plasma Etch System





High Electric Field, low pressure

Mask Material



Low Electric Field, High Pressure (or liquid etch)

Other Details of Plasma Systems

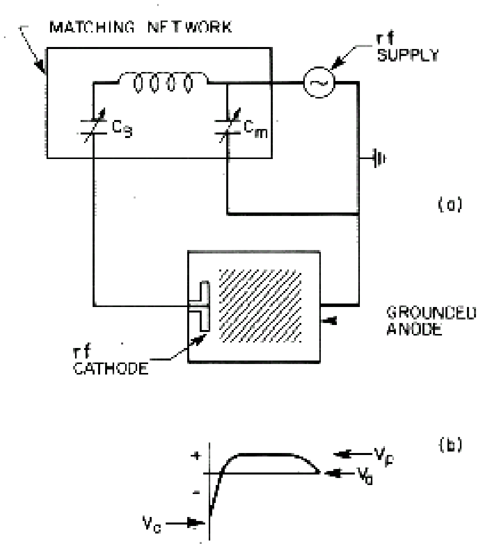


FIGURE 2
(a) A schematic representation of an rf plasma discharge where the power is supplied to the rf cathode through a matching network. (b) A plot of the average potential between the anode (V_a), the cathode (V_c), and the plasma (V_p). The horizontal position axis is meant to coincide with (a).

- The glow region contains many electrons, and thus is highly conducting.==> Resistor Model element
- The Sheaths have had their electrons stripped via the induced electric field. Thus, only limited ionic conduction occurs, along with a “depletion region capacitance” (this region is depleted of electrons).
- The above lumped model results.
- Note the frequency dependence of the plasma impedance.

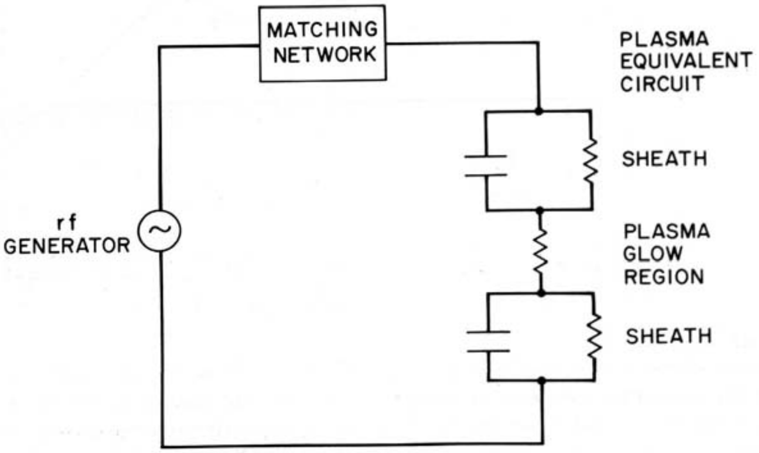


FIGURE 3
An equivalent circuit for an rf plasma discharge.

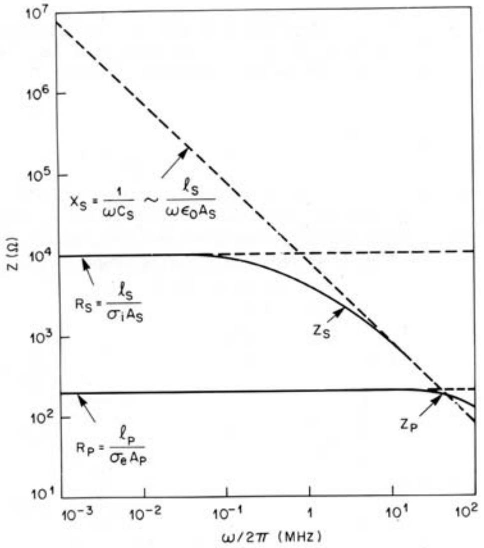


FIGURE 4
Calculated sheath and plasma impedances which show how the sheath impedance changes from resistive to capacitive with increasing frequency. The plasma remains resistive over the frequency range of interest. R and X are the resistive and reactive components respectively of the total impedance, Z. The subscripts s and p denote the sheath and plasma respectively. (*After Dautremont-Smith, Gottscho, and Schutz, Ref. 6.*)

Other Details of Plasma Systems

Note also that at low frequencies, the ions are accelerated to higher energies (longer times) before the field reverses, resulting in higher energy ions bombarding the surface.

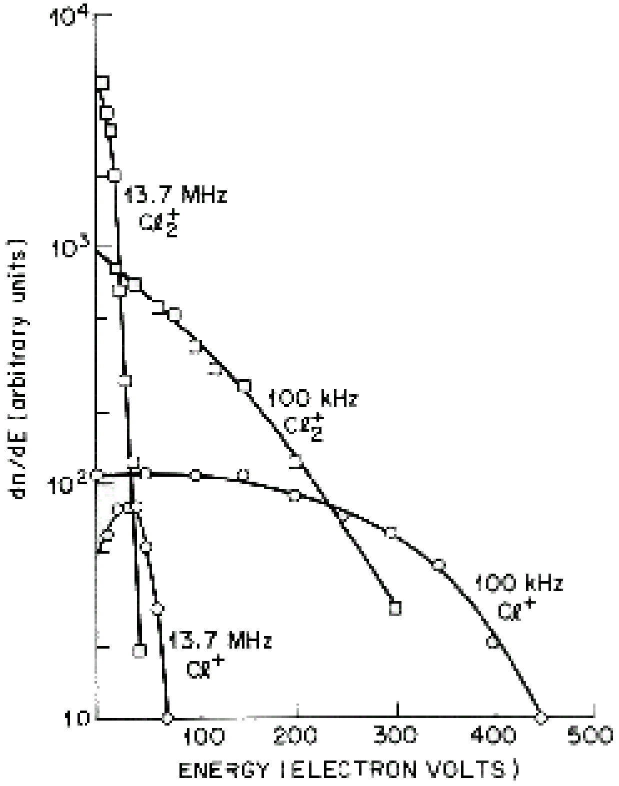
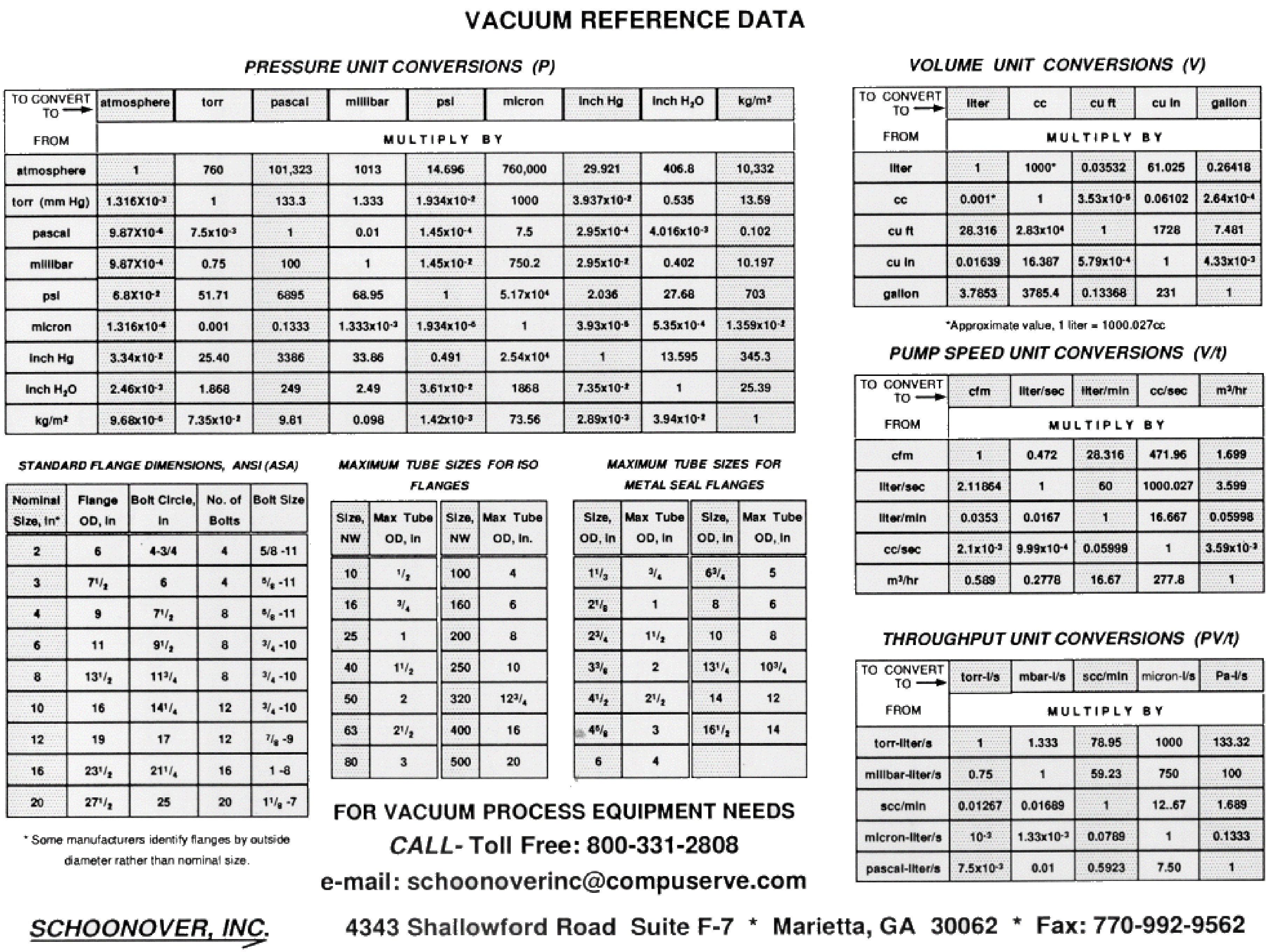


FIGURE 5

Ion bombardment energy distribution in a 40 Pa Cl_2 plasma with 0.6 W/cm^2 and a 1.0 cm electrode spacing. (*After Bruce, Ref. 8.*)



VACUUM REFERENCE DATA

PRESSURE UNIT CONVERSIONS (P)

TO CONVERT TO → FROM	atmosphere	torr	pascal	millibar	psi	micron	inch Hg	inch H_2O	kg/m²
	MULTIPLY BY								
atmosphere	1	760	101,323	1013	14.696	760,000	29.921	406.8	10,332
torr (mm Hg)	$1.316X10^{-3}$	1	133.3	1.333	$1.934x10^{-2}$	1000	$3.937x10^{-2}$	0.535	13.59
pascal	$9.87X10^{-6}$	$7.5x10^{-3}$	1	0.01	$1.45x10^{-4}$	7.5	$2.95x10^{-4}$	$4.016x10^{-3}$	0.102
millibar	$9.87X10^{-4}$	0.75	100	1	$1.45x10^{-2}$	750.2	$2.95x10^{-2}$	0.402	10.197
psi	$6.8X10^{-2}$	51.71	6895	68.95	1	$5.17x10^{4}$	2.036	27.68	703
micron	$1.316x10^{-6}$	0.001	0.1333	$1.333x10^{-3}$	$1.934x10^{-5}$	1	$3.93x10^{-5}$	$5.35x10^{-4}$	$1.359x10^{-2}$
inch Hg	$3.34x10^{-2}$	25.40	3386	33.86	0.491	$2.54x10^{4}$	1	13.595	345.3
inch H_2O	$2.46x10^{-3}$	1.868	249	2.49	$3.61x10^{-2}$	1868	$7.35x10^{-2}$	1	25.39
kg/m²	$9.68x10^{-5}$	$7.35x10^{-2}$	9.81	0.098	$1.42x10^{-3}$	73.56	$2.89x10^{-3}$	$3.94x10^{-2}$	1

VOLUME UNIT CONVERSIONS (V)

TO CONVERT TO → FROM	liter	cc	cu ft	cu in	gallon
	MULTIPLY BY				
liter	1	1000*	0.03532	61.025	0.26418
cc	0.001*	1	$3.53x10^{-5}$	0.06102	$2.64x10^{-4}$
cu ft	28.316	$2.83x10^{4}$	1	1728	7.481
cu in	0.01639	16.387	$5.79x10^{-4}$	1	$4.33x10^{-3}$
gallon	3.7853	3785.4	0.13368	231	1

*Approximate value, 1 liter = 1000.027cc

PUMP SPEED UNIT CONVERSIONS (V/t)

TO CONVERT TO → FROM	cfm	liter/sec	liter/min	cc/sec	m³/hr
	MULTIPLY BY				
cfm	1	0.472	28.316	471.96	1.699
liter/sec	2.11864	1	60	1000.027	3.599
liter/min	0.0353	0.0167	1	16.667	0.05998
cc/sec	$2.1x10^{-3}$	$9.99x10^{-4}$	0.05999	1	$3.59x10^{-3}$
m³/hr	0.589	0.2778	16.67	277.8	1

STANDARD FLANGE DIMENSIONS, ANSI (ASA)

Nominal Size, in*	Flange OD, in	Bolt Circle, in	No. of Bolts	Bolt Size
2	6	4-3/4	4	5/8 -11
3	$7^1/_2$	6	4	$^5/_8$ -11
4	9	$7^1/_2$	8	$^5/_8$ -11
6	11	$9^1/_2$	8	$^3/_4$ -10
8	$13^1/_2$	$11^3/_4$	8	$^3/_4$ -10
10	16	$14^1/_4$	12	$^3/_4$ -10
12	19	17	12	$^7/_8$ -9
16	$23^1/_2$	$21^1/_4$	16	1 -8
20	$27^1/_2$	25	20	$1^1/_8$ -7

* Some manufacturers identify flanges by outside diameter rather than nominal size.

MAXIMUM TUBE SIZES FOR ISO FLANGES

Size, NW	Max Tube OD, in	Size, NW	Max Tube OD, in.
10	$^1/_2$	100	4
16	$^3/_4$	160	6
25	1	200	8
40	$1^1/_2$	250	10
50	2	320	$12^3/_4$
63	$2^1/_2$	400	16
80	3	500	20

MAXIMUM TUBE SIZES FOR METAL SEAL FLANGES

Size, OD, in	Max Tube OD, in	Size, OD, in	Max Tube OD, in
$1^1/_3$	$^3/_4$	$6^3/_4$	5
$2^1/_8$	1	8	6
$2^3/_4$	$1^1/_2$	10	8
$3^3/_8$	2	$13^1/_4$	$10^3/_4$
$4^1/_2$	$2^1/_2$	14	12
$4^5/_8$	3	$16^1/_2$	14
6	4		

THROUGHPUT UNIT CONVERSIONS (PV/t)

TO CONVERT TO → FROM	torr-l/s	mbar-l/s	scc/min	micron-l/s	Pa-l/s
	MULTIPLY BY				
torr-liter/s	1	1.333	78.95	1000	133.32
millibar-liter/s	0.75	1	59.23	750	100
scc/min	0.01267	0.01689	1	12..67	1.689
micron-liter/s	10^{-3}	$1.33x10^{-3}$	0.0789	1	0.1333
pascal-liter/s	$7.5x10^{-3}$	0.01	0.5923	7.50	1

FOR VACUUM PROCESS EQUIPMENT NEEDS

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