FYS4310

Cultural enlightenment on vacuum

and
Plasma

FYS4310

Program -

Why and for whom
Where in semiconductor processing and analysis is vacuum required,
Various vacuum kinds , ranges, ideal gas,
Conductance, Pumping speed
Adsorption, Desorption, surfaces, cleanliness
Pumps; Rotation, Roots, Sorption, Diffusion, Turbo, Ion, Subl.Cryo
Vacuum gages; Thermo-couple, Pirani, Membrane, Penning, Ionization gage

Plasma
What is it
Characteristics
DC
AC
RIE systems

FYS4310 Vakuum

Why and for ALL

Many here are experimentalists
Will be exposed to vacuum

The best insurance against damage is
understanding of what we're doing (postulate)

Vacuum used in many contexts
for processing and characterization of 1/2-cond

Needs to know about vacuum to understand the process

FYS4310 Vakuum

Where, vacuum in 1/2 process ?

almost everywhere

Vacuum chuck

LP CVD

Metal deposition, evaporation

RIE, sputtering etching

Ion implantation

MBE,(CBMBE, MOCVD, ALE)

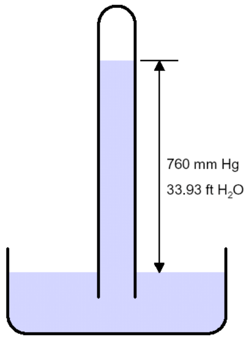
Electron beam lithography

Diagnostics - SIMS, AES, SEM, TEM, RBS

Units of Pressure Measurement

- 1 atmosphere =
  - 760 mm Hg = 760 torr
  - 760,000 millitorr or microns
  - 29.9213 in. Hg
  - 14.6959 psi
  - 1.01325 bar
  - 1013.25 millibar
  - 101,325 pascals (Pa)
  - 407.189 in. H_2O
  - 33.9324 ft. H_2O

1 Pascal = 1 N/m^2
1 Torr = 1 mm Hg
1 micron = 1 μm Hg



R. B. Darling / EE-527

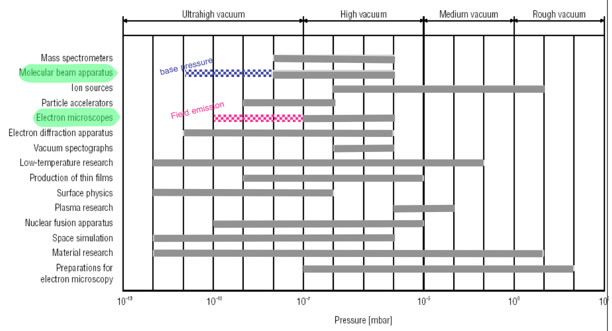
Vacuum ranges -coarse classification

Low vacuum (LV), Rough(ing) vacuum
760 Torr to 10^{-3} Torr

High vacuum (HV)
10^{-3} Torr to 10^{-8} Torr

Ultra high vacuum (UHV)
10^{-8} Torr to 10^{-12} Torr

Vacuum ranges -analysis



Pressure ranges (p < 1000 mbar) of physical and chemical analytical methods

Partial pressure i air

Atmosphere

Gas	Symbol	Volume Percent	Partial Pressure, Torr
Nitrogen	N_2	78	593
Oxygen	O_2	21	159
Argon	Ar	0.93	7.1
Carbon Dioxide	CO_2	0.03	0.25
Neon	Ne	0.0018	1.4 x 10^{-2}
Helium	He	0.0005	4.0 x 10^{-3}
Krypton	Kr	0.0001	8.7 x 10^{-4}
Hydrogen	H_2	0.00005	4.0 x 10^{-4}
Xenon	Xe	0.0000087	6.6 x 10^{-5}
Water	H_2O	Variable	5 to 50, typ.

FYS4310 Ideal gas -repetition

- V = volume of enclosure
- N = number of molecules
- N_m = number of moles = N/N_A
- n = particle density = N/V
- P = pressure
- T = absolute temperature
- k_B = Boltzmann's constant = 1.381×10^{-23} J/K
- N_A = Avogadro's number = 6.022×10^{23} particles/mole
- R = Gas constant = $N_A k_B$ = 8.315 J/mole-K

$$PV = N_m RT$$
$$PV = Nk_B T$$
$$P = nk_B T$$

FYS4310 Ideal gas -Maxwell v distribution

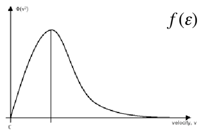
Equation of state

$$pV = N\,\mathrm{k}T$$

Energy (id. gas temperature)

$$E_{kin} = N(\tfrac{1}{2}m\overline{v_x^2} + \tfrac{1}{2}m\overline{v_y^2} + \tfrac{1}{2}m\overline{v_z^2}) = \tfrac{3}{2}NkT$$

Maxwell velocity distribution, random velocity direction



$$f(\varepsilon)\frac{1}{\exp\left(\frac{\varepsilon-\mu}{\mathrm{k}T}\right)\pm 1} \approx \lambda\exp(-\varepsilon/\mathrm{k}T)$$

$$\varepsilon_n = \frac{\hbar^2}{2m}\left(\frac{\pi n}{L}\right)^2 = \tfrac{1}{2}mv^2$$

$$\Phi(v^2) = 4\pi\left(\frac{m}{2\pi k_B T}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

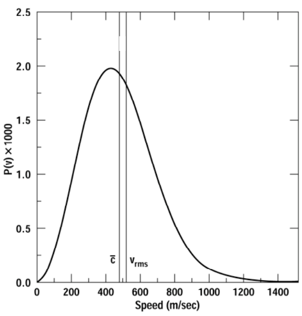


Figure 10.1 A Maxwellian speed distribution of particles. $P(v)$ is the probability that a particular particle will have the magnitude of velocity.

FYS4310 Impingement Rates

- The number of molecules with a velocity from v_x to $v_x + dv_x$ is $dN_{vx} = N\phi(v_x^2)\,dv_x$.
- A = area under consideration.
- Only those molecules within striking distance $v_x dt$ will hit the wall during dt seconds.
- The number of molecules with velocities from v_x to $v_x + dv_x$ impinging upon the wall during dt is

$$dNi = \frac{N}{V}Av_x\phi(v_x^2)dv_x dt \qquad \text{integrate:} \qquad \int_0^\infty v_x\,\phi(v_x^2)\,dv_x = \left(\frac{k_B T}{2\pi m}\right)^{1/2}$$

$$\frac{dN_i}{Adt} = \frac{N}{V}\left(\frac{k_B T}{2\pi m}\right)^{1/2} = (2\pi m k_B T)^{-1/2} P$$

Mean Free Path

- MFP is the average distance a gas molecule travels before colliding with another gas molecule or the container walls.
- σ is the diameter of the particles
- $\pi\sigma^2$ is the cross-sectional area for hard-sphere collisions

$$\text{MFP} = \frac{V}{N\pi\sigma^2\sqrt{2}} = \frac{k_B T}{P\pi\sigma^2\sqrt{2}}$$

For common gases, {H_2O, He, CO_2, CH_4, Ar, O_2, N_2, H_2}, at T = 300 K:

$$\text{Mean Free Path (cm)} = \frac{5 \times 10^{-3}\ \text{torr-cm}}{\text{Pressure (torr)}}$$

Gas Flow - 1

- Viscous Flow
  - occurs for pressures greater than 10^{-2} torr
  - gas molecules constantly collide with one another
  - collisions with each other are more frequent than wall collisions
  - gas behaves like a coherent, collective medium; it acts like a fluid
- Free Molecular Flow
  - occurs for pressures less than 10^{-2} torr
  - gas molecules travel for large distances between collisions
  - collisions with walls are more frequent than with each other
  - gas molecules fly independently of each other

FYS4310

Gas flow equations, pumping velocity

Through-put $Q = \frac{dG}{dt}\frac{P}{\rho_m}$ $\qquad \frac{dG}{dt} = \frac{d}{dt}(\rho_m V)$ Mass flow rate

ρ_m=mass density

Units t.ex Torr*liter/min for std volume 1 atm. 0°C

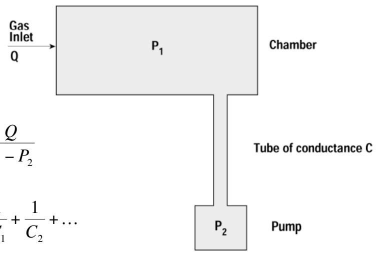
FYS4310

Gas flow equations, pumping speed

Gas Throughput

- Q = PS
- P = gas pressure in torr
- S = pumping or leaking speed in liters/second (L/s)
- Q = gas throughput in torr-liters/second (torr-L/s)
  - This is the quantity of gas moving through an orifice per unit time.
- Q is directly related to the power needed to move the gas:
  - 1 Watt = 7.50 torr-L/sec = 1000 Pa-L/sec
- C = gas conductance in liters/second (L/s)
- Q = C(P_2 - P_1)

Pumps conductance



$$C = \frac{Q}{P_1 - P_2}$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots$$

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

Butterfly valve, vacuum control

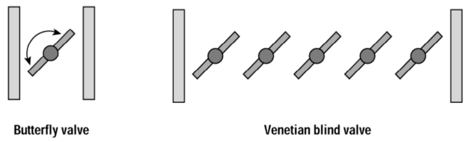


Figure 10.3 Variable conductance valves used in small- and large-diameter vaccum lines.

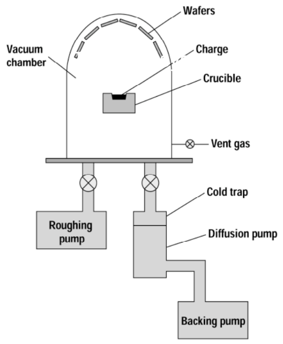
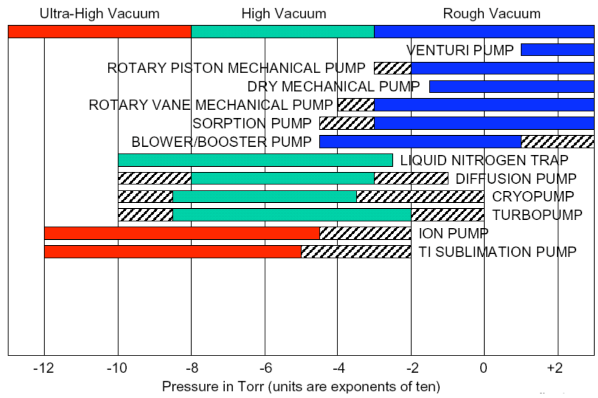


Figure 12.1 A simple diffusion-pumped evaporator showing vacuum plumbing and the location of the charge-containing crucible and the wafers.

Vacuum Pump Pressure Ranges



Rotary vane pump

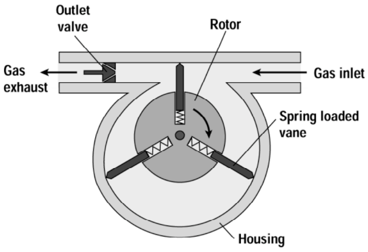
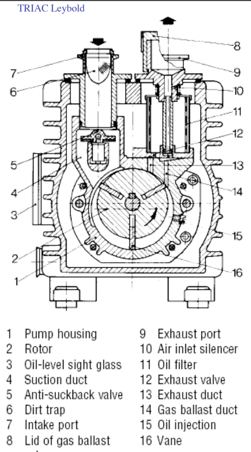


Figure 10.5 One of the most common types of pumps for microelectronic processing is the rotary vane vaccum pump.

Rotary vane pump

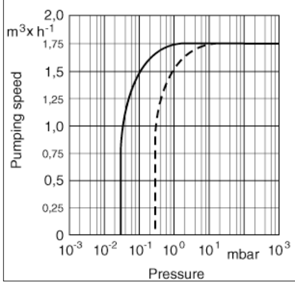
TRIAC Leybold

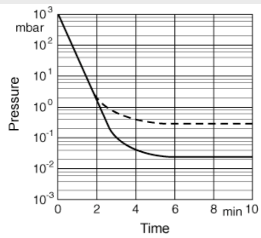


Rotary Vane Mechanical Pumps - 3

- Gases are removed by compressing them slightly above atmospheric pressure and then forcing them through a check valve.
- The rotary vane modules are immersed in an oil bath.
- The purpose of the oil is to:
  - cool the pump
  - lubricate the rotary vanes
  - provide a lip seal for the vanes
  - open the second stage exhaust valve at low inlet pressures
- They are powered by an electric motor:
  - Belt drive: 250 to 400 rpm
  - Direct drive: 1725 rpm (most common type)

Rotary vane pump





Pumping characteristics

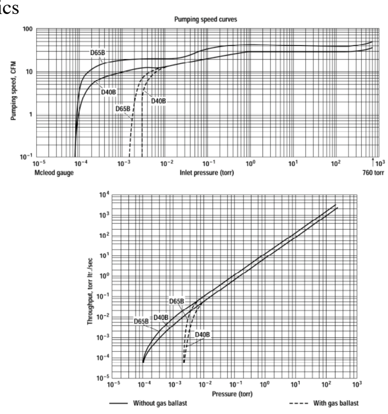


Figure 10.6 The pumping characteristics of Leybold D65® and D40® two-stage rotary vane vacuum pump with and without gas ballasting *(courtesy Leybold)*.

Two valve piston pump

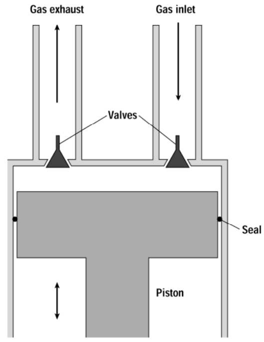


Figure 10.4 A schematic of a single stage two valve piston pump.

Roots blower pump

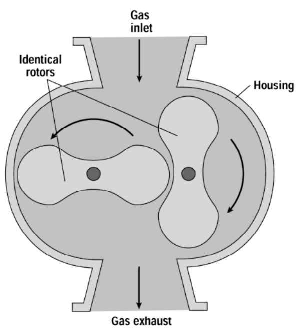


Figure 10.7 Schematic diagram of a Roots blower.

Compression ration as function of inlet pressure

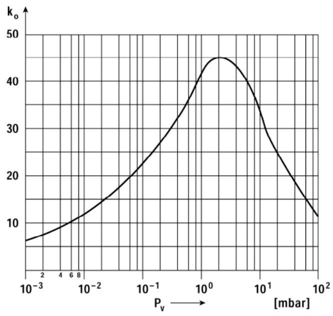
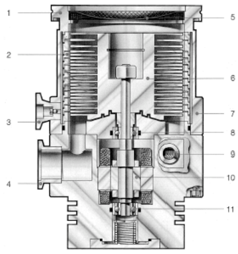


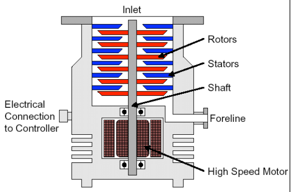
Figure 10.8 Compression ratio as a function of inlet pressure for a typical Roots blower *(courtesy Leybold)*.

Turbo pump



1 High vacuum inlet flange
2 Stator pack
3 Venting flange
4 Forevacuum flange
5 Splinter guard
6 Rotor
7 Pump casing
8 Ball bearings
9 Cooling water connection
10 3-phase motor
11 Ball bearings

Fig. 2.52 Schematic diagram of a grease lubricated TURBOVAC 151 turbomolecular pump



Pumping speed compression ratio Turbo

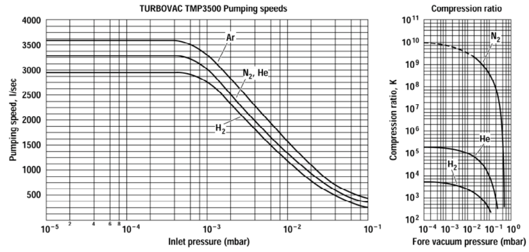
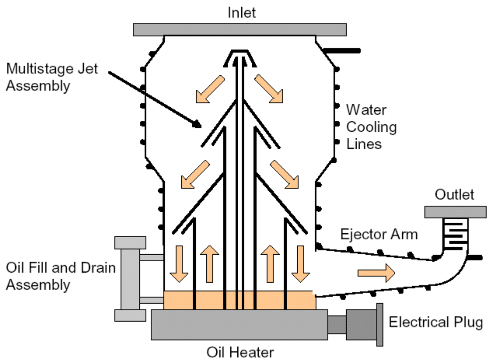


Figure 10.11 Pumping speed and compression ratio of a typical turbo pump as a function of inlet pressure for several representative gasses *(courtesy Leybold)*.

Diffusion pump



Diffusion pump

- Oil is vaporized and propelled downward by an internal boiler and multistage jet assembly.
- Oil vapor reaches speeds of 750 mph or more (supersonic).
- Oil vapor streams trap and compress gases into bottom of pump, which are then ejected out into the foreline arm.
- Oil vapor is condensed on sides of pump body which are water cooled.
- Can only operate at pressures of 100 mT or less.
- A mechanical foreline pump is required for operation.
- Multistage jet assembly is designed to fractionate the oil, using lighter weight fractions for higher vapor velocities.
- Typically 300 - 2800 L/s pumping speeds.

R. B. Darling / EE-527

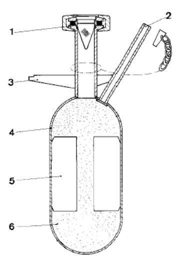
Diffusion pump

- Potential Problems:
  - Backstreaming of oil vapor can occur if forepressure becomes too large.
    - Backstreaming occurs for pressures of 1 to 10 mTorr.
    - Cold cap on top of multistage jet assembly helps to reduce this.
    - Liquid nitrogen filled cryotrap also helps to reduce this.
    - Maximum tolerable foreline pressure (critical forepressure) must not be exceeded, or pump will "dump" or "blow-out", sending oil up into the chamber.
  - Pump can overheat if cooling water fails
    - Most pumps have a thermal cutout switch.
  - Pumping requires low vapor pressure oil
    - Water, dirt, or other impurities will raise vapor pressure.
    - Only special oils are suitable for diffusion pump use.

Diffusion Pump Oils

- Diffusion pump oils have very low vapor pressure.
- Types
  - Hydrocarbon oils
    - Apiezon A, B, C, Litton Oil, Convoil-20
  - Silicone oils
    - DC-704, DC-705, Invoil 940
  - Polyphenyl ethers
    - Santovac 5, Convalex 10
  - Fatty esters
    - Octoil, Butyl Phthalate, Amoil, Invoil
  - Fluoroether polymers
    - Krytox, Fomblin

(Ad)Sorption pump



1 Inlet port
2 Degassing port
3 Support
4 Pump body
5 Thermal conducting vanes
6 Adsorption material (e.g. Zeolith)

Fig. 2.59 Cross section of an adsorption pump

(Ad)Sorption pump

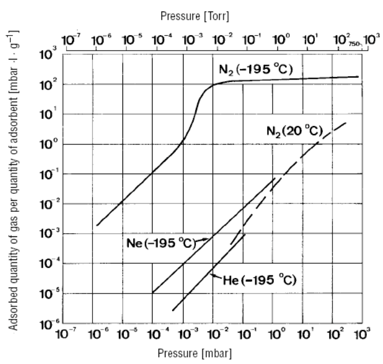
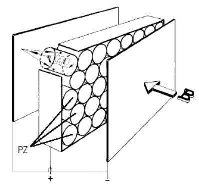


Fig. 2.60 Adsorption isotherms of zeolite 13X for nitrogen at -195 °C and 20 °C, as well as for helium and neon at -195 °C

Ion pump



←⊕ Direction of motion of the ionized gas molecules
•→ Direction of motion of the sputtered titanium
– – – Spiral tracks of the electrons
PZ Penning cells

Fig. 2.61 Operating principle of a sputter-ion pump

Ion pump

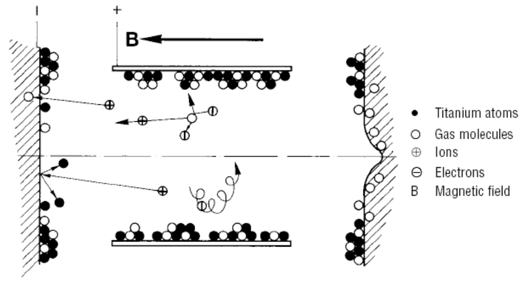
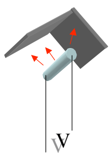


Fig. 2.62 Electrode configuration in a diode sputter-ion pump

Ti sublimation pump



$2x10^{-5}$ -$5x10^{-7}$ torr

Fast pumping speed

Typical dutycycle
2 min every other hour

Cryo pump

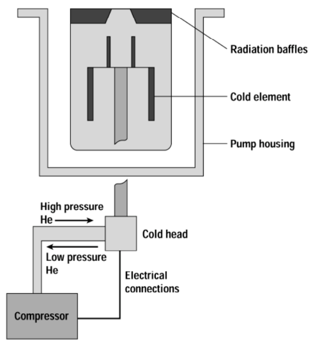


Figure 10.12 Schematic view of a typical cryopump.

Vacuum gages

Bourbon tube

Thermo couple
Pirani gages

Membrane sensors

Viscous friction sensor

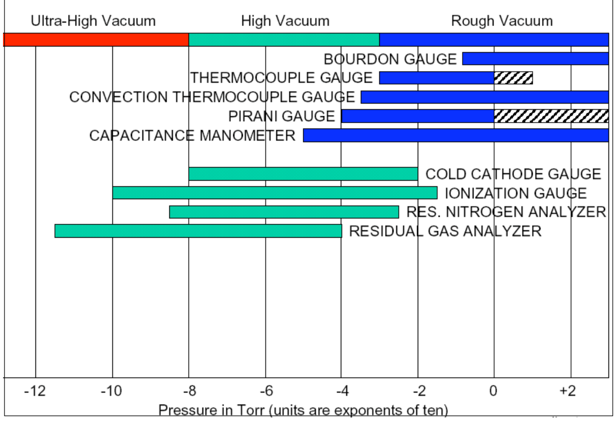
Penning

Ionization gage

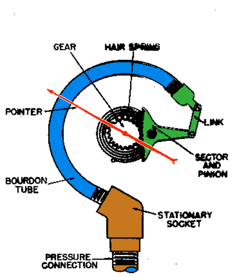
Quadruple mass spectrometer

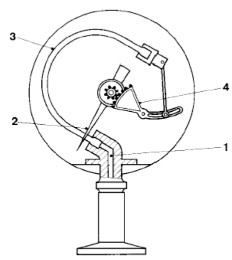
Leak-detection

Vacuum Gauge Pressure Ranges



Vacuum-gage,Bourdon tube





1 Connecting tube to connection flange
2 Pointer
3 Bourdon tube
4 Lever system

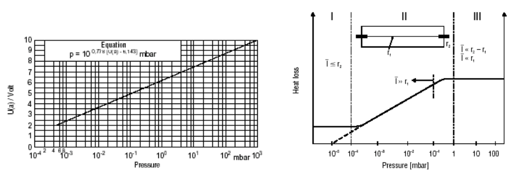
Fig. 3.2 Cross-section of a Bourdon gauge

Atm. down to 20-30 Torr

Vacuum gages, thermocouple

T/C

Atm- 10^{-3} (10^{-4}) torr



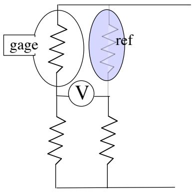
I Thermal dissipation due to radiation and conduction in the metallic ends
II Thermal dissipation due to the gas, pressure-dependent
III Thermal dissipation due to radiation and convection

Fig. 3.10 Dependence of the amount heat dissipated by a heated filament (radius r_1) in a tube (radius r_2) at a constant temperature difference on the gas pressure (schematic diagram)

Vacuum gages, Pirani

Atm- 10^{-3} (10^{-4}) torr

Wheatstone bridge - eg. to ref pressure, eg.



Vacuum gages, membrane sensor

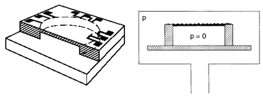


Fig. 3.4 Piezoelectric sensor (basic diagram)

range for the sensor type 1atm downto 10^{-4} torr

Each membrane 3-4 dekader,
Different membrane thickness

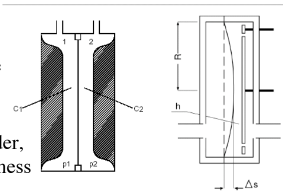


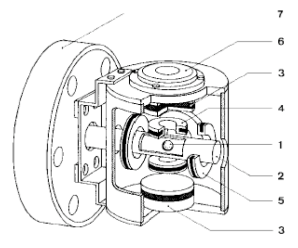
Fig. 3.5 Capacitive sensor (basic diagram)

Vacuum, viscous friction sensor

$$-f\cdot\frac{df}{dt}=\frac{10}{\pi}\cdot\frac{p\cdot\sigma}{\bar{c}\cdot r\cdot\rho} \quad (3.2)$$

p = gas pressure
r = radius of the ball
ρ = density of the ball material
$\bar{c}$ = mean speed of the gas particles, dependent on type of gas
σ = coefficient of friction of the ball, independent of the type of gas, nearly 1.

reading 5-60 s
Transfer standard



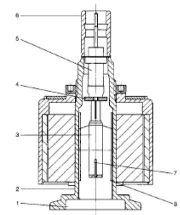
1 Ball
2 Measuring tube, closed at one end, welded into connection flange 7
3 Permanent magnets
4 Stabilization coils
5 4 drive coils
6 Bubble level
7 Connection flange

Fig. 3.9 Cross-section of the gauge head of a VISCOVAC VM 212 spinning rotor gauge (SRG)

Vacuum gages, penning

Cold Cathode
Ionization pressure gage

10^{-1} Torr down to 10^{-6} Torr



1 Small flange DN 25 KF; DN 40 KF
2 Housing
3 Ring anode with ignition pin
4 Ceramic washer
5 Current leadthrough
6 Connecting bush
7 Anode pin
8 Cathode plate

Fig. 3.12 Cross-section of PENNINGVAC PR 35 gauge

Vacuum sensors, hot cathode

10^{-5} ..10^{-11} torr

Bayard-Alpern

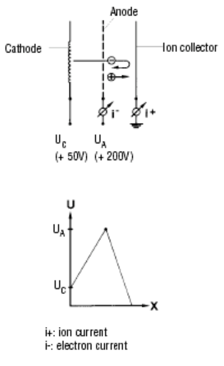


Fig. 3.13 Schematic diagram and potential curve in a hot-cathode ionization vacuum gauge

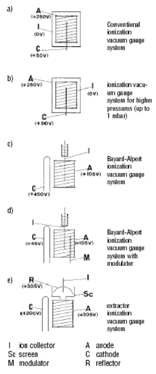
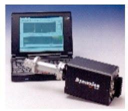


Fig. 3.16 Schematic drawing of the electrode arrangement of various ionization vacuum gauge measuring systems

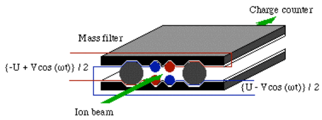
Vacuum gages, quadrupole mass spectrometer

Measure partial pressure



MEMS based Quadrupole

500 μm selfalign poles in V-grooves



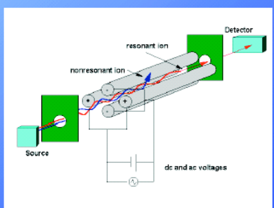
Vakuum sensorer,

Quadrupole Mass Spectrometer

- Four parallel metal rods.
- Two opposite rods have potential:

  $U + V\cos(\omega t)$

  $-(U + V\cos(\omega t))$

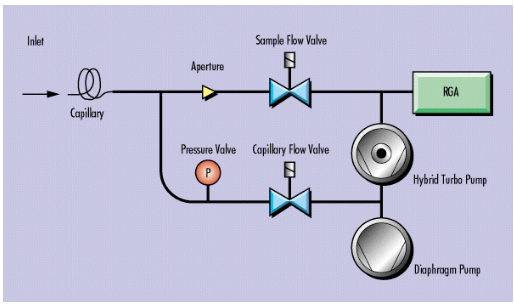


- Only ions with a definite mass to charge ratio pass through the filter.
- Consequence of complicated solution to Maxwell's equations

N. Govindaraju presentation

Vacuum gages

Leak-detection



O Ring seals

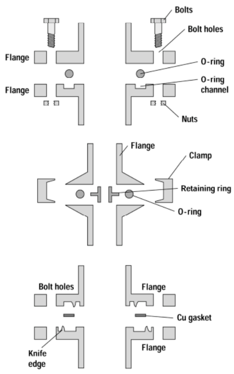


Figure 10.13 Two types of O-ring seals for medium vacuums and the Conflat® flange used for sealing high-vacuum systems.

PLASMA

What is it
Characteristics
Uses of plasma in semiconductor processing
How is it produced

PLASMA what is it, Chracteristics

Specificlly the plasma we are interested in

partly ionized gas *(1 torr -10^{-4}torr)*
Typically .01 percent ionized
Typically 1 percent radicals (atoms fragments)
Electrons (density 10^{9}-10^{12} cm^{-3})

Non-equilibrium
hot electrons, (mean T_e=10^4 - 10^5 K)
gas temperature (~ RT)

Electrical field *(80-100 V/cm)*
Ignition by breakdown or photo-ionization
Energy conversion -electrical energy -pot energy of radicals and free atoms. Energy transfer by free electrons

PLASMA uses in 1/2 cond. process

Ion source - ion implanter
Resist stripper
Reactive Ion Etcher
Sputter deposition
Ion source - SIMS, AES, RBS,FIB
Light bulb in Lithography
Lighting up the lab

PLASMA how is it produced

DC - *both electrodes conductive*

AC

Paralell plate reactor

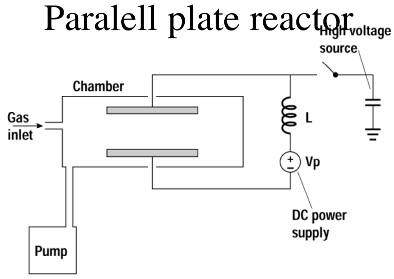


Figure 10.14 A simple parallel plate plasma reactor.

Plasma simple charge distribution

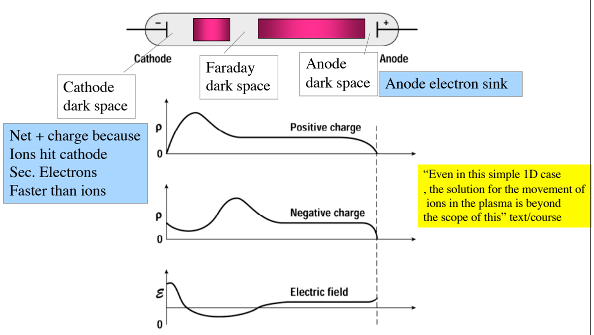
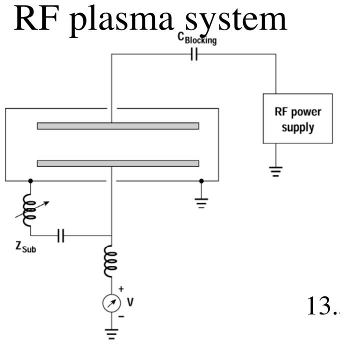


Figure 10.15 Positive and negative charge densities and electric field as a function of position in the plasma.

RF plasma system



13.56 MHz

Figure 10.17 Schematic of an RF plasma system.

RF potential

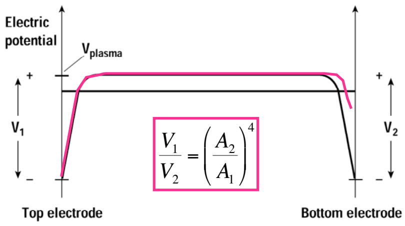


Figure 10.18 Typical plot of dc voltage as a function of position in an RF plasma.

High density plasma system

Why?
The ions and radicals do the job
How/methods
coupled plasma, magnetron plasma, electron resonance plasma
Characteristics
ion concentrations above 10^{11} cm^3

Magnetically confined plasma

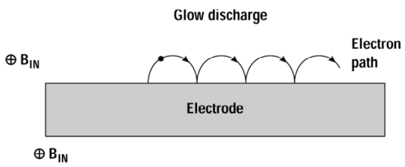
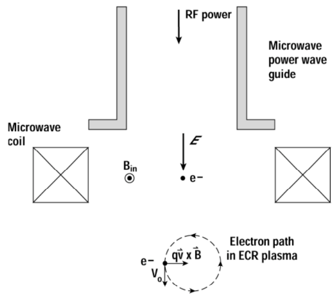


Figure 10.19 In a simple magnetically confined plasma, electrons ejected from the cathode are confined by the Lorentz force to stay in the cathode dark space.

ECR plasma

Electron cyclotron resonace source



Resonans
$\omega = 2\pi f = qB/m$

f **>1GHz**

Figure 10.20 In an ECR plasma, an alternating field causes the electrons to move in circular orbits, dramatically increasing the ion density.

ICP system

Inductively Coupled Plasma

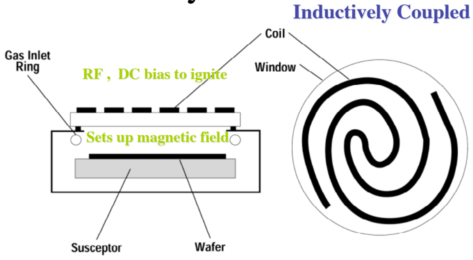


Figure 10.21 Typical ICP system showing side and top views.