Vacuum Technology

Introduction and the Why

- Most thin film deposition techniques involve a vapor coming in contact with a substrate.
- Proper film growth requires a controlled environment.
  - Either a known amount of a given type of gas (O_2, N_2, etc.) or nothing at all (vacuum).
- First we’ll see how gases behave (gas kinetics).
- Then we’ll look at the instruments that we use to control the environment.

The Size of a Molecule

(a very rough calculation)

- Take water (liquid H_2O) as an example.
- Oxygen has 8 protons and 8 neutrons for a total of 16 nucleons and Hydrogen has 1 proton. So water has 16+1+1=18 nucleons

$$m_P \approx m_N \approx 1.66\times10^{-24} g$$

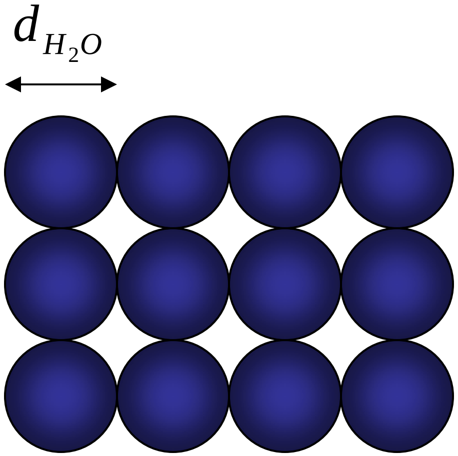
$$m_{H_2O} = 18 m_N = 2.99\times10^{-23} g$$

$$N_{H_2O} = 1/m_{O_2} = 3.35\times10^{22} molecules/g$$

$$\rho_{H_2O} = 1.00 g/cm^3$$

$$V_{H_2O} = \frac{1}{\rho_{H_2O} N_{H_2O}} = 2.99\times10^{-23} cm^3/molecule$$

$$d_{H_2O} = 2\times\sqrt[3]{\frac{3}{4}V_{H_2O}} = 5.64\times10^{-8} cm$$



The Distance Between Molecules in a Gas

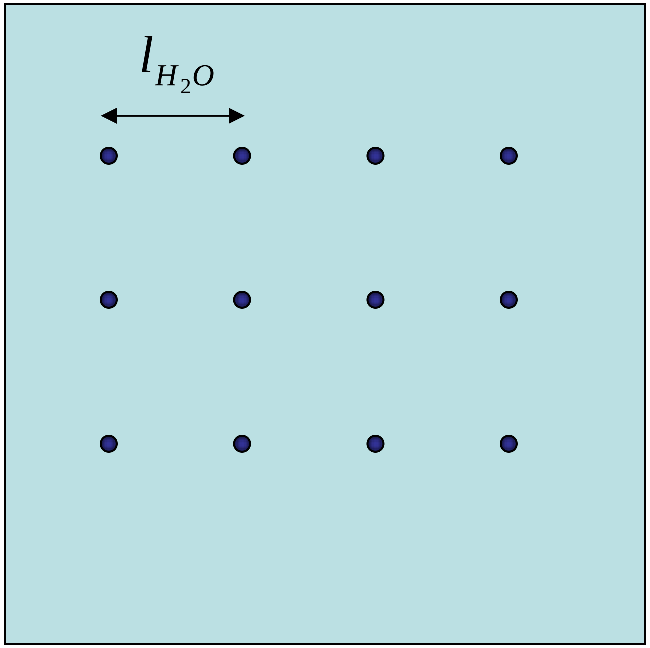
- Now take water vapor (gaseous H_2O).

$$\rho_{H_2O} = 0.8\times10^{-3}\, g/cm^3$$

$$V_{H_2O} = \frac{1}{\rho_{H_2O} N_{H_2O}} = 3.73\times10^{-20}\, cm^3/molecule$$

$$l_{H_2O} = \sqrt[3]{V_{H_2O}} = 3.34\times10^{-7}\, cm$$

$$l_{H_2O} \approx 6 d_{H_2O}$$



Pressure

- Pressure is the force exerted per unit area.
- It is directly proportional to the number of particles (atoms/molecules).

- For an ideal gas, $\boxed{PV = Nk_BT}$

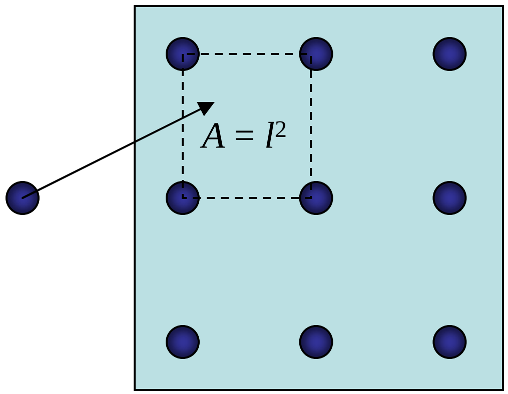
- Units are in Torrs
- Atmospheric pressure is 760 Torr
- Low vacuum ~ 10^{-1} - 10^{-5} Torr
- Standard vacuum ~ 10^{-5} - 10^{-6} Torr
- Ultrahigh Vacuum (UHV) ~ 10^{-8} - 10^{-11} Torr

Mean Free Path

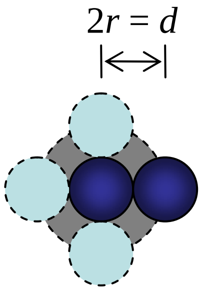
- In a vapor, gas molecules will be moving freely.
- Their motion is interrupted only by collisions with other molecules or the container.
- The average distance a molecule can move between collisions is called the mean free path.

Rough Calculation of the MFP

- Suppose there is a gas molecule trying to get through an array of gas molecules.



Area blocked by one molecule



Probability that a collision will occur

$$R = \pi d^2 / l^2$$

Average number of layers between collisions

$$1/2R = l^2 / 2\pi d^2$$

$$MFP = \frac{l}{2R} = \frac{l^3}{2\pi d^2} = \frac{1}{2\pi n d^2}$$

where n is the number of gas molecules per cm^3

Rough Calculation of the MFP

In an ideal gas $$n = \frac{N}{V} = \frac{P}{k_B T}$$

P: Pressure
k_B : Boltzmann Constant (1.38×10^{-23} J/K)
T: Temperature in K

$$MFP = \frac{1}{2\pi n d^2} = \frac{k_B T}{2\pi d^2 P}$$

More accurately $$\boxed{MFP = \frac{\sqrt{2} k_B T}{2\pi d^2 P}}$$

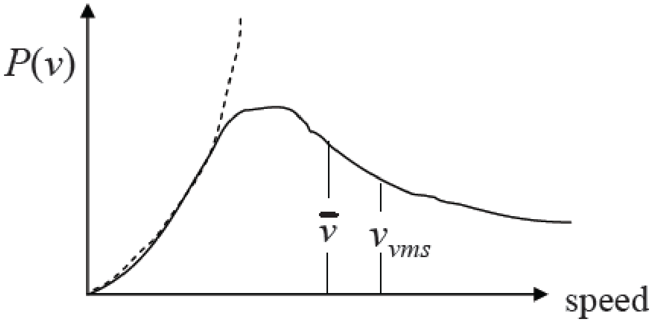
P (Torr)	**MFP (cm)**
760	10^{-5}
1	10^{-2}
0.001	10

Gas Velocities

Generally gases follow Maxwell statistics for speed distribution

Probability distribution of
the speed of molecules

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

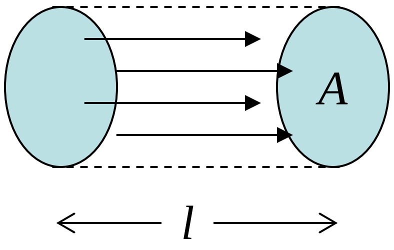


Average speed of a molecule

$$\boxed{\bar{v} = \int vP(v)dv = \sqrt{\frac{8k_B T}{\pi m}} \approx 500m/s}$$

Flux

Flux is the number of atoms or molecules hitting a surface per unit time



Total number of molecules in volume V

$$N = nV = nAl = nAvt$$

The flux

$$\boxed{J = \frac{N}{At} = nv}$$

$$J = nv = \frac{P}{k_BT}\sqrt{\frac{8k_BT}{\pi m}} = \frac{P}{\sqrt{\pi m k_B T}}$$

Knudsen Number

- A measure of the type of gas flow

$$\boxed{K_n = \frac{MFP}{L}}$$

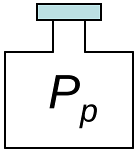
L is a dimension of
the vacuum chamber

- If $K_n < 1$, many molecules in chamber, pressure is high, the flow is <u>viscous</u> (like a fluid).
- If $K_n > 1$, few molecules in chamber, pressure is low, gas flow is <u>molecular and ballistic</u>.

Gas Flow and Pumping

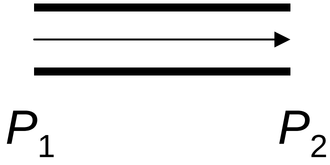
- The flow rate of a gas is expressed in number of molecules pre unit time.

$$Q = \frac{dN}{dt} = Q_{pump} + Q_{component}$$



$$Q_{pump} = P_p S$$

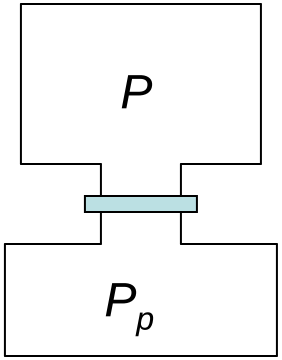
Pump Speed



$$Q_{component} = C\left(P_1 - P_2\right)$$

Conductance

Effective Pump Speed and Pump Time



Chamber $$Q_{chamber} = C\left(P - P_p\right)$$

Pump $$Q_{pump} = P_p S_p$$

$$\boxed{S_{eff} = \left(\frac{1}{C} + \frac{1}{S_p}\right)^{-1}}$$

Vacuum components in series have their speeds added in reciprocal form.

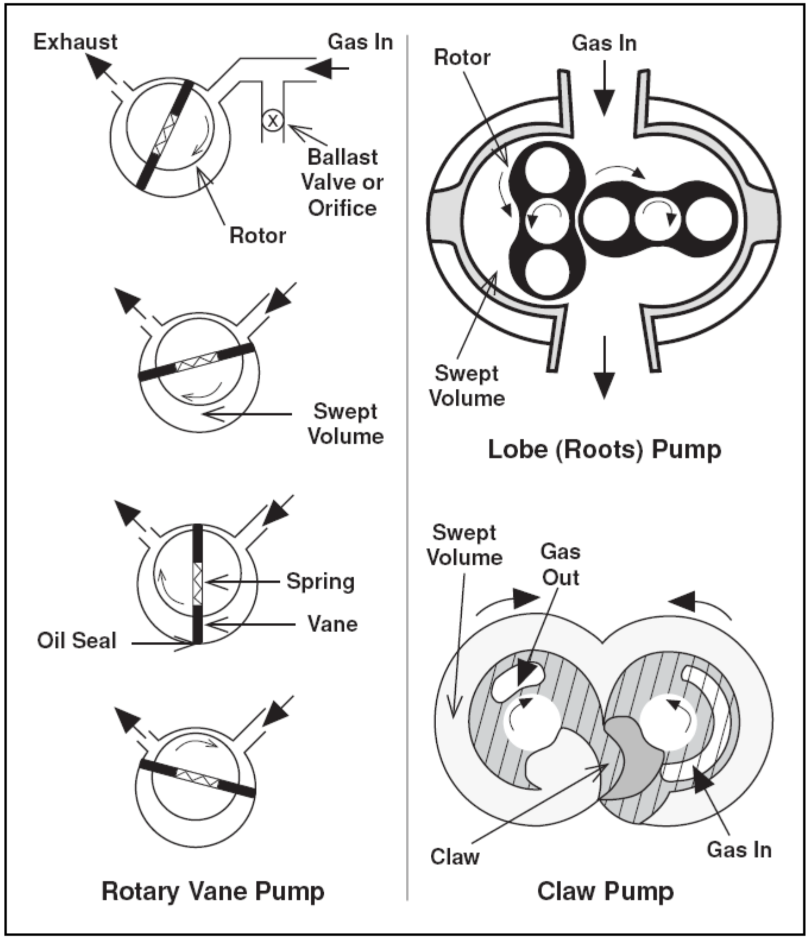
$$P = P_0 \exp\left(-S_{eff} t / V\right) \longrightarrow \boxed{t = \frac{V}{S_{eff}} \ln\left(\frac{P_0}{P}\right)}$$

Vacuum Pumps

- Two general classes exist:
- Gas transfer – physical removal of matter
  - Mechanical, diffusion, turbomolecular
- Adsorption – entrapment of matter
  - Cryo, sublimation, ion

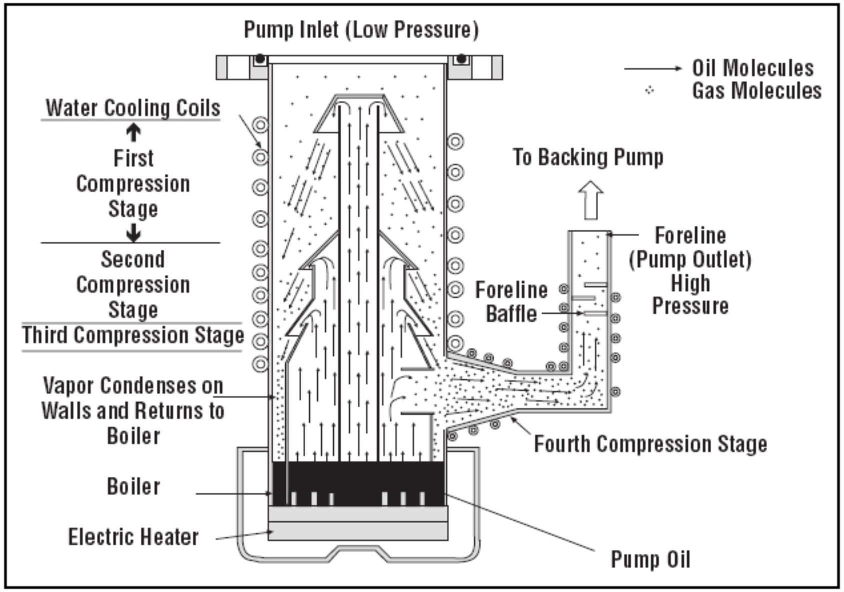
Mechanical Pumps

- Good workhorse pump
- Works from atmospheric pressure to ~1mT
- Uses oil, mechanical vibrations
- High flow rate



Diffusion Pumps

- Uses hot Si oil
- No vibrations
- From 1 mT to 10^{-9} T with LN cooling.
- Wide range of flow rates.
- Requires mechanical pump.



Turbo Molecular Pumps

- High rpm rotor blades impart momentum to molecules
- Can go from 1 mT to 10^{-9} T
- Can have vibrations
- Needs mechanical pump

Ion Pumps

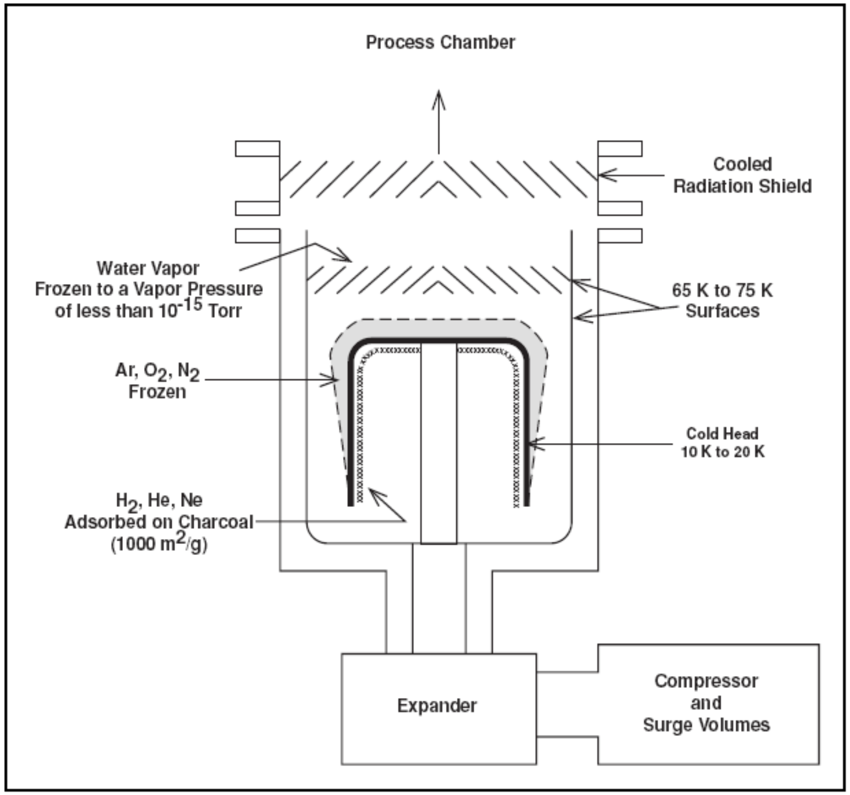
- Use a magnetic field to direct ions to pump walls and embed there.
- Wide range of flow rate and pressure (still need mechanical pump)
- No moving parts or oil
- Need high voltage and magnetic fields.

Ti Sublimation Pumps

- A freshly created Ti surface actively retains gas molecules.
- Similar advantages and disadvantages as ion pumps

Cryo Pumps

- Gases are adsorbed on cold pump walls
- Needs recharging
- Can reach UHV but needs other pump
- Coolers can cause vibrations



Deposition Chambers

- For standard vacuum, we can use a glass, Pyrex or stainless steel chamber.
  - Use it for CVD, sputtering and vapor deposition.
  - Mostly for lower quality, polycrystalline films
- For UHV, use a stainless steel chamber
  - Use it in MBE, CVD, sputtering
  - High quality, epitaxial films
  - Can be “baked”.