Appendices

Appendix I

PERIODIC TABLE

SYMBOLS OF ELEMENTS AND THEIR ATOMIC NUMBERS

	I A	II A	III A	IV A	V A	VI A	VII A	VIII A			I B	II B	III B	IV B	V B	VI B	VII B	Nobel Gases
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	(113)	(114)	(115)	(116)	(117)	(118)
	(119)	(120)	(121)	(154)	(155)	(156)	(157)	(158)	(159)	(160)	(161)	(162)	(163)	(164)	(165)	(166)	(167)	(168)

LANTHANIDES	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
ACTINIDES	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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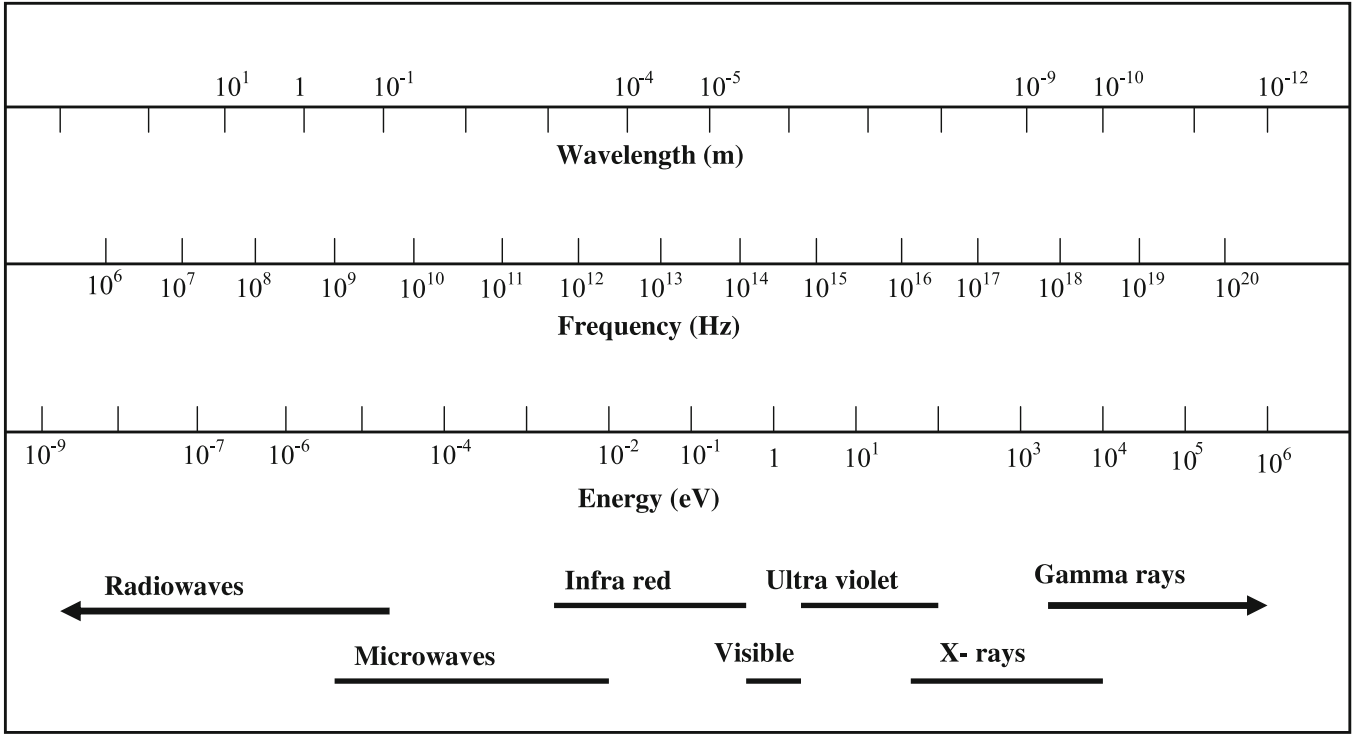
Appendix II

ELECTROMAGNETIC SPECTRUM



Appendix III

List of Fundamental Constants

Physical quantity	Symbol	Value	SI	CGS
Speed of light in vacuum	c	2.9979	10^{8} ms^{-1}	10^{10} cm. s^{-1}
Electronic charge	e	1.6021	10^{-19} C	–
		4.8032	–	10^{-10} esu
Boltzmann constant	k_B	1.3806	10^{-23} JK^{-1}	10^{-16} erg .K^{-1}
Planck's constant	h	6.6262	10^{-34} J s	10^{-27} erg. s
Electron rest mass	m_e	9.1095	10^{-31} kg	10^{-28} g
Proton rest mass	m_p	1.6726	10^{-27} kg	10^{-24} g
One electron volt	eV	1.6021	10^{-19} J	10^{-12} erg
Avogadro's number	N_A	6.0221×10^{23} mol^{-1}	–	–
Permittivity of free space	ε_0	–	$10^{7}/4\pi c^{2}$ Fm^{-1}	1
Permeability of free space	μ_0	–	$4\pi \times 10^{-7}$ Na^{-2}	1
Bohr magneton	μ_B	9.2741	10^{-24} J T^{-1}	10^{-21} erg G^{-1}
Bohr radius (radius of hydrogen atom)	r_0	5.2917	10^{-11} m	10^{-9} cm
Atomic mass constant	m_u	1.6605	10^{-27} kg	10^{-24} g

Appendix IV

Vacuum Techniques

Vacuum is the space devoid of any gas, liquid, solid or any particles. Vacuum is needed for various purposes such as packaging of food, materials deposition and processing, analysis equipment and many other applications. Extent of vacuum is measured with reference to normal atmospheric pressure at sea level i.e. one atmosphere. This in turn is measured as the pressure exerted by air on unit area of a flat surface. Pressure is defined as force per unit area. The SI unit for pressure is Pascal (Pa) defined as N/m^2. At sea level mercury column height is 760 mm. This is usually used to measure pressure. Traditionally, in different parts of the world different groups have been using different units of vacuum. However, the reference is always atmospheric pressure at sea level and vacuum is the pressure smaller than atmospheric pressure. Some common units used to measure pressure are torr, Pa and mbar. They are inter-related as follows:

1 atmosphere = 760 torr = 1.013×10^5 Pa
1 torr = 1 mm of Hg = 10^{-3} mbar
1 bar = 750 torr
1 Pa = 7.5 mtorr

For the sake of convenience the vacuum ranges are roughly identified as follows (note that the demarcation lines between different ranges are rather blurred).

Low vacuum	10^5 Pa (750 torr) to 3.3×10^3 Pa (25 torr)
Medium vacuum	3.3×10^3 Pa (25 torr) to $\sim 10^{-1}$ Pa (7.5×10^{-4} torr)
High vacuum	10^{-1} Pa (7.5×10^{-4} torr) to 10^{-4} Pa (7.5×10^{-7} torr)
Very high vacuum	10^{-4} Pa (7.5×10^{-7} torr) to 10^{-6} Pa (7.5×10^{-9} torr)
Ultra high vacuum	10^{-6} Pa (7.5×10^{-9} torr) to 10^{-10} Pa (7.5×10^{-13} torr) or below

From the kinetic theory of gases, mean free path of gas molecules λ is

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

where d is diameter of a molecule and n is number density of molecules.

Flux of gas molecules striking a surface, per unit time and on unit area are given as

$$\varphi = 3.513 \times 10^{22} \frac{P}{(MT)^{1/2}} \text{ molecules/cm}^2\text{.s}$$

where P is pressure, M is weight of molecule and T is temperature.

Some molecules may stick to the surface (adsorbed) and some may get released back or simply bounce back to the ambient. In the vacuum technology terminology, when a surface releases gas molecules in the vacuum system it is known as 'outgassing'.

Vacuum System

In order to obtain a vacuum in some chamber (usually made of glass, steel or some other metal or alloy) it is necessary to connect it through various pipe lines, vacuum valves, traps (to avoid gases or pump fluids entering the vacuum chamber) to different pumping devices called 'vacuum pumps'. It may be necessary to use one or more pumps to achieve an adequate vacuum which is measured by using 'vacuum gauges'. In order to achieve desired vacuum it is necessary to pay enough attention to the materials used not only for making the vacuum chambers but also to various sealings, valves, traps, vacuum pumps, vacuum gauges, fluids etc. which may be used to obtain, retain, or measure vacuum. The commonly used chamber materials are glass, stainless steel and in some cases aluminum alloys. Some materials used to connect ports with some modules or close some chamber parts are known as flanges. They are sealed using rubber gaskets (viton), gold, tin or indium wires. Often there are glass to metal connectors or ceramics to metal connectors needed to make electrical connections for performing different types of operations in a vacuum chamber. The detailed discussion on materials is beyond the scope of this book and can be found in the references given at the end of the appendix.

Vacuum Pumps

A variety of vacuum pumps have been designed with varying pumping speeds and are in use depending upon the vacuum requirement i.e. whether low vacuum, high vacuum or some other range is required. Before we proceed to the vacuum pumps let us define the pumping speed.

Pumping speed (S) of a vacuum system is defined as the volume (V) or amount of a gas removed from the pump in time t.

$$S = V/t$$

Throughput (Q) is defined as the quantity of a gas in units of pressure and amount of gas passing from some point in certain time. Throughput is also known as 'gas load'.

$$\begin{aligned} Q &= \text{pressure} \times \text{volume/time} \\ &= \text{torr} \times \text{litres/ sec} \ \text{ or Pa} \times \text{m}^3\text{/ sec} \end{aligned}$$

Throughput is related to the pumping speed as

$$Q = P.V/t = P.S$$

The vacuum pumps can be divided into two types: (1) Gas transfer type and (2) Entrapment.

Major gas transfer type of pumps are rotary pump, root's pump, diffusion pump and turbo-molecular pump. Major entrapment type of pumps are sorption pump, ion pump, sublimation pump and cryo pump.

In the following we shall outline the principles of some of these pumps in brief. More details should be found in the references given at the end of the appendix.

Rotary Vane Pump

This type of pump is used to obtain the vacuum from atmospheric pressure to ~0.13 Pa. The pump body is usually made of steel. The pump consists mainly of a disk type rotor (see Fig. A.1) which rotates off-centric with respect to the chamber centre. Two vanes attached to the centre of the rotor make tight seal between the rotor and the chamber (stator) during rotation, thereby sweeping a gas from the inlet side to the outlet side without much of back-streaming of the gas. Due to compression of the gas on the outlet side, pressure increases which is sufficient to open a valve and let the gas be thrown out. The pump body is immersed in oil.

The rotors rotate at ~2,000 to 5,000 rpm and small clearance needs to be kept between rotor and the stator which limits the vacuum that can be achieved. Most of the rotary pumps are also provided with 'gas ballast' arrangement. There are other versions of rotary pump like rotary plunger pump and trochoid pump. One may also use 'double stage or two stage' rotary pump.

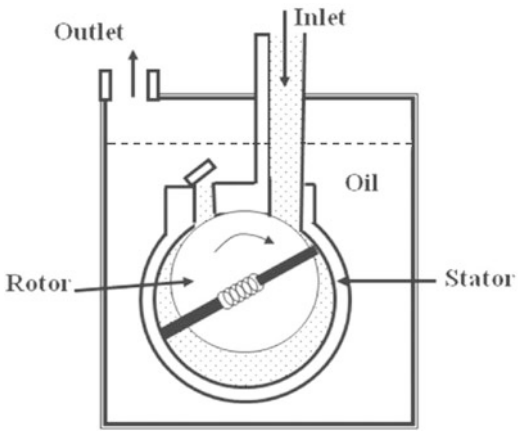


Fig. A.1 Schematic diagram of a rotary pump

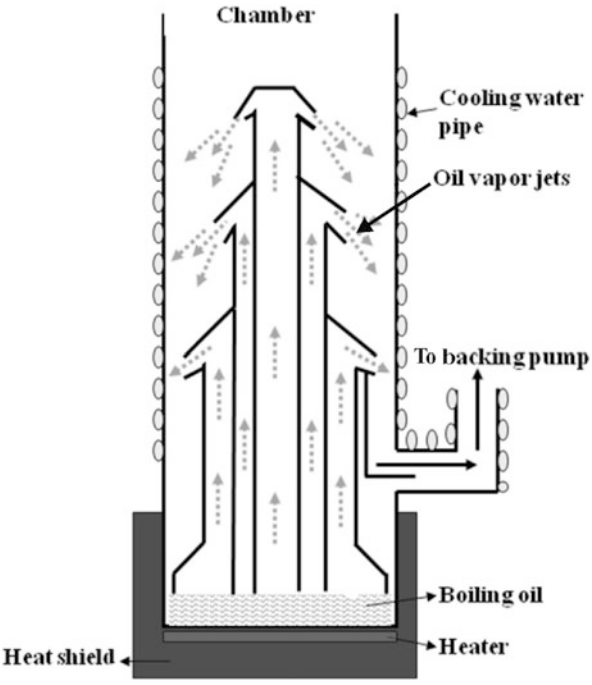


Fig. A.2 Schematic diagram of a diffusion pump

Diffusion Pump

The usual operating range of a diffusion pump is $\sim 10^{-1}$ to $\sim 10^{-3}$ Pa. However with the use of proper oil and good design it can be extended even to $\sim 10^{-7}$ Pa. However, like a rotary pump, diffusion pump cannot operate just by itself. It needs a backing pump like a rotary pump to pump away the gas at high pressure. A diffusion pump consists (see Fig. A.2) of an outer cylinder in which an assembly of a chimney-like

structure is kept. There is oil at the bottom of the pump body which can be heated by an external heater. There is also a metallic water tubing which surrounds the body of the diffusion pump. The chamber to be evacuated to high vacuum is first pumped down to $\sim 10^{-1}$ Pa using a rotary or other suitable pump and then the valve of diffusion pump is opened to the chamber to be evacuated. The heater when started evaporates the oil which passes at very high velocity through the nozzles in the downward direction. The gas molecules from the chamber diffuse in the oil jets and are forced downwards. The oil is cooled by the water flowing in the tubing surrounding the pump body and gas molecules rush in the outlet region where they are pumped by a pump like rotary pump. The process can keep on repeating to gain and continue the desired vacuum state inside the vacuum chamber.

Sorption Pump

It is one of the simplest pumps with the capability of achieving vacuum, starting from the atmospheric pressure upto $\sim 10^{-3}$ Pa. Pumping speed is initially upto $\sim 10^{-1}$ Pa very high and then slows down. The pump works on the principle of adsorption of gases on cooled surfaces. In a cylindrical steel chamber highly porous material like molecular sieves, zeolite or charcoal is filled. The pump body is cooled by liquid nitrogen by filling it in the outer jacket of the pump. The gases in the experimental chamber are simply sucked by the cool surface of the absorbant and retained as long as the surface is cold enough. After achieving the desired vacuum in the main chamber the intake port is isolated and liquid from the outer jacket is removed. The pressure due to gases can be released by simply venting through the degassing port. Often heating can be used to accelerate the degassing and making the sorbent surface fresh. The sorption pump can be reused. Oil-free pumping without any moving parts (no vibrations) makes this pump suitable for many experiments (Fig. A.3).

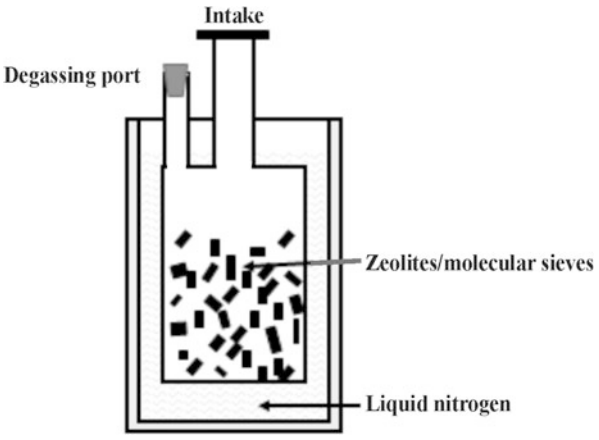


Fig. A.3 Schematic diagram of a sorption pump

Ion Pump

This pump operates in the range of $\sim 10^{-1}$ to 10^{-6} Pa. It also needs pre-pumping by another pump like a diffusion pump. However, unlike diffusion pump which constantly needs a backing pump to operate along with it, the ion pump can be left to itself once it starts. The pumping action simply requires that the gas be ionized. With the cathode-anode assembly (upto 4–5 KV) with parallel magnetic field (3–4 KGauss), initial ionization is triggered by stray electrons or radiation in the chamber. The electrons are accelerated in path of spiral towards anode and ionize on the way the neutral gas molecules inside the chamber. The gas atoms/molecules with positive charge are then accelerated towards the cathode where they can react and get adsorbed as well as sputter cathode material viz. titanium. It gets deposited in other parts like anode where too pumping of gas can occur. Usually diode and triode pump geometries are available (Fig. A.4).

Triode ion pump is just a modified version of the diode pump in order to avoid the argon instability. The insertion of a slotted type cathode assembly enables the argon ion to get embedded without resputtering. Different gases get pumped at different speeds depending upon their reactivity with the cathode material viz. titanium (Fig. A.5).

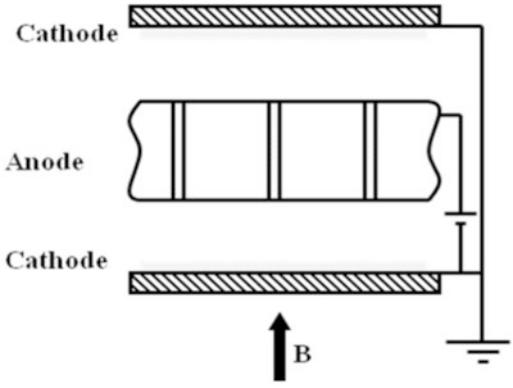


Fig. A.4 Schematic diagram of an ion pump with diode configuration

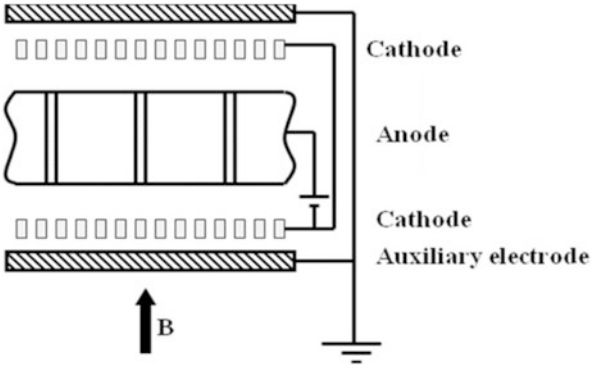


Fig. A.5 Schematic of a triode ion pump

Vacuum Gauges

There are three types of vacuum measurement devices called 'vacuum gauges'.

1. Mechanical gauges – like U-tube manometer, dial strain gauge, capacitance gauge and McLeod gauge. These gauges measure the actual force exerted by the gas or air.
2. Transport gauges – like Pirani and thermocouple gauges. They work on the principle of conductivity of a gas or air.
3. Ionization Gauges – depend upon the ionization of the gas in vacuum system. Cold cathode ionization gauge, hot filament ionization gauge and Bayard-Alpert gauge are the examples of ionization gauges.

We shall discuss in brief few gauges below.

U-tube Manometer

As shown in Fig. A.6 one end of a glass tube is open to the atmosphere (pressure P_1) and other end is connected to the vacuum system of which pressure is to be measured. The tube is partially filled with mercury or some other liquid with low vapour pressure. Initially, when the vacuum system is not pumped height of the liquid column in both the arms would be equal. When there is a pressure difference due to vacuum system evacuation, the liquid level in the arm connected to the vacuum system would rise and a height difference 'h' would be observed in the two arms. If P_2 is the pressure in the vacuum system,

$$P_1 - P_2 = h\rho g$$

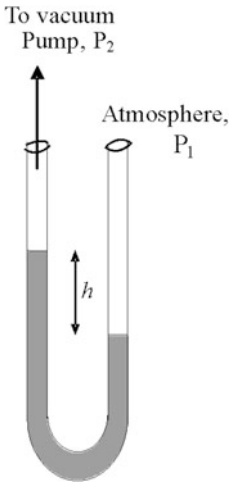


Fig. A.6 U-tube manometer

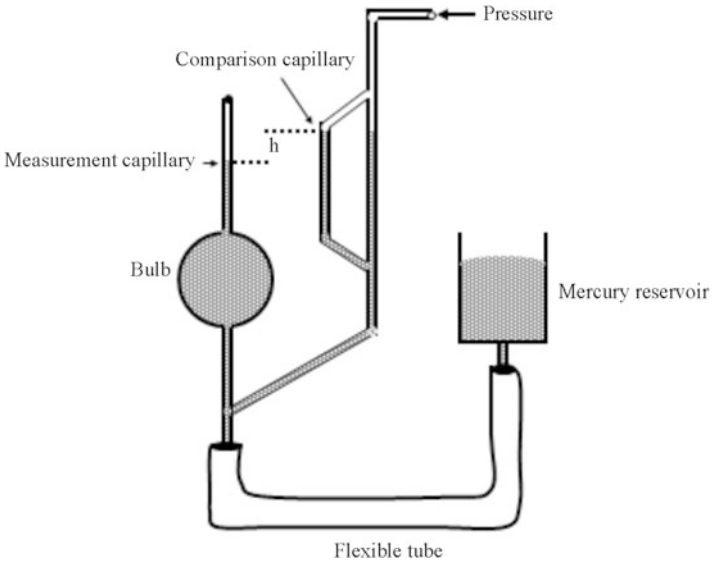


Fig. A.7 A McLeod gauge

where ρ is the density of the liquid and g is the gravitational constant. Knowing all the quantities except pressure (P_2), it can be estimated from above equation.

As illustrated in Fig. A.6 one end can be sealed to know vacuum before pumping mercury, so that changes in the atmospheric pressure need not be known.

McLeod Gauge

The construction of this gauge is as shown in Fig. A.7. Initially the mercury level is brought to point 1. Gas is at pressure P and bulb is also at same pressure. Volume of the bulb is V, hence gas volume in bulb is V. Reservoir of mercury is lifted up so that the mercury reaches top of capillary. Gas in the capillary of diameter d and bulb is compressed. It can be shown that pressure is given as reservoir is lifted up so that the level of mercury is at the level of capillary.

Pirani Gauge

A filament is made the part of Wheatstone bridge. Initially when the system is at atmospheric pressure the resistance bridge is balanced. When the system starts getting evacuated and the heated filament starts losing its heat, its resistance changes disturbing the balance. Consequently the current flowing in the ammeter in the

bridge serves as a pressure reading. The filament resistance is a function of the heat lost by it to the colliding gas molecules.

Thermocouple Gauge

Thermocouple gauge also works on the same principle as Pirani gauge i.e. thermal conductivity of gases. If large number of gas molecules are present in the system more heat will be taken off the heated filament or wire than otherwise. Heat conducted is proportional to the gas density and becomes a measure of vacuum. Only difference in Pirani and thermocouple gauge is that instead of resistivity change as in Pirani gauge, temperature of a heated wire is directly measured by a thermocouple (thermocouple is a temperature measuring device which works on the principle that if two dissimilar metal junctions are made and one is hot and the other is cold then there is a current flow which depends on the temperature difference between the two junctions). The temperature of the heated wire is in turn a measure of vacuum.

Cold Cathode Gauge (Penning Gauge)

It is similar in principle to an ion pump. However, the dimensions of the electrodes are small and it is not designed to pump large volume of gases in the vacuum system but derive only a small amount for the measurement of a gas.

An anode maintained at high voltage (∼2 kV D.C.) is placed between two flat cathode plates. A magnetic field is applied parallel to the electric field. Gas is ionized under the influence of applied electric and magnetic fields. The ion current is a measure of amount of pressure of gas inside the system as amount of gas being ionized is a function of amount of gas molecules present inside (Fig. A.8).

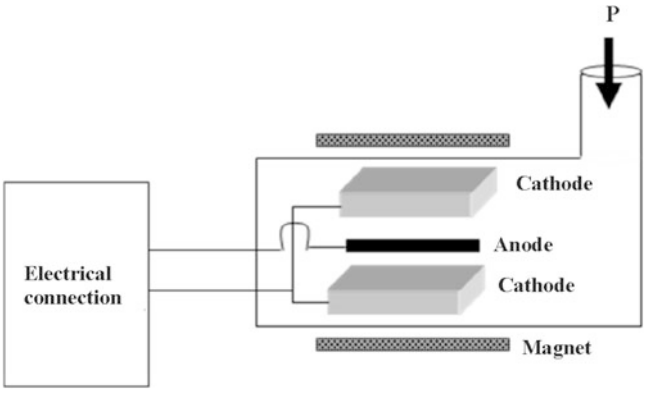


Fig. A.8 A penning gauge

Hot Cathode Ion Gauge

In this gauge a hot filament is surrounded by a metal grid and both are placed inside a cylindrical metal collector. The grid is held at ∼200 V positive potential with respect to the filament. Electrons from the filament are accelerated towards the grid and can shoot up slightly beyond the grid but are repelled by the negatively held collector and again attracted by the grid. They may oscillate to some extent around the grid and cause ionization of the gas inside the gauge. The ionized gas molecules or atoms when positively charged get accelerated towards the collector causing a current which is proportional to the density of gas molecules or pressure inside the vacuum system (Fig. A.9).

Major problem with this kind of ion gauge is that at low pressure, when ions are accelerated towards the collector, without any collisions with other molecules, they are able to produce X-rays or UV radiation while they strike the collector. This radiation in turn can produce additional ionization which results into additional ion current. Thus even with lower vacuum one observes larger ion current or higher pressure than actually exists in the system. Thus the gauge becomes inaccurate in the ultra high vacuum regime.

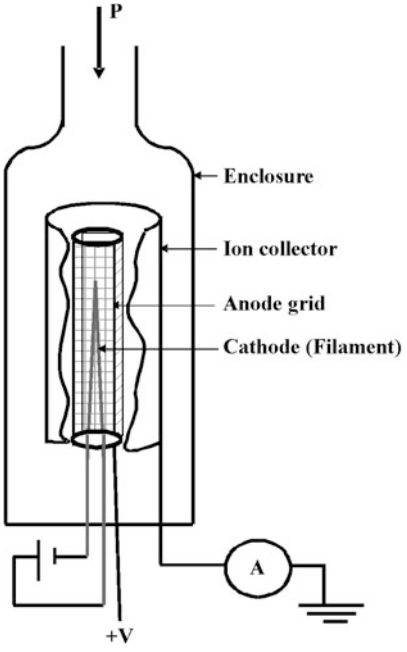


Fig. A.9 Schematic of an ion gauge

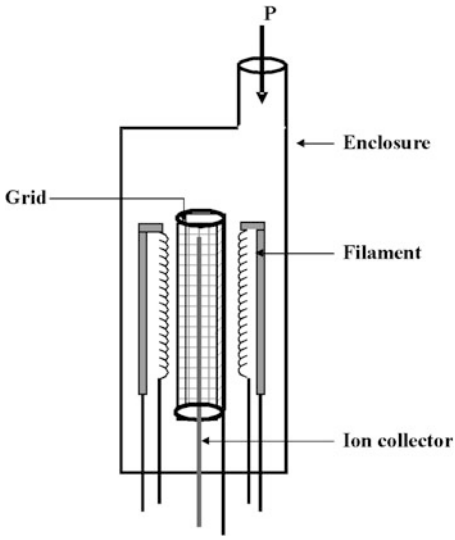


Fig. A.10 Schematic of a B-A gauge

Bayerd-Alpert (B-A) Gauge

An improvement in the design of ionization gauge is made in the Bayerd-Alpert gauge so as to increase the accuracy of the gauge in the ultra high vacuum range. In order to overcome the limitation due to the so-called 'X-ray limit' of an ionization gauge discussed above, the large area collector is replaced by a thin collector, a metal wire, placed at the centre of the gauge head. The collector is surrounded by the metal grid and the filament is placed outside the grid. This enables the pressure measurement upto $\sim 10^{-8}$ Pa (Fig. A.10).

Below $\sim 10^{-8}$ Pa, pressure/vacuum measurement even with a B-A gauge becomes unreliable. Often partial pressure gauges like mass spectrometers are employed to understand the composition of residual gases inside the vacuum systems at such a high vacuum.

Further Reading

A. Chambers, R.K. Fitch, B.S. Halliday, *Basic Vacuum Technology* (IOP Publishing Ltd., Bristol, 1989).

L.I. Maissel, R. Glang, *Handbook of Thin Film Technology* (McGraw Hill Company, New York, 1970)

A. Roth, *Vacuum Technology*, 2nd edn (North-Holland, Amsterdam, 1982)

Appendix V

Properties of Some Semiconductors

Semi-conductor	Structure(s)	Lattice constant(s)/Å	Bulk band-gap at 300 KeV	[a]Electron effective mass/m_0	[a]Hole effective mass/m_0	Static dielectric constant
Si	Cubic, Diamond	5.431	1.12 (i)	0.98; 0.19	0.16;0.49	11.4
GaAs	Zinc blende	5.653	1.42 (d)	0.067	0.082	13.1
GaSb	Zinc blende	6.098	0.72 (d)	0.042	0.4	15.7
Ge	Cubic, Diamond	5.646	0.66 (i)	1.64; 0.082	0.04;0.28	16
ZnO	Wurtzite	$a = 3.25$, $c = 5.2$; $a = 4.58$	3.35 (d)	0.29	1.21	9
	Rock salt					
ZnS	Zinc blende	5.42	3.68 (d)	0.4	0.61	5.2
ZnSe	Wurtzite; Zinc blende	$a = 3.82$, $c = 6.626$; $a = 5.668$	2.7 (d)	0.17	1.44	9.12
InP	Zinc blende	5.869	1.35 (d)	0.077	0.64	12.4
InAs	Zinc blende	6.058	0.36 (d)	0.023	0.4	14.6
InSb	Zinc blende	6.479	0.17 (d)	0.0145	0.4	17.7
CdS	Wurtzite	$a = 4.16$, $c = 6.756$	2.42 (d)	0.21	0.8	5.4
CdSe	Zinc blende	6.05	1.7 (d)	0.13	0.45	10
CdTe	Zinc blende	6.482	1.56 (d)	0.11	0.4	10.2
PbS	Rock salt	5.9362	0.41 (d)	0.25	0.25	17
PbSe	Cubic	6.117	0.27 (d)	0.047	0.041	280
PbTe	Rock salt	6.462	0.31 (d)	0.17	0.2	30

[a] 'm_0' stands for the standard electron mass $= 9.1 \times 10^{-31}$ kg. 'i' and 'd' are for indirect and direct band gaps respectively

Appendix VI

Kronig Penney Model (1-D)

Free electron theory cannot explain the various observed properties of solids. The band theory could explain the various properties like conductivity, Hall effect etc. correctly. The origin of bands in a solid can be understood by considering the motion of an electron in a one dimensional periodic lattice. The model was first proposed by Kronig and Penney way back in 1930 and bears their name. Kronig and Penney assumed that the electron experiences, as illustrated in Fig. A.11 a periodic potential with a period $(a + b)$.

Potential energy is zero between 0 and a and maximum (V_o) at 0 and a. Atomic nuclei are separated by a period of $(a + b)$. Thus

$$0 < x < a. \quad V = 0 \tag{A.1}$$

$$-b < x < 0, \quad V = V_0 \tag{A.2}$$

Schrödinger equations for the two regions are

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} E\psi = 0 \ (0 < x < a) \tag{A.3}$$

and

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} (E - V_0)\,\psi = 0 \ (-b < x < 0) \tag{A.4}$$

We assume that, for the electron, $E < V_0$.

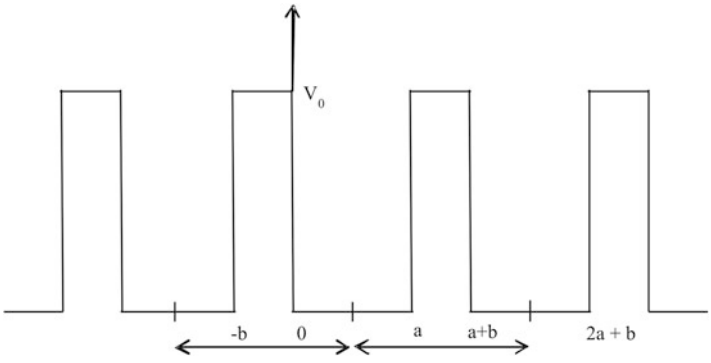


Fig. A.11 Periodic potential in a 1-D lattice

Put

$$\frac{2mE}{\hbar^2} = \alpha^2 \tag{A.5}$$

and

$$\frac{2m}{\hbar^2}(V_0 - E) = \beta^2 \ \ (\text{as } E < V_0) \tag{A.6}$$

The Bloch theorem for the motion of an electron in the periodic potential states that if $u(x) = u(x + a)$ where 'a' is the lattice spacing then

$$\psi(x) = e^{\pm ikx}\, u(x) \tag{A.7}$$

is the plane wave solution of the Schrödinger equation modulated by the periodicity of the lattice.

Using (A.7) and substituting in Eqs. A.3 and A.4 we get

$$\frac{d^2u}{dx^2} + 2ik\frac{du}{dx} - \left(a^2 + k^2\right)u = 0 \quad (\text{for } 0 < x < a) \tag{A.8}$$

and

$$\frac{d^2u}{dx^2} + 2ik\frac{du}{dx} - \left(\beta^2 + k^2\right)u = 0 \quad (\text{for } -b < x < 0) \tag{A.9}$$

Consider the following solutions for these equations as

$$u_1 = Ae^{i(a-k)x} + Be^{-i(a+k)x} \quad (\text{for } \ 0 < x < a) \tag{A.10}$$

and

$$u_2 = Ce^{(\beta - ik)x} + De^{-(\beta + ik)x} \quad (\text{for } \ -b < x < 0) \tag{A.11}$$

where, A, B, C and D are constants. These constants have to be chosen such that they satisfy the boundary conditions

For continuity:

$$u_1(0) = u_2(0) \text{ and } \left(\frac{du_1}{dx}\right)_{x=0} = \left(\frac{du_2}{dx}\right)_{x=0} \tag{A.12}$$

For periodicity:

$$u_1(a) = u_2(-b) \text{ and } \left(\frac{du_1}{dx}\right)_{x=a} = \left(\frac{du_2}{dx}\right)_{x=-b} \tag{A.13}$$

These lead to four linear equations involving constants A, B, C and D.

The four equations have a solution if the determinant of coefficients of A, B, C, and D vanishes.

This leads to the equation

$$\frac{\beta^2 - \alpha^2}{2\alpha\beta} \sinh\ (\beta b) \sin(\alpha a) + \cosh\ (\beta b) \cos(\alpha a) = \cos k\,(a + b) \tag{A.14}$$

If $V_0 \to \infty$ and $b \to 0$ but $V_0 b$ is finite then

$$\frac{m V_0 b a}{\hbar^2 \alpha} \sin\ (\alpha a) + \cos\ (\alpha a) = \cos(ka) \tag{A.15}$$

By writing

$$p = \frac{m V_0 b a}{\hbar^2} \tag{A.16}$$

We get simplified form of Eq. A.14 as

$$P \frac{\sin\ (\alpha a)}{\alpha a} + \cos\ (\alpha a) = \cos(ka) \tag{A.17}$$

R.H.S can take values between $+1$ and -1. This implies only allowed values of αa for which L.H.S. lies between ± 1. Thus one can see that

1. Electron energy spectrum has values separated by forbidden regions.
2. With increasing αa band width increases.
3. Width of a band decreases as P increases (Fig. A.12).

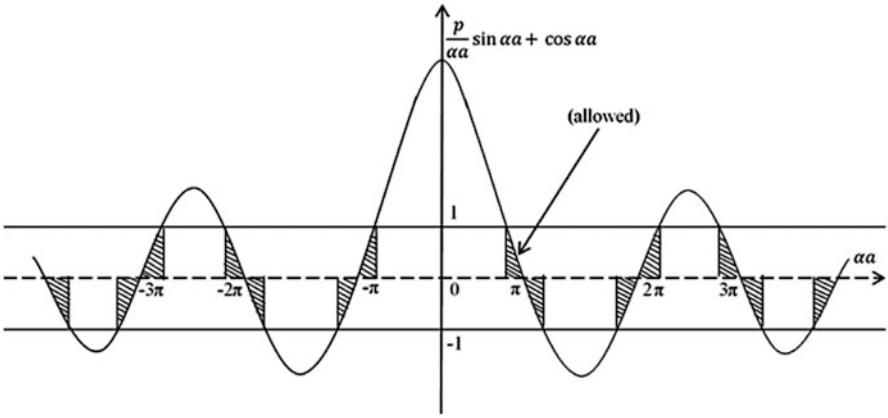


Fig. A.12 Graphical representation of Eq. A.17

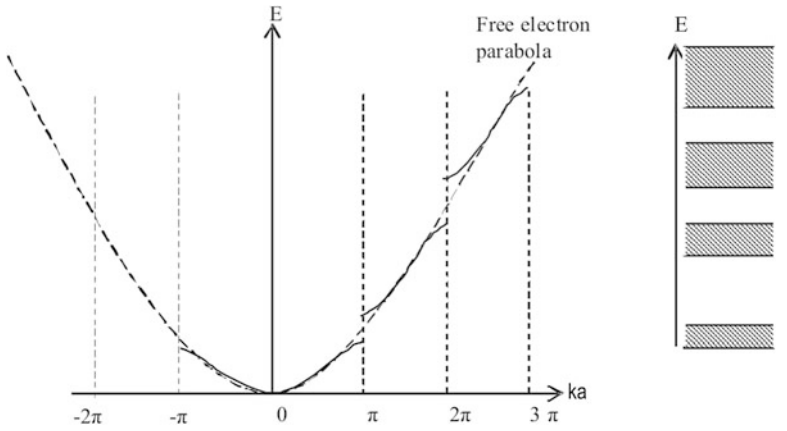


Fig. A.13 On the left hand side a plot of E against ka for an electron in a periodic lattice, as predicted by Kronig Penney model is shown. The *dotted* free electron parabola shows the effect of neglecting the periodic potential in a solid and simply assuming the electron gas. Illustration on the right hand side is schematics showing how electron energy band separation decreases as we go on increasing the energy

When $P \to \infty$ allowed region narrows down to aline spectrum.
If, $P \to \infty$,

$$\sin\ \alpha a = 0\ \text{ i.e. }\ aa = \pm n\pi,\ \ \text{where } n = 1, 2, 3, \ldots$$

$$\alpha^2 = \frac{2mE}{\hbar^2} = (n\pi)^{\mathbf{2}} \tag{A.18}$$

Therefore $$E_n = \frac{n^2\hbar^2\boldsymbol{\pi}^{\mathbf{2}}}{2m}$$

When E is plotted against ka, we get a plot as illustrated in Fig. A.13.

Further Reading

A.J. Dekker, *Solid State Physics* (Macmillan, London, 1952)
C. Kittel, *Introduction to Solid State Physics*, 5th edn (Wiley Eastern Ltd., New Delhi, 1994)

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S.K. Kulkarni, *Nanotechnology: Principles and Practices*,
DOI 10.1007/978-3-319-09171-6

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