speeds as high as 10 to 50 L/s [21]. One getter ion pump package has a combined pumping speed of 1000 L/s [22]. NEG pumps have a large capacity for pumping hydrogen [16]. The NEG pump has been used in fusion machines [19,23,24] because it can operate without a magnetic field, and has a high hydrogen pumping speed at room temperature. With the assistance of an ion pump to handle the methane and argon, the NEG can reach base pressures of 10^{-9} Pa. The CERN large positron collider uses 27 km of linear NEG pump with a speed of 500 L/s per meter of chamber [24]. Getter pumping is also found in Tokamaks to control the density of hydrogen plasmas and remove chemically active impurities. The use of glow discharge cleaning has been shown to have no deleterious effects on the operation of a Zr-Al NEG [25]. Hseuh and Lanni [26] have established a worst case pressure of less than 3×10^{-9} Pa in an accelerator storage ring using a linear Zr-V-Fe alloy and lumped ion pumps 10 m apart. Getter pumps are now finding other applications, such as for purifying gases used in semiconductor device processing equipment.

14.2 ION PUMPS

The development of the ion pump has made it possible to pump to the ultrahigh vacuum region without concern for heavy organic contamination. This pump exploits a phenomenon formerly considered detrimental to vacuum gauge operation—pumping gases by ions in Bayard-Alpert and Penning gauges. Ions are pumped easily because they are more reactive with surfaces than neutral molecules and if sufficiently energetic can physically embed themselves in the pump walls. If the ions were generated in a simple parallel-plate glow discharge, for example, the pumping mechanism would be restricted to a rather narrow pressure range. Above about 1 Pa the electrons cannot gain enough energy to make an ionizing collision and below about 10^{-1} to 10^{-2} Pa the electron mean free path becomes so long that the electrons collide with a wall before they encounter a gas molecule. Ions can be generated at lower pressures if the energetic electrons can be constrained from hitting a wall before they collide with a gas molecule. This confinement can be realized with certain combinations of electric and magnetic fields.

The pumping action of a magnetically confined dc discharge was first observed by Penning [27] in 1937, but it was not until two decades ago that Hall [28] combined several Penning cells and transformed the phenomenon into a functional pump. Some elemental forms of the (diode) sputter-ion pump are shown in Fig. 14.5. [29]. Each Penning cell is approximately 12 mm in diameter × 20 mm long with a 4-mm gap between the anode and the cathode. Modern pumps are constructed of modules of cells arranged

around the periphery of the vacuum wall with external permanent magnets of 0.1 to 0.2 T strength and cathode voltages of ~ 5 kV.

The electric fields present in each Penning cell trap the electrons in a potential well between the two cathodes and the axial magnetic field forces the electrons into circular orbits that prevent their reaching the anode. This combination of electric and magnetic fields causes the electrons to travel long distances in oscillating spiral paths before colliding with the anode and results in a high probability of ionizing collisions with gas molecules. The time from the random entrance of the first electron into the cell until the electron density reaches its steady-state value of ~ 10^{10} electrons/cm^3 is inversely proportional to pressure. The starting time of a cell at 10^{-1} Pa is nanoseconds, while at 10^{-9} Pa it is 500 s [30]. The ions produced in these collisions are accelerated toward the cathode, where they collide, sputter away the cathode, and release secondary electrons that in turn are accelerated by the field. Many other processes occur in addition to the processes necessary to sustain the discharge; for example a large number of low energy neutral atoms are created by molecular dissociation and some high energy neutrals are created from energetic ions by charge neutralization as they approach the cathode, collide, and recoil elastically.

The actual mechanism of pumping in an ion pump is dependent on the nature of the gas being pumped and is based on one or more of the following mechanisms: (1) precipitation or adsorption following molecular dissociation; (2) gettering by freshly sputtered cathode material; (3) surface burial under sputtered cathode material; (4) ion burial following ionization in the discharge; and (5) fast neutral atom burial. (Ions are neutralized by surface charge transfer and reflected to another surface

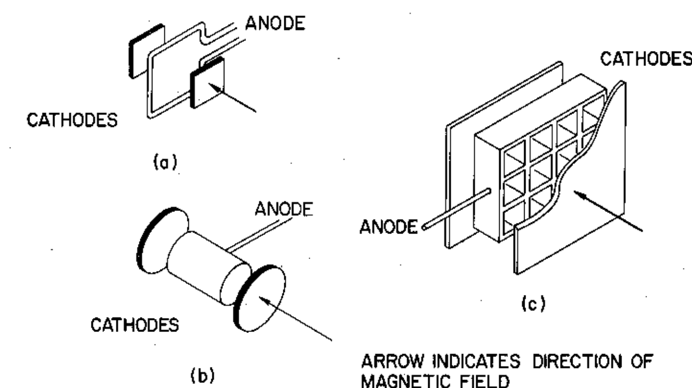

Fig. 14.5 Early forms of the diode sputter-ion pump: (a) ring anode cell [27]; (b) long anode cell [31]; same cell with Ti cathodes [32], (c) multicell anode [28]. Reproduced with permission from *Proc. 4th Int. Vac. Cong. (1968)*, p. 325, D. Andrew. Copyright 1969, The Institute of Physics.

where they are pumped by burial.) The first four of these mechanisms were elucidated by Rutherford, Mercer and Jepsen [33], and the role of the elastically scattered neutrals was explained by Jepsen [34]. These mechanisms are illustrated in Fig. 14.6.

Organic gases, active gases, hydrogen, and inert gases are pumped in distinctly different ways. There are a few generalities. Initially, gases tend to be pumped rapidly and their partial pressure decays to a steady state [34-36]. In steady state reemission rates equal pumping rates. This is more pronounced with noble than with active gases. Pumping speeds cannot be uniquely defined for a gas independent of the composition of other gases being pumped simultaneously. The sputter ion pump is capable of reemitting any pumped gas. This reemission or memory effect complicates the interpretation of some experiments.

Organic gases are easily pumped by adsorption and precipitation after being dissociated by electron bombardment [33].

Active gases such as oxygen, carbon monoxide, and nitrogen are pumped by reaction with titanium, which is sputtered on the anode surfaces, and by ion burial in the cathode. These gases are easily pumped because they form stable titanium compounds [33].

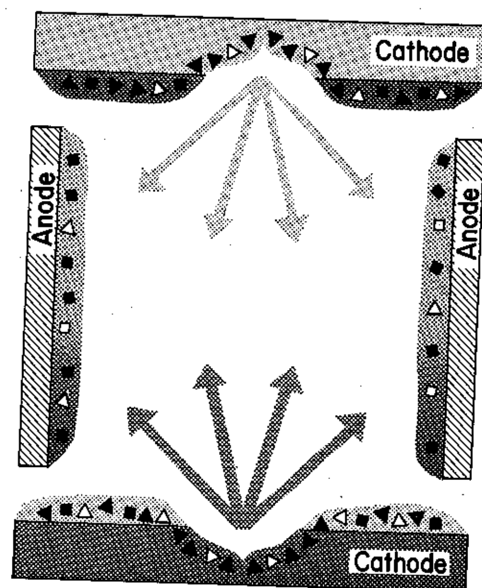

Fig. 14.6 Schematic diagram showing sputter deposition and pumping in a Penning cell: ■ chemically active gases buried as neutral particles; ▶ Chemically active gases ionized before burial; □ inert gases buried as neutral particles; △ inert gases ionized before burial. Reprinted with permission from *Proc. 4th Int. Vac. Congr. (1968)*, p. 325, D. Andrew. Copyright 1969, The Institute of Physics.

Hydrogen behaves differently. Its low mass prevents it from sputtering the cathode significantly. It behaves much like it does in a TSP. It is initially pumped by ion burial and neutral adsorption [34,37] and diffuses into the bulk of the titanium and forms a hydride. Sustained pumping of hydrogen at high pressures will cause cathodes to warp [33] and release gas as they heat. The hydrogen pumping speed does not rate limit unless cathode surfaces are covered with compounds that prevent indiffusion. The pumping of a small amount of an inert gas, say argon, cleans the surfaces and allow continued hydrogen pumping [38], whereas a trace amount of nitrogen will reduce the speed by contaminating the surface [37].

Noble gases are not pumped so efficiently as active gases in a diode pump. They are pumped by ion burial in the cathodes and by reflected neutral burial in the anodes and cathodes. The noble gas pumping on the cathodes is mostly in the area near the anodes where the sputter build-up occurs. Because most of the neutrals are reflected with low energies in the diode pump, their pumping speed in the anode or other cathode is low; for example, argon is pumped only at 1 to 2% of the active gas speed.

Argon, in particular, suffers from a pumping instability. Periodically the argon pressure will rise as pumped gas is released from the cathodes. Figure 14.7 [29] illustrates some of the geometries that were devised as a solution to the problem of low argon pumping speed and its periodic reemission. Brubaker [39] devised a triode pump with a collector surface that operated at a potential between the anode and cathode (Fig. 14.7*a*).

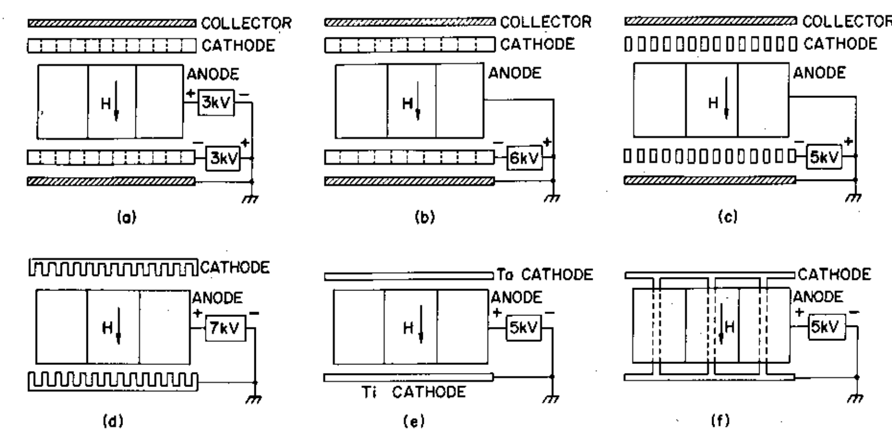

Fig. 14.7 Pump designs for inert gas pumping: (a) The triode pump of Brubaker [39]; (b) triode pump of Hamilton [40]; (c) triode Varian Noble Ion Pump [41]; (d) slotted cathode diode of Jepsen et al. [42]; (e) differential ion pump of Tom and Jones [43]; (f) magnetron pump of Andrew et al. [46]. Reprinted with permission from *Proc. 4th Int. Vac. Congr. (1968)*, p. 325, D. Andrew. Copyright 1969, The Institute of Physics.

Its function was to collect low energy ions that could not sputter. Hamilton [40] showed it worked equally well when the collector surface was held at anode potential (Fig. 14.7*b*). In the triode pump the argon pumping speeds are as high as 20% of the nitrogen speed. This high speed (high implantation rate) results from the high energy of the neutrals which are scattered at small angles from the cathode walls with little energy loss. Sputtering is much more efficient at these small angles than at normal incidence and sputtering of titanium on the collector is more efficient than in the diode pump. The slotted cathode [42] attempts to accomplish this sputtering with one less electrode than the triode (Fig. 14.7*d*). This pump has an argon pumping speed of 10% of the speed for air. Tom and Jones [43] devised the differential diode ion pump sketched in Fig. 14.7*e*. One titanium cathode was replaced by a tantalum cathode. In this manner the recoil energy of the scattered noble gas neutrals, which depends on the relative atomic weight of the cathode material and gas atom, is increased [44,45]. This gives more effective noble gas pumping than in the diode pump. An argon-stable magnetron structure, (Fig. 14.7*f*), was devised by Andrew et al. [46]. The central cathode rod is bombarded by a high flux of ions at oblique angles of incidence. The sputtering of the rod creates a flux that continually coats the cathode plates and the impinging ions and results in a net argon speed of 12% of the air speed [46]. Among the designs discussed here for increasing the argon pumping speed and reducing or eliminating its instability the triode and differential diode are in most widespread use.

The operating pressure range of the sputter-ion pump extends from 10^{-2} to below 10^{-8} Pa. A characteristic pumping speed curve of a diode and a triode pump are shown in Fig. 14.8. If starting is attempted at high pressures, say 1 Pa, a glow discharge appears and the elements heat and release hydrogen. As the pressure is reduced, the glow discharge extinguishes and the speed rapidly increases. At low pressures the speed decreases because the sputtering and ionization processes decrease. The exact shape of a pumping speed curve is a function of the magnetic field intensity, cathode voltage, and cell diameter-to-length ratio. As the pressure decreases, the ionization current decreases proportionately and the pressure in the pump may be obtained from the ion current without the need for an ionization gauge tube.

The lifetime of a diode pump is a function of the time necessary to sputter through the cathodes. A typical value is 5000 h at 10^{-3} Pa or 50,000 h at 10^{-4} Pa. The triode, which pumps slightly better than the diode at high pressures, is also easier to start at high pressures and has a lifetime of less than half the diode. In both pumps the life may be shorter due to shorting of the electrodes by loose flakes of titanium.

The sputter ion pump has the advantage of freedom from hydrocarbon contamination and ease of fault protecting but does suffer from the

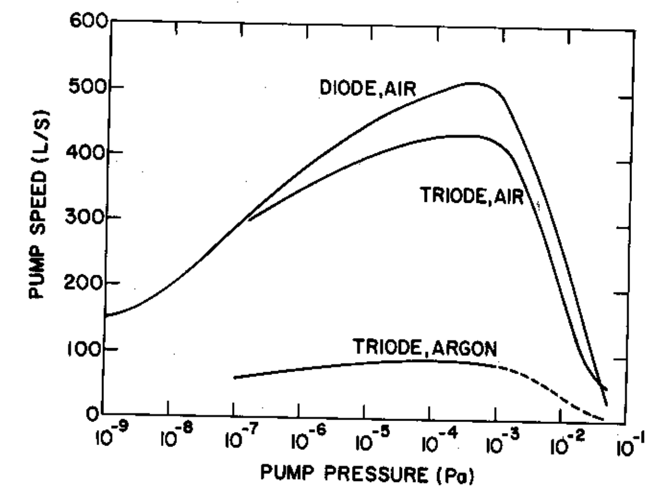

Fig. 14.8 Pumping speeds for air and argon for the 500-L/s Varian diode Vac Ion pump and for the 400-L/s triode Vac Ion pump. Speeds measured at the inlet of the pump. Reprinted with permission from Varian Associates, 611 Hansen Way, Palo Alto, CA 94303.

reemission of previously pumped gases, particularly hydrogen, methane and the noble gases.

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PROBLEMS

14.1 †Why does a non-evaporable getter (NEG) need to be heated to an activation temperature before being operated as a pump?

14.2 †How is a non-evaporable getter restored after saturation?

14.3 A TSP has an oxygen speed of 3000 L/s on a liquid-nitrogen-cooled surface at 1.33×10^{-4} Pa. How many titanium atoms must strike the pump surface per second per unit area?

14.4 Using the average sticking coefficients given in Table 14.2, calculate the room-temperature pumping speeds per unit area for oxygen, hydrogen, carbon dioxide and nitrogen.

14.5 Calculate the nitrogen pumping speed of the pump shown in Fig. 14.1 assuming it has a 30-cm diameter inlet, is 30-cm diameter in length and is cooled with water. Now replace the water with liquid nitrogen and calculate its speed. Why did the speed not increase significantly?

14.6 †How is a TSP restored after it is saturated?

14.7 99.99% argon is admitted into a chamber connected to an ion pump. The RGA shows a methane peak which is 10% of the argon peak. Explain.

14.8 †Why are ion pumps not used for routine pumping in the 10^{-4}-Pa pressure range?

14.9 †Why place a grounded screen over an ion pump inlet?

14.10 †For what reason is dry nitrogen used as a vent or flush gas in ion-pumped systems?