

THE ION PUMP

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Until recently no serious attempt has been made to utilize the phenomenon of 'Electrical Clean-up of Gases' [2] as the sole means of maintaining ultra-low pressures. About ten years ago Alpert and his co-workers [1] found that lower pressures are obtained in well-baked vacuum systems if the ion gauge is allowed to run and the diffusion pump is valved off. More recently, Gurewitsch and Westendorp [3] have shown that the Penning discharge with titanium electrodes can be an effective ion pump.

A clean, hydrocarbon-free vacuum is needed today in many instances. The high-energy machines of nuclear physics, the particle accelerators, require this kind of vacuum. The exceptionally high-purity materials of the semiconductor field are processed and sometimes alloyed under vacuum. When this is done, the best vacuum obtainable is required. Ultra-sensitive analyzers which are used for monitoring the composition of these materials must of necessity use vacuum systems. Again, all contaminants must be avoided.

The ion pump is the ideal means to achieve these low pressures. Since it is constructed entirely of low vapor pressure metals, it adds no contaminant to the system. No traps are required to isolate the vacuum pump to prevent the contamination of the system by the pump itself. Further, its pumping action is independent of pressure. There is no low pressure limit of its operation.

THEORY

An ion pump, as the name suggests, accomplishes its pumping action through the use of ions. It is desirable that ions be made in the most efficient manner. This appears to be done with a Penning discharge in a magnetic field. Having made the ions, they are utilized to achieve pumping action in two ways. First, they may be removed from the apparatus by burial in the cathode. Second, the ions on their impingement into the cathode, sputter some of the cathode material on to other parts of the apparatus. If the sputtered cathode material is a highly reactive metal, like titanium, it will react chemically with the molecules of many gases and thus remove them from the system. This is why the ion pumps are sometimes called getter-ion pumps.

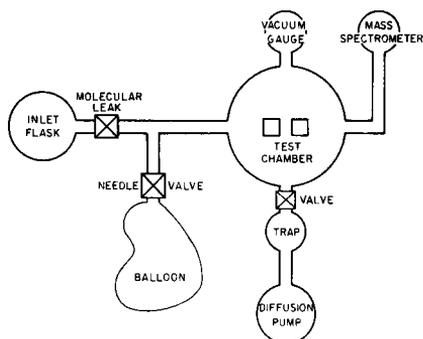


Fig. 1.—Vacuum system schematic.

When proper attention is given to the trapping of the electrons at the ends of the anode structure, the Penning discharge is found to be stable at the lowest pressures attainable. Hobson and Redhead [4] have reported Penning discharges at pressures of the order of 10^{-12} mm. The fact that the discharge current is nearly proportional to the pressure over a pressure range of many decades indicates that the intensity of the ionizing electron beam is independent of pressure.

Gases which do not react chemically with the sputtered cathode material must be pumped solely by burial in the cathode. Continued sputtering (erosion) of the cathode surface exposes these atoms, releasing them to the system. In the simple two-electrode Penning structure, this leads to instabilities in the pumping action for the noble gases.

EXPERIMENTAL PROCEDURE

The apparatus used is shown schematically in Fig. 1. The test chamber is evacuated by an oil diffusion pump through a trap. Gas is admitted to the system from either of two inlet systems. The total pressure is monitored by a Bayard-Alpert type ion gauge, and the partial pressures by the mass spectrometer. The use of the mass spectrometer has two advantages. First, it is responsive only to the pressure of a chosen gas. Second, it has a pumping speed which is quite small relative to the pumping speed of the ion gauge and so it makes a minimum disturbance to the pressure in the system.

It is apparent that the ion pump (Penning discharge) operates in parallel with the conventional pumps. In this manner, the pressures of all gases quickly attain equilibrium values when the discharge is turned on or off.

EXPERIMENTS

The first two experiments to be reported demonstrated that the noble gases are pumped effectively at the cathode, and not at the anode. The apparatus

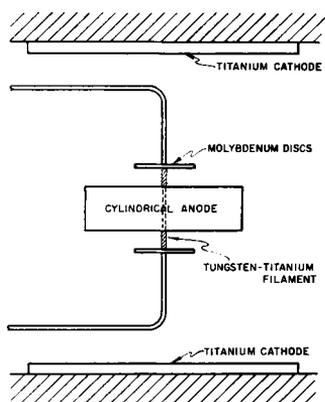


Fig. 2.

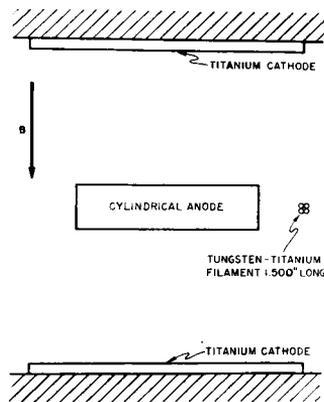


Fig. 3.

Fig. 2.—Two-electrode unit designed to test the influence of a freshly deposited layer of titanium on the anode alone.

Fig. 3.—Two-electrode unit designed to test the influence of a freshly deposited layer of titanium on the cathode surfaces.

of Fig. 2 was used for the first experiment. It had previously been shown that the presence of a small cylindrical electrode on the axis, at cathode potential, makes no discernible change in the volt-ampere characteristic. Midway between the cathodes is a short titanium-tungsten filament. The cathode surfaces are shielded from the evaporated titanium by the molybdenum discs. The anode surface, however, receives titanium directly from the hot filament. With argon flowing through the test chamber, the filament was heated to evaporate the titanium. No appreciable change was noted in the argon pressure by the mass spectrometer.

To test the effect of evaporating titanium on to the cathode of the discharge, the apparatus of Fig. 3 was used. This is similar to that used in the first experiment, except that now the titanium reaches the cathodes, and not the active portions of the anode. The evaporation of titanium while the discharge was running caused the argon pressure to decrease 30 times. Further, under these conditions the discharge current is essentially equal to the product of the time rate of removal of the gas molecules and the electronic charge. This is consistent with two assumptions. First, that the cathode current is primarily ionic. Second, that the neutralized ions do not return to the test chamber when they are protected from the erosive effect of the cathode sputtering.

The above experiments show that the pumping action of the Penning discharge is greatly enhanced if the cathode area receives a fresh deposit of titanium. Obviously, the optimum rate at which the titanium is deposited is pressure dependent. The inclusion of filaments in an ion pump is impractical. An insufficient amount of titanium can be evaporated from such

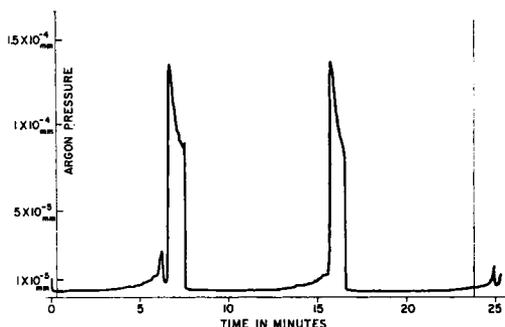


Fig. 4.—Mass spectrometer record of the pressure of argon in a system pumped solely by a two-electrode unit. This is an example of the instabilities in the pumping of the two-electrode units.

a filament, and the rate of evaporation is not readily made proportional to the pressure. Ideally, the discharge itself should be made to cause the deposition of titanium on the ion collector.

Many experiments have been made on the pumping characteristics of a two-electrode Penning discharge for argon. Instabilities of many kinds were noted. Fig. 4 shows the strip chart recorder trace of the pressure of argon in a system pumped solely by the Penning discharge. No external adjustments were made on the apparatus during this time. The period of the instabilities in this case is about nine minutes. Periods of eight seconds have been observed.

The apparatus of Fig. 5 shows a test unit which was designed to test the possibility of using a portion of the ions to effectively sputter titanium on to the cathode, so as to overcome the erosion action of the ions incident on the cathode. Two insulated titanium cones are placed over the two cathodes, on the axis of the device. When these cones are made negative relative to the cathode, the energy with which the ions strike the cones is increased. This enhances the sputtering of titanium from the cones.

The behavior of the apparatus of Fig. 5, when it is pumping argon in parallel with a conventional oil diffusion pump through a copper foil trap, is shown in Fig. 6. The pressure indicated by the slowly falling line denotes the argon pressure in the absence of ionic pumping. The decay represents

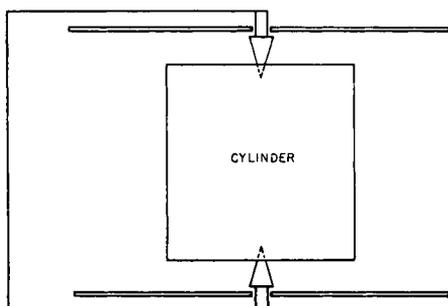


Fig. 5.—Three-electrode unit. The cones of titanium, placed on the axis, constitute the third electrode. When they are energized negatively with respect to the main cathode, the pumping speed for argon is greatly enhanced.

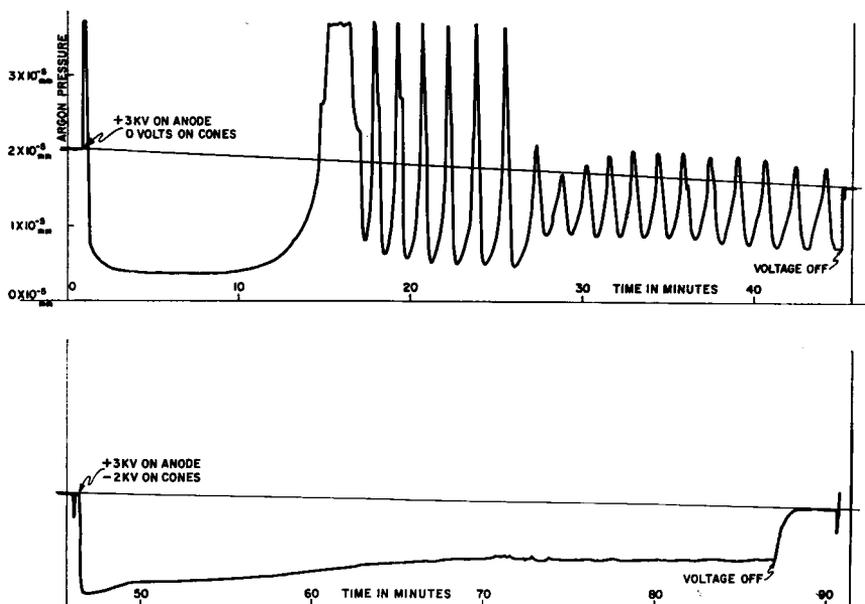


Fig. 6.—Mass spectrometer record of the pressure of argon in the unit shown in Fig. 5. Note the lower, steady pressure which results from the application of potential to the cones (Sputter cathodes).

the exhaustion of the gas in the flask of Fig. 1. The initial influence of the discharge is to cause the pressure of argon to rise. During the first 45 minutes the cones are placed at cathode potential. The pressure decreases to a low value, but soon rises to a very high value, off scale on this record. Thereafter, it goes through successive intervals of pumping and outgasing, at the rate of nearly 1 c/min. At the end of a 45-minute period of erratic pumping, the voltage is turned off and the pressure rises to the value at which the conventional pump removes the argon as fast as it enters the system from the flask. The anode is again energized, and the cones are made 2000 V negative with respect to the cathode. Now the pumping action is continuous, and at a higher rate than before. This is evidenced by the lower pressure of the argon as seen by the mass spectrometer.

The increased pumping speed which results from the application of a negative potential to the cones is due to the increased ion collection efficiency on the cathodes. The titanium which is showered from the cones on the main cathodes discourages the release of the pumped gas by subsequent ion bombardment. The ions of argon which are driven into the cones are released as neutral molecules by the continued bombardment of the cones. However, only a small portion of the total number of ions formed strike the cones.

To test the relative merits of a three-electrode and a two-electrode struc-

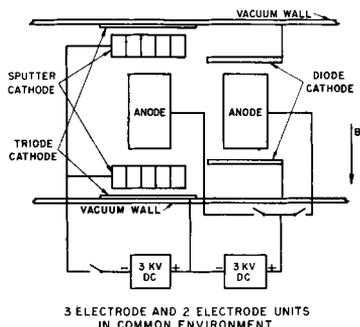


Fig. 7.—A two-electrode and a three-electrode unit in the same environment. These were operated simultaneously in argon at a pressure of 10^{-6} mm.

ture, the apparatus of Fig. 7 was assembled. Here we have a different type of three-electrode unit placed in the same envelope with a two-electrode unit. This third electrode (sputter cathode) is of cellular structure, energized at -3 kV.

The two units were operated in parallel in an argon pressure of 10^{-6} mm. Periodically they were operated singly and their pumping speeds measured. The pumping speed of the three-electrode, in l/sec, is shown in Fig. 8. Fig. 9 shows the same data for the two-electrode unit. Here we note a decrease in pumping speed with time. Finally, in Fig. 10, we show the ratio of the observed pumping speeds for the two units.

In the two-electrode unit, the sputtering action of the positive ions erodes the cathodes, forming a depression near the axis. Ions which strike the sides of the depression tend to sputter titanium from one side to the other. This is not conducive to effective pumping.

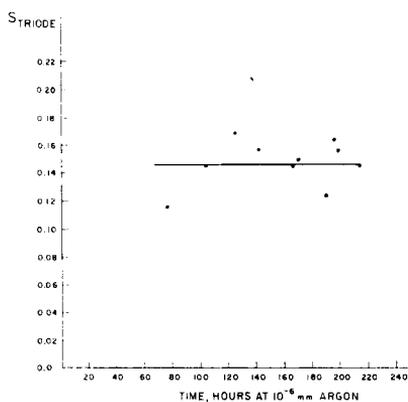


Fig. 8.

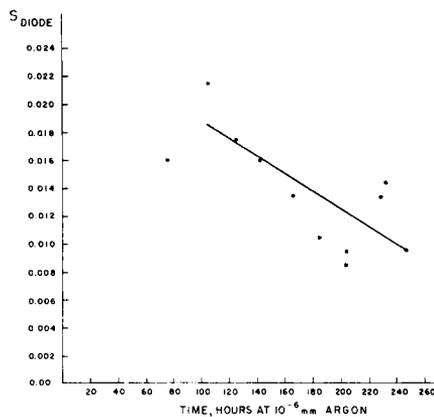


Fig. 9.

Fig. 8.—Speed of three-electrode unit, l/sec as a function of time.

Fig. 9.—Speed of two-electrode unit, l/sec as a function of time.

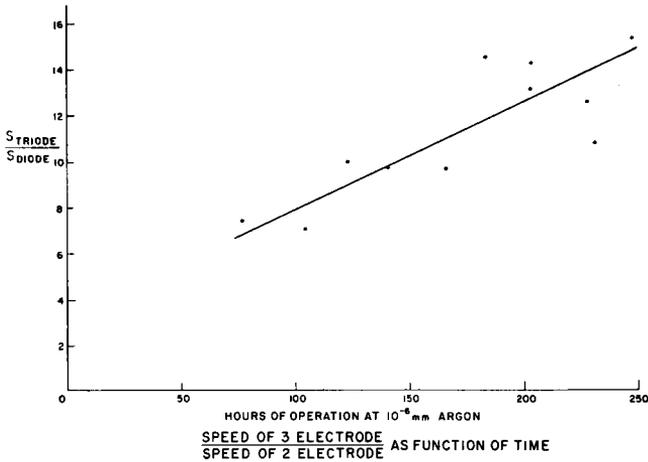


Fig. 10.—Ratio of the pumping speeds of the three-electrode to the two-electrode unit as a function of time.

After operating in an argon atmosphere for a period of time, the cathodes on a two-electrode structure were eroded to a depth of 1.7 mm. The cathode of the three-electrode structure showed no visible erosion. The edges of the sputter cathodes which faced the anode were thinned, but less than ten per cent of the available titanium had been removed.

The pumping speed of units similar to the three-electrode unit of Fig. 7 has been observed for other gases. Relative to the speed for argon, the speed for hydrogen is seven, that for air three, and for helium it is one-fourth. The lower speed for helium is due largely to the smaller ionization cross section. The larger speeds for hydrogen and air are attributed to the gettering action of the sputtered titanium for these gases.

DISCUSSION

We have many records of the type illustrated by Figs. 4 and 6. We also have records which show a reasonable stability for a period of time. However, the two-electrode units are prone to exhibit rather severe pumping instabilities when pumping the noble gases. The three-electrode units, on the other hand, are comparatively free from this defect. Further, they are only slightly influenced by small voltage fluctuations, as compared to the two-electrode units.

In summary, the addition of the third electrode to a unit with a given anode gives the following improvements: (1) The pump operates stably with time. (No intermittencies in pumping.) (2) The pumping speed for argon

is increased ten times. (3) The pumping speed for air is increased four times. (4) Life of pump is very greatly increased, and the efficiency of operation remains high throughout the life of the pump.

It is a pleasure to acknowledge the benefits of many helpful discussions of this work with Dr. Clifford E. Berry. His continued support and encouragement are much appreciated. Further, the aid given by Mr. Fred Pickett through his craftsmanship in the design, construction and assembly of the apparatus is gratefully remembered.

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