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Overview on the Development of UHV Ion Pumps

Luca Bonmassar

Varian Vacuum Technologies, Via F.lli Varian 54 10040 Leini, Torino, Italy

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The paper reviews the development of ion pumps, their operating principles and describes particular designs. The performance of ion pumps when used for various gases, their range of operation and fields of application are discussed.

keywords : Ion pump, Diode, Starcell, Vacuum

I. Introduction

The earliest evidence of a pumping effect of a gas discharge was reported in 1858 by Plucker [1,2]: "Certain gases react... with the platinum cathode and the resulting compounds are deposited on the walls. So we approach... the absolute vacuum." In 1916 Vegard [3] observed a change in the absorption when changing the cathode material, demonstrating that the absorption is related to the cathode. In 1937 as an offshoot of his work on electrical discharge in gases, F. Penning developed a cold cathode ionization gauge for measuring pressures in the range from 10^{-3} to 10^{-5} Torr. He reported that: "..., owing to the discharge, a certain amount of the gas disappears.". [4,5] The Penning cell has been used as a commercially available vacuum gauge ever since. Four years later in 1949 Gurewitsch and Westendrop applied for a patent on various form of single cell pumps, and use of different cathode materials. [6] Later on they found out that the use of Titanium cathodes increases strongly the pumping speed of hydrogen and measured a pumping speed of 0.03 l/s for hydrogen. [7] In 1958 Hall presented an "Electronic ultrahigh vacuum pump" with a multicell anode and a pumping speed of 10 l/s at 10^{-7} Torr. [8] The industrial application of ion pumps (IPs) for ultra high vacuum were pioneered by a group of engineers and scientists at Varian Associates in the late 1950's and in the early 1960's. The IPs nowadays in use are the result of these efforts.

In the next section the principles of ion pumping are described.

Section 3 gives some details about the Penning cell, which is the building brick of the sputter ion pump.

Section 4 describes the modern sputter ion pump.

Section 5 explains the pumping mechanism for different gases.

In section 6 the performance of the different kind of pumping elements are analysed, while in the last section the main applications are described.

II. Principles of Ion Pump

All the pumps whose pumping mechanism depends on the creation of charged particles are usually referred to as "ion pumps". In the ion pumping mechanism the gas molecules are transferred from the gas phase to the solid phase inside the system.

* [E-mail] bc.lee@varianinc.com

The basics working mechanism of an ion pump is the following:

a. Capital Letter electrons are trapped
b. Capital Letter molecules of the background gas are ionized by collision with the electron cloud
c. Capital Letter these ions are accelerated by the electric field
d. Capital Letter the ions are implanted in the surface on which they impinge
e. Capital Letter some atoms are emitted from the surface due to bombardment (sputtering)
f. Capital Letter the bombarded surface consists of a chemical reactive material, so the sputtered particles create an active surface that will trap the gas

The first aim of any ion pump is to create a cloud of electrons that can ionize the gas. At the working pressure of an ion pump the gas density is very low, so the probability that an electron create a ionizing collision is small. Therefore the ion pumps are designed in order to obtain the highest ionization rate with a reasonably low electric field. In order to increase the ionization probability you can increase the number of electrons or increase the electron path. The electron current is usually limited by power consideration, while the main factor in the design of an ion pump is an arrangement for extending the electron's path. The first approach was to use a hot filament to create electrons and an electrostatic field to trap them. [9-15] The description of this kind of pump is beyond the scope of this paper.

The most popular ion pump and now the only one commercially available is the Sputter-Ion Pump. The building brick of the ion pump is the Penning cell, whose characteristics are outlined in the next section.

III. Electrical Characteristics of the Penning Cell

The Penning cell is composed of a cylindrical anode and two cathode plates.

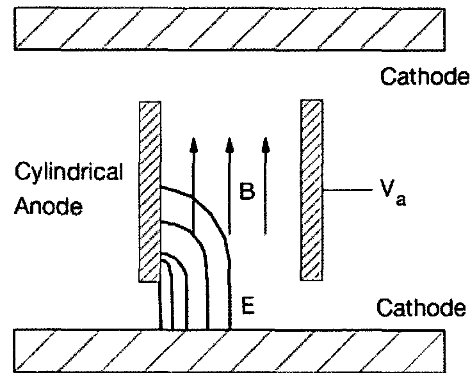

Fig. 1. Long-anode Penning structure

A voltage of a few kV is applied between anode and cathode. Along the anode axis is applied a magnetic field of about one kilogauss. Due to the combined action of the magnetic and the electric field the electrons follow a cycloidal trajectory.

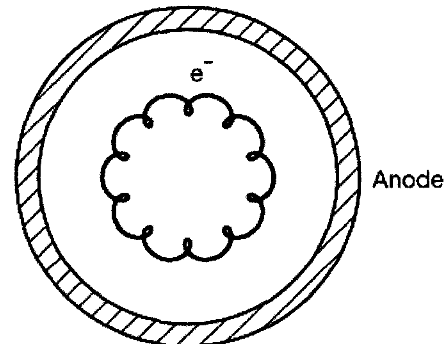

Fig. 2. Example of electron trajectories in a Penning cell

The electrons will never reach the anode unless they collide with the gas. If the electron energy is bigger than the ionization energy the electron, colliding with the gas, can create an ionizing event.

Let τ be the probability that a positive ion will cause an avalanche-initiating electron to be freed at or near the cathode and na be the number of electrons arriving at the cathode. Thus a self sustaining Townsed avalanche is obtained if the following equation is satisfied [16]:

$$na < 1 + \frac{1}{\tau} \quad (1)$$

The self-sustaining discharge can be maintained down to 10^{-13} mbar. The ions created, due to their big mass, are not trapped by the Penning cell and reach quickly the cathode.

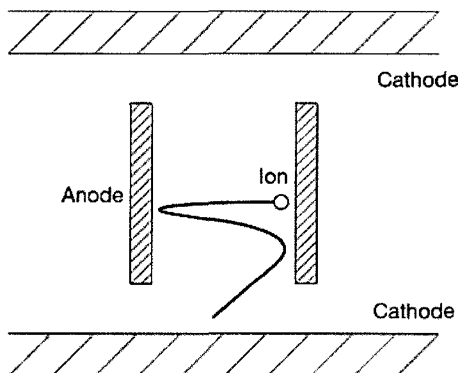

Fig. 3. Example of ion trajectories in a Penning cell

So for pressure lower than 10^{-3} mbar the electron density is much bigger than the ion density and a negative non-neutral plasma is obtained inside the anode.

If q is the total charge trapped inside the cell, f is the fraction of electron which have enough energy to ionize the gas and τ is the mean time between two ionizing collisions, the total current can be evaluated by:

$$I = -fq / \tau \quad (2)$$

τ can be approximated by:

$$\tau = C / P \quad (3)$$

where P is the gas pressure and C a constant depending on the gas species. Substituting (3) in (2) we obtain an equation for the ratio I/P for a Penning cell:

$$I/P = fq/C \quad (4)$$

An evaluation of q can be obtained by solving the Poisson equation in the approximation of constant electron density inside the cell and neglecting the axial field. A detailed discussion can be find in literature. [16-18] We give here only a qualitative description.

a. I/P is proportional to the length of the cell. This linearity arise from the fact that the amount of charge that can be contained inside an Penning cell is directly proportional to the length of the anode.
b. At low voltage three factors discourage the establishment of a self-sustaining discharge.

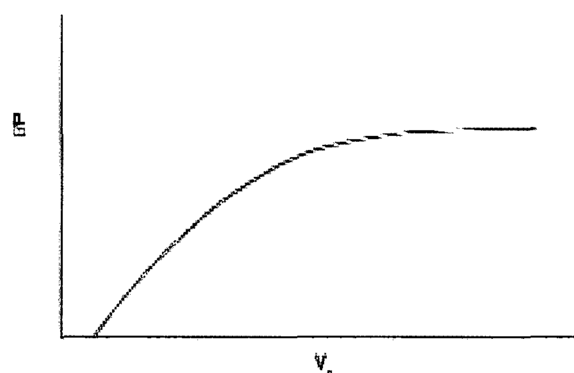

Fig. 4. Quality dependence of I/P on anode voltage for a Penning cell

One factor is that the number of ionizing collision made by an avalanche initiating electron is necessarily less than (Va/Vi), where Va is the anode voltage and Vi the ionizing potential of the gas. A second factor is that other collision processes become dominant at low electron energy. The third factor is that depends on the ion energy.

c. At intermediate voltage I/P rise rapidly with Va because q depends linearly with anode voltage Va, f increases monotonically with Va and q increases through the dependence of on ion energy.
d. If B is too small the electron orbit are too large for the discharge to exist. Above some critical value of B the existence of the discharge become possible as indicated by theories for striking characteristics. [19-24]

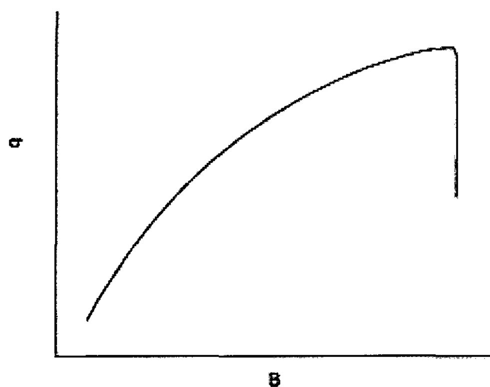

Fig. 5. Quality dependence of q on magnetic field B for a Penning cell

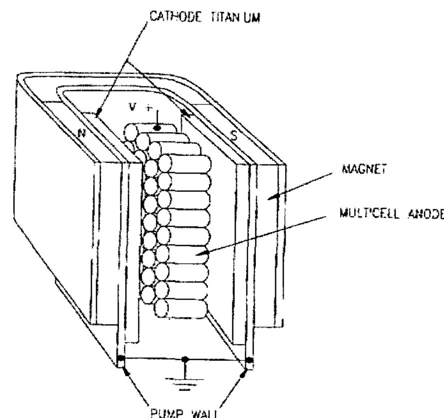

Fig. 6. Basic configuration of a sputter-ion pump

When B becomes so large that the electron maximum energy falls below the ionization energy other collision processes can cause q to fall to zero. It's important to notice that I/P is independent of either B or the cell radius ra provided that their product is constant. Thus the condition:

$$B \cdot r_a = \text{coustant} \quad (5)$$

is of evident practical utility in designing an ion pump.

The gas species affects I/P through the constant C, which varies inversely with collision cross section. Other properties of the gas affect I/P through the coefficient.

Ⅳ. The Sputter Ion Pump

The sputter-ion pump is composed of an array of Penning cells, with the cylindrical anode made of stainless steel and the two cathode made of titanium.

The cathode is at ground and the anode at a positive potential. The electrodes are enclosed in a stainless steel body. The magnetic field is obtained using permanent magnets and an iron yoke.

The number of gas molecules pumped is proportional to the ion current via the sputtering yield. If Q is the throughput (the number of molecules pumped per time unit), I the ion current and P the pressure then:

$$Q = h \cdot I \quad (6)$$

where h is a constant depending in the parameter of the pump. But for the definition of S we have:

$$S = Q/P = h \cdot I/P \quad (7)$$

Equation (7) clearly shows that the pumping speed is proportional to the ratio of current versus pressure. That's why the optimization of this parameter for the Penning cell becomes so important.

As previously discussed increasing the cell length will increase I/P. But this will also increase the gap between the magnet and, as a consequence, decrease the magnetic field, which has a negative effect on the ratio of ion current vs. pressure. The cell radius doesn't affect the Penning cell performances. So decreasing the radius allows the increasing of the charge trapped by the Penning cells. But in order to have the same I/P the product of the magnetic field and the radius must be constant. So decreasing the radius would mean to increase also the magnetic field.

Theoretical and experimental evaluation lead to the optimization of all these parameters.

[25-27] Titanium was chosen for its sputtering yield and for its property of reacting with active gases. The radius of cells is normally between 15 and 25 mm, the height is between 10 and 40 mm and the magnetic field varies from 1 to 1.5 kGauss. A voltage of 3kV is necessary to ensure the starting of the discharge. The current rises with voltage till a plateau is reached at 7 kV.

With such parameters the I/P ratio for a single Penning cell is from 5 to 30 A/mbar, while the pumping speed varies from 0.3 to 2 l/s. [28, 29]

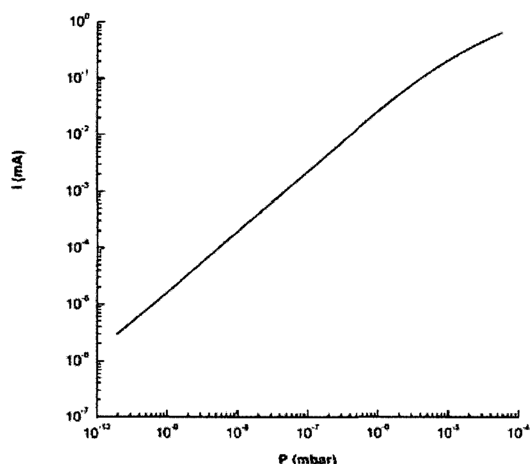

Fig. 7. Typical ion current vs pressure for a single cell sputter ion pump

The behaviour of the pumping speed of an ion pump slightly deviates from the model outlined before. The real dependence of current vs. pressure is given by the following:

$$I = kP^{n} \tag{8}$$

where n lies between 1.1 and 1.2. So the pumping speed at pressure lower than 10^{-6} mbar can be estimated by:

$$S = Q/P = h \cdot I/P = hkP^{n-1} \tag{9}$$

This equation shows how the pumping speed slightly increases with pressure.

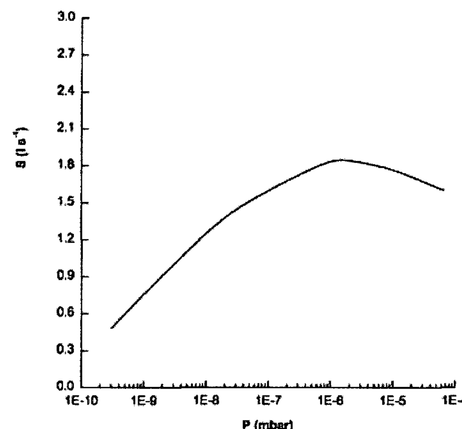

Fig. 8. Typical pumping speed vs pressure for a single cell sputter ion pump

At higher pressure (and consequently gas density) the current that can be trapped inside a Penning cell cannot rise indefinitely, causing a deviation from linearity of the current vs. pressure curve and a decrease of the pumping speed. Increasing further the pressure the voltage becomes too low and/or the heating for power dissipation is too high to allow stable operation.

V. Pumping Mechanism for Different Gases

The sputter-ion pump can pump a vast variety of gas, heavy hydrocarbons and noble gases included. Pump mechanism and as a consequence pumping speed are different for different gases. [30]

5.1 Active Gases (O_2, N_2, CO, CO_2)

As already mentioned the ions, created by the ionizing collision of the trapped electron with the gas, can sputter the titanium from the cathode by bombarding it. As a consequence on the anode and the pump walls a film of titanium is created. The gas molecules chemically react with the film creating a stable compound.

The ions implanted on the cathode are not pumped in a stable way. The continuous

cathode bombardment causes the implanted ions to be emitted back in the system

5.2 Hydrogen

The hydrogen is an active gas, but its pumping mechanism is different because of its small mass. [31] In the range of energy of the ion created in the ion pump the sputtering yield is a function of the ratio of the mass of the missile particle and the mass of the target atoms.

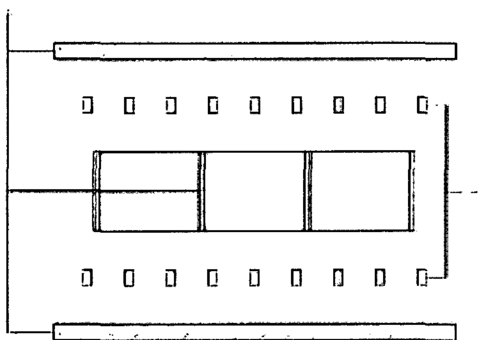

Fig. 9. Triode sputter-ion pump configuration

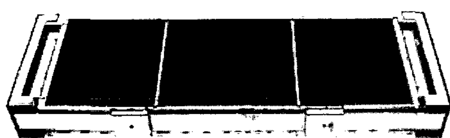

Fig. 10. Conventional triode element

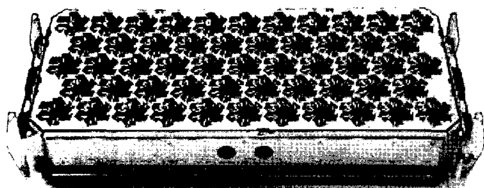

Fig. 11. Starcell triode element

Therefore the sputtering for hydrogen impinging on titanium is considerably low. What results is a lower pumping speed for hydrogen compared to the one for the other higher mass reactive gases.

On the other hand the experimental data show a pumping speed for hydrogen about double than the speed for N2 or O2.

Due to its small atomic radius the hydrogen implanted in the cathode diffuses in the bulk. Moreover the solubility of hydrogen in titanium is relatively high (about 1 %). As a result the hydrogen can be steadily pumped and in large quantity.

If a large quantity of hydrogen is pumped the cathode elongates, and must be designed to avoid distortion.

5.3 Noble Gases

Noble gases are not reactive and cannot be pumped by the titanium film. However the sputter-ion pumps have a pumping speed for noble gases of about 2-3 % of the standard pumping speed.

When an ion impinge on the cathode there's a probability that it's neutralized and scattered back, maintaining a large part of its energy. [32] These high-energetic neutrals are then implanted on the anode. Their depth of implantation is big because of the high energy. On the anode there's no sputtering ad the neutrals aren't released. The ions implanted in the cathode are instead released due to the continuous sputtering.

5.4 Complex Molecule

Complex molecules such as heavy hydrocarbons are cracked by the collision with the electrons and then pumped with the same mechanism of the active gases. For example CH4 is pumped at a speed similar to the one of N2.

5.5 Gas Mixture

The pump performance can be greatly affected when pumping gas mixture. For example adding an high mass gas (such as Krypton) will increase the pumping speed for active gases, due to the increased number of sputtered titanium atoms. Other effects to be taken into account are the inhibition of the hydrogen diffusion or the increased gas desorption from the cathode due to a stronger bombardment. [33]

Ⅵ. Type of Pumping Elements

6.1 Diode

The Diode element is composed of two flat titanium cathode.

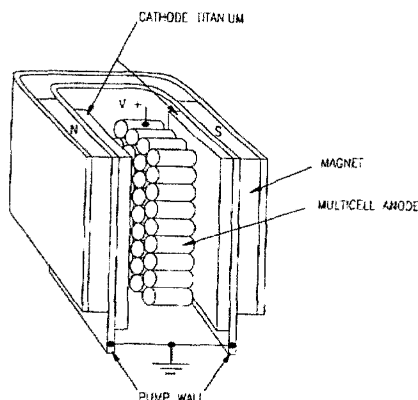

Fig. 12. Basic configuration of a sputter-ion pump

It has the highest pumping speed for the active gases and hydrogen, and so it's the best element for UHV.

When pumping noble gases the probability of having back scattering of neutrals is low (2-3 %). As the bombardment continues these ions are released and, because they are not pumped effectively, can create pressure burst. This phenomenon is known as noble gas instability. As a result the Diode element is not suitable for pumping noble gases and not even air (which is composed of 1 % by Argon).

6.2 Noble Diode

In order to increase the pumping speed and stability for noble gases we need to increase the probability that the ions are bounced back as neutrals when colliding on the cathode.

One approach is to use a heavier material for the cathode. The Noble Diode element has one cathode made of titanium (mass 48) and one of Tantalum (mass 181). With this solution the pumping speed for noble gases is about 20 % of the pumping speed for active gases. The pumping speed for hydrogen decreases because of the different diffusion of hydrogen in tantalum. The noble diode pump as an improved stability when pumping noble gases

6.3 Triode

A different approach is to use glancing angles of incidence of ions. In fact the reflection probability is much higher at glancing angles than at normal incidence. Furthermore the sputtering yield is higher for very small angles than for normal incidence. [34]

This led to the design of titanium cathodes with a grid structure made of several titanium strips. The cathodes are powered at a negative potential while the anode is at ground. The energetic neutrals may either glance on the cathode and be buried on the pump walls or be back scattered and be buried on the anode.

The pumping speed for noble gases is increased up to 20-25 % of nitrogen pumping speed. The pumping speed for active gases is the same for noble diode and triode, while the pumping and capacity for hydrogen is higher for triode pumps (because both cathodes are made of titanium). When pumping large amount of hydrogen the triode cathode may distort and create short circuit. To overcome this problem a triode pump has been designed with cathode plates showing a cell structure with radial sharp fins, called Starcell^{TM}. [35]

Ⅶ. Applications

The sputter-ion pumps have gained an important role in the UHV field. They are chosen mainly for three characteristics:

a. Can pump any type of gas
b. Have no moving parts and so are vibration free
c. Are absolutely free from any contaminants
   The sputter-ion pumps were originally developed for the electron tubes industry.

Due to the clean vacuum obtainable with a sputter-ion pump they are widely employed in mass spectrometer.

Due to the capability of the sputter-ion pump of pumping any kind of gas (noble gases and heavy hydrocarbons included) they are generally used in particle accelerators, and often in combination with getter pumps. [36]

In the gun and columns of the SEM microscope and in general with any kind of charged beam device the sputter-ion pump is used because of its absence of vibrations.

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초고진공 이온펌프의 개발에 관한 개관

Luca Bonmassar

베리안 진공기술연구소, Torino 10040, Italy

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본 총설논문에서는 초고진공 이온펌프의 개발에 대한 고찰을 하였으며, 이온펌프의 동작원리와 특정 디자인에 대하여 설명하였다. 다양한 가스를 사용할 때의 이온펌프의 성능과 동작범위, 그리고 응용분야 등을 논의하였다.

주제어 : 이온펌프, 다이오드, 스타셀, 진공

* [전자우편] bc.lee@varianinc.com