



PERGAMON

Vacuum 57 (2000) 283–293

VACUUM

SURFACE ENGINEERING, SURFACE INSTRUMENTATION
& VACUUM TECHNOLOGY

www.elsevier.nl/locate/vacuum

Bayard–Alpert gauge with additional ion collector for pressure measurements from 10^{-9} – 10^1 mbar

R. Kauert, St. Wilfert, Chr. Edelmann*

Department of Vacuum Science and Technology, Faculty of Natural Sciences, Otto-von-Guericke University Magdeburg, Institute of Experimental Physics, Universitätsplatz 2, PB 4120, 39016 Magdeburg, PB 4120, Germany

Abstract

Commercial hot filament ionization gauges of Bayard–Alpert type can be used for the pressure measurement usually below the upper pressure limit of 10^{-2} mbar. There are some special gauge types for high-pressure measurement, but the requirements for the gauge designs for high- and low-pressure measurement are contradictory. The aim of our gauge construction is to combine low and high-pressure measurement in one gauge in a very simple way without changing of electrode potentials. This was achieved by introducing a second ion collector behind the cathode of a Bayard–Alpert structure. This construction was optimized with the help of numerical calculations and tests by experimental work. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the past decades many types of hot filament ionization gauges for limited pressure ranges were developed and investigated. Beside Bayard–Alpert gauge [1] there were suggested many other special types of ionization gauges for the measurement of very low pressures (e.g. [2–4]) and of higher pressures in the vacuum range (e.g. [5]).

The requirements for the low-pressure measurement are:

- high sensitivity, realized by long electron paths and a high ion collection efficiency,
- low X-ray effect, realized by an ion collector with a small area exposed to the X-ray-radiation of the anode
- low electron stimulated desorption (ESD effect).

* Corresponding author. Tel.: 391-67-18556; fax: 391-67-18109.

E-mail address: iep.vacuum@physik.uni.magdeburg.de (C. Edelmann).

The requirements for measurement of higher pressures in the vacuum range are according to Schulz and Phelps:

- low sensitivity, realized by short electron paths and low electric field strength between cathode and anode (Edelmann et al. [6,7] suggested in contradiction to the opinion of Schulz and Phelps a high electric field strength!),
- stable pressure independent sensitivity, realized by well-defined electron paths and a large area ion collector to avoid the formation of ion space charges in the surrounding of the ion collector.

At higher pressures of measuring range hot filament ionization gauges show a typical drop down of the sensitivity with increasing pressure. The I_+ vs. p characteristic passes a maximum and shows an ambiguous course, i. e. one value of ion current corresponds with two different values of pressures. Thus, an univocal pressure measurement is not possible. One possibility to avoid this ambiguousness was suggested by Edelmann and Kiessling [7]. They extended the Schulz-Phelps construction by an additional grid. One part of the ion current reaches the ion collector, but the other part is captured by the grid. The ratio of both currents depends on the ion drift velocity and thus it depends on the gas pressure too. But this is only a special gauge for the measurement of higher pressures in the vacuum range. To cover a wide range of pressure one has to find a compromise, because the requirements for low- and high-pressure measurements are contradictory. There are some attempts to combine both principles in one gauge.

Blank and Petzold [8] used a Bayard–Alpert gauge with a conducting inner wall of the bulb of the glass envelope. For low pressures this additional electrode was grounded, and the gauge works like an ordinary Bayard–Alpert gauge, but in the high-pressure regime the conducting inner wall works as anode and the grid works as an ion collector. But in this construction a switching over of the electrode potentials is necessary to change the operation from low- to high-pressure mode.

For the extension of the measuring range Edelmann [11] suggested to use the pressure dependence of the ion drift velocity. In this case the ratio of ion currents collected at two different ion collectors is used for the pressure indication.

2. The principle of a simple wide range extension unit

The basic idea of our construction is to combine an usual UHV gauge like a Bayard–Alpert gauge with a second ion collector behind the filament (cf. Fig. 1). In the lower-pressure range the gauge works in the conventional way. The electron paths cross the grid and oscillate around the grid. The ion current is measured by the ion collector placed in the grid axis. But in the high-pressure range the region between the second ion collector, the hot cathode and the anode grid works like a Schulz–Phelps gauge. The higher the pressure, more electrons cannot cross the anode grid without an ionizing collision with gas molecules in the small space between cathode and grid. These ions are collected by the second collector. In the following the common ion collector in the centre of the grid is denoted as IC1. The additional ion collector behind the cathode will be denoted as IC2.

Our construction looks like a gauge of Redhead [9], but it operates quite different. Redhead investigated the influence of the field around the filament on the launching angle of electrons and the sensitivity. He introduced a screen behind the filament for the stabilization of the field around the filament. In our construction the second ion collector works as a screen for

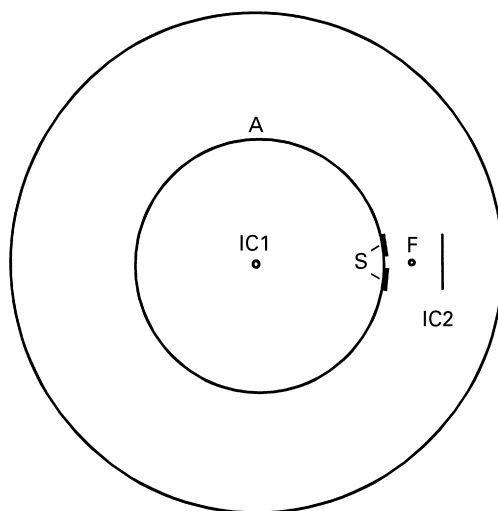


Fig. 1. Principle of the simple wide range extension gauge A — Anode, IC1 — ion collector 1, IC2 — ion collector 2, F — filament, S — screen.

stabilization of potentials too, but the main function is to capture the ions generated between filament and anode.

The main advantage of our concept is to avoid the switching over of electrode potentials. Only the measurement of two ion currents registered at first and second ion collector is necessary for pressure reading, if the pressure raises from the low to the high-pressure regime.

Edelmann [10] introduced a similar construction. But this gauge has to switch over electrode potentials too.

A special problem of our new gauge construction occurs in the pressure reading at IC2. The electrons which start at the cathode can ionize gas particles during their flight from the cathode to the anode grid. But at lower pressures the probability for this is rather small. The electrons may oscillate around the grid and after this they may return to the region around IC2. If an ionization occurs, the ion probably will be captured by IC2. These ions cause a non-linearity in the gauge characteristic. To avoid this kind of ions an additional anode screen was introduced. This screen was made of two small metal strips spot welded onto the grid opposite to the cathode. This slit between these two plates has to be wide enough to enable the electrons from the cathode to pass the anode grid, but it has to be small enough to prevent that electrons from the interior of the anode grid return to the cathode region.

3. Numerical investigations

For the numerical investigation of this gauge the computer program IONTRA3d [12,13] was used. This program allows the creation of three-dimensional models by the finite difference method and the calculation and plotting of charge carrier trajectories. Initial values of trajectories and the occurrence of elastic and ionizing collisions are controlled by a pseudo-random number generator.

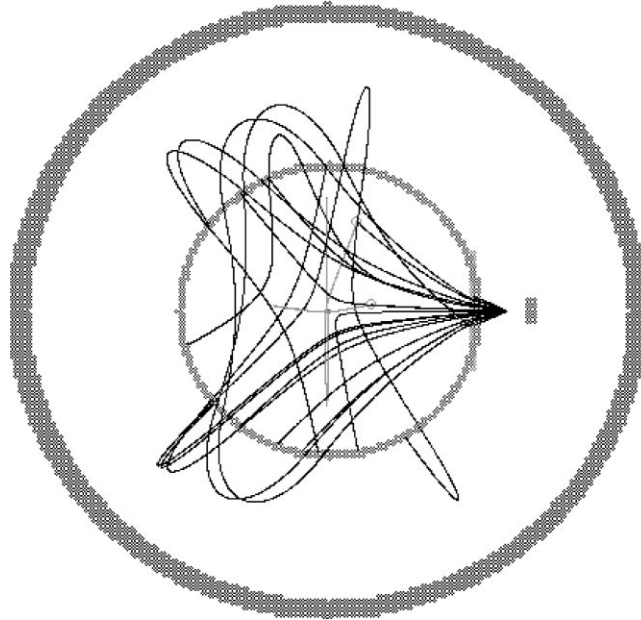


Fig. 2. Electron and ion trajectories at a pressure of 3×10^{-3} mbar (black lines: electron trajectories, grey lines: ion trajectories).

For this reason, the simulation can be denoted as Monte-Carlo simulation. Space charge effects are neglected by this calculations.

Fig. 2 shows some electron and ion trajectories calculated with IONTRA3d at a pressure of 3×10^{-3} mbar. The initial values of trajectories are also set by a random number generator. If the electrons ionize a gas molecule, they would do it probably inside the grid region. Two ionizations occur in this special demonstrated case. In this and in the following figure too the ionizations are marked by a small circle around the location where the ionization occurred. Not all ions in the grid region are collected by IC1. In this special case the two ions are not collected by IC1 because of the small diameter of this electrode. They escape on the open ends of the grid. Fig. 3 shows the trajectories at a pressure of 1×10^{-1} mbar. Now almost all electrons ionize a gas molecule. But the part of them which ionize in the small region between cathode and grid increases with increasing pressure. One can see two ions collected at IC2 in Fig. 3, which demonstrates the operation principle in the high-pressure region.

4. Experimental set-up

An UHV pumping system was used to investigate the behaviour of our gauge. The vacuum scheme of the commercially produced calibration system CS 1001¹ is shown in Fig. 4. An ultimate

¹ Leybold AG, Cologne, Germany.

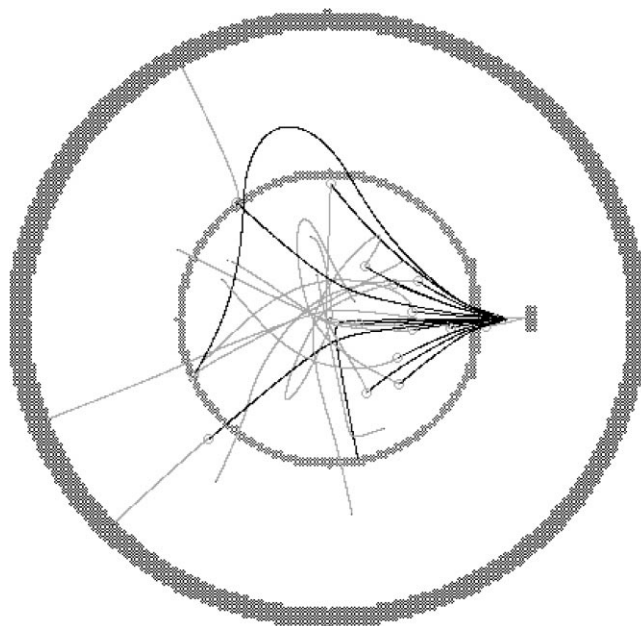


Fig. 3. Electron and ion trajectories at a pressure of 1×10^{-1} mbar (electron trajectories: black, ion trajectories: grey).

pressure of 1×10^{-9} mbar was attained with the help of a combined turbomolecular and a rotary pump system. Using a separately evacuated gas inlet system a high purity of the test gas was guaranteed. For the registration of the wide-pressure range, three different calibrated reference gauges were used: a commercial Bayard–Alpert gauge IE 414 (see footnote 1), a spinning rotor gauge (see footnote 1) and two diaphragm gauges of the Baratron type.²

The principle of the electric circuit for the operation of the ionization gauge is demonstrated in Fig. 5. The cathode voltage V_C was applied between the ground and the middle of the direct-heated cathode. The anode voltage (electron accelerating voltage) V_A , which was measured between cathode and anode, was provided by two high voltage power supplies PS 310.³ The electron current was stabilized with a special controller circuit constructed by us, and the both ion currents were measured with two similar electrometer amplifiers produced by KEITHLEY.

The test ionization gauge, as shown in Fig. 6, was constructed on a commercial UHV flange with electrical feedthroughs (see footnote 1). The cylindrical anode grid was made by spot welding of 0.2 mm diameter molybdenum wire wound with 1 turn per mm around the stainless-steel support wires with 1 mm diameter. The anode screens were made from molybdenum sheets and were spot welded on the grid. The split width between these two plates was 1 mm. There was also a test gauge with the same dimensions but without anode screens.

² MKS Instruments.

³ Stanford Research Systems.

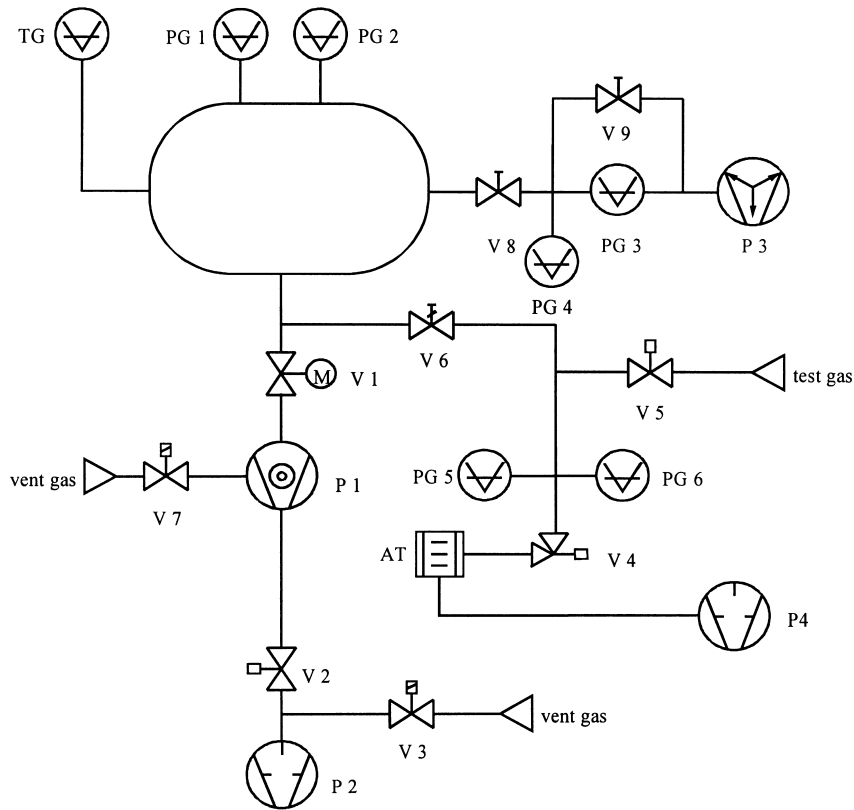


Fig. 4. Vacuum scheme of the used calibration system CS 1001: P1: turbo molecular pump; P2, P4: rotary pump; P3: sputter ion pump; PG1: Bayard–Alpert gauge IE 414; PG2: spinning rotor gauge; PG3, PG4: Baratron gauges; PG5: diaphragm gauge PIEZOVAC; PG6: Pirani gauge THERMOVAC; TG: test gauge; V1–V8: valves, (V6: variable leak valve); AT: adsorption trap.

IC1 consists of a fine tungsten wire of 0.11 mm diameter. The plate-like ion collector outside the grid (IC 2) was manufactured from 1 mm thick stainless-steel sheet. Both, the distance between anode and cathode and the distance between cathode and IC2 too, were 1 mm. An iridium filament coated with yttrium oxide was used as cathode.

5. Experimental results

Some tests were performed for the determination of optimum operating voltages. These tests have shown that it is possible to realize this contradictory requirements of low- and high-pressure measurement by using the following voltages: anode voltage $V_A = 150$ V, cathode voltage $V_C = 50$ V.

The electron current was chosen according to the following criteria: for measuring of low and very low pressures relatively high emission currents are necessary to reduce the ESD effect and to

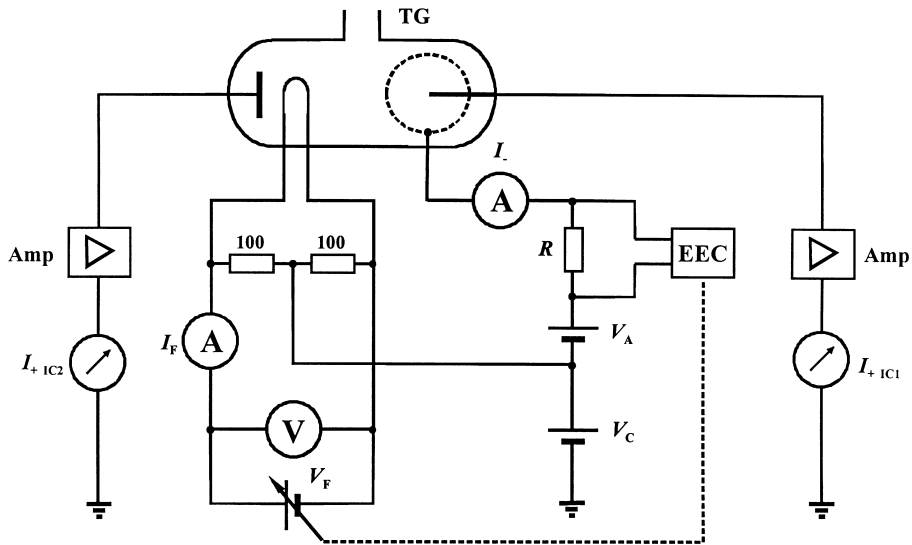


Fig. 5. Principle of the electric circuit of the gauge (TG — test gauge, I_{+IC1} — collector current 1, I_{+IC2} — collector current 2, I_F — filament current, V_F — filament voltage, I_- — electron current, V_A — anode voltage (electron accelerating voltage), V_C — cathode voltage, R — stabilizing resistance, ECC — electron current controller).

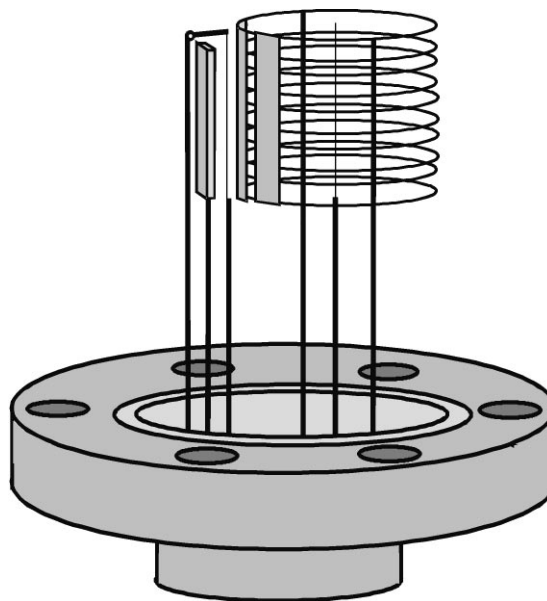


Fig. 6. The constructed test gauge with anode screens.

record noiseless ion currents, but for the registration of high pressures very low electron currents are required to avoid strong space charges. Furthermore, low filament heating power enables a longer life time for the cathode. Therefore, the gauge was used with an adapted electron current in an appointed interval of pressure (cf. Table 1).

Table 1
Electron emission current at different pressure ranges

p (mbar)	(μA)
$< 10^{-6}$	500
10^{-6} – 10^{-3}	50
$> 10^{-3}$	5

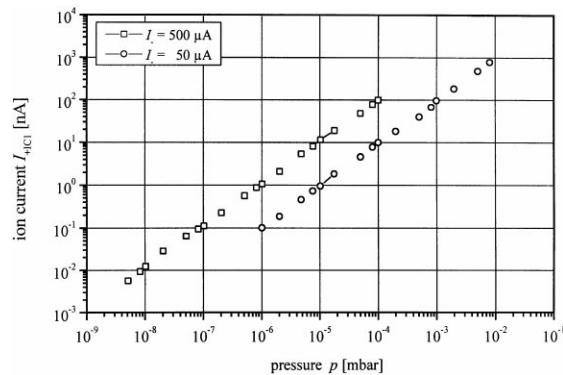


Fig. 7. Ion current at ion collector 1 vs. pressure at two different electron emission currents, gas species N_2 .

The relation between the ion current and the pressure (at constant electron current) was investigated in a pressure range between 10^{-9} and 10^{-2} mbar (low-pressure measurement). In this case only the ion current at IC1 is used for pressure measurement. The I_{+IC1} vs. p curve (Fig. 7) shows in accordance with the well-known Barkhausen equation the typical linear dependence. The corresponding sensitivity of the gauge is shown in Fig. 8. In comparison to an usual Bayard–Alpert system the value $C_{IC1} \approx 2 \text{ mbar}^{-1}$ of our gauge (for nitrogen) is relatively small. This can be explained by the presence of the anode screens influencing the length of electron paths significantly and the small distance between cathode and grid. By means of the Alpert method [1] an X-ray limit of $p_x = 6 \times 10^{-10}$ mbar was found ($I_- = 500 \mu\text{A}$).

In the rough vacuum range the ion current recorded at collector IC2 is the basis for pressure reading. The ion currents vs. pressure characteristic is shown in Fig. 9. This figure gives a comparison of the plots of I_{+IC2} vs. p for the same gauge but with and without anode screens. Corresponding to the theory of ionization gauges at high pressures the ion currents at IC1 and IC2 passes through a maximum and then drops down rapidly with increasing pressure. As expected, the current registered at IC1 reaches its maximum at a lower pressure ($p_{\text{maxIC1}} \approx 3 \times 10^{-1}$ mbar) than the ion current acquired at IC2 ($p_{\text{maxIC2}} \approx 5$ mbar). The plot of I_{+IC2} vs. p for the gauge with anode screens shows a better straight line as the gauge without anode screens, but the ion current is not proportional to p . Instead of this one finds $I_{+IC2} \propto p^n$ with $n \approx 0.86$ similar to the results of [14].

Caused by short electron trajectories in the small region between the hot filament and the anode grid at high pressures the sensitivity C determined at IC2 is very low. The difference of the C_{IC2} vs. p plots using gauge with and without the anode screens is shown in Fig. 10.

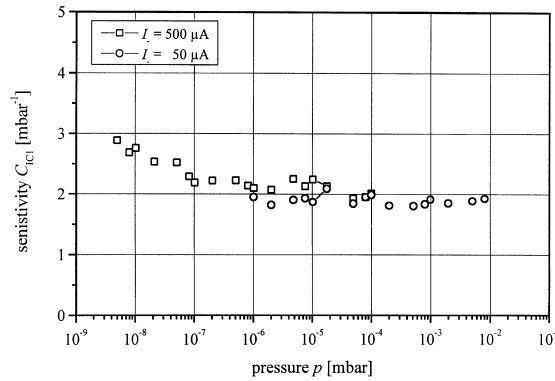


Fig. 8. Sensitivity at ion collector 1 vs. pressure at two different emission currents, gas species N_2 .

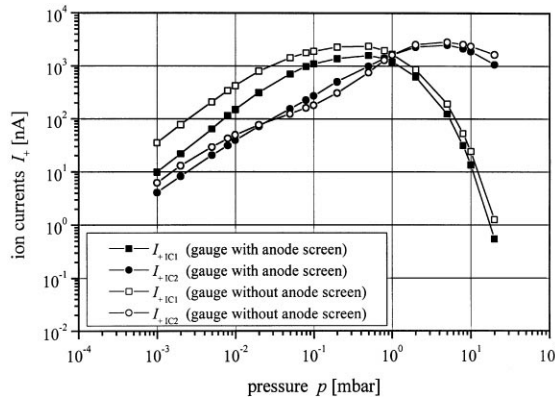


Fig. 9. Comparison of $I_+ - p$ characteristics with and without anode screens in the high pressure region, $I_e = 5 \mu A$; gas species N_2 .

As shown above, the ion current at IC2 drops down at pressures above 1 mbar. Thus, the pressure reading becomes ambiguous. For this reason the ratio of the ion currents I_{+IC1} and I_{+IC2} was used to extend pressure indication. This ratio (cf. Fig. 11) shows a non-linear rising curve in a range between 1 and 20 mbar. Above 20 mbar a drop of the characteristic was observed. The evaluation of the non-linear pressure-dependent ratio of the two ion currents can be performed electronically, for example by a microcomputer. In every case, an extension of the measurement range of this gauge up to 20 mbar is possible by an additional use of this effect.

6. Conclusions

It could be shown, that an additional ion collector (IC2) placed behind the cathode can enlarge the measuring range of a Bayard–Alpert gauge to higher pressures in an easy way. Switching over of electrode potentials is not necessary. It is advantageous to use an adapted electron emission current. The problem of non-linearity of pressure reading at IC2 can be minimized with two anode

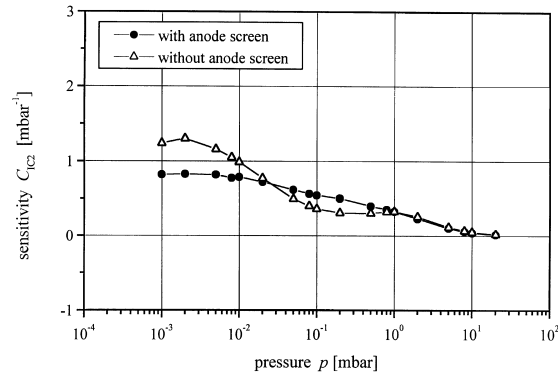


Fig. 10. Sensitivity at ion collector 2 vs. pressure with and without anode screen, emission current $I_- = 5 \mu\text{A}$, gas species N_2 .

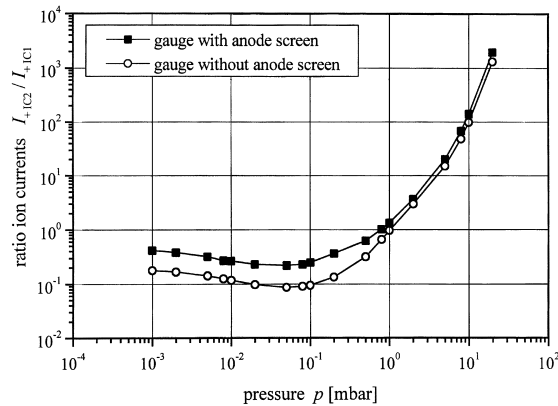


Fig. 11. Ratio of ion currents vs. pressure with and without anode screen, emission current $I_- = 5 \mu\text{A}$, gas species N_2 .

screens in front of the cathode, because the electrons can be hindered to return to the cathode region. The measuring range of this gauge can be further enlarged up to 20 mbar by using the ratio of the ion currents measured at IC1 and IC2. This characteristic is non-linear, but it would be no problem to evaluate this curve electronically.

Acknowledgements

The authors wish to express their thanks to Mr. G. Nuglisch who built up the test ionization gauges very carefully and with skilled hands.

References

- [1] Bayard RT, Alpert D. Rev Sci Instr 1950;21:571.

- [2] Redhead PA. *J Vac Sci Technol* 1966;3(4):173.
- [3] Helmer JC, Hayward WH. *Rev Sci Instr* 1964;37:1652.
- [4] Groszkowski, J. *Le Vide* 1969;142:226.
- [5] Schulz GJ, Phelps AV. *Rev Sci Instr* 1957;28:1051.
- [6] Edelmann Chr. *Vacuum* 1986;36:503.
- [7] Edelmann Chr, Kiessling J. *Exp Tech Phys* 1978;26:569.
- [8] Blank H, Petzold K. *Vacuum* 1985;15:127.
- [9] Redhead PA. *J Vac Sci Technol* 1969;6:848.
- [10] Edelmann Chr. *Offenlegungsschrift DE 40 34 452 A1*.
- [11] Edelmann Chr. *Vacuum* 1987;37:179.
- [12] Kauert R, Kieler OFO, Biehl St, Knapp W, Edelmann Chr, Wilfert St. *Vacuum* 1998;51:53.
- [13] <http://graf350.urz.uni-magdeburg.de/~kauert/iontra3d.html>
- [14] Cleaver JS. *J Sci Instr* 1967;44:969.