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AN IONIZATION GAUGE USING A CHANNEL ELECTRON

MULTIPLIER FOR PRESSURES BELOW 10^{-12} TORR

by

D. Blechschmidt



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Abstract

A new ionization gauge of an estimated low pressure limit below 10^{-15} Torr and of a sensitivity of 2×10^9 Torr $^{-1}$ is presented. The ions which are produced in an ionizer of conventional design, are extracted through a shield aperture and collected by the funnel type cathode of a channel electron multiplier. Since the high gain of this multiplier allows the gauge to be operated with an emission current of only several nanoamperes, practically no heat is produced in the gauge. The gauge is mounted on a $4\frac{1}{2}$ inch conflat flange and has approximately the size of a normal Bayard Alpert gauge. A general expression for the low pressure limit of hot filament ionization gauges is given. The results as obtained from this expression for gauges of similar geometry are discussed together with the low pressure limit as found for the new gauge.

I. Introduction

Since new techniques to achieve pressures of below 10^{-12} Torr have been developed⁽¹⁾, gauges with an appropriate low pressure limit are required. For hot ionization gauges, it is well known that this limit is caused by electron induced desorption of molecules and ions and by x-rays emitted from the anode. For a gauge of sensitivity K operating at an emission current I_a the low pressure limit is given by

$$P_{\text{lim}} = P_m + (I_x + I_i) / KI_a ; \quad (1)$$

where P_m is the pressure rise in the ionizing volume due to molecules desorbed from the anode; I_x is the current of electrons emitted by the

collector under the bombardment of x-rays originating from the anode and I_i is the current of positive ions desorbed from the anode to the collector. The current of electrons released from the collector by x-rays may be written

$$I_x = G Y_c Y_a I_a ; \quad (2)$$

where G is the geometric factor which is defined as the fraction of total flux of x-rays emanating from the anode, intercepted by the collector. Y_c is the photoelectric yield of the collector, irradiated by x-rays and Y_a is the number of x-rays produced at the anode per incident electron.

If a gauge is operated at pressures, where the assumption holds that readsorption may be neglected against the desorption, the electron induced desorption of molecules and ions from the anode may be calculated from

$$dn = dn_m + dn_i = -n(Q_m + Q_i)I_a dt/eF ;$$

where n is the number of molecules adsorbed per unit surface area of the anode; Q_m and Q_i are the desorption cross sections for molecules and ions respectively, and F is the surface area of the anode.

Hence

$$dn/dt = -(n_0(Q_m + Q_i)I_a/eF)\exp(-t/\tau) ; \quad (3)$$

with

$$\tau = eF/(Q_m + Q_i)I_a$$

From (3) we find the collector current due to desorbed ions :

$$I_i = -w \cdot \frac{dn_i}{dt} eF = wn_0Q_iI_a \exp(-t/\tau) ; \quad (4)$$

where w is the probability that a desorbed ion gets to the collector and n_0 denotes the initial density of residual gas molecules adsorbed at

the anode.

Finally, the pressure rise in the ionization gauge due to electron induced molecular desorption may be written :

$$P_m = - cF \frac{dn_m}{dt} / s = (cn_o Q_m I_a / es) \exp(-t/\tau) \quad (5)$$

s is the pumping speed at the gauge and $c (= 2.8 \times 10^{-20} \text{ Torr} \times \text{Å}^3/\text{molecule})$ is a factor relating the number of molecules to the units of vacuum technology.

From Eqn. (1), (2), (4) and (5) follows

$$P_{lim} = GY_c Y_a / K + (P_{m,o} + P_{i,o}) \exp(-t/\tau); \quad (6)$$

with

$$P_{m,o} = cn_o Q_m I_a / es; \quad P_{i,o} = wn_o Q_i / K;$$

From Eqn. (6) the following facts become evident :

- a) one cannot expect to decrease the low pressure limit of a hot ionization gauge by more than two orders of magnitude by a better choice of the anode and collector material, since the parameters Y_a , Y_c , Q_m and Q_i in Eqn. (6) do not vary much with the kind of material;
- b) a high emission current I_a yields a low desorption time constant τ , the desorption however, begins with a high pressure rise when the gauge is set in operation. If a clean anode can be obtained by previous electron bombardment at low pressures, it is thus advantageous to operate the gauge at a low emission in order to get a low desorption and stable degassing rate. Furthermore, the thermal radiation from the gauge to the vacuum system is consequently reduced;
- c) the parameter n_o depends on the anode material and the residual gas composition, it is however, very much more influenced by the degassing

procedure before the gauge is used for measurements. It must be degassed in several steps at decreasing residual pressures in order to prevent readsorption and to obtain low coverage densities n_0 ;

- d) low x-ray limits are achieved either by decreasing the geometry factor or by a high sensitivity. The factor w is determined by the geometry and by the potential field distribution in the gauge ²⁾.

Since it is rather impossible to increase the sensitivity of a gauge of Bayard Alpert type ³⁾, without increasing its volume, many efforts have been made to construct a gauge with a low geometry factor but of a high sensitivity by means of ion optics ^{2,4 - 7)}. A gauge based on this principle is the Extractor gauge, for which a low pressure limit of some 5×10^{-13} Torr was found ⁴⁾. Sensitivities of some 10^5 Torr⁻¹ have been realised in Orbitron gauges ^{8,9)}. They are operated at very low emission currents of typically some 10^{-7} A, their geometry factor, however, is of the order of 0.05. Considering the fact that it is operated at an anode potential of more than 1 kV, Y_a is a factor of 10 higher than for the Bayard Alpert gauge ¹⁰⁾ and thus from Eqn. (1) and (2), an x-ray limit of 3×10^{-13} Torr is to be expected.

Multipliers are used in residual gas analysers as ion detection devices, and thus their application to low pressure gauges is consequently logical. In particular Channel Electron Multipliers ^{11, 12)} (Channeltrons) with their high gain seem to be the best means to construct gauges with a high sensitivity. They are light in weight, small, bakeable and less expensive than conventional multipliers. Gauges which are equipped with channeltrons may be operated at very low emission currents. As a consequence the x-ray limit decreases together with the desorption from the anode and the thermal radiation.

In the last few years, two gauges equipped with multipliers have been presented. But either the construction was not appropriate to vacuum conditions ¹³⁾ or the sensitivity was too low and limited the operation of the gauge to pressures of more than 1×10^{-11} Torr ¹⁴⁾.

In this paper, a gauge using a channeltron and having a very simple and rugged design is presented.

II. Construction and Operation

A cutaway drawing of the gauge is shown in Fig. 1. A tungsten filament of 0.15 mm in diameter emits the electrons which are accelerated towards the anode grid cage. The ions created within this grid cage are extracted through a hole of 3 mm diameter in a cylindrical electrode shielding the channeltron. The channeltron is provided with a funnel shaped cathode of about 45° acceptance angle and a maximum diameter of 5 mm; it collects some of the ions which are created within the grid cage. The other end of the channeltron tube is open; a small sheet of stainless steel collects the electrons leaving the tube.

The whole gauge system is mounted on a $4\frac{1}{2}$ inch conflat flange with ceramic feedthroughs. It can be baked at 400°C , the gain loss of the channeltron was found to be about 1.3.

The gauge was tested in a vacuum system of basic pressure of 5×10^{-12} Torr nitrogen equivalent. The pressure measurements were performed with a Helmer gauge (Varian). The channeltron gauge was operated with a filament potential of +50 V with respect to the grounded vacuum system. The anode potential was +175 V, the shield electrode together with the output end of the multiplier were grounded. The collector current was determined by an electrometer and by counting techniques. The channeltron was usually operated at a cathode potential of -2.5 kV. The potential field distribution for the gauge as calculated by a digital computer using the above data is drawn in Fig. 2.

III. Results

Fig. 3. shows the collector current I_c as a function of the pressure of injected hydrogen and nitrogen with the emission current as the parameter. For collector currents of less than $3 \times 10^{-8}\text{A}$, it can be seen that

the curves are a set of parallel, straight lines. From this linearity, may already be concluded that the low pressure limit of the gauge is below 10^{-12} Torr. At collector currents of more than 3×10^{-8} A, the channeltron begins to saturate due to space charge effects¹²⁾.

The sensitivity of the gauge was determined from the slope of these curves and plotted in Fig. 4 against the pressure measured for a nitrogen injection. In this picture the emission current is the parameter. The sensitivity is rather constant for emission currents below 10^{-7} A and for pressures below 10^{-9} Torr. The decrease at higher pressure is due to the saturation of the channeltron. Even for emission currents of above 10^{-7} A, a pressure independent sensitivity of $2 \times 10^9 \text{Torr}^{-1}$ may be expected for pressures below 10^{-12} Torr from Fig. 4. Thus, measurements of pressures down to 10^{-15} Torr yield collector currents of more than 10^{-13} A operating the gauge at 10^{-7} A emission current only.

The high sensitivity which is found for the new gauge can be explained from the gain of the channeltron which is of the order of 10^8 . Since the sensitivity of a Bayard Alpert gauge of comparable size is about 20Torr^{-1} , a sensitivity for the new gauge of $2 \times 10^9 \text{Torr}^{-1}$ is expected.

In order to test the degassing properties, to check the linearity of the relation collector current to emission current and the operation of the gauge at increased cathode negative potentials, the collector current was determined as a function of the emission with the cathode potential as the parameter. The result is plotted in Fig. 5. The measurements were performed at a pressure of 7×10^{-12} Torr nitrogen equivalent. For a cathode potential, of -2.5 kV, the collector current increases linearly with the emission up to a value of 3×10^{-8} A where saturation effects set in.

At lower cathode potentials, the collector current is no longer a linear function of the emission current. Using counting techniques together with pulse height discrimination, it was found that the deviation from linearity at low emission currents is due to noise in the

channeltron. In order to suppress the noise, the gauge may be operated either at about the starting voltage of the channeltron (which is -2.2 kV in this particular case) or the noise rate must be discriminated by using counting techniques. The noise discrimination is rather easy to perform, since there is a big gap in the pulse height spectrum between the noise and the pulses due to ions extracted from the grid cage. This however, will be studied in more detail in future. The curve as measured from discrimination and counting technique at a cathode potential of -2.5 kV is shown in Fig. 5. It can be seen, that elimination of the noise yields the same results as measurements with the electrometer.

IV. Estimation of the low pressure limit

In order to find the x-ray limit of the new gauge, the variation of energy method was applied at a pressure of 1×10^{-11} Torr. The collector current was measured as a function of the electron energy $E = eU_{af}$ (where U_{af} is the potential difference between the grid and the filament) and plotted in Fig. 6. At a pressure, where the x-ray effect is expected to contribute to the pressure reading, an increase of the collector current with increasing electron energy may be interpreted to be due to x-rays: the yield of x-rays created at the anode is given by a power law¹⁰⁾ $Y_a = \text{const} \cdot U_{af}^n$ ($1 < n < 1.5$); however, the ionization cross section decreases for electron energies of more than about 150 eV. The curves drawn in Fig. 6. decrease monotonically for energies of more than 175 eV. The x-ray limit is estimated from this measurement to be below 1×10^{-12} Torr.

A more accurate value for the low pressure limit is obtained from an estimate using Eqn. (6). By comparison of the results as found for similar types of gauges where the low pressure limit is already known, the validity of this estimation may be checked. A Bayard Alpert gauge, an Extractor gauge as described by Redhead²⁾ and an Orbitron as studied by Fitch et al⁸⁾ have been selected to check Eqn. (6).

The necessary data for the calculation of the low pressure limit is listed in Table I, together with the results from Eqn. (2) and (6).

The geometry factor G for the channeltron gauge has been calculated from

$$G = \frac{\pi r_a^2}{2F} \left[\ln \left\{ \left(\frac{r_g}{l_g} \right)^2 + 1 \right\}^{\frac{1}{2}} + \arctg \left(\frac{l_g}{r_g} \right) - \arctg \left\{ \frac{(l_g - h)}{r_g} \right\} \right] ; \quad (7)$$

where r_a and r_g are the radius of the shield aperture and of the grid respectively, l_g is the grid length and h the height of the grid below which the x-rays are shielded from the funnel cathode. The derivation of Eqn. (7) is given in some more detail in the Appendix.

From Table I, it is evident that the low pressure limit of the channeltron gauge is determined only by the contamination of the anode by adsorbed gases. For a surface coverage of 10^{12} molecules/cm², which is about 1% of a monolayer, a low pressure limit for the new gauge operating at 10^{-8} A of 2×10^{-15} Torr is found. Since the low pressure limits for the other gauges as obtained from Eqn. (6) are within the same order of magnitude as the values which are confirmed by measurements, it is believed that the value for the channeltron gauge is correct. The x-ray limit for this gauge, being in the order of 10^{-17} Torr may be neglected. Since the new gauge can be operated at an emission current of 5 mA at 10^{-15} Torr, before channeltron saturation occurs, the grid contamination may be reduced to below 10^{12} molecules/cm² because the time to form 1% of a monolayer at this pressure is about three weeks.

There is no reverse x-ray effect¹⁵⁾ in the channeltron gauge, since electrons, emitted from surrounding surfaces (shield electrode, vacuum chamber) by x-rays from the anode, cannot get to the funnel cathode due to its high negative potential.

V. Summary

A new ionization gauge using a channeltron has been described. If the channeltron is operated near the starting voltage and at output currents far below saturation, a pressure independent sensitivity of the gauge of the order of some 10^9 Torr⁻¹ is achieved. The x-ray limit is thus below

10^{-16} Torr. The low pressure limit is determined by degassing of the anode grid only, it is in the order of 10^{-15} Torr for an emission current of 10^{-8} A and a surface coverage of about 1% of a monolayer.

Since the gauge is expected to yield collector currents of some 10^{-13} A even at the low pressure limit for an emission current of 10^{-7} A, the effect of degassing and of thermal radiation are some orders of magnitude lower than for conventional gauges.

The new gauge is of the size of a normal Bayard Alpert gauge and of simple design. Since channeltrons are not very expensive, the new gauge is an appropriate and cheap means to measure pressures below 10^{-12} Torr.

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Appendix

For the calculation of the geometry factor two assumptions were made :

- the emission flux density of x-rays σ , is uniform over the anode grid surface
- the diameter of the hole in the shield electrode r_a , is small compared with respect to the distance from the hole to the anode grid.

Thus we get for the flux of x-rays from the anode through the shield hole

$$I_h = \sigma \pi r_a^2 \int_F \frac{df(\underline{r})}{4\pi r^2}$$

where $df(\underline{r})$ is a surface element of the anode grid at a distance r from the hole. The total flux of x-rays emitted from the anode is $I_F = \sigma F$, hence

$$G = \frac{I_h}{I_F} = \frac{\pi r_a^2}{2F} \left[\{ \ln(r_g/l_g)^2 + 1 \}^{\frac{1}{2}} + \operatorname{arctg}(l_g/r_g) - \operatorname{arctg} \{ (l_g - h)/r_g \} \right] \quad \S$$

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Figure captions

Fig. 1 : Cutaway drawing of the gauge, The funnel cathode of the channeltron (1) is on a high negative potential, the output end of the channeltron together with the shield electrode (2) are grounded, the potential of the grid cage (3) is +175 V, the collector sheet (4) is connected to a grounded electrometer and the filament (5) is at a potential of +50 V.

Fig. 2 : Potential field lines of the gauge.

Fig. 3 : The collector current I_c as a function of the pressure; injected nitrogen : solid line, injected hydrogen : dash-dotted line. The emission current I_a is the parameter, the cathode potential is -2.5 kV.

Fig. 4 : The sensitivity K of the gauge of nitrogen as a function of the pressure with the emission current I_a as a parameter, the cathode potential is -2.5 kV.

Fig. 5 : The collector current I_c as a function of the emission I_a for different negative cathode potentials. The result from a measurement using counting techniques is added for a cathode potential of -2.5 kV (CT).

Fig. 6 : The collector current I_c as a function of the grid to filament potential U_{gf} for two different cathode potentials as measured at 1×10^{-11} Torr.

Table I

	Bayard Alpert gauge	Extractor gauge	Orbitron gauge	Channeltron gauge	
G	3.6×10^{-3}	2.3×10^{-5}	5×10^{-2}	8×10^{-2}	xrays/electron
Y _a	10^{-5}	10^{-5}	10^{-4}	10^{-5}	electrons/xray
Y _c	2×10^{-2}	2×10^{-2}	2×10^{-2}	10^{-1}	Torr ⁻¹
K	25	13	2×10^5	2×10^9	Torr
P _{lim, x}	3×10^{-11}	4×10^{-13}	3×10^{-13}	4×10^{-17}	Torr
I _a	1×10^{-2}	1×10^{-3}	1×10^{-6}	1×10^{-8}	A
F	1.0	1.0	0.1	1.0	cm ²
w	2.5×10^{-2}	0.15	100	10	%
P _{m,0}	2×10^{-10}	2×10^{-10}	2×10^{-13}	2×10^{-15}	Torr
P _{i,0}	1×10^{-11}	1×10^{-12}	5×10^{-14}	5×10^{-18}	Torr
τ	16 sec	160 sec	4 hours	185 days	
P _{lim}	3×10^{-11}	2×10^{-12}	5×10^{-13}	2×10^{-15}	Torr

List of parameters as used for the calculation of the low pressure limit from Eqn. (6), together with the results obtained for the x-ray limit $P_{lim,x} = GY_a/K$ and the low pressure limit. As the low pressure limit appears to be time dependant, it is given for an initial coverage of the anode of 10^{12} molecules/cm² and after an operation time of 30 min at an emission I_a. A cross section for electron induced desorption of ions, $Q_i = 10^{-20}$ cm² and of molecules $Q_m = 10^{-18}$ cm² has been assumed (19) as well as a pumping speed at the gauge of $s = 1 \ell/\text{sec}$.

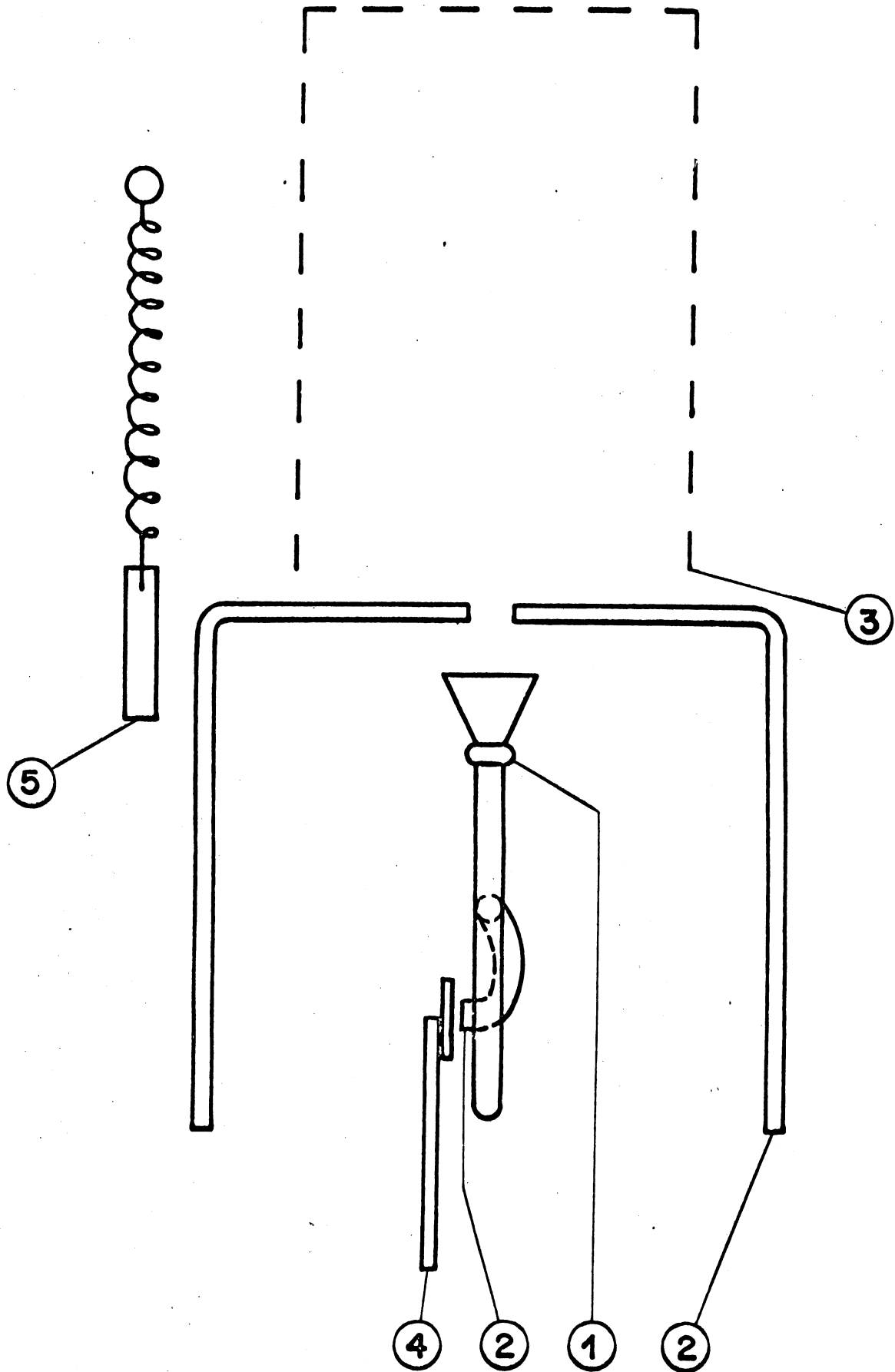
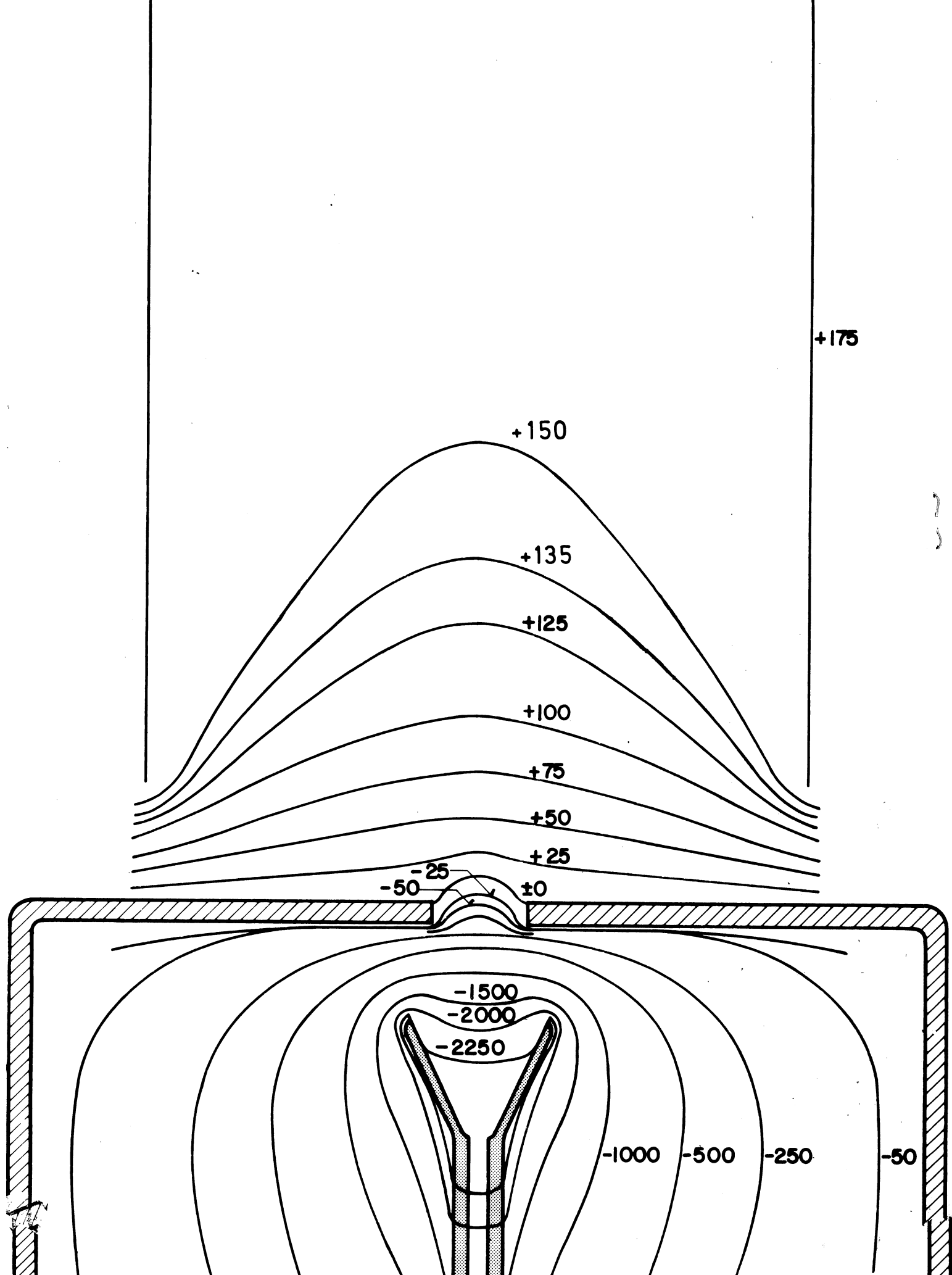


Fig. 1.



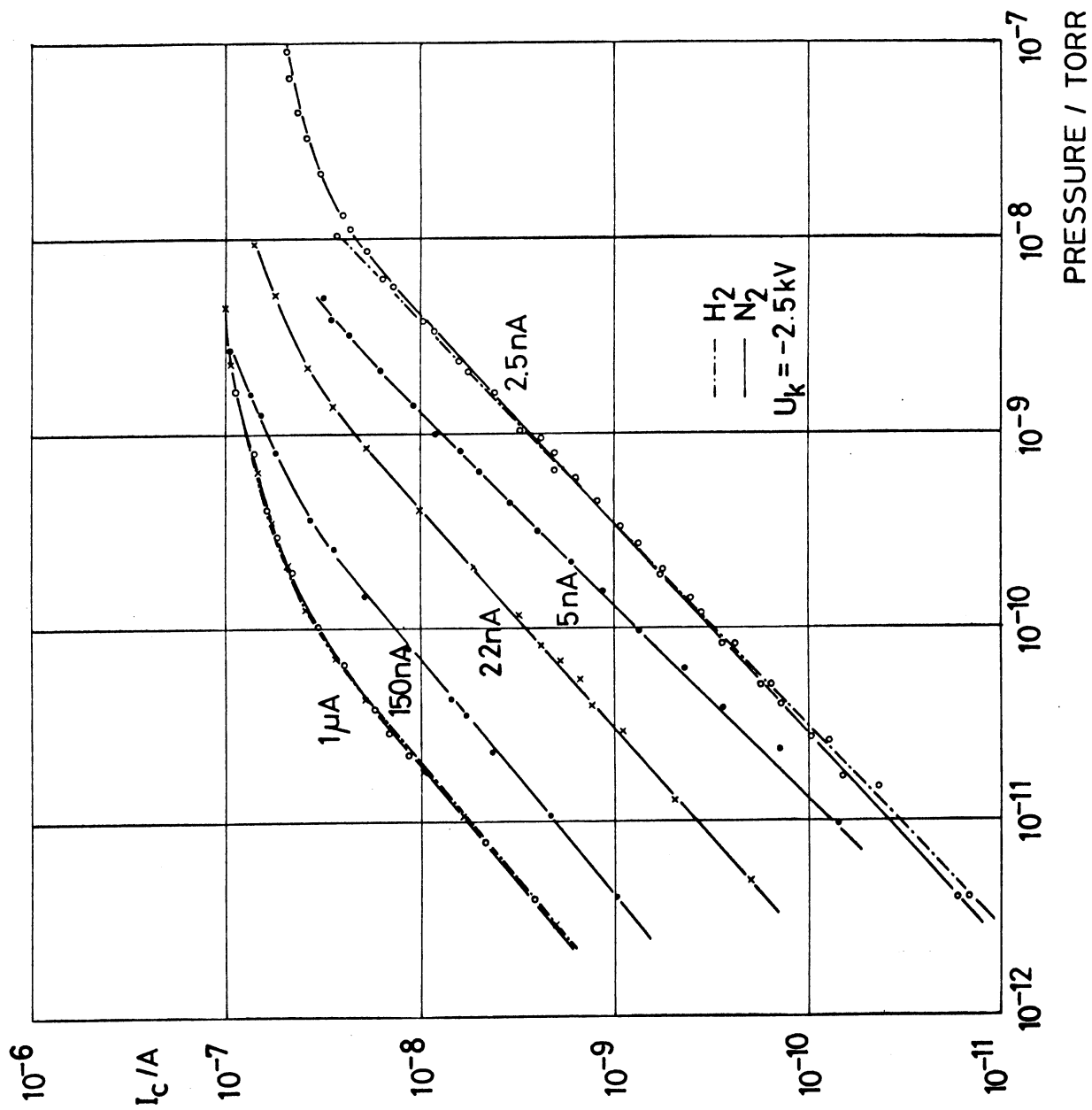


Fig. 3.

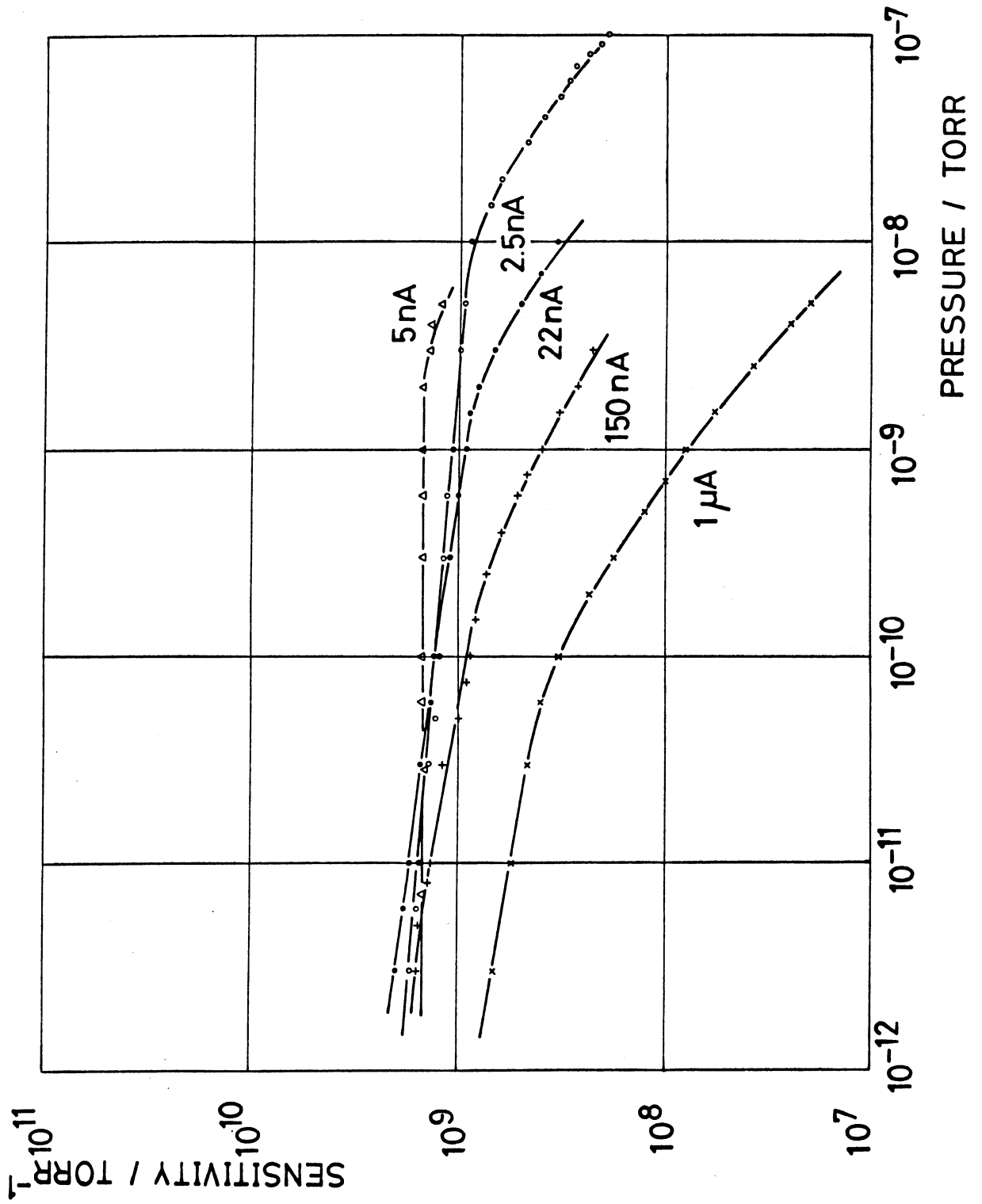


Fig. 4.

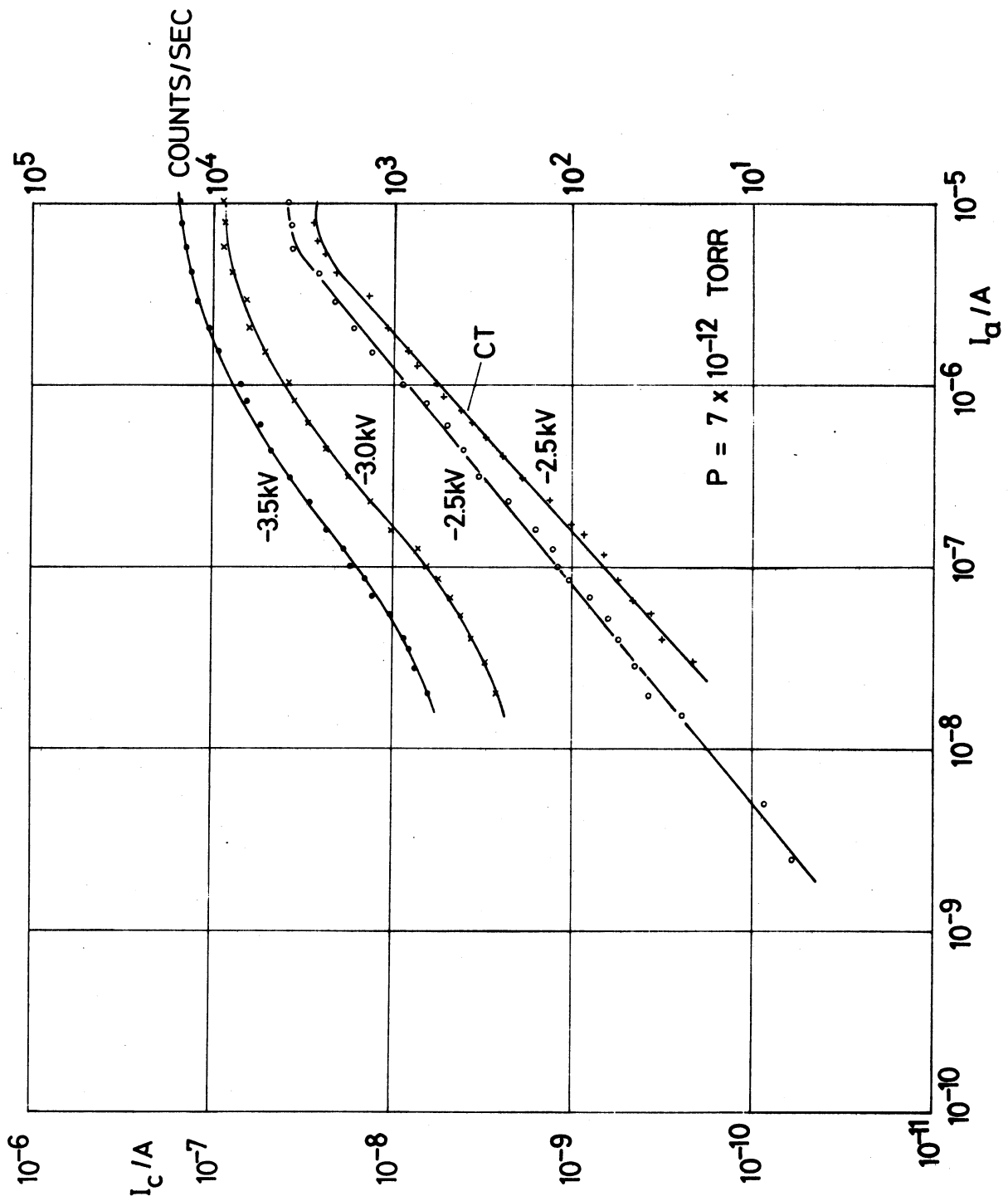


Fig. 5.

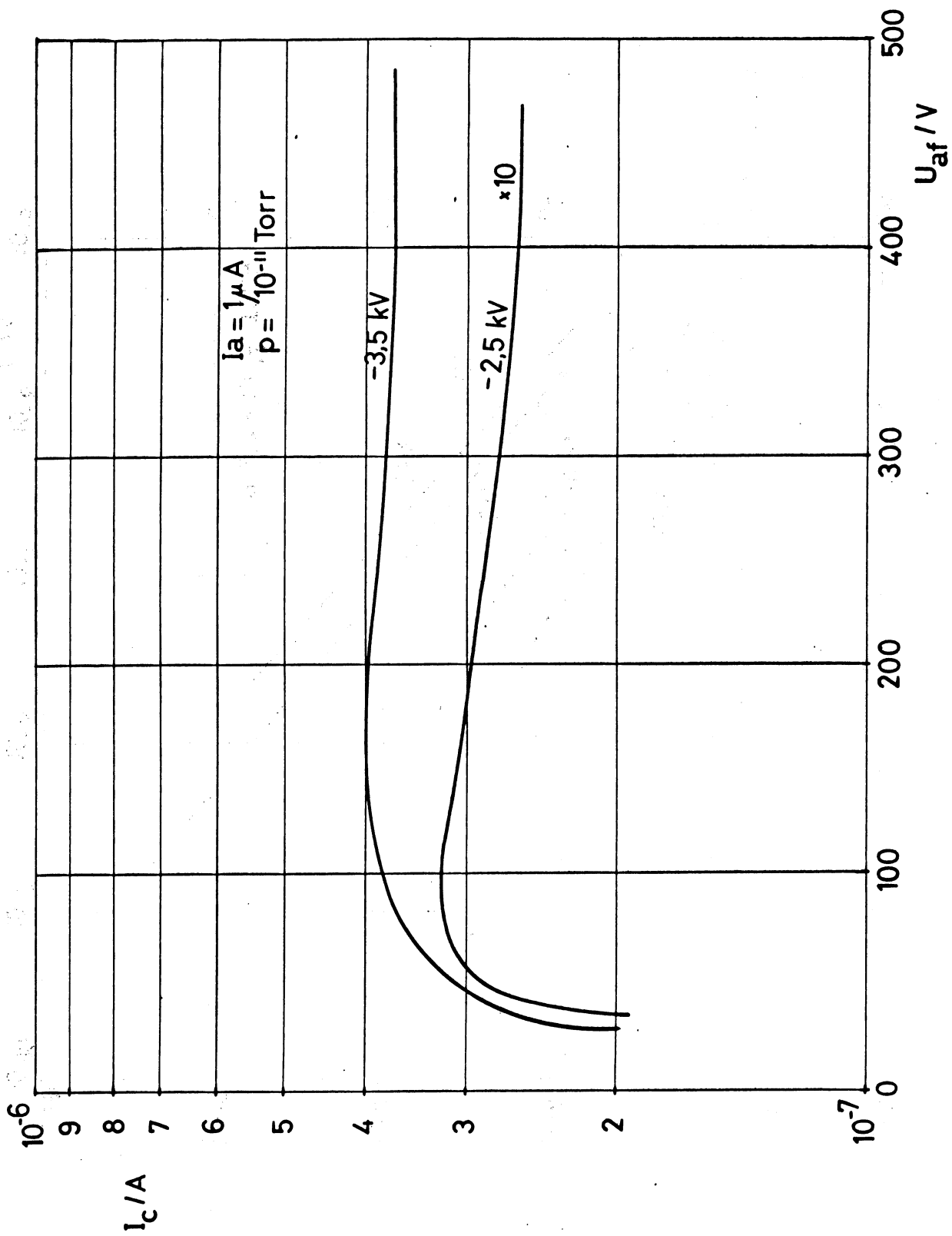


Fig. 6.