The Collection of Positive Ions by Means of Screened Probes

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Abstract

Using a multiple grid probe it was possible to separate the currents flowing from the plasma to the collector into their electron and ion components. Two measuring methods were used to achieve this. This involved investigating the retardation part of the ion curve and the ratio of electron to ion saturation currents. These studies were made mainly in a thermal cesium plasma which was obtained by means of contact ionization on a plane tantalum plate.

In this plasma the retardation part of the ion current curve plotted as a function of the probe potential was found to be exponential, thus indicating a Maxwellian velocity distribution of the ions. It was possible to evaluate the ion temperature from the slope of the retardation part of the ion curve. This curve was followed by a distinct saturation of the ion current to the collector. The ratio of electron to ion saturation current obtained by these measurements was very close to

$$\sqrt{\frac{m^+}{m_-}} \quad \text{for cesium}$$

The ion and electron temperatures determined from the probe characteristic were in the vicinity of the temperature of the hot emitter plate which was at about 2500 °K.

1. Introduction

The Langmuir probe technique is recognized as a standard method of plasma investigation. By measuring the current to a probe placed in a plasma as a function of its potential relative to that of a plasma electrode, the principal parameters of the plasma, such as electron concentration, electron temperature and the potential of the plasma in the vicinity of the probe surface, can be obtained. However, the ion energy distribution or the ion temperature cannot be subjected to experimental investigation using a Langmuir probe in its simple form, because several difficulties such as are described in the following enter into such probe measurements.

When a negative probe is inserted into a plasma the probe surface is enveloped by a sheath that shields the plasma from the region of strong electric fields near such a probe. Due to this shielding the sheath edge is very near at the plasma potential, but this shielding is not quite perfect and a small part of the potential drop can penetrate beyond the sheath edge. This penetration of the electric field into the plasma could accelerate positive ions up to appreciable energies of the order of kT^-, where T^- is the plasma electron temperature. The analysis by BOHM[1] shows that under this condition the ion current density to a probe in a plasma with $T^- \gg T^+$ does not strongly depend on T^+, but it follows the following formula

$$J^+ = QN^+ \sqrt{\frac{2}{m^+}} \sqrt{\frac{kT^-}{2}} \; e^{\left(-\frac{1}{2} + T^+/3T^-\right)} \qquad (1)$$

where N^+ = plasma ion density
k = Boltzmann constant
J^+ = ion current density
Q = elementary charge
m^+ = the ion mass, and
T^-, T^+ = temperature of the electrons and ions.

According to BOHM's formula (1), the ion current to a negative biased probe is more dependent on the electron temperature than on the ion temperature, contrary to Langmuir's conception of the thermal ion flux to the probe obeying the equation

$$J^{+} = \frac{1}{4} N^{+} Q \sqrt{\frac{8kT^{+}}{\pi m^{+}}} \qquad (2)$$

However, the electron saturation current can be considered as the thermal electron flux to the probe and is expressed by:

$$J^{-}_{sat} = \frac{N^{-}}{4} Q \sqrt{\frac{8kT^{-}}{\pi m^{-}}} \qquad (3)$$

where N^{-} = electron density/(cm^3)

m^{-} = electron mass gm

$\sqrt{\frac{8kT^{-}}{\pi m^{-}}}$ = mean thermal electron velocity(cm/sec)

Q = elementary charge.

With J^{-}_{sat} and T^{-} derived from the slope of the electron retardation part of the Langmuir characteristic, the electron density of the plasma can be evaluated.

With the application of BOHM's equation (1) and equation (3) for the case when $T^{+} \ll T^{-}$ the ratio of electron to ion saturation current would be

$$\frac{J^{-}_{sat}}{J^{+}_{sat}} \simeq \sqrt{\frac{e}{2\pi}} \sqrt{\frac{m^{+}}{m^{-}}} \simeq 0.65 \sqrt{\frac{m^{+}}{m^{-}}} \qquad (4)$$

This expression is independent of the electron and ion temperature. Thus in this case when $T^{+} \ll T^{-}$ the mean ion temperature cannot be determined from the expression in eq.(4).

In the case of a thermal plasma with $T^{+} \simeq T^{-}$ it is more adequate to use eq.(2) rather than BOHM's formula eq.(1), so that instead of Eq.(4) the ratio of saturation currents could be written as

$$\frac{J^{-}_{sat}}{J^{+}_{sat}} = \sqrt{\frac{T^{-}}{T^{+}}} \sqrt{\frac{m^{+}}{m^{-}}} \qquad (5)$$

The ion current from the plasma to a Langmuir probe is much smaller than the electron probe current (both according to eq.(4)

and eq.(5).
Furthermore, the retardation part of the ion current to the probe is expected at probe potentials more positive than the plasma potential at which the electron saturation current is reached. This causes that from a Langmuir probe characteristic only the electron and ion saturation currents and the electron retardation current can be measured with sufficient accuracy. The ion saturation current of such a characteristic is measured at relatively high negative probe potentials which are in most cases very distant from the plasma potential. It is therefore difficult to derive the correct ion saturation current from the slope of the ion saturation characteristic as observed mostly. Furthermore, the ion retardation characteristic cannot be separated from the Langmuir curve.

Owing to these difficulties we started to investigate ion characteristics in a plasma using grid probes. Such a grid probe consists of a collector separated from the plasma by one or several grids. By varying the potential of the grid the charged particles flowing to the probe assembly can be separated into its ion and electron part, so that at the collector a pure ion or electron probe characteristic could be measured. A sketch of such a grid probe as was used in our following investigations is shown in fig. 1.

For a distinct interpretation of the ion current characteristic the following conditions of the state of the plasma and the method of measurements have to be fulfilled:

a) The gas pressure of the discharge must be kept so low that no collisions of the collected particles with gas atoms may occur between the edge A and the collector electrode C (fig. 1) and the electrons and ions must obey the law of free fall on their way from the plasma edge to the probe collector.

b) The velocity distribution of those charge plasma particles the characteristic of which is to be measured, should not be disturbed by the grid probe assembly. Therefore, the electric field along its way from the plasma to the collector must be uniform. This condition is fulfilled only when the sheath thickness is much larger than the grid spacing. - The sheath thickness can be derived from the Child's law, which in the case of cold ions obeys the following formula:

$$J^{+} \equiv \frac{\sqrt{2}}{9\pi}\sqrt{\frac{Q}{m^{+}}}\;\frac{U^{3/2}}{\sigma^{2}} \qquad (6)$$

where U = probe voltage in volts with respect to the plasma potential

J^{+} = ion current density in amp/cm^{2}

σ = sheath thickness in cm,

or when an initial Maxwellian velocity distribution of the collected ions is taken according to DARROW[2]:

$$J^{+} = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{Q}{m^{+}}}\;\frac{U^{3/2}}{\sigma^{2}}\left(1 + \frac{2.66}{\sqrt{\eta}}\right) \qquad (6a)$$

$$\text{with } \eta = \frac{QU}{kT^{+}}$$

In order to ensure that the field between the grid and the plasma be uniform, the grid spacing ϕ must be smaller than the sheath thickness σ or from eq.(6a)

$$\phi \ll \sigma = 2.36 \text{ x } 10^{-4}\left(\frac{U^{3/2}\left(1 + \frac{2.66}{\sqrt{\eta}}\right)}{J^{+}\sqrt{m^{+}}}\right)^{1/2}$$

c) When the condition b) or eq.(7) is fulfilled, it is also ensured that no electric fields can penetrate from inner grids or the collector through the outer grids into the plasma. By such penetrating fields the characteristic curve would be disturbed.

2. Apparatus

The investigations of the ion current collection with a multiple grid probe were carried out in a contact-ionized cesium plasma. The cesium plasma apparatus in which the following measurements were made was developed by GUILINO[3]. It is shown in fig. 2. In this apparatus a beam of cesium atoms is directed through a collimator, consisting of small channels, towards a hot tantalum plate, heated up to temperatures between 2000 and 2500 °K by electron bombardment from the emitter backside. On reaching this heated emitter plate the cesium atoms are contact-ionized. The ions and electrons - emitted thermically at the hot plate - flow ambipolar into the plasma chamber which consists of a glass tube with an inner diameter of about 7.5 cm. During the operation the base gas pressure in the plasma chamber was always less than 10^{-5} torr. The plasma density was in the range of 10^{8} cm^{-3}. The plasma temperatures T^{+} and T^{-} were near the temperature of the hot end plate.

The details of the screened probe and the circuit connections are shown in fig. 3. The probe assembly consists of two grids in front of a collector mounted on concentric cylinders of different diameters, and so proper screening assures that no particles can reach the collector unless they pass through both the grids. The outermost grid G_1 was of stainless steel, consisting of 40000 meshes/cm^2 with 50% transparency, while the inner grid G_2 had about 1025 meshes/cm^2 and was made of 0.04 mm platinum wire. Both grids and the collector were about 2 cm in diameter. The distance between the collector and the outer grid was about 1 cm. The inner grid was situated midway. The grid probe was axially inserted into the plasma through an orifice using a gland.

3. Measuring Methods, Results, and Discussion

The following methods of separating the probe currents into their electron and ion parts were used:

1) The grid potential V_g was kept constant with respect to the plasma potential V_p and the potential of the collector V_c was varied.

2) V_c was kept constant (strongly positive for electron or strongly negative for ion collection) and V_g was varied.

All potentials are referred to the emitter plate, which was grounded.
Method 1) was first applied by LANGMUIR[4] and co-workers, while method 2) was originated by BOYD[5].

When a plane Langmuir probe is at plasma potential there is no electric field between the probe and the plasma and in this case electrons and ions would be streaming towards the probe with their respective thermal velocities. At probe voltages different from plasma potential the probe current would be composed of the sum of ion saturation current and electron retardation current for probe voltages negative to plasma potential, and similarly it would be composed of electron saturation current and ion retardation current for probe voltages positive to the plasma potential.

Now if a grid is interposed between the plasma and the collector, the collector current characteristic as a function of the collector potential V_c and of the grid potential V_g would be modified in the following manner (see also fig. 4):

1. $V_c < V_g < V_p$

Under these conditions the electron current is composed of the ion saturation current and a current due to those electrons possessing energies perpendicular to the probe surface larger than QV_c. The electron collector current J_c as a function of the collector voltage V_c corresponds in this case to a Langmuir characteristic with probe voltages $V_{pr} < V_g$.

2. $V_g < V_c < V_p$

Under these conditions the total collector current is the sum of the ion saturation current and an electron current which is contributed by those electrons possessing kinetic energy greater than QV_g. The J_c-V_g characteristic corresponds to the Langmuir characteristic with probe voltages $V_{pr} < V_g$ and J_c as a function of V_c is constant at fixed V_g.

3. $V_g < V_p < V_c$

Here as in the cases 1) and 2) the grid is transmitted by all the ions and by electrons with energies larger than QV_g. The collector current is composed of the total electron current transmitted through the grid at potential V_g and due to ions with energies larger than QV_c. In this potential range of the grid probe, the collector characteristic (J_c-V_c curve) is composed of a constant electron current component with the superposition of the retardation part of the ion current characteristic. At sufficiently high negative grid voltages V_g, the electron current component to the collector can be made so small, that the collector characteristic yields only the ion current characteristic from which the ion velocity distribution could be derived.

Experimental grid probe curves are shown in fig. 5. During this experiment both the grids were at the same potential and the grid voltage V_g was varied in steps from - 3.1 to - 12.5 V. The collector potential was varied continuously using a saw tooth generator from - 5 to + 1 V. The curves showing variations in the collector current as the collector voltage was varied, are shown here; the grid voltage was thereby varied as a parameter. These grid probe curves have the following characteristics:
For strongly negative grid voltages (V_g = - 5 to - 12.5 V) no plasma electrons are able to penetrate the grid, so that the collector current voltage curves are only formed by the ion current characteristics. The ion current is fairly constant in its saturation part and it decreases exponentially with V_c for values of $V_c > -1.2$ V. At grid potentials $V_g > -3.5$ V, the ion current curves are superposed partially by an electron current characteristic, formed by plasma electrons with energies greater than $Q(V_g - V_p)$.
These measurements show an increase of the ion saturation current, for negatively growing grid voltages, as is also found with Langmuir probes. A possible cause for this could be an increase of the penetration of the sheath field into the plasma when the grid is more negative.
From these curves it is also seen, that for $V_c > V_p$ and inspite of

a highly negative biased grid, the collector draws a small negative current which increases with V_c. We believe that this current is carried by electrons generated at the grid by secondary processes and driven by the E-field between grid and the collector, these electrons thereby flowing to the collector. In order to suppress these peculiar collector currents one further grid (with 1025 meshes/cm^2 and made of 0.04 mm diameter Pt wires) was interposed between the collector and the outer grid. By means of this second grid which was at highly negative potential with respect to the potentials of the outer grid, this peculiar collector current could be reduced considerably.

In actual measurements this double grid probe was used for determining the retardation part of the ion curve (method 1). Here the outer grid voltage V_{g1} was varied as a parameter while the inner grid voltage V_{g2} was made strongly negative (- 20 V) for ion collection and strongly positive (+ 20 V) for electron collection. Using a sawtooth generator the collector potential was thereby varied from - 5 to 0 V with respect to the emitter. Linear and semilog plots of these curves are shown in figs. 6a and 6b. These curves show that the ion retardation currents J_c increase nearly exponentially with V_c and show a bend corresponding to the saturation of ion current.

The semilog curves of fig. 6b show that for grid voltages below the plasma potential ($V_g < - 3V$) the ion temperature determined from the retardation part of the ion curve gave consistent values of the order of 2500 ^oK. However, for grid voltages positive to - 3V the retardation part is not consistent. Temperaturesdetermined from the slope of these curves are different for different grid voltages and are higher at more positive grid voltages V_{g1}. The reason for this inconsistency in "temperature" derived from the ion characteristic may lie in the fact that as the grid potential approaches the plasma potential the sheath thickness approaches to small values. The necessary condition that the grid spacing ϕ should be much smaller than the sheath thickness σ (see eq.(7)) is thereby not fulfilled. As a result of this the potential distribution of the grid structure is not one-dimensional. The charged particles in this case could undergo change in the transverse velocity component and from the collector characteristics no plasma ion velocity distributions can be derived.

The above method 1 does not give the real magnitude of ion saturation current as already discussed (with regard to fig.5), where we mentioned that the increase in ion saturation current could be due to negatively growing voltages that could cause penetration of the grid field into the plasma. Contrary to such an increase in ion saturation current with increasing $-V_{g1}$ we observe in fig. 6b a slight decrease in ion current. This decrease could be due to a part of the current flowing to the highly negative intermediate grid ($V_{g2} = -20$ V). This current to the intermediate grid was not accounted in our collector characteristic.

Besides this above discussed grid probe method (method 1), a method 2, as is described in the following, is suitable for determining the ratio of electron to ion saturation currents. Here the collector potential is kept constant (the inner grid and the collector are at the same potential) and strongly negative (- 25 v) for ion collection or strongly positive (+ 25 V) for electron collection. The potential of the outer grid V_{g1} was varied positive and negative relative to the plasma potential. The ratio of electron to ion saturation current was thereby determined.

Such measurements were first made by BOYD[5] in a low pressure argon glow discharge.

In fig. 7 typical collector current-grid voltage (V_{g1}) characteristics are shown as measured according to method 2, just described. As is seen from this figure the transition of the ion current curve from its deceleration to its saturation part near the plasma potential show two bends. A possible reason for this could be the disturbance of the ion velocity distribution when the sheath edge in front of the outer grid disappears at $V_{g1} \simeq V_p$ and thus the condition according to the eq.(7) is not fulfilled. We do not believe, that this is the driving mechanism of this peculiar ion current behaviour, because the electron current curve at its transition into the saturation current is normal, as is seen from fig. 7. We believe rather that at the one end, situated at the more positive V_{gl}, the pure thermal ion flux to the probe assembly is measured.

The higher ion saturation current, which occurs at the second bend at a more negative grid potential, we understand could result due to the penetration of the electric field from the grid through the plasma sheath into the plasma. This electric field accelerates the plasma ions in the presheath and increases the ion current to the probe assembly according to BOHM's concept, described before.

This supposition is also supported by the experimental result of the ratio of electron to ion saturation current. With the ion saturation current, taken near the first bend of the ion current curve this ratio is measured to be ≃ 470, very close to the value according to eq.(5).

$$\frac{J^-_{sat}}{J^+_{sat}} = \left(\frac{m^+}{m^-}\right)^{1/2} = 494 \text{ for cesium plasma with } T^- = T^+$$

When, however, the upper saturation current at a V_{gl} more negative is chosen, this ratio sometimes varied down to a minimum value of 385, smaller than the theoretical value according to eq.(5). Measurement of this current ratio from normal Langmuir probe characteristics under similar experimental conditions gave $(J^-_{sat}/J^+_{sat}) \lesssim 100$.

The above interpretation of the ion current characteristic is furthermore supported by the fact that the values of the plasma potential coincide better with the grid potential, at which the transition to the smaller ion saturation current occurs.

This grid probe method 2 is not so suitable for measurement of ion temperature in the plasma, from the slope of the retardation part of the separated ion characteristic, because in these measurements the grid potential is varied positive relative to the plasma potential and large plasma electron currents, disturbing the plasma, are drawn by the grid electrode. On the other hand, this method 2 is the only adopted method to measure the ion current saturation characteristic near the plasma potential.

4. Conclusions

The Langmuir method (method 1) is convenient for ion temperature determination from the retardation part of the ion curve; and the Boyd method (method 2) is suitable for estimating the saturation current ratio.

In a thermal cesium plasma we observed:

1) a distinct ion saturation current to the probe;
2) the retardation part of the ion curve is exponential, from which a Maxwellian distribution for ions is to be expected;
3) the transition region between the ion retardation and ion saturation was disturbed, presumably due to the drift in the presheath or due to the grid not being covered with a plasma sheath of sufficient thickness;
4) the ratio of electron-to-ion saturation current determined from the Boyd method (our method 2) gave values very close to $\sqrt{\frac{m^+}{m^-}}$;
5) the Langmuir method (our method 1) gave consistent values of ion temperature of $T^+ \simeq T^- \simeq 2500\ ^oK$ in a cesium plasma.

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Figure Captions

Fig. 1	Ion sheath and grid dimensions in front of the collector
Fig. 2	Cs Apparatus "Alma 1"
Fig. 3	Construction and Circuit of the Grid Probe
Fig. 4	Collector characteristic of grid probe
Fig. 5	Collector characteristic of grid probe for different grid bias
Fig. 6	a) Separated Electron-Ion Currents b) Separated Electron-Ion Currents
Fig. 7	Separated electron-ion current

Ion sheath and grid dimensions in front of the collector

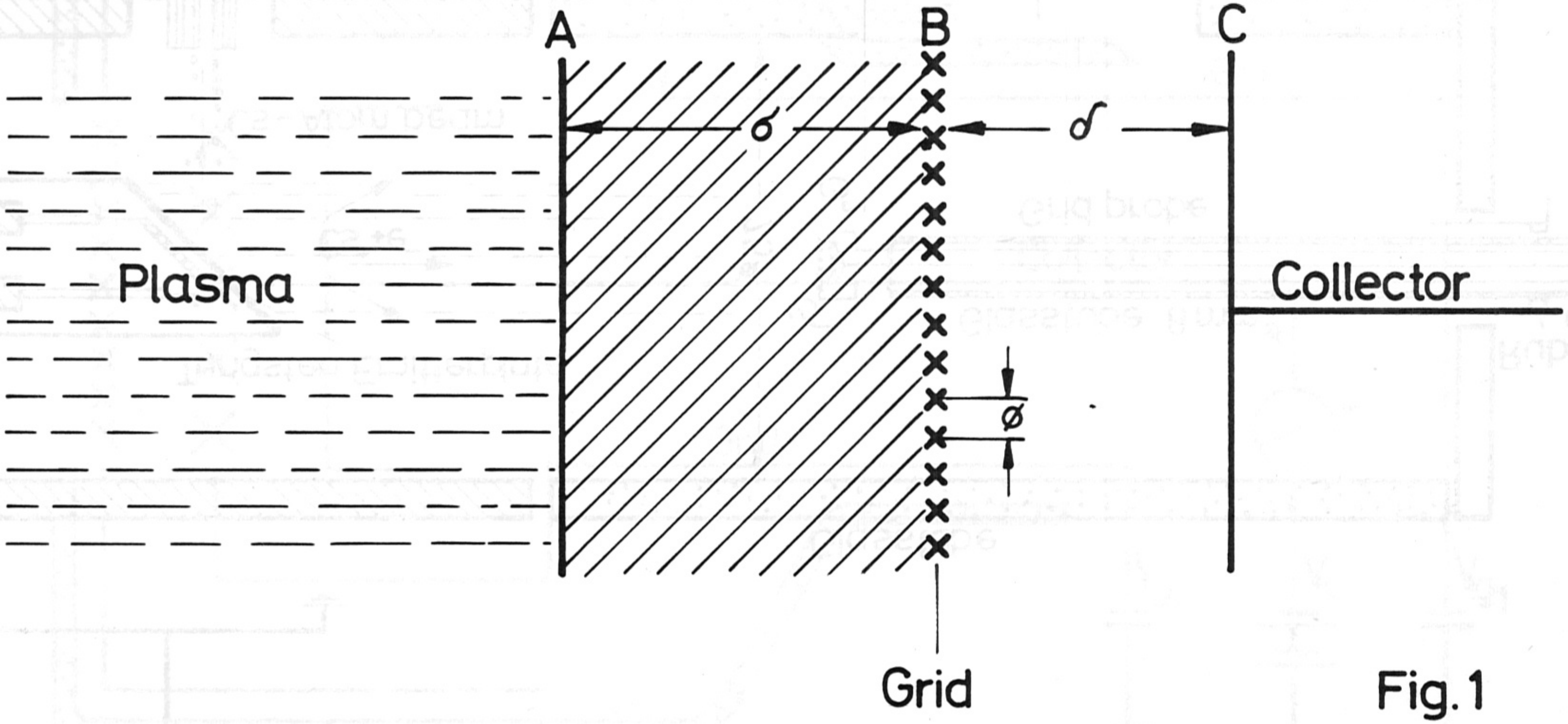


Fig.1

Cs Apparatus "Alma1"

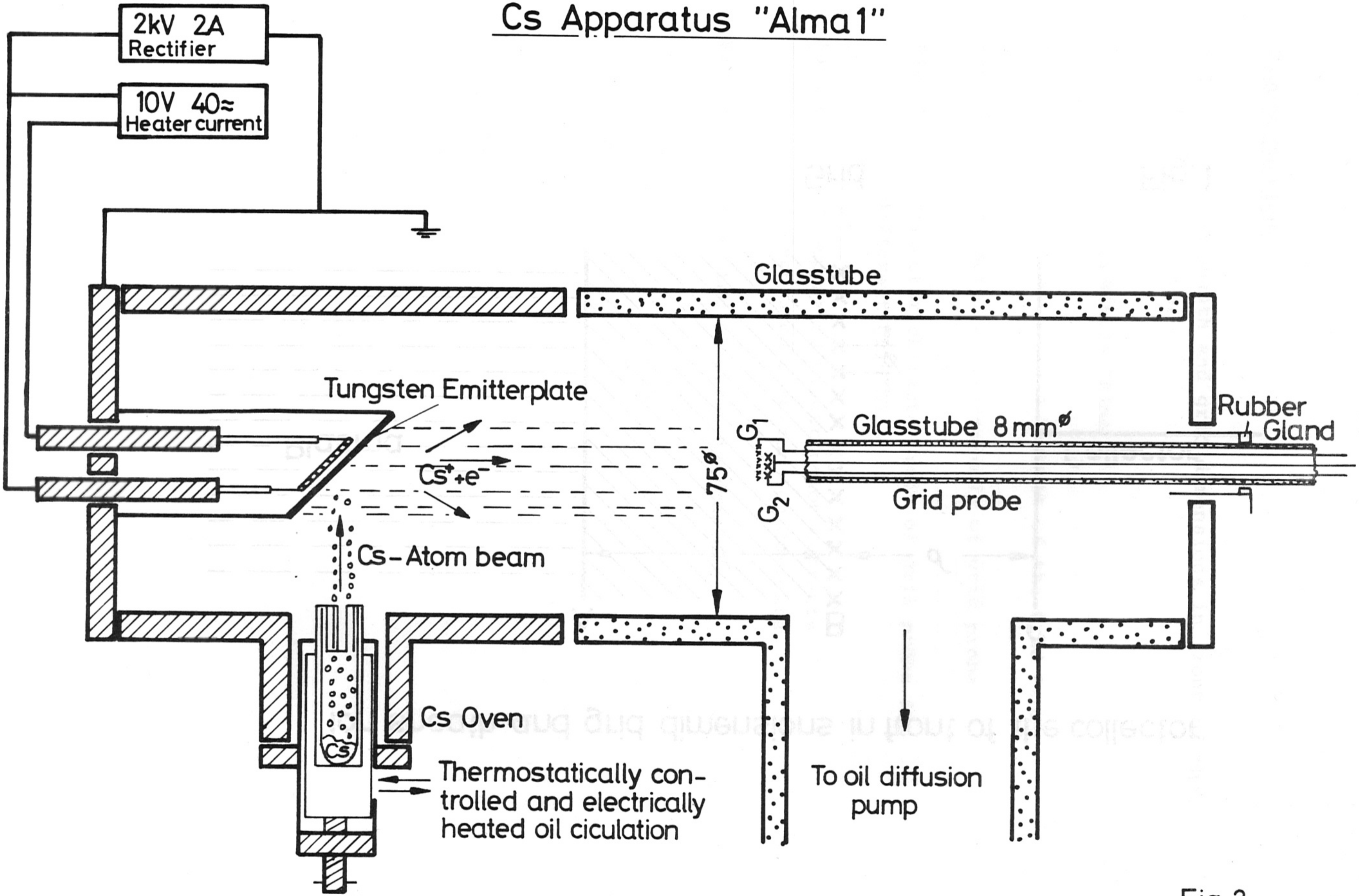


Fig. 2

Construction and Circuit of the Grid Probe

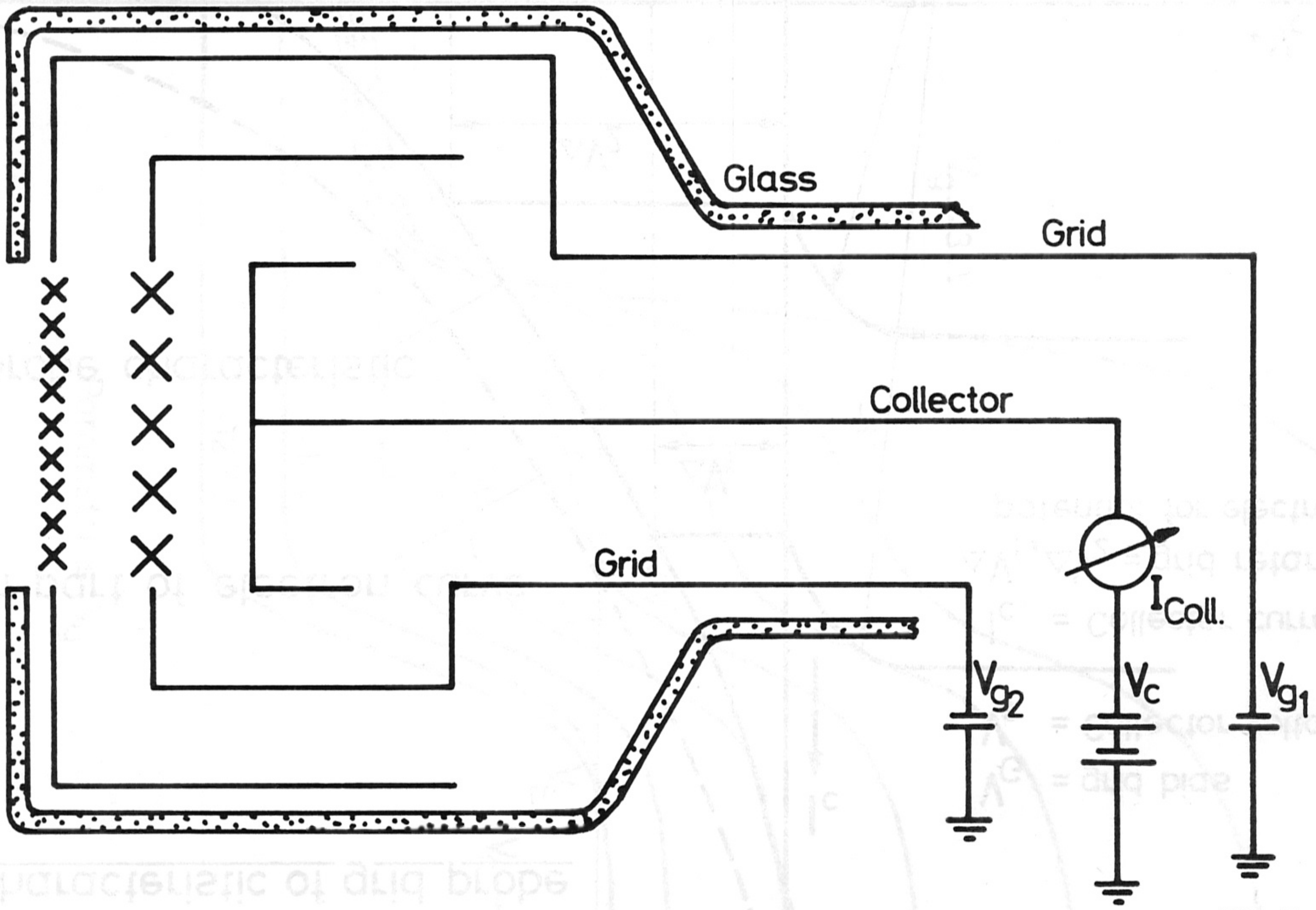


Fig. 3

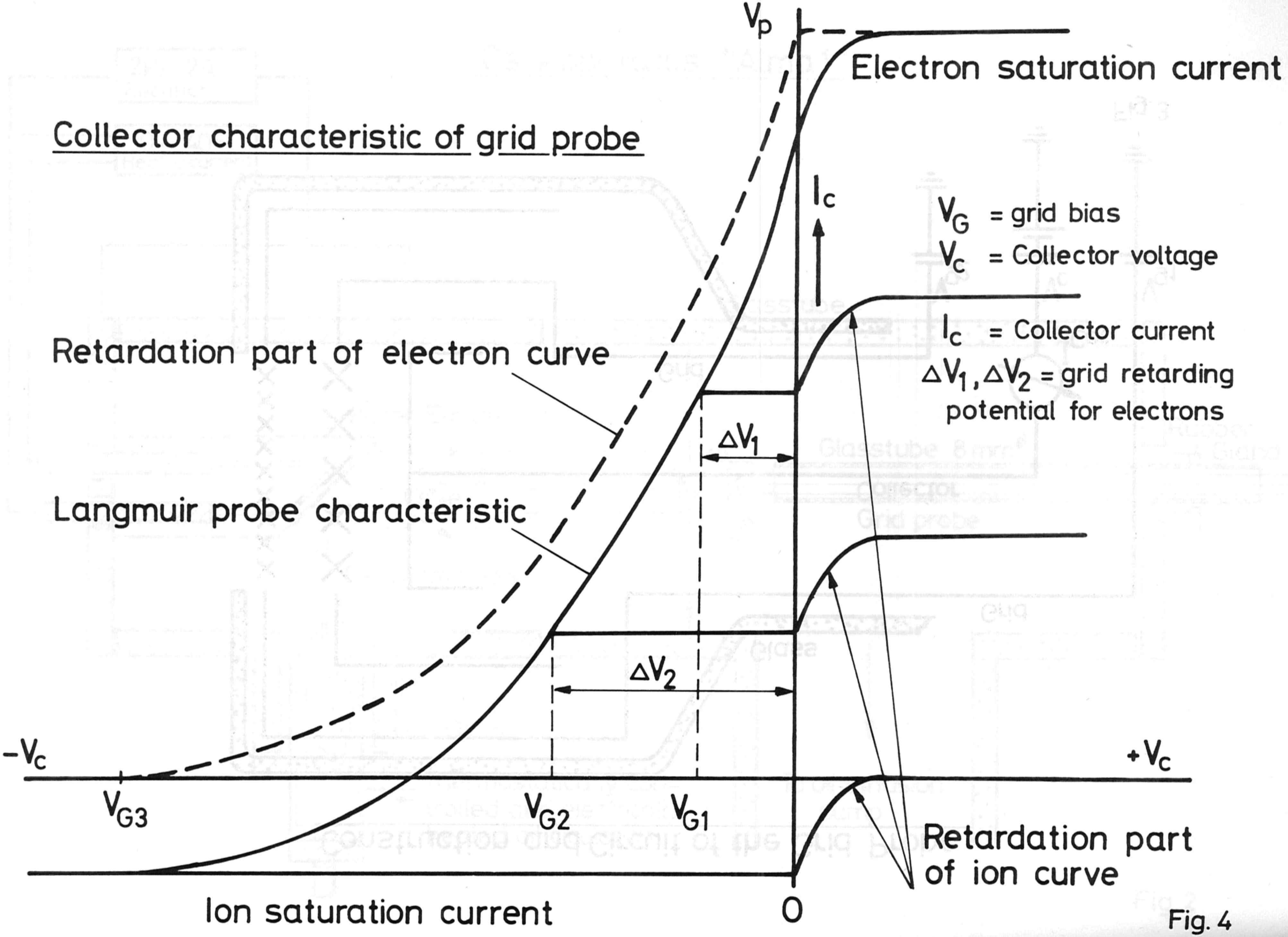
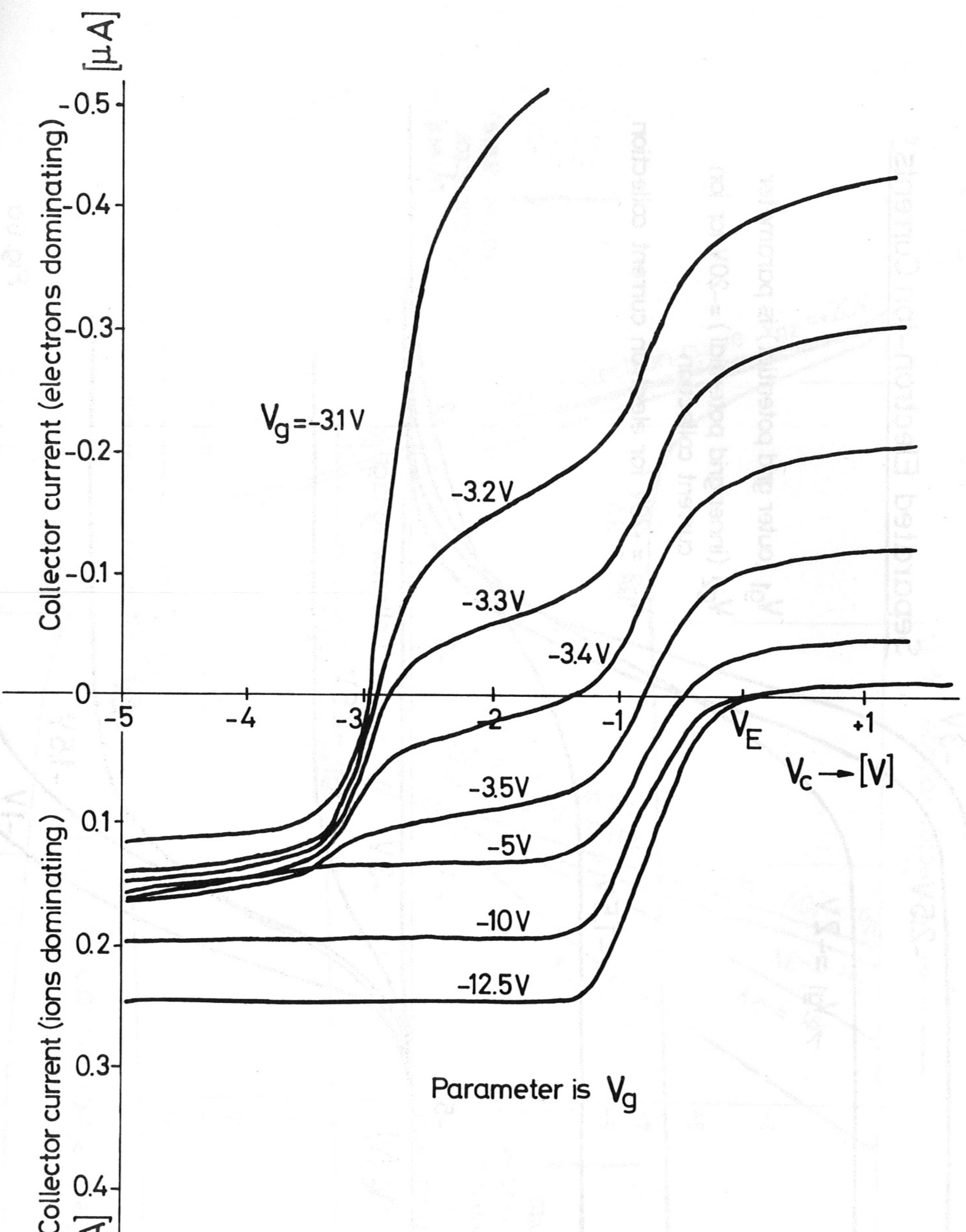

Collector characteristic of grid probe
V_p
Electron saturation current
I_c
V_G = grid bias
V_c = Collector voltage
I_c = Collector current
$\Delta V_1, \Delta V_2$ = grid retarding potential for electrons
Retardation part of electron curve
Langmuir probe characteristic
ΔV_1
ΔV_2
$-V_c$
$+V_c$
V_{G3}
V_{G2}
V_{G1}
Retardation part of ion curve
Ion saturation current
0

Fig. 4



Collector characteristic of grid probe for different grid bias.

Fig. 5

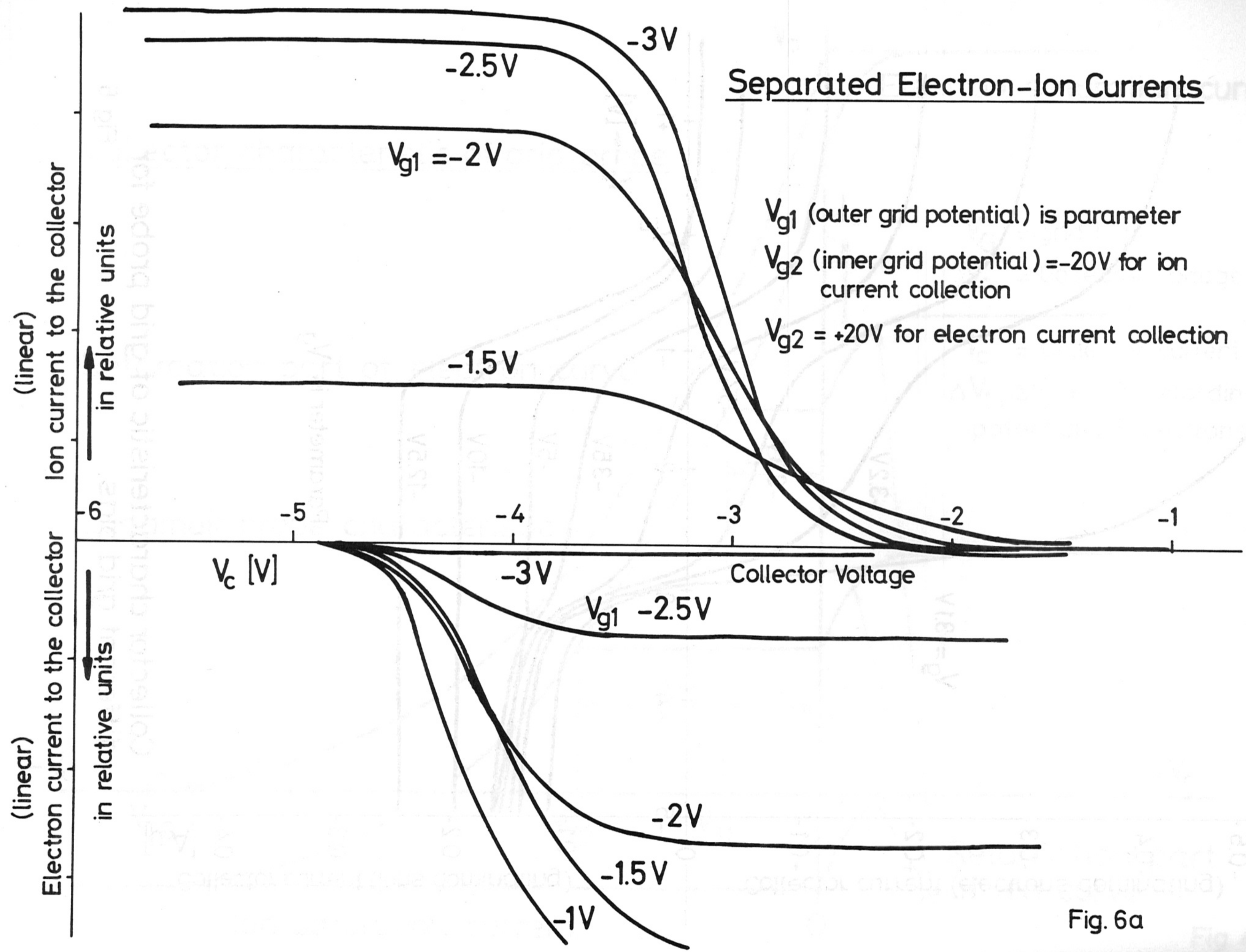

Separated Electron–Ion Currents
V_{g1} (outer grid potential) is parameter
V_{g2} (inner grid potential) = −20V for ion current collection
V_{g2} = +20V for electron current collection
(linear) Ion current to the collector in relative units
(linear) Electron current to the collector in relative units
V_c [V]
Collector Voltage
-6
-5
-4
-3
-2
-1
-3V
-2.5V
V_{g1} = −2V
−1.5V
−3V
V_{g1} −2.5V
−2V
−1.5V
−1V

Fig. 6a

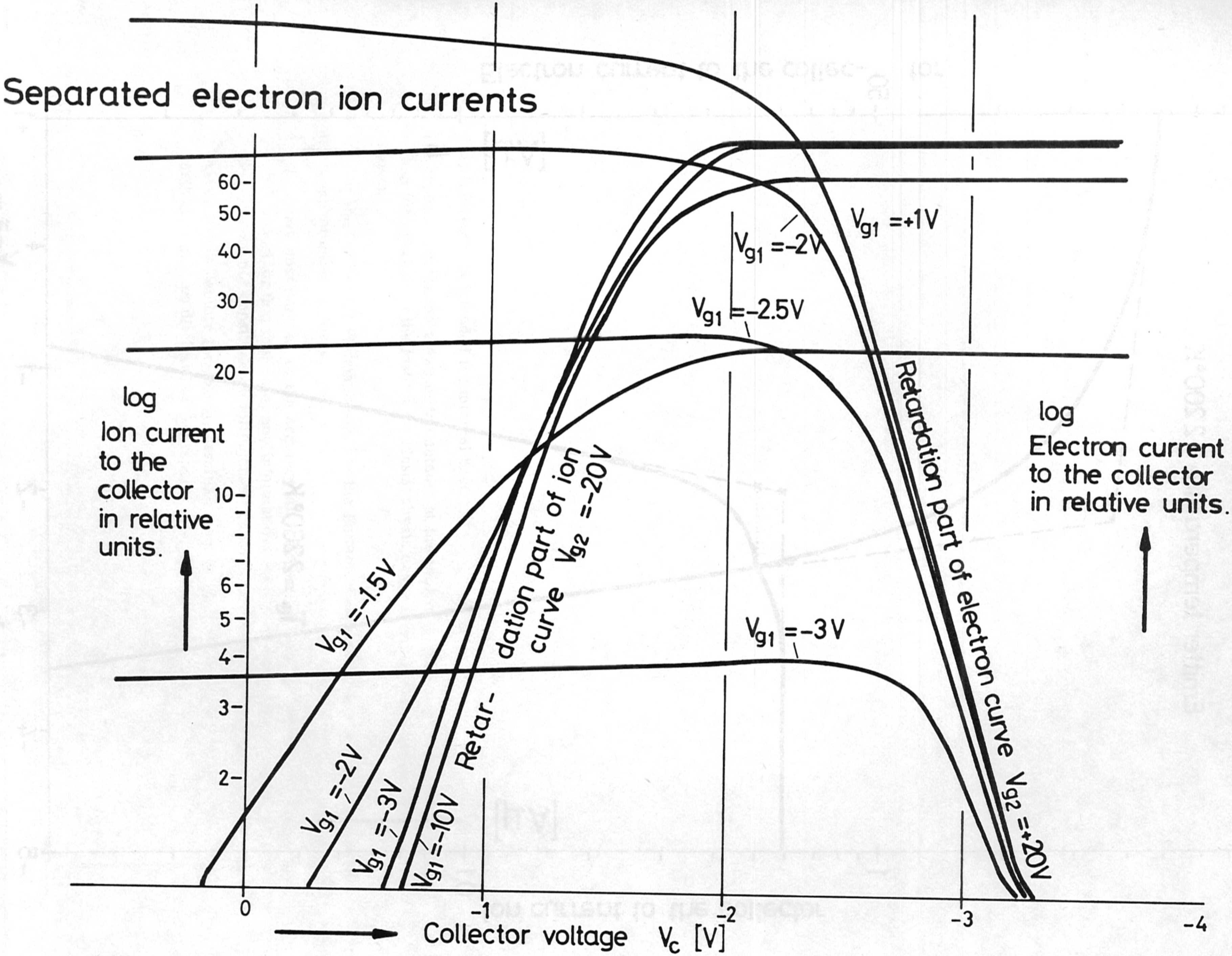
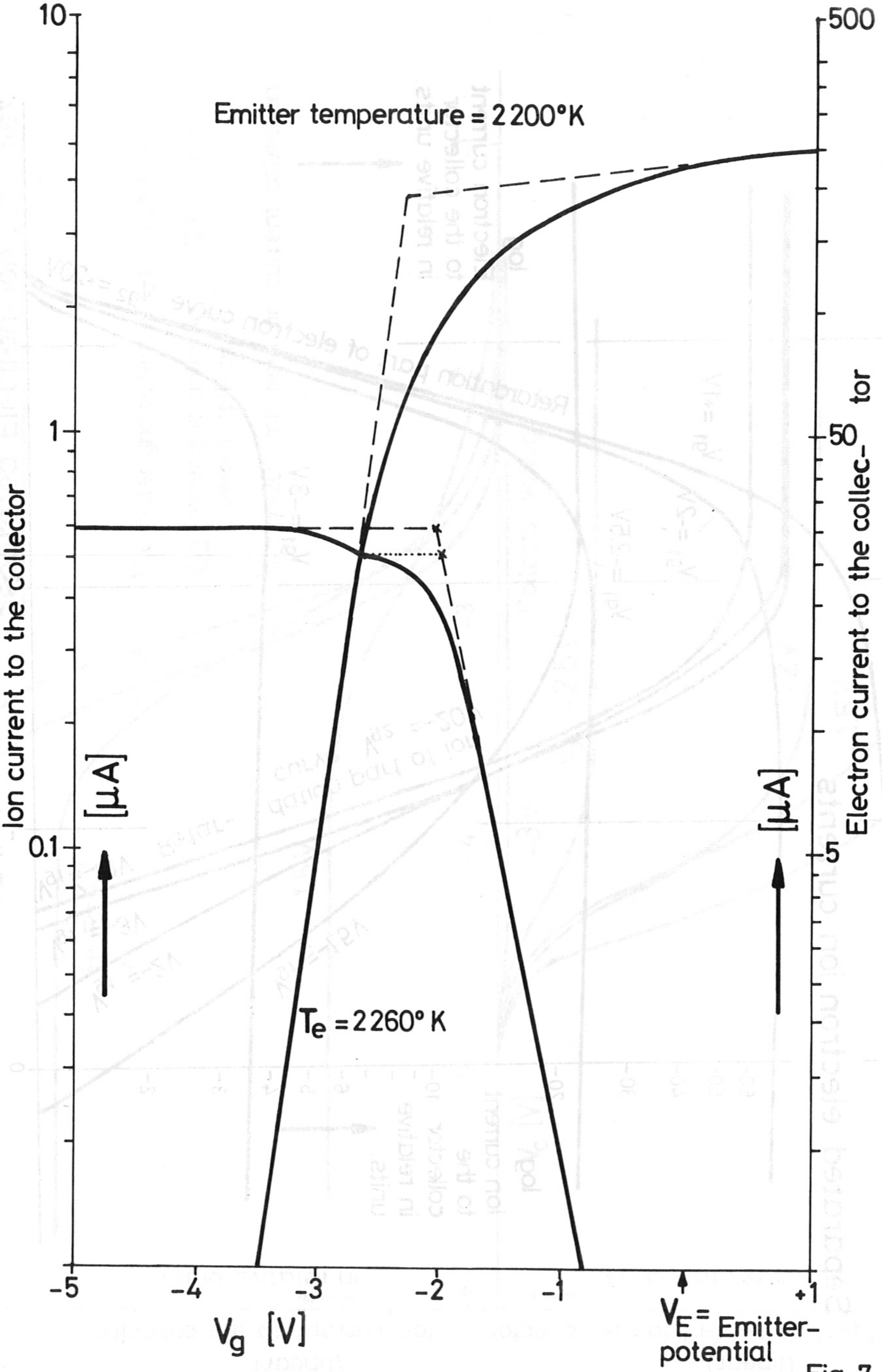

Separated electron ion currents

Fig. 6b



Separated electron-ion current
10
1
0.1
500
50
5
Emitter temperature = 2200°K
T_e = 2260° K
Ion current to the collector [µA]
Electron current to the collec-tor [µA]
-5
-4
-3
-2
-1
+1
V_g [V]
V_E = Emitter-potential

Fig. 7