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A FIXED-BIAS, FLOATING DOUBLE-PROBE TECHNIQUE WITH SIMPLE LANGMUIR PROBE CHARACTERISTICS

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A Fixed-Bias, Floating Double-Probe Technique With Simple Langmuir Probe Characteristics

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ABSTRACT

A new floating double-probe method is presented which has advantages over other floated-probe systems heretofore described in the literature. The method utilizes two electrodes, one of constant area and the other with a variable area, and the two-electrode configuration is separated by a fixed bias voltage. The current-voltage characteristics of the new technique, which are generated by varying the area of the one electrode, are identical to those of a simple Langmuir probe thus coupling all the advantages of a floated-probe system with the simple analysis scheme generally applied to the Langmuir probe for the determination of plasma density and temperature.

I. INTRODUCTION

The use of electrical probes for plasma diagnostics has enjoyed a relatively long history which began primarily with the pioneering work of Irving Langmuir[1] who made famous the technique of the single electrical probe, the Langmuir probe. Over the years considerable advances have been made in understanding the details of single-probe response in the presence of all types of plasmas and other techniques have been introduced in an effort to circumvent some of the possible difficulties and perturbations that could be introduced by a Langmuir probe measurement of plasma density and temperature.

After the work of Langmuir the first major contribution to the experimental techniques of plasma diagnositics by electrical probes was the floating double-probe technique of Johnson and Malter[2]. The latter technique was then followed by the floating triple-probe method of Yamamoto and Okuda[3,4] and the variable-area probe technique of Fetz and Oechsner[5].

In a continuing effort to develop new and improved techniques for plasma diagnostics a fixed-bias, floating double-probe method is herein presented which not only has the advantage of the floated systems of References 2-5 but has additional advantages not possessed by the latter techniques. Unlike the latter techniques the analysis required for the determination of electron temperature and density are quite simple since the current-voltage characteristics of the fixed-bias, floating double-probe technique are exactly those of the simple Langmuir probe.

In the succeeding section the new technique will be described and compared with those methods already mentioned; and experimental evidence will be presented which supports the validity of the technique.

II. DESCRIPTION OF TECHNIQUE

The fixed-bias, floating double-probe technique employs a fixed-area probe which is biased with respect to an electrode of variable area, as illustrated in Fig. 1, and the two-electrode system is floated (i.e. the associated circuitry is electrically isolated from any other electrodes which may be in contact with the plasma). With a bias voltage V_B fixed in magnitude the collecting surface of the variable-area electrode is changed and the current I which flows between the two electrodes is measured as well as the electric potential of the fixed-area probe V_P which is referenced to a point different from that of the electrode of variable area. The measurement of electric potential must be made in such a way that the effective current drain is zero (this guarantees electrical isolation and minimizes possible distortion of plasma parameters by the diagnostic technique), and the potential of the reference point must be fixed with respect to that of the plasma. The current collection properties of the fixed-area probe are those of a simple Langmuir probe with the values of current I and voltage V_p supplying the two parameters for the usual characteristic, and with the region of probe operation (i.e. saturation or retarding field currents) merely being a function of the polarity and magnitude of the bias voltage as well as the collecting surface of the variable-area electrode. None of the latter three parameters, however, enter the analysis scheme for determining the density and temperature of the plasma. These points will subsequently be illustrated.

From the considerations of the fixed-bias, floating double-probe technique the potential of the probe V_p and the current I flowing between the two electrodes, with the bias voltage V_B and plasma parameters held constant, are variables which are dependent upon the collecting surface of the variable-area electrode A_v. An understanding of this dependence can be achieved by first recalling that in any floated-probe system the total collected current must equal zero, that is $i_p + i_v = 0$ where i_p and i_v are the net currents collected from the plasma by the probe and the variable-area electrode, respectively. This constraint yields the identity given by

$$i_{p+} + i_{v+} - i_{p-} - i_{v-} = 0 \tag{1}$$

with the relationship for the circuit current I defined by

$$I = i_{p-} - i_{p+} = i_{v+} - i_{v-}. \tag{2}$$

The subscripts p and v refer to the probe and variable-area electrodes, respectively, while + and - are used to designate the ion and electron components of the net current. For purposes of illustration it will be assumed that there are just two charged species - singly charged positive ions and negative electrons of masses M (Ar^+ will be the assumed ion in the illustration) and m, respectively. It will also be assumed that each specie has a Maxwellian energy distribution with its own characteristic temperature T_+ and T_- and that the variable-area electrode and the probe are perfect cylinders with radii which are much smaller than the thickness of the plasma sheath. (These assumptions merely establish a set of conditions for purposes of illustration and have no general bearing on the operation of the diagnostic technique itself.) Under these conditions and after rearrangement and proper cancellation of terms Eq. (1) may be approximated by Eq. (3) when $0 \geq \chi_p \geq \chi_p^f$ and $\chi_v \leq \chi_v^f$ or when $\chi_p \leq \chi_p^f$ and $\chi_v^f \leq \chi_v \leq 0$ (i.e. when both electrodes repel electrons - in the first case the probe is operating at potentials greater than or equal to its floating potential and in the second case the corresponding operation is at potentials less than or equal to the probe's floating potential)

$$\frac{A_v}{A_p} = \frac{\exp(\chi_p) - \sqrt{-4m\chi_p/\pi M}}{\sqrt{-4m\chi_v/\pi M} - \exp(\chi_v)} \tag{3}$$

and by Eq. (4) when $\chi_p \le \chi_p^f$ and $\chi_v \ge 0$ (i.e. when the probe repels electrons while the variable-area electrode attracts them).

$$\frac{A_v}{A_p} = \frac{\exp(\chi_p) - \sqrt{-4m\chi_p/\pi M}}{-\sqrt{4(1+\chi_v)/\pi}} \tag{4}$$

In Eqs. (3) and (4) χ (with appropriate subscript) is the electric potential V (with the same subscript) measured with respect to the plasma potential V_o and normalized to kT_-/e as shown in Eq. (5)

$$\chi = \frac{e(V - V_o)}{kT_-} \tag{5}$$

where e is the absolute charge of an electron and k is the Boltzmann constant; and the potentials χ_v and χ_p are related through the bias voltage V_B as shown in Eq. (6)

$$\chi_p - \chi_v = \pm \frac{eV_B}{kT_-} \tag{6}$$

where $+eV_B/kT_-$ and $-eV_B/kT_-$ correspond to the cases of positive and negative bias, respectively. In Eqs.(3) and (4) the expressions for ion and electron saturation currents have been taken from Chen[6] in the limit $T_+/T_- \to 0$ and the superscript f has been used to denote the floating potential. (The floating potential of an electrode immersed in a plasma is defined to be that potential at which no net current flows to the electrode from the plasma.)

The dependence of χ_p and the dimensionless current density $J_p(=I/n_- e\sqrt{kT_-/2\pi m}\, A_p)$ on A_v as established by Eqs.(2),(3),(4) and (6) is illustrated in Fig. 2 with $|\pm eV_B/kT_-| = 15$. (Under the specified conditions J_p is given by the right-hand numerator of Eq.(3).) In that figure it can be seen in both cases of bias that $J_p = 0$ only when $A_v/A_p \to 0$ and that $\chi_p \to \chi_p^f$ in the same limit. In the case of positive bias (dotted curves), increasing values of A_v/A_p results in diminishing values of $-\chi_p$ with corresponding increases in J_p in the sense of net electron current. A value of $A_v/A_p = 62$ finally establishes the probe at the plasma potential $\chi_p=0$ and values of $A_v/A_p > 62$ will permit collection of electron saturation current by the probe (this regions is not included in the figure). In the case of negative bias (solid curves), values of $-\chi_p$ increase from $-\chi_p^f$ as A_v/A_p increases from zero permitting the collection by the probe of net ion current. A cut-off is shown on the χ_p scale which simply reflects the restriction on the maximum value of $-\chi_p$ imposed by the magnitude of the bias voltage and the floating potential of the variable-area electrode. The dependence of $-\chi_p)_{max}$ on V_B and χ_v^f is given by

$$-\chi_p)_{max} = -\chi_v^f + \frac{eV_B}{kT_-} \qquad (7)$$

which in the case illustrated in Fig. 2 yields $-\chi_p)_{max} = +4.75 + 15 = +19.5$. (Under the assumed conditions of the illustrations $\chi_p^f = \chi_v^f$.)

The example presented in Fig. 2 clearly shows that a probe's current and electric potential can be varied simply by altering the area of the reference electrode while maintaining a constant bias voltage between the two. When J_p is plotted as a function of χ_p a current-voltage characteristic results which is identical to that normally referred to as a Langmuir probe characteristic. From an experimental point of view J_p (i.e. I) can be measured in a straightforward manner but χ_p can only be established by the measurement of V_p with respect to another electrode (not the variable-area electrode) in contact with the plasma whose potential remains constant with respect to the plasma. In many types of discharges there already are electrodes in contact with the plasma and these can be used for the measurement of V_p. If there are no suitable electrodes available for the measurement of V_p then one can be inserted in the plasma which will not disturb the equilibrium condition of the plasma and perturb the plasma parameters of density and temperature. This third electrode (the probe and variable-area electrode being counted as the first and second) can be made as small as practicable and the restriction on the voltage measurement technique will guarantee that the third electrode remain at its floating potential which is fixed with respect to the potential of the plasma.

As mentioned earlier the parameters I and V_p supply the necessary information for the current-voltage characteristic which is identical to that of a simple Langmuir probe and which can be analyzed by standard techniques to determine the density and temperature of the plasma. This will be experimentally demonstrated in the next section.

III. EXPERIMENT

The fixed-bias, floating double-probe technique described above was experimentally tested in three totally different plasma environments.

In the first case the plasma was that of an inductively-coupled hf discharge of cylindrical geometry with length and diameter equal to 9.5 cm. The discharge was maintained by a single-turn coil which was inductively coupled to a hf generator operating at 27 Mhz. The plasma volume was bounded along its length by a metal plate on one end and by a wire grid on the other. The gas was argon and the operating pressure was 1.0×10^{-3} torr. (The electrode and plasma configuration is schematically illustrated in Fig. 3.) The probe was made of 0.1 mm diameter tungsten wire and was 4.2 mm in length. The electrode of variable area was constructed from a 2 mm diameter molybdenum rod which was mechanically coupled to a linear motion feedthough. The collecting area of the variable-area electrode was changed simply by increasing or decreasing the extension of the molybdenum rod beyond the end of a coaxial glass insulating tube. The magnitude of the bias voltage V_B was 85 volts and the probe potential V_p was measured with respect to the end surfaces of the discharge which were maintained at earth ground.

Fig. 4 shows a typical result for the current-voltage characteristic of the fixed-bias, floating double-probe as presented by the display of an X-Y recorder. This particular characteristic is shown for two levels of current sensitivity and was collected under conditions for which $n_- = 2.9 \times 10^{10} cm^{-3}$ and $T_- = 7.2 \times 10^4$ °K where the latter parameters of electron density and temperature were determined by applying the standard procedures of Langmuir probe analysis in the retarding field region. This involves subtracting a linear extrapolation of the ion saturation current (the region $V_p - V_o \leq -40$ in Fig. 4) from the net current I with the result being the electron current i_{p-}. For electrons with a Maxwellian distribution a plot of $\ln(i_{p-})$ vs $V_p - V_o$ yields a straight line for values of $V_p \leq V_o$ and the slope of this line is related to the electron temperature through Eq. (8).

$$T_- = \frac{e}{k} \frac{d(V_p - V_o)}{d[\ln(i_{p-})]} \tag{8}$$

Figure 5 shows a plot of $\ln(i_{p-})$ vs $V_p - V_o$ as taken from Fig. 4 (the solid circles). The potentials in both these figures have been defined so that $V_p - V_o = 0$

corresponds to the intersection of the two-tangents shown as dashed lines in Fig. 5. The slope of the curve in the retarding field region, $V_p \leq V_o$, then yields $T_- = 7.2 \times 10^4$ ^oK when Eq. (8) is employed. The value of n_- has been determined by employing the two-tangent technique (see Ref. 7) where the intersection of the two dashed lines in Fig. 5 has been taken as the value of the electron current at plasma potential, $i_{p-}(0)$, and the number density has been determined through the use of Eq. (9).

$$n_- = \frac{i_{p-}(0)}{eA_p} \sqrt{\frac{2\pi m}{kT_-}} \qquad (9)$$

Under identical conditions the probe was operated in a simple Langmuir mode (i.e. a variable bias voltage was applied between the probe and the grounded electrodes, the end plate and grid in Fig. 3; in this mode the probe was disconnected from V_B and the variable-area electrode) and results taken from the corresponding current-voltage characteristic are shown as open circles in Fig. 5. The agreement between the two techniques supports the position that the current-voltage characteristic of the fixed-bias, floating double-probe technique is exactly the same as that in the technique of the simple Langmuir probe. Of course, the latter statement is true only when the sampling electrodes are identical.

The fixed-bias, floating double-probe technique was also tested in a cylindrical metal vacuum chamber of length and diameter approximately equal to 180 cm and 120 cm, respectively, under two different conditions of plasma environment. In one case the parent gas was argon at 1.0×10^{-3} torr and the plasma generation technique was that of electron-bombardment with an operating configuration similar to that described by Branner, Friar and Medicus[8] and Goldan and Leavens[9]. In the second case the plasma was an approximate simulation of conditions in the ionospheric D-region with the parent gas being nitric oxide at 4×10^{-2} torr and the plasma generation technique being that of photoionization. The photon source was a combination of neon and krypton discharge lamps with the radiation filtered through LiF windows. The probe was made of 0.127 mm diameter tungsten wire and was 12 mm in length. The elctrode of variable area was a right-triangular section of 0.25 mm tungsten with sides 46 x 46 x 65 mm. It was sandwiched between two parallel sections of bakelite and was coupled to a rotary-motion feedthrough at the vertex of one of its 45° angles. By the rotary motion the triangular electrode could have varying degrees of its surface area exposed to the plasma (in a manner similar to the operation of a variable parallel-plate capacitor). The bias voltage in the argon discharge was 50 volts while in the case of nitric oxide it was 67 volts (for no particular reason except that $V_B > 5.5\ kT_-/e$ is a minimum requirement on the bias voltage for generating the current-voltage characteristic between the plasma and floating potentials in a positive-bias configuration) and V_p was measured with respect to the vacuum chamber which was maintained at earth ground. The electrode configuration and plasma generating devices are schematically illustrated in Fig. 6 while the corresponding current-voltage characteristics are shown in Figs. 7 and 8. The standard retarding-field analysis was carried out on the results of Fig. 7 and yielded $n_- = 1.3x(10^7)\ cm^{-3}$ and $T_- = 3.1x10^4\ {}^oK$ while the corresponding parameters in Fig. 8 are estimated[10] at $7x10^2\ cm^{-3}$ and 300 ^oK, respectively. The data were collected in a point-by-point fashion and are presented as solid circles for the fixed-bias double-probe technique and as open circles when the fixed-area probe was operated in a normal Langmuir configuration (variable bias voltage applied between the probe and the vacuum chamber). As in the case of the hf discharge the current-voltage characteristics of the fixed-bias double-probe and the simple Langmuir probe are identical. This agreement confirms the theoretical foundations of the fixed-bias, floating double-probe technique and makes possible the use of simple Langmuir probe analysis in a floating-probe system.

IV. COMMENTS AND CONCLUSIONS

It has been demonstrated that the fixed-bias, floating double-probe technique can measure plasma parameters of density and temperature with all the advantages of a floated probe system in addition to a simple analysis scheme which is identical to the general procedures of analysis in the Langmuir probe technique.

The fixed-bias double-probe can sample a far greater portion of the electron energy distribution than the symmetric double-probe of Johnson & Malter[2]. This makes possible a more accurate determination of the electron energy distribution as well as the electron temperature for the Maxwellian case. Another important consideration is the influence of non-uniform plasma parameters. Johnson & Malter[2] have pointed out that non-uniform electron densities and plasma potentials introduce no errors in the electron temperature measurement by their double probe. However, if the two probes of their double-probe system are immersed in different electron temperature environments the determination of the corresponding electron temperatures is considerably more complex. On the other hand, if the two electrodes (the probe and the variable-area electrode) of the fixed-bias double-probe system are immersed in regions of plasma volume which possess totally different values on n_-, T_-, and V_o, the determination of these plasma parameters is uneffected since only the currents collected by the fixed-area probe are analyzed. The determined plasma parameters correspond only to the plasma region sampled by the fixed-area probe.

When compared with the variable-area probe technique of Fetz and Oechsner[5], the fixed-bias double probe demonstrates many advantages. When one employs the method of the variable-area probe it is necessary to simultaneously record the three changing parameters of current, voltage and area. In the fixed-bias double-probe method, however, only voltage and current need be measured since the area of the second electrode does not enter into the analysis scheme. This, of course, makes the fixed-bias double-probe amenable to X-Y recorder or oscilloscope display of the characteristic. Another disadvantage of the variable-area probe technique is that its region of operation is limited to potentials greater than about $-2\ kT_e/e$ volts with respect to the plasma potential thus making it subject to magnetic effects and influences of plasma oscillations[11] The method of the fixed-bias double-probe has no such limitation.

In the floating triple-probe technique described by Okuda and Yamamoto[4] a potential divider in parallel with a variable bias voltage is placed between two electrodes (here referred to as primary electrodes) of different areas with the center tap of the potential divider attached to a third electrode. The technique requires 1) the variation of the bias voltage and the measurement of current flowing between the primary electrodes, 2) a simultaneous variation of the center tap on the potential divider in order to maintain the third electrode at its floating potential, and 3) a corresponding measurement of the potential difference between the smaller of the two primary electrodes and the electrode attached to the center tap. It is clear that the technique is somewhat cumbersome and that without automatic techniques for instantly nulling the current to the third electrode the use of X-Y recorder and oscilloscope displays for the current-voltage characteristic is not practical.

In comparison with the simple Langmuir probe method a floated-probe system is generally considered to have less distorting effects on the plasma parameters it is attempting to measure. This is generally considered to be true since a floated-probe system, by definition, collects no net current from the plasma and provides no current loops to active electrodes which may be employed in the method of plasma generation. Floated-probe systems do, however, destroy charge by virtue of recombination and charge absorption which takes place at the probe surfaces. If the charge depletion rate is significant in comparison to the rate at which charge is created in the plasma volume then the parameters of plasma density and temperature may in fact be altered. The probability of this occurring is enhanced as probe areas are increased and as more and more current passes between the probes. It is therefore quite clear that, regardless of the technique employed, all electrodes involved in the measurement should be as small as practicable. This consideration indicates that the symmetric double-probe method of Johnson and Malter[2] would appear to be the most reliable (the new technique reported here as well as the techniques of Refs. 2 and 4 will be considered under the present comparison with the assumption that the sampling electrodes in all cases are the same size) but this apparent advantage leads to the disadvantage that only a very small portion of the electron energy distribution is sampled. Okuda and Yamamoto[4] have removed the problem of limited energy sampling by employing two primary electrodes of greatly different areas and a third electrode for establishing a reference potential. In doing so they have not only complicated the measurement technique as discussed above but have also increased the rate of charge depletion by increasing the total collecting surface of the probing system. In comparison, the fixed-bias floating double-probe technique will always have a smaller total electrode area exposed to the plasma in the energy sampling regions which correspond to the latter methods. If the electron energy is being sampled in the range of probe-to-plasma potentials given by $-\chi_p^f - 1 \leq -\chi_p \leq -\chi_p^f + 1$ (this is typically the region of operation for the symmetric double-probe) then the total electrode area of the fixed-bias double-probe system $A_t(f\text{-}b)$ is in the range $A_p \leq A_t(f\text{-}b) < 2\ A_p$ (these values have been taken from Fig. 2) while the total area of the symmetric double-probe system is constant at $2A_p$. In sampling the electron energy in the transition region of probe response, $\chi_p^f \leq \chi_p \leq 0$, the fixed-bias double probe system has a total area which varies from A_p at $\chi_p = \chi_p^f$ to $63A_p$ at $\chi_p = 0$ (see Fig. 2). To cover this same region the triple-probe system employs a constant electrode area which is nominally greater than 200 A_p. Although the above comparisons of relative areas were made on the basis of the plasma conditions used to generate Fig. 2, the results are generally and qualitatively applicable to all plasma conditions. From the standpoint of area influences the advantage of the fixed-bias, double-probe technique is therefore established.

In summary, the advantages of the fixed-bias, floating double-probe technique are: (1) It is a floated system which permits a minimum electrode exposure to the plasma and consequently can be expected to impose a minimum influence upon the plasma parameters it is measuring. (2) It can sample the entire electron energy distribution permitting a more detailed study of that distribution and a more accurate determination of the electron temperature in the Maxwellian case. (3) No variable bias voltage is needed to generate the current-voltage characteristic. (The advantage here must be weighed according to the specific application.) (4) And finally, the current-voltage characteristics are identical to those of a simple Langmuir probe, permitting the use of the standard Langmuir probe analysis techniques for the determination of plasma density and temperature.

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FIGURE CAPTIONS

Fig. 1. Illustration of the fixed-bias, floating double-probe configuration.

Fig. 2. Dependence of the fixed-area probe's dimensionless current density $J_p(=I/n_-e\sqrt{kT_-/2\pi m}A_p)$ and dimensionless potential χ_p on the collecting surface of the variable-area electrode A_v.

Fig. 3. Illustration of the fixed-bias, floating double-probe system in an inductively-coupled hf discharge.

Fig. 4. A fixed-bias, floating double-probe characteristic in an inductively-coupled hf argon discharge.

Fig. 5. Semilogarithmic plot of the electron current response in the current-voltage characteristic presented in Fig. 4. Comparison is made with the results of a simple Langmuir probe characteristic.

Fig. 6. Illustration of the fixed-bias, floating double-probe configuration employed in the plasmas generated by electron bombardment and photo-ionization.

Fig. 7. Fixed bias, floating double-probe characteristic compared with that of a simple Langmuir probe in an argon plasma generated by electron bombardment.

Fig. 8. Fixed-bias, floating double-probe characteristic compared with that of a simple Langmuir probe in a photoionized nitric oxide plasma which represented an approximate simulation of conditions in the ionospheric D-region.

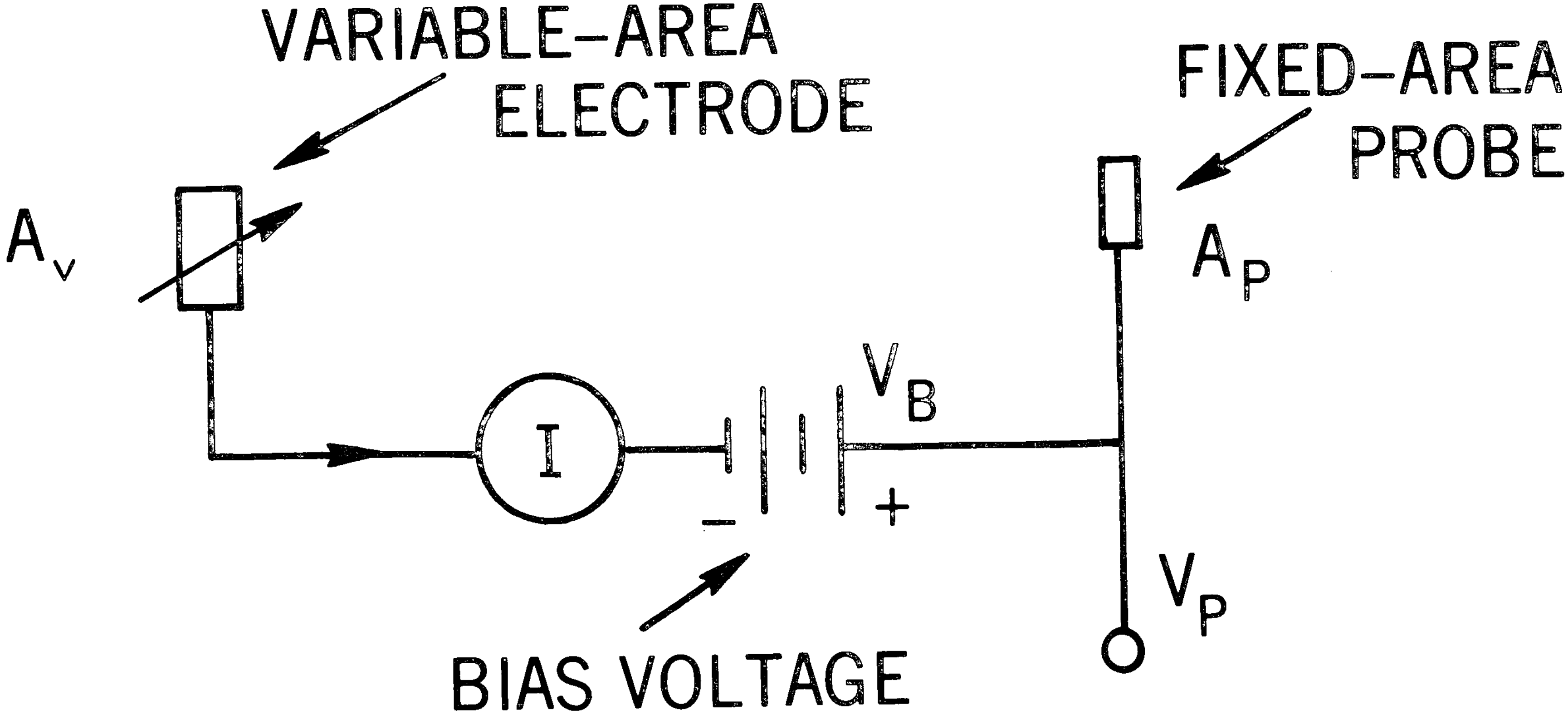
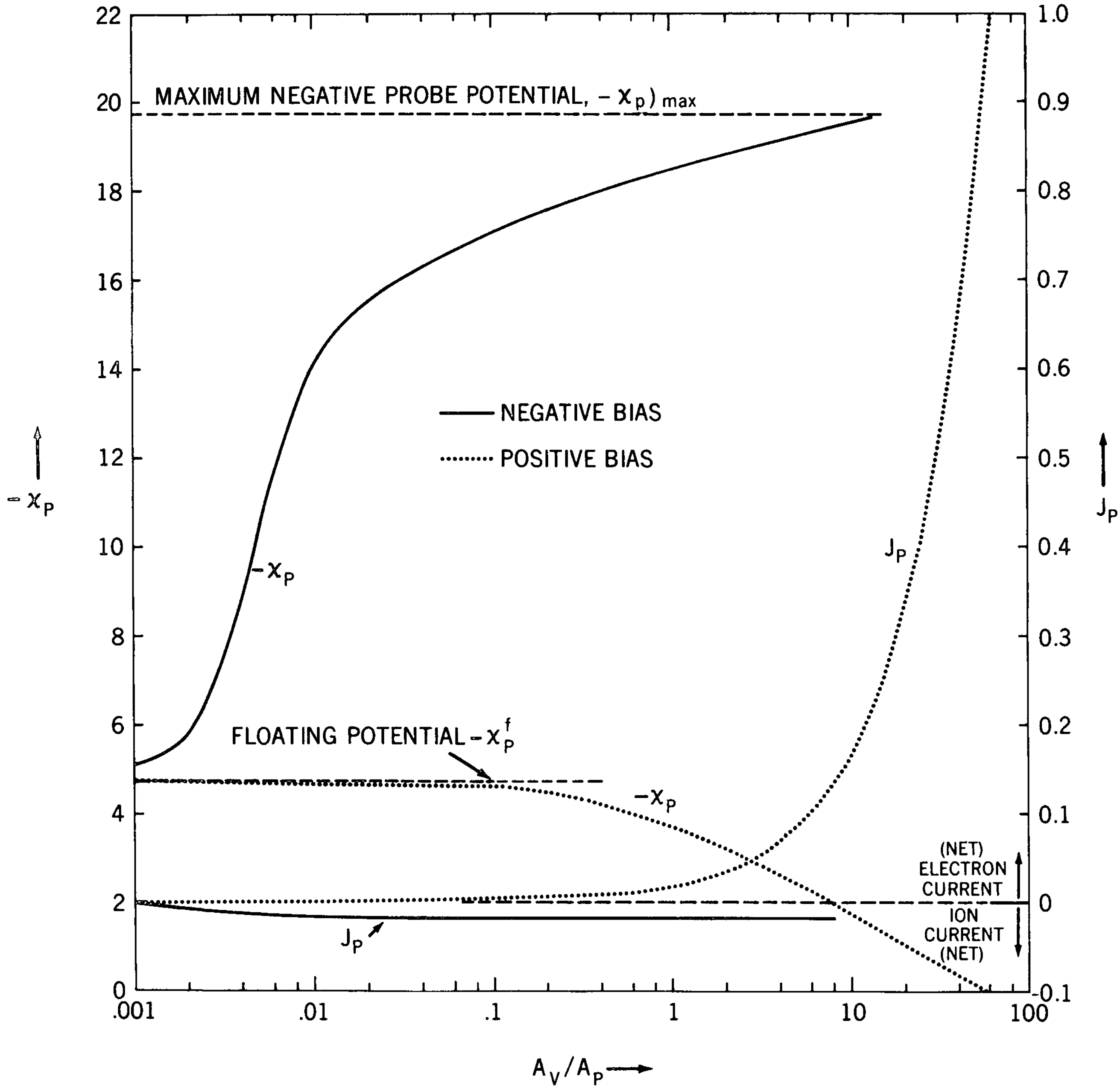

VARIABLE-AREA
ELECTRODE
FIXED-AREA
PROBE
A_v
A_P
I
V_B
−
+
V_P
BIAS VOLTAGE

Figure 1



MAXIMUM NEGATIVE PROBE POTENTIAL, $-\chi_p)_{max}$
NEGATIVE BIAS
POSITIVE BIAS
$-\chi_P$
J_P
FLOATING POTENTIAL $-\chi_P^f$
$-\chi_P$
(NET) ELECTRON CURRENT
ION CURRENT (NET)
J_P
A_V/A_P

Figure 2

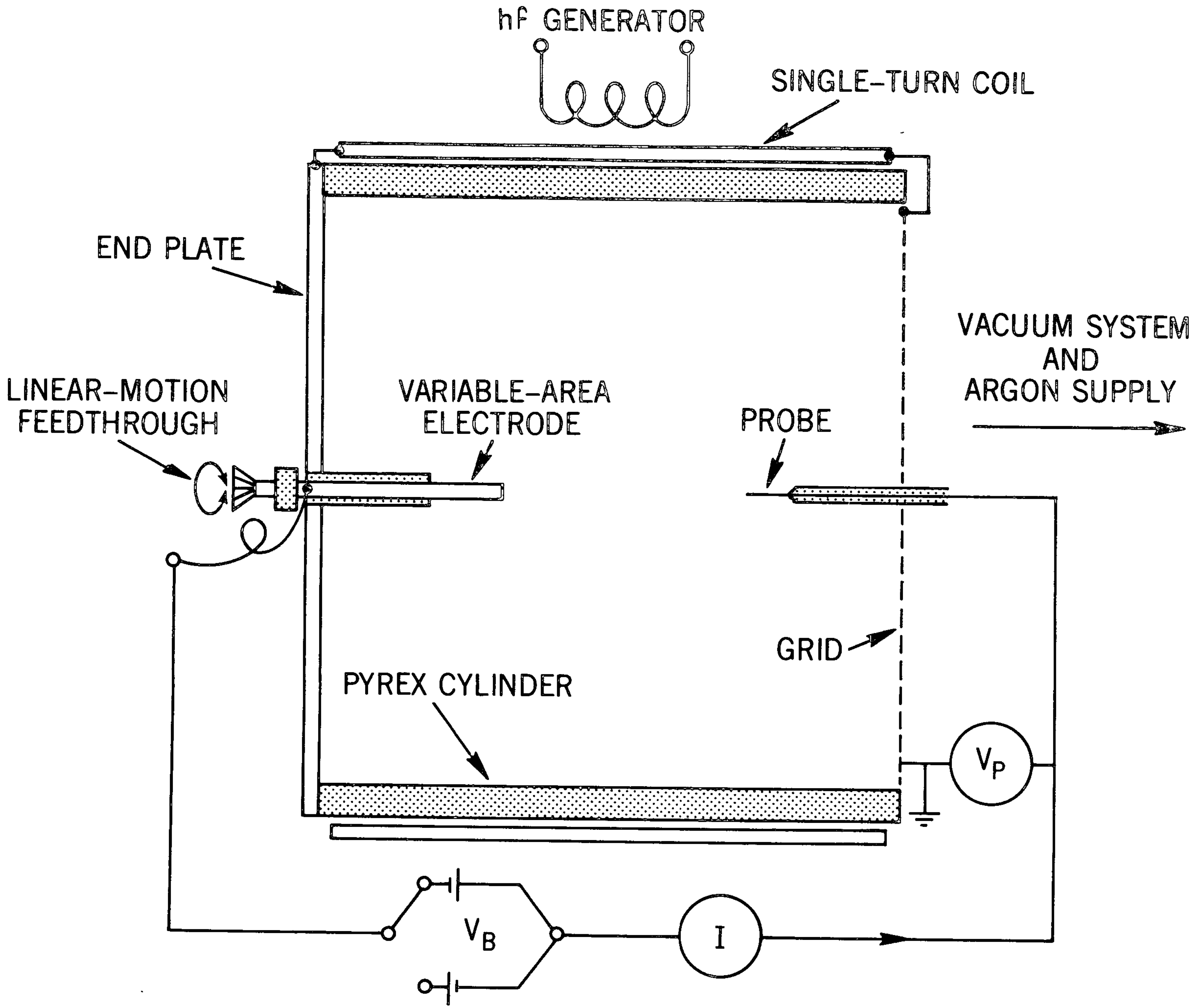

hf GENERATOR
SINGLE-TURN COIL
END PLATE
VACUUM SYSTEM
AND
ARGON SUPPLY
LINEAR-MOTION
FEEDTHROUGH
VARIABLE-AREA
ELECTRODE
PROBE
GRID
PYREX CYLINDER
V_P
V_B
I

Figure 3

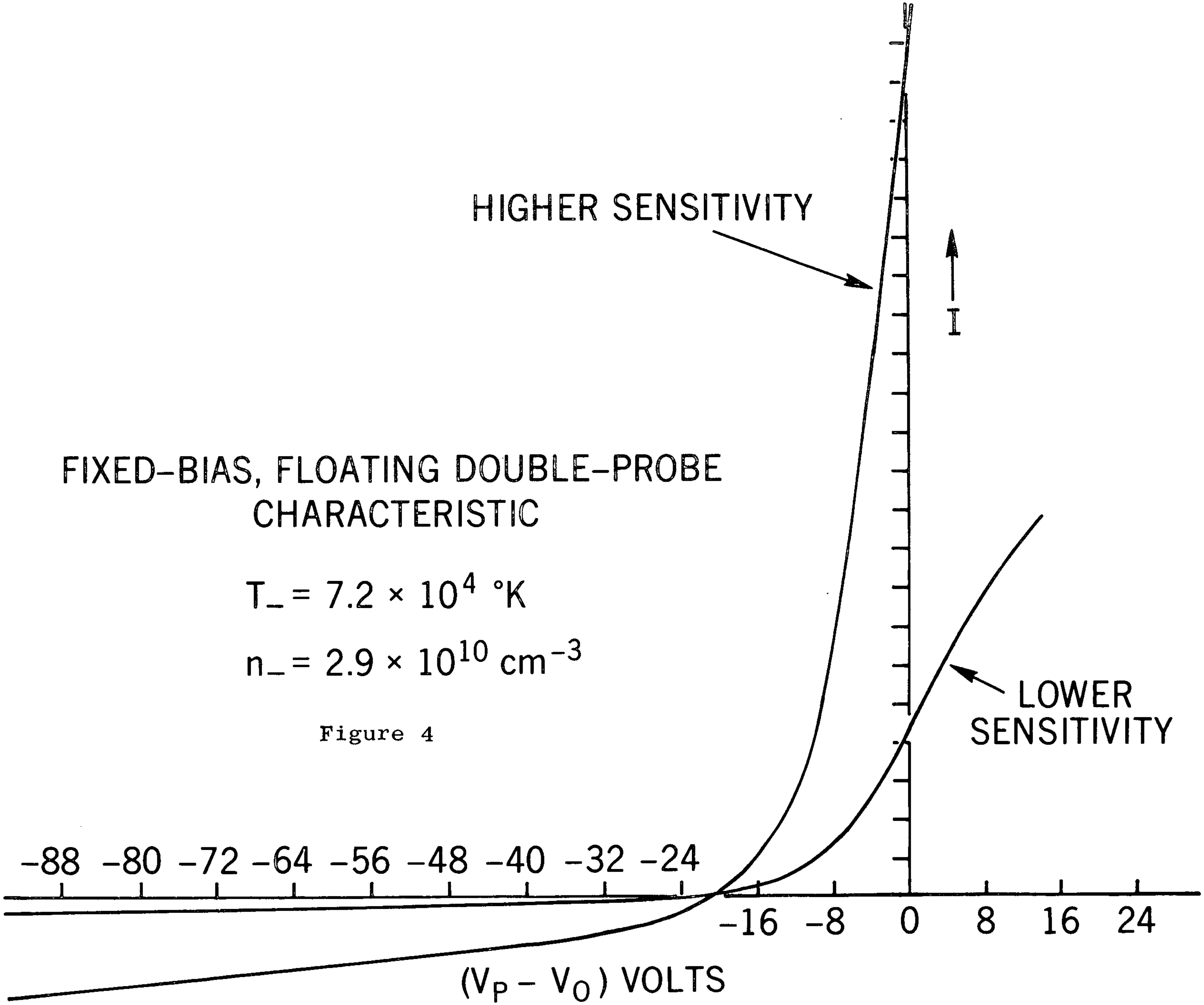
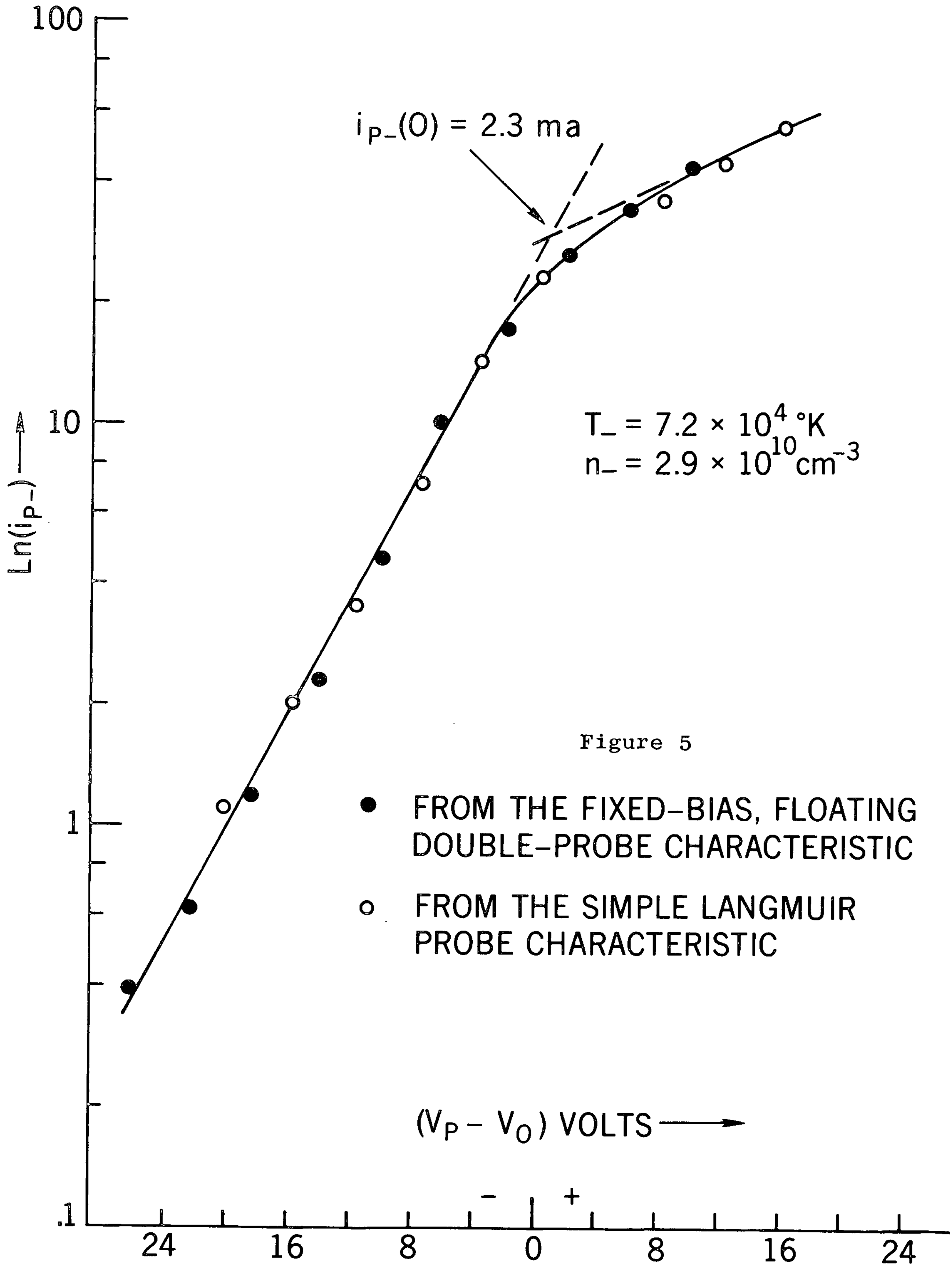

HIGHER SENSITIVITY
I
FIXED-BIAS, FLOATING DOUBLE-PROBE CHARACTERISTIC
$T_{-} = 7.2 \times 10^4$ °K
$n_{-} = 2.9 \times 10^{10}$ cm^{-3}
LOWER SENSITIVITY
−88 −80 −72 −64 −56 −48 −40 −32 −24
−16 −8 0 8 16 24
$(V_P - V_O)$ VOLTS

Figure 4



100
10
1
.1
Ln(i_P-) →
i_P-(O) = 2.3 ma
T_ = 7.2 × 10^4 °K
n_ = 2.9 × 10^10 cm^-3
● FROM THE FIXED-BIAS, FLOATING DOUBLE-PROBE CHARACTERISTIC
○ FROM THE SIMPLE LANGMUIR PROBE CHARACTERISTIC
(V_P – V_O) VOLTS →
– +
24
16
8
0
8
16
24

Figure 5

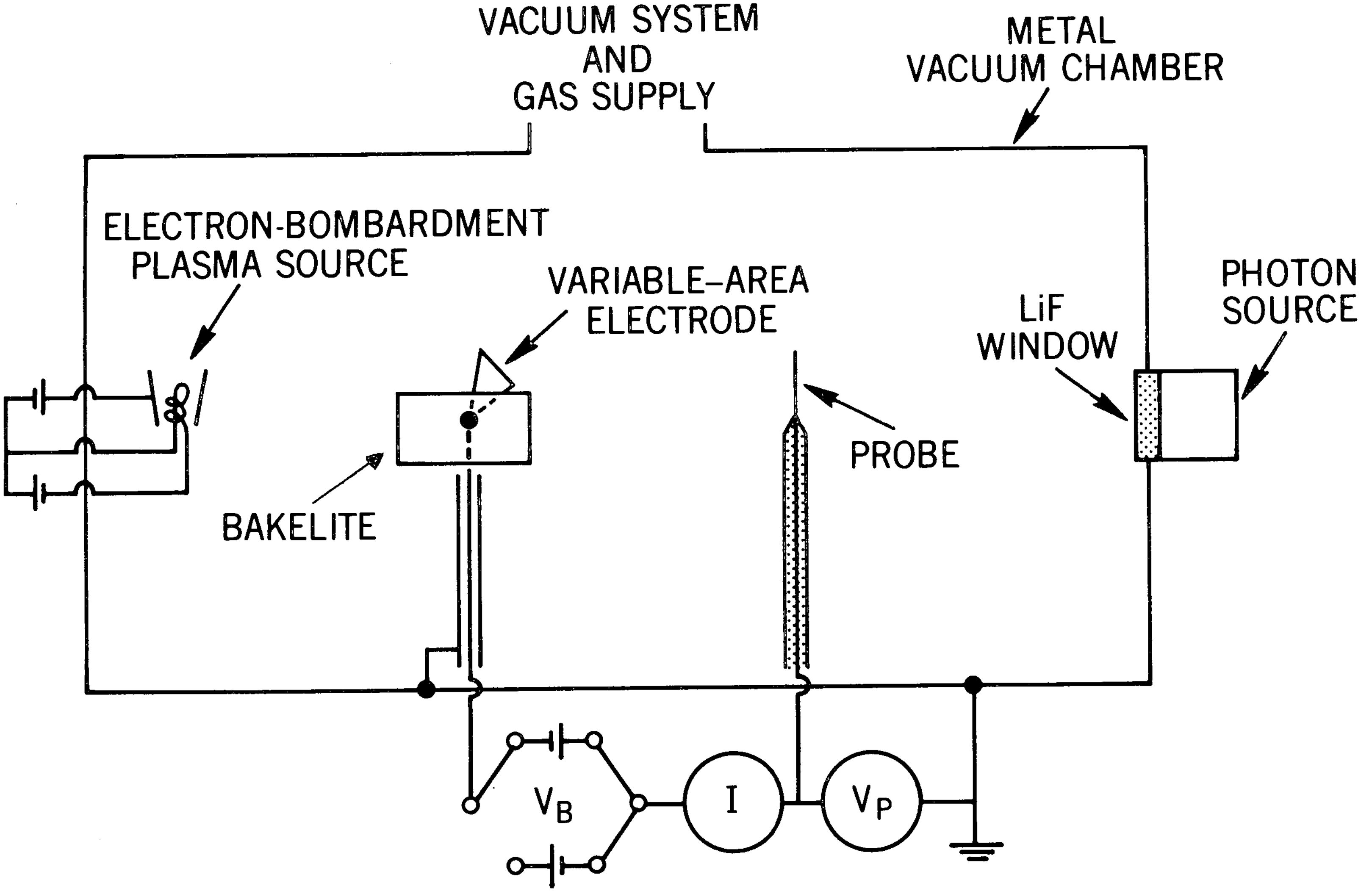
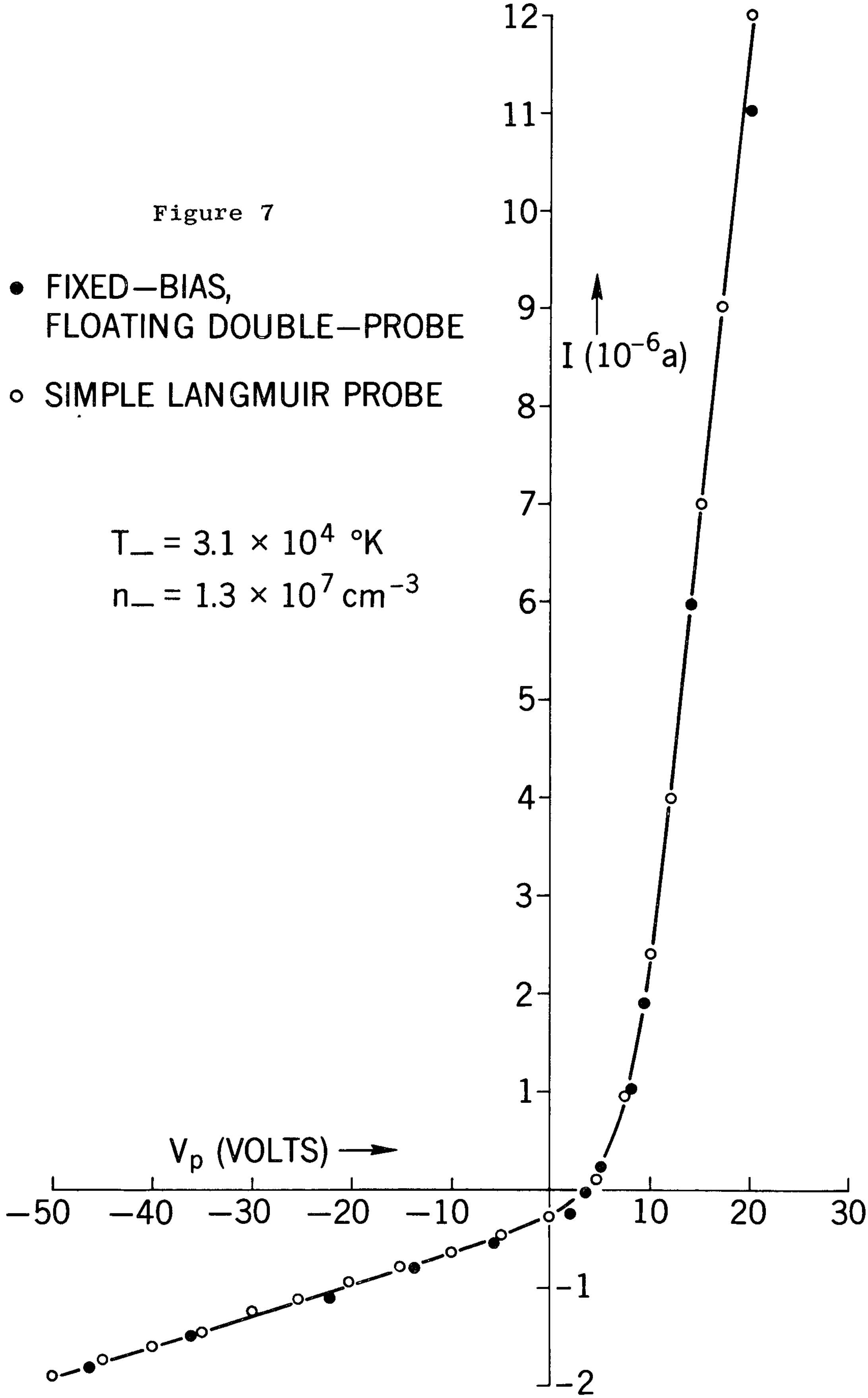

VACUUM SYSTEM
AND
GAS SUPPLY
METAL
VACUUM CHAMBER
ELECTRON-BOMBARDMENT
PLASMA SOURCE
VARIABLE–AREA
ELECTRODE
LiF
WINDOW
PHOTON
SOURCE
PROBE
BAKELITE
V_B
I
V_P

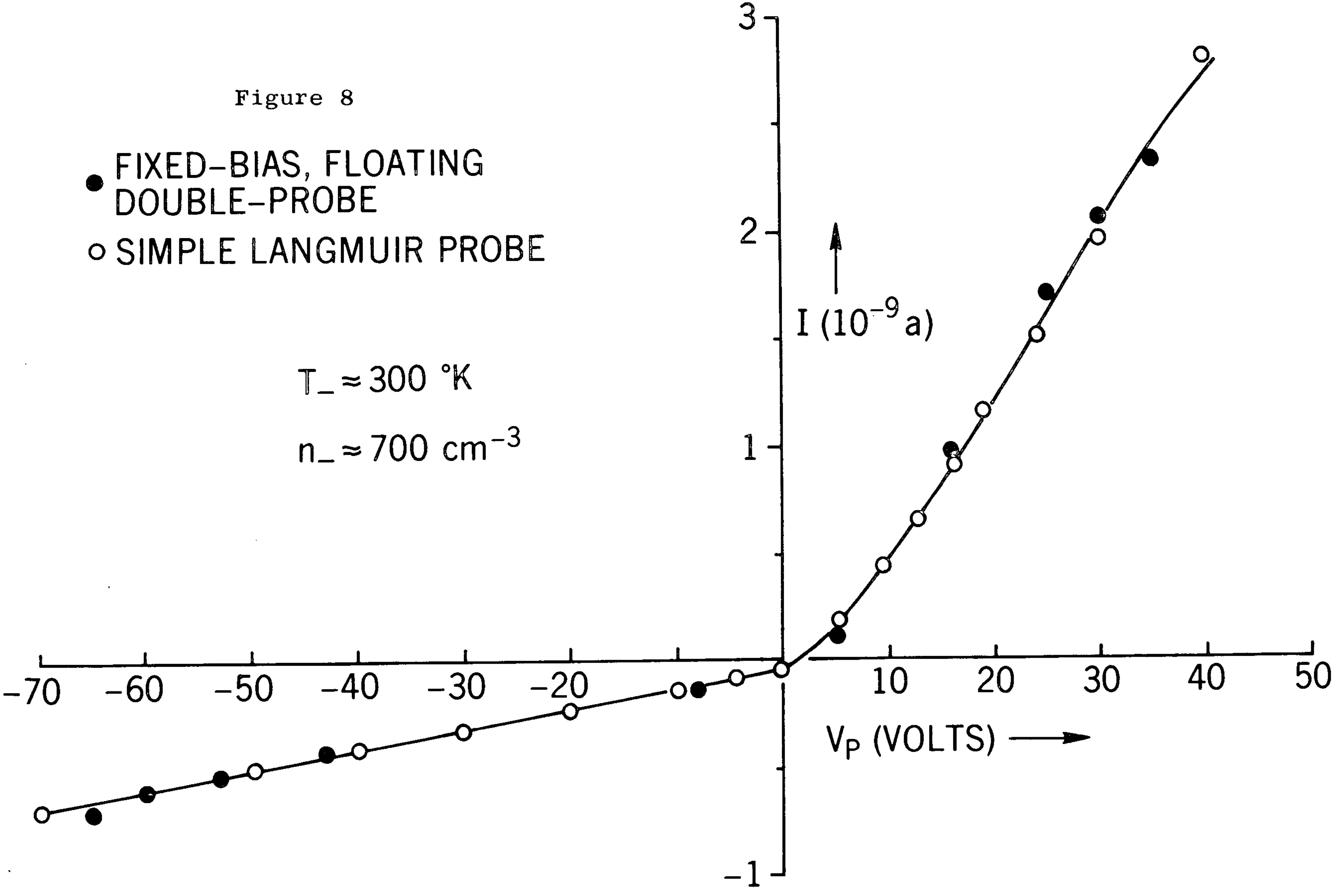
Figure 6



● FIXED—BIAS, FLOATING DOUBLE—PROBE
○ SIMPLE LANGMUIR PROBE
$T_{-} = 3.1 \times 10^4$ °K
$n_{-} = 1.3 \times 10^7\ cm^{-3}$
I (10^{-6}a)
V_p (VOLTS)
12
11
10
9
8
7
6
5
4
3
2
1
−1
−2
−50
−40
−30
−20
−10
10
20
30

Figure 7

Figure 8



● FIXED-BIAS, FLOATING DOUBLE-PROBE
○ SIMPLE LANGMUIR PROBE
T_ ≈ 300 °K
n_ ≈ 700 cm⁻³
I (10⁻⁹ a)
3
2
1
−1
−70
−60
−50
−40
−30
−20
10
20
30
40
50
V_P (VOLTS)