Emissive probe as a reference electrode in probe measurements

T. Kimura and K. Ohe
Department of Systems Engineering, Nagoya Institute of Technology, Showa-ku, Nagoya 466, Japan

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An emissive probe is used as a reference electrode in probe measurements. Some conditions for its use are discussed in a typical plasma. Application of the method to a He positive column results in good agreement of probe current–voltage characteristics with those conventionally detected with respect to the discharge electrode.

I. INTRODUCTION

A single probe[1,2] is applicable even for measuring plasma parameters in electrodeless discharges and flowing plasmas, since a large reference probe is used in place of discharge electrodes.[3,4] It is known that the electron temperature detected with respect to the reference probe appears to be somewhat high and the electron density low, because the probe surface area is not always large enough to neglect the potential shift in sweeping the probe bias voltage.[5] An analysis for Ar or Hg plasmas has revealed that the reference electrode should have an area 10^4 times larger than a single probe, though the area depends on the ion mass.[5] In practice, however, such a large probe may cause a large error in probe measurements, because the current collected by the probe tends to be restricted due to blocking effects.[5]

When an emissive probe (EP) is more negatively biased than the plasma potential, electrons thermionically emitted are locally trapped near the EP, while for the positive bias, the electrons are returned to the probe. Thus, there results in a current–voltage (I–V) characteristics with a slope of T_w/q,[6,7] where T_w is the wire temperature and q the electron charge. The EP can thus determine the plasma potential with an accuracy of T_w/q.[8–10] On the other hand, the EP can supply a large amount of emitted electrons, which compensate the current collected by a Langmuir probe (LP). Such an EP infers us to use as a reference electrode for the LP. There may be some advantages in the EP electrode, i.e., even a tiny one can emit electrons enough to be used as the electrode, eventually minimizing the disturbance to the plasma. Heating to emit electrons also contributes to reduce contamination of the electrode surface.

In the present paper, a tiny EP is proposed as a reference electrode. Our proposed system is examined in a He positive column. The possibility of EP as a reference is described in Sec. II, followed by a discussion of the conditions to be used in Sec. III. An application of the system to a He positive column is described in Sec. IV.

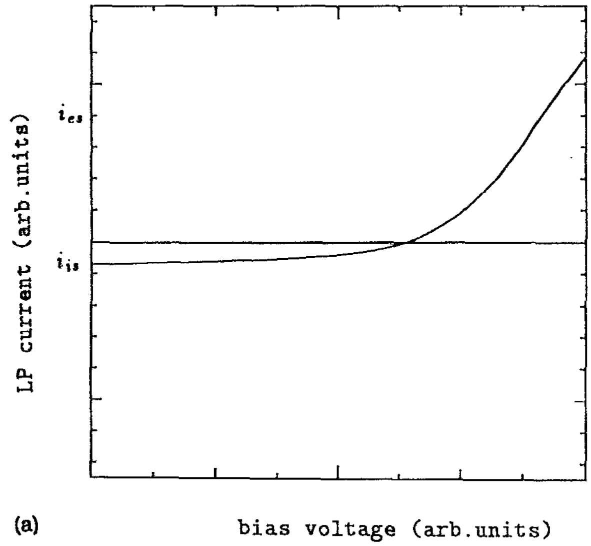
II. EP AS A REFERENCE ELECTRODE

In measurements of the LP, an important thing is to avoid the potential shift of the reference electrode during sweeping of the probe bias voltage. Usually, one of the discharge electrodes is used as the reference due to their large surface area, which can supply a large amount of electrons. The EP may be also used as the reference, if the EP can supply sufficient electrons without the potential shift. For simplicity, the EP reference operation is described under no magnetic field as follows. If the slope of T_w/q were neglected in the I–V characteristics of EP, the EP potential could not shift during sweeping of the LP bias voltage. In practice, however, since there is an exponential dependence of I on V, the shift must be taken into account. An explanation is given using the schematic I–V characteristics of LP and EP in a uniform plasma with no applied electric field as shown in Figs. 1(a) and 1(b). We assume that the EP probe current i_{pE} at a large negative bias voltage is larger than the LP electron saturation current i_{es}. The EP potential shift V_{sh} increases with the LP electron current in the electron retarding bias voltage, additionally evolving a positive voltage ΔV_1 upon electron saturation, compared with that using the discharge electrode as the reference, where ΔV_1 is obtained as a bias voltage for $i_{pE}=-i_{es}$. On the other hand, the shift also increases with the LP ion current i_{is} in the ion saturation bias voltage, additionally yielding a negative voltage ΔV_2, which corresponds to $i_{pE}=-i_{is}$. As shown in Figs. 1(a) and 1(b), in most experiments the voltage $|\Delta V_2|$ is much less than $|\Delta V_1|$, thus enabling us to approximate V_{sh} as ΔV_1. As a result, if ΔV_1 is neglected or compensated, the EP can be used as the reference electrode in probe measurements.

A system to compensate ΔV_1 is available, if it is finite. This may be a negative feedback system using the proportional-integral (PI) controller shown in Fig. 2(a). If another single probe (SP) is installed in the vicinity of LP, a certain floating voltage V_0 which is correlated to ΔV_1 may appear between the SP and EP. Therefore, suppressing V_0 eventually corresponds to compensation of ΔV_1. The block diagram including the PI controller to suppress V_0 is shown in Fig. 2(b), where $G(s)$ is a response function of SP to $V_{sh}(s)$, s being the Laplace operator. We can deduce $V_0(s)$ from the block diagram as

$$V_0(s)=G(s)V_{sh}(s)/[1+G(s)K_p(1+1/T_Is)] \qquad (1)$$

in the closed loop, where K_p and T_I are the gain and the time constant of the controller. By adjusting K_p and T_I, we can make the amplitude of the denominator in Eq. (1) much larger than 1 at the low frequency. Thus the shift ΔV_1 is minimized enough to neglect error in sweeping the LP bias voltage. In the present paper, no effect of the magnetic field is argued, though the field causes a large distortion in the I–V characteristics.



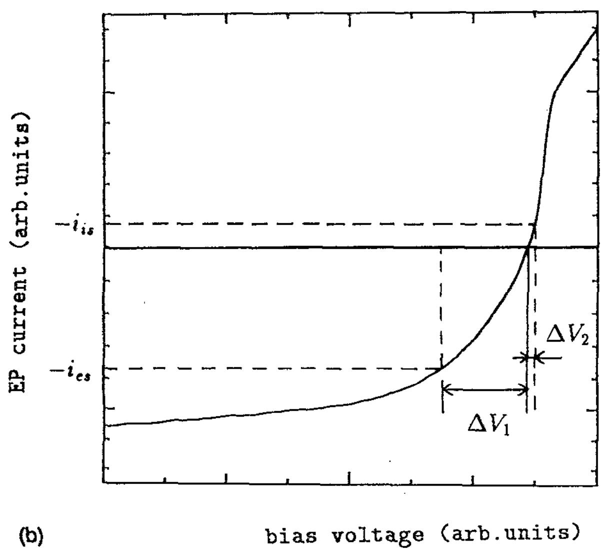


FIG. 1. Typical I–V characteristics of LP (a) and EP (b).

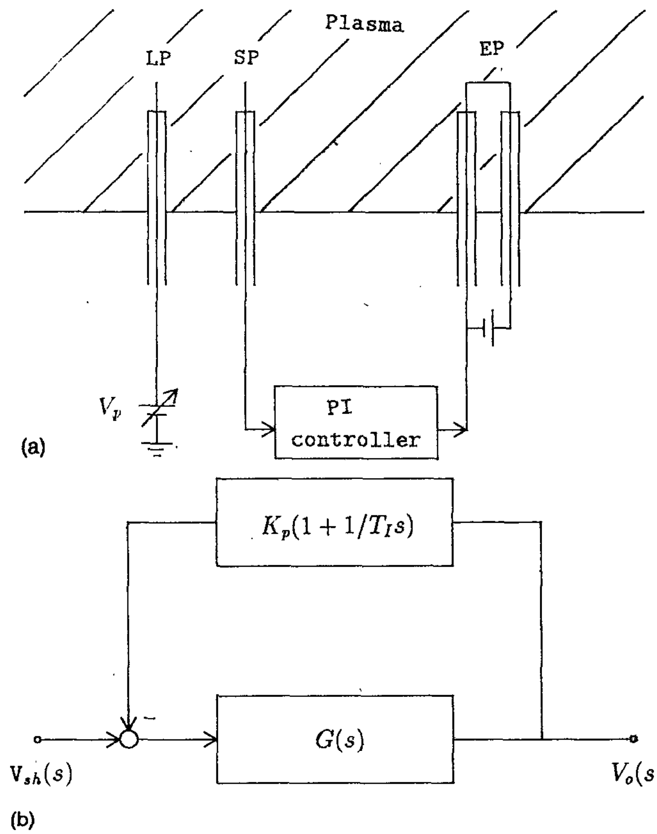


FIG. 2. (a) Schematic diagram of LP, EP, and SP. (b) Feedback block diagram for the compensation.

III. SOME CONDITIONS USING EP AS REFERENCE

As discussed above, the EP can be used as the reference electrode under $|i_{es}|<|i_{pE}|$. However, this condition is not always satisfied, because i_{pE} and i_{es} are their own functions of the electron density n_e, the averaged electron energy $\bar{\epsilon}$, and the probe dimension. Discussion of conditions using the EP as the reference electrode may yield a useful information for practical uses. For simplicity, we discuss some conditions in a uniform plasma with Maxwellian electrons of temperature T_e. Furthermore, the following are assumed as well: (1) Both the EP and the LP are cylindrical and long enough to neglect the edge effect. (2) Thermionically emitted electrons are space-charge-limited like in a vacuum diode. (3) There is no collision in the sheath of EP. The thermionically current I_{em} emitted into the plasma is then approximated as[11]

$$I_{em}=9\times10^{-6}V_E^{1.5}l_{em}/\lambda_D, \quad (2)$$

where l_{em} is the EP length, λ_D the Debye length, V_E the voltage difference between plasma potential and V_{pE}, and V_{pE} the EP applied voltage. The current i_{es} given by[1,2]

$$i_{es}=0.25n_e(8T_e/\pi m)^{0.5}2\pi r_L l \quad (3)$$

is saturated with the EP electron saturation current i_{esE} as

$$i_{esE}=0.25n_e(8T_e/\pi m)^{0.5}2\pi r_E l_{em}, \quad (4)$$

where r_L and r_E are the LP and EP radii, respectively, and l the LP length.

In many experiments, during sweeping the bias voltage of EP by 5 V from the plasma potential, the EP current i_{pE} exponentially varies from its electron saturation to the ion saturation, beyond which i_{pE} is little dependent of the bias voltage. Suppression of 5 V by the PI controller is thus in practice. From the above discussion, the condition of $|i_{es}|<|i_{pE}|$ leads one to deduce the following relation from Eqs. (2) to (4):

$$i_{es}<I_{em}|_{V_E=5\text{ V}}-i_{esE}\exp(-5q/T_e). \quad (5)$$

Satisfying relation (5), the n_e-T_e domain is calculated by giving numerical values to l_{em}, l, r_L, and r_E. Some typical domains for the respective parameters are shown in Figs. 3(a) and 3(b). In plasmas with n_e and T_e below respective curves the EP can be used as the reference electrode, when the EP voltage shift in sweeping the LP bias voltage is suppressed by the PI controller.

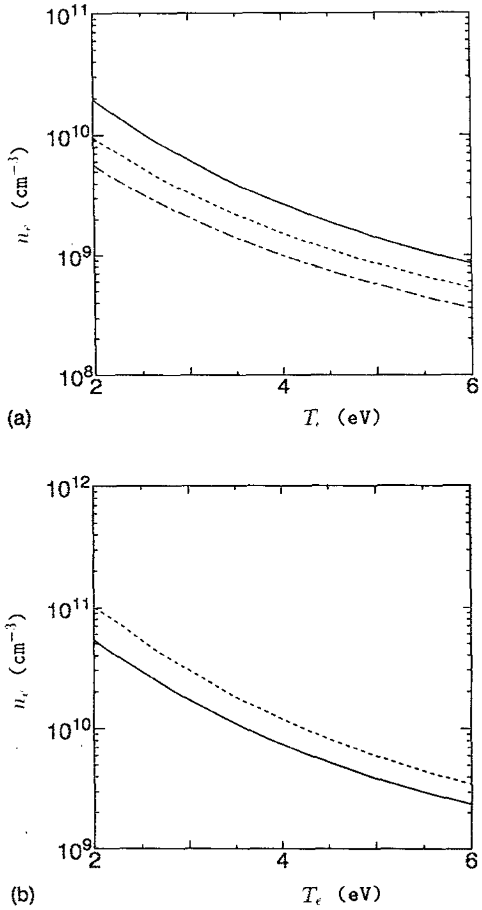


FIG. 3. (a) n_e-T_e domains for some r_L, where $l_{em}=10$ mm, $l=5$ mm, and $r_E=0.05$ mm, where solid, dotted, and dashed curves are to $r_L=0.05$ mm, $r_L=0.075$ mm, and $r_L=0.1$ mm. The relation (5) is satisfied below respective curves. (b) Those for some l_{em}, while $l=5$ mm, $r_L=0.05$ mm, and $r_E=0.03$ mm, where solid and dotted curves are to $l_{em}=10$ mm and $l_{em}=15$ mm.

IV. APPLICATION OF SYSTEM TO He POSITIVE COLUMN

The schematic diagram of the experiment is shown in Fig. 4(a). A glass tube 50 mm in diameter and 800 mm in length is filled with a He gas $P=0.32$ Torr and operated at the discharge current I_d from 5 to 80 mA, in which the positive column is free from any low-frequency oscillation such as an ionization wave. A LP (diameter 0.06 mm, length 4 mm) and EP (diameter 0.06 mm, length 10 mm) are equipped 100 and 300 mm from the anode, respectively. The EP is heated by a 1.55-A dc current. A SP 0.06 mm in diameter and 4 mm in length is installed 115 mm from the anode. A PI controller composed of electric circuits is shown in Fig. 4(b), where K_p and T_I can be varied from 1 to 20, and from 5×10^{-5} to 5×10^{-4} s, respectively.

A 20-Hz ramp voltage, with 50-V peak to peak, is used to sweep V_p. The probe current i_p detected on 10 Ω is amplified by a differential amplifier with 1-MΩ input impedance. The signals are fed to a A/D converter, in which the signals are digitized by a sampling period of 12 μs into 2048 words with 12-bit resolution. After being averaged 128 times by repeating the voltage, the digitized signals are transferred to a personal computer to calculate the electron energy distribution function (EEDF) $F(\epsilon)$ by the well-known Druyvesteyn method[12]

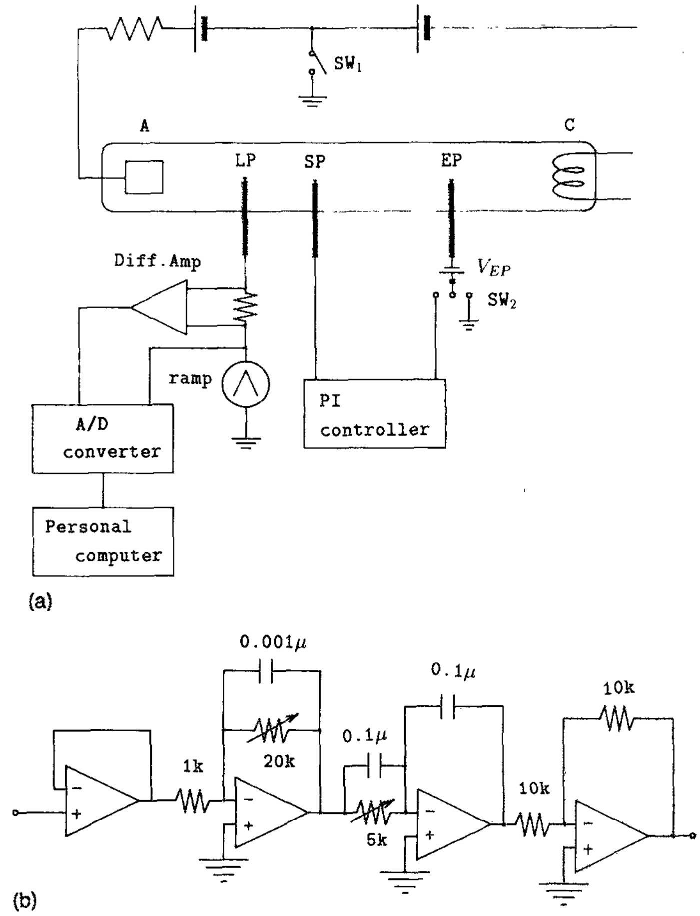


FIG. 4. (a) Schematic diagram of experimental apparatus. (b) PI controller circuits.

$$F(\epsilon)=\frac{4}{(Aq^2n_e)}\left(\frac{m}{2q}\right)^{1/2}(V)^{1/2}i_p'', \qquad (6)$$

where A is the LP surface area, m the electronic mass, i_p'' the second derivative of i_p with respect to V_p, V_p the LP applied voltage against the EP, ϵ the electron energy, and V the voltage difference between the voltage at $i_p''=0$ and V_p.

The electron energy probability function (EEPF) $f(\epsilon)$ is then deduced as

$$f(\epsilon)=F(\epsilon)\epsilon^{-1/2}. \qquad (7)$$

To improve the signal-to-noise ratio, the EEPF is averaged over ten traces of i_p'', which is detected by a finite impulse response (FIR) filter method.[13]

The validity of EP as the reference electrode may be examined by comparing the plasma parameters detected by the EP with those by the discharge electrode. If we can find little difference between them, the EP can be used as the reference electrode. A tiny EP may be helpful to minimize disturbances by the electrode installation as well as to protect the electrode from reduction in its surface area due to contaminations. Thus, the plasma parameters by the EP

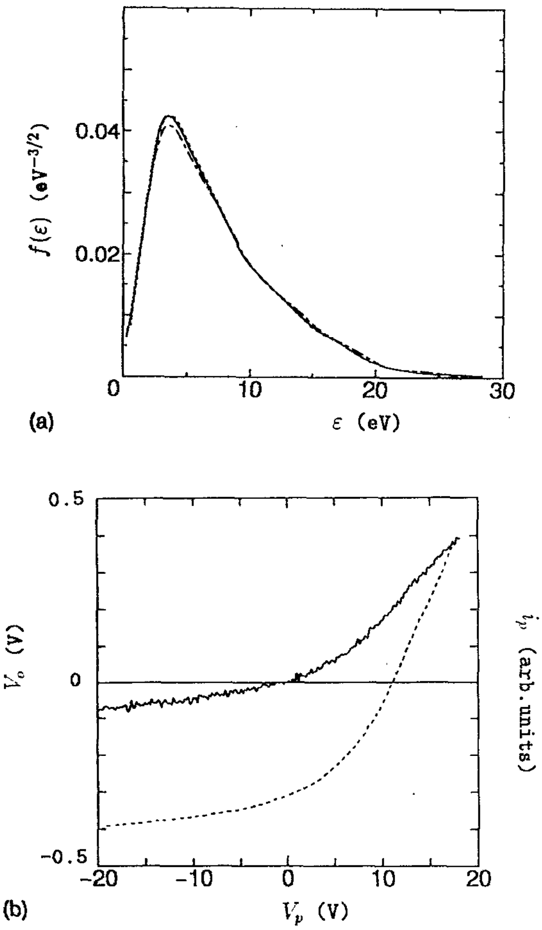


FIG. 5. (a) EEPFs detected by procedures (1), (2), and (3) described in IV, where the solid curve is to (1), the dashed one is to (2), and the dotted one is to (3). (b) V_0 and i_p of LP vs V_p.

can be more accurately detected. Furthermore, if potential shift in sweeping the LP bias voltage still remains, the shift is compensated by the PI controller. An experiment to clarify the reference action of EP is performed. Three *I–V* characteristics are detected under the following procedures using (1) one of the discharge electrode as the reference, (2) the EP, and (3) the EP with the PI controller. These procedures are explained by Fig. 4(a). Switching SW_1 to the ground and SW_2 off, then the LP probe bias is swept against one of the electrodes, corresponding to (1). Switching SW_1 off and SW_2 to the ground through a bias voltage V_{EP}, which cancels a dc voltage difference between the EP and LP, the probe bias is against the EP, corresponding to (2). Switching SW_2 to the output of the controller while SW_1 off, the bias is against the EP with the compensation, corresponding to (3).

TABLE I. Plasma parameters detected by procedures (1), (2), and (3).

I_d (mA)	n_e ($\times 10^9$ cm^{-3})	n_{e1} ($\times 10^9$ cm^{-3})	n_{e2} ($\times 10^9$ cm^{-3})	$\bar{\epsilon}$ (eV)	$\bar{\epsilon}_1$ (eV)	$\bar{\epsilon}_2$ (eV)
80	10	10	9.7	7.9	8.0	8.2
40	4.5	4.4	4.0	8.2	8.3	8.6
17	1.9	1.8	1.7	8.2	8.1	8.3
4	0.65	0.65	0.63	8.5	8.5	8.8

The EEPFs measured in procedures (1), (2), and (3) are shown in Fig. 5(a), where $f(\epsilon)$ is normalized as $\int_0^\infty \epsilon^{1/2} f(\epsilon) d\epsilon = 1$. The EEPF in (3) agrees with that in (1), while the EEPF in (2) slightly differs from that in (3) in the low-energy region. The difference may be caused by the EP potential shift, which is inferable from the dependence of V_0 and i_p on V_p shown in Fig. 5(b). We can deduce the increase of V_0 with i_p from the monotonic increase of V_0 and i_p, which results in reducing the maximum value in $f(\epsilon)$ in Fig. 5(a). Table I shows n_e and $\bar{\epsilon}$ detected by three procedures, where n_e and $\bar{\epsilon}$ are given by $n_e = \int_0^\infty \epsilon^{1/2} f(\epsilon) d\epsilon$ and $\bar{\epsilon} = \int_0^\infty \epsilon^{3/2} f(\epsilon) d\epsilon$, respectively. The density n_{e1} and the energy $\bar{\epsilon}_1$ agree with n_e and $\bar{\epsilon}$, respectively, while n_{e2} is lower than n_e, and $\bar{\epsilon}_2$ is somewhat higher, where suffix 1 and suffix 2 are for the procedures (3) and (2), respectively.

The EP can thus be used as a reference electrode in probe measurements, when the potential shift is negligible. On the other hand, when the shift is finite, its compensation by the controller minimizes errors in the probe measurements.

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