Abstract—Plasma diagnostics of the electron temperature was performed through a hollow-cathode-type discharge tube using a pulsed and floating probe method. This method detects a shift in the floating potential when a pulse signal is fed into the probe through an intermediary blocking capacitor. The electron temperature was calculated in a previous study using the Bessel function of the $n$th order; however, the proposed method greatly simplifies the calculation. In the duty ratio between 10% and 30%, the electron temperature measured using the pulsed and floating probe methods was approximately equal to the tail electron temperature, and it was varied by adjusting the duty ratio.

Index Terms—Electron temperature, floating potential, floating pulsed probe, Langmuir probe, plasma diagnostics.

I. INTRODUCTION

PLASMA has applications in various industrial processes, such as manufacturing semiconductor devices. Throughout this process, the plasma must be maintained at the optimal process conditions with carefully adjusted plasma parameters. For advancements in process plasma, it is crucial to control the plasma more precisely and improve the plasma parameter measurement technology [1]. Several methods for measuring plasma levels have been reported, such as the probe method that involves directly inserting a probe into the plasma.

In 1926, Mott-Smith [2] developed the most renowned electrical probe measurement method called the Langmuir probe method, whose schematic is shown in Fig. 1(a). A probe is inserted into the plasma, and the plasma parameters are measured using the current–voltage characteristics of the probe. However, the probe’s constant exposure to plasma gradually contaminates it, thereby distorting the current–voltage characteristic graph. Consequently, the measured plasma parameters are erroneous. In addition, the electron current increases near the space potential and perturbs the plasma.

Various probe methods have been developed using the Langmuir probe method to improve the precision of plasma parameters and facilitate plasma measurement in complex scenarios. The major probe methods are the plasma absorption probe [3], [4], [5], emissive probe [6], [7], [8], and double probe methods [9], [10], [11]. However, the Langmuir probe method is widely used due to its simple configuration and low cost. Therefore, a novel probe method must achieve more precise measurements than the conventional Langmuir probe method while preserving these advantages.

Various probe methods have been investigated to overcome the limitations of the Langmuir probe method. Among these methods is the floating probe method, in which an ac voltage is applied to the probe via a blocking capacitor. This method has been studied by Braithwite et al. [12] and Lee et al. [13], among others [14], [15], [16]. Another method, known as the pulsed probe method [17], [18], uses a pulse signal for probe measurements. Recently, Deguchi and Itatani [19], [20] proposed the insulated pulse probe method, in which the surface of the probe is covered with an insulator and the plasma density and electron temperature are measured from the probe current response when a square-wave pulse voltage is applied.

In our previous study, a novel floating probe method was proposed to measure the electron temperature in an electrically isolated state using the shift in the floating potential of the probe on the application of an ac voltage, as shown in Fig. 1(b). The value obtained using this method was similar to that obtained using the Langmuir probe method [21], [22], [23].

In this study, a pulsed and floating probe method is proposed to measure the tail electron temperature by applying a square pulse wave to the probe, as shown in Fig. 1(c). The output voltage was measured to calculate the floating potential and electron temperature. The sinusoidal, triangular, and square-wave ac voltages applied in the conventional floating probe method are replaced with a square pulse wave. The electron temperature is calculated using the duty ratio and amplitude of the output pulse voltage. Because the proposed method has the features of the floating and pulsed probe methods, it is referred to as the “floating pulsed probe method.” The measured electron temperature exhibits strong dependence on the output voltage and duty ratio.

II. EXPERIMENTAL SETUP

The apparatus used in this study was the same as that used in the previous study [21], [22], [23]. Fig. 2 shows the apparatus...
used for the proposed tone burst floating probe method. The electric circuit of the dc hollow cathode-type discharge tube is shown in Fig. 2(a). The discharge was performed using argon (99.9999%) at a total gas pressure of 0.3–0.8 torr and a current of 10–40 mA. The probe volt–ampere ($V$–$I$) characteristics were measured using a digital electrometer (ADC 8252, ADC Corporation, Tokyo, Japan) with the switch set to ON, as shown in Fig. 2(a). The probe voltage was varied from $-30$ to $5$ V.

For the proposed floating pulsed probe method and the previous simple floating probe method [21, [22, [23], an ac voltage was applied using a function generator (AFG 3022 B, Tektronix Corporation, Tokyo, Japan) through an intermediary 0.1-$\mu$F blocking capacitor. Pulse square waveforms of 10 kHz frequency, the duty ratios of 5%-50%, and the voltages from 5 to $20 V_{pp}$ were applied. Monitoring was performed using a digital oscilloscope (DPO 2024; Tektronix Corporation, Tokyo, Japan). In the previous study, stable values were obtained at a frequency of 50 kHz. As shown in Fig. 2(a), the electrometer switch was turned off because the probe $V$–$I$ characteristics were not measured.

In this study, the measurement error of the floating potential is within $\pm5\%$, similar to that in our previous study [23].

Schematic images of the probe, anode, and cathode are shown in Fig. 2(b). Twelve stainless steel rods of 1.0 mm diameter were used as anodes. A hollow cylinder with an outer diameter of 22 mm, an inner diameter of 16 mm, and a length of 50 mm was used as the cathode. A thin tungsten wire (diameter: 0.1 mm and length 2.0 mm) was used as the probe. At the center of the hollow region, the probe was in proper contact with the discharge tube.

The objective of this study was to investigate the electron temperature in a negative glow. Thus, a hollow cathode discharge was chosen because the reference electrode used in the probe method could be used as the anode. The space potential in the negative glow was approximately equal to the anode potential, and the measurement could be performed in a state having small space potential shift noise.
TABLE I
FLOATING POTENTIALS AND ELECTRON TEMPERATURES IN HOLLOW-CATHODE DISCHARGE BY LANGMUIR PROBE AND FLOATING PULSED PROBE METHODS

| Pressure (Torr) | Current (mA) | $V_f$ (V) | $T_{e1}$ (eV) | $T_{e2}$ (eV) | $|dV_f|$ (V) | $T_e$ (eV) |
|----------------|--------------|-----------|--------------|--------------|-------------|------------|
| 0.3            | 10           | -3.34     | 2.27         | 0.36         | 5.33        | 2.22       |
| 0.5            | 20           | -1.69     | 2.66         | 0.66         | 3.82        | 2.76       |
| 0.7            | 30           | -3.28     | 2.81         | 1.39         | 3.33        | 3.06       |
| 0.8            | 40           | -3.18     | 3.67         | 0.58         | 4.29        | 3.60       |

a) Frequency: 10 kHz at 10 $V_{pp}$, duty ratio 10%

III. RESULTS AND DISCUSSION

In this section, the experimental results obtained using the Langmuir, floating, and floating pulsed probe methods are discussed.

A. Measurement of Electron Temperature by Langmuir Probe Method

Fig. 3 shows the $V$–$I$ characteristics and discharge state of the probe at a gas pressure of 0.5 torr and a discharge current of 20 mA that increased with increasing bias voltage, thereby exhibiting a nonlinear current–voltage curve. This curve is consistent with previously reported measurements [21], [22], [23]. The floating potential ($V_f$) at which the probe current reaches zero was $-1.69$.

From the $V$–$I$ characteristics, $T_e$ was calculated according to Maxwell’s distribution using the Langmuir probe method. In (1), $T_e$ depends on the derivative of the logarithm of electron current ($I_e$) with respect to the applied probe voltage $V$, which is given as follows:

$$\frac{d}{dV} \ln I_e = \frac{e}{kT_e}.$$  \hspace{1cm} (1)

The probe current ($I_p$) is the sum of the ion current ($I_i$) and $I_e$

$$I_e = I_p - I_i.$$  \hspace{1cm} (2)

To calculate $I_e$ using $I_p$, $I_i$ was obtained as a tangent line to the high-negative-bias voltage region, as shown in Fig. 3.

Fig. 4 shows a semilog plot of $I_e$. Two lines were observed from $-7.5$ to $-2.5$ V and $-0.2$ to $0.2$ V, and their corresponding $T_e$ values were calculated. Fig. 4 shows that the tail ($T_{e1}$) and bulk ($T_{e2}$) electron temperatures were 2.66 and 0.66 eV, respectively.

Table I summarizes $V_f$ and $T_e$ obtained in this experiment. The conditions shown in Table I were experimentally measured. Because of the effect of contamination film on the probe, precise measurement results could not be obtained at low discharge currents relative to pressure. Therefore, the experiments were conducted at a sufficiently large discharge current for pressure.
B. Measurement of Electron Temperature by Floating Pulsed Probe Method

The conventional floating probe method facilitates the measurement of the effective electron temperature by applying sinusoidal wave, square, and triangular waves using a blocking capacitor. The formula for calculating the electron temperature on applying a sinusoidal wave is

\[ \Delta V_f = V_f - V_{f0} \approx -\frac{k_B T_e}{e} \ln \left( \frac{eV}{k_B T_e} \right) \]

(3)

where \( V_{f0} \) and \( V_f \) are the floating potentials before and after the application of ac signal, respectively; \( k_B \) is Boltzmann’s constant; and \( V \) is the applied voltage of the probe. The Bessel function used in (3) complicates the calculation of electron temperature [21], [22], [23].

In the new floating pulsed probe method, the applied ac signal changes from sinusoidal, square, and triangular waves to a square pulse wave. If the electron energy distribution function is assumed to be Maxwell’s distribution, \( I_e \) flowing through the probe becomes an exponential function when a voltage of \(-V\) is applied with respect to the space potential, which is given as follows:

\[ I_e(V) = I_0 \exp \left( -\frac{eV}{k_B T_e} \right). \]

(4)

As shown in Fig. 4, the electronic current decreases exponentially as the probe voltage negatively increases.

In this case, the floating potential of the probe becomes \(-V_f\) when a pulse waveform of duty ratio \((d)\) and amplitude \((A)\) is applied through the blocking capacitor, as shown in Fig. 5. Here, \(-V_H\) and \(-V_L\) are the probe voltages when the pulse voltage is switched ON and OFF, respectively. Therefore, \( V_L - V_H = A \), where \( V_f \) is the average pulse voltage and

\[ V_f = dV_H + (1 - d)V_L. \]

(5)

Equation (5) can be expressed without using \( V_L \). On substituting \( V_L = V_H + A \) in (5) to express \( V_H, A \), and \( d \), the following is obtained:

\[ V_f = dV_H + (1 - d)(V_H + A) = V_H + (1 - d)A \]

\[ \rightarrow V_H = V_f - (1 - d)A. \]

(6)

In contrast, (5) is expressed without using \( V_H \). Similarly, on substituting \( V_H = V_L - A \) in (5) to express \( V_L, A \), and \( d \), the following is obtained:

\[ V_f = d(V_L - A) + (1 - d)V_L = -dA + V_L \]

\[ \rightarrow @V_L = V_f + dA. \]

(7)

This is simply a substitution of the pulse voltage relation \( V_L - V_H = A \) in (5) that can be converted into (6) and (7). Using this relation, \( V_H \) and \( V_L \) can be expressed in terms of \( V_f \) when the pulse voltage is turned on or off.

The dc current did not flow because the pulse voltage was applied through the capacitor. Therefore, the dc voltage (average voltage) applied across the capacitor was the floating potential. When no pulse was applied, i.e., when the duty ratio was 0%, the floating potential of the normal Langmuir probe characteristic was matched, and the voltage was set to \( V_{f0} \). In contrast, the average voltage while applying the pulse was \( V_f \). About 100% duty corresponds to the application of \( A \) through a capacitor. Because the dc current from the plasma does not flow into the probe, the voltage between the plasma and probe is \(-V_{f0}\).

Furthermore, a quasi-static probe voltage change can be expressed using the following integral equation by substituting (6) and (7) into the components of \(-V_H \) at pulse ON \((0-d)\) and \(-V_L \) at pulse OFF \((d \approx 1)\):

\[ i_e(V_f, A, d) = I_0 \int_0^d \exp \left[ -\frac{eV_H}{k_B T_e} \right] dt \\
+ I_0 \int_d^1 \exp \left[ -\frac{eV_L}{k_B T_e} \right] dt \\
= I_0 \int_0^d \exp \left[ -\frac{eV_f - e(1 - d)A}{k_B T_e} \right] dt \\
+ I_0 \int_d^1 \exp \left[ -\frac{eV_f + edA}{k_B T_e} \right] dt \\
= I_0 \exp \left( -\frac{eV_f}{k_B T_e} \right) \left[ \exp \left( \frac{e(1 - d)A}{k_B T_e} \right) + (1 - d) \exp \left( -\frac{edA}{k_B T_e} \right) \right]. \]

(8)
Equation (8) can be simplified using the function $\Phi(A,d)$. If $A$ and $d$ of the pulse voltage are independent variables, the following is obtained:

$$\Phi(A,d) = d \exp\left[\frac{e(1-d)A}{k_B T_e} \right] + (1-d) \exp\left(-\frac{e d A}{k_B T_e}\right).$$  \hfill (9)

Using (9), (8) can be represented as follows:

$$i_e(V_f, A, d) = I_0 \exp\left(-\frac{e V_f}{k_B T_e}\right) \Phi(A,d).$$ \hfill (10)

In the floating pulsed probe method, the total conducted current is zero because it passes through a blocking capacitor, and the electron and ion currents are equal. A floating potential is observed on the probe. For an ion current of $I_i$

$$i_e(V_f, A, d) = I_0 \exp\left(-\frac{e V_f}{k_B T_e}\right) \Phi(A,d) = I_0.$$ \hfill (11)

If $V_{f0}$ is the floating potential before application of the ac signal

$$i_e(V_f, 0, 0) = I_0 \exp\left(-\frac{e V_{f0}}{k_B T_e}\right) = I_0.$$ \hfill (12)

Equations (11) and (12) can be expressed as follows:

$$\exp\left(-\frac{e V_f}{k_B T_e}\right) \Phi(A,d) = \exp\left(-\frac{e V_{f0}}{k_B T_e}\right).$$ \hfill (13)

Equation (13) can be clearly represented using the following equation:

$$\exp\left[\frac{e (V_f - V_{f0})}{k_B T_e}\right] = \Phi(A,d).$$ \hfill (14)

The shift in the floating potential ($\Delta V_f$) resulting from the application of a pulsed voltage is

$$\Delta V_f = V_f - V_{f0} = \frac{k_B T_e}{e} \ln \left[ \exp\left(-\frac{e d A}{k_B T_e}\right) \left[ \exp\left(\frac{e A}{k_B T_e}\right) + (1-d) \right] \right]$$

$$= \frac{k_B T_e}{e} \ln \left[ 1 - d + 1 \exp\left(\frac{e A}{k_B T_e}\right) - \frac{e d A}{k_B T_e} \right].$$ \hfill (15)

Thus, the effective electron temperature was measured using the floating potential before and after the application of the pulse voltage. From (15), the proposed floating pulsed probe method facilitates the calculation of electron temperature without using the Bessel function, and it is simpler to analyze compared to the conventional floating probe method. The proposed method is unaffected by the frequency of the applied ac voltage, similar to the floating probe method. However, for extremely low or high frequencies, the measurements using an oscilloscope were difficult. Therefore, the frequency was set to a constant value of 10 kHz.

### C. Result of Floating Pulsed Probe Method

Fig. 6 shows the results of varying the output pulse voltage at a pressure of 0.5, a discharge current of 20 mA, a constant duty ratio of 10%, and a constant frequency of 10 kHz. The range of the applied pulse voltage was 5 to 20 $V_{pp}$. At low applied voltages, the shift in floating potential was small and the measurement was unstable. The electron temperature converged in the range of 2.6–2.9 eV for pulse voltages greater than 10 $V_{pp}$, which is consistent with the tail electron temperature $T_{e1}$ measured using the Langmuir probe method. The electron temperature measured using the floating pulsed probe method was calculated using the shift in the floating potential, similar to the floating probe method. Therefore, the calculated electron temperature is approximately equal to the tail electron temperature $T_{e1}$, which is the effective electron temperature near the floating potential.

Fig. 7 shows the results of varying the duty ratio with a constant pulse voltage. The experiments were conducted at a frequency of 10 kHz, an applied voltage of 10 $V_{pp}$, a pressure of 0.5 torr, and a discharge current of 20 mA. The duty ratio was in the range 5%–50%. The results showed good agreement with the electron temperature in the Langmuir probe method at a duty ratio of 10%–30%. For a duty ratio greater than 30%, the electron temperature is very high. Compared to the results of the Langmuir probe method, the deviation was large, and precise measurement of the electron temperature was not possible.

Fig. 8 shows the result of $\Delta V_f$ ($V_f - V_{f0}$) with respect to the duty ratio. For a very small duty ratio in the floating pulsed probe method, a sufficient pulse waveform did not flow into the probe, and measurement was not possible. However, as the duty ratio approached 50%, the shift in the floating potential gradually decreased [23]. The results of previous studies on the floating probe method have shown that precise electron temperature measurement is not possible in the range of small shifts in the floating potential. Similarly, in the floating pulsed probe method, precise measurement of the electron temperature was not possible at a duty ratio of 30%–50%.

![Fig. 6. Electron temperatures in response to pulse waves as a function of input voltage at 10 kHz and duty ratio of 10%.

![Fig. 7.](image)

![Fig. 8.](image)
where the shift in floating potential increased. In the range of 10%–20% duty ratio with the largest shift in floating potential, it was possible to measure the electron temperature close to the tail electron temperature $T_{e1}$ measured using the Langmuir and floating pulsed probe methods.

The appropriate value of the duty ratio $d$ is determined using the formula for calculating the electron temperature in the floating pulsed probe method. Therefore, using (15), the value of $d$ at which the shift in the floating potential is the greatest is considered. To make (15) dimensionless, $\Delta \eta_f = e(V_f - V_{f0})/k_B T_e$, $\eta = eA/k_B T_e$ is denoted, and

$$\Delta \eta_f = \ln \left(1 - d + de^{\eta}\right) - d \cdot \eta. \tag{16}$$

Using (16), the shift in the floating potential can be determined at varying $d$. Fig. 9 shows the shift in the floating potential $\Delta \eta_f$ with respect to $\eta$ at $d = 5\%$, 10\%, 30\%, and 50\%. Fig. 9 shows that $d$ has a maximum variation with respect to the applied pulse voltage of approximately 10\%. Because the shift in the floating potential is obtained as the average of the interval of $V_H$ in which the electron current increases and that of $V_L$ in which the electron current is small, the signal weakly depends on the duty ratio at low amplitudes. On increasing the amplitude, the change in duty ratio becomes pronounced. However, when the duty ratio is less than 50\%, the influence of the interval of $V_H$ decreases. Therefore, an optimum value exists for the duty ratio with respect to the change in the floating potential.

Table I shows the shifts in the floating potential and effective electron temperature obtained for all discharge conditions. The electron temperatures in the Langmuir and floating pulsed probe methods converged in the range 2.0–4.0 eV. Table I summarizes the effective electron temperatures in these methods under similar experimental conditions. On comparing the respective electron temperatures, a difference of 0.25 eV at 0.7 torr was observed, which was the most significant. The smallest difference was 0.05 eV at 0.3 torr. Thus, the difference between the electron temperatures of the two methods was within 0.3 eV.

The experimental results indicate that the effective electron temperature calculated using the floating pulsed probe method
is in good agreement with the tail electron temperature in the Langmuir probe method. The experiments were performed under stable discharge conditions with a sufficient discharge current flowing for the gas pressure in the chamber. The desirable experimental conditions involved stabilizing the plasma and sufficiently exposing it to the probe. The gas pressure and discharge current were adjusted for each discharge mechanism to satisfy these two conditions. The appropriate pulse signal for accurately measuring the electron temperature was between 10 and 20 V<sub>pp</sub> with a duty ratio between 10% and 20%.

IV. CONCLUSION

The electron temperature during the cylindrical hollow cathode discharge was calculated using the floating pulsed probe method, which is a modified conventional floating-probe method. The calculation was performed using the shift in the floating potential before and after applying the pulse waveform to the probe through the blocking capacitor. When a pulse waveform with a voltage of 10 V<sub>pp</sub> and a duty ratio between 10% and 20% were applied, the electron temperatures calculated using the floating pulsed probe method were in good agreement with those of the Langmuir probe method.

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