Electron Temperature Measurement by Floating Probe Method Using AC Voltage

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Abstract This study presents a novel floating probe method to measure electron temperatures using a hollow cathode-type discharge tube. The proposed method detects a shift in the floating potential when an AC voltage is applied to a probe through an intermediary blocking capacitor. The shift in the floating potential is described as a function of the electron temperature and the applied AC voltage. The floating probe method is simpler than the Langmuir probe method because it does not require the measurement of volt-ampere characteristics. As the input AC voltage increases, the electron temperature converges. The electron temperature measured using the floating probe method with an applied sinusoidal voltage shows a value close to the first (tail) electron temperature in the range of the floating potential.

Keywords: electrostatic probe, Langmuir probe, floating potential, electron temperature, sheath

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(Some figures may appear in colour only in the online journal)

1 Introduction

Plasma technologies play a crucial role in designing semiconductor devices and are widely used in various semiconductor manufacturing processes, such as plasma-enhanced chemical vapor deposition [1–3], sputtering [4–6], and etching [7–9]. Measurement of plasma parameters, such as floating potential, space potential, and electron temperature (\(T_e\)), is critical for the precise control of these manufacturing processes [10]. Therefore, accurate measurement of plasma parameters is important for the next-generation of semiconductor manufacturing processes for high density integrated circuits [11,12].

Conventional methods to measure plasma parameters include the use of electrostatic probes (Langmuir probe method) [13], high-frequency probes [14,15], neutral analysis [16], and laser spectroscopy [17]. In particular, the Langmuir probe method, shown in Fig. 1, is primarily used for plasma diagnostics because of its simple configuration [18].

Here, the measuring probe is directly inserted into the discharged plasma (Fig. 1(a)). The volt-ampere characteristics of the electric circuit used in the Langmuir probe method can be measured as illustrated in Fig. 1(b). Fig. 1(c) shows a typical non-linear volt-ampere characteristic curve of the probe current (\(I_p\)). However, this \(I_p\) value includes the effect of ion current (\(I_i\)) as well as electron current (\(I_e\)). It is, therefore, necessary to remove the effect of \(I_i\) in order to measure \(I_e\) accurately.

In this study, we propose a new floating probe method to measure the tail electron temperature as shown in Fig. 1(d). This method monitors the shift in the floating potential when an AC voltage is applied to the probe through an intermediary blocking capacitor. The measurement of volt-ampere characteristics is not required. Therefore, \(T_e\) can be directly calculated using the floating probe method. However, a limitation of the proposed method is its inability to measure more than one \(T_e\) when multiple electron temperatures are involved. Moreover, the electron energy distribution function cannot be authentically measured using the Druyvesteyn method [19]. Further, the electron density cannot be measured using this floating probe method because the probe current is not measured. However, if the variation in probe characteristics is approximated as an exponential function, then \(T_e\) can be used as it is because a DC does not flow into the probe. Thus, the proposed floating probe method gives a measure of the effective \(T_e\) near the floating potential. This is because the low-energy electron temperature (the second \(T_e\) in the characteristics) in the hollow cathode-type discharge can be considered negligible.

In this study, the effects of some AC voltage waveforms in the floating potential and also the effect of \(T_e\) in a DC hollow cathode-type discharge tube have been systematically investigated. The relationship between the measured values of \(T_e\) using the Langmuir probe and the floating probe methods is also examined.
2 Experimental setup

Fig. 2 shows the apparatus for the proposed floating probe method. The electric circuit of a 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 0.5 Torr and current 10 mA (as shown in Fig. 2(b)).

The probe volt-ampere characteristics were measured using a digital electrometer (ADC 8252, ADC Co., Tokyo, Japan) with the switch set to ON, as shown in Fig. 2(a). The probe voltage was varied from −30 V to 5 V.

For the proposed floating probe method, an AC voltage was applied using a function generator (AFG 3022B, Tektronix Co., Tokyo, Japan) through an intermediary 0.1 µF blocking capacitor. Sinusoidal or rectangular waveforms, with frequencies from 10 kHz to 1 MHz and voltages from 0 V to 20 $V_{pp}$ (0 V to 10 V amplitude) were applied and monitored using a digital oscilloscope (TDS 2024B, Tektronix Co., Tokyo, Japan). The electrometer switch was turned OFF, as shown in Fig. 2(a), because it was not necessary to measure the probe volt-ampere characteristics.

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

In the following section, experimental results obtained using the Langmuir probe and the floating probe methods are presented and analyzed.

3.1 Langmuir probe method

Probe volt-ampere characteristics with a grounded plate are shown in Fig. 3(a). The probe current displayed a sharp increase over a bias voltage of -2 V. Similar observations were made for the characteristics displayed in Fig. 1(c). This remarkable increase in discharge current was in agreement with measurements reported in an earlier study [20]. The floating potential (Vf) value was -1.1 V when the probe current was 0 A, and the space potential (Vp) with a zero second derivative was 1.8 V.

![Fig. 3](image)

**Fig. 3** (a) Probe and (b) electron current as a function of the probe bias voltage at hollow cathode-type discharge tube

Tc was measured using the Langmuir probe method and assumed to follow the Maxwell distribution. As observed in Eq. (1), Tc depends on the derivative of the logarithm of Ip with respect to the applied probe voltage (V).

\[
\frac{d}{dV} \ln I_p = \frac{e}{kT_e}. \tag{1}
\]

However, the Langmuir probe method measures the probe current Ip, including the ion current Ii and electron current Ie. Therefore, it is necessary to deduct Ii from Ip. To estimate Ie from Ip, the tangential line in the large negative bias voltage range (as shown in Fig. 3(a)) is considered as Ii, then, Ie is equal to Ip - Ii. The semi-log plot of Ie is shown in Fig. 3(b). Two groups of Tc are depicted corresponding to Tc1 = 3.61 ± 0.47 eV for the tail electron temperature, and Tc2 = 0.16 ± 0.02 eV for the bulk electron temperature.

However, some errors may have been introduced in finding the slope of the tangent line to estimate Ii. Moreover, removing the effects of the fast Te (tail electron temperature) makes it difficult to measure the slow Te (bulk electron temperature) accurately.

Another approach to calculate the Maxwellian Te using the Langmuir probe method can be represented as follows [21]:

\[
V_p - V_f = \frac{kT_e \ln \left( \frac{m_i}{2.3m_e} \right)}{2e}, \tag{2}
\]

where m_i and m_e are the ion and electron masses, respectively. This method detects the difference between Vf and Vp.

In the Langmuir probe method, a DC voltage is applied because it is necessary to measure the volt-ampere characteristics to calculate Tc, as described in Eqs. (1) and (2). However, in this study, we propose the use of the floating probe method to detect a shift in Vf when an AC voltage is applied to a probe through an intermediary blocking capacitor. This method relies on the floating potential Vf, and the computed Tc represents the tail Tc in the region of Vf.

3.2 Floating probe method

When a sinusoidal voltage is applied to the probe through the intermediary blocking capacitor, the floating potential of the probe sheath between the plasma and the probe is denoted as Vf. The sinusoidal voltage E sin ωt, having a frequency of \( \omega \) rad/s, is superimposed on the voltage. In the case of Vp, when the ion saturation current is I0, the current (Ip(V)) has a slope S with respect to V and can be represented as follows:

\[
I_p(V) = I_{0} + S(V - V_p). \tag{3}
\]

The current that permeates the sheath (I) may be written as a function of the voltage as:

\[
I(V_f + E \sin \omega t) = I_i(V_f) - I_e(V_f + E \sin \omega t)
= I_{0} + S(V_f + E \sin \omega t - V_p) - I_e(V_f + E \sin \omega t). \tag{4}
\]

Eq. (4) can be rewritten using Boltzmann’s equation with tail Tc:

\[
I(V_f + E \sin \omega t)
= I_{0} + S(V_f + E \sin \omega t - V_p) - I_{0}\exp\left(\frac{e(V_f - V_p)}{kT_e}\right)
\times \exp\left(-\frac{eE}{kT_e} \sin \omega t\right), \tag{5}
\]

where I0 is the saturated electron current. Eq. (5) can be rewritten using a Fourier series expansion and harmonic analysis:

\[
I(V_f + E \sin \omega t) = I_{0} + S(V_f + E \sin \omega t - V_p)
- I_{0}\exp\left(\frac{e(V_f - V_p)}{kT_e}\right)I_{0}\left(\frac{E}{kT_e}\right) \sin \omega t.
\]
\[-I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)2I_0(\frac{eE}{kT_e})\sin\omega t\]
\[+I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)2I_2(\frac{eE}{kT_e})\sin2\omega t\]
\[+I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)2I_0(\frac{eE}{kT_e})\sin3\omega t, \]  
(6)

where \(I_n(x)\) is a modified Bessel function of the \(n\)th order. When the sinusoidal voltage is superimposed on the sheath voltage, the direct electron current displays a drastic increase. This is observed because \(I_0(x)\) rises sharply with \(x\).

In the case of a floating potential without an applied sinusoidal voltage, \(V_t\) can be replaced with \(V_{V0}\), and \(E\) is set to zero in Eq. (6). As a result, \(I_0\) becomes equal to \(I_i\):
\[I_{\phi} + S(V_{V0} - V_p) - I_{\phi}\exp\left(\frac{e(V_{V0} - V_p)}{kT_e}\right) = 0. \]  
(7)

When a sinusoidal voltage is applied to the probe through the intermediary blocking capacitor, Eq. (4) can be rewritten with a zero DC component:
\[I_{\phi} + S(V_t - V_p) - I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)I_0(\frac{eE}{kT_e}) = 0. \]  
(8)

The ion current without a sinusoidal voltage (no modulation) can be represented as:
\[I_{i0} = I_{\phi} + S(V_{V0} - V_p). \]  
(9)

Eqs. (7)–(9) can be rewritten as:
\[\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)I_0(\frac{eE}{kT_e})\exp\left(\frac{e(V_{V0} - V_p)}{kT_e}\right) = 1 + \frac{S}{I_{i0}}(V_t - V_{V0}). \]  
(10)

Thus, the shift in the floating potential due to an applied sinusoidal voltage can be represented as:
\[V_t - V_{V0} = \frac{kT_e}{e}\ln\left\{1 + \frac{S}{I_{i0}}(V_t - V_{V0})\right\}\]
\[= \frac{kT_e}{e}\ln\left\{I_0(\frac{eE}{kT_e})\right\} + \frac{kT_e}{e}\ln\left\{1 + \frac{S}{I_{i0}}(V_t - V_{V0})\right\}. \]  
(11)

However, the value of \(S(V_t - V_{V0})/I_{i0}\) is considerably less than 1 in the case of \(V_p\); therefore, Eq. (11) can be rewritten as:
\[V_t - V_{V0} \approx -\frac{kT_e}{e}\ln\left\{I_0(\frac{eE}{kT_e})\right\} + \frac{kT_e}{e}\frac{S}{I_{i0}}(V_t - V_{V0})\]
\[= -\frac{kT_e}{e}\ln\left\{I_0(\frac{eE}{kT_e})\right\} \cdot \frac{1}{1 - \frac{kT_e}{e}\frac{S}{I_{i0}}}. \]
(12)

The shift in the floating potential was described as a function of \(T_e\) and \(E\); therefore, \(T_e\) can be calculated from the measured floating potential shift.

When a rectangular wave voltage \(V_t(\omega t)\) with an amplitude voltage \(E\) and a frequency \(\omega\) is superimposed on the voltage, similarly to the case of sinusoidal voltage, Eq. (6) can be stated as:
\[I(V_t + V_R(\omega t)) = I_{\phi} + S(V_t + V_R(\omega t) - V_p)\]
\[= -I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)\cosh\left(\frac{eE}{kT_e}\right)\]
\[= -I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)\frac{4}{\pi}\sinh\left(\frac{eE}{kT_e}\right)\sin\omega t\]
\[= -I_{\phi}\exp\left(\frac{e(V_t - V_p)}{kT_e}\right)\frac{4}{3\pi}\sinh\left(\frac{eE}{kT_e}\right)\sin3\omega t. \]  
(13)

The shift in the floating potential due to an applied rectangular wave can be represented as the following equation:
\[V_t - V_{V0} = \frac{kT_e}{e}\ln\left\{\frac{1 + \frac{S}{I_{i0}}(V_t - V_{V0})}{I_0(\frac{eE}{kT_e})}\right\}\]
\[= -\frac{kT_e}{e}\ln\left\{\cosh\left(\frac{eE}{kT_e}\right)\right\} + \frac{kT_e}{e}\ln\left\{1 + \frac{S}{I_{i0}}(V_t - V_{V0})\right\}. \]  
(14)

And finally, Eq. (14) can be rewritten using Eq. (12):
\[V_t - V_{V0} \approx -\frac{kT_e}{e}\ln\left\{\cosh\left(\frac{eE}{kT_e}\right)\right\}. \]  
(15)

When the rectangular wave is applied, the shift in the floating potential is described as a hyperbolic function of \(T_e\) and \(E\).

Fig. 4(a) shows the shifts in the floating potential as a function of the input AC voltage, in response to sinusoidal waves of 10 kHz, 100 kHz, and 1 MHz. After the application of an AC voltage, the floating potential was obtained from the mean value of the sinusoidal wave. A reduction in the floating potential was observed in response to all applied voltages. Electrons accumulated around the probe because the AC voltage was applied through an intermediary blocking capacitor. Therefore, a negative potential was set up around the probe, as reported in a previous study \cite{22}. As the input voltage is increased from 3 V to 10 V, the shift in the floating potential was observed to decrease at a convergent rate. By increasing the input voltages from 1 V to 3 V, the shift in the floating potential is observed to gradually decrease. The effect of the input voltage on the shift in the floating potential at a high voltage was much stronger than that at a lower voltage. It is estimated that the increase in \(I_e\) is suppressed when the input voltage is increased. Moreover, the frequency of the sinusoidal waves does not affect the shift in the floating potential.
However, Fig. 4(b) shows the shifts in the floating potentials of 10 kHz, 100 kHz, and 1 MHz rectangular waves as a function of the input voltage. Similar to the sinusoidal waves in Fig. 4(a), a reduction in the floating potential was observed, and the shift in the floating potential decreased as the input AC voltage was increased. The shifts in the floating potential were similar in the case of both sinusoidal and rectangle waves.

Fig. 5 shows the characteristics of $T_e$ obtained using the floating probe method with applied 10 kHz, 100 kHz, and 1 MHz sinusoidal (Fig. 5(a)) and rectangular (Fig. 5(b)) waves, as a function of the input voltage. For the applied sinusoidal wave, the value of $T_e$ was calculated from Eq. (15) in response to an applied rectangular wave voltage. As shown in Fig. 5(b), $T_e$ increased as the input voltage increased. This increase is in contrast with that exhibited for the sinusoidal wave (Fig. 5(a)). As the input voltage was increased, $T_e$ gradually increased and settled around 5 eV. The converged values of $T_e$, in response to applied rectangular waves, were higher than those obtained in response to sinusoidal waves. In the case of applied rectangular waves, it was assumed that the wave was strained due to the presence of numerous harmonic components that are likely to cause a higher value of $T_e$.

These results indicate that the proposed floating probe method is computationally simpler than the Langmuir probe method, since it does not require measurement of the volt-ampere characteristics and the calculation of $T_e$ is relatively simple. Nevertheless, a difference is observed in the number of electron temperatures: the number of temperatures was two in the Langmuir probe method, whereas it was one in the floating probe method, affecting the tail $T_e$ in the $V_f$. 

$T_e$ was calculated from Eq. (15) in response to an applied rectangular wave voltage.
region. In addition, the electron energy distribution function cannot be measured using the Druyvesteyn method. However, if the change in probe characteristics can be approximated to an exponential function, the obtained $T_e$ value can be used because a DC does not flow into the probe. Thus, the proposed floating probe method gives a measure of the effective $T_e$ near the floating potential, because the low energy $T_e$ (bulk $T_e$), observed in the hollow cathode-type discharge, can be considered negligible. The proposed method uses a DC component and differs in this aspect from the method reported by M H Lee et al [25]. Moreover, the harmonic components of the applied AC voltages were found to affect the values of $T_e$ when comparing the results of the sinusoidal and rectangular waves. As the input voltage was increased, $T_e$ decreased independently of signal frequency. The electron temperature, measured using the floating probe method with an applied sinusoidal voltage, exhibited a value close to tail $T_e$ in the $V_f$ region.

4 Conclusions

This study proposed a method to measure electron temperatures using a hollow cathode-type discharge tube. The application of alternating voltages through intermediary blocking capacitors produces a shift in the floating potential, and this shift was used to compute the electron temperature $T_e$. Unlike the Langmuir probe method, the proposed floating probe method does not require volt-ampere characteristics. Thus, the floating probe method allows a relatively simple approach to calculate $T_e$.

The effects of certain AC voltage waveforms on the floating potential and $T_e$ were systematically investigated. The number of $T_e$ in the Langmuir probe method was two, whereas in the proposed floating probe method, it was only one. This affected the tail $T_e$ in the $V_f$ region. Finally, the value of $T_e$ in the floating probe method was close to the tail $T_e$ in the $V_f$ region.

References

7 Coburn J W and Winters H F. 1979, J. Appl. Phys., 50: 3189
10 Lindl J. 1995, Phys. Plasmas, 2: 3933

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