Monitoring of plasma parameters in afterglow of surface-wave argon plasma by a floating harmonic probe method

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Abstract: To monitor plasma parameters in afterglow, we have developed an electrical probing technique based on a floating harmonic probe (FHP) method. The FHP method is a continuous monitoring technique of electron temperature (T_e) and ion density, and has a feature to be able to monitor the parameters in reactive plasmas. In this study, an FHP system with measurement and floating-potential (V_f) monitoring probes is tested to diagnose an afterglow plasma, which has features low T_e and fast variation of V_f.
Keywords: FHP method, Afterglow plasma, Electron temperature, Ion density

1. Introduction

Electronic probing methods such as a Langmuir probe (LP) are major plasma-diagnostic techniques utilized to evaluate various parameters in plasmas. [1,2] In the application of the probe diagnostics to reactive plasmas, DC-based probing methods including the LP has difficulties in quantification of the parameters due to contamination of the probe surface. [3] For the reactive-plasma diagnostics, a floating harmonic probe (FHP) method has been attracted attention. [4,5] The FHP method is an AC-based probing measurement and it detects an AC current flowing from the ion sheath to the measurement circuit through the probe surface. Output plasma parameters of the FHP method are electron temperature T_e and ion density n_i typically calculated with an assumption of Maxwellian electron energy distribution function (EEDF). Measurement of the T_e and n_i by the FHP method has been demonstrated during reactive sputtering processes. [6,7] One of the key features of the FHP method is continuous monitoring. The FHP method derives the parameters from AC currents at harmonic frequencies of an applied voltage and there is no scan of voltage or frequency during the procedure. Therefore, we are able to obtain temporal variation of T_e and n_i by the continuous operation of FHP measurement. [8,9]

In a research field of low-pressure plasma chemistry, investigation of plasma parameters in an afterglow phase are important both in fundamental and application studies. For instance, in low-temperature argon (Ar) plasmas, it was reported that an energy relaxation scheme of excited Ar atoms differs in the afterglow phase from that in the steady state with electric-power input. [10] Also, in advanced plasma etching processes, pulsed discharge operation generating negative ions in the afterglow phase has been performed to reduce positive changes accumulated on a hardmask layer. [11] For further understanding and control of the afterglow-plasma chemistry, it is indespensable to develop a methodology to obtain temporal evolution of electron-related plasma parameters in the afterglow phase.

From these backgrounds, our target of this study is to monitor T_e and n_i in the afterglow plasma by the FHP method. We have to consider two characteristic bahaviors of the afterglow plasmas: (1) low T_e and (2) rapid decrease of a floating potential (V_f). For the bahavior (1), it is expected that an appropriate amplitude of the applied AC voltage in the FHP measurement should be smaller, due to reduction of a voltage width of electron-repulsive region in a current–voltage (I–V) curve measured in the LP method. To understand influence of the applied-voltage amplitude V_0 on the output parameters of FHP, we performed FHP measurements with various V_0 values in the steady state of a surface-wave Ar plasma.

For the behavior (2), when the V_f decreases rapidly in the afterglow phase, the measurement circuit of conventional FHP system flows a transient current to release charges at a DC-current blocking capacitor in the circuit. The transient current makes the afterglow measurement difficult in the FHP method. In this study, we developed a modified FHP measurement system that has no capacitor in the circuit. An additional V_f-monitoring probe was connected to the system to make the circuit electrically floated and the AC voltage was applied through a signal transformer. We compared the conventinal and modified FHP systems in the measurement of afterglow phase of the surface-wave plasma.

2. Floating harmonic probe (FHP) method

The FHP is a method to derive T_e and n_i at a metal probe tip by analyzing the AC current flowing the probe circuit. For the measurement, a kHz-order AC voltage ($V_0\cos(\omega t)$) is applied through a capacitor C_B which blocks DC current flow and keeps the probe-tip potential near the floating potential V_f decided by the plasma parameters. A voltage at the probe tip V_{pr} becomes

$$V_{pr} = (V_f + V_{dc}) + V_0\cos(\omega t) \qquad (1)$$

where V_{dc} is the DC self-bias voltage. The current flowing the probe i_{pr} is a sum of the electron i_e and ion i_i currents. When we assume a Maxwellian EEDF and a constant ion saturation current i_{is}, the i_{pr} becomes

$$i_{pr} = i_{is} - i_e = i_{is} - i_{es}\exp\left(-\frac{V_s - V_{pr}}{T_e}\right) \qquad (2)$$

where i_{es} is the electron saturation current, V_s is the plasma potential, and T_e is in units of eV. In the FHP method, the DC component in the i_{pr} is zero due to the presence of C_B, and the i_{pr} is expressed a sum of AC current elements with fundamental and harmonic frequencies of the applied voltage. A ratio of the amplitudes of the fundamental 1ω and second-harmonic 2ω currents is correlated to the T_e as following. [4]

$$\frac{|i_{1\omega}|}{|i_{2\omega}|} = \frac{I_1(V_0/T_e)}{I_2(V_0/T_e)} \quad (3)$$

For the measurement of temporal variation of T_e, we used an approximation of $T_e \sim (V_0|i_{1\omega}|/4|i_{2\omega}|)$ which is available when $V_0/T_e < 1$. [8,9] The n_i is calculated using a following relationship. [4]

$$n_i = \frac{|i_{1\omega}|}{2(0.61 e u_B A)} \frac{I_0(V_0/T_e)}{I_1(V_0/T_e)} \quad (4)$$

where e is the elementary charge, u_B is the Bohm velocity, and A is the area of probe-tip surface.

Figure 1 shows a relationship between the applied AC voltage in the FHP method and the *I*–*V* curve measured in the LP method. The probe current i_{pr} has harmonic-frequency components because of a nonlinearlity of the electron-repulsive region in the *I*–*V* curve. When the T_e considerably decreases (red *I*–*V* curve in Fig. 1), for instance transition from steady-state to afterglow plasma, a voltage range of the electron-repulsive region becomes narrows. For the FHP measurement using the above scheme, it is necessary to keep the V_0 smaller than the $V_s - (V_f + V_{dc})$. We experimentally analyzed the influence of V_0 on the calculated T_e and n_i in this study.

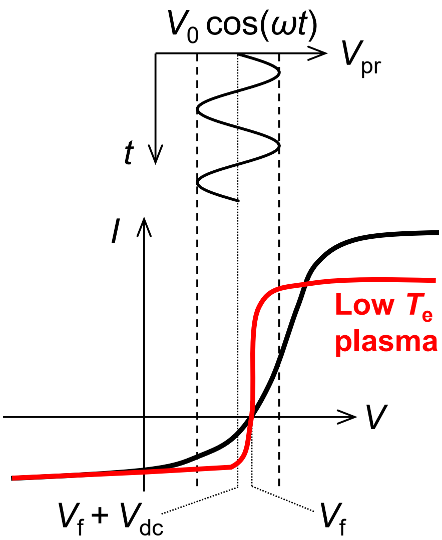

Fig. 1. Schematic of a relationship between the applied AC voltage in the FHP method and the *I*–*V* curve measured in the LP method. The red line shows an *I*–*V* curve of low T_e plasma (e.g. afterglow) considered in this study.

3. Experimental setup

The surface-wave plasma was generated by a microwave transffered from an anntena to the vacuum chanber through a quatz plate. (Fig. 2(a)) The microwave power was at 300 W. An argon gas flow was fed into the chamber with a flowrate of 10 sccm, and a pressure of Ar gas was at 10 Pa. Temporal changes of the input microwave power and the optical emission intensity were monitored during the experiments.

We inserted two cylindrical probes made of W metal with a diameter of 1.5 mm. One is for the FHP measurement with a length of 10 mm, and another is for the V_f monitoring with a length of 1 mm. Their tips were at 12.5 mm away from the center of the chamber.

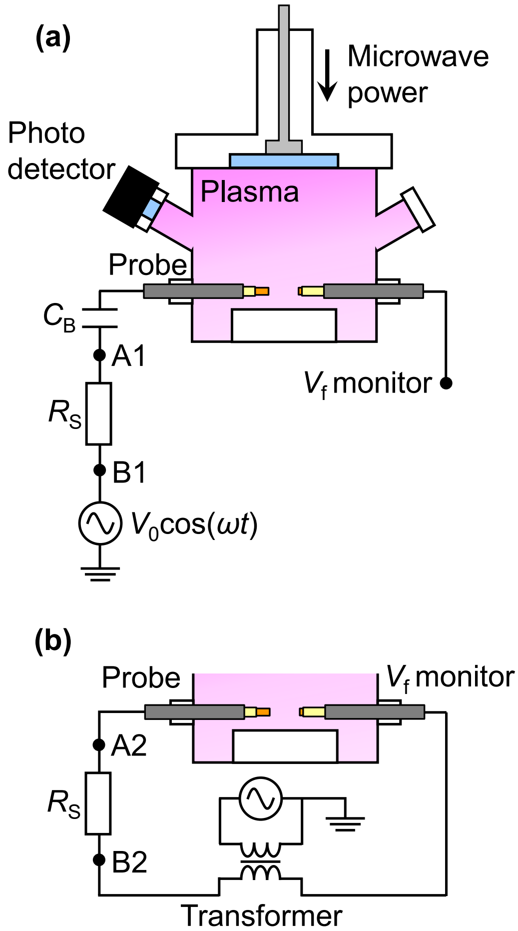

Fig. 2. Schematic diagrams of (a) conventional FHP measurement system and (b) modifird FHP measurement system developed in this study.

The conventional FHP measurements were performed with a circuit shown in the left of Fig. 2(a). An AC signal source (50 kHz), a sensing resistor R_S (1 Ω), and a blocking capacitor C_B (100 μF) were connected in series. From the differencial voltage between nodes A1 and B1, we measured the AC current flowing in the probe. The differencial voltage amplitudes at the fundamental and second-harmonic frequencies were measured by a differencial amplifier and a lock-in amplifier. During the measurement, we recorded the voltage of V_f-monotoring probe.

Figure 2(b) shows the circuit of modified FHP measurement without the C_B developed in this study. In order to keep the probe voltage at the V_f, we connected the FHP and V_f-monitoring probes and applied the AC voltage through a signal transformer. Considering the difference in the probe area exposed to the plasma, a major current flow between the transformer and the plasma is through the FHP probe tip. Note that this system is not to form a current roop similar to a conventional double probe method. The probe currents in this system is designed to flow into the ground through the plasma and sheath on the chamber wall. From the differencial voltage between nodes A2 and B2, we analized the AC current flowing in the probe.

4. Results

4.1. Influence of applied AC-voltage amplitude V_0

From the conventional FHP measurement of a surface-wave Ar plasma in the steady state with the V_0 values from 0.125 to 10 V, we evaluated the influence of V_0 on the measurement results. Figure 3 shows the measurement results of T_e calculated by fitting of Eq. (3) and n_i calculated from Eq. (4).

The calculated T_e value increases from 1.2 to 1.5 eV in a V_0 range between 5 and 10 V. This suggests that the high-voltage region in the applied AC voltage V_{pr} is in the electron-saturation region of the *I–V* curve. The saturation of *I–V* curve suppresses the amplitude of $i_{2\omega}$ generated by the nonlinear property of *I–V* curve in the electron-repulsive region. There is no clear indication of n_i variation by the V_0 increase observed in this study.

From these results, it is concluded that, in the FHP measurement especially applied to low-T_e plasmas, the increase of applied AC voltage amplitude V_0 can be a source of overestimation in the T_e calculation.

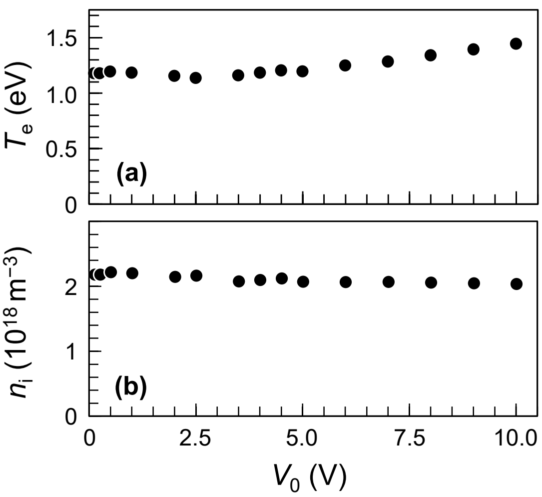

Fig. 3. (a) Electron temperatures T_e and (b) ion densities n_i measured by the conventional FHP method with various V_0 values. Discharge conditions were at Ar, 10 Pa, 300 W.

4.2. Monitoring of T_e and n_i in afterflow plasma

Here, we monitored behaviors of the FHP measurement circuit and the plasma parameters in the afterglow phase of surface-wave discharge. Figure 4 shows temporal changes of the input microwave power (Fig. 4(a)), the emission intensity (Fig 4(b)), the V_f (Fig. 4(c)), and the voltage at the note A1 (Fig. 4(d)), respectively, measured with the conventional FHP system and the V_f-monitoring probe (Fig. 2(a)). The data shown here were averaged results over 16-times measurement in the same conditions.

After turning-off the microwave power (at t = 0), the plasma emission intensity immediately decreased below the detection limit. There are fast decrease of V_f from 12 to 5 V at t = 0 and then slow decrease with a time duration over 8 ms. These indicates the plasma characteristics changes to the afterglow immediately at t = 0. And it has the afterglow phase for ~10 ms. We also observed a fast decrease of the voltage at node A1 and recoverly to the zero with the same timescale with afterglow duration. The voltage variation is observed due to a transient phenomena of RC serial circuit in the conventional FHP system. The transient voltage variation affects the probe voltage (V_{pr}) and the AC current measurement ($i_{1\omega}$, $i_{2\omega}$) which are the fundamental parameters for the FHP method.

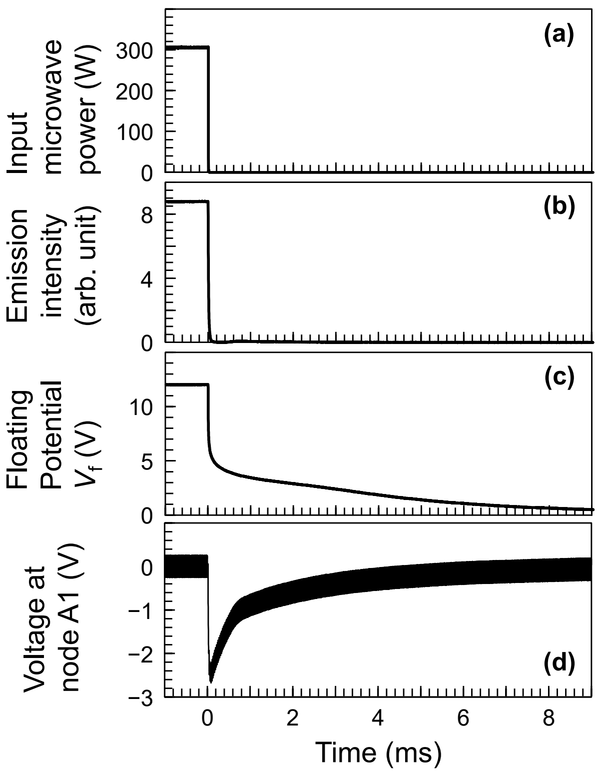

Fig. 4. Temporal changes of (a) input microwave power, (b) emission internsity, (c) floating potential V_f, and (d) voltage at node A1 measured in afterglow phase of surface-wave plasma, with the conventional FHP system and the V_f-monitoring probe shown in Fig. 2(a).

Figure 5(a) shows a temporal variation of the voltage at node A2 in the afterglow phase, measured using the modified FHP system shown in Fig. 2(b) without AC-voltage application. The measured voltage curve is similar to the variation of V_f (Fig. 4(c)). This indicates that the FHP probe in the system follows the V_f during the afterglow measurement. From the $i_{1\omega}$ and $i_{2\omega}$ measured with V_0 = 0.1 V, we calculated the T_e using the approximated procedure and the n_i from Eq. (4) as shown in Figs. 5(b) and 5(c). The T_e decreases rapidly toward 0.1 eV (t = 0 ~ 0.5 ms). Then, the T_e is almost constant at 0.1 eV (t = 0.5 ~ 7.5 ms). This trend is consistent with the physics of afterglow plasma, where the electrons lose their energy by elastic collisions with neutral particles when there is no external energy input. On the other hand, the n_i decreases linearly to time (t = 0 ~ 8 ms). These results suggest that the modified FHP system developed in this study, which is electrically floated to the ground, enables us to capture characteristic features of afterglow plasmas.

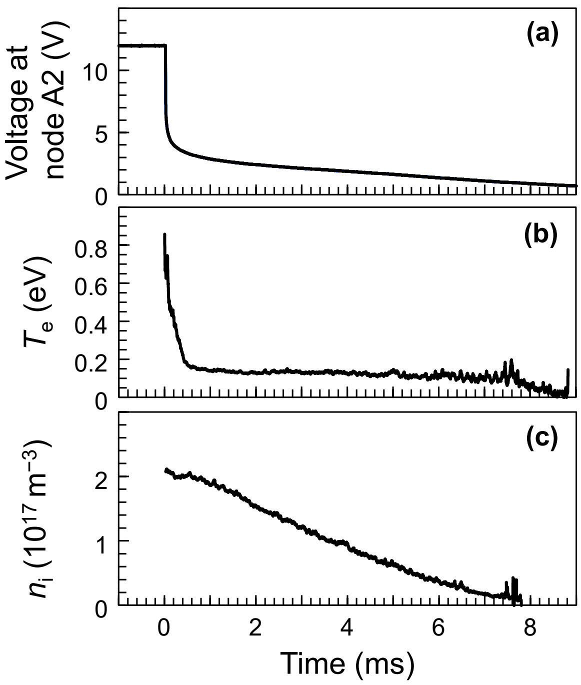

Fig. 5. Temporal changes of (a) voltage at node A2, (b) eletron temperature T_e, and (c) ion density n_i measured in afterglow phase of surface-wave plasma, with the modified FHP system shown in Fig. 2(b).

5. Summary

In this study, we evaluated the FHP method considering its application to diagnose the afterglow plasma, which possess low T_e and fast variation of V_f. It was indicated that excessive amplitude of the applied AC voltage in the FHP can be a source of overestimation in the T_e calculation expecially in the low-T_e plasma diagnostics. Also, when a fast variation of the V_f occurs, there are transient voltage variation and current flow in the conventional FHP circuit. Influence of the transient phenomena cannot be avoided when we install a capacitor in the FHP system. From these results, we developed a modified circuit of the FHP without the C_B and applied a smaller amplitude of AC voltage. The measurement circuit of the modified FHP system is electrically floated and follows the V_f during the measurement. The rapid T_e decrease to 0.1 eV immediately after turning-off the microwave power and gradual n_i decrease with a time duration of 8 ms were measured by the modified FHP system. It is concluded that this newly-developed FHP system enables us to monitor temporal variation of key plasma parameters in afterglow plasmas.

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