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Study on the axial uniformity of surface wave-excited plasma column sustained along a metal rod

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We proposed a novel method to generate high-density microwave-excited plasma along metal surfaces. In our previous work, 2.45-GHz microwaves were confirmed to propagate as surface waves along the interface between overdense (>10^{11} cm^{-3}) plasma and a graphite rod biased at a negative voltage against a grounded chamber. The generated plasma showed columnar structure surrounding the rod surface, and thus we called it metal-antenna surface wave-excited plasma (MASWP) column. In this work, we investigated the effect of gas pressure, negative voltage, and microwave power on the spatial distribution of MASWP column sustained along a copper rod (25 cm in length and 1 cm in diameter). It was confirmed that length of MASWP column became longer along the metal rod with increasing gas pressure and applied voltage. Increasing microwave power was not effective to lengthen MASWP column. Furthermore, MASWP was sustained along a stainless-steel ball 3.0 cm in diameter at an Ar gas pressure of 42 Pa with an input microwave power of 100 W, where a negative voltage of −82 V was supplied to the ball against a grounded chamber. Overdense plasma (electron density>10^{11} cm^{-3}) was sustained along the entire surface of the ball.

Key words: microwave, surface wave, high-density plasma, ion sheath, metal object

1. INTRODUCTION

Manufacturing industries have employed various plasma-enhanced surface treatments (PEST) such as surface cleaning, surface activation, and surface coating [1]. These PESTs are often employed to process the surface of a three-dimensional metal object such as a mechanical component [2], after its shape is fabricated by mechanical processes such as cutting, grinding, and polishing. In order to uniformly process such a three-dimensional metal object with PEST, it is important to obtain uniform plasma distribution along the surface of the object, regardless of its complex shapes.

Conventionally, DC plasmas have been employed for such requirements, because DC plasma is sustained uniformly along the three-dimensional surface of a metal object by employing the object itself as an electrode [1]. However, plasma electron density of DC plasma is relatively low (n_e≈10^9–10^{10} cm^{-3}), compared to those (n_e≈10^{11}–10^{13} cm^{-3}) of various high-density plasmas (HDP) such as surface wave-excited plasmas (SWP), inductively coupled plasmas (ICP), and electron cyclotron resonance (ECR) plasmas [1]. One of the significant disadvantages owing to low n_e is low processing speed, and thus HDPs for uniform PEST of complex shapes are strongly desired.

However, conventional HDPs are not compatible with uniform PEST of complex shapes, because they are typically generated at a position away from substrates processed and transported toward the substrates; in other words, they are not uniformly sustained along the surface of a metal object as in DC plasma systems for uniform PEST of complex shapes. However, recently, we developed a new HDP source [3,4], where high-density microwave-excited plasmas were sustained along the surface of a long graphite rod at a negative voltage. In the plasma, which was called metal-antenna surface wave-excited plasma (MASWP), SWs were confirmed to propagate along the interface between the overdense plasma and underdense region in ion sheath surrounding the rod surface [3]. Such SWs are considered to propagate along various shapes of metal object at a negative voltage. Therefore, MASWPs are expected to generate high-density plasmas along the three-dimensional surface of a metal object as uniformly as DC plasmas. In this work, as a first step to verify the expectation, we demonstrated the generation of MASWP along the rounded surface of a stainless-steel ball.

2. EXPERIMENTAL SETUP

Figure 1 shows the configuration of the MASWP source presently investigated, together with a defined cylindrical coordinate system. The stainless-steel cylindrical chamber was 15 cm in diameter and 50 cm in length. The upper end of the chamber was connected to a coaxial waveguide (WX-39D) through which 2.45-GHz microwaves were introduced via a quartz plate (3.8 cm in diameter and 1.0 cm in thickness) as a vacuum seal. In experiments with a rod antenna, a copper rod 1.0 cm in diameter was inserted along the center axis with its one end contacting the quartz surface; the other end of the rod was connected to a high-voltage DC power supply in order to apply a negative voltage of V_t against the grounded chamber. In experiments to demonstrate MASWP generation along a three-dimensional metal object, a stainless-steel ball 3 cm in diameter was supported by two rod antennas as shown in the figure. The power supply was operated under a constant-voltage mode where the current I_t collected by the rod surface changes at a fixed voltage. Note that the surface of a metal antenna was exposed directly to surrounding gases from z=3.4 to 25 cm, while the rest of the surface was covered with an insulating tube made of alumina. The Langmuir probe was inserted in the axial direction along r=3.0 cm, equipped with an automatic linear drive to measure the axial variation in plasma properties. In all experiments, Ar was employed as a working gas.

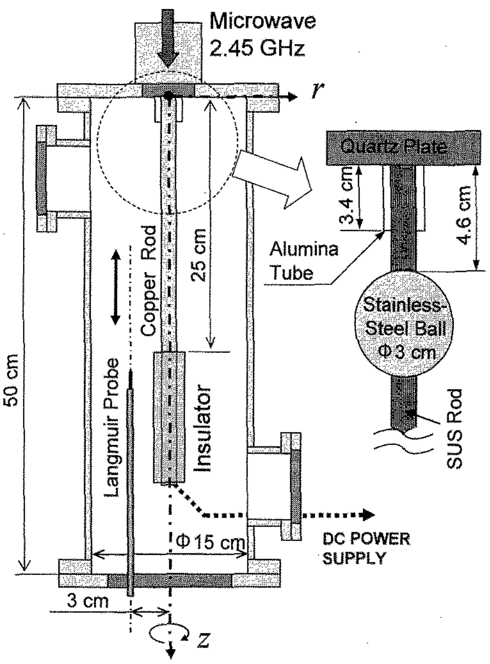

Fig. 1 Schematic of the metal-antenna surface wave-excited plasma source.

3. RESULTS AND DISCUSSION

3.1 Plasma generation along a copper rod

In order to generate MASWP uniformly along the surface of a metal object, it is preferable that microwaves propagate longer distance along the interface between metal and bounding overdense SWP sustained. Thus, to investigate under which condition MASWP extends longer along metal surfaces, plasma generation tests with a copper rod antenna were conducted at different negative voltages V_t and gas pressures p_n with different input microwave powers P_{in}. Ar plasma was first ignited with P_{in}=130 W at V_t=0 V and p_n=29 Pa, where SWP was generated locally along the surface of the quartz plate placed at the entrance of the chamber. Following the ignition, V_t was gradually increased in magnitude. Figures 2(a)–2(d) show the axial distributions of (a) electron density n_e, (b) plasma potential V_p, (c) electron temperature T_e, and (d) floating potential V_f at different V_t=−15, −30, −70, and −100 V. As seen in Fig. 2(a), the length of the MASWP column became longer with increasing V_t. At the same time, the distribution of T_e became flatter with increasing V_t; this was because plasma generation region extended longer along the rod axis with increasing V_t. The same tendency was also shown in the distributions of V_p and V_f, because these values are theoretically the linear functions of T_e [1]. However, larger noises were seen in the distributions of T_e than in those of V_p and V_f as shown in Figs. 2(c)–2(d). This is because the determination of T_e from a result of Langmuir probe measurement employs much more complex processes than those of V_p and V_f [1]. Theoretically, the distributions of T_e, V_p, and V_f should be similar each other, and such a similarity was actually recognized in Figs. 2(b)–2(d).

To which axial position SWs propagated along a copper rod was estimated as follows. In the MASWP source presented, microwaves propagate along the interface between overdense plasma and underdense region in ion sheath near the metal rod [3]. The relative permittivity of the underdense region is ~1 for 2.45-GHz microwaves owing to significantly low electron density therein. Thus, the critical density n_c for SW propagation in this source is considered to be close to n_c=1.5×10^{11} cm^{-3} for SW propagation between vacuum and overdense plasma. Thus, SWs were considered to propagate to the axial position where n_e became ~1.5×10^{11} cm^{-3} on the distribution of n_e. Note that slight turnoff points were recognized on V_p at the axial positions A, B, and C for V_t=−30, −70, and −100 V, respectively. Each turnoff point almost conforms to the axial position where n_e becomes ~1.5×10^{11} cm^{-3} on the corresponding distribution of n_e. This was because power absorption from microwaves was conducted between the entrance of the chamber and the turnoff point z_t, while the plasma merely diffused from upstream to downstream without power absorption at $z>z_t$. Therefore, the distributions of V_p and T_e were relatively flat owing to the power absorption at $z<z_t$, while their decrease rate became larger at $z>z_t$ where microwaves did not propagate.

Figures 3 shows the axial distributions of n_e of the MASWP columns, obtained with P_{in}=130 W at V_t=−100 V and different p_n=4, 10, 29, and 54 Pa. As seen in this figure, the length of the MASWP column became longer with increasing gas pressure. This phenomenon was also confirmed using a graphite rod antenna in our previous work [4]. Figure 4 shows the axial distributions of n_e of the SWPs, obtained at p_n=29 Pa with different P_{in}=70, 130, 190, and 250 W.

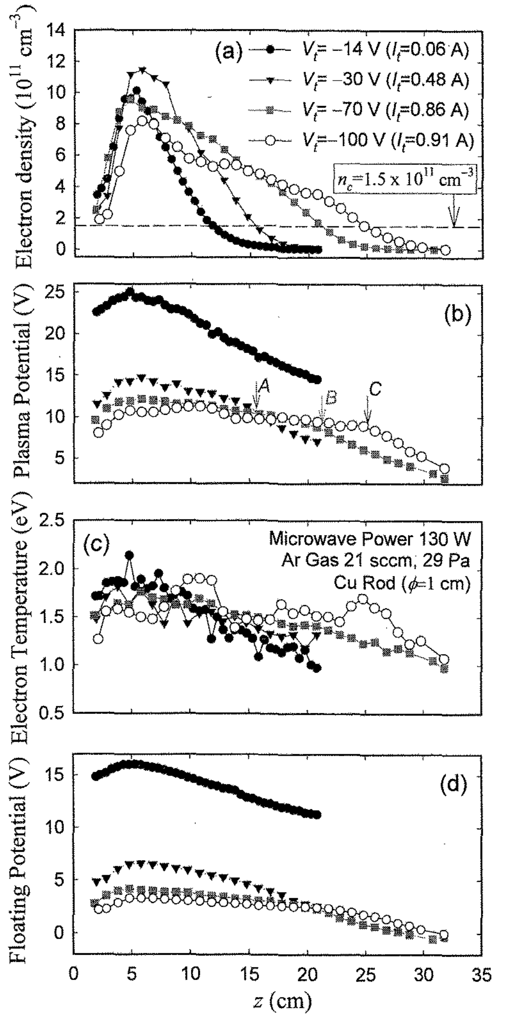

Fig. 2 Axial distributions of (a) electron density n_e, (b) plasma potential V_p, (c) electron temperature T_e, and (d) floating potential V_f at different negative voltages of V_t=−15, −30, −70, and −100 V supplied to a copper rod antenna. The plasmas were sustained with an input microwave power of 130 W at a gas pressure of 29 Pa.

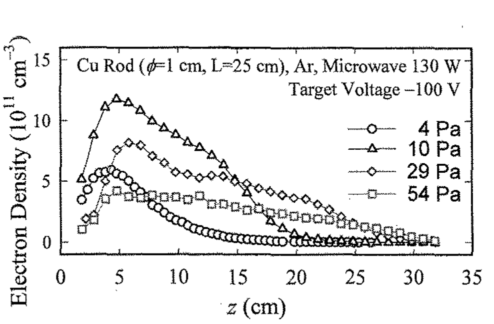

Fig. 3 Axial distributions of n_e in the MASWP columns, obtained with an input microwave power of 130 W and at different gas pressures of 4, 10, 29, and 54 Pa and a negative voltage of −100 V supplied to a copper rod antenna.

The maximum value of n_e at around z=5 cm increased with increasing P_{in}, while the plasma

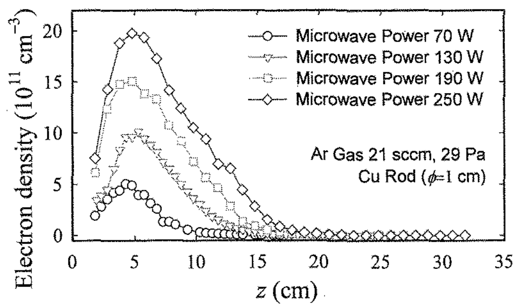

Fig. 4 Axial distributions of n_e in the SWPs, obtained with different input microwave powers of 70, 130, 190, and 250 W at a gas pressures of 29 Pa. No DC bias was supplied to a copper rod antenna.

did not extend significantly by the increase of microwave power.

Figure 5 shows the relation between the length of a MASWP column obtained and the total power ($P_{in}+V_t \times I_t$) employed. The length of a MASWP column was defined as a distance between the entrance of the chamber and an axial position where n_e=n_c. This figure clearly shows that increasing V_t and p_n is more effective to extend the MASWP column than increasing P_{in}. These results indicated that higher V_t and p_n were preferable to generate MASWP more uniformly along the surface of a metal object.

3.2 Plasma generation along a stainless-steel ball

To confirm generation of MASWP along metal objects except rods, we tried to sustain plasma along a stainless-steel ball as shown in Fig. 1. Ar plasma first ignited with P_{in}=100 W at p_n=42 Pa and V_t=0 V. Following the ignition, V_t was gradually increased in magnitude from 0 to −82 V, accompanied by the extension of the plasma along the z direction. Note that V_t=−82 V was the maximum in this experiment, because arc discharge occurred at $|V_t|$>82 V. Figure 6(a) shows the photograph taken from the side window at V_t=−82V, clearly showing that the emission from the plasma surrounded the entire surface of the ball. Note that Fig. 6(b) is the photograph of the DC plasma sustained at V_t=−390 V and p_n=79 Pa without microwaves, where uniform plasma was generated along the ball surface. Figure 7(a) shows the axial distributions of n_e along r=3 cm at V_t=0 and −82 V, indicating that the surface of the ball was surrounded by high-density MASWP over the entire surface of the ball at V_t=−82 V. Compared to the axial distribution of n_e of the DC plasma shown in Fig. 7(b), the axial distribution of n_e of the MASWP was not perfectly uniform. For more uniform plasma generation along the entire surface, a little more device may be required; for example, it is considered to be effective to employ standing surface waves by reflecting the waves at the one end of the ball.

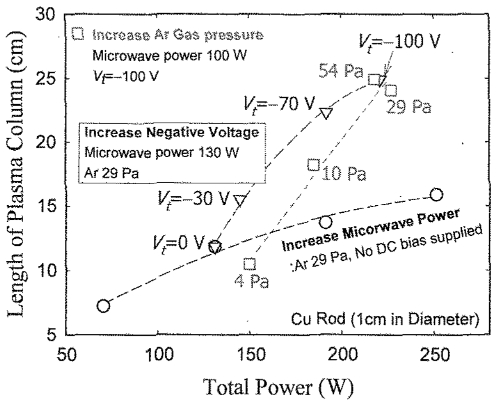

Fig. 5 Relationship between the length of a MASWP column obtained and the total power ($P_{in}+V_t \times I_t$) employed. P_{in}, V_t, and I_t are microwave power employed, negative voltage supplied to the copper rod, and current collected by the rod surface, respectively.

4. CONCLUSION

In our previous work, a microwave-excited high-density plasma, which was called a metal-antenna surface wave-excited plasma (MASWP), was sustained along the surface of a long graphite rod at a negative voltage. It was expected that such microwave-excited high-density plasmas can be generated along the three-dimensional surface of a metal object as uniformly as DC plasmas. Thus, in this work, we tried to demonstrate MASWP generation along the rounded surface of a stainless-steel ball. At first, to investigate under which condition MASWP extends longer along metal surfaces, plasma generation tests with a copper rod antenna 1 cm in diameter were conducted at different negative voltages V_t and gas pressures p_n with different microwave powers P_{in}. Increasing V_t (0 to −100 V) and p_n (4 to 54 Pa) was more effective to extend the MASWP column than increasing P_{in} (70 to 250 W). Furthermore, plasma generation along a stainless-steel ball 3 cm in diameter was also demonstrated with P_{in}=100 W at p_n=42 Pa and V_t=−82 V, where the high-density (>10^{11} cm^{-3}) MASWP surrounded the entire surface of the ball.

Acknowledgement

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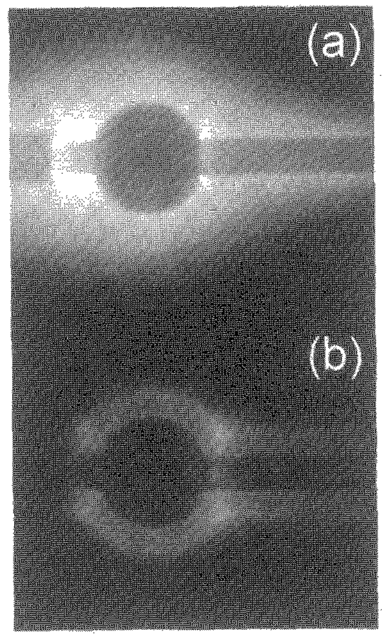

Fig. 6 (a) Microwave-excited high-density plasma generated with a stainless-steel ball 3cm in diameter at a negative voltage of V_t=−82 V, with an input microwave power of 100 W at an Ar gas pressure of p_n=42 Pa. (b) DC plasma generated with the same antenna at V_t=−390 V and p_n=79 Pa without microwaves.

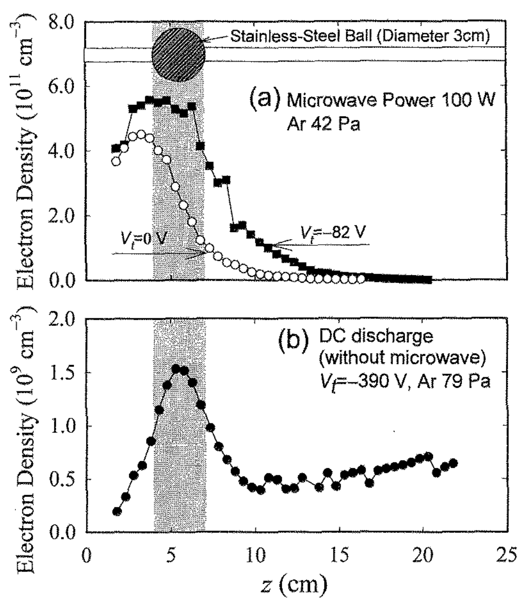

Fig. 7 (a) Axial distributions of electron density n_e in the MASWPs along a stainless-steel ball 3cm in diameter, generated with an input microwave power of 100 W at negative voltages of V_t=0 and −82 V and Ar gas pressure of p_n=42 Pa. (b) Axial distribution of n_e, generated with the same antenna at V_t=−390 V and p_n=79 Pa without microwaves.

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