Study on Wave Mode Control in Slot-excited Microwave Plasmas

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A spatial structure of waves and plasma uniformity in microwave discharge using a multi-slotted planar antenna are investigated by experimental measurements and calculations. In the experiments, analyses of light emission intensities and the measurements of radial mode number by an electric field probe show that the main component of the radial mode number is 4-6. In the calculation, it is shown that the mode number spectrum of radiated waves is very wide in the case of a surface wave plasma device due to a few slot openings, although that is narrow due to multiple slots in case of multi-slot excited plasma. As a result, it is possible to eliminate mode jumps and hysteresis for a wide range of parameter because the radiated waves are controlled by the multi-slotted planar antenna. Thus, it is important to control the mode spectrum of the radiated waves for uniform and stable plasma production in the slot-excited microwave discharge devices.

Keywords: multi-slotted planar antenna, standing wave, wave mode, surface wave eigenmodes, resonance absorption, aperture function

1. Introduction

It has been known that the slot-excited microwave discharges can produce the plasma suitable for plasma-aided manufacturing that requires large area, low damage, and high speed processing. In the slot-excited device, the microwave propagates through a waveguide, a cavity space, a slot plate, and a dielectric window, and then into a plasma. Surface wave plasma (SWP) device often uses the slot plate with a few slots resulting in the jump or the hysteresis behavior of plasma profile when charging the input power [1]. On the other hand, multi-slot excited plasma (MSP) device, in which the slot plate has slot openings of more than 1000, has produced uniform plasmas with smooth change in the densities for a wide range of the input power and gas pressure [2].

We consider the reason for the difference in plasma production between SWP and MSP. In both plasmas, the plasma is mainly produced by surface waves and/or enhanced microwave fields due to the resonant absorption that locate just under the dielectric window [3]. Therefore, the plasma profile is determined by the spatial structure of the waves characterized by the azimuthal mode number m and the radial mode number n. If the multiple modes of (m, n) are excited by the slot antenna, the plasma selects one mode for one value of the densities and the modes change as the input power changes. This is the case for SWP. In the case for MSP, it is expected that these problems can be prevented by understanding and controlling the spatial structure of the waves.

In this study, first of all, we measure the electric field distributions near plasma-quartz interface by an electric field probe and light emission intensities by a CCD camera, and compare theoretical values with them. Next, we investigate the relation of aperture function of the antenna and the radiated spectrum by numerical calculation. As a result, it is shown that the mode jumps of the surface wave and spatial resonance are suppressed in the MSP device.

2. Experimental equipments

Figure 1 shows the experimental equipment schematically. A discharge chamber has the radius of R = 250 mm and a depth of 380 mm, and the quartz window with the same diameter and a thickness of 30 mm is set on the top. The multi-slotted planar antenna is installed on the glass window and is driven by a microwave source at a frequency of $\omega/2\pi$ = 2.45 GHz. The antenna consists of a feeder connected to the microwave source, the slot plate with concentric array of slots distributed over the plate, and a back plate. We use the waveguide for the TE_{11} mode with a polarizer for the rotating TE_{11} mode excitation [4]. A quadruple three stub tuner is inserted between the polarizer and the slot antenna to prevent the power reflected from the antenna/plasma from going back into the polarizer. Slots are 23-26 mm in length, 2 mm in width, and 4 mm in slot interval in the radial direction, and are distributed all over about 1000 pieces except the central part. Ar gas pressure p is controlled at 10-300 mTorr and the flow rate is set at 100 sccm. Plasma parameters are measured by a radially fast-scanning probe. Two-dimensional distribution of the light emission from the plasma is monitored using the CCD camera located beneath a substrate stage. The electric field distribution of the radial direction is measured

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by the electric field probe movable in the radial direction at z =10 mm.

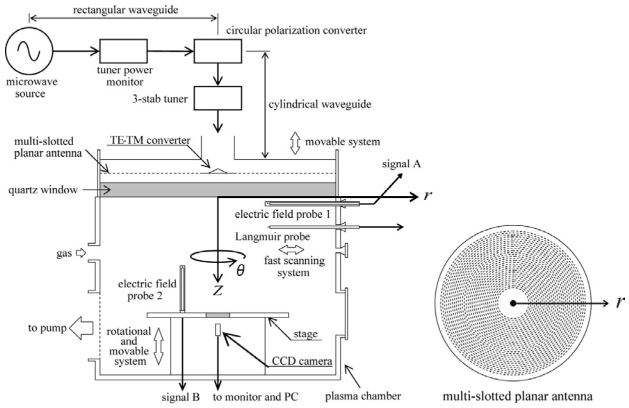

Fig. 1. The experimental equipment.

The plasmas were generated in various conditions of the incident powers P_{in} and Ar gas pressures, and the ion saturation current density J_{is} was measured by the Langmuir probe. Figure 2 shows the relationship of J_{is} to external parameters, where P_{ref} is reflected power.

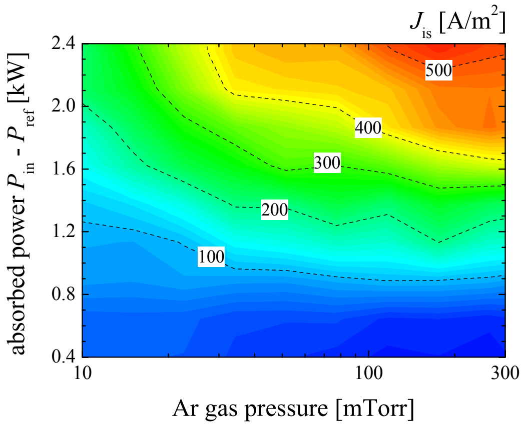

Fig. 2. The relationship of the ion saturation current density to the incident power and Ar gas pressure.

3. Structure of waves

The dispersion relation of the surface wave eigenmodes for TM waves in a cylindrical plasma approximated by a simple 2-layer model consisting of the dielectric window and a plasma layer is calculated by

$$\frac{p_1}{\varepsilon_1}\tanh(p_1 h) + \frac{p_2}{\varepsilon_p} = 0, \quad (1)$$

$$\frac{q_1}{\varepsilon_1}\tan(q_1 h) - \frac{p_2}{\varepsilon_p} = 0, \quad (2)$$

where

$p_1 = \sqrt{\lambda^2 - k_0^2\varepsilon_1}$, $p_2 = \sqrt{\lambda^2 - k_0^2\varepsilon_p}$, $q_1 = \sqrt{k_0^2\varepsilon_1 - \lambda^2}$,

$\varepsilon_1 = 4.0, \varepsilon_p = 1-(\omega_{pe}/\omega)^2, k_0 = \omega/c, \lambda = j_{mn}/R, h = 0.03$,

ε_1 is a dielectric constant of the quartz window, ω_{pe} is plasma angular frequency, c is the velocity of light, h is the thickness of the quartz window, j_{mn} is the n-th root of the m-th Bessel function [$J_m(j_{mn}) = 0$] [3]. Equations (1) and (2) represent dispersion equations of pure and hybrid modes, respectively. Figure 3 shows the dispersion relation of the surface wave eigenmodes based on the density distribution of Fig. 2 with the assumed electron temperature T_e of 3 eV. It is observed that various surface wave eigenmodes are excited and jumps at specific densities will take place.

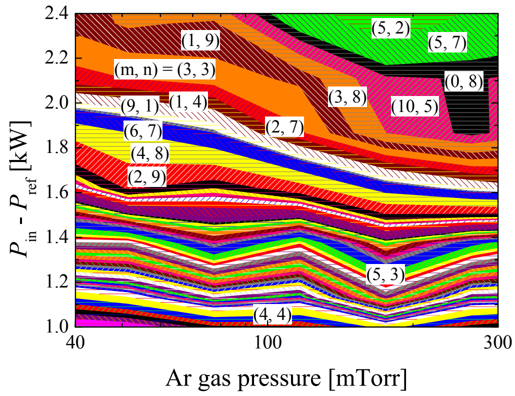

Fig. 3. The surface wave eigenmodes.

Figure 4(a) shows the light emission intensities measured by the CCD camera for the rotating mode excitation, P_{in} = 1.51 kW and p = 200 mTorr. If the plasmas predominantly absorb the microwave power by Joule heating, its intensity is proportional to E^2, where $E(r,\theta)$ represents the electric field. The main component of E is the axial component E_z which has a radial dependence of J_m. Moreover it is reported that m = 1 in the device [5]. Assuming that the brightness variation along the radius in Fig. 4(a) is represented by a linear combination of $J_1^2(j_{1n}r/R)$ (n = 1, 2,…), we plot the coefficient of spectrum as a function of n obtained from the least square fit and normalization procedure in Fig. 4(b). It is observed that the predominant component of the radial mode number is 5. Figure 5 shows the result of the CCD data as P_{in} and p change. The predominant component of n for the CCD data taken for different P_{in} and p is 5-6. In Fig. 3 and Fig. 5, the mode number in the plasma produced in MSP device has only two variation out of possible several tens for the density variation of one order of magnitude.

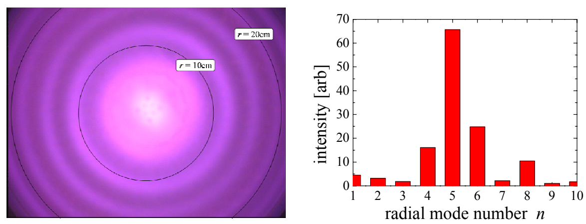

Fig. 4. (a) The light emission intensities measured by the CCD camera, P_{in} = 1.51 kW, p = 200 mTorr, and (b) the spectrum of the mode in the radial direction.

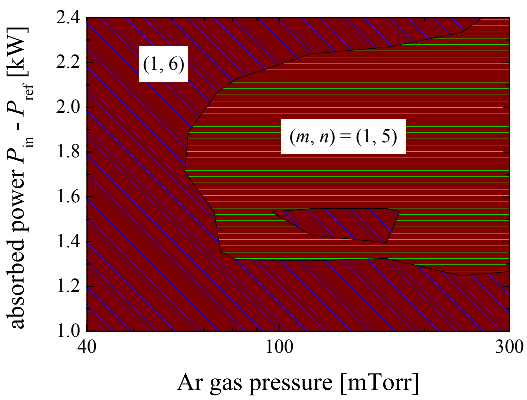

Fig. 5. Analysis of the light emission intensities.

We measured the radial mode number n of the electric field near the plasma-quartz interface by the electric field probe movable in the radial direction in order to confirm the result from the CCD camera measurements. The radial mode number n is obtained by the number of zeros of $E_z(r)$ in the radial range of $0 < r \leq R$. It is reported that the electric field has a peak at some distance from the glass plasma interface, and the electric field has the peak at $z = 1$ cm in the case of $P_{in} = 1.5$ kW and $p = 10$ mTorr [5]. Since the probe is set up at $z = 1$ cm, Fig. 6 shows the radial mode number n measured by the electric field probe at $P_{in} = 0.5$-2.5 kW and $p = 10$ mTorr. It is observed that the predominant component of the radial mode number is 4-6 in these conditions. The analysis of the light emission intensities and the measurements of the radial mode number by the electric field probe both show that the main component of the radial mode number is 4-6.

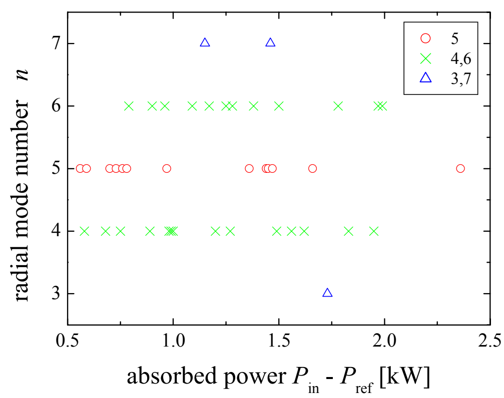

Fig. 6. The radial mode number n measured by the electric field probe.

4. Numerical analyses of the radiated spectrum

The antenna has two characteristics of formation of the standing wave in the upper part of the antenna and the radiation under the antenna, because it is the planar antenna composed of the multi small slots. In the former case, it means that the standing wave of the rotating TM_{15} mode is formed easily because the antenna slot plate works as metallic boundary. In the latter case, it means that the electric field distribution similar to the upper part of the antenna is formed easily just under the antenna with the radiation of the standing wave pattern formed in the upper part of antenna through the multi small slots. It is expected that the electric field distribution radiated to the plasma side with the antenna can be easily controlled from these.

Figures 7(a) and 8(a) shows the aperture function of the antenna in case of the multi-slots antenna and a few slots antenna, respectively. The aperture function of the antenna is given by $g(x,y)$ that equals to 1 for opening part and 0 for the other. The aperture function of the multi-slotted planar antenna is of a fine periodic rectangle shape spread all around. On the other hand, the aperture function of the antenna for a few slots antenna has a few delta functions corresponding to slots of elongate shape often used for produce SWP [1]. Then the electric field distribution in the upper part of the antenna is given by

$$f_{mn}(r,\theta) = \mathrm{J}_m\left(j_{mn}\frac{r}{R}\right)\cos(m\theta) \quad : \quad 0 \leq r \leq R, \qquad (3)$$

where the azimuthal mode number m is 1 and the radial mode number n is 5 by controlling the electric field distribution in the upper part of the antenna. From the aperture function of the antenna g and the electric field distribution in the upper part of the antenna, $f(x,y) = f_{15}$, the mode number spectrum of the radiated wave under the antenna is a convolution integral of the spectrum of the spatial resonance modes in the cavity space and the aperture function of the slot plate (and the dielectric window) as given by

$$F * G = \iint F(a,b)G(m-a, n-b)dadb, \qquad (4)$$

where F and G is the spectrum of f and g, respectively. Figure 7(b) shows the result of the convolution integral with the multi-slotted planar antenna. It is observed that similar electric field distribution is easily formed in the upper and lower sides of the antenna with dominant $n = 5$ mode, because the range of the wavenumber spectrum of the electromagnetic radiation is narrow with the multi-slotted planar antenna. Figure 8(b) shows the result of the convolution with a few slots antenna. It is observed that it sustains multiple modes under the antenna, because the range of the wavenumber spectrum of the electromagnetic radiation is broad. From the above-mentioned discussion, the spatial structure depends on the radiated spectrum from the antenna to the plasma, and the radiated spectrum is determined by the combination integral of the aperture function of the antenna and the radiation of the standing wave pattern formed in the upper part of the antenna.

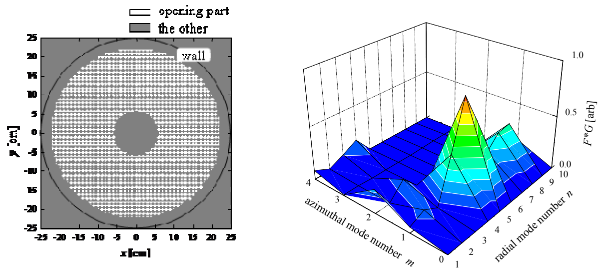

Fig. 7. (a) The aperture function, and (b) the radiated spectrum with the multi-slots antenna.

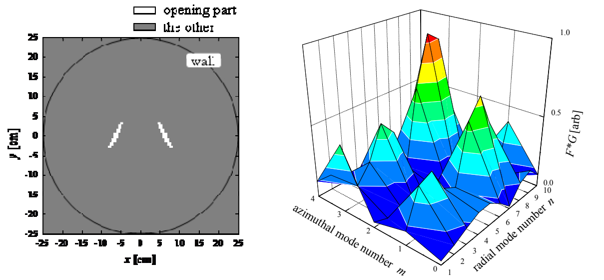

Fig. 8. (a) The aperture function, and (b) the radiated spectrum with a few slots antenna.

5. Summary

The planar microwave discharges using the multi-slotted planar antenna have been investigated. In experimental measurements of the electric field distribution of the radial direction measured by the electric field probe and light emission intensities by the CCD camera, the predominant component of n is 4-6 in different P_{in} and p. In numerical analyses of the radiated spectrum, the wave mode absorbed in the plasma is similar to the standing wave mode formed in the upper part of the antenna and limited to the mode spectrum with the multi-slots antenna. Therefore, it is important to control the mode spectrum of the radiated waves for uniform and stable plasma production in the slot-excited microwave discharge devices. It can be expected that plasma formed with the electric field distribution controlled by the external parameters is produced by controlling the radiation of the standing wave pattern formed in the upper part of the antenna in the device.

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