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Mode transition of power dissipation and plasma parameters in an asymmetric capacitive discharge

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ABSTRACT

Electrical characteristics and plasma parameters were experimentally investigated in asymmetric capacitively coupled plasma with various argon gas pressures. At a low discharge current region, the transferred power to the plasma was proportional to the current, while the transferred power increased proportionally to square of the current at a high discharge current region. The mode transition of power dissipation occurred at the lower discharge current region with the high gas pressure. At the low radio-frequency power or low discharge current, the plasma density increased linearly with the discharge current, while at the high power or high discharge current, the rate of an increase in the plasma density depended on the gas pressures. A transition of the discharge resistance was also found when the mode transition of the power dissipation occurred. These changes in the electrical characteristics and the plasma parameters were mainly caused by the power dissipation mode transition from the plasma bulk to the sheath in the capacitive discharge with the asymmetric electrode, which has extremely high self-bias voltages.

1. Introduction

Capacitively coupled plasmas (CCPs) are widely used in semiconductors, displays, and solar cells processes. These plasma processes commonly use deposition and etching [1]. The deposition process mainly uses radicals, which are usually created by dissociation collisions between back ground gases and electrons, as a chemical reaction. Thus, the efficient plasma generation and small ion bombardment are needed for the deposition process and an input power should be transferred to the plasma bulk, rather than the sheath. While, the etching process primarily uses ion bombardment energy to the wafer for the etch-patterning with a high aspect ratio and thus, a relatively large sheath voltage compared to that in the deposition process is needed.

In accordance to the reasons, two types of the CCP reactors are general: i) CCPs with symmetric electrode size, ii) CCPs with asymmetric electrode size. The symmetric CCPs are usually used to the deposition processes and the asymmetric CCPs are well used to the etching or sputtering processes. The reason for the different applications of the two types of CCPs is mainly originated to the power dissipation characteristics in the CCPs. Therefore, researches on the power dissipation in CCPs are essential for the understanding of fundamental physics itself and plasma process applications.

The power dissipation in the CCPs has been studied by a few researchers, Beneking [2], Godyak et al. [3,4], and You et al. [5–7]. According to their experimental results, the power dissipation in the CCP can be analyzed into two parts roughly. At a primary region of the discharge, the applied power is mainly dissipated to the electrons in the plasma bulk, while the power is dissipated to the ion bombardment energy in the sheath with an increase in the discharge current. To explain the correlation between the power dissipation and the discharge current, Godyak et al. developed a modified plasma equivalent model [3,4]. In the study, the power consumed in the plasma is explained to a total sum of the plasma bulk and the sheath. The power dissipated in the bulk plasma, P_e, can be equivalent to the multiple of the potential drop V_p, which is the radio-frequency (*rf*) voltage across the bulk plasma in root-mean-square value, and the discharge current, I_p. The power dissipated in the sheath, P_i, can be written as the multiple of the sheath resistance, R_{sh}, which is used to explain the power loss in the sheath, and the square term of the discharge current, I_p^2. Therefore, the total power dissipated in plasma, P_d, is expressed by the following equation.

$$P_d = P_e + P_i = I_p V_p + {I_p}^2 R_{sh} \tag{1}$$

You et al. [5–7] studied the power dissipation mode transition in a relatively symmetric CCP under various external parameters, such as magnetic field [5], driving frequency [6], and gas pressure [7]. Although the study for the discharge mode transition has been performed theoretically and experimentally, most of researches have been done in the symmetric CCP which has two nearly identically sized electrodes, and there have been little studies on the discharge characteristics in the asymmetric CCP.

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The CCP reactors discharge with asymmetrically sized electrodes is often used in the plasma processes. In case of the asymmetric CCP, the discharge mode and its mode transition point for the power dissipation can show a different trend compared to the result in the symmetric CCP. As one of the examples, Table 1 shows a simple calculation of the dc self-bias voltage [8] induced around each powered electrode from Eq. (2). Here, a uniform plasma density was assumed.

$$V_{bias} = V_{rf} \sin\left(\frac{\pi}{2}\frac{A_b - A_a}{A_b + A_a}\right) \tag{2}$$

where A_a and A_b are the sheath areas at each electrode and V_{rf} is the *rf* voltage applied. Since the dc self-bias depends on the electrodes areas and the *rf* voltage, the dc self-bias induced in a discharge with the extremely asymmetrical electrodes was negatively far larger than that in a nearly symmetric system. It implies that the power dissipated by the ions in the sheath becomes larger in this extremely asymmetric CCP. Therefore, the mode transition of power dissipation and discharge characteristics are different in an asymmetric discharge.

For these reasons, the electrical characteristics were experimentally investigated in an extremely asymmetric system in this study. The plasma parameters and electrical characteristics were measured with various argon gas pressures and input powers. This study on the power deposition characteristics can be also related to the discharge property of both large-area CCP and the *rf* biased high density plasma [9,10] because the *rf* bias in the high density plasma sources has a similar configuration to the asymmetric CCP used in this study.

2. Experimental set-up

As shown in Fig. 1, our experiments were performed in a cylindrical aluminum discharge chamber; 26 cm in diameter, height of 19 cm. A side wall of the chamber is grounded and the top of the chamber is floated. A biased electrode of stain steel is set to 7 cm apart from a bottom of the chamber. The biased electrode is 1 cm thick. The discharge gap is formed by the chamber and the biased electrode separated by a distance $L = 11$ cm. *rf* power of 12.5 MHz is transferred to the biased electrode through a matching network and a coaxial cable. Electrical characteristic measurements are performed with a voltage–current monitor (ENI.INC, V-I probe) mounted on the powered electrode. The discharge power P_d was obtained from amplitudes of the measured voltage V_m, the measured current I_m, and the phase shift θ between them as [11]

$$P_d = I_m V_m \cos\theta \tag{3}$$

Argon gas pressures used in this experiment were in the range from 1.33 Pa to 26.66 Pa to observe gas pressure effect on the power dissipation mode transition. To investigate the correlation between the plasma parameters and the electrical characteristics, plasma parameters, such as plasma density and electron temperature were measured by using the floating harmonics method [12]. In brief, when a sinusoidal voltage is applied to the probe tip with a floating potential, the current flowing through the probe has multiple harmonics corresponding to the fundamental frequency of the probe system due to the nonlinearity of sheath. We set the probes on three positions; (A) at the center, (B) near electrode, (C) near wall. From the harmonic current components, the plasma density and the electron temperatures can be found.

Table 1
Calculated dc self-bias with various area ratio of two electrodes and *rf* voltages.

Area ratio of two electrodes	1.5	5	10	10
V_{rf} [V]	200	200	200	600
Calculated dc self-bias [V]	−61.77	−173.15	−191.86	−575.59

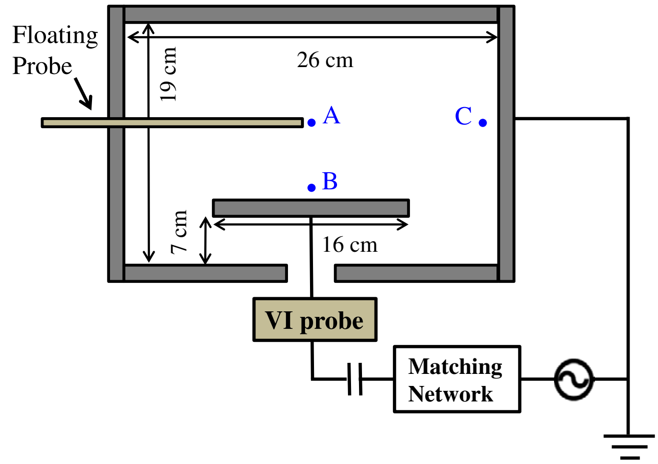

Fig. 1. A schematic of the experimental set-up.

3. Experimental results

Fig. 2 shows the measured discharge power curve against the discharge current in the asymmetric CCP. At a low discharge current, the discharge power is linearly proportional to the discharge current, which indicates that the applied power is mainly transferred to the electrons in the plasma bulk. With an increase in the discharge current, the discharge power curve respect to the discharge current became steeper. This implies that the applied power is more deposited to the ions in the sheath at the *rf* biased electrode. Therefore, it is expected that the mode transition for the power dissipation occurred more rapidly with the discharge current and at high gas pressure.

To confirm the mode transition for the power dissipation, fitting for the measured discharge power curve was done, as shown in Fig. 3. Beneking [2] modeled power dissipation in the sheath, as follows:

$$P_i = \left(\sqrt{2}\right)^{2.5}\left(\frac{5}{3\varepsilon_0 A}\right)^{1.5}\left(\frac{2k}{3\sqrt{P_g}}\right)\left(\frac{I}{\omega}\right)^{2.5} \tag{4}$$

where A, ε_0, k, P_g, and ω are the area of the discharge electrode, the permittivity in vacuum, the mobility constant, the gas pressure, and the

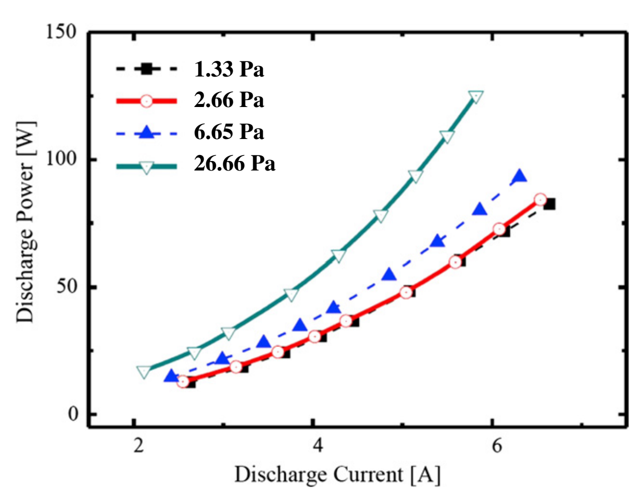

Fig. 2. Discharge current versus discharge power.