I. INTRODUCTION

Atmospheric pressure glow discharge sources have recently received increasing attention due to their many advantages, such as no need for expensive high vacuum equipment, low overall costs, simple systems, and ease of operation. Because of these advantages, many types of atmospheric plasma sources have been developed in a wide range of frequencies from direct current (dc) to microwave, or in a short pulse. Among them, radio-frequency (rf) capacitive discharge plasma sources have their own merits due to the relatively low breakdown voltage at atmospheric pressure and the possible wide employment in industries such as microcircuit manufactures and surface modifications. In addition, the study on discharge modes is important in the application of large area uniform glow discharges at atmospheric pressure.

Study of the rf capacitive $\alpha$ and $\gamma$ discharge modes was started for a better understanding of their roles in pump gas lasers. After the first observation by Levitskii, discharge mode characteristics and transition parameters have been studied in a wide range of gas pressures from 10 mTorr to a few hundred torr. The characteristic features of the two discharge modes were determined by whether the sheath breakdown occurred due to the electron multiplication by secondary electron emission. In other words, the ionization in $\alpha$ mode, sometimes called as a low-current discharge, is supported by the bulk plasma electrons, but ionization in $\gamma$ mode, also referred to as high-current discharge, is maintained by the secondary electrons emitted from the electrodes. In the early work on the discharge modes at atmospheric pressure, $\gamma$ mode generation was suspected because of its similarity with the filamentary arc and unstableness, and thus the mode was designated as a failure mode or a reversed mode. Recently, however, further investigation reported the existence of the $\gamma$ mode and $\alpha-\gamma$ mode transitions in atmospheric capacitive discharges. In this work, we report and discuss the properties of $\alpha$ and $\gamma$ modes, and further, the existence of the normal and abnormal glow regimes in the $\alpha$ mode. The plasma under study was produced in larger area electrodes ($\sim 30$ cm$^2$) than those of the previous works ($\sim 1$ cm$^2$).

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic illustration of the experimental setup under study. The discharge source has two parallel copper electrodes which have the same diameter of 60 mm for avoiding the self-bias voltage between the electrodes. The bottom electrode was powered by a 13.56 MHz rf supply (Dressler Cesar1312) through an $L$-type impedance matching network. Both electrodes were cooled by a chilled water. Helium gas (99.99%) was introduced by using a flow meter, and the chamber pressure was maintained at 1 atm by pressure instruments (Pfeiffer Vacuum, Piezo gauge APR260, single gauge reader TPG261). Since it was found that the breakdown voltage, the current-voltage curve, and the spectroscopic results were more or less unchanged at various helium flow rates up to 10 l/min, it was fixed at 2 l/min for reducing the control parameter in the experiment. Electrical characteristics of the discharge were investigated by a current probe (Tektronix TCP202), a voltage

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$\alpha$, $\gamma$, and normal, abnormal glow discharge modes in radio-frequency capacitively coupled discharges at atmospheric pressure

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Discharge modes, $\alpha$ and $\gamma$, of a radio-frequency helium capacitively coupled discharge at atmospheric pressure were investigated with the discharge gap distance between electrodes varied from 1 to 5 mm. As similarly observed in other experiments, the $\alpha$ and $\gamma$ mode and the $\alpha-\gamma$ mode transition were observed with large drops in the voltage (310–179 V) and the phase angle between the voltage and current (54°–18°), and a contraction of the plasma volume (8.5–0.17 cm$^3$, at 3 mm gap distance). The discharge voltage where the $\alpha-\gamma$ mode transition occurred versus the gap distance showed a similar behavior with the Paschen curve for a gas breakdown. Depending on the gap distance, normal and abnormal glow regimes were observed in the $\alpha$ mode. At 1 and 2 mm, the $\alpha$ mode remained in the abnormal glow discharge until the $\alpha-\gamma$ mode transition occurred as the discharge current increases. At 3 mm, however, the $\alpha$ mode was excited as a normal glow discharge with a constant current density (17 mA/cm$^2$) but it became an abnormal glow discharge as the current increased. At 4 mm, the $\alpha$ mode was sustained as a normal glow discharge, then the transition to the $\gamma$ mode occurred. Using a simple resistor-capacitor circuit model and a $\alpha$ sheath breakdown model, the discharge modes and the mode transition properties were studied.

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probe (Tektronix P6015A), and an impedance analyzer (MKS VI-probe4100) through a digital oscilloscope (Tektronix TDS3012). The visible spectrum and the emission intensity emitted from the plasma were obtained by a spectrometer (Chromex 250ks) with a charge coupled device (SBIG ST-6) detector.

III. RESULTS AND DISCUSSIONS

Figure 2(a) shows a typical current ($I$) versus voltage ($V$) characteristic curve at the 3 mm gap distance between the electrodes. As the current was increased by increasing the input power level ($P_{in}$) of the rf power supply, the discharge voltage and the current density were also increased. At a certain current (1.06 A) and voltage (310 V), an abrupt change in the discharge occurred showing the $\alpha$–$\gamma$ mode transition, which was accompanied by the voltage drop from 310 to 179 V, a reduction of the $I$–$V$ phase angle from 54° to 18°, and a contraction of the discharge volume from 310 cm$^3$ to 179 V, a reduction of the transition, which was accompanied by the voltage drop from 245 V and 17 mA/cm$^2$, respectively, which is a typical characteristic of the normal glow discharge. Being different from other previous experiments both at atmospheric pressure$^{10,11}$ and moderate pressure, it is believed that the normal glow discharge in the $\alpha$ mode could be observed in our experiment because a relatively large area electrode was used$^{9,13}$ in the range of the power density dissipated to the plasma in the lower than that ($\sim$990 W/cm$^3$) in the $\gamma$ mode. The large power density in the $\gamma$ mode is due to the decreased plasma volume, which can be evidenced from the almost same dissipated power [$P_{diss}=1/T\int_0^T I(t)V(t)dt$ where $T$ is a rf period] between the two modes, shown in Fig. 2(c).

Once the plasma covered the whole discharge area, both the discharge current and the current density increased linearly proportional to the applied voltage, which is typically seen in the abnormal glow discharges. Figure 2(d) depicts the current density of the $\alpha$ mode obtained from the measured plasma area and the $I$–$V$ curve. Up to about 0.5 A of the discharge current, the plasma area linearly increased whereas the voltage and the current density remained constant at 245 V and 17 mA/cm$^2$, respectively, which is a typical characteristic of the normal glow discharge. Being different from other previous experiments both at atmospheric pressure$^{10,11}$ and moderate pressure, it is believed that the normal glow discharge in the $\alpha$ mode could be observed in our experiment because a relatively large area electrode was used ($\sim$ 30 times larger) with which the lower input power density was possible.

Figure 3 shows photographs of the $\alpha$ and $\gamma$ discharge modes and the corresponding visible emission intensity profiles obtained by the image processing of the photographs. As shown in the enlarged photographs, the $\alpha$ mode [Fig. 3(a)] has brightest regions near the electrodes, but exhibits a dark region between the brightest layer and the electrode. In the $\gamma$ mode, shown in Fig. 3(b), on the other hand, the brightest layer exists at the electrode surface. This kind of emission

![FIG. 1. A schematic illustration of the experimental setup.](image1)

![FIG. 2. (a) Current–voltage ($I$–$V$) curve and (b) current–phase angle curve. At a certain current and voltage, the discharge was changed from $\alpha$ mode to $\gamma$ mode with a momentary arc generation. Hysteresis in the $I$–$V$ curve was observed by varying the input power. (c) The dissipated power $P_{diss}$ versus current. (d) The $\alpha$ mode was excited as a normal glow discharge at the constant discharge voltage (245 V) and the current density (17 mA/cm$^2$). The interelectrode spacing was 3 mm.](image2)
profile was seen not only in other atmospheric pressure discharges but also in moderate-pressure discharges.

To further understand the characteristics of each mode and the transition between them, a simple series-circuit model composed of a resistor \( R \) and a capacitor \( C \) representing the sheath capacitance was used as suggested in Refs. 10 and 11. From the measurements of discharge current, voltage, and phase angle between them, the discharge resistance \( R \) and the reactance \( X = 1/\omega C \) where \( \omega = 2\pi \times 13.56 \text{ MHz} \) in this case) in the \( \alpha \) mode were obtained, and they were plotted with respect to the discharge current in Fig. 4(a). In the normal glow discharge regime, both \( R \) and \( X \) were decreased as the current increased. It is because in the normal glow regime [Fig. 2(b)], the plasma covering the area of the electrode \( S \) was enlarged along with the current, and \( R \propto 1/S \) and \( C \propto S \). However, the ratio \( X/R \) which is related to the phase angle \( \phi = \arctan(X/R) \) was decreased, indicating that the increment of \( C \) was larger than the decrement of \( R \). In the abnormal discharge regime, on the other hand, the increase of input power was consumed to increase the discharge current and the current density through more ionization with the fixed plasma area \( S \) (Fig. 2). More ionization brings about the decrease of \( R \) and the increase of \( C \) through the decrease of sheath width as seen in Fig. 4(b). Here, the sheath was assumed to be a simple parallel plate capacitor. However, a slight increase of the ratio \( X/R \), shown in the abnormal glow regime [Fig. 4(a)], indicates that the increment of \( C \) was smaller than the decrement of \( R \). It is known that the discharge mode abruptly changes to the \( \gamma \) mode when the applied voltage reaches the \( \alpha \) sheath breakdown voltage. As depicted in Fig. 4(b), the \( \alpha \) sheath width before the mode transition occurred was calculated to be approximately 500 \( \mu \text{m} \). Interestingly, the thickness of the dark region right next to the electrode surface shown in the middle figure of Fig. 3(a) corresponds to the similar value. The measured \( I/V \) curve, phase angle, and the estimated sheath width in the \( \alpha \) mode are in a good agreement with the computational results denoted as region \( J \) of Ref. 12.

Figures 5(a) and 5(b) show the typical visible emission spectra of the \( \alpha \) and the \( \gamma \) modes at the same input power level of 200 W. The upper (lower) spectra refers to the \( \alpha \) (\( \gamma \)) mode. Due to the helium feeding gas, excited helium atomic lines (388.9, 447.2, 471.3, 492.2, 587.6, 667.8, 706.5 nm, etc.) were dominantly observed. In addition, \( N_2^+ \) (approximately 391.4 nm) and \( N_2 \) molecular spectra (between 335 and 381 nm) and excited oxygen atom emission lines (777.4 nm) were observed because of the ambient air and gas impurities. The emission intensity of the whole visible wavelength region of the \( \gamma \) mode was ten times larger than that of the \( \alpha \) mode. The rotational temperature, nearly equal to the gas temperature, \( \text{14, 15} \) was obtained through the analysis of \( N_2^+ \) molecular spectrum (first negative system, 0-0 band), and as Figs. 5(c) and 5(d) show, it was increased from 305 K in the \( \alpha \) mode to 473 K in the \( \gamma \) mode. In the temperature measurement, the helium atomic line at 388.9 nm, blended in the molecular band, was excluded. In the \( \gamma \) mode, especially the helium atomic lines such as 471.3 and 492.2 nm, which were emitted from the high energy levels close to the helium ionization energy (24.58 eV), were remarkably increased. It
resulted from the increase of excitation temperature from 3200 K in the α mode to 5140 K in the γ mode as shown in Figs. 5(e) and 5(f). The excitation temperature was measured from the Boltzmann plot using ten helium atomic lines, for which the spectroscopic setup was calibrated using a mercury calibration lamp and the atomic line table. It provides the information on the electron kinetic energy or the electron temperature tendency due to the direct electron impact excitation.

The I/V characteristics of the discharge were further investigated by varying the gap distance between the electrodes. At less than 2 mm gap distance, the discharge spread over the electrode surface immediately after the breakdown occurred. The I/V curve shown in Fig. 6 confirms that an α mode was excited and maintained as an abnormal glow discharge at 1 and 2 mm until the α–γ mode transition. At 3 mm, the discharge started as a normal glow and then became an abnormal glow as the input power was increased. At 4 mm the discharge was initiated and sustained as a normal glow discharge all the way until the transition voltage. However, the α mode was not observed at more than a 5 mm gap, where the discharge either directly became a γ mode or was extinguished. As increasing the discharge gap from 1 to 4 mm, the discharge initiation current of the α mode was decreased from 0.45 to 0.27 A, where the small initiation current corresponded to the normal glow discharge regime. The normal glow regime at the onset of the α mode is originated from the large load impedance due to the large gap distance \(d \propto 1/C \propto d\), which enabled the small current supplied by the rf generator.

Figure 7(a) illustrates the breakdown voltage \(V_{br}\) at various discharge gap distance, where the electric field between the two electrodes for breakdown is nearly constant at 920 V/cm. Figure 7(b) shows the dependence on the gap distance of the α–γ mode transition voltage \(V_{tr}\) and the voltage of the γ mode \(V_{n}\) which is in fact in the normal glow regime. \(V_{n}\) was slightly increased along with the increase of the gap distance in order to produce enough electron-ion pairs for the discharge sustainment as in dc glow discharges. By increasing the gap distance, \(V_{tr}\) also increased. Supposed that the bulk plasma and the sheath are represented as a resistor \(R\) and a capacitor \(C\), \(V_{tr}\) shown in Fig. 7(b) can be divided into \(R\) and \(C\) with the ratio given in Figs. 4(a). Therefore, \(V_{tr}\) of 310 V at the 3 mm gap is divided into \(R: X = 1:1.4\), which are 130 and 180 V, respectively. Therefore, the electric field across the 500 µm thick sheath is estimated to be approximately 3.6 kV/cm, which is larger than the electric field for gas breakdown.
According to the $\alpha$ sheath breakdown model for the $\alpha \rightarrow \gamma$ mode transition, the $\alpha$ sheath thickness $d_s$ is assumed as a discharge gap, and the plasma and the electrode play the role of an anode and a cathode, respectively. From the model, the transition condition for sheath breakdown can be expressed by the well-known Townsend criteria with the discharge gap distance $d$ replaced by the sheath thickness $d_s$ as

$$\gamma(e^{\alpha d_s} - 1) = 1,$$

$$E = \frac{V_b}{d_s},$$

$$\alpha(E) = Ap \exp \left( - \frac{Bp}{E} \right),$$

where $\alpha$ and $\gamma$ are the first Townsend and the secondary electron emission coefficient, respectively. $A$ and $B$ are constants for a discharge gas, $E$ is the electric field applied between electrodes, and $p$ is pressure (Torr). The sheath breakdown voltage $V_b$ can be induced from the following formula:

$$V_b = \frac{Bp}{\ln(Ap) - \ln[\ln(1 + \gamma^{-1})]}$$

which is equal to the Paschen curve for gas breakdown, except the replacement of the gas gap $d$ with the sheath thickness $d_s$.

From Eqs. (3.3) and (3.4), the minimum voltage $V_{\text{min}}$ of the $\alpha \rightarrow \gamma$ transition is expressed as

$$V_{\text{min}} = \frac{2.72B}{A} \ln(1 + \gamma^{-1}) \approx 153 \text{ V}$$

$$p d_{s,\text{min}} = \frac{2.72}{A} \ln(1 + \gamma^{-1}) \approx 4.5 \text{ Torr cm},$$

where $A$ and $B$ for helium are $2.8$ and $34 \text{ V cm}^{-1}\text{Torr}^{-1}$, respectively, and $\gamma$ is set to be $0.01$. In the case of the $1 \text{ mm}$ gap distance, the normal glow regime began to appear.
gap distance at 1 atm, $V_g$ was measured as 245 V, and $pd_g=32$ Torr cm with $d_g=420$ μm obtained from the simple R–C circuit model and the I–V measurement. These values are larger than 153 V and 4.5 Torr cm. Therefore, one can see a similarity in trends between the relation of $V_g$ versus $d$ [Fig. 7(b)] and the right-hand branch of the Paschen curve [Fig. 7(a)].

IV. SUMMARY

The α and γ normal and abnormal glow discharge modes were investigated in 13.56 MHz rf capacitively coupled helium plasma, produced at atmospheric pressure. The mode transition from α to γ at a specific voltage and current was accompanied by a large voltage drop, phase angle decrease, plasma volume contraction, and rising of rotational and excitation temperatures. A simple R–C circuit model showed that the sheath thickness in the α mode was decreased to 500 μm just before the sheath breakdown occurred and thus resulting in the α–γ mode transition. At 3 and 4 mm of the discharge gap, it was initiated as a normal glow discharge with a constant voltage and constant current density. At discharge gaps under 2 mm, on the other hand, an α mode was excited as an abnormal glow discharge as in typical moderate pressure capacitive discharges and other atmospheric discharges. At the gap distance between 1 and 5 mm, the α to γ mode transition voltage increased along with the gap distance, which is a similar trend as in the right hand side of the Paschen curve for gas breakdown. The experimental result demonstrated that the gap distance strongly influenced not only on the α mode excitation but also on the α–γ mode transition. In addition, it is shown that the α mode provides a desirable discharge condition for industrial applications such as relatively low gas temperature and large discharge area.

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