Driving frequency effects on the characteristics of atmospheric pressure capacitive helium discharge

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Atmospheric pressure helium discharge characteristics were investigated for varying driving radio frequencies in the range between 1.86 and 27.1 MHz. As the driving frequency is raised, both gas breakdown and $\alpha$-$\gamma$ transition voltages decrease due to the reduction in the electron drift loss. In addition, different discharge features such as normal, abnormal, $\alpha$, and $\gamma$ modes show certain dependences on the frequency. Using a simple circuit model, the changes in sheath thickness from 2.35 to 0.11 mm, electron density from 0.26 to $15.6 \times 10^{11}$ cm$^{-3}$ was obtained by raising the frequency from 1.86 to 27.1 MHz. © 2008 American Institute of Physics.

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Atmospheric pressure glow discharges have been intensively studied due to their many advantages. By utilizing various driving frequencies from direct current to microwave, a wide variety of plasma sources has been attempted to achieve their specific purposes. Among them, radiofrequency (rf) capacitively coupled plasmas are considered to be widely applicable because of its relatively low breakdown voltage at the atmospheric pressure as well as many experiences and extensive employment in industries at low pressure such as for microcircuit manufacturing and material treatments.

In low pressure plasmas, the effects of driving rf frequency and dual frequency have been studied as a means of separately controlling electron energy and ion energy, and the results are actively in use in processing plasmas. In atmospheric pressure plasmas, however, not many fundamental studies on the frequency effects have been performed except the one-dimensional numerical simulation and experiments under 10 MHz. Studies of the role of driving frequency in the discharge properties will be of great importance not only for understanding physics but also for applications of the plasmas. In this letter, we present discharge properties of current-voltage characteristics, $\alpha$-$\gamma$ mode transition, and electron density as the driving frequency is varied in the wide frequency range between 1.86 and 27.1 MHz.

An atmospheric pressure discharge was produced between two parallel copper electrodes of the same diameters of 60 mm, being cooled by chilled water. The discharge gap between the electrodes was fixed at 3 mm. The bottom electrode was powered by a function generator (Marconi Instruments 2023) and a power supply (Amplifier Research 500A100A) through an impedance matcher. The voltage, current, and phase angles between them were measured by a voltage probe (Tektronix P6051A), a current probe (Tektronix TCP 202), and a digital oscilloscope (Tektronix TDS 3012). The helium gas pressure was fixed at 763.5 Torr using pressure control instruments (Pfeiffer Vacuum, APR260, TPG261). The detailed description of the setup is found in Ref. 11.

In Fig. 1(a), we show the dependence of gas breakdown voltage $V_{\text{break}}$ on driving frequency $f_d$. Upon varying $f_d$ from 1.86 to 3.39 MHz, $V_{\text{break}}$ rapidly decreases from 420 to 297 V, but it rather slowly decreases from 290 to 237 V as $f_d$ is changed from 10.4 to 27.1 MHz. It is noted that all the voltages and currents in this paper are rms values unless noted otherwise. The decrease in $V_{\text{break}}$ due to the increasing $f_d$ is related to the electron oscillation amplitude $A = 1.414(\mu_e)V_{\text{break}}/\omega_d l$, where $\langle \mu_e \rangle$ is the average electron mobility ($\langle \mu_e \rangle = 1178.8$ cm$^2$/V s at the atmospheric pressure), $\omega_d = 2 \pi f_d$, and $l$ is the discharge gap distance. Gas breakdown by high frequency electric fields at the atmospheric pressure is explained by a competition between the volume ionization and the electron loss by electron drift and diffusion. If $A$ is comparable to or larger than $l$, the electron drift loss by electron oscillation becomes significant, resulting in an increase in $V_{\text{break}}$. As $f_d$ is increased, however, the electron loss by the oscillatory drift becomes reduced.

![FIG. 1. (a) Gas breakdown voltage $V_{\text{break}}$ and (b) maximum electron oscillation amplitude $A$ for various driving frequencies from 1.86 to 27.12 MHz.](image-url)
because A becomes smaller than $l$. Calculation of A shows that it decreases from 2.8 mm at 1.86 MHz to 0.1 mm at 27.1 MHz, as depicted in Fig. 1(b). At frequencies less than 3.39 MHz, $V_{\text{break}}$ rapidly increases as $f_d$ is lowered [Fig. 1(a)] since A becomes comparable to or larger than $l/2$, which is 1.5 mm in this case.

Figure 2 describes the discharge current $I_d$ versus voltage $V_d$ characteristic curves in the $\alpha$ discharge mode (i.e., up to right before the $\alpha$-$\gamma$ mode transition) as the input rf power is raised at ten different driving frequencies. The $I_d$-$V_d$ curve for both $\alpha$ and $\gamma$ modes at 13.6 MHz is found in our previous report. The first observation from the figure is that the operating voltage range in the $\alpha$ mode is lower with the higher $f_d$, which may be favorable for practical applications. At $f_d < 10.4$ MHz [Fig. 2(a)], the increase in $V_d$ with respect to $I_d$ indicates that the plasma is maintained in the abnormal glow discharge with covering the whole electrode surface. At $f_d \geq 10.4$ MHz [Fig. 2(a)], on the other hand, the normal glow discharge first appears in which only a part of the electrode is filled with the plasma. It is noted that by raising the discharge current, the differential conductivity is changed from negative to positive, exhibiting the minimum voltage at which the normal glow discharge becomes the abnormal glow. In other words, the abnormal glow discharge starts at the minimum discharge voltage $V_d$ and current density $j_n$, where $j_n$ is discharge current divided by discharge area $S$. Such discharge characteristics are similar to the moderate pressure cases.\(^8\)

In Fig. 3(a), the relationship between $V_n$ and $j_n$ with $f_d$ in the range of 10.4–27.1 MHz is demonstrated. As $f_d$ is raised, $V_n$ decreases and $j_n$ increases. It is largely due to the decrease in the sheath voltage for the frequency augmentation.

In the atmospheric pressure plasma, the voltage drop across the sheath $V_n$ and the sheath thickness $d_s$ are obtainable by considering the sheath as a capacitor and the bulk plasma as a resistor connected in series.\(^9\)-\(^11\) From a simple R-C series circuit, the voltage across the sheath $V_n$ is obtained by $V_n = V_d \sin \phi$, where $V_d$ is the measured discharge voltage and $\phi$ is the measured phase angle between $V_d$ and $I_d$. In addition, the sheath capacitance $C$ is obtained by $C = \omega_d^2/(\omega_d^2 V_d \sin \phi)$, from which the sheath thickness $d_s$ is evaluated from $d_s = e_0 S/C$ with the measured discharge area $S$. In Fig. 3(b), we plotted $(V_d)_{\alpha}$, $(V_d)_{\gamma}$, and the current density $j_n$ just before the $\alpha$-$\gamma$ mode transition, where $(V_d)_{\alpha}$ corresponds to the right end point of each curve in Fig. 2. As shown in the figure, both $(V_d)_{\alpha}$ and $(V_d)_{\gamma}$ decrease from 544 to 175 V (68% reduction) and from 544.2 to 71 V (87% reduction), respectively, as $f_d$ is raised. On the other hand, the current density $j_n$, which is the measured discharge current $(I_d)_{\alpha}$ divided by the discharge area $S$ just before the mode transition, increases from 2.4 to 95.8 mA/cm\(^2\). These results are attributed to the increase in electron density at higher frequency due to more trapped electrons inside the discharge region.\(^8\)-\(^10\)

Since the $\alpha$-$\gamma$ mode transition at the atmospheric pressure can be described as $\alpha$-sheath breakdown, the electron density right before the $\alpha$-$\gamma$ mode transition $(n_{\gamma})_{\alpha}$ is evaluated from the sheath thickness $(d_s)_{\alpha}$ from the following equation:\(^8\)-\(^9\),\(^12\)-\(^14\)

$$n_e = \frac{b p}{(e/e_0)(d_s/2)\ln[a \ln(1 + \gamma^{-1})] + \ln(pd_s^2)},$$

where $a$ and $b$ are 2.8 and 34 V cm\(^{-1}\) Torr\(^{-1}\) for helium, $p$ is pressure in Torr, $\gamma$ is the secondary electron emission coefficient, and $e$ is the electron charge. In Fig. 4, we show $(d_s)_{\alpha}$ and $(n_{\gamma})_{\alpha}$ for various $f_d$. As $f_d$ is raised, $(d_s)_{\alpha}$ decreases from 2.35 to 0.11 mm and $(n_{\gamma})_{\alpha}$ increases from 2.6 $\times$ 10\(^4\) to 1.56 $\times$ 10\(^{12}\) cm\(^{-3}\). The $(d_s)_{\alpha}$ and $(n_{\gamma})_{\alpha}$ dependence on $f_d$ results from the enhanced electron trapping in the bulk plasma.\(^9\),\(^10\) At higher frequency, electrons are more effectively trapped inside the plasma region during the half period of the driving rf because the electron transit time $\tau_e$ is larger than the half-period $\tau_f$, i.e., $A < l$. For instance, the values of

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**Fig. 2.** Discharge current and voltage curve (a) below 3.39 MHz and (b) above 10.4 MHz in the $\alpha$ mode.

**Fig. 3.** (a) Discharge voltage $V_n$ and current density $j_n$ at the start of abnormal glow discharge vs $f_d$. (b) Discharge voltage $(V_d)_{\alpha}$, sheath voltage $(V_d)_{\beta}$, and current density $j_n$ just before the $\alpha$-$\gamma$ mode transition vs $f_d$. 

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(τe, τf) = (l/ μeE, 0.5/fd) for the measured electric fields E = (Vd)u/l at 2.00, 3.39, 13.6, and 27.1 MHz are 149 and 250, 177 and 147, 290 and 37, and 454 and 18, respectively. Therefore, the reduced electron loss and enhanced ionization that resulted from more trapped electrons bring about the smaller sheath thickness and larger electron density at higher f’d.8–10

The experimental results are compared with the numerical work based on the one-dimensional self-consistent continuum model.9 As depicted in Fig. 4, the simulation and the experiment results of (d’s)u and (n’e)u are in good agreement. The small discrepancy is believed to be due to the different discharge gap distances.

In summary, by raising the driving frequency, the gas breakdown and the α-γ transition voltages are decreased due to the decrease in the electron oscillation amplitude. At higher frequencies over 3.39 MHz, where the electron oscillation amplitude is smaller than half of the gap distance or the electron transit time is shorter than the half period of the driving rf, the normal glow discharge is observed with the rather smaller reduction in the gas breakdown voltages. As the driving frequency is higher, the operating voltage range significantly reduces and the electron density (as large as 1.56 × 10^{12} cm\(^{-3}\)) becomes larger. These results suggest that the high driving frequency may be favorable to an enhanced processing efficiency with higher plasma reactivity and more reliable operation.

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