Operation Mode on Pulse Modulation in Atmospheric Radio Frequency Glow Discharges

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Abstract The discharge operation regime of pulse modulated atmospheric radio frequency (RF) glow discharge in helium is investigated on the duty cycle and frequency of modulation pulses. The characteristics of radio frequency discharge burst in terms of breakdown voltage, alpha(α)-gamma(γ) mode transition voltage and current are demonstrated by the discharge current voltage characteristics. The minimum breakdown voltage of RF discharge burst was obtained at the duty cycle of 20% and frequency of 400 kHz, respectively. The α-γ mode transition of RF discharge burst occurs at higher voltage and current by reducing the duty cycle and elevating the modulation frequency before the RF discharge burst evolving into the ignition phase, in which the RF discharge burst can operate stably in the γ mode. It proposes that the intensity and stability of RF discharge burst can be improved by manipulating the duty cycle and modulation frequency in pulse modulated atmospheric RF glow discharge.

Keywords: pulse modulation, atmospheric glow discharge, discharge operation mode

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(Some figures may appear in colour only in the online journal)

1 Introduction

Atmospheric pressure glow discharges (APGDs) are receiving a great deal of attention because of their convenient applications without the vacuum chamber, such as thin film synthesis, surface modification and functionalization [1−4], which suggests the feasibility of on-line employment of APGDs in material processing. APGDs can be generated with the excitation of radio frequency (RF) power, which provides the atmospheric plasmas with higher plasma density [1−3], compared to that of the atmospheric dielectric barrier discharge (DBD) excited by kilo hertz range power [5,6]. On the other hand, the RF APGD consumes much electrical power and has high gas temperature of several hundred degrees, which consequently induces the discharge instability of evolving from the uniform and large volume alpha(α) discharge mode into the restricted gamma(γ) discharge mode with elevating the discharge intensity [7,8]. It has been proposed to modulate the RF power to generate pulse modulated (PM) RF APGD, in which the power consumption and gas temperature can be reduced with securing the plasma density [9,10]. The discharge stability in terms of discharge operation mode can also be improved in PM RF APGD by switching off RF discharge frequently. Here, the discharge operation modes of RF discharge burst in PM RF APGD were investigated experimentally on the modulation pulses in terms of repetition frequency and duty cycle. The discharge characteristics in terms of gas breakdown voltage, α-γ mode transition voltage and transition current were measured to demonstrate the discharge operation mode. It proposes a way of generating the stable RF APGD with proper pulse modulation.

2 Experimental setup

The pulse modulated atmospheric RF glow discharges are generated between the two identical round copper electrodes with the diameter of 20 mm and the gap distance of 2.4 mm, respectively. The electrode unit is housed within a Perspex box fed with a through helium flow at a rate of 5 SLM at 760 Torr. The schematic of the experimental setup is shown in Fig. 1. The pulse modulated RF sinusoidal signal at 13.56 MHz is generated by a function generator (Tektronix AFG 3102), which is then amplified by a power amplifier (AR150A100B) before delivering to the power electrode via an impedance matching
network. The discharge current and applied voltage are measured by a wideband current probe (Pearson 2877) and a wideband voltage probe (Tektronix P5100), respectively, and their waveforms are recorded on a digital oscilloscope (Tektronix TDS 3024B).

3 Results and discussion

The typical waveforms of applied voltage and discharge current in the PM RF APGD are shown in Fig. 2. The modulation frequency and duty cycle are set to be 100 kHz and 50%, respectively. The RF power is applied every 5 µs, as demonstrated by the applied voltage, whose amplitude is around 480 V. The discharge current shows an ignition phase with the temporal duration of about 1 µs before reaching the stable state with the amplitude of around 260 mA. It suggests that the RF APGDs operate with discharge bursts manipulated by the modulation pulses [9].

The waveforms of applied voltage and discharge current during the RF discharge burst are shown in Fig. 3. The amplitudes of applied voltage and discharge current are kept at around 480 V and 250 mA, respectively. The waveform of discharge current leads that of applied voltage, which is consistent with the RF APGDs without pulse modulation [7,8].

The current voltage characteristics of RF discharge bursts are measured to demonstrate the discharge operation modes, which are shown in Fig. 4 with the pulse frequency of 900 kHz and duty cycle at 20%, 30% and 90%, respectively. Before the gas breakdown, the voltage goes up linearly with current and the slopes at the duty cycle of 20%, 30% and 90% are similar, which suggests that the electrode works as a capacitor without the discharge. With the peak voltage elevating to 605 V, 550 V and 410 V at the duty cycle of 20%, 30% and 90%, the discharges are ignited with the peak currents of 202 mA, 162 mA and 110 mA, respectively. It is shown that the gas breakdown voltage reduces with increasing the duty cycle, which can be explained by the reduction of the temporal duration between the two successive RF discharge bursts, and the plasma species generated in the previous RF discharge burst will assist the ignition of the successive RF discharge burst [9,10]. With the ignition of discharge, the voltage grows monotonously with current at the duty cycle of 30% and 90%, which is consistent with the RF APGDs without pulse modulation. At the duty cycle of 30% and 90%, the last measured point shows the discharge just before evolving into γ mode, which indicates the α-γ transition voltage and current of 650 V and 585 V, 302 mA and 232 mA, respectively.

Fig. 3 Waveforms of applied voltage and current during the radio frequency discharge burst.

Fig. 4 Current voltage characteristics of pulse modulated radio frequency discharges at the modulation frequency of 900 kHz and duty cycles of 20%, 30%, 90%, respectively.
It is worth noting that at the duty cycle of 20%, after the gas breakdown, the voltage grows from 605 V to 760 V and then reduces to 710 V with the current increasing from 202 mA to 350 mA. It suggests that $\alpha$-$\gamma$ transition occurs at the voltage and current of 760 V and 270 mA, respectively, with changing the resistance of discharge from positive to negative, which was also found in RF APGDs accompanying the mode transition from $\alpha$ mode into $\gamma$ mode [7]. It can be understood that the RF discharge burst operating within the ignition phase with the duration of about 220 ns at modulation frequency and duty cycle of 900 kHz and 20%, respectively, which lasts a few RF cycles [11]. It proposes that the RF discharge burst can be operated stably and uniformly at a low duty cycle with a high discharge voltage and current. Further, the RF discharge burst can be operated even in $\gamma$ mode, which provides another way to improve the stability of RF discharge in $\gamma$ mode instead of introducing a dielectric barrier.

Fig. 5 presents the dependence of the breakdown voltage on duty cycle and modulation frequency, in which the modulation frequency and duty cycle are fixed at 900 kHz in Fig. 5(a) and 20% in Fig. 5(b), respectively. In Fig. 5(a), the breakdown voltage reduces monotonously from 650 V to 395 V with duty cycle growing from 10% to 60%, and keeps around 400 V when the duty cycle goes further up to 90%. The reduction of breakdown voltage with duty cycle can be understood by the reduction of time interval between two successive RF discharge bursts with higher duty cycle [11]. When the duty cycle is above 60%, the time interval between two successive RF discharge bursts is below 450 ns, which suggests the discharge operates in the continuum discharge mode [9]. In Fig. 5(b), the breakdown voltage shows the minimum amplitude of 450 V at a modulation frequency of 400 kHz. The breakdown voltage goes monotonously up to 615 V and 605 V when the modulation frequency goes down to 100 kHz and up to 900 kHz, respectively. Given that the breakdown voltage is determined by the generation and extinguishment of plasma species [12], the temporal duration of RF discharge burst and time interval between two successive RF discharge bursts of 0.5 $\mu$s and 2.0 $\mu$s are considered to be the proper parameter for the ignition of RF discharge burst with the modulation frequency and duty cycle of 400 kHz and 20% in this experiment.

Fig. 6 gives the dependence of $\alpha$-$\gamma$ transition voltage on duty cycle and modulation frequency, in which the modulation frequency and duty cycle are fixed at 900 kHz in Fig. 6(a) and 20% in Fig. 6(b), respectively. As shown in Fig. 6(a) with the fixed modulation frequency of 900 kHz, the transition voltage reduces from 760 V to 570 V with the duty cycle growing from 20% to 50% and keeps around 650 V with duty cycle going further to 90%. On the other hand, by fixing the duty cycle at 20%, the transition voltage keeps around 650 V when the modulation frequency increases from 100 kHz to 700 kHz, and grows to 760 V when the modulation frequency goes further to 900 kHz, as shown in Fig. 6(b). It suggests that the discharge operation mode transition voltage is elevated by compressing the time duration of the discharge burst with the low duty cycle and high modulation frequency.

Fig. 7 shows (a) duty cycle and (b) modulation frequency dependent on the transition current at the modulation frequency of 900 kHz and duty cycle of 20%, respectively. The maximum transition current of 302 mA is achieved at the duty cycle of 30%, as shown in Fig. 7(a). With the duty cycle going up to
60%, the transition current goes down to 232 mA, which keeps the magnitude as the duty cycle goes further up to 90%. On the other hand, the transition current reduces to 270 mA at the duty cycle of 20%. Fortunately, the RF discharge burst operates stably in the γ mode, as indicated in Fig. 4. It is worth noting that the transition voltage of 760 V at a duty cycle of 20% is higher than that of 650 V at a duty cycle of 30%, as shown in Fig. 6(a), which suggests that the α-γ mode transition of RF discharge burst happens with a higher voltage and lower current at the duty cycle of 20%, compared to that at the duty cycle of 30%. It can be explained by the few RF cycles (2–3) in the RF discharge burst with the modulation characteristics in terms of frequency at 900 kHz and duty cycle at 20% [11]. The RF discharge burst operates in the ignition phase, which also explains the stable operation of RF discharge burst in the γ mode at the duty cycle of 20%, as shown in Fig. 4.

The transition current grows from 222 mA to 332 mA with elevating the modulation frequency from 100 kHz to 700 kHz and fixing the duty cycle at 20%, as shown in Fig. 7(b). As the modulation frequency increases further to 800 kHz and 900 kHz, the transition current reduces to 310 mA and 270 mA, respectively, which can also be understood by the limited RF cycles in the RF discharge burst. It suggests that the RF discharge burst can operate stably in the α mode with high intensity in terms of discharge current by reducing the duty cycle and elevating the modulation frequency before the discharge burst evolves into the ignition phase with a few RF cycles. On the other hand, as the RF discharge burst operates in the ignition phase, the discharge can be sustained stably in the γ mode, which also secures the intensified RF discharge burst.

4 Conclusions

The atmospheric pulse modulated RF glow discharge has been parametrically studied on the characteristics of pulse modulation in terms of duty cycle and frequency, which play an important role in the ignition and operation mode of RF discharge burst. The minimum breakdown voltage of RF discharge burst was obtained at the duty cycle and frequency of 20% and 400 kHz, respectively. The operation mode of RF discharge burst was demonstrated by the current voltage characteristics. It shows that the transition voltage reduces with duty cycle below 50% with the fixed modulation frequency of 900 kHz, and grows with modulation frequency above 700 kHz and a fixed duty cycle of 20%. On the other hand, the transition current goes down with increasing the duty cycle and goes up with increasing the modulation frequency, besides for the duty cycle at 20% and modulation frequencies at 800 kHz and 900 kHz, respectively. As the RF discharge burst operates in the ignition phase with a few RF cycles by reducing the duty cycle and elevating the modulation frequency, the stable operation of RF discharge burst of γ mode was achieved.

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