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Characteristics of pulse-modulated radio-frequency atmospheric pressure glow discharge

Jianjun Shi [a,*], Yeqing Cai [a], Jing Zhang [a], Yun Yang [b]

[a] College of Science, Donghua University, Shanghai 201620, PR China
[b] Atlantic Hydrogen Inc., Fredericton, NB, Canada E3B6E9

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ABSTRACT

In this letter, the electrical and optical characteristics of pulse-modulated radio-frequency atmospheric pressure glow discharge are presented. The 13.56 MHz glow discharge is modulated with pulses at repetition frequency of 100 kHz. It is shown that the discharge during power on has similar characteristics to that of discharge without pulsing, except during the discharge ignition and extinguishment phase. The spatio-temporal evolution of discharge in phases of ignition and extinguishment is studied by time-resolved imaging and optical emission spectrograph.

1. Introduction

Increasing studies have recently been reported on nonthermal atmospheric pressure glow discharges (APGDs), motivated by their considerable application potential, such as surface modification [1–3] and biological manipulation [4,5]. These plasma sources can be obtained at atmospheric pressure without need of vacuum system and are commonly generated at kilohertz [5–8] and megahertz [1,3,9–13]. In kilohertz range, the discharge is typically in form of dielectric barrier discharge (DBD) with sinusoidal excitation, in which one or several discharge events with duration from several microseconds to sub-microsecond are ignited during each half cycle. Dielectric barriers are considered to be essential for discharge stability and uniformity [5,6]. In the case of bare electrodes without dielectric barriers, stable glow discharges can be generated by applying nanosecond pulses at repetition frequency of kilohertz [7,8] or sinusoidal excitation at megahertz. In radio-frequency (rf) APGDs, the discharge event is continuum because the electrons and other species cannot follow the oscillation of rf power and are trapped in discharge gap [10,11]. In consequence, the discharge characteristics, compared to DBDs, rf APGDs have higher plasma intensity [12] and lower excitation voltage [13], but the gas temperature is much higher [9,14]. It suggests that rf APGDs can provide extensive plasma chemistry for application efficiency, but the application scope is highly restricted for thermal sensitive application [1–5].

It has been proposed to achieve low-temperature rf APGDs by modulating rf excitation with pulses at repetition frequency up to hundreds of kilohertz [9,15,16]. By controlling discharge generated only at pulse on time, continuum discharge is separated into fractions in time scale. It has been demonstrated the gas temperature, consumption power and discharge reactivity can be manipulated in pulse-modulated rf APGDs. The discharge mechanism may also alter with modulation pulses in terms of repetition frequency and duty cycle [9]. However, detailed discharge mechanism with pulse modulation is still not clear, especially in phases of discharge ignition and extinguishment. Here, an experimental study on pulse-modulated rf DBDs at repetition frequency of 100 kHz in atmospheric helium is presented.

2. Experimental setup

The pulse-modulated rf atmospheric pressure plasma system is shown in Fig.1. The discharge was obtained between two parallel copper round plates with an identical diameter of 20 mm. The surface of each electrode was covered by a square alumina sheet of 25×25 mm^2, 0.5 mm in thickness and 9.0 in relative permittivity. The gas gap between the two dielectrically insulated electrodes was fixed at 2.4 mm and the unit was enclosed in a Perspex box with a helium flow of 5.0 l/min at 760 Torr.

A sinusoidal rf signal at 13.56 MHz and its pulse-modulation signal at 100 kHz were simultaneously generated by a two-channel function generator (Tektronix AFG 3102). The duty cycle of modulation pulses can be set from 1% to 100%. The resulting pulse-modulated rf signal from functional generator was then amplified by a power amplifier (AR 150A100B) before delivered to one of parallel copper electrode (power electrode) via a home-made impedance matching network. The discharge current and applied voltage were measured by a wideband current probe (Pearson 2877) and a wideband voltage probe (Tektronix P6015A), and their waveforms were recorded on a digital oscilloscope (Tektronix TDS 3034C). The plasma images between two dielectrically insulated parallel electrodes were

* Corresponding author.
E-mail address: JShi@dhu.edu.cn (J. Shi).

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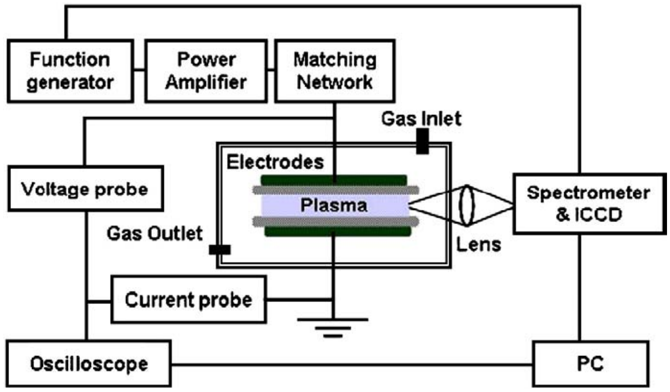

Fig. 1. Schematic diagram of experimental setup.

captured by an intensified charge coupled devices (ICCD) camera (Andor i-Star DH720), which was triggered by the same pulse signal used for modulating the rf signal. Optical emission spectrum was obtained using a spectrometer system (Andor Shamrock) with a focal length of 0.3 m and the gratings of 600 or 2400 grooves/mm. The exposure time of 100 ns or 5 ns is set when taking plasma images and optical emission spectra.

3. Results and discussion

In experiments, the rf DBD was modulated by pulses with repetition frequency and duty cycle of 100 kHz and 50%, respectively. The modulated applied voltage is shown in Fig. 2(a). It clearly shows that the applied rf power can be switched on and off properly, corresponding to the modulation pulses. During rf power on, the discharge is sustained and their current and voltage waveforms are shown in Fig. 2(b). The amplitudes of applied voltage and discharge current are around 500 V and 270 mA, respectively. This current–voltage characteristic is very similar to that of rf discharge without pulse-modulation. It suggests that even with pulse-modulation, the discharge mechanism and characteristics during discharge burst are kept same as that in rf APGDs, which has been studied extensively previously.[9,11–13]

To show the dependence of optical emission from pulse-modulated rf DBDs on duty cycle of modulation pulses, the optical emission spectrum and intensity of specific line were taken with fixed peak value of applied voltage of 500 V. Fig. 3 presents the optical emission spectra in the wavelength range from 200 nm to 800 nm at duty cycle of (a) 1% and (b) 99%, respectively. Although the emission intensity at 99% is about one order magnitude higher than that at 1%, the emission lines shown in spectra are same. The different group of emission lines are corresponding to different species in discharge, such as OH, N, N_2^+, He, O. The existence of these N_2 and O_2 related species is due to the air tightness of discharge unit. In helium discharge with gas mixture of N_2 and O_2, helium metastable atoms play an important role, not only on electron generation by penning ionization, but also on generation of N_2 and O_2 related excited species. [17] It suggests that the intensities of emission lines in optical emission spectrum can be used to indicate the intensity of metastable helium atom in discharge. The dependence of optical emission intensities on duty cycle is presented in Fig. 4. The emission lines at wavelengths of 309 nm, 391 nm, 706 nm and 777 nm, as representation of dominating species in discharge, correspond to OH, N_2^+, He and O, respectively. It shows that the optical emission intensities of N_2^+ and O are much higher than that of OH and He. It is also interesting to mention that the intensity of O grows faster with duty cycle than N_2^+ and their increasing slopes change both at duty cycle of 20%. This slope changing is consistent with results in [9]. The proposed mechanism is that a discharge operation mode transition occurs at repetition frequency and duty cycle of 100 kHz and 20%.

In pulse-modulated rf DBDs, the discharge characteristics are dominated by discharge bursts when rf power is on. Here, one discharge burst in terms of (a) applied voltage, (b) discharge current and (c) plasma image intensity are presented in Fig. 5. The image intensities are obtained from plasma images taken with exposure time of 100 ns at each time instant. The magnitude of discharge current and image intensity start to increase when rf voltage is applied. This is corresponding to discharge ignition phase. It takes ~1.5 μs for discharge current getting to stable state, from ~100 mA to ~280 mA, while the image intensity grows much quicker (~0.4 μs) to its peak value. The difference of time instant obtained from discharge current and image intensity can be explained that location of maximum image intensity transits from central of discharge gap to electrode surface during discharge ignition phase, which is also illustrated by a hump of image intensity before it reaches stable.[9] This transition of

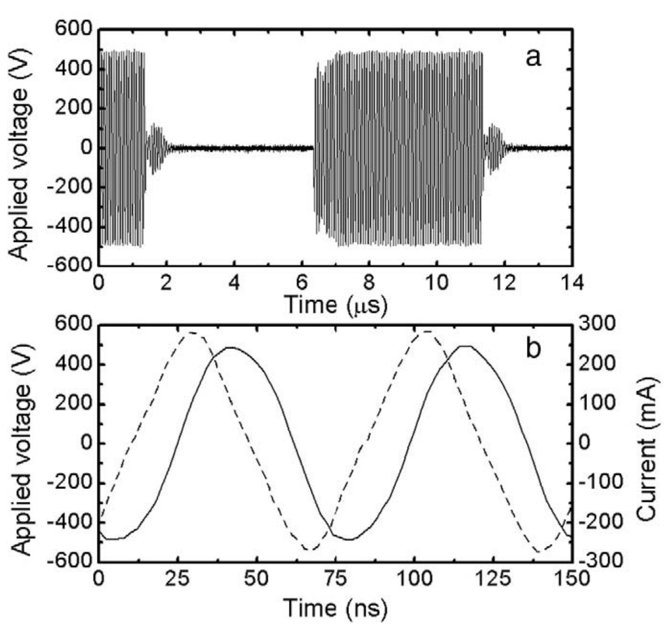

Fig. 2. (a) The applied voltage at frequency of 13.56 MHz is modulated by pulses with repetition frequency of 100 kHz and duty cycle of 50%; (b) the current (dash) and voltage (solid) waveforms during power on.

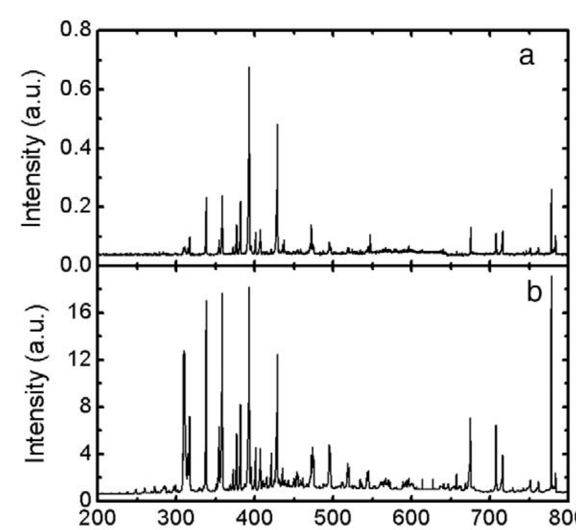

Fig. 3. The spectrums of optical emission from pulse-modulated rf APGD at duty cycle of 1% and 99% are shown in (a) and (b), respectively.