

# Discharge characteristics of glow discharge in atmospheric Argon excited by sub-microsecond high voltage pulses

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## Abstract:

The sub-microsecond high voltage pulse excited glow discharges in atmospheric argon are studied. The discharge is generated between two copper electrodes both covered with ceramic sheets. The electrical characteristics of two discharge events in each voltage pulse in terms of discharge current amplitude and time instant at current peak are investigated on voltage pulse duration at gas gap 1 mm and 2.5 mm, respectively. The time-resolved imaging with 5 ns exposure time is used to demonstrate the spatio-temporal evolution of discharge. It is found that there are two discharge events happened for each pulse voltage. The magnitudes of both discharge currents are almost independence of voltage pulse duration with discharge gap of 1.0 mm. However, the magnitude of second discharge current goes up to the maximum magnitude and then goes down with the voltage pulse duration at 2.5 mm gap. It is proposed that the exhaustion time of space charges in 2.5 mm discharge gap is higher than that in 1.0 mm discharge gap.

## I. INTRODUCTION

Atmospheric pressure glow discharges (APGDs) are studied intensively for their considerable application potential, such as material processing<sup>1-3</sup> and biological manipulation<sup>4,5</sup>. Most focus on APGDs are generated with sinusoidal excitation at frequencies of kilohertz to megahertz, and much less on pulsed APGDs. Normally, the homogenous APGDs can be obtained with dielectric in kilohertz range or with barrier bare electrode in megahertz range. Compared to sinusoidal APGDs, pulsed APGDs tend to have low power consumption and gas temperature with maintenance of relatively high plasma intensity<sup>6,7</sup>. To remove the dielectric barrier, short pulse voltage with time duration below microsecond is used to generate APGDs<sup>8-12</sup>. It is demonstrated that by reducing high voltage pulse duration ultimately to 10 ns, APGDs can be obtained even in air<sup>10</sup> and such short high voltage pulse can significantly increase the plasma density<sup>11</sup>. It was also found that only one discharge event occurred at pulse voltage falling phase with bare metal electrode<sup>8</sup> and two discharge events happened with

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one of electrode covered with dielectric barrier, one at after voltage reaching amplitude and the other during voltage falling phase<sup>9,12</sup>. Here, we studied the discharge characteristics of pulsed APGDs in argon sustained between two parallel electrodes covered by dielectric barriers with pulse duration in the range of several hundreds nanosecond.

## II. EXPERIMENTAL SETUP

The pulsed APGD system employed here had two parallel copper round plates with a diameter of 20 mm. The discharge was enclosed in a Perspex box with an argon gas flow of 3 liter per minute at 760 torr. The surfaces of both electrodes were covered by a square ceramic sheet of 50 x 50 mm<sup>2</sup>, 0.8 mm in thickness and 9.0 in relative permittivity. A trigger signal at repetition frequency of 1 kHz generated by a function generator (Tektronix AFG 3102), was used to trigger the pulse generator (PVX4130), which was powered by a high voltage DC power supply (SPELLMAN SL10P1200). The resulting high voltage (up to 10 kV) pulses with pulse duration from 150 ns to 1 ms was then delivered to

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the top copper electrode. The applied voltage and discharge current were measured by a wideband voltage probe (Tektronix P6015A) and a wideband current probe (Pearson 2877), and their waveforms were recorded on a digital oscilloscope (Tektronix TDS 3034C). The plasma images were taken with an intensified charge coupled devices (iCCD) camera (Andor i-Star DH734), which was also triggered by the same pulse signal from the function generator. Optical emission spectra were measured by an Andor Shamrock spectrometer (SR-750-B1) with a focal length of 0.75m and a grating of 300 grooves/mm.

### III. RESULTS AND DISCUSSIONS

The waveforms of applied pulse voltage and current at gas gap 1 mm are shown in Fig. 1 (a). The pulse voltage of this unipolar voltage pulse is about 3 kV, which has the rising time of about 40 ns, the falling time of about 60 ns and the pulse duration of around 400 ns. It is clearly shown two peaks in current waveform, which means that there are two discharge events happened for each voltage pulse. The first discharge current peak with amplitude of 0.9 A occurs at the time instant of 50 ns. The second discharge current peak with amplitude of 0.8 A happens at the time instant of 360 ns during the voltage falling phase, what its polarity is negative. There is a small hump of current in Fig. 1 can be recognized at the time instants around 10 ns, corresponding to the voltage rising phase, which can be attributed to the contribution from the displacement current. The amplitudes of both humps are much lower than that of current peaks, which means that the current peaks can be considered to be discharge current with neglecting of displacement current. The inserted images of (a) and (b) in Fig. 1 are discharge images at the time instants of first and second current peak with exposure time of 5 ns, respectively. It is interesting to note that the image intensity of first discharge (a) is much greater than that of second discharge (b), although the amplitudes of first current and second current are close to each other. This difference of image intensity suggests the different discharge mechanism of the first and second discharge. The first discharge ignited after pulse voltage reaching its

amplitude and the ignition is depended on magnitude of pulse voltage rather than voltage pulse duration. When pulse voltage is insufficient for gas breakdown directly, the reconstruction of electric field by space charges produced in preionization play an important role on generation of discharge above instantaneous cathode surface. The second discharge is induced at the end of the falling voltage flank without simultaneously consuming energy from the external circuit. The energy needed is provided by the accumulated surface and space charges left by first discharge, which is also found in the previous studies<sup>8</sup>.

By fixing pulse voltage around 3 kV and gas gap at 1 mm, the discharge characteristics in terms of discharge current are shown in Fig. 2 with voltage pulse duration at around 200 ns, 400 ns, 600 ns and 800 ns. It shows that the first discharge keeps magnitude and time instant, which suggests that first discharge is depended mostly on the characteristics during rising phase of voltage pulse, rather than the voltage pulse duration. On the other hand, the second discharge occurs exactly at the voltage falling phase for pulse duration. The peak value of second discharge is also almost same. These results indicate that the characteristics of two discharge event change little by enlarging voltage pulse duration, except the time interval between two discharge events.

The waveforms of current is studied by expanding the voltage pulse duration with fixed pulse voltage magnitude of 3 kV and gas gap at 2.5 mm is shown in Fig. 3. The amplitude of first discharge current keeps and the amplitude of second discharge current goes up to the maximum magnitude of 0.8 A at the pulse duration of 600 ns. To verify the variety with the voltage pulse duration above, Fig.4 shows the amplitude of second discharge current with the voltage pulse duration 200 ns to 800 ns with fixed pulse voltage magnitude of 3 kV at gas gap 1 mm and 2.5 mm, respectively. It is found that the magnitudes of second discharge currents are almost independence of voltage pulse duration with discharge gap of 1.0 mm. However, the amplitude of second discharge current goes up to the maximum magnitude of 0.8 A at the time instant of 650 ns and goes down with the voltage pulse

duration.

A simple model of electrons travel on the background ions is considered here because the electron mobility coefficient ( $394 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ ) is much higher than that of ions ( $1.9 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ ) in atmospheric argon. In the case of 2.5 mm gas gap, just after the extinguishment of first discharge with the positive current, the electrons move towards the top dielectric surface, leaving a region above the bottom electrode surface with background ions and exhausted electrons. This resulted distribution of space charges induce the formation of sheath region above the bottom electrode surface, which can be illustrated by the second discharge image of (b) shown in Fig. 1. Also the residual space charges in discharge gap contribute for the discharge current in second discharge event, which explains the high amplitude of second discharge current. According to the proposed model, in the discharge gap, the amount of space charge in terms of ions reaches the maximum magnitude with the exhaustion of electron and the resulted electric field is enhanced most intensively, which induces the maximum amplitude of second discharge current. With further expanding of voltage pulse duration, the combination of ions and electrons on the top electrode become important and the enhancement of electric field reduces, which explains the declining of second discharge amplitude. It suggests in the pulsed APGDs with ceramic sheet insulated both electrodes, the maximum amplitude of second discharge current can be achieved with exhaustion of electrons generated in the first discharge. However, in the case of 1 mm gas gap, because of the shorter gap, the exhaustion time of ions is lower than that of 2.5 mm discharge gap. Therefore, the time instant of the maximum amplitude of second discharge current may not be observed at 1 mm gas gap.

## SUMMARY

It is found that there are two discharge events happened for each pulse voltage, the first discharge ignited after pulse voltage reaching its amplitude and the ignition is depended on magnitude of pulse

voltage. The second discharge occurs exactly during pulse voltage falling phase and it is ignited with assistance of space charge accumulation on ceramic sheet surface. The magnitudes of both discharge currents are almost independence of voltage pulse duration with discharge gap of 1.0 mm. However, the magnitude of second discharge current goes up to the maximum magnitude and then goes down with the voltage pulse duration at 2.5 mm gap. It is proposed that the exhaustion time of space charges in 2.5 mm discharge gap is higher than that in 1.0 mm discharge gap.

## ACKNOWLEDGEMENT

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**Figures:**

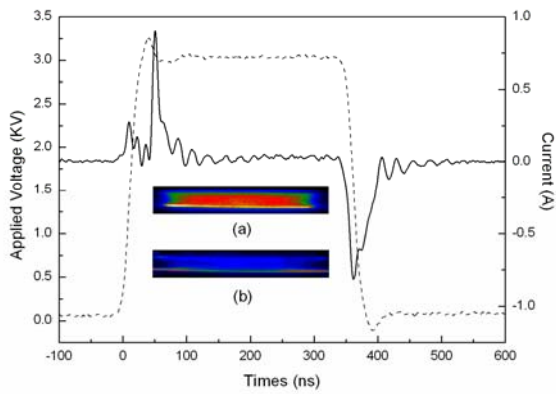


FIG. 1. (Color online) The waveforms of applied pulse voltage (dash) and discharge current (solid). The inserted images of (a) and (b) show discharge appearances taken by iCCD with exposure time of 5 ns.

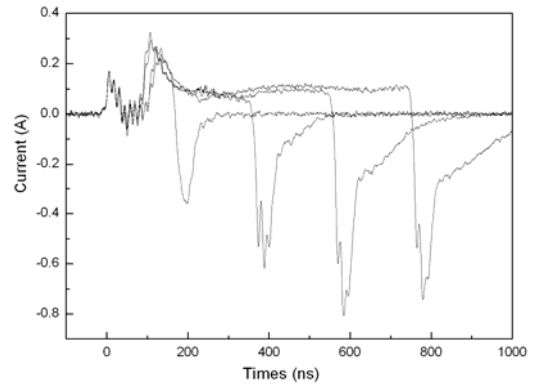


FIG. 3. Waveforms of current on voltage pulse duration with pulse voltage magnitudes around 3 kV at 2.5 mm gas gap.

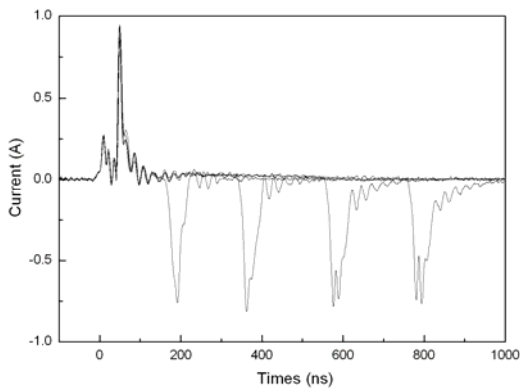


FIG. 2. Waveforms of current on voltage pulse duration with pulse voltage magnitudes around 3 kV at 1 mm gas gap.

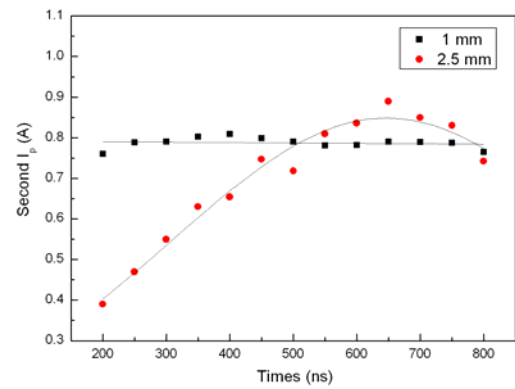


FIG. 4. (Color online) The second current amplitude as a function of voltage pulse duration with pulse voltage fixed at 3 kV at gas gap 1 mm and 2.5 mm respectively.