EXPERIMENTAL STUDY OF MULTIPLE CURRENT PULSES IN ATMOSPHERIC PRESSURE GLOW DISCHARGES

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Abstract

In this paper, we present recent experimental investigations of a glow barrier discharge under different operating conditions. Depending on the frequency and amplitude of the applied voltage, we find regimes with one, two, or more discernible and reproducible current pulses per half cycle. Under certain circumstances, these pulses may be interpreted as successive breakdowns of the inter-electrode gap. We also find regimes where the multi-peak behavior probably represents the dynamics of the cathode layer.

1. INTRODUCTION

Experimental and theoretical studies of atmospheric pressure discharges have been motivated by numerous possible applications for plasma processing such as thin film deposition [1, 2], the reduction of thin oxide layers [3], ozone formation [4], the sterilization of biological samples [5], etc. Commonly used dielectric barrier discharges (DBD) typically operate in an unstable mode and consist of a large number of filamentary micro discharges (short-lived streamer channels). However, under specific conditions, it is possible to obtain a transversely uniform barrier discharge mode at atmospheric pressure [6-8]. This uniform barrier discharge mode can be considered as atmospheric pressure glow discharge (APG). Both discharge forms use a dielectric barrier that limits the lifetime of the discharge through charge accumulation on the dielectric. In this way, the transition of the discharge to a spark discharge is prevented. APG’s seem to be advantageous compared to DBD’s for applications that require uniform plasma treatment such as the deposition of uniform thin films. Unfortunately, APG’s are difficult to maintain and usually have the tendency to switch over into the filamentary DBD mode. APG operation usually requires a special composition of the process gas, for instance, the addition of large quantities of helium. APG’s and DBD’s are usually operated with AC high voltages of several kilovolts and frequencies between 50 Hz up to several tens of kilohertz. The conventional wisdom of the APG mechanism is that during each half-cycle of the applied voltage only one current pulse appears. During the pulse, charge accumulates on the dielectric that reduces the voltage across the gas gap and leads to the extinction of the discharge [7]. The voltage reverses during the next half-cycle that leads to a gap voltage above the breakdown threshold, which results in a new current pulse. However, under certain conditions the discharge evolution can differ from this simplest scenario. In this paper, we present the experimental investigation of the APG discharge behavior in a wide range of operation conditions.

2. Experimental setup
The experimental setup used to study an APG is sketched in Fig. 1. The discharge system was assembled inside a vacuum chamber. The system was pumped to a pressure of \(10^{-1}\) Torr, and then the chamber was filled with helium up to the operating pressure (760 - 600 Torr). A gas flow of several slm was maintained to prevent possible impurity accumulation inside the chamber during operation.

The discharge was generated between two circular planar electrodes. The upper aluminum electrode has 40 mm diameter and is mounted on a teflon holder. The electrode and the electrode holder are covered by a 2.3 mm thick circular glass plate, 14 cm in diameter. A linear operator allows us to vary inter-electrode distance in the range 0-12 mm. The bottom electrode consists of two electrically separated parts. The center electrode part is a 30 mm-diameter mesh. A copper guard ring with an external diameter of 40 mm forms the outer electrode part. The guard ring is used to avoid edge effects, which would otherwise lead to a change of both the barrier and gap capacitance with the gap distance \(d\). The electrode is covered by another 14 cm-diameter, 2.3mm thick glass plate.

Fig. 2 shows the equivalent electrical circuit of the discharge. The electrodes are covered by the glass plates, which form two dielectric barriers with capacitance \(C_d\). The inter-electrode gap is represented by the gap capacitance \(C_g\) in parallel with a non-linear discharge resistance \(R_p(t)\). The upper electrode is connected to the output of a TREK 20/20B high voltage amplifier driven by an external signal generator. The driving frequency can be varied in the range of 50Hz-40kHz. The amplitude of the applied voltage can be varied between 0 and 5kV. The amplifier’s 1/2000-voltage-divider was used to control the applied voltage waveform. The capacitor \(C_m\) was used to monitor the voltage drop across the dielectric barrier (\(U_d\)) separately from the voltage drop across the inter-electrode gap (\(U_g\)). This method relies on the
fact that the ratio between the voltage drops across the barrier capacitance $C_d/2$ and $C_m$ remains constant regardless of the value of the gap capacitance $C_g$. The ratio $U_d/U_m$ was obtained from a set of measurements with zero inter-electrode gap. In this case, the barrier capacitances $C_d/2$ and $C_m$ form a capacitive voltage divider. For a sinusoidal voltage waveform with amplitude $U_0$ and frequency $\omega$, the current amplitude is:

$$I_n = U_n \cdot \omega C_d C_m / (2C_m + C_d).$$

The voltage amplitude across the test capacitor $C_m$ is

$$U_m = U_n \cdot C_d / (2C_m + C_d).$$

Subtracting this voltage from the applied voltage $U_0$, we obtain the voltage drop across dielectric barriers

$$U_d = U_n - U_m = U_n - 2C_m / (2C_m + C_d).$$

Consequently, we have

$$I_d = I_n - I_m = 2C_m / C_d = k.$$

Therefore, the voltage in the inter-electrode gap $U_g(t)$ can be reconstructed from the measured applied $U_a(t)$ and test capacitor $U_m(t)$ waveforms:

$$U_g(t) = U_n(t) - U_m(t) \left(1 + \frac{2C_m}{C_d}\right) = U_n(t) - U_m(t) (1 + k).$$

A 50 Ohm resistor was used to monitor the current flowing through the circuit.

6. Experimental results and discussion

Figure 3 shows typical oscillograms of the voltage and the current waveforms during several half cycles of the alternating applied voltage. At the beginning of each half cycle, the increasing applied voltage leads to an increase of gap voltage up to a breakdown threshold. After the threshold is reached, the discharge starts and an observable current pulse appears. During the pulse, the gap voltage decreases due to the charging of the dielectric barriers. The gap voltage drops up to a value which is too low to sustain sufficient electron generation and the discharge current rapidly falls off. At the next half cycle, the applied voltage reverses and the opposite current peak appears. In this particular case, the discharge operates in the commonly known mode with one current peak per one half cycle.
Figure 4 shows a discharge operating with two current peaks per each half cycle. The main difference to the conditions in fig. 3 is that the operating frequency is lower. In this case, there is enough time for the gap voltage to increase after the first leading current pulse disappears. It is clearly seen that the second pulse appears at about the same threshold level of the gap voltage.

In principle, an infinite set of current pulses may be obtained as long as the power supply is able to provide an increasing applied voltage. Figure 5 shows the regime with six discernible current pulses. Each current pulse leads to a decrease in gap voltage until the discharge current diminishes. The threshold behavior and repeated character of the current pulses indicates that the discharge operates with successive breakdowns during one half cycle. We also note that the leading peak always appears at a
higher voltage threshold than the following peaks do. This seems to be a result of a difference in the initial breakdown conditions. After the first breakdown, some residual electrons and metastable atoms are trapped in the discharge gap that leads to a lower threshold voltage at next breakdown [7,8].

Figure 5 demonstrates also that the shape of the current pulses depends on the applied voltage waveform. In the case of a sinusoidal voltage waveform (fig.5a), the amplitude of the secondary current pulses decreases and their width increases while the derivative of the applied voltage becomes lower. For triangular waveform excitation (fig.5b), the current pulses almost remain identical up to the last one. This effect can be explained considering the current limiting effect by the dielectric barriers. The current through the dielectric barrier is \( I_s = C_d \frac{dU_d}{dt} \) that gives an upper limit for discharge current. The charge deposited on the dielectric surface during single pulse is almost constant and can be estimated as \( q \equiv I_p \cdot \tau \) (here \( I_p \) is the pulse amplitude and \( \tau \) is the pulse half-width).

Assuming \( I_p = I_s \) and \( \frac{dU_s}{dt} = \frac{dU_d}{dt} \) we can estimate the current pulse duration \( \tau \equiv \frac{q}{C_d \left( \frac{dU_d}{dt} \right)^2} \) and pulse amplitude \( I_p \equiv C_d \frac{dU_d}{dt} \). That qualitatively describes the observed behavior.

In our experiments, we also find discharge current peaks, which differ from the ones described above. Figure 6 shows small satellite current peaks, which follow the leading current pulse. Such behavior could not be observed at low excitation frequencies. In the range of 10-25 kHz, we observed different regimes with one, two or three satellite current pulses. These pulses appear at the almost flat part of the gap voltage and therefore are not associated with a gap voltage increase and a new breakdown.

The satellite current pulses can possibly be explained by the dynamics of cathode charge sheath. At the final stage of the leading current pulse, the electric field is no longer high enough to sustain steady state electron generation. The electric field in the gap still drives the electron current in the quasi-neutral plasma. This current has to be sustained by a cathode sheath expansion towards the anode. This leads to a redistribution of the electric field between the plasma and sheath regions while the total voltage drop across the gap remains nearly constant. Consequently, both the voltage drop across cathode sheath and
the sheath length increase. In this way, the avalanche multiplication of electrons in the sheath can rapidly increase and produce a significant current response. Qualitatively the same results were also obtained in [9] by means of numerical simulations.

7. Concluding remarks

The experimental results showed that the behavior of the uniform barrier discharge mode strongly depends on the operating conditions. Depending on the frequency and amplitude of the applied voltage, the discharge switches from a one-pulse to a multiple current pulse regime. We also showed that the current pulse dynamics is governed by the derivative of the applied voltage. Therefore, the characteristics of the power supply and the external circuit can strongly affect the barrier discharge behavior.

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References