Cathode Plasma Radiation in a Repetitive Pulsed Diffuse Discharge in an Inhomogeneous Electric Field

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Authors' contributions

This work was carried out in collaboration between all authors. The author EKhB carried out the experiment, made the estimations and wrote with the author VFT the first draft of the manuscript. The authors AGB and MVE carried out the experiments. All the authors read and approved the manuscript.

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ABSTRACT

The radiation produced by nanosecond repetitive pulsed discharges in nitrogen, air, and argon was studied, including its study with a CCD camera. It is shown that within the first nanosecond, diffuse plasma covers the lateral surface of a conical cathode at relatively low electric field strength (~10^5 V/cm). The nature of this phenomenon is discussed. Photos of the discharges in nitrogen, air, and argon in an inhomogeneous electric field with different cathode materials and at different pressures are presented.

Keywords: Runaway electron preionized diffuse discharge; photoemission; repetitive pulsed mode; CCD camera.

1. INTRODUCTION

The runaway electron preionized diffuse discharges (REP DDs) in gases at increased pressures have long attracted the attention of researchers, finding more and more practical applications [1, 2]. The generation of runaway electrons and X-rays in an inhomogeneous electric field allows forming diffuse discharges without any additional gas preionization source. This type of discharge was obtained both in the single pulse mode [1] and in the repetitive pulsed mode [2]. The objective of the work is to investigate the repetitive pulsed discharges in nitrogen, air, and argon with conical cathodes made of stainless steel and duraluminium.

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2.1 Experimental Details

For initiation of a discharge, we used a FPG-60 generator which produced voltage pulses of negative polarity with a voltage rise time of 2–3 ns and FWHM of 4–5 ns. In the experiments, the amplitude of the incident voltage wave was normally 10–15 kV; the pulse repetition frequency was ~500 Hz. The diffuse discharge was ignited between a conical cathode (vertex angle 30°, vertex rounding-off radius ~0.1 mm) and a plane anode located in a discharge chamber. The electrode separation was 4 mm. Voltage increase (or interelectrode gap decrease) resulted in the formation of a spark discharge while voltage reduction (or interelectrode gap increase) caused a transition into a pulsed corona discharge. The pressure in the discharge chamber was varied from 1 to 100 kPa. The voltage across the discharge gap was measured with a capacitive divider. The discharge current was measured with a shunt composed of chip resistors. Photos of the discharge were taken with an HSFC-PRO four-channel CCD camera and with a SONY A100 digital camera. The high (subnanosecond) timing accuracy of the pulse generator and CCD camera allowed us to take photos of the discharge glow in the gap within the first nanosecond after applying a voltage pulse to the gap.

2.1 Methodology

A few words about the nature of the phenomenon considered in the paper – photoelectronic emission [3]. When different materials are irradiated with the light, electrons can be liberated from the material if the photon energy is higher than the work function for a given material. The work function determines the long-wavelength edge of the photoeffect and for most substances it lies in the visible and near-ultraviolet region of the spectrum (1.5-5.6 eV, 800-220 nm). Discharge radiation contains various quanta including those capable of causing photoelectronic emission from the cathode material. Radiation efficiency in regard to photoeffect is characterized by a quantum yield – a number of the emitted electrons per a quantum. For many metals [3], the quantum yield in the visible and near-ultraviolet regions of the spectrum is of the order 10^{-3}, and in the far ultraviolet it is of the order $10^{-2} – 10^{-1}$.

3. RESULTS AND DISCUSSION

Figure 1 shows photos of the discharge taken with the digital camera. Each photo presents integral discharge glow in 250 pulses. It is clearly seen that the discharge glow covers part of the lateral surface of the cathode cone. The discharge glow at the lateral surface of the cathode can be diffuse or represent bright spots which can merge in the integral photos. The discharge plasma covered the lateral surface on all sides. This was seen in the integral photos made from the edge (the photos are not presented in the paper). These photos as well as the others obtained in the work show that with the duraluminium cathode, bright spots at the vertex of the cone and its lateral walls appear in a wider range of pressures. The number of bright spots in the discharge in argon is much larger than that in the discharges in air and nitrogen, all other things being equal. As the pressure is increased, both the diffuse discharge glow and its individual spots at the lateral wall of the cone shift to the cone vertex, and the radiation intensity of the discharge plasma at the lateral walls thus decreases. At equal pressures, the radiation intensity in nitrogen is higher than that in air, and the diffuse plasma covers a larger part of the lateral surface of the cone.

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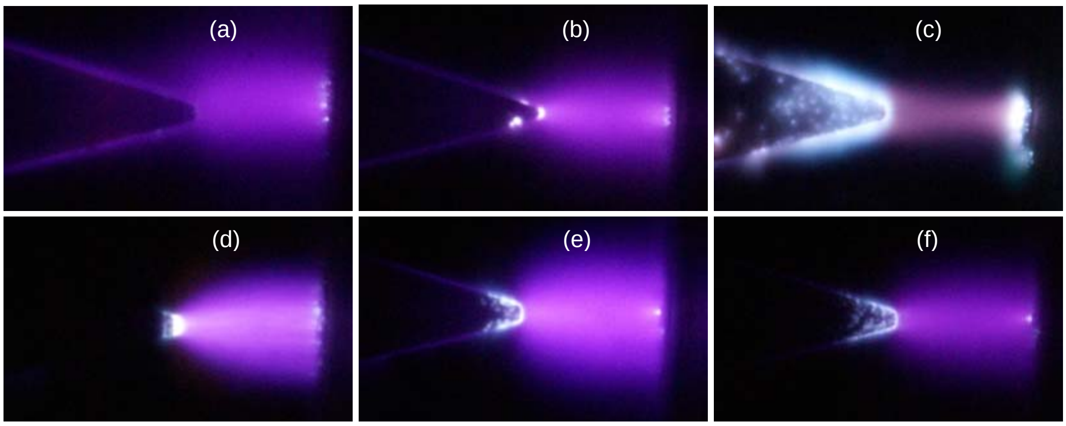

Fig. 1. Photos of gas discharge plasma glow. Pulse repetition rate is 500 Hz. Interelectrode gap is 4 mm, the cathode is on the left side of the photos. There is the stainless steel cathode in all the photos except (b). (a) 12 kPa pressure air. (b) 12 kPa pressure air, duraluminium cathode. (c) 12 kPa pressure Ar. (d) 50.5 kPa pressure N_2. (e) 25.3 kPa pressure N_2. (f) 25.3 kPa pressure air.

Figure 2 shows photos of the discharge glow taken with the CCD camera with indication of the time intervals at which they were taken after the rise of the glow in the gap. It is seen that even within the first nanosecond of the discharge operation, the glowing plasma covers the cathode surface extending to more than a millimeter from its pointed edge. At the next stages of the discharge operation (2–4 ns and 5–7 ns), this glow is also present but it is hardly visible against the bright cathode spots and brighter plasma glow in the gap. Note that the time at which cathode spots appear depends on the gas kind and pressure. Under our experimental conditions, the most rapid formation of cathode spots was observed for the gap filled with argon and with duraluminium cathode.

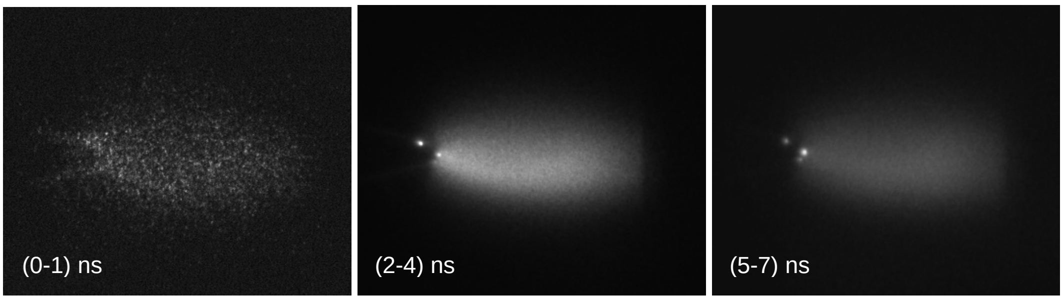

Fig. 2. Photos of discharge glow in N_2 shot per pulse. 50.5 kPa pressure N_2. Interelectrode gap d=4 mm. Pulse repetition rate is 400 Hz.

Here the question arises: What is the factor that assists the ignition of the discharge at the lateral surface of the cathode within the first nanosecond? Calculation of the electric field by the ELCUT Student 5.10.1.1140 program package [4] shows that the maximum macroscopic electric field at the cathode vertex is $7.6 \cdot 10^5$ V/cm (the task was adapted to a small number of mesh nodes). At the maximum voltage across the discharge gap, the electric field strength at the cathode surface 0.5 mm away from the cathode vertex is $3 \cdot 10^5$ V/cm, and 1 mm away from the cathode vertex, it is $1.9 \cdot 10^5$ V/cm. With this difference in the electric field strength at

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the cone vertex and at the lateral surface of the cathode, the field emission current from the vertex of the cone is orders of magnitude higher than the field emission current from its lateral surface [5]. This means that the electrons initiating the gas discharge arise at the cone vertex, and hence, the field emission from the lateral surface of the cathode takes no part in the discharge ignition. Let us assess the possibility of initiation of the discharge from the lateral surface of the cathode by the ions generated near the cone vertex (where the electric field strength is maximal and where the gas discharge plasma primarily arises). For this assessment, we use the formula for the drift velocity of positive ions in an electric field [5]: $v = C\cdot(E/p)^{0.5}$, where E is the electric field strength, p is the gas pressure in torr, and $C = 1.1\cdot10^4$ for nitrogen. For the nitrogen pressure p = 50.7 kPa, the drift velocity of positive ions in the electric field at the cathode vertex ($E = 7.6\cdot10^5$ V/cm) is $4.9\cdot10^5$ cm/s, and the distance traveled by them in 1 ns is 4.9 μm. Thus, it is obvious that in a time of 1 ns, the ions fail to travel any large distance from the cathode vertex to the lateral surface of the cathode and to contribute to the initiation of the discharge.

4. CONCLUSION

We think that the plasma covering the lateral surface of the cathode is due to the ignition of the discharge through photoemission from the lateral surface. The photoemission from the lateral surface is caused by resonance radiation of the discharge plasma developing from the cone vertex [6] and possibly by characteristic radiation of the gas due to runaway electrons [7].

ACKNOWLEDGEMENTS

We acknowledge financial supports from Russian Foundation for Basic Research (Project No. 12-08-00105-a).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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