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APPLIED PHYSICS

Uniform Action of Plasma of a Nanosecond Pulsed High-Voltage Discharge on the Surface of a Flat Anode

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Abstract—The results of an experimental study of the effect of a plasma of a nanosecond pulsed high-voltage discharge in air at atmospheric pressure, excited in a sharply nonuniform electric field, on the surface of a flat-grounded electrode are presented. It is shown that at relatively large interelectrode distances between the pointed cathode and the flat anode, a diffuse discharge is implemented, which ensures a uniform action of the discharge plasma on the anode surface.

Keywords: diffuse discharge, spark discharge, spatial structure of the discharge, electrode erosion

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INTRODUCTION

Low-temperature plasma and its practical applications are currently attracting considerable attention from researchers. The range of its applications includes modification surfaces of materials, industrial waste treatment, biotechnology and plasma medicine, catalysis, plasma cutting, welding, plasma initiation of ignition and combustion, plasma aerodynamics and other fields of modern industry, medicine, and agriculture. A large number of publications, including monographs and reviews [1–8], are devoted to this topic. The use of low-temperature plasma is currently also considered as one of the effective approaches to reduce diseases caused by pathogenic viruses, including COVID-19 [9]. Plasma generation using electric discharges of various types is the simplest and most technologically advanced method in laboratory and industrial conditions [1–4]. Fast pulsed discharges with a voltage rise rate of 100 V/ns and higher make it possible to form a plasma with a higher density of chemically active particles, which ensures higher efficiency of technologies based on gas-discharge plasma [10]. From this point of view, nanosecond high-voltage discharges in a nonuniform electric field, in which the electron runaway effect is implemented, are of particular interest [11–13]. This provides the possibility of implementing a diffuse discharge at an increased gas pressure, including atmospheric one, and, accordingly, generating a dense chemically active low-temperature plasma in the discharge gap. The formation mechanism, breakdown dynamics, and main properties of the discharge plasma of this type are described in [14].

The impact of a high-voltage discharge plasma in air at atmospheric pressure on the anode was studied earlier both in pulsed and repetitively pulsed discharge modes. In [15–20] devoted to the study of the dynamics and structure of a pulsed spark discharge, as well as the effect of the discharge plasma on a grounded electrode, it has been established that current microchannels with a diameter of one to tens of micrometers are formed near the point electrode already at the initial stage of the discharge development, reaching a flat grounded electrode as the gap is passed. An erosion microstructure is recorded on the grounded electrode in the impact zone, which correlates with the structure of current microchannels. Microcraters with diameters from 5 to 35 μm were found in the impact zone [20].

Obviously, this mode of exposure is undesirable in cases where uniform processing/modification of the material surface are necessary. Pulsed and repetitively pulsed nanosecond discharges in an inhomogeneous electric field formed by runaway electrons are promising from the point of view of achieving the uniformity of surface treatment of materials. As already noted, in this case, it is possible to form a diffuse discharge at atmospheric pressure, which is important in practice. In [19, 21, 22], the spatial structure of a diffuse pulsed and repetitively pulsed nanosecond discharge in a nonuniform electric field formed in air at atmospheric pressure and the effect of the plasma of this discharge on the surface of a grounded electrode were studied. It was found that a diffuse form of the discharge is implemented when the excitation conditions are optimized. At the same time, bright spots may or may not be

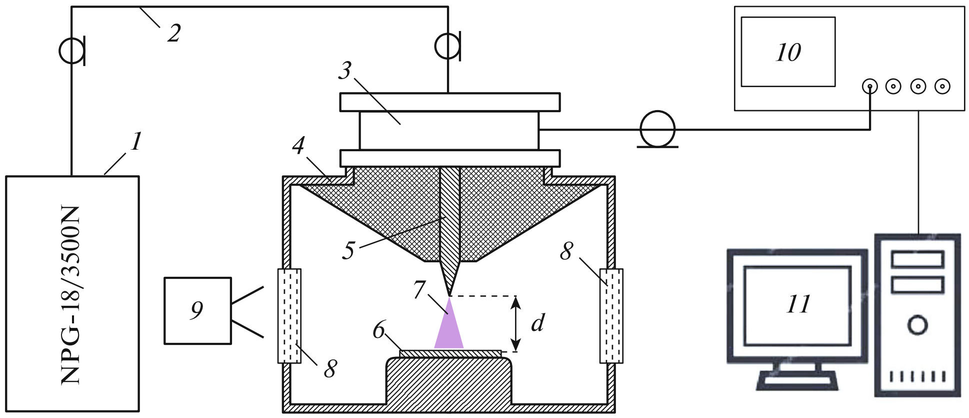

Fig. 1. Block diagram of the experimental setup: (*1*) NPG-18/3500N generator; (*2*) high-voltage cable; (*3*) reverse current shunt; (*4*) discharge chamber; (*5*) cathode; (*6*) anode; (*7*) discharge zone; (*8*) chamber windows; (*9*) Sony A100 camera; (*10*) TDS MDO3102 oscilloscope; (*11*) computer.

observed on the surface of the grounded electrode, depending on the size of the interelectrode gap, polarity and amplitude of the voltage pulse. In the first case, an erosive microstructure of the surface of the grounded electrode is observed in the impact zone. In the second case, the impact of the discharge plasma on the surface of the grounded electrode is less intense and is analyzed by the state of the soot layer deposited on the surface of the grounded electrode. It occurred that after exposure to 10 pulses, the soot layer demonstrates a change in the color of the surface without the continuous damage to the layer.

This work is a continuation of [19] and is devoted to the study of a single action of the plasma of a nanosecond pulsed high-voltage discharge on the state of the surface of a flat grounded electrode under various exposure modes.

EXPERIMENTAL

Figure 1 shows a block diagram of a setup, using which the experiments were carried out. It included a NPG-18/3500N high-voltage generator [23] (*1*), which was started in the single-pulse mode, a high-voltage cable with a characteristic impedance of 75 Ω (*2*), a low-inductance reverse current shunt made of chip resistors (*3*), a discharge chamber (*4*) with an electrode block of a potential cathode (*5*) and a flat grounded anode (*6*), Sony A100 digital camera (*9*), TDS oscilloscope MDO3102 (bandwidth of 1 GHz, sample rate of 5 GHz) (*10*), and computer (*11*). The front duration, FWHM, and the amplitude of voltage pulses in the incident wave were ≈3 ns, ≈6 ns, and ≈18 kV, respectively. The cathode was made in the form of a steel rod 6 mm in diameter with a pointed end with an angle at the top of ≈50° and a curvature radius of the top of ≈0.2 mm. A grounded copper plate 25 mm in diameter and 1 mm thick served as the anode. The interelectrode gap *d* varied from 2 to 10 mm. The discharge was formed in the interelectrode gap in air at atmospheric pressure when the generator was turned on once. To increase the sensitivity of the autograph method (autographs are traces of the impact of the discharge plasma onto the anode) a soot layer ≈10 μm thick was deposited on the surface of the copper plate facing the cathode [22]. When calculating the current and voltage on the discharge gap, a signal from the reverse current shunt was used, as well as previously known information about the time shape and amplitude of the pulse formed by the (incident) voltage wave generator. The shape of the discharge was recorded with a Sony A100 camera through the side windows in the discharge chamber (*8*). The state of the anode surface after a single exposure to the discharge plasma at various *d* values was determined using a LOMO MIKMED-1 microscope.

RESULTS AND DISCUSSION

During the experiments, the *d* value was varied from 2 to 10 mm, oscillograms of current pulses from the reverse current shunt were recorded, the form of the discharge and traces of the effect of the discharge plasma on the anode were photographed when the generator was turned on once. The energy reserve of the voltage pulse in the incident wave according to the estimate based on the data on the time shape and amplitude of the voltage pulse, as well as the impedance of the high-voltage cable, was ≈23 mJ. It should be noted that because of the mismatch between the gas-discharge load and the power supply circuit, a series of reflected pulses arrived at the discharge gap in addition to the first voltage pulse. According to the estimate, the energy input into the discharge plasma from the first voltage pulse at $d = 6$ mm is ≈16 mJ. This indicates that the effect of the discharge plasma on the anode occurs predominantly during the first of the voltage pulses arriving at the discharge gap. At *d* values

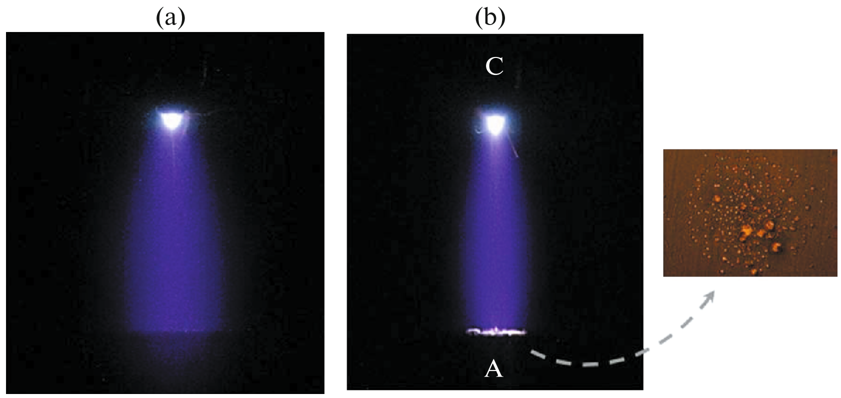

Fig. 2. Appearance of the discharge at $d = 6$ mm in the case of an anode made of a copper plate (a), a copper plate covered with a soot layer (b); impact traces on the anode ((b), inset on the right). C, cathode; A, anode.

≤4 mm, a spark discharge was observed, which resulted in the impact traces on the surface of a copper plate coated with a soot layer and on the surface of a plate without a soot layer. The outer diameter of the zone with impact traces observed with a microscope is ≈5 mm. The diameter of the zone within which the most intense action is carried out, leading to the removal of the soot layer from the surface of the plate and the appearance of craters 50–60 μm in diameter on the surface of the copper plate, is ≈1 mm. Partial removal of the soot layer from the surface of the plate in places of the current passage in channels with a diameter of 20–50 μm is observed in the annular zone with inner and outer diameters of ≈1 and ≈2 mm, respectively. At $d > 4$ mm, a diffuse discharge is implemented, the characteristic view of which is shown in Fig. 2. The intensity of the glow and the amplitude of the discharge current decrease when the interelectrode gap increases. At $d = 10$ mm, the breakdown is hampered and is observed in approximately 50% of cases. Accordingly, when d increases, the intensity of the effect of the discharge plasma on the anode surface is reduced. As follows from Fig. 2, at $d = 6$ mm, the presence of a soot layer on the anode surface causes the appearance of anode spots, and they do not arise on the anode surface without a layer soot. It can be seen from the figure that the diffuse form of the discharge is implemented in both cases.

During the analysis of the anode surface, it was established that traces of a single exposure are not visible on a plate without a soot layer. At the same time, it can be observed on the surface of the plate covered with a soot layer in the zone of the most intense impact in the form of a circle with a diameter of ≈2 mm that the soot layer is removed from the surface of the plate at the points of the current passage in channels with a diameter of 20–150 μm (right-hand inset in Fig. 2b). In this regard, it can be assumed that the microchannel structure of the discharge under these conditions can be formed when the ionization wave approaches directly the anode surface covered with a soot layer or because of the instability of the ionization wave front at its propagation in the gap [16–18]. It can also be assumed that the microchannel structure of the discharge is also implemented in the case when there are no anode spots and, when viewed from the side, the discharge glow is diffuse (Fig. 2a). An increase in d to 8 and 10 mm leads to a weakening of the effect of the discharge plasma on the anode surface. In this case, anode spots do not appear including on a plate covered with a soot layer. In the impact zone with a diameter of ≈2 mm on the soot layer covering the plate, slight changes in the surface structure of the layer are observed without its destruction. It follows from this that the discharge mode, implemented in a single pulse at $d \geq 8$ mm, provides a uniform effect of the discharge plasma on the anode surface.

CONCLUSIONS

The state of the surface of a flat grounded electrode upon a single exposure to a plasma of a nanosecond pulsed high-voltage discharge in air at atmospheric pressure was studied under various exposure modes. It has been established that by increasing the interelectrode distance to 8–10 mm, it is possible to reduce the intensity of exposure and implement the mode of uniform treatment of the material surface in a separate pulse. At an interelectrode distance of 4 mm or less, a spark discharge was observed, which led to the formation of an erosion structure on the surface of the grounded electrode, which consisted of a set of craters with a diameter from unity to ten microns.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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