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LABORATORY TECHNIQUES

Generators of Diffuse Plasma at Atmospheric Pressure

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Abstract—Devices that form low-temperature diffuse nanosecond-discharge plasma in a flow of various gases at the atmospheric pressure are described. To form diffuse plasma, negative voltage pulses with an amplitude of several tens of kilovolts and a duration of 5 ns were fed to a point–plane gap in the pulse–periodic mode. By varying the geometry of the discharge gap, the shape of the cathode, and the composition of the working gas, it is possible to obtain plasma with a wide range of parameters and modify the surfaces of various materials with areas of up to several tens of square centimeters.

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Low-temperature nonequilibrium plasma is widely used in modern micro- and nanoelectronics, medicine, and biomedical technologies. Diffuse discharges that are initiated (preionized) by runaway electrons (REPDDs) in various atmospheric-pressure gases are the most promising sources of low-temperature plasma among the available ones. This allows the technological process of modifying the surface properties of various materials to be substantially simplified.

The generation of a discharge of this type usually occurs in a highly inhomogeneous electric field, which is formed by electrodes with a small radius of curvature, when voltage pulses with an amplitude of more than 100 kV, a duration of units–tens of nanoseconds, and a subnanosecond front duration are fed to the electrodes [1]. Electrodes with a small radius of curvature provide the electric-field enhancement, as a result of which the generation of runaway electrons and X-ray radiation is observed, thus leading to the discharge-gap preionization and ensures a diffuse character of discharges in gases at elevated pressures.

Such sources make it possible to produce dense nanosecond-discharge plasma with a specific power of the energy deposition of several hundred megawatts per cubic centimeter at low pulse-repetition frequencies (<10 Hz) [2]. The electron concentration and temperature in REPDD plasma depend on the amplitude of the voltage pulse and its time characteristics, as well as on the geometry of the discharge gap. At the atmospheric pressure of helium and nitrogen, the average electron temperature in REPDD plasma that is formed by a RADAN-220 generator is several electronvolts [3], while the electron concentration is $\sim 10^{15}$ cm^{-3} [3] and $\sim 10^{14}$ cm^{-3} [4], respectively. Inert gases [5], air, SF_6 gas [6], and methane [7] can also be used as the working gases.

The possibility of using the REPDD mode for creating diffuse-plasma sources that operate at a pulse repetition frequency of up to 2 kHz was shown in [8]. The maximum electron concentration in volume-discharge plasma at the atmospheric pressure is reached at the center of the interelectrode gap. Its values are $\sim 2 \times 10^{16}$ cm^{-3} in argon, $\sim 4 \times 10^{14}$ cm^{-3} in nitrogen, and $\sim 3 \times 10^{14}$ cm^{-3} in air. The maximum electron temperatures are 3.5 eV in nitrogen and 3 eV in air. Moreover, diffuse discharges may generate plasma channels, which overlap in the gas-discharge gap, without the formation of sparks, thus providing satisfactory uniformity of the effect on the treated surface at the atmospheric pressure.

Hence, sources that are able to generate low-temperature plasma on the basis of REPDDs in various atmospheric-pressure gases are characterized by highly active plasmochemical processes and allow the possibility of varying the electron density, temperature, and degree of ionization, thus allowing these processes to be used for modifying the surfaces of various materials, including thermosensitive substances.

The objective of this study was to develop facilities for processing surfaces of various metals and dielectrics by dense plasma at the atmospheric pressure of air and other gases.

One of the designs of a diffuse-plasma generator, which allows modification of the surfaces of flat circular samples with diameters of up to 10 mm, is shown in Fig. 1.

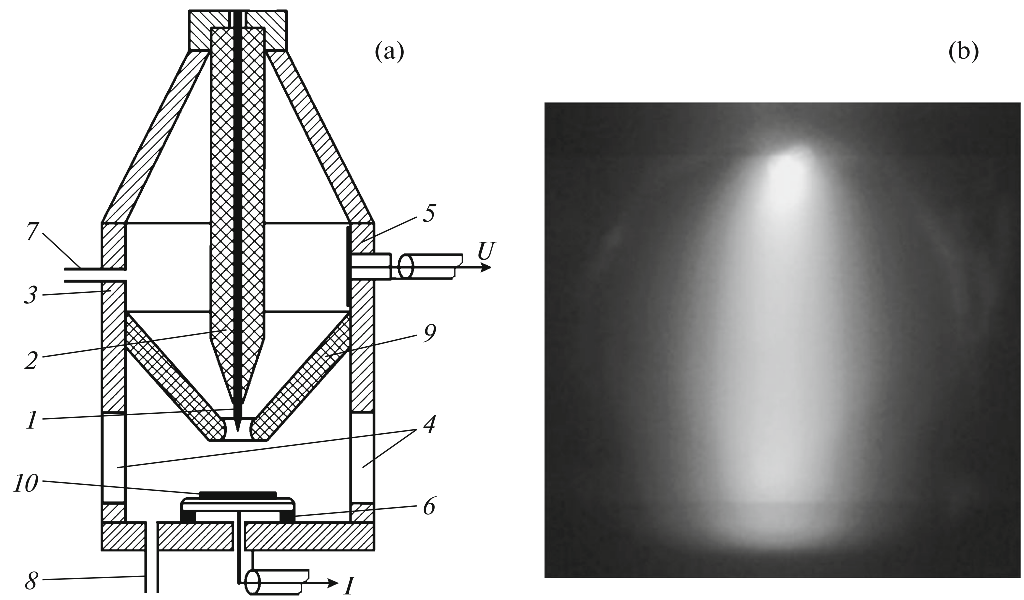

Fig. 1. (a) The design of the plasma generator no. 1: (*1*) pointed cathode, (*2*) caprolon insulator, (*3*) metal housing, (*4*) quartz windows, (*5*) capacitive divider, (*6*) current shunt, (*7*) gas puffing, (*8*) gas exhaust, (*9*) nozzle, (*10*) anode; (b) a photograph of the glow of diffuse discharge plasma in a nitrogen flow.

The generator contains a pointed cathode (*1*) with a small radius of curvature, which was manufactured from tool steel and pressed into a caprolon insulator (*2*). The operation of the generator was tested visually through 20-mm-diameter quartz windows (*4*), which were encased in a metal frame (*3*), as well as by measuring the voltage across the discharge gap and the discharge current using, respectively, a capacitive divider (*5*) and a shunt (*6*), which was manufactured from low-inductance chip resistors.

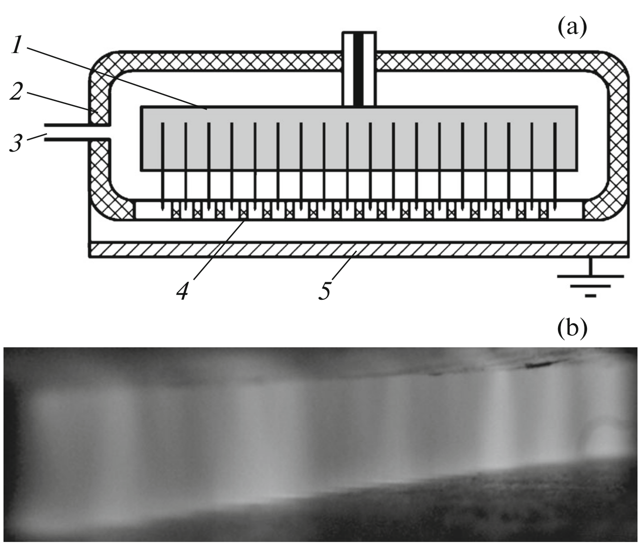

Fig. 2. (a) The design of the plasma generator no. 2: (*1*) pointed cathode, (*2*) polyvinyl chloride housing, (*3*) gas puffing, (*4*) slot for plasma emission, (*5*) anode; (b) a photograph of the diffuse plasma glow taken at an angle of 45° to the axis of the discharge gap.

The working gas was supplied to the discharge chamber through a hole (*7*); the outlet holes (*8*) are located in the bottom part of the frame (*3*). A gas flow that was directed along the cathode was formed by a conical caprolon nozzle (*9*). The distance from the pointed cathode to the flat anode (*10*), on which a modified sample was formed, could be varied in a range of 1–20 mm. Figure 1b shows a photograph of the glow from diffuse discharge plasma in a nitrogen flow at a circulation speed of 5 L/min, a voltage-pulse repetition frequency of 40 Hz, and an interelectrode gap of 12 mm. The cathode is in the top position.

A generator of another design (Fig. 2) allows modification of the surfaces of flat samples with dimensions of 10 × 130 mm. The cathode (*1*) with a length of 130 mm is manufactured of 18 steel needles that are positioned in a row at a distance of 8 mm from one another. The generator case is manufactured from a 100-mm-diameter polyvinyl chloride tube (*2*) with union nipples (*3*) for puffing the working gas. In the lower part of the tube, there are holes (*4*) under each needlelike electrode, through which gas-discharge plasma is blown out. The distance between the cathode (*1*) and flat anode (*5*) on which a sample is placed varies from 10 to 20 mm.

The discharge shape (Fig. 2b) has the form of luminous diffuse conical jets with vertices near the needle points and with overlapping bases. The distance from each needle to the anode is adjusted so as to provide an identical glow intensity for all jets and uniform overlapping of the bases of the conical channels, thus

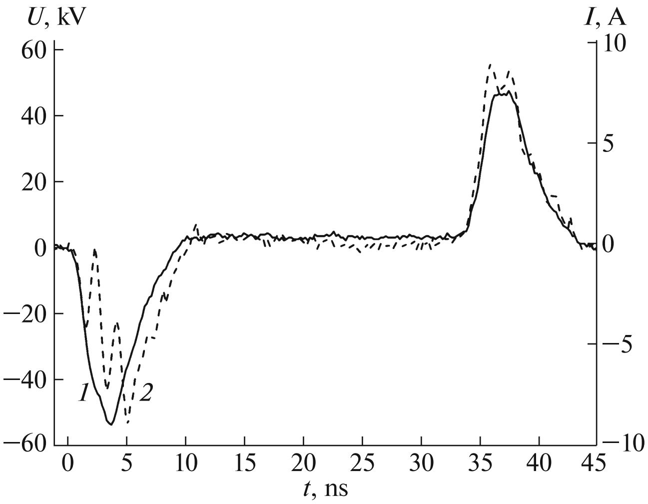

Fig. 3. Characteristic oscillograms of the operation of generator no. 1 that was powered by the GIN-100-1 source: (*1*) voltage across the discharge gap and (*2*) discharge current.

ensuring the uniform illumination of the modified surface.

The generators were powered by GIN-100-1 [9] and NPG-18/3500N [10] high-voltage sources, which formed negative-polarity voltage pulses with amplitudes of incident waves of 14–52 kV, durations of 3–5 ns, and repetition frequencies of up to 3.5 kHz when operating into a matched load.

Depending on the interelectrode gap and the voltage-pulse amplitude, the plasma-formation modes can be varied. Figure 3 shows oscillograms of the discharge current and the pulse voltage across the discharge gap for large gaps, which were measured with the help of the current shunt and the capacitive voltage divider on generator no. 1 using a Tektronix TDS-3034 oscilloscope.

According to Fig. 3, voltage pulses are partially reflected from the load (discharge gap) and then from the voltage source (in this case, the pulses change their polarity due to a substantial decrease in its internal resistance) and then repeatedly arrive at the discharge gap. At large gaps, the amplitude of the second voltage pulse is comparable with the amplitude of the first pulse. The time within which the reflected pulse returns to the discharge gap is equal to the time of its double trip along the length of the high-voltage cable through which the voltage is fed. Thus, a sequence that consists of the main pulse from the generator and several reflected pulses of alternate polarity arrives at the gap. The deposited pulse peak power was 475 kW in the first pulse and 420 kW in the second pulse. Consequently, apart from UV radiation, vacuum UV radiation of diffuse-discharge plasma [11], and the characteristic radiation with low-energy X-ray quanta [12–14], both an electron beam and positively charged ions exert an effect on the flat electrode.

As the interelectrode gap decreases the deposited power increases in the first pulse and decreases in the second pulse.

The described generators allow the generation of diffuse low-temperature discharge plasma in a flow of various gases at atmospheric pressure. This is of great practical importance in investigations of the influence of plasmochemical processes on the surfaces of various materials.

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