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PLASMA, HYDRO- AND GAS DYNAMICS

Formation of Ball Streamers at a Subnanosecond Breakdown of Gases at a High Pressure in a Nonuniform Electric Field

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The formation of a diffuse discharge plasma at a subnanosecond breakdown of a “cone–plane” gap filled with air, nitrogen, methane, hydrogen, argon, neon, and helium at various pressures has been studied. Nanosecond negative and positive voltage pulses have been applied to the conical electrode. The experimental data on the dynamics of plasma glow at the stage of formation and propagation of a streamer have been obtained with intensified charge-coupled device and streak cameras. It has been found that the formation of ball streamers is observed in all gases and at both polarities. A supershort avalanche electron beam has been detected behind the flat foil electrode in a wide range of pressures in the case of a negatively charged conical electrode. A mechanism of the formation of streamers at breakdown of various gases at high overvoltages has been discussed.

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INTRODUCTION

The streamer mechanism of a breakdown of gases at high pressures and high overvoltages is actively studied [1–13]. This mechanism explains a comparatively fast breakdown of a gap at overvoltages of tens of percent [1–3]. The breakdown at overvoltages of 500% and more at a negative polarity of the electrode with a small radius of curvature is classified as a breakdown initiated by runaway electrons [4, 5]. Under these conditions, a diffuse discharge is ignited and can be transformed to a spark discharge under certain conditions [4, 14]. However, a diffuse discharge at atmospheric pressure of the gas and above also appears at a positive polarity of the electrode with a small radius of curvature [14, 15]. Under these conditions, runaway electrons move toward the positively charged pointed electrode and cannot preionize the gas ahead of the front of a streamer. The simulation of the breakdown in a nonuniform electric field shows that the properties of streamers can be quite accurately described by specifying the initial electron density in a gap [9, 12].

Ball streamers were detected in a number of experimental studies of the breakdown in nitrogen and air at atmospheric pressure and at high reduced electric field strength

$$E/p = U/pd \approx 100 \text{ kV/(cm Torr)},$$

where E is the electric field strength, p is the pressure, U is the voltage across the gap, and d is the width of the interelectrode gap [6, 16, 17]. However, the mechanism of formation of such streamers has not yet been revealed.

The aim of this work is to study the formation of streamers at the breakdown of cone–plane gaps filled with molecular and atomic gases at high overvoltages and at both polarities with a high-speed shooting method, as well as to determine the main characteristics of the mechanism of their formation under these conditions.

EXPERIMENTAL SETUP AND METHODS OF MEASUREMENTS

Experiments were performed at the setup whose layout is shown in Fig. 1.

Three FID generators (Antares, St. Petersburg) were successively connected to a gas-discharge chamber. Two generators (GIN-100-1, $U \approx 25$ kV, $\tau_{0.5} \approx 3$ ns, and $\tau_{0.1-0.9} \approx 2$ ns and GIN-55-01, $U \approx 55$ kV, $\tau_{0.5} \approx 1$ ns, and $\tau_{0.1-0.9} \approx 0.7$ ns) formed negative voltage pulses, whereas the third generator (GIN-50-1, $U \approx 25$ kV, $\tau_{0.5} \approx 10$ ns, and $\tau_{0.1-0.9} \approx 2$ ns) formed positive voltage pulses. Voltage pulses were applied across the cone–plane gap with a nonuniform distribution of the electric field strength. The discharge chamber was filled with air, nitrogen, methane, hydrogen, argon, neon, or helium. The pressure of gases was varied in the range of 12.5–400 kPa. The high-voltage electrode in most of the experiments had the shape of a cone with a base diameter of 6 mm and an opening angle of 60°, whereas the grounded elec-

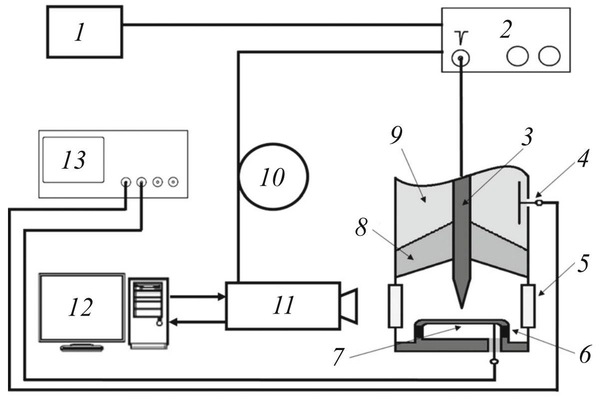

Fig. 1. Layout of the experimental setup: (*1*) triggering generator, (*2*) generator of nanosecond high-voltage pulses, (*3*) high-voltage conical electrode, (*4*) capacitive voltage divider, (*5*) quartz windows, (*6*) chip resistors, (*7*) grounded flat electrode, (*8*) insulator, (*9*) transformer oil, (*10*) delay line or delay generator, (*11*) four-channel ICCD camera or streak camera, (*12*) computer, and (*13*) oscilloscope.

trode was flat. To extract an supershort avalanche electron beam (SAEB) from the discharge gap and to measure its parameters, the flat electrode was made of a 10-μm-thick aluminum foil. A number of experiments were performed with a tubular (∅ = 6 mm) high-voltage electrode with a sharp edge. The high-voltage electrodes were made of aluminum or stainless steel. The width of the interelectrode gap was varied from 3 to 8 mm.

Plasma glow at the stage of formation and propagation of the streamer was detected by an HSFC-Pro four-channel intensified charge-coupled device (ICCD) camera. The width of the interelectrode gap was 3 mm. In order to reach a large depth of field, we used a quartz lens with a diameter of 5 cm and a focal length of 27.6 cm. The minimum exposure time of the ICCD camera was 3 ns. In order to detect plasma glow at the stage of formation and propagation of the streamer, the channels of the ICCD camera were switched on at 2–3 ns prior to the arrival of the voltage pulse at the gap. Owing to the presence of jitter and the collection of data (~10^2 realizations), the streamer was recorded at different stages of its formation and the dynamics was reconstructed. It is noteworthy that the exact time matching of the images to voltage pulses is absent in this case.

The velocity of the streamer was estimated as the velocity of the light front. To this end, the time dependence of the intensity of radiation from different regions along the gap was recorded by a Hamamatsu C10910-05 streak camera equipped with an Acton Spectra Pro SP-2300 (Princeton Instruments) monochromator. The dimensions of the region along the length and width of the gap were 250 μm and 4 mm, respectively. The time dependence of the intensity of radiation of the 0–0 band of the second positive system of nitrogen was recorded at the discharge in nitrogen and air. The time dependence of the intensity of 750.4-nm radiation of the argon atom was recorded at the discharge in argon. The resulting time dependence of the radiation intensity in each region was obtained by averaging over 300 pulses.

The gas-discharge chamber was equipped with a capacitive voltage divider, a current shunt made of chip resistors, and a collector for detecting the SAEB current under the conditions when negative voltage pulses were applied to the conical electrode. The diameter of the receiving part of the collector was 16 mm and its time resolution was ≈60 ps.

Voltage, discharge current, and SAEB current pulses were recorded in a separate series of experiments. The conditions of the experiment (type of gas, pressure, interelectrode distance, and voltage at the output of the GIN generator) were the same as in experiments with ICCD and streak chambers. Signals from the capacitive voltage divider, current shunt, and collector were recorded with a LeCroy WaveMaster 830Zi-A digital oscilloscope (the passband 30 GHz and discretization step 12.5 ps).

WAVEFORMS OF THE VOLTAGE, DISCHARGE CURRENT, AND SAEB CURRENT PULSES

Typical waveforms of the voltage, discharge current, and SAEB current pulses at the discharge in nitrogen at various pressures are shown in Fig. 2.

According to Fig. 2, the breakdown at a nitrogen pressure up to 100 kPa occurs on the front of a voltage pulse. With an increase in the nitrogen pressure, the delay time and breakdown voltage increase, whereas the amplitude of the SAEB current decreases. The SAEB was not detected at nitrogen pressures below 50 kPa because the energy of electrons in the SAEB (<40 keV) is insufficient for overcoming the 10-μm-thick aluminum foil. An increase in the pressure is accompanied by an increase in the breakdown voltage and, consequently, in the maximum energy of electrons in the SAEB, which is the product eU_m, where e is the elementary charge and U_m is the amplitude of the voltage. However, with increasing nitrogen pressure, the reduced electric field strength decreases and the ionization drag of electrons increases. In addition, this leads to a decrease in the total number of runaway electrons in the SAEB. Furthermore, the type of gas affects the efficiency of generation of runaway electrons: the larger the number of electrons in a molecule or an atom, the larger the ionization loss force. The amplitudes of the SAEB current were maximal in He and H_2.

When positive voltage pulses were applied to the conical electrode, the SAEB was not detected behind

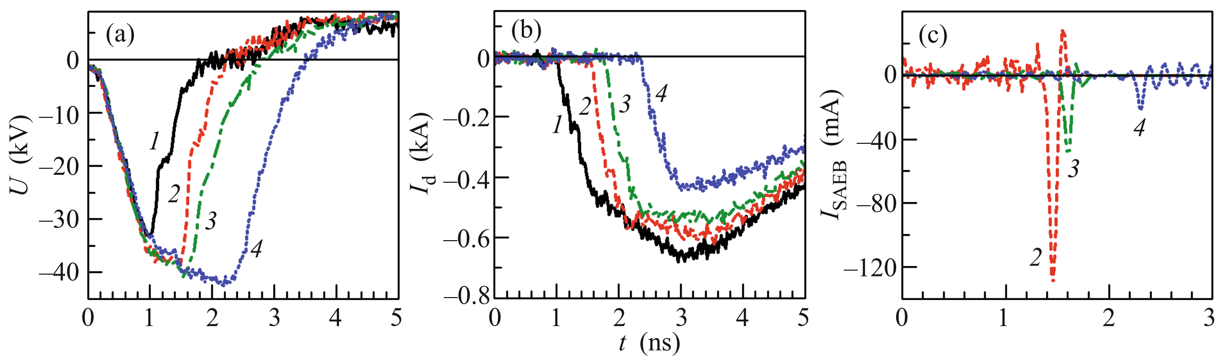

Fig. 2. (Color online) Waveforms of pulses of the voltage U, discharge current I_d, and SAEB current I_{SAEB} passed through a 10-μm aluminum foil in nitrogen at pressures of (*1*) 12.5, (*2*) 50, (*3*) 100, and (*4*) 200 kPa. The results were obtained with the GIN-100-1 generator.

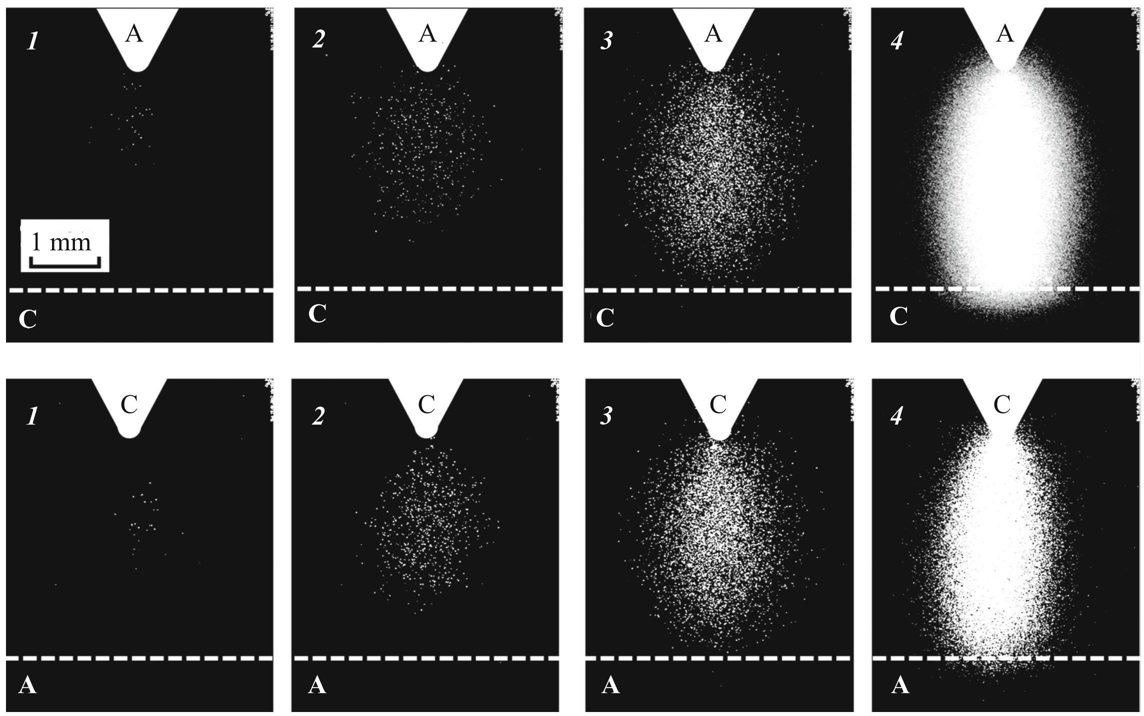

Fig. 3. Images of plasma glow at various times in the pre-breakdown stage of the nanosecond discharge at a nitrogen pressure of 100 kPa for the (upper images) positive polarity (GIN-50-1) and (lower images) negative polarity (GIN-100-1). Here, A is the anode and C is the cathode.

the plane foil cathode because electrons moved toward the conical anode.

DYNAMICS OF PLASMA GLOW FROM THE GAP

When nanosecond positive and negative voltage pulses were applied across the gap, a diffuse (volume) discharge was formed in all gases and in the entire range of pressures. The diffuse character of the discharge is due to the formation of a large streamer (Fig. 3).

The specificity of the formation of the streamer under these conditions is that the streamer at the initial stages has the shape of a ball. According to Fig. 3, glow is first detected at a certain distance from the conical electrode (frames *1*) and the glowing region grows at the next stages not only in the direction of the discharge gap axis but also in the transverse direction (frames *2*). As a result, the streamer acquires an almost ball shape. At the next stages (frames *3*), the formed plasma (streamer) also has the shape close to a ball, which grows in the process of propagation, and the streamer itself is adjacent to the conical electrode.

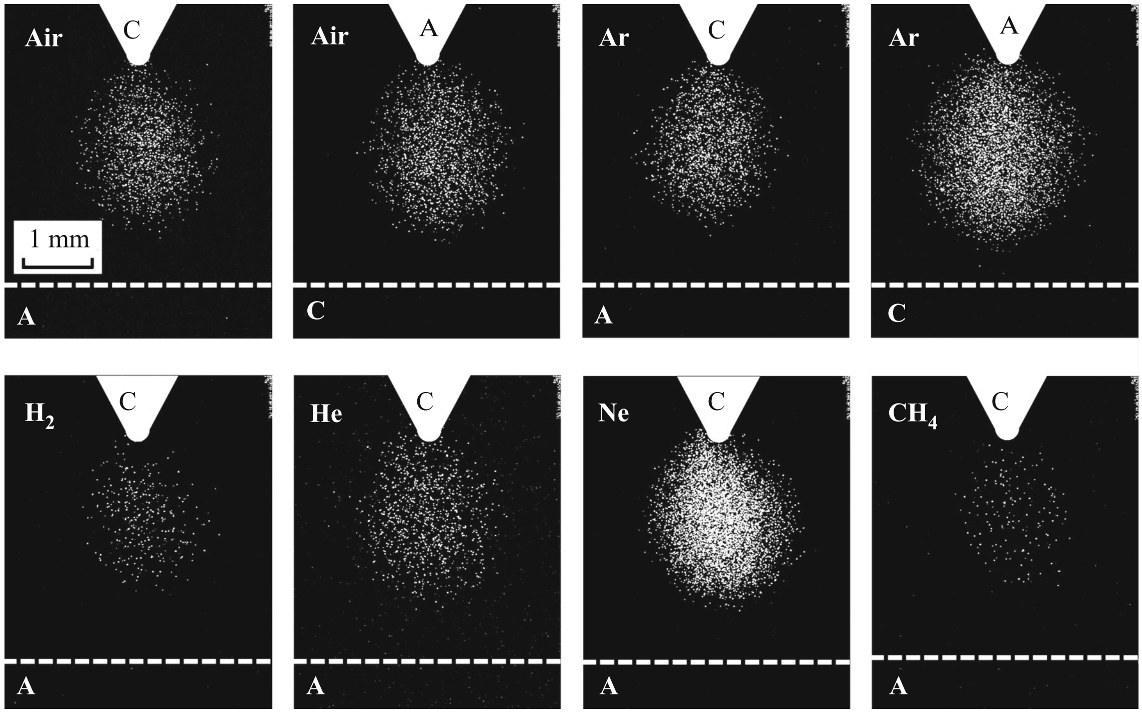

Fig. 4. Images of plasma glow in the pre-breakdown stage of the nanosecond discharge in various gases at atmospheric pressure. Here, A is the anode and C is the cathode.

When the streamer reaches the flat electrode, the conduction current in the plasma increases sharply and the radiation intensity also increases (frames *4*).

Figure 4 shows the images of ball streamers in other gases at a negative polarity of the conical electrode, as well as at a positive polarity in air and argon.

According to Figs. 3 and 4, the ball streamer is detected in both atomic and molecular gases at both polarities of the voltage pulse. The dynamics of formation and propagation of streamers is similar in all gases. The transverse dimensions of the streamer decrease with an increase in the gas pressure. The type of gas also slightly affects the dimensions of the streamer.

When the pressure of argon, air, and nitrogen was ≈400 kPa, the formation of two parallel-propagating streamers with the transverse dimensions smaller than those in the case of a single streamer was sometimes observed. Several streamers propagating toward the grounded flat electrode were formed in all studied gases and at all pressures in the case of the tubular high-voltage electrode with a sharp edge.

A bright spot was usually formed on the conical cathode when the plasma bridged the gap. Furthermore, the bright spot could appear on the conical anode. At the pressure of gases of 200–400 kPa, spots appeared on both the conical and flat electrodes after the plasma bridged the gap.

Theoretical studies confirm the possibility of the formation of a streamer with large transverse dimensions. In particular, it was shown in [9, 12] that the subnanosecond breakdown in a nonuniform electric field is due to the formation of a streamer with the transverse dimensions reaching 1 cm at an interelectrode gap of 1.5 cm.

The average propagation velocity of the streamer was estimated from the difference in time of appearance of plasma glow near the conical electrode as compared to the flat electrode in streak-camera data. A signal level of 2% of the amplitude value was taken as the beginning of a radiation pulse. In particular, the average velocity of the streamer in nitrogen at a pressure of 100 kPa was 1.8 cm/ns. The analysis of the time dependence of the plasma radiation intensity from different regions along the gap shows that the propagation velocity of the plasma front to the middle of the gap is lower than that from the middle to the flat electrode. This conclusion is consistent with the data obtained in [18, 19], where glow from different regions of the discharge gap was detected by a photodiode with a time resolution of ~80 ps. The velocity of the streamer usually increased with a decrease in the pressure.

MECHANISM OF FORMATION OF BALL STREAMERS

The reported results indicate that, at the breakdown of the cone–plane gap by the nanosecond negative and positive voltage pulses, the ball streamer is formed and bridges the gap at a high velocity. In all gases, the streamer appears near the conical electrode and the dynamics of its formation is almost the same in all these gases. Therefore, the observed dynamics of the formation of the streamer at the breakdown under these conditions should be described by a single universal mechanism. This mechanism should explain high ionization rates of a gas (which is confirmed by a high propagation velocity of the streamer) and large transverse dimensions of the streamer.

As is known, at the breakdown in the presence of high overvoltage, the electric field strength at the front of the streamer/ionization wave exceeds the critical value for the regime of continuous acceleration of electrons. We believe that the gas under these conditions is efficiently ionized by fast electrons with energies of hundreds of electronvolts to several keV. The cross sections σ_i for the ionization of molecules and atoms are usually maximal at these energies of electrons. In particular, the cross section σ_i for the nitrogen molecule is maximal at the energy of electrons of 100 eV [3], and the "tail" of the cross section extends to several keV.

The presence of fast electrons in discharges with a high overvoltage follows from the calculations performed in [10, 13, 20, 21] and Kunhardt and Byszewski [20] proposed to call them "trapped" electrons. The electric field far from the head of the cathode-directed streamer and positive cone is weaker; consequently, the process of increasing energy of electrons is slowed and ceases at large distances. Correspondingly, fast electrons do not appear. However, fast electrons effectively ionize gas near the head of streamers, thus ensuring fast propagation of streamers. This mechanism explains the efficient ionization of the gas in front of the head of the streamer with both positive (cathode-directed streamer) and negative (anode-directed streamer) charges.

In the case of the negatively charged conical electrode, electrons with energies of tens of keV and above (runaway electrons) ensure the preliminary ionization of the gas ahead of the front of the streamer, and some of these electrons are detected behind the foil anode (see Fig. 2c) [14, 18, 19, 22–24]. In [22], runaway electrons were also detected behind the side window of the discharge chamber, where the foil and subsequent collector were placed. This indicates the generation of runaway electrons not only in the direction of the anode but also in the side direction.

In the case of the positively charged conical electrode, the preliminary ionization of the gas is accomplished by soft X rays (characteristic and bremsstrahlung) appearing at the deceleration of fast electrons. A high efficiency of the generation of characteristic radiation at the deceleration of runaway electrons in light gases was theoretically demonstrated in [25]. Characteristic radiation was experimentally detected at the discharge in a nonuniform electric field in nitrogen and air [26], as well as in argon at low pressures [27]. The detection of X rays from narrow interelectrode gaps was also reported in [28, 29]. In addition, X rays at the formation of the streamer near the anode with a small radius of curvature were detected in [30].

CONCLUSIONS

To summarize, it has been shown that a large ball streamer is formed at the breakdown of the cone–plane gap filled with various gases (air, nitrogen, methane, hydrogen, argon, neon, and helium) at a high rate of increasing voltage across the gap ($\sim 10^{13}$ V/s) and at both polarities. The front of the streamer propagates at a velocity of several centimeters per nanosecond and higher. A diffuse discharge is ignited after the streamer bridges the gap. A runaway electron beam is detected behind the foil anode when the conical electrode is negatively charged.

In view of a similar observed dynamics of the formation and propagation of streamers in both molecular and atomic gases at various pressures and at both polarities, we have proposed a new mechanism of the formation of streamers. According to this mechanism, a high ionization rate of the gas at both polarities is ensured by fast electrons with energies of hundreds of electronvolts to several keV and the gas is preionized by runaway electrons with energies of tens of keV and higher in the case of the negatively charged pointed electrode and by X rays (characteristic and bremsstrahlung) in the case of the positively charged one.

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