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Influence of preionization on the microchannel structure of a spark discharge in air in a pin-plane gap

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The initial phase of a spark discharge in the gap between the pin (cathode) and a plane 1.5 mm long in atmospheric pressure air under conditions of preliminary photoionization by an auxiliary discharge was investigated by the method of shadow photography. In the absence of preionization, the discharge from the first nanoseconds after breakdown is an aggregate of a large number of micron-diameter channels. It was found that the electron concentration resulting from preionization, estimated at 10^8-10^9 cm^{-3}, increases the degree of uniformity of the discharge channel in the near-cathode region; however, in the near-anode region, the channel remains microstructured. Within the framework of the mechanism of microstructure formation due to the instability of the ionization wave front, a criterion for the formation of a uniform discharge is obtained and an explanation of the results obtained is presented.

Keywords: spark discharge, preionization, photoionization, instability of the ionization front, microstructure, shadow photography method

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Introduction

Research into the influence of preionization on the dynamics of gas discharges is relevant, e.g., to the design of gas lasers, plasma-chemical technology, etc. The key objective of preionization is often the generation of a sufficiently uniform discharge in a required volume within a specified time interval.

The problem of generation of uniform discharges in large volumes and at high pressures (on the order of 1 atm and higher) has been addressed in a number of studies (see, e.g., review [1] and references therein). It is assumed that the spatial overlap of neighboring electron avalanches until their reaching a critical size (on the assumption of their uniform distribution throughout the working volume) is the condition of a uniform discharge evolution [1,2]. Critical radius r_{cr} is the radius of the avalanche head at the moment of avalanche-to-streamer transition, and the uniformity of distribution of avalanche initiation points throughout the working volume is guaranteed by external preionization. As a result, the initial electron density, which should be $n_0 > r_{\text{cr}}^{-3} = 10^4\,\text{cm}^{-3}$, is produced [1,3]. With further refinement of this model, the criterion of ignition of a volume discharge was updated to require the presence of initial electron density $n_0 > 10^7\,\text{cm}^{-3}$ in the gap. This agreed better with experimental data [1]. At the initial stage of discharge evolution, this condition should prevent the formation of individual current filaments with diameters on the order of 0.1 cm and subsequent discharge contraction.

At the same time, it was found in [4–10] that discharges being uniform in outward appearance may feature an internal microstructure (i.e., be composed of a large number of microchannels). This microstructure could not be resolved using optical and electron-optical methods [4].

The microstructure within the volume of a discharge gap has been detected relatively recently with the use of laser probing and shadow and interference techniques based on it [4–7]. The mechanism of microchannel formation due to instability of the ionization front at the initial discharge phase is regarded as one of the most plausible explanations of this phenomenon [9–15].

Various types of gas discharges have been demonstrated to be microstructured [4–10]. In view of this, the question of the influence of preionization on the spatial structure of such discharges appears intriguing and practically relevant.

This study is a continuation of [4,5], but differs from them in that the two-frame version of the shadow photography technique was used. This expands considerably the opportunities for collection of data on the processes associated with gas discharges. In the present study, we introduce the results of examination of the influence of preionization on the microchannel structure of a spark discharge in air in a pin–plane gap at the initial stage of its evolution.

1. Experimental setup and procedure

The diagram of the experimental unit is presented in Fig. 1. The majority of its elements were characterized in detail in [4,5]. Pulsed voltage generators (PVGs) output voltage pulses with an amplitude of 25 kV and a 0.1–0.9 rise time of approximately 7 ns. These pulses were sent to discharge gaps via cable lines. One generator (PVG 1) produced the primary (studied) discharge, and the other (PVG 2) was responsible for the auxiliary discharge for photoelectric preionization of air for the primary discharge. PVGs were activated with a preset delay. The length of each cable line for supply of the primary and auxiliary discharges was 7 m.

The electrode system for the primary discharge had a pin–plane geometry. An axially symmetric pin electrode was fabricated from stainless steel and had a length of 19 mm, diameter of 14 mm, an apex angle of 36°, and a curvature radius of 0.15 mm. A plane electrode was fabricated from an aluminum alloy and had the working part close in shape to a segment of a sphere with a diameter of 4.5 cm and a thickness of 1.5 cm. The interelectrode gap was 1.5 mm.

The auxiliary discharge was generated between the core and the braiding at the end of a cable cut perpendicularly to the axis. The plane of cut was parallel to the axis of the primary discharge gap and was located at a distance of 1 cm from it.

Voltage U and current I were measured for the primary discharge, and only current I_i was measured for the auxiliary discharge. These measurements were performed at the PVG output. A capacitance divider and a shunt resistance were used to measure the voltage and the current, respectively. The temporal resolution of the divider and the shunt was no worse than 1 ns. Signals were recorded using an oscilloscope with a bandwidth of 500 MHz and a sample rate of 2 Gs/s.

An optical detection system was used to examine the primary discharge. The system included a probing radiation source (solid-state laser with a wavelength of 532 nm and a pulse FWHM of 6 ns), lenses, light filters, and digital electron-optical detectors. A plane-parallel laser beam crossed the discharge region at a right angle to the pin electrode axis and was detected by the electron-optical camera. The laser beam at the discharge generation region had a crosswise size of approximately 1 cm and a Gaussian profile.

A shadow photography procedure with a two-beam optical scheme was implemented based on this system. The two-beam scheme allowed us to retrieve two frames in a single pulse (Fig. 1). Angle α between the laser beams was approximately 15°. The image in the discharge gap region was formed for each beam with a lens with a focal length of 23 cm at the photocathode of the electron-optical detector. The magnification coefficient was 10. The exposure of each frame was set by the laser pulse duration. The time interval between shadowgraph frames could be varied by altering optical path lengths K_1 and K_2 of the beams. In the experiments in this study, the time interval was 5 ns. The frames were timed relative to the moment of breakdown, and the time characterizing them corresponded to the start of imaging.

Different stages of the discharge process were visualized by shifting the moments of actuation of the laser and the electron-optical detector relative to the moment of breakdown. The resolving power of the optical system was 5 μm per three pixels.

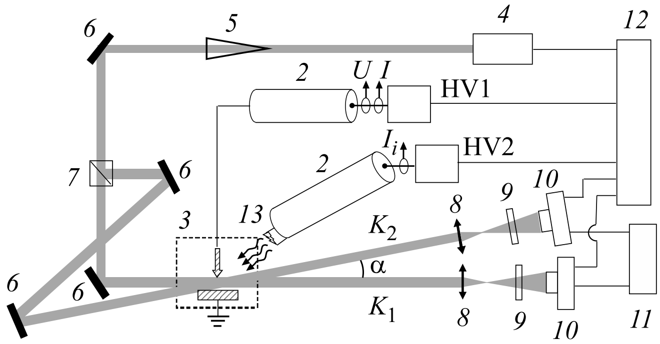

Figure 1. Diagram of the experimental unit. HV1 and HV2 — pulsed voltage generators, *2* — cable line, *3* — discharge gap, *4* — probing signal source (laser), *5* — collimator, *6* — rotary mirror, *7* — light-dividing element, *8* — lens, *9* — light filters, *10* — electron-optical detector, *11* — PC, *12* — synchronization unit, *13* — auxiliary discharge for preionization of the discharge gap.

The integral glow of the auxiliary discharge was imaged with a digital camera.

2. Experimental results and discussion

The experiments were performed in air under normal conditions. The same discharge without preionization was studied in reasonable detail in [4,5].

The experiments were carried out both with and without preionization of the discharge gap. In the former case, the discharges were synchronized so that the breakdown of the primary gap occurred at the maximum of the auxiliary discharge current. Fragments of oscilloscope records of the current and the voltage at the output of PVG 1 and the current at the output of PVG 2 are shown in Fig. 2. An oscillatory process with exponential current and voltage decay was initiated in the discharge circuit after the breakdown of the primary gap. The oscillation period was 0.6 μs, and the amplitude and the decay time of current were 1 kA and 1.2 μs, respectively. The onset of the current rise (and the voltage decay) was assumed to be the moment of breakdown. Preionization had no noticeable effect on the oscilloscope records of the primary discharge. The amplitude of current of the auxiliary discharge was approximately 1 kA. Its integral glow is shown in Fig. 3.

Figure 4 presents the shadowgraphs of the discharge without preionization. It can be seen that the discharge channel is a complex of a large number of microchannels. It should be noted that the degree of uniformity in the cathode region of the channel differed from one pulse to the other. For example, the microstructure is evident in the cathode region in Figs. 4, *a* and 4, *b*. The cathode region of the channel in the shadowgraphs in Figs. 4, *c* and 4, *d*, which correspond to a different pulse and roughly the same

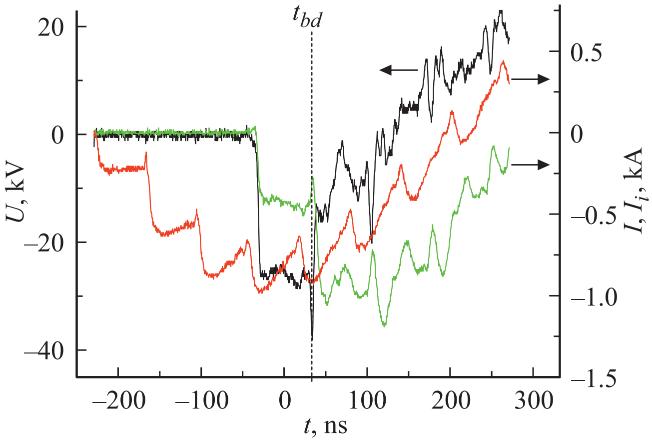

Figure 2. Oscilloscope records of current I (green curve, online) and voltage U (black curve) at the output of PVG 1 and current I_i (red curve, online) at the output of PVG 2, t_{bd} — is the moment of breakdown.

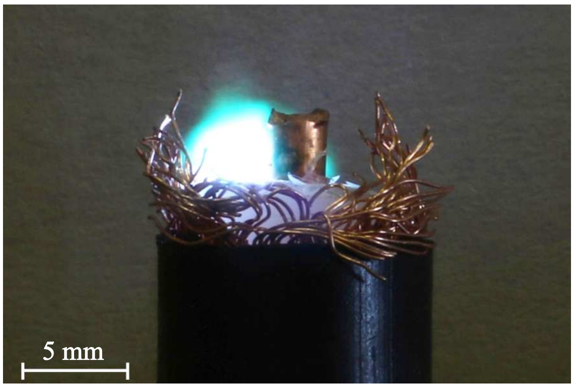

Figure 3. Photographic image of the auxiliary discharge.

times, appears to be more uniform, and microchannels are not resolved here. Note that the observation of a uniform (structureless) channel near a pin cathode was reported in [7].

Figure 5 presents the shadowgraphs of the discharge with photoelectric preionization of the gap by an auxiliary spark discharge. It can be seen that the channel remains uniform and structureless in the region spanning from the cathode to approximately half the length of the gap. The microchannel structure, which is retained at later stages, is evident in the remaining part of the channel. This pattern was observed for up to 15–20 ns after breakdown in all pulses. We point out that in certain cases, the microstructure was observed throughout the entire channel (cathode region included) at later stages. It should be noted that the external ionization source kept working at that time.

Thus, preionization enhances the degree of channel uniformity at the initial stage of the discharge. A two-phase structure is formed in this case: the channel is divided into a structureless region in contact with the cathode and a microstructured region in contact with the anode. The experiments basically demonstrate that the used preionization source does not guarantee the generation of a uniform discharge in the entire gap.

Let us examine the mechanism of influence of preionization on the discharge microstructure within the model of its formation due to the ionization front instability [9,10]. According to this model, the ionization front may become unstable under certain conditions with respect to spatial perturbations of the electron density in a specific range of their sizes [9–15]. The development of instability results in the emergence of microchannels. It is evident that in order to suppress this instability, the characteristic distance between electrons produced due to preionization should not exceed the characteristic size of an inhomogeneity with a positive growth increment. Assuming that the radius of this inhomogeneity corresponds to radius r_{inst} of microchannels at the initial discharge stage, the initial electron density for the measured values of $r_{\text{inst}} = 10\,\mu$m is estimated at $n_0 > r_{\text{inst}}^{-3} = 10^9\,\text{cm}^{-3}$.

The data from [16,17], where a spark discharge was examined as a source of photoionization with parameters close to the ones used in the present study, may help estimate the electron density provided by such a source.

According to the results of measurements for a discharge in air at atmospheric pressure [16], average radiation power w in the ultraviolet range was approximately $2\,\text{mJ/(cm}^2{\cdot}\text{s)}$ at a distance of 1 cm from the discharge. The electron density upon photoionization in the region of a discharge channel with length $l = 1.5$ mm and radius $r = 150\,\mu$m may be estimated as

$$n_e = wS_{\text{ch}}\Delta t/(W_i V_{\text{ch}}).$$

Inserting $W_i = 14.5$ eV (nitrogen ionization potential), $\Delta t = 100$ ns (characteristic duration of exposure to the ionization source), $S_{\text{ch}} = 2rl$ (section area of the channel along its axis), and $V_{\text{ch}} = \pi r^2 l$ (channel volume), we find $n_e \approx 10^{10}\,\text{cm}^{-3}$. The obtained value should apparently be regarded as an overestimate, since it is based on an idealized assumption of a hundred-percent efficiency of photoionization by ultraviolet radiation.

A combined experimental and computational approach to the determination of the electron density in photoionization of nitrogen at atmospheric pressure was used in [17]. The obtained value was $n_e \approx 5 \cdot 10^7\,\text{cm}^{-3}$ at a distance of 8 cm from the source at the moment when the discharge current reaches its amplitude value. The electron density at a distance of 1 cm from the source should be higher. It appears justified to project the data obtained for nitrogen to air on condition that relatively intense photoionization sources considered here are used within the time of their operation.

Thus, it may be assumed that preionization of the gap with an auxiliary spark discharge in the present experiments provides electron density $n_e = 10^8{-}10^9\,\text{cm}^{-3}$.

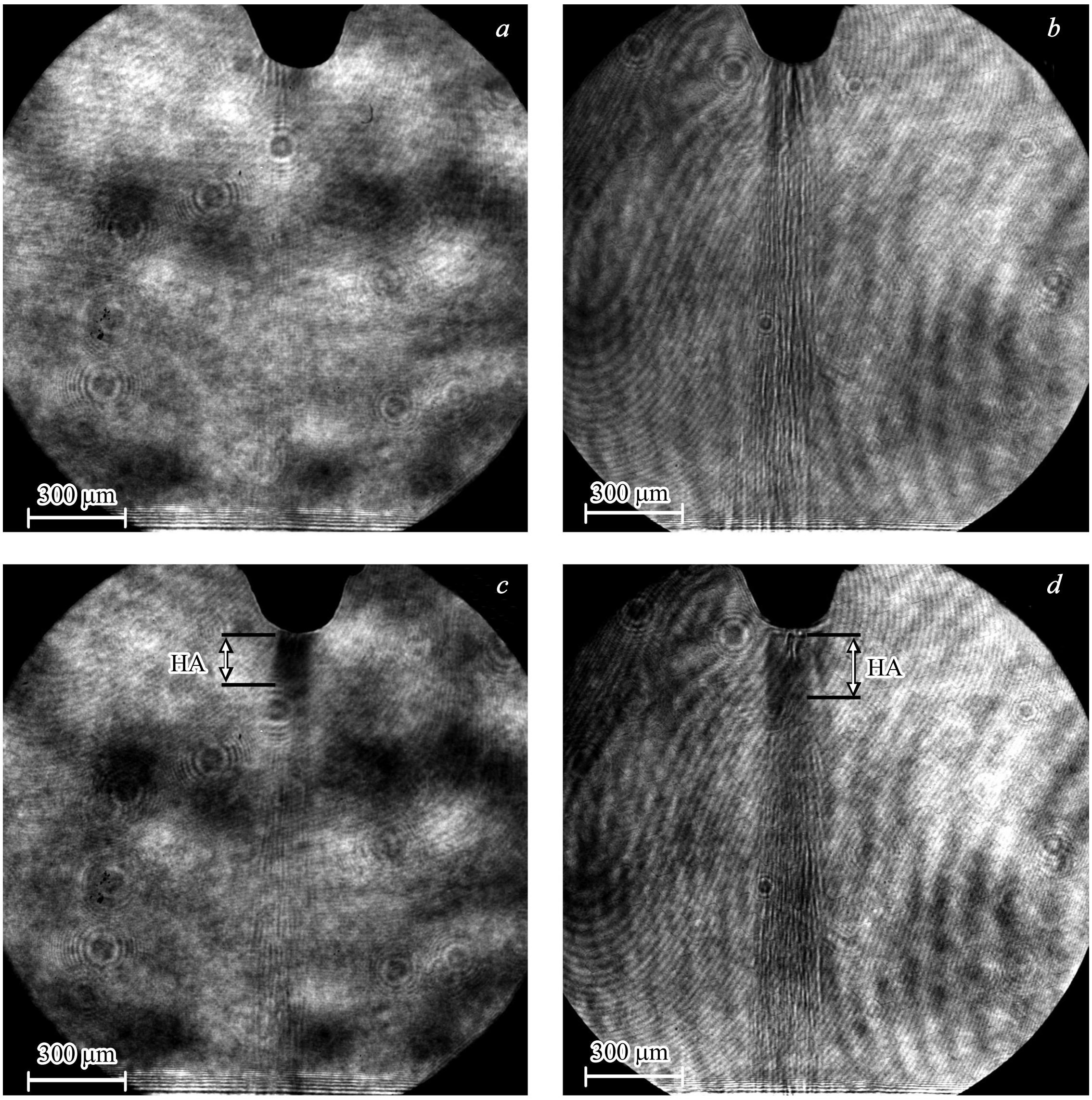

Figure 4. Shadowgraphs of the discharge without preionization. Pairs of images (a, b) and (c, d) were obtained in different pulses. Time relative to breakdown: a — 9, b — 14, c — 10, d — 15 ns. HA is the region with an increased degree of uniformity.

The obtained estimates suggest that the electron density produced due to preionization is not sufficient to form a uniform channel within the entire gap. At the same time, the presence of a relatively strong electric field, which governs emission and ionization processes and produces an increased electron background, in the cathode region should be taken into account. Apparently, the contribution from external photoionization guarantees in this case the formation of a uniform channel section extending to approximately half the length of the discharge gap.

Intense ionization processes in the cathode region, which govern the specifics of development of the ionization instability, apparently also account for the fact that a uniform channel section in this region was often observed even without external preionization. The dynamics of the indicated processes were discussed in detail in [10].

The following conclusions may be drawn from the obtained results. First, an external preionization source more intense ($n_e \gg n_0$) than the one used in the present study should ensure the generation of a uniform discharge within the entire gap. Second, if a discharge is microstructured, the minimum preionization electron densities needed for a uniform discharge may be considerably higher than the values adopted earlier [1,3].

Conclusion

The influence of preionization by radiation from an auxiliary discharge on the dynamics of the initial stage of a spark discharge in a pin (cathode)–plane gap with a length of 1.5 mm in air at atmospheric pressure was examined using the two-frame shadow photography technique.

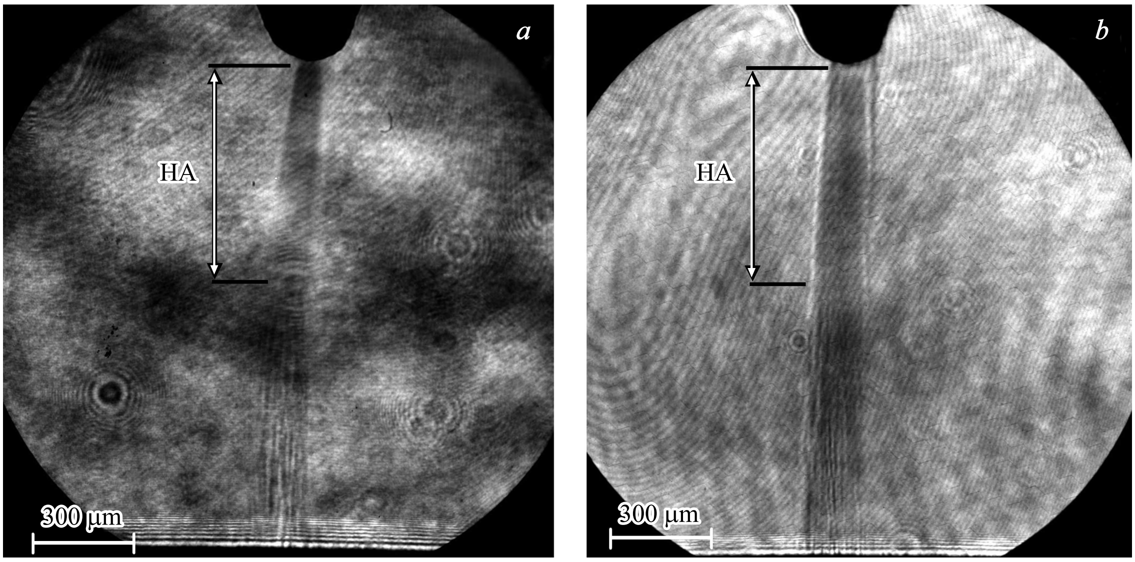

Figure 5. Shadowgraphs of the discharge with preionization. Images were obtained in a single pulse. Time relative to breakdown: *a* — 7, *b* — 12 ns. HA is the region with an increased degree of uniformity.

It was demonstrated that the channel formed without preionization is microstructured (i.e., is a complex of a large number of microchannels) from the first nanoseconds after breakdown. The channel section in the cathode region was either microstructured or uniform in different pulses.

It was found that preionization enhances the degree of channel uniformity at the initial stage of the discharge: the channel is divided into a structureless region extending from the cathode to approximately half the length of the gap and a microstructured region in the anode region.

It was hypothesized that the degree of uniformity is enhanced in the case of preionization due to the suppression of instability of the front of the ionization wave that governs the microstructure formation. The critical preionization electron density above which the ionization instability does not develop was estimated. The obtained value (on the order of $10^9\,cm^{-3}$) was close to the preionization electron density estimated at $10^8-10^9\,cm^{-3}$.

It is expected that a more intense external preionization source providing an electron density well above the critical one should ensure the generation of a uniform discharge within the entire gap.

It was noted that in the case of microstructured discharges, the minimum preionization electron density needed for a uniform discharge may be considerably higher than the values adopted earlier $(10^4-10^7\,cm^{-3})$ [1,3].

Conflict of interest

The authors declare that they have no conflict of interest.

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