The Effect of Pre-Ionization Inhomogeneities on the Dynamics of a Subnanosecond Pulsed Electrical Breakdown in Gas Gaps[1]

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Abstract – The initiation and the development of a breakdown of highly overvoltaged gas gaps by voltage pulses having the rise time of 1 ns or shorter are studied experimentally and in theoretical terms. The study revealed that ionization processes leading to the breakdown start in the gas volume and not from the surface of the electrodes. The gap flashover is followed by ionization wave processes initiating in the gas volume and playing the decisive role at the first phase of the breakdown. The dynamics of the ionization waves strongly depends on the initial distribution of free electrons over the gas gap. The distribution of ionization waves is analyzed when the initial electrons are distributed nonuniformly over the gap. It is shown that their nonuniform distribution initiates the simultaneous propagation of cathode- and anode-oriented ionization waves. These waves cause a redistribution of the electrical field in the gas gap and a region of a strong field, whose intensity is sufficient for the onset of emission processes and the generation of a short beam of fast electrons near the cathode, is formed at the cathode for a very short (up to 100 ps) time.

1. Introduction

Our study [1] dealt with an experimental and theoretical investigation of the initiation of a breakdown of highly overvoltaged gas gaps by voltage pulses having the rise time of 1 ns or shorter. It was shown that two types of the initial stage of a subnanosecond gas breakdown are observed at the streak photographs of glow accompanying breakdown from one pulse to another under the same experimental conditions. Modeling, which was performed assuming the presence of free electrons with a uniform initial distribution in the volume of the gas gap, was in good agreement with experimental streak photos of the glow of the "first type" [1]. This paper deals with the analysis of propagation of ionization waves in the case of a nonuniform distribution of initial free electrons in the gap.

2. Experiment

The experiments were performed on the same equipment and in the same conditions (the pressure and the type of the gas, the pulse parameters, etc.) as those in [1]. The present paper discusses in detail the observed breakdown of the "second type" [1]. It was already noted in [1] that this is the most typical variant of the glow development at the initial stage of the breakdown.

Figure 1 presents streak photographs of the glow accompanying the breakdown of the "second type", which are time-scanned in the direction parallel to the electrode plane. The development dynamics of the ionization waves observed in the gas gap is interpreted qualitatively in [2]. In our opinion, the breakdown progresses as follows.

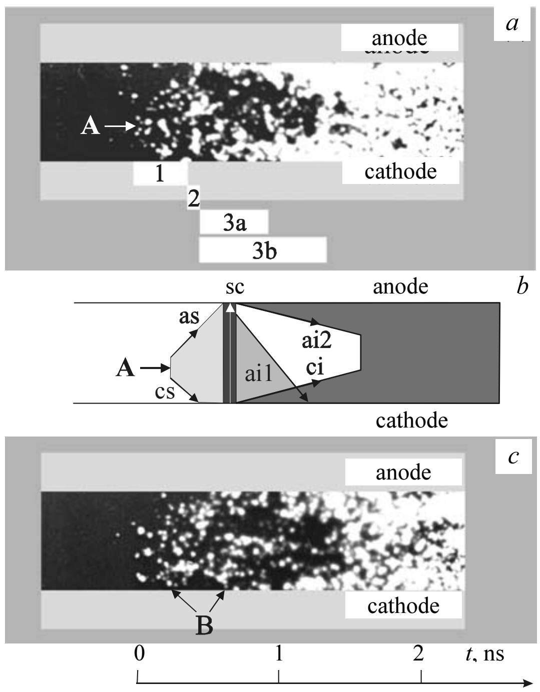

Fig. 1. Streak photographs of the glow accompanying the breakdown of gas gaps 3.55 mm wide (nitrogen, 4.5 atm) (*a*, *c*); computer processing of the photograph in Fig. 1, *a* on the 1:1 scale (*b*). The zero of the time scale in this figure is taken as the instant when the glow appears in the gap. Here cs – the cathode streamer; as – the anode streamer; ai1 and ai2 – the anode ionization waves; ci – the cathode ionization wave; sc – spark channel

The glow, which appears first (phase 1, Fig. 1, *a*), most probably is due to ionization of the gas under the

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action of an electron avalanche propagating in the gas. Several electron avalanches can be formed simultaneously. This supposition is confirmed by the fact that it is by no means always possible to exactly establish the point (point A in Fig. 1, *a*) in the gas gap, which is the origin of the breakdown, because the number of such points may be more than one. Therefore we see a superposition of images of several avalanches and smearing of the initial portion of the breakdown streak photos (Fig. 1, *c*). An electron avalanche distorts the electrical field in the gap, leading to the formation of secondary electrons on account of the gas ionization in zones of the strong field. Plasma formations (cathode {cs} and anode {as} streamers) start going to the cathode and the anode at a speed of about $5 \cdot 10^8$ cm/s (all calculations in this section are performed for Fig. 1, *a*). When the anode and cathode streamers reach the surface of the electrodes, a bright bridge or a weakly ionized spark channel (sc) appears between the electrodes (phase 2, Fig. 1, *a*). It is difficult to exactly measure the glow propagation rate in the spark channel because the glow lasts for not over 100–150 ps and ionization can take place over the whole gas gap. Most probably, *V*sc is higher than $2 \cdot 10^9$ cm/s. In turn, the formation of the spark channel causes the propagation of two new ionization waves from the anode (ai1 and ai2). The wave ai1 (phase 3a) goes from the anode to the cathode at a speed *V*ai1 = $7 \cdot 10^8$ cm/s, while the wave ai2 (phase 3b) has a speed *V*ai2 = $2 \cdot 10^8$ cm/s. Concurrently with the wave ai2, an ionization wave (ci) (phase 3b) starts propagating at a speed *V*ci = $2 \cdot 10^8$ cm/s from the cathode. This wave obviously results from the field emission and, probably, even the explosive emission processes on the cathode surface. Most probably, the waves ai2 and ci are just responsible for the growth of the spark channel conduction. As these waves propagate, the electrical field increases at the center of the gap in the weakly ionized zone between their boundaries. At a certain moment of time (the end of the phase 3b) this zone is ruptured completely (the situation is analogous to the breakdown of an electrical capacitor). In our experiment the end of the phase 3b corresponded to the gas gap current of ~1.4 kA and higher.

Modeling of processes in the gas

The streak photos of glow at the initial stage of the breakdown formation underlied the basis of a numerical model of physical processes taking place in the gas gap. The model, which is described comprehensively in [1], was used for simulation.

Calculations were made for several variants of the problem with different initial conditions. The variant assuming that one or several initial free electrons spaced ≈ 1/3*d* (*d* is the gap width) from the cathode in a small region ≈ 0.1*d* in size is in the best qualitative agreement with the experimental streak of the glow shown in Fig. 1, *a*. Such fluctuation of initial free electrons is quite probable considering that while their average concentration $i_s \sim 10^3$ cm^{-3}, they amount to units in number throughout the interelectrode volume. From the viewpoint of the model formalism, this corresponds to the following initial conditions: n_e, $i = 10^4$ cm^{-3} at a distance of 1 to 1.3 mm from the cathode in the gap and n_e, $I = 0$ in the rest of the volume. The electrical field causes the electrons to drift towards the anode and ionize the gas (Fig. 2), leaving behind positively charged ions analogously to the situation in an electron avalanche. As a result, the electrical field is distorted to such an extent that it becomes almost zero in the region of the maximum concentration of electrons (Fig. 3). Therefore the increase in the concentration and the drift of electrons are reduced considerably in this region. Near the cathode the field increases to its maximum, leading to a sharp buildup of ionization in this region by electrons released from the cathode as a result of photoemission. Consequently, the plasma region come nears the cathode. Once the cathode layer providing a sufficient supply of electrons from the cathode has been formed, the electrical field is redistributed. It is amplified between the plasma column and the anode, but decreases in the column. A certain number of electrons can be present for different reasons (runaway, photoionization, etc.) in 0.7 ns near the plasma column in the region of the high field. While moving and intensively ionizing the gas, these electrons bring the plasma column closer to the anode. If this is the case, the time scan should contain two ionization fronts directed towards the cathode and the anode respectively (Fig. 4). The cathode-oriented wave will move faster and will reach the electrode sooner. This picture is confirmed qualitatively in experiment (see Fig. 1). The arrows in Fig. 1, *c* show the region **B** with a distinct boundary of the plasma layer at the cathode.

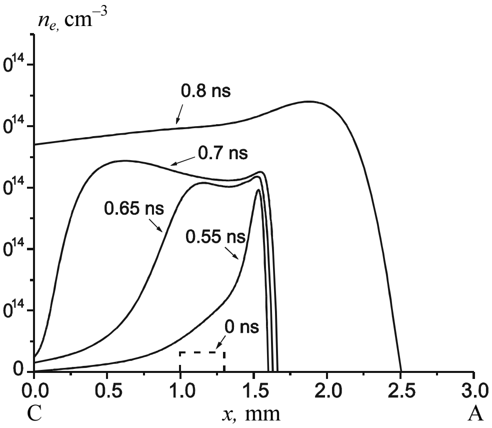

Fig. 2. Variation of the concentration of electrons in the gas gap during the discharge development in the case of inhomogeneous pre-ionization. The cathode (C) to anode (A) distance is plotted on the abscissa axis

It is known that "fast" electrons, whose energy is comparable with the accelerating voltage [3, 4], appear under the action of nano- and subnanosecond pulses at pressures of the order of the atmospheric pressure during the discharge formation. Their presence can influence the breakdown formation dynamics because high penetrability of fast electrons and bremsstrahlung quanta leads to ionization of the gas far from primary ionization centers. As a result, the discharge looses its spatially compact shape and acquires a diffusion or multichannel character [5]. The criterion of transition from the streamer mechanism of the gas discharge to the continuous acceleration of electrons is formulated in [6] as $E_c/p = 3.88 \cdot 10^3\ Z/I$, where E_c is the critical field in V/(cm torr), Z is the atomic number of the gas, and I is the mean energy of the inelastic losses in electron-volts. In the case of nitrogen $Z = 14$, $I = (75–80)$ eV, and $E_c/p =$ $= 590$ V/(cm.torr). The critical field E_c for nitrogen at 4.5 atm is 1.946 MV/cm. However, with some probability, electrons can pass to the continuous acceleration regime at lower fields too. In our experiment the electrical field intensity near the cathode edge was 0.6–1.1 MV/cm [2], while the average field in the gap was ≈ 0.394 MV/cm, i.e. $E/E_c = 0.2–0.57$. Therefore the possibility for the appearance of "fast" electrons should be analyzed at different stages of the breakdown taking into account an inhomogeneous distribution of the electrical field in the interelectrode gap (Fig. 3). One of common methods for such analysis is simulation of the electron motion by the Monte Carlo method. According to the simulation results, an effective transition to the continuous acceleration regime occurs just at the moment when the plasma column comes right up to the cathode and a field appears between them equal to ~ 1 MV/cm and higher. Fig. 5 presents a calculated dependence of the current density of "fast" electrons reaching the anode. It is seen that the current density of "fast" electrons is ~ 10^2 A/cm^2 and the pulse length is ≈ 10–10 s. Fig. 4 shows two variants of the development of the ionization front towards the anode. The ionization front resulting only from photoionization processes and the one formed with participation of fast electrons are marked with a dash-and-dot and a solid line respectively. It is seen that the propagation rate of the anode-oriented ionization wave increases approximately 4 times when fast electrons are involved (probably, even more in reality since their contribution was estimated in a first approximation only). In our opinion, the phase 2 (Fig. 1), which lasts for about 100–150 ps, when the glow propagation rate is higher than $2 \cdot 10^9$ cm/s, just corresponds to the appearance and the propagation of a beam of "fast electrons".

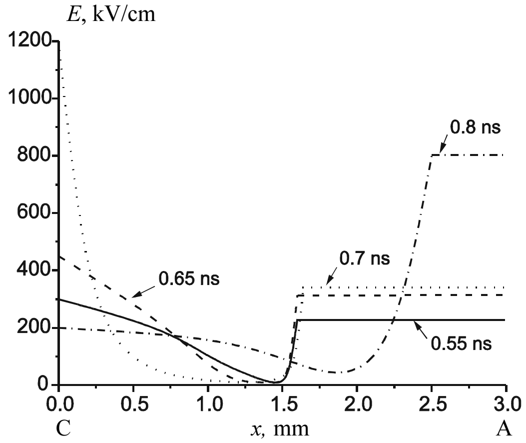

Fig. 3. Variation of the electrical field intensity in the gap during the discharge development in the case of inhomogeneous pre-ionization. The cathode (C) to anode (A) distance is plotted on the abscissa axis

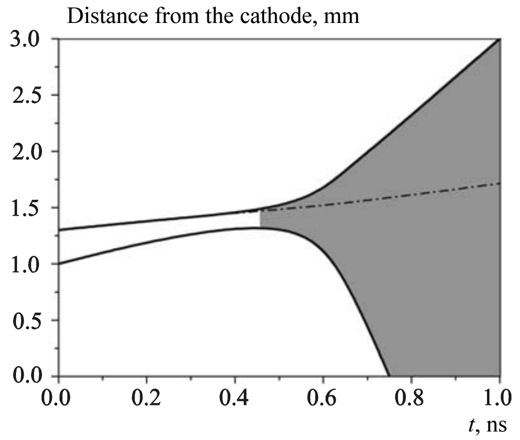

Fig. 4. Development of ionization waves and the glow in the gap in the case of inhomogeneous pre-ionization. The gray background means the visible glow of the gas

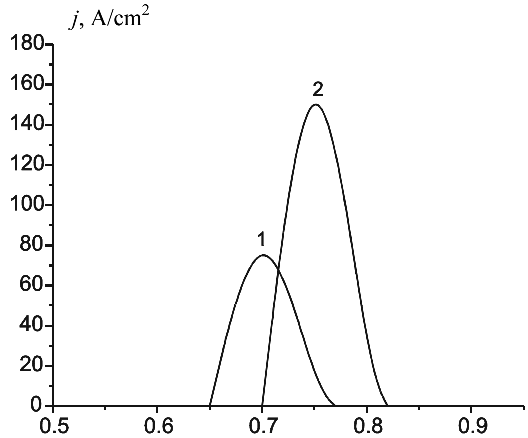

Fig. 5. Time dependences of the current density of fast electrons in the case of homogeneous [1] (curve 1) and inhomogeneous (curve 2) pre-ionization

It should be noted however that the contribution of "fast" electrons to the gas ionization is negligibly small as compared to the contribution from plasma ("slow") electrons for two reasons. Firstly, the concentration of "fast" electrons accounts for ~ (0.1–1)% of the total concentration of electrons. Secondly, the "fast" electron current pulse duration is less than 0.1

of the full time of the breakdown formation. Their role in the formation of the ionization wave front is that as the electrons cross the space between the ionization front boundary and the anode, they weakly ionize the gas and form "seed" electrons initiating new avalanches, which jointly "move" the ionization front to the anode.

3. Conclusion

The experimental and theoretical investigation of the initiation and the development of a breakdown of highly overvoltaged gas gaps by voltage pulses having the rise time of 1 ns or shorter demonstrated that ionization processes, which lead to the breakdown, begin in the gas volume rather and not from the surface of the electrodes. The glow bridging of the gap is followed by development of wave ionization processes, which start in the gas volume and dominate at the first stage of the breakdown. The development dynamics of ionization waves considerably depends on the initial distribution of free electrons in the gas gap. Because of the development of the ionization waves and a redistribution of the electrical field in the discharge gap, a region of a high field, whose intensity is sufficient for the onset of emission processes at the cathode and the generation of a short beam of fast electrons in the near-cathode region, is formed near the cathode in the discharge gap.

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