Streak Investigations of the Initial Phase of a Subnanosecond Pulsed Electrical Breakdown in Gas Gaps[1]

S.N. Ivanov, V.V. Lisenkov, and V.G. Shpak

Institute of Electrophysics, 106, Amundsena str., Ekaterinburg, 620016, Russia
Phone: 8(343) 267-88-24, Fax: 8(343) 267-87-94, E-mail: stivan@iep.uran.ru

Abstract – Streak investigations of the glow, which accompanies the breakdown of highly overvoltaged gas gaps by voltage pulses having the rise time of 1 ns or shorter, is performed. The gap flashover is followed by ionization wave processes starting in the gas volume and playing the decisive role at the first phase of the breakdown. The dynamics of the ionization waves in the interelectrode gap is calculated in a one-dimensional approximation. A uniform distribution of the initial electrons over the volume of the gas gap is taken as the initial condition. The calculation results are in qualitative agreement with the relevant experimental data. It can be stated therefore that the breakdown can be initiated from the volume of the gas rather than from the surface of the electrodes.

1. Introduction

The study of mechanisms responsible for the initiation of a pulsed electrical breakdown of gas gaps in a subnanosecond time span has always presented big interest for gas discharge physics, but has been limited by performance capabilities of pulse generators and measuring instruments. Recent generators provide high-voltage pulses with the fronts of up to 100 ps and the amplitudes of ~ 105 V, making it possible to build up considerable overvoltages across the discharge gap. Since ionization processes are short in these conditions, the study of the initiation dynamics of a subnanosecond gas breakdown presents a very difficult problem.

Given below are results of experimental and theoretical investigations into the dynamics of the initiation and the development of a breakdown of highly overvoltaged gas gaps during its initial stage (within the time shorter than 1 ns).

2. Experiment

The experiments were performed on an installation based on a small-size voltage pulse generator (PG) type RADAN-303 [1]. The installation allowed recording of subnanosecond high-voltage pulses applied to the gas gap simultaneously with the streak investigations of the glow accompanying pre-breakdown and breakdown processes in the gap. The designs of the installation and the test chamber, as well as the experimental technique are described comprehensively in [2].

An "AGAT CF3M" streak camera was used in the experiments. It provided the time-scanned of the glow (over the spectral range of 0.4 to 1.2 μm) on the plane parallel to the plane of electrode surface.

The test gas was nitrogen. The electrodes were made of copper. The configuration of the electrodes in the discharge gap is given [2]. The gas gap received voltage pulses with the amplitude of 70 kV, the front of about 1 ns at the level of 0.1–0.9, and FWHM of about 2 ns (Fig. 1). In this case the voltage rise time at the pulse front was up to $7 \cdot 10^{13}$ V/s. The electrode surface was pre-aged by applying several hundreds of high-voltage pulses before measurements.

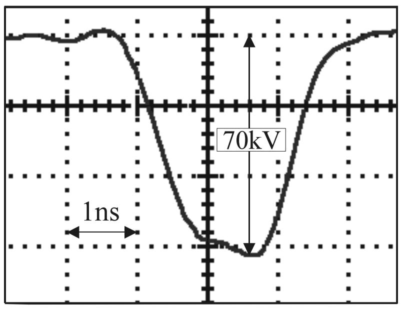

Fig. 1. The pulse at the test gas-discharge gap

Figure 2 presents some experimental photographs of the glow, which accompanies the gas breakdown (nitrogen, 4.5 atm). It is seen in these photographs that the breakdown sets in almost across the whole gas gap as a homogeneous or nearly homogeneous glow having a weak intensity. Brighter ionization waves begin propagating in the gap 300–500 ps after the glow appears. We shall refer to the breakdown with this development dynamics as the breakdown of the "first" type. It should be noted that such patterns are not necessarily the case. The glow appears much more often at some local point in the gas gap or some area of it and then propagates towards the electrodes [3]. We shall assume this breakdown development dynamics to be the breakdown of the "second" type. Both types of the breakdown are observed from one pulse to another under the same experimental conditions. That is,

[1] This study was supported by the Russian Foundation for Basic Research (Grant No. 08-02-00982-a) and the Presidium of the Ural Branch RAS (a joint project of basic research by UB and SB RAS).

the situation has the statistical character. In this report we shall attempt to explain the mechanism underlying the development of the breakdown of the "first" type. The breakdown of the "second" type is discussed in detail elsewhere [3].

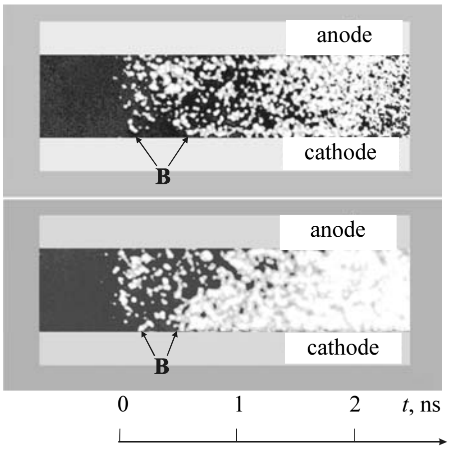

Fig. 2. Streak photographs of the glow accompanying the breakdown of gas gaps 3.55 mm wide (nitrogen, 4.5 atm). The zero of the time scale in this figure is taken as the instant when the glow appears in the gap. **B** is the boundary of the plasma layer at the cathode

3. Modeling of processes in the gas

The streak photographs of the glow accompanying the initial stage of the breakdown formation were the basis of the numerical model of physical processes taking place in the gas gap. The physical basis of the model was a system comprised of balance equations for concentrations of electrons (n_e), ions (n_i) and excited molecules (n^*) and the Poisson equation:

$$\frac{\partial n_e}{\partial t} + \frac{\partial n_e v_e(E)}{\partial x} = v_i(E) n_e, \qquad (1.3.1)$$

$$\frac{\partial n_i}{\partial t} = v_i(E) n_e, \qquad (1.3.2)$$

$$\frac{\partial n_*}{\partial t} = v_e(E) n_e - \frac{n_*}{\tau_r}, \qquad (1.3.3)$$

$$\frac{\partial^2}{\partial x^2} = \frac{e}{\varepsilon_0}(n_e - n_i) \qquad (1.3.4)$$

with the boundary conditions at the cathode

$$\varphi = 0,\ j_e = \gamma_i \mu_i E n_i + \gamma_{ph} \int_0^d \frac{n_*}{\tau_r} dx \qquad (1.3.5)$$

and the anode

$$\varphi = Up(t), \qquad (1.3.6)$$

where φ is the potential, E is the electrical field intensity, v_e is the electron drift rate, μ_i is the ion mobility, v_i and ν_e are ionization and excitation frequencies, γ_i is the secondary ion-electron emission coefficient, γ_{ph} is the photoemission coefficient, and j_e is the electron current density. The constants of the processes involving electrons were determined from the electron energy distribution function, which was obtained by the Monte Carlo simulation of the electron motion. The calculations were made for conditions approaching the experimental conditions, i.e. at the nitrogen pressure of 4 atm and the interelectrode gap equal to $d = 3$ mm. The voltage at the electrodes was approximated by the function

$$U_p(t) = \begin{cases} \dfrac{U_0}{\tau_f} t,\ t < \tau_f; \\ U_{0,} \quad t \geq \tau_f, \end{cases}$$

where $\tau_f = 10^{-9}$ s is the voltage rise time and $U_0 = 100$ kV is the voltage pulse amplitude.

A uniform distribution of free electrons and ions over the volume of the gas gap at the concentration $n_{e,i} = 10^3$ cm^{-3}, which was a background concentration for the ambient air, was taken as the initial conditions. Conditionally speaking, three electrons – one electron per millimeter – are present in the gap at this concentration of background electrons at the initial stage of the breakdown. When an electrical field is applied to the gap (the calculation was performed assuming an average field in the gap equal to 300 kV/cm), the electrons start drifting to the anode. The curves in Figs. 3,

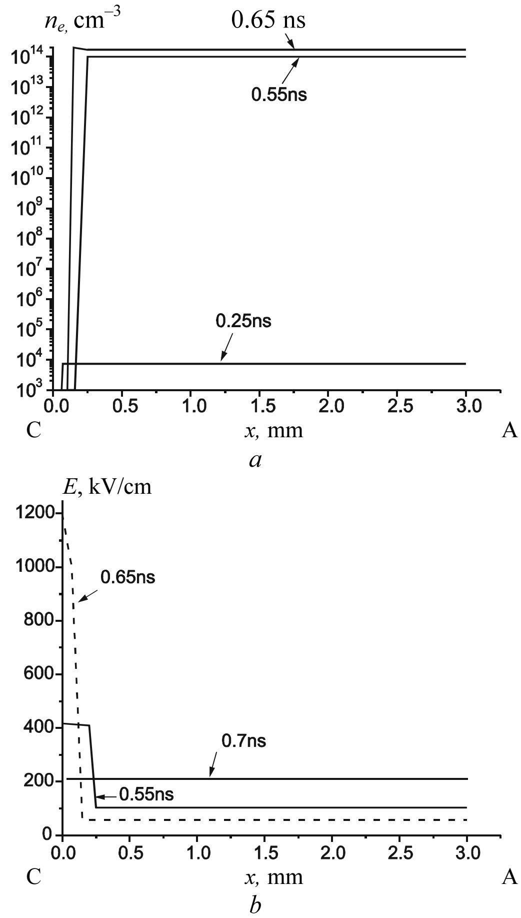

Fig. 3. Variations of electron concentration (a) and electrical field intensity (b) in the gas gap for the discharge development in the case of a uniform pre-ionization. The cathode (C) to anode (A) distance is plotted on the abscissa axis

a and *b* show the variation of the electron concentration and the electrical field intensity in the gap during development of a discharge. The cathode-to-anode distance is plotted on the abscissa axis. It is seen that at the initial stage (in the first 0.55 ns), when the concentration of electrons in the gap is comparatively small, the plasma column moves away from the cathode for up to 0.25 mm. In this case the concentration of electrons in the plasma column (the region of the quasi-neutral plasma occupying most part of the interelectrode volume) grows quickly (Fig. 4, a portion of the curve A). Because the mobility of electrons is higher than that of ions, a charge-depleted zone, in which the ion concentration is much larger than the electron concentration, is formed between the plasma column and the cathode. The ions partially screen the external field: the field decreases in the plasma column and is intensified in the near-cathode region. Consequently, the growth of the electron concentration in the column slows down (Fig. 4, a portion of the curve B) and the ionization rate increases concurrently in the near-cathode region. As a result, the ionization wave (the boundary of the plasma column) quickly (in time interval of 0.55–0.7 ns after the process starts) nears the cathode and forms a cathode layer ensuring the required supply of electrons to the discharge. The field distortions caused by an uncompensated charge of ions vanish; the field in the plasma column increases; and the concentration of electrons begins growing again (Fig. 4, a portion of the curve C).

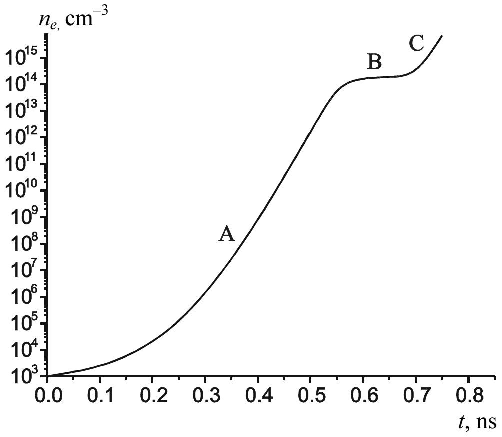

Fig. 4. The concentration of electrons in the plasma column in the case of a uniform pre-ionization

According to these calculations, the streak of the glow should have a uniform illumination with the increasing intensity of the whole gap except the near-cathode region. Fig. 5 presents a computer approximation of the pattern. Later the illumination region should approach the cathode.

Such streak photos are observed in some experiments, but their number accounts for not more than 10–15% of all the obtained photographs. The breakdown of the "second" type is observed by far more frequently. Our later paper [3] is dedicated to the analysis of the breakdown of the "second" type.

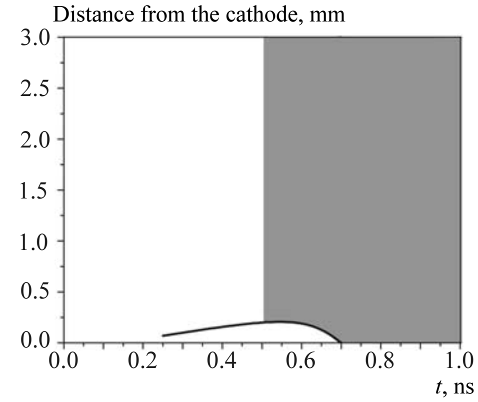

Fig. 5. Development of ionization waves and the glow in the gap in the case of a uniform pre-ionization. The gray background shows the visible glow of the gas

The results, which we obtained for nitrogen at a pressure of 40 atm [4], can also be referred to the breakdown of the "first" type. A typical streak of the discharge glow is shown in Fig. 6. A bright glow quickly (in < 100 ps) fills the whole gap. The very initial stage of the breakdown formation (in the first 100 ps) cannot be seen in detail in the photographs because its duration is comparable with the time resolution of the AGAT SF3M streak camera used in the experiments. This situation can also be explained in terms of the calculation model assuming a uniform pre-ionization.

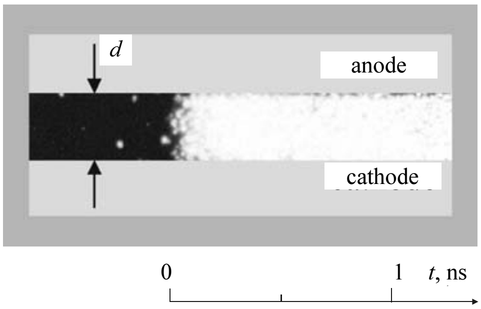

Fig. 6. Streak photographs of the glow accompanying the breakdown of gas gaps 1.42 mm wide (nitrogen, 40 atm). The zero of the time scale in this figure is taken as the instant when the glow appears in the gap

The calculations were made for an interelectrode gap with $d = 1.4$ mm receiving a voltage pulse of the amplitude $U_0 = 150$ kV and the rise time $\tau_f = 0.3$ ns. Similarly to the case of 4 atm, a positively charged layer is formed at the cathode and this layer distorts the electrical field in the gap. However, since the layer is thin (*xc*) (Fig. 7), it cannot considerably reduce the electrical field in the plasma column (E_p). At the same time, the field in the near-cathode region increases up to ~ 10^7 V/cm, leading to a great rise of the field emission current. As soon as it equals the current in the plasma column, the cathode layer thickness decreases to $x_c \sim 1/\alpha$… (α being the collision ionization coefficient). Then the layer parameters are "self-adjusted" so that the field emission current equals the current in the plasma column, i.e., the discharge current.

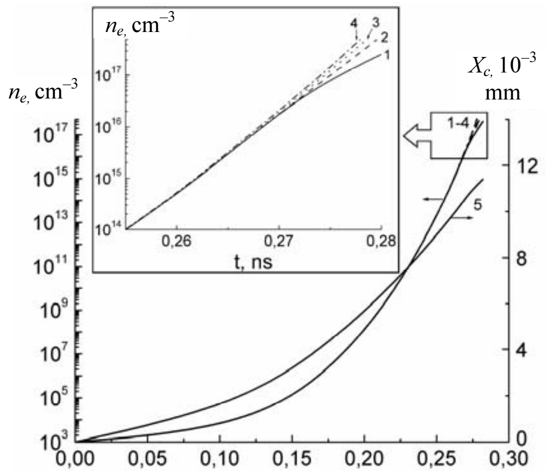

Fig. 7. Time dependences of the electron concentration n_e (1–4) and the length of the near-cathode region x_c (5) at different field gain coefficients (β) at the cathode: 1 – β = 1; 2 – β = 5; 3 – β = 20; 4 – β = 40

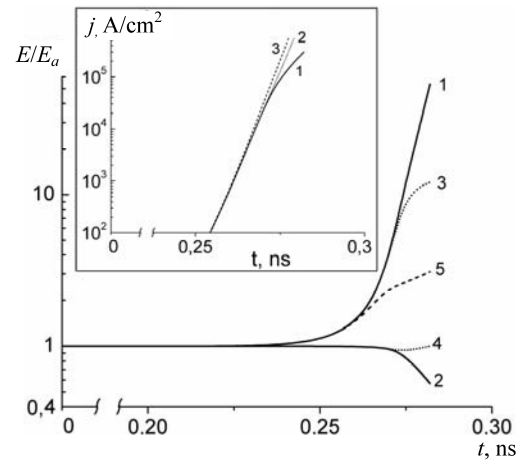

Fig. 8. Dependences of the ratio of the fields in the near-cathode region (E_c) and the plasma column (E_p) to the average field $E_a = U(t)/d$, where $U(t)$ is the gap voltage and d is the interelectrode distance: 1 – E_c/E_a, 2 – E_p/E_a at β = 1; 3 – E_c/E_a, 4 – E_p/E_a at β = 5; 5 – E_c/E_a at β = 20. Shown in the inset are time dependences of the current density: 1 – β = 1, 2 – β = 20, 3 – β = 40.

The field emission current should be calculated considering that each cathode has its electrical field gain coefficient because of the presence of micro-points. A typical value of this coefficient is β ~ 10, but it is specific for each cathode. Since β was unknown in our experiments, we had to make calculations for the gain coefficients β = 1, 5, 20, and 40.

According to the calculations, the variation of β values influences, in the main, only the field in the near-cathode region (E_c) (Fig. 8) and changes little the qualitative picture of the ionization processes (Fig. 7).

Thus, the picture of the discharge glow will qualitatively correspond to the one depicted in Fig. 5 with the only difference that the dark near-cathode region will be practically invisible because of its small size (~ 10^{-2} d = 0.014 mm).

4. Conclusion

The experimental-theoretical investigation of the processes 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 the ionization processes, which cause the breakdown, begin in the gas volume due to the multiplication of background free electrons. Modeling of wave ionization processes in the gas volume with the supposition of a uniform distribution of initial free electrons is in good agreement with part of the streak photographs of the glow accompanying the breakdown observed in the experiment. The other streak photos correspond to a nonuniform distribution of initial free electrons. Processes taking place in these conditions will be analyzed in our later report [3].

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