Kinetic Processes and Ionization of Medium at Initial Stage of Subnanosecond Gas Breakdown

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Abstract - The pre-breakdown and initial stages of switching of overvoltaged high-pressure gas gaps (nitrogen, 30-40 atm) under the action of high-voltage subnanosecond pulses were studied experimentally and theoretically. The breakdown looked like a bright flash, which filled the interelectrode gap almost homogeneously in a time of about 100 ps. The experimentally observed phenomena were interpreted taking into account heating of electrons by their collisions with gas molecules and ionization of the gas under the electron impact. Calculations demonstrated that the gas was ionized by "hot" electrons in step or like a flash. This result correlated well with relevant experimental data. It was concluded that high-pressure gas commutators could provide voltage pulses having fronts a few tens of picoseconds long.

1. Introduction

The study of mechanisms responsible for initiation of a pulsed breakdown at the gas pressure of tens of atmospheres is of special importance for understanding the physics of the gas discharge and its possible practical applications. It was noted [1] that high-voltage pulses with shortest fronts were generated just in high-pressure gas commutators. Although high-pressure gas gaps are widely used in electrophysical equipment, the research of mechanism of development of a pulsed breakdown in gases over the subnanosecond range is considerably behind their practical use. The small-size voltage pulse generators type RADAN [2], which form subnanosecond high-voltage pulses with smoothly adjustable parameters, open up new opportunities for the investigations of pulsed breakdown in subnanosecond range. These generators were designed at the Institute of Electrophysics (Ural Branch RAS) in the last 15 years. They were used in experiments concerned with recording of the luminescence, which accompanies the pre-breakdown and initial stages of switching of high pressure gas gaps under the action of ultrashort voltage pulses. Models of the breakdown at the initial stage (at the first several hundred picoseconds) of its development were proposed. The outlooks for the use of high-pressure gas switches in generation of high-voltage pulses with picosecond fronts were evaluated.

2. Experimental

The experiments were performed using an installation [3, 4] based on a small-size high-voltage pulse generator type RADAN-303 [5]. The installation provided synchronous recording of subnanosecond high-voltage pulses applied to the gas gap and the streak investigations of the luminescence accompanying pre-breakdown and breakdown processes in the gap. Today the high-speed streak photographing [6] is the only method for determination of the breakdown nucleation region in the discharge gap and the breakdown progress dynamics. The experimental setup was described comprehensively in [3, 4].

The test chamber (Fig. 1) represented a 50-Ohm length of a gas-filled coaxial line with an additional peaking gap and the test gas-discharge gap, which were made as discontinuities of the central electrode. The gas-tight gap adjusting unit (item 12, Fig. 1) ensured that the gap width was preset to within 0.05 mm.

The test gas was nitrogen since it is used most often in high-pressure spark gaps. The gas pressure in our experiments was adjusted at 30 to 40 atm. The gas-discharge gap received a high-voltage pulse (Fig. 2a) with a controlled voltage up to 180 kV, the rise time of (300-400) ps at the levels of 0.1-0.9, and FWHM equal to (0.5-1.5) ns. The voltage rise rate at the pulse front was $(4\text{-}5)\times10^{14}$ V/s. The amplitude of the pulse voltage at the breakdown gap was stabilized at the level of fractions of a percent. Measurements were made using a C7-19 oscilloscope whose transient

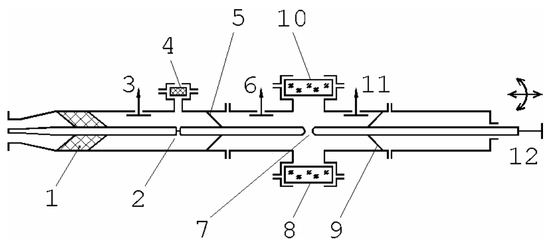

Fig. 1. Test chamber: 1-input insulator; 2-peaking gap; 3,6 and 11-capacitive voltage dividers; 4-6mm diameter window (organic glass); 5,9-bearing insulators; 7- test gas-discharge gap; 8,10-20mm diameter windows (glass), and 12-electrod-moving gear

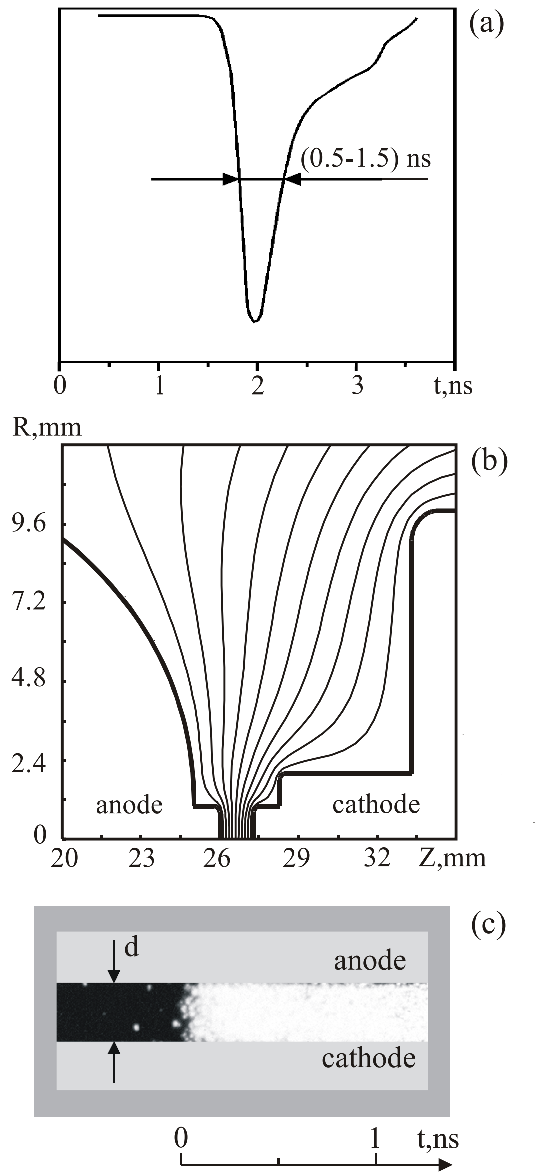

Fig. 2. The pulse at the test gas-discharge gap (a); the configuration of the discharge gap electrodes and the distribution of the electrical field in the gas gap (b); streak photograph of the glow accompanying breakdown processes in nitrogen at 40 atm., gap width d=1.42 mm (c)

response was limited at 300 ps by a cable delay line.

The configuration of the discharge gap electrodes and the distribution of the electrical field in the gas gap are shown in Fig. 2b. Here Z is the axis of symmetry of the system cathode-anode. The gas gap was ruptured at the edge of cylindrical bosses 2 mm in diameter projecting from the surface of the cathode and the anode. These bosses served for spatial affixment of the breakdown channel to the depth resolution zone of the AGAT-SF3M streak chamber intended for photograph the luminescence, which accompanied pre-breakdown and breakdown processes in the gas gap. The electrodes were made of copper. Measurements were made only after the electrode surface was trained with several hundred high-voltage pulses. The electrical field distribution was computed using the interactive program for calculation of electron guns SAM [7]. The cathode edge radius was taken equal to 0.2 mm. The calculated value of the normal component of the electrical field (as calculated from the pulse amplitude) was E_1 = (0.9-1.4) MV/cm on the plane of the most protruding part of the cathode and E_2 = (1.7-2.4) MV/cm on the cathode edge.

Figure 2c presents a typical streak photograph of the luminescence accompanying the gas breakdown. It was time-scanned on the plane parallel to the plane of electrode surface. The bright luminescence quickly (<100 ps) filled the whole interelectrode gap. The luminescence covered the gap at an efficient rate higher than 1.4×10^9 cm/s. The very beginning of the breakdown formation (the first 100 ps) could not be seen in detail in the streak photographs, because the duration of this stage was comparable with the time resolution of the streak camera.

3. The Model of the Initial Stage of the Breakdown

The following model was adopted for interpretation of the experimental data. Electrons are heated intensively due to their frequent collisions with neutrals. "Hot" electrons ionize the gas. The energy losses of electrons includes elastic collisions with neutrals and the ionization loss. According to relevant estimates, the energy loss for elastic collisions is small because electrons and gas molecules have largely different masses and, therefore, it may be neglected. In this case, the situation is described by the following system of equations:

$$3/2\,\partial T_e/\partial t = eEu_e - \dot{w}_i\,; \qquad (1)$$

$$\partial n_e/\partial t = (n_0 - n_e)t_i^{-1}. \qquad (2)$$

The terms on the right side, which correspond to ionization, are defined by integrals

$$\dot{w}_i = \langle s_i v_e w_e f_e \rangle_e\,; \qquad (3)$$

$$t_i^{-1} = \langle s_i v_e f_e \rangle_e\,, \qquad (4)$$

where s_i is the ionization cross-section [8]. The electron velocity distribution function f_e, which is used for averaging, is assumed to be a Maxwell function, because elastic collisions have the shortest relaxation time [8]. The first term on the right side of equation (1), which is responsible for Joule heating of electrons, contains the drift velocity u_e defined by the relationship:

$$u_e = aE/p + u_{e0}\,, \qquad (5)$$

where p being the pressure; $a = 2.5\times10^5$ tor cm^2/sV; $u_{e0} = 2\times10^6$ cm/s in accordance with the data reported in [9]. Calculations were made using the following data: the gas concentration $n_0 = 4\times10^{20}$ cm^{-3}; the electrical field intensity in the gap $E = 2\times10^6$ V/cm; the voltage rise time $t_f = 0.3\times10^{-9}$ s. The voltage pulse shape was approximated by a half-sinusoid. Calculation results are shown as plots in Figs. 3a, b.

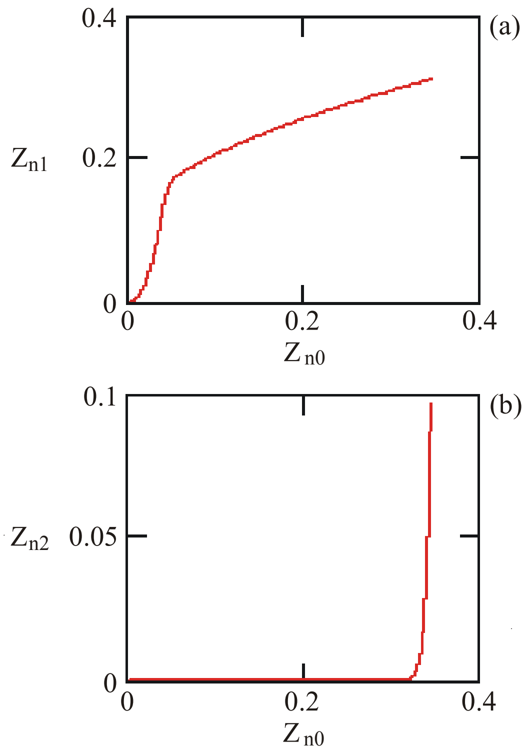

Fig. 3. Calculations of the dimensional temperature of electrons (a) and the concentration of charged particles (b)

The abscissa in these plots is the dimensional time referred to the length of the voltage pulse front (Z_{n0}). The ordinate (Fig. 3a) is the dimensional temperature of electrons referred to the ionization potential of gas molecules (Z_{n1}). It is seen that first the temperature increased rapidly thanks to Joule heating, but then the ionization loss came into play and the curve became more flattened. The ordinate in Fig. 3b is the dimensional concentration of charged components (electrons and ions) referred to the initial gas concentration (Z_{n2}). During the first 100 ps (33% of the voltage rise time in the gap) ionization was nearly absent. Then the gas ionized sharply as a flash during 10-20 ps (3-7 % of the voltage rise time in the gap). The temperature of electrons at that moment accounted for 0.3-0.35 of the ionization potential, i.e. the gas was ionized by "hot" electrons. The light flash was also observed in the experiment. It may be confirmed therefore that the chosen model was valid. Ionization was not calculated above 10-15%, because in this case it was necessary to consider Coulomb interactions and, hence, the task would be considerably complicated. We think however that the character of the flash will not change. We did not intend to take into account the coordinate dependence of the ionization process either. The ionization process was so accelerated at the experimental pressure and the electrical field intensity that it was almost homogeneous in the interelectrode gap.

4. Conclusion

The experiments on the pulsed breakdown of overvoltaged (1.7-2.4 MV/cm) high-pressure (30-40 atm) gas gaps demonstrated that the breakdown dynamics was so short at the initial stage that the recording equipment did not resolve any inhomogeneities in space and time. The breakdown was observed as a bright flash, which filled almost homogeneously the interelectrode gap during ~100 ps. The experimentally observed phenomena were interpreted taking into account heating of electrons as a result of their collisions with gas molecules and considering ionization of the gas under the electron impact. At the beginning (up to 0.2 of the ionization potential) the temperature was determined by Joule heating and then the growth of the temperature decelerated due to the impact ionization loss. The concentration of charged components (the formation of electrons and ions) increased in step or as a flash with the characteristic delay time of ~100 ps relative to the beginning of the process. The flash was 10-20 ps long. According to calculations, the temperature of electrons at the moment of the flash accounted for 0.3-0.35 of the ionization potential, i.e. the gas was ionized by "hot" electrons. A good correlation between calculated and experimental data pointed to validity of the adopted model. According to estimates, high-pressure gas commutators can provide high-voltage pulses with fronts of several tens of picoseconds. It may be expected that further research in this direction will lead to additional optimization of parameters and development of new superfast overvoltaged high-pressure gas commutators.

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