Subnanosecond breakdown of a point-to-plane gap at negative and positive polarities

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Abstract. The influence of the polarity of high-voltage nanosecond pulses on the prebreakdown stage duration at the subnanosecond breakdown of a 1-cm point-to-plane gap filled with air (13-800 kPa) has been experimentally studied. Furthermore, the influence of the shape of the plane electrode surface on the one has been studied too. Waveforms of voltage and current pulses were analyzed. It was found that when a streamer appears near the pointed electrode, a dynamic displacement current flows due to the redistribution of electric field strength in the gap. This allowed us to establish the instant of appearance of the streamer relative to the instant of applying the voltage across the gap. It was established that the positive streamer appears later than the negative one at low air pressure. As a result, the inversion of the polarity effect is observed. An increase in air pressure, as well as the use of a plane electrode, on the surface of which there are sharp protrusions, reduce this time gap. It disappears at air pressure of 400-800 kPa. The processes taking place in the gap are discussed.

1. Introduction

In gas discharge physics, it is known that the breakdown voltage of gaps with an asymmetric distribution of the electric field strength (e.g., point-to-plane gap) depends on the polarity of voltage pulses. In a quasistatic electric field, the breakdown voltage with a negative pointed electrode is approximately twice as high as with a positive one [1]. This effect was called the "polarity effect". The reason for the polarity effect is the shielding of the negative pointed electrode by a cloud of immobile positive ions. In case of the positive pointed electrode, electric field strength is amplified by ions. Much attention has been paid to high-voltage nanosecond discharges at high overvoltage due to the development of pulse technology and the widespread use of nanosecond voltage generators. In such discharges, the inversion of the polarity effect was observed: the breakdown voltage with the negative pointed electrode was less than with the positive one [2-6]. However, the ordinary polarity effect was observed at high pressure [5]. In [5, 6], it was suggested that the inversion of the polarity effect is due to the large time of explosion center formation on a plane cathode. Note that for the first time the inversion of the polarity effect was observed, apparently, in [7]. Currently, there is no clear understanding of the reasons of the inversion of the polarity effect. In this work results of experimental study of the influence of polarity and the shape of the plane electrode surface on breakdown characteristics are presented.
2. Experimental setups and methods
The first experimental setup consisted of a discharge chamber, GIN-50-1 nanosecond voltage generator of positive polarity with a variable amplitude, and a Tektronix TDS3054B digital oscilloscope (500 MHz, 5 GSa/s). The discharge chamber was equipped with a CVD and current shunt composed of chip-resistors. Voltage pulses were applied across a needle-to-plane gap. Interelectrode distance was 8.5 mm. Waveforms of voltage and current were registered in the threshold for breakdown of the gap conditions, as well as at high voltages. This allowed us to study the displacement current at different voltage amplitudes, which arises as a result of the redistribution of the electric field strength during the propagation of the streamer. The obtained data were useful in analyzing the waveforms obtained on the second setup.

The block diagram of the second experimental setup is presented in figure 1. The setup consisted of RADAN-220 generator, a discharge chamber equipped with a capacitive voltage divider (CVD) and current shunt composed of chip-resistors, as well as Agilent DSO-X6004A oscilloscope (6 GHz, 20 GSa/s). The RADAN-220 generator produces high-voltage nanosecond pulses of both polarities with a fixed amplitude (U ≈ 110 kV, τ₀=2 ns, τᵣ ≈ 0.5 ns). Voltage pulses were applied to a 6-mm diameter tubular electrode made of twisted 50-µm Al foil. Grounded plane electrode was made of an Al disk. Two designs of the plane electrode were used. The first plane electrode was polished, and the second one had periodical circular grooves which formed sharp circular edges. The depth of the grooves was 1 mm and the period was 0.5 mm. Such design provides an amplification of electric field strength. Interelectrode distance was 1 cm. Signals from the CVD and current shunt were registered with the oscilloscope (50 pulses were recorded for each experimental point). The discharge chamber was filled with air. The pressure ranged from 13 to 800 kPa.

![Block diagram of the experimental setup](image)

Figure 1. Block diagram of the experimental setup.

3. Results of the experiment
3.1. Dynamic displacement current
It is well known that a time-varying electric field causes a displacement current. The appearance and formation of a dense plasma in the gap leads to a redistribution of the electric field strength. As a result, a displacement current “flows” in the gap. To underline the fact that this current is caused precisely by the streamer propagation, and not by a change in the external electric field, it was called the dynamic displacement current (DDC). The DDC can be registered by a current shunt connected in series to the electrical circuit. However, under typical conditions with the formation delay of 1 ns or less, the registration of the DDC is a complex task requiring recording equipment (shunts, oscilloscopes) with a high temporal resolution. In this regard, we decided to study the displacement current under conditions close to the threshold for the breakdown of the gap. Then we gradually
increased the voltage pulse amplitude and watched the DDC change. This experiment has been carried out on the first setup.

Waveforms of voltage and current at different voltage pulse amplitudes (8, 13, 20 kV) are presented in figure 2. The minimum voltage amplitude at which the formation of the streamer was observed was ≈15 kV (figure 2a). Note that the streamer formation under these experimental conditions has been studied using an ICCD camera in [8] as well as under more extensive conditions in [9]. The formation delay was ≈10 ns. It allowed us to register the DDC. It is seen that a displacement (capacitive) current \( C \frac{dU(t)}{dt} \) \((C – \) the gap capacity, \( U(t) – \) voltage) is observed at applying a voltage across the gap (figure 2a, arrow 1). The appearance of the streamer near the pointed electrode is accompanied by the DDC (figure 2a, arrow 2). The DDC value depends on the streamer velocity. An increase in the streamer velocity leads to an increase in the rate of the redistribution of electric field strength, hence, the DDC value becomes higher. In accordance with the waveforms, the streamer has a high velocity at initial and final stages, when the streamer is close to bridging the gap (figure 2a, arrows 2, 3). After bridging the gap, a combination of conduction current and displacement (capacitive) current is observed (figure 2a, arrow 4). The average streamer velocity was ≈9 \times 10^6 \text{ cm/s} [8]. The DDC increases with the voltage amplitude increasing (figure 2b, arrows 2, 3). It indicates an increase in the streamer velocity. Furthermore, at the final stage, the DDC reaches values comparable to the discharge current, but the gap is not bridged yet. Note that the conduction current of the same value flows in the streamer plasma at the same time. At the maximum value of the voltage, the DDC becomes practically indistinguishable at initial and final stages (figure 2c, arrows 3, 4) due to limited time resolution of the Tektronix TDS3054B digital oscilloscope (500 MHz, 5 GSa/s). These results can be extended to the data obtained on the second setup, presented below.

![Figure 2](image_url)

**Figure 2.** Waveforms of voltage and current obtained on the first setup: 1 – displacement (capacitive) current \( C \frac{dU(t)}{dt} \), 2 – dynamic displacement current when the streamer starts moving, 3 – dynamic displacement current when the streamer is arriving to the plane electrode, 4 – combination of conduction and displacement (capacitive) currents \( C \frac{dU(t)}{dt} \).

### 3.2. The influence of polarity and the shape of the plane electrode surface on the subnanosecond breakdown

Let’s consider the waveforms of the voltage and current pulses registered on the second setup at different polarities, pressures, as well as with different plane electrodes (figure 3). The presented waveforms are the result of averaging over 50 implementations. As on the first setup, a displacement (capacitive) current \( C \frac{dU(t)}{dt} \) is observed at applying a voltage across the gap (figure 3, arrows 1). Its value reaches up to 200 A due to the short voltage pulse rise time and high amplitude. Then the streamer appears. Its formation and propagation is accompanied by the DDC (figure 3, arrows 2). The DDC reaches 1-2 kA due to the high velocity of the streamer \( (10^5-10^6 \text{ cm/s}) [10] \). Such values of the DDC were also obtained in [11]. These values are comparable with the discharge current after the breakdown. Apparently, a decrease in a voltage occurs due to the high current that flows on the circuit during the streamer propagation. The decrease in the voltage during the streamer propagation at the subnanosecond breakdown of a point-to-plane gap was shown in simulations [12] and analytical
The observed voltage decrease is not a random event or an artifact of the registration system. This feature is reproduced from pulse to pulse and depends on the gas pressure, or rather on the streamer velocity.

**Figure 3.** Waveforms of voltage and current obtained on the second setup. Air pressure of (a, d) 13 kPa, (b, e) 100 kPa, (c, f) 800 kPa. Top: polished plane electrode. Down: grooved plane electrode. Black lines correspond to negative polarity (waveforms are inverted); red lines correspond to positive polarity. 1 – displacement (capacitive) current $C \cdot \frac{dU(t)}{dt}$, 2, 3 – dynamic displacement current during the streamer propagation.

The dynamic of the DDC allows us to analyze the influence of polarity and the shape of the plane electrode surface on the subnanosecond breakdown. At air pressure of 13 kPa, there is a significant difference between negative and positive polarity. The figure 3a shows that the positive streamer appears $\approx$ 200 ps later than the negative one. Analysis of individual 50 waveforms of current showed that the spread in time of individual pulses with respect to the average is about $\pm$ 25 ps at negative polarity and about $\pm$ 130 ps at positive one. This difference is due to the mechanism of the initial electrons appearance. Field electron emission from the tubular cathode provides the appearance of initial electrons at negative polarity. At positive polarity, the autoionization of atoms and molecules occurs on the surface of the tubular anode [14]. Ions accelerated by a very high electric field pre-ionize the gas in the vicinity of the anode. Efficiency of this process depends on the gas pressure. An increase in the gas pressure leads to an increase in the ion current density. Furthermore, the frequency of collisions between ions and gas molecules increases. As a result, the positive streamer appears earlier (figure 3b, c), and stability of the positive streamer appearance has become the same as the negative streamer. However, together with the increase in pressure, the reduced electric field strength decreases and the streamer formation slows down, as it can be seen in figure 3c (arrow 2). Thus, at low air pressure the inversion of the polarity effect is observed due to a large statistical lag. An increase in air pressure leads to a decrease in the difference between the breakdown voltage at positive and negative polarity, as in [6]. At air pressure range of 400-800 kPa, it is difficult to determine at what polarity the streamer appears earlier.

The difference between the breakdown voltage at positive and negative polarity at low pressure was decreased by using the grooved plane electrode instead of the polished one (figure 3d vs figure 3a); it is seen that the positive streamer appears earlier with the groove plane electrode. The statistical lag was decreased. This was made possible by field emission from the grooved plane
electrode (cathode). The emitted electrons are accelerated in a high electric field near the grooved electrode and move toward the tubular anode, pre-ionizing the gas. This effect disappears as the pressure increases.

The influence of the shape of the plane electrode surface on the breakdown at both polarities are shown in figure 4. It is seen that there is no significant difference in the waveforms of currents at negative polarity (figure 4a-c). At positive polarity as well as at low pressure (figure 4d), the streamer appears earlier while using the grooved plane electrode (cathode) due to field electron emission. There is no influence of the shape of the plane electrode surface on the appearance of the streamer at an air pressure of 50 kPa and higher. Apparently, electrons emitted from the grooved plane electrode do not reach the vicinity of the tubular anode. The autoionization of atoms and molecules provides pre-ionization of the gas near tubular electrode at a pressure of 50 kPa and higher under the conditions of the experiment.

The formation of cathode spots at both polarities must occur during the propagation of the streamer. This process is promoted by high electric field strength, as well as high (1-2 kA) values of the DDC. It means that a high-density current flows through a microprotrusions on the cathode surface when the streamer moves toward a plane electrode. However, the formation of cathode spots has not been studied experimentally.

**Figure 4.** Waveforms of voltage and current obtained on the second setup. Air pressure of (a, d) 13 kPa, (b,e) 50 kPa, (c, f) 800 kPa. Top: negative polarity (waveforms are inverted). Down: positive polarity. Black lines correspond to the polished plane electrode; blue lines correspond to the grooved plane electrode.

**4. Conclusion**

The data of carried out experiments show that the breakdown voltage at positive polarity differs significantly from that at negative one at subnanosecond breakdown of a point-to-plane gap filled with a low-pressure gas. This difference is caused by a large statistical lag at positive polarity. It was assumed that this is due to the difference in the mechanism of initial electrons creation. At negative polarity, electrons emitted from a negative pointed electrode and accelerated in high electric field pre-ionize the gas in the vicinity of this electrode. At positive polarity, accelerated ions produced by autoionization of atoms and molecules on the surface of the pointed anode provide preliminary
ionization of the gas. However, the autoionization requires two orders of magnitude higher electric field strength than field electron emission. Moreover, the density of ion current depends on gas pressure. Consequently, the efficiency of initial electrons creation by these processes is different. It has been experimentally shown that as a pressure increases up to atmospheric the statistical lag decreases at positive polarity. Furthermore, the shape of the plane electrode surface (cathode – at positive polarity) affects the statistical lag. Field emission from the one can provide a preliminary gas ionization in the vicinity of a pointed electrode (anode).

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