Time-Space Radial Development of Nanosecond Dielectric Barrier Discharge in Flat Air Gaps under Atmospheric Pressure

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Abstract. The study of the time-spatial radial development of the nanosecond dielectric barrier discharge in open air was carried out by means of segmented electrode technique. It was found experimentally that the discharge development depends on the air gap height. Discharge currents through the segments in 1-mm and 2-mm air gaps started almost simultaneously with a time delay relative to each other no more than 1 ns. An increase of the delay between discharge currents appearance and a certain order of their appearance was observed with increasing the height of the gap. Different development of the discharge correlated with a different growth rate of electric field strength in the gap and the ratio $E/p$.

1. Introduction

Nanosecond dielectric barrier discharge (NDBD) is a discharge, characterized by a current pulse with a current density of several amperes per cm$^2$, which takes place between electrodes, if one of them is isolated from the gap by a dielectric. The NDBD can be realized by providing high growth rate of voltage at the electrodes of the discharge gap [1–4].

Obtaining the NDBD in atmospheric air at natural humidity has been a breakthrough for applied science as it allows realizing a volume low-temperature plasma without additional preionization sources in open air. Extensive research of the NDBD depending on parameters of the voltage applied to the electrodes such as amplitude, repetition rate, growth rate, has been carried out for the last ten years. However the task of the NDBD development in millimeter air gaps is not fully understood. Evolution of the NDBD in time and space is analyzed mainly through high-speed photography with a time resolution of a few nanoseconds [5]. Nevertheless, even such method is not always possible to separate the temporal events taking place in the air gap, so another approach to the investigation of the NDBD has been used in the study. The study of the time-spatial radial dynamics of the NDBD in millimeter air gaps was conducted with the use of a ring segmented electrode [6, 7], together with the use of high-precision diagnostic devices enabled to achieve resolution accuracy of 200 ps.

2. Experimental setup

The experimental setup is presented in figure 1. Unipolar negative high-voltage square pulses with the pulse width of 600 ns, amplitude of 20 kV with rise time of the voltage pulse (10–90 %) $\approx$ 40 ns are formed at the electrodes of the discharge gap by a specially developed semiconductor high voltage generator (HVPG) [8]. Pulse repetition rate $f$ was set to 30 Hz during the experiment.

In figure 1 the discharge gap is shown as a set of capacitors C1, C2, C3 and C4, corresponding to the equivalent capacitances of the gaps, formed by the ring segmented electrode and the high voltage electrode, covered by the alumina ceramics plates with $\varepsilon = 9$ and dimensions 50×50×2 mm. Due to the same area of all the segments these capacitances were quite the same either, excepting the edge segment, as its capacity was bigger than the other ones due to the fringing field effect.

The NDBD was ignited in atmospheric air at natural humidity of 40–60 %. The height of the discharge gap ranged from 1 to 3 mm during the experiment.
Figure 1. Experimental setup.

The voltage at the electrodes was measured by Tektronics P6015A high-voltage probe. The time-space development of the NDBD was estimated through the comparison of the current waveforms in different volumes of the gap $I_1$, $I_2$, $I_3$ and $I_4$, obtained using synchronized low-inductance resistive current sensors (50 Ohm). The voltage and currents signals were observed by LeCroy WaveRunner 104Xi-A oscilloscope (bandwidth of 1 GHz, sampling rate of 10 GS/s). The degree of NDBD homogeneity was analyzed through the method of optical diagnostics, which was based on comparison of the light emission brightness distribution in the gap with the brightness curve of the ideal isotropic glow source discussed in detail in [9].

3. Experimental results and discussion

Due to the obtained experimental results, the different delays between discharge ignitions in different segments were observed in dependence on the height of the discharge gap $d$. Currents in the segments (corresponding in figure 1: C1 – central segment, C2 – next to the central segment, C3 – next to C3, C4 – the edge segment) developed nearly at the same time at $d = 1–2$ mm: the delay time between them was no more than 1 ns. Moreover, they appeared in a random order. The typical current waveforms in the segments at $d = 2$ mm are shown in figure 2a.

As for $d = 3$ mm the delay between discharges increased to 3-5 ns, and the discharges ignited in a definite way. The first discharge started in the central segment, the second – in the second segment and so on, spreading radially, as it was shown in figure 2b.

Figure 3 shows brightness distribution of the glow in the central layer of the gap cross section (layer thickness = 10 μm), obtained by the use of digital photo processing for $d = 1$ mm (figure 3a), $d = 2$ mm (figure 3b) and $d = 3$ mm (figure 3c).

In figure 3 value $\sigma$ is a standard deviation and it is obtained by the formula:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=0}^{n} (D_i - L(a, i))^2},$$

where $D_i$ – experimental brightness values, $L(a, i)$ – the ideal brightness curve, obtained according to the electrode shape, $i$ – a pixel number of the photo image, corresponding to the horizontal coordinate of the gap from one edge to another, $n$ – a total number of pixels. $\xi$ is an average experimental brightness value.

As one can see from figure 3 the ratio $\sigma/\xi$ is different for different heights of the gap.
Figure 2. Typical current waveforms at voltage rise in different segments at various height of the discharge gap $d$: a) $d = 2$ mm, b) $d = 3$ mm.

Figure 3. Brightness distribution in the central layer of the air gap (10 μm). $L(\alpha,i)$ – ideal brightness distribution, $D_i$ – experimental brightness values. $\sigma$ – standard deviation, $\xi$ – average brightness value. a) $d = 1$ mm, b) $d = 2$ mm, c) $d = 3$ mm.
The minimum value of $\sigma/\xi = 0.3$ is observed in 1-mm air gaps. With the height increasing this ratio also increases. Thus, it can be concluded that the degree of NDBD homogeneity got worse with increasing the air gap.

The ratio $E/p$ in the air gap, and the growth rate of electric field strength in the air gap $dE/dt$ appeared to play the major role in the NDBD development, as the gas composition and parameters of the discharge gap and the external circuit were the same during all experiments.

The growth rate of electric field strength in the discharge gap $dE/dt$ was estimated to study the causes of various discharge behavior depending on the height. For the calculations we used the value of the voltage at the electrodes at the ignition moment, i.e. at the moment of the discharge current appearance.

NDBD was ignited at different voltage across the electrodes depending on the height of the air gap. The voltage amplitude across the electrodes at the ignition moment was 10.8 kV for 1-mm gap, 14.5 kV – for 2 mm gap and 19 kV – for 3-mm gap.

The equivalent circuit of the discharge gap in the absence of the discharge is a voltage divider: barrier capacity and “air gap” capacity, connected in series [10–12]. Therefore, the ignition voltage at the gap can be calculated taking into account factor $k$, defined as:

$$k = \frac{C_b}{C_a + C_b},$$  \hspace{1cm} (2)

where $C_b$ – barrier capacity and $C_a$ – “air gap” capacity. In our experiments $C_b = 15$ nF, $C_a$ decreased form 6 pF to 2 pF depending on the height of the discharge gap $d$.

Thus, the ratio $E/p$ can be estimated by the following expression:

$$\frac{E}{p} = \frac{kV_{in}}{p d},$$  \hspace{1cm} (3)

It is easy to estimate the growth rate of electric field strength in the air gap with known $k$ and growth rate of the applied to the electrodes voltage $dV/dt \approx 250$ V/ns, which is determined by the peculiarities of the HVPG operation [8]. It can be calculated for a flat gap by the formula:

$$\frac{dE}{dt} = \frac{dV}{dt} \cdot \frac{k}{d}.$$  \hspace{1cm} (4)

Table 1 shows the values of $E/p$ and the growth rate of electric field strength in the air gap for three values of the gap heights 1, 2 and 3 mm, the NDBD was realized at.

| $d$ (mm) | $E/p$ (V/(Torr-cm)) | $dE/dt$ (kV/(cm-ns)) |
|---------|----------------------|-----------------------|
| 1       | 96                   | 1.7                   |
| 2       | 80                   | 1.0                   |
| 3       | 71                   | 0.7                   |

As it can be seen from the data, presented in table 1, the greatest $E/p$ and growth rate of the electric field strength in the air gap have been obtained in 1-mm gaps.

4. Summary

According to the obtained experimental data it was shown that the NDBD in millimeter air gaps under atmospheric pressure and natural humidity developed in various ways depending on the height of the air gap, when applying to the electrodes the voltage pulses with rise time 40 ns. It was found out that the higher degree of homogeneity of the NDBD corresponded to the rather synchronous development of the discharge currents in the gap with delay between them no more than 1 ns. It was obtained from the experimental data that $E/p$ and the growth rate of electric field in the air gap $dE/dt$ in this regime had the highest value for the investigated range of air gaps. It was shown that at $E/p \geq 80$ V/(Torr-cm) and $dE/dt \geq 1$ V/(Torr-cm) the volume diffuse NDBD was realized in 1-mm and 2-mm air gaps, while at a lower value $dE/dt$ and $E/p < 80$ V/(Torr-cm) the existence of the volume diffuse NDBD in millimeter air gaps is difficult, as it has been confirmed experimentally for $d = 3$ mm, when $dE/dt \approx 0.7$ kV/(cm-ns).

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