The effect of the exposed electrode oxidation on the filamentation thresholds of a nanosecond DBD

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Abstract. The paper presents the results of a study of the effect of an oxide film formed on the edge of an electrode on the filamentation threshold voltage of a surface nanosecond DBD. Since the oxidation of the discharge edge has a significant effect on the discharge operation mode and dissipated power, some changes in the filamentation thresholds should be observed. The presented data include the filamentation thresholds of a discharge on an aluminum electrode in synthetic air in the pressure range of 1–10 bar in the case of a new electrode and an electrode covered by an oxide layer. The studies were carried out for both positive and negative polarity of the supply voltage pulse at two pulse shapes with different voltage growth rates. The effect of pulse shape, as well as the effect of air humidity on the filamentation threshold, is discussed.

1. Introduction

Dielectric barrier discharge (DBD) is widely used for surface treatment [1,2], plasma chemistry [3–5], in plasma medicine and biology [6,7], as well as in plasma aerodynamics [8–10]. Recently, interest in pulsed nanosecond DBDs has grown significantly due to the extensive possibilities of its use for controlling the ignition and combustion processes [11,12], in particular, at high pressures. This interest is primarily due to the prospects for using this type of discharge in the development of novel internal combustion engines.

At atmospheric pressure, nsDBD has a more or less homogeneous structure, formed by an ionization wave propagation along the dielectric surface. At higher pressures, the filamentation of the discharge occurs. The mechanism of the filamentation of the AC and nanosecond discharge seems to be different. The filamentation of the barrier discharge, driven by a sinusoidal voltage, occurs in at least tens of microseconds as a result of the development of ionization-overheating instability [13]. The filamentation of nsDBD also occurs [14], however, the underlying mechanisms seem to be fundamentally different. The typical times for the nsDBD filamentation can be less than 10 ns. According to [15,16], the filamentation happens both at negative and positive polarities of the pulse; streamer-to-filament transition is a function of the applied high voltage and the gas pressure. Plasma in the filaments is close to local thermal equilibrium; the electron density is on the order of $10^{18}$–$10^{19}$ cm$^{-3}$ which exceeds the electron density on the streamer mode by 3–4 orders of magnitude.

As was demonstrated in [17], the operation mode of a sinusoidal surface DBD can change significantly upon the formation of an oxide film on the electrode edge. This also affects the
filamentation thresholds [18] due to the decrease of the power dissipation in the discharge. The question naturally arises about the effect of electrode erosion on discharge processes in a nanosecond DBD.

The present work was devoted to the study of the change in the filamentation thresholds of nsDBD on an aluminum electrode in the pressure range of 1–10 bar due to the formation of an oxide film on the electrode edge as a result of a barrier discharge treatment. However, during the study, it was revealed that other factors, such as air humidity and the shape of a high voltage pulse, can either contribute to the variations of the critical voltage for the discharge filamentation.

2. Experiment details

Figure 1 shows the experimental setup. The electrode was a 20 μm thick aluminum foil glued onto a dielectric barrier (ceramics, ε=10.4) with a controlled adhesive sublayer 5 μm thick. The oxidized version of the electrode was prepared by treating it by a sinusoidal surface DBD with a frequency of 100 kHz and an amplitude of 3.4 kV for 4 hours. This treatment led to the buildup of an oxide layer on the electrode sections corresponding to the microdischarge attachment points (with an electrode thickness of 20 μm, the layer has a width of about 200 μm). The layer has a thickness of about 2 μm and is penetrated by starting microdischarges, as evidenced by the presence of many craters on its surface [19,20].

The electrode system was placed into a gas chamber, filled by air up to pressure 3-10 bar. The light emission of the discharge was recorded using an Andor iStar DH720 ICCD camera with an exposure of 12 ns. Dry and humid air were used as the working gas. Humid air was obtained by water evaporation inside the gas chamber. The exact value of the humidity was not controlled; still, conditions during the measurements were kept above the dew point. After each series of measurements, the gas chamber was re-filled to remove the products of discharge operation.

![Figure 1. Scheme of the experiment.](image)

To power the system, a pulse voltage generator (FID) was used with a high-voltage attenuator installed in the output cable. The electrode system was connected to the discharge module via a 40 m long coaxial cable. Pulse parameters were measured by back current shunt (BCS) in the middle of the cable. Two pulses from different pulse generators were used, with their shapes given in Figure 2b for two amplitudes. In the pulse 1 the voltage increases up to 80% during first 4ns, with a full pulse amplitude attained in a gradual growth during remaining 20ns. Oscillations within 15% of the pulse amplitude are obtained due to the multiple pulse reflections between the FID exit and attenuator. For the pulse 2, a steep 2ns front is followed by a nearly constant plateau with a duration of 15ns and voltage variation within 5% $U_{\text{max}}$. The incident pulse was partially reflected from the electrode system, which led to increase of the voltage on the discharge gap. The voltage across the discharge gap was determined as a sum of the falling and reflected pulse amplitude (Figure 2a).
The camera was triggered by an attenuated signal from BCS. The delay was adjusted in such a way that the exposure starts corresponded to the beginning of the discharge development. To achieve this, a minimum exposure was set on the camera, then the launch delay varied from early to late until the moment when the images showed a noticeably weak glow of the beginning discharge. Next, the exposure was increased by 12 ns, and an experiment was conducted with these camera settings. It was found that the filamentation delay decreases with increasing voltage; therefore, the observed thresholds correspond to the chosen delay from the pulse start.

![Figure 2. a) Current trace measured by BCS. U stands for the reference voltage used in the filamentation threshold estimations. b) Comparison of the incident pulse shape for two pulse generators used (negative polarity).](image)

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3. Experimental results

3.1. Discharge images. Filamentation onset criterion

Figure 3 shows ICCD images of a nanosecond discharge at both supply voltage polarities and two
pressures. The discharge was considered filamentary if at least 3 filaments were recorded in the images obtained for the first 10 ns of the pulse arriving at the discharge gap, with their length significantly exceeding the length of the discharge in the streamer form. The same criterion was used in earlier works devoted to the study of nsDBD filamentation [14–16,21].

3.2. Discharge memory effect
It was found that with an increase in the pulse repetition frequency, filamentation can occur earlier than in a single pulse mode. Figure 4 shows the discharge images obtained in a similar manner at two pulse repetition rates. The maximum frequency of the ICCD camera is 3 Hz, so at higher pulse repetition frequency the camera captures each 50th pulse. It is seen that in the first pulse the discharge is realized in a streamer form; however, in subsequent pulses, the structure of the discharge undergoes significant changes.

**Figure 4.** ICCD images of nsDBD for different numbers of pulses for 2 repetitive rates. Negative polarity, 2.5 bar.

It was found that the maximum pulse repetition rate with no “memory” effect on the discharge development observed is 10 mHz for negative pulse polarity and 50 mHz for positive polarity. Long times of the discharge memory suggest that its mechanism is associated with the accumulation of surface charge on the dielectric surface. Furthermore, the increase of air humidity leads to the inhibition of the memory effect. In a humid air, no interaction between the pulses at PRF up to 100Hz is observed. Presumably, this is due to the formation of a water film on the surface of the dielectric, which significantly increases the surface conductivity [22].

To exclude memory effects, the filamentation thresholds were determined at a repetition rate of 10 mHz for both polarities of the supply voltage pulse.

3.3. Filamentation thresholds
Figure 5 shows the dependencies of the threshold voltage values on the gas pressure. One can see that with a negative pulse polarity, filamentation occurs at much lower voltage values. Positive pulse polarity is characterized by a much stronger pressure dependence. Both curves for negative and positive polarity converge to approximately the same voltage of 12-14 kV at high pressures. These data qualitatively correspond to the previous findings, obtained in air on different barrier materials (PVC) [15,16].
Figure 5. Dependence of the threshold values of the filamentation voltage on the pressure of synthetic air for nanosecond DBD using new and oxidized electrodes. Data are given for both polarities of the incident pulse and for two pulse shapes.

It was revealed that the filamentation thresholds are affected by the presence of an oxide layer on the edge of the electrode. In the case of negative polarity, the threshold curve shifts upward, and the effect is more noticeable at high pressures. However, with positive pulse polarity, filamentation occurs earlier on oxidized electrodes.

The filamentation thresholds were measured using two different pulse generators producing pulses of different shapes (Figure 5). It was found that the shape of the transition curves is qualitatively similar, although when a pulse with a steeper front (pulse 2) is supplied, the discharge remains homogeneous up to higher pressures.

Conclusion
The critical voltage for the surface nanosecond discharge filamentation was measured on two types of Al electrodes: new ones and the ones covered by 2 μm oxide layer. The experiment was carried in dry and humid synthetic air for the two pulses with different voltage shapes. The filamentation threshold voltage decreases with increasing pressure for both positive pulse polarity (strong dependence) and negative polarity (weak dependence), which qualitatively corresponds to the previous findings [15,16]. It is found that in the case of oxide layer present on the electrode, the thresholds shift up for negative polarity and down for positive one. At present, there is no clear understanding of the mechanisms of filamentation of nanosecond sDBD; therefore, it is difficult to explain this effect of the presence of an oxide layer on the filamentation thresholds.

The filamentation threshold voltage is affected by the shape of the control pulse. Shorter rise time of the voltage should provide better synchronization of processes within the ionization front, and as a result, higher uniformity of the streamer form of the discharge. The filamentation thresholds were found to be systematically higher for the control pulse with a shorter rise time.

A long-lasting interaction between subsequent discharges with t=O(10s) was discovered, presumably occurring due to the surface charging. The discharge memory is longer for negative pulse and practically disappears in humid air.

In general, it should be concluded that along with the gas composition, nsDBD filamentation threshold is affected by a number of factors, changing the homogeneity of the initial streamer burst. These factors include the surface charge distribution after the backward discharge of the previous
pulse, overvoltage in the streamer head, affected by the pulse shape, and condition of the electrode edge.

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