Self-Organization of Microdischarges in Dielectric Barrier Discharge Plasma

A. Chirokov, A. Gutsol, A. Fridman, K. Sieber, J. Grace, and K. Robinson

***Abstract*—Although microdischarges in dielectric barrier discharges (DBDs) have been studied for the past century, their mutual interaction, discussed in this paper, was explained only recently. This interaction is responsible for the formation of microdischarge patterns reminiscent of two-dimensional crystals. Depending on the application, microdischarge patterns may have a significant influence on DBD performance, particularly when spatial uniformity is required. This paper briefly describes the subtle physics behind the microdischarge interaction and resultant pattern formation. The theory of the microdischarge interaction is presented along with experimentally observed microdischarge patterns.**

***Index Terms*—Dielectric barrier discharges (DBDs), gas discharges, microdischarge interaction, pattern formation.**

IN contrast to a glow-discharge, the dielectric barrier discharges (DBD) consists of a large number of bright filaments. These filaments are actually microdischarges that repeatedly strike at the same place as the polarity of the applied voltage changes, thus appearing to the eye as bright filaments.

A microdischarge "footprint" pattern obtained from a storage phosphor imaging plate that was placed on the inner electrode surface to be directly exposed to the DBD is shown in Fig. 1(left). The discharge was produced in air at room temperature between two parallel electrodes 5 cm wide and 5 cm long, placed about one millimeter apart (0.762 mm) with their 25 cm^2 surfaces facing one another. The electrodes were driven by sinusoidal voltage at a frequency of 20.9 kHz. The storage phosphor imaging plate was used to detect the microdischarge "footprint" distribution. The use of storage phosphor imaging plates offers some advantage over photographic film for imaging microdischarges in barrier discharges. For example, in contrast to the nonlinear sensitometric response of photographic emulsions, storage phosphor plates show a wide-range linear response with respect to impinging energy. This means that the signal intensity at any particular pixel is directly proportional to the amount of energy deposited. We have verified in our equipment that the signal intensity in the images is linearly proportional to the dissipated energy in the barrier discharge cell.

Storage phosphor imaging plates can be excited both optically and by electron bombardment. It is important to assess the relative contribution of each type of excitation in the imaging system. To determine the contribution of photostimulable centers from the discharge ultraviolet (UV) emission to the overall image intensity, we ran a set of experiments where the position of the imaging plate with respect to the quartz dielectric barrier was changed. In one set of exposures, the imaging plate was placed above the quartz dielectric and directly exposed to the discharge [shown in Fig. 1(left)]. A second set of exposures was done where the imaging plate was located under the quartz dielectric so that only light emitted from the discharge could cause a signal on the imaging plate. We found that the overall intensity of the signal readout from the imaging plate (when it was located under the dielectric during exposure) was about an order of magnitude lower than the signal obtained during readout when the plate was exposed directly to the discharge. We conclude that electron bombardment of the phosphor from the microdischarge is the main excitation responsible for the formation of photostimulable centers on the imaging plate.

In Fig. 1(left), the dark spots correspond to filaments, i.e., "families" of microdischarges. Significantly, these microdischarge "footprints" are surrounded by white areas, indicating the absence of microdischarges strikes in their vicinity. One may, therefore, conclude that there are places in the discharge volume where no microdischarges strike, and these prohibited regions tend to surround the individual microdischarges. This observation provoked the development of a deeper understanding of the microdischarges interaction in DBDs. The detailed description of this experiment can be found in [1], [2].

The observed microdischarge patterns imply that the microdischarge interaction must have two main features:

1) Repetition of microdischarges in the same place every voltage cycle due to existence of a preionized channel and surface charge left by the previous microdischarge (microdischarge *remnant* [3]): the so called *memory effect*. This effect results in formation of bright filaments.
2) "Repulsion" of nearby microdischarge within the same voltage cycle by the microdischarge *remnant*, because of local electric field distortion. This "repulsion" results in self-organization of microdischarges into a regular structure. This effect bears similarity to phenomena observed in dusty plasmas, where charged microparticles form Coulomb crystals.

Microdischarge repulsion and the consequent repulsion of filaments is not as obvious a phenomenon as repulsion of negatively charged microparticles in dusty plasmas, which may explain why the patterns in DBDs observed earlier were not satisfactorily explained. The formation of the microdischarge starts with streamers strike. After an individual streamer propagation event, the electrons leave the gap far more quickly than the ions,

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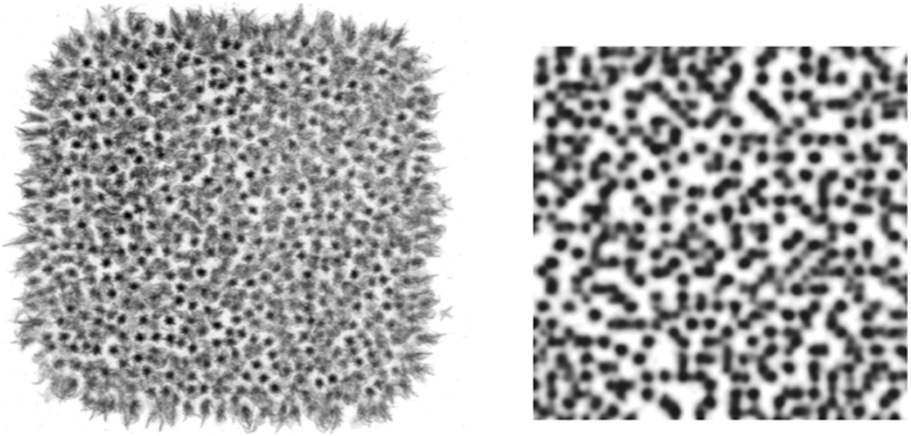

Fig. 1. Microdischarge "footprint" pattern obtained with a storage phosphor imaging plate exposed in a DBD gap in air using 10 excitation cycles at 20.9 kHz and a discharge gap of 0.762 mm. Left figure: Image obtained from storage phosphor plate. Right figure: Simulation image (enlarged central part) with added noise for visual comparison with Fig. 1 (left).

thereby producing residual net positive space charge. Because of the residual positive charge, the electric field strength increases in the cathode region and decreases in the anode region. The loss of field strength at the anode (where streamers originate) prevents the formation of neighboring streamers and their consequent microdischarges. Thus, microdischarges effectively repel each other.

The microdischarge interaction can be illustrated using extended cellular automata (CA) [4]. From a physical perspective, each cell in this model represents a parallelepipedic volume in the gap located between the electrode surfaces. The upper and lower surfaces of each cell are bounded by the surfaces of the dielectrics that cover the electrodes. The CA transformation rules define a new state for a cell after a given time step, using data about the states of all the cells in the CA and additional information, such as the driving voltages imposed upon the system as a whole. It is assumed that the probability P for the avalanche to streamer transition depends only on the local value of the electric field E (which is a superposition of the external electric field and fields of all streamer remnants formed earlier):

$$P(E) = 1 - (1/(1 + \exp(S(E - E_0)/E_0))).$$

In the equation above, S (the memory effect strength) is a parameter related to the ability of the discharge to accumulate memory about previous streamers; E_0 is an electric field value necessary for streamer formation according to the Meek criterion. The position of a streamer strike is determined using a Monte Carlo method, based on probability values in each cell. Streamer strike is an initial phase of microdischarge formation, thus position of streamer strike defines position of microdischarge. As streamers can appear randomly in time as well as in space, an additional Monte Carlo simulation is used to decide whether a streamer will occur in a given time step. In this model, the assumption of microdischarge interaction is incorporated through the radius of influence of each microdischarge remnant. Every microdischarge contributes to the total cumulative influence map, which is stored in the CA cells. The radius of influence of a microdischarge remnant is the characteristic distance at which the remnant has an appreciable effect on the electric field. Thus, the position of each streamer strike is not truly random, because it depends on the placement of the microdischarge remnants. In reality, the influence of the remnant decreases with time. This effect is important in the case of very high number density of microdischarges (high-discharge power).

The main output from the program is a density map of microdischarge activity in simulated discharge volume that corresponds to the surface exposure of the photostimulable phosphor imaging plate or web. A typical result for a simulation over ten discharge excitation cycles (with added noise) is shown in Fig. 1(right). Physical dimensions of DBD cell and applied voltage in the model Fig. 1(right) were the same as in experiment Fig. 1(left). The gray scale intensity at any particular cell is proportional to the number of microdischarges striking the cell. The simulation shows that the occurrence of microdischarges across the simulation lattice is nonuniform; some regions are well treated by microdischarges and some are not treated at all. This nonuniformity is the result of interactions between streamers and microdischarge remnants. The simulation image shows good qualitative agreement with the experimental storage phosphor image. Self-organization of microdischarges appears to be a strong effect and a dominant feature of the dielectric barrier discharge. The underlying memory and repulsion effects thus create quasi-Coulomb crystal patterns in DBDs. The detailed analysis and comparison of experimental and simulated microdischarge patters can be found in [2].

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