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The traces of positive charge interactions at surface dielectric barrier discharge

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ABSTRACT

This study presents an experimental confirmation of the surface positive charges drifting to the exposed electrode in the cathode layer of atmospheric surface dielectric barrier discharges (SDBD) using the etching method. Local surface erosion around the microprotrusions on the polyimide near the exposed electrode provides an experimental confirmation of the interaction of the positive surface charges with the exposed electrode in SDBD.

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Experimental investigations of the physics in the cathode layer in atmospheric surface dielectric barrier discharge (SDBD) have never been unattainable by using any instruments and methods.1–3 In our previous work, the existence of the cathode layer in atmospheric SDBD was experimentally visualized using the specific nature of a spatially selective inhomogeneous reaction of positive ions and reactive neutral species on the polymer surface of SDBD.1,4

Soloviev presented surface positive ions drifting to the exposed electrode in 5–10 ns during the formation of the cathode layer in SDBD by numerical methods.1 The typical electric field value for the cathode layer is about 300 kV cm−1.1 Babaeva et al. computationally simulated that when a streamer envelops a small dielectric particle of radius 45 μm present on a dielectric at 1 atm, O2 ions of energies up to a few eV strike the bottom of the particle due to a few hundred kV/cm caused by a transiently formed sheath around the particle.5

For the experimental verification of the drifting surface positive ions in the cathode layer, the SDBD of polyimide dielectric (Kapton ENC) for single-side discharge was prepared. The manufacturing method of the SDBD for this experiment is the same as that referred to in Ref. 4. Kapton ENC (Toray-Dupont, Japan) especially contains several hundreds of micro-scale irregular-shape protrusions per 1 cm2 on one side of the both surfaces. The protrusions are composed of a material similar to polyimide. It is known that the micro-protrusions occur during the casting process. Because the length of the cathode layer in SDBD is approximately 22 μm, the protrusions with the diameter and height under a few μm on the polyimide dielectric of SDBD provide a satisfactory experimental environment for verifying the surface positive ions drifting from to the exposed electrode.1,4 Figure 1 presents a schematic view of the experimental setup.

FIG. 1. Schematic view of the experimental setup: EE: exposed electrode (orange), MD: micro-discharge (pink), AD: adhesive (gray), PI: polyimide, Kapton ENC (dark green), GE: ground electrode (orange), and AC: high voltage AC.
Figs. 2 and 3. The discharge is operated at 16.6 kHz at 2 kV AC. The pristine and discharged surfaces with differences in discharge time (10 s and 20 s) near the exposed electrode were observed using a field-emission scanning electron microscope (FE-SEM, S-4800, Hitachi, Japan).

Figure 4 presents the protrusions discharged for 10 s observed within 20 μm from the exposed electrode. All surfaces adjacent to the protrusion are not etched. It is observed that the peripheries of the protrusions are partially etched. Figure 5 presents the electron images of the protrusions discharged for 20 s. It is observed with certainty that all peripheries of the protrusions are etched. In Figs. 4 and 5, the bulk of the protrusions does not appear to be etched. Only the interfaces of the protrusions and the polyimide surface are locally etched where they are exposed to positive surface charges in air.

Even though the cathode layer could be filled with reactive oxygen species and they could be diffused onto the surface during the relaxation phase, the local erosion around the protrusions in the cathode layer is caused not by the neutral reactive oxygen species but by the positive oxygen ions during the negative voltage phase. At the given AC driven frequency (16.6 kHz) and voltage amplitude (2 kV), the time interval between microdischarges is approximately 1.3 μs. The time interval is much shorter than the life time of O(^3P) and metastable oxygen molecules, which implies that they are collided with the electrons of the next microdischarge. Therefore, most of the reactive neutral species produced above the dielectric surface do not reach the surface. In addition, the relevant reaction timescale of ions is in the range of 10 ns to 1 μs.

During the positive voltage phase, the space near the exposed electrode is also filled with positive ions drifted from a positive streamer flying above the dielectric surface. The ions

![FIG. 2. (a)–(d) Top views of the electron microscopy images of pristine protrusions on the Kapton ENC. The white scale bars correspond to 1 μm.](image-url)

![FIG. 3. (a)–(d) Side views of the 3D laser scanned images of pristine protrusion on Kapton ENC. In each figure, the width of the yellow area indicates the width of the scanned protrusions.](image-url)
are repelled to the dielectric near the exposed electrode. Therefore, the direction of positive ion bombardment with respect to the protrusions is opposite to the case of the negative phase. The amount of the positive surface ions during the positive voltage phase is lower than during the negative one. However, our experimental result does not show the same two-dimensional asymmetric erosion around the protrusions as expected from the previous numerical simulation.1,9

In conclusion, the visual verification of the surface positive ions in the cathode layer is conducted. Local surface erosion around the protrusions on the polyimide dielectric in the cathode layer experimentally confirms the interaction of positive surface charges with the exposed electrode in SDBD since the simulation treats the general positive ions without specifying \( \text{N}_2^+ \) or \( \text{O}_2^+ \). Although one can estimate that the proposed experimental method could be an analogous approach to verify the existence of energetic positive ions in a few hundred kV/cm, however, the observation does not give information on the energy of the positive ions.1,5

![FIG. 4. (a)–(f) Top views of the electron microscopy images of the protrusions operated for 10 s.](image)

![FIG. 5. (a)–(f) Top views of the electron microscopy images of the protrusions operated for 20 s.](image)
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