Pattern formation and boundary effect in dielectric barrier glow discharge

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In this paper, we report the experimental results on the characteristics of plasma patterns with different planar electrode shapes in dielectric barrier glow discharge. The formation and the evolution of the discharge patterns at different voltages were investigated. The results show that the plasma patterns in this glow-barrier system form at the beginning of the discharge pulse. The limited size of planar electrodes and the electric field distribution are important factors for the pattern formation.

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I. INTRODUCTION

In spatially extended nonlinear dissipative systems, a large variety of self-organized spatial structures are exhibited and the understanding of the self-organized patterns in these systems is one of the greatest challenges in modern natural sciences [1]. Dielectric barrier discharge (DBD) is one kind of such nonlinear systems although it is well known for its industrial applications including UV source, ozone generation and plasma display panels (PDP) [2]. Driven by ac voltage, various patterns have been observed in experiments in DBD system, including random spots, self-organized rings, hexagonal patterns, superlattices, etc. [3–11]. These patterns achieved in DBDs could be used in some special fields such as localized-material growth [12] and plasma-photonic crystals [13]. The mechanism of the pattern formation, however, is still unclear which might be important for understanding of the physical process of DBD as well as its practical application.

The discharge mode of DBD depends on *pd* value (product of the pressure and the discharge gap). Generally, a glow discharge may be sustained at lower value (typically $pd \leq 13.3$ hPa·cm) while a filamentary discharge occurs at higher *pd* value which is controlled by streamer mechanism [14], although recently a glow discharge at high pressure up to atmospheric pressure ($pd = 66 \sim 133$ hPa·cm) may also be achieved under some special conditions [15–17]. The plasma patterns may form in both glow DBD and filamentary DBD. The patterns in filamentary DBD have similar characteristics. They form in various structures by re-arrangement or self-organization of the separated plasma channels [4,6–9]. These discharge channels are generally time independent and appear randomly over the planar-electrode surface during the rising of ac voltage. The electrode shape has little effect on the pattern formation in the filamentary discharge. In glow discharge mode, however, the electrode boundary might play an important role in the pattern formation. For example, Stollenwerk *et al.* [11] have found that the self-organized patterns are generated first from the outer edge of the electrodes in planar DBD. But, how the electrode shape affects the plasma patterns is still unknown.

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In this paper, we focus on the behavior of pattern formation in glow DBD and the boundary effect of electrodes. We will show that the patterns depend strongly on the shape of the electrode and the electric field distribution. The article is organized as follows: Section II describes the experimental setup. Section III gives the overview of the observations of plasma patterns under various conditions, and a general discussion of the formed patterns. The article closes with a conclusion in Sec. IV.

II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. The discharge cell is a sealed-glass vessel with internal dimensions of $40 \times 25 \times 1$ mm^3. The thickness of the two glass plates is of 1 mm and the relative permittivity is of 10.5. The vessel was pumped to very low pressure ($\leq 10^{-5}$ hPa), then filled with pure neon of pressure $p = 30$ hPa. To increase the secondary electron emission coefficient of Ne^+ ions and lower the operation voltage, a 0.5 μm MgO layer was coated on the inner surface of the

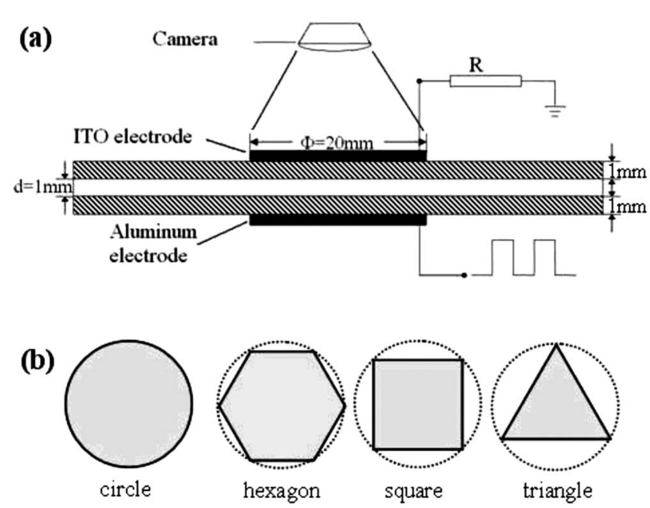

FIG. 1. (a) Sketch of DBD system. The cell is comprised of a glass vessel, sealed by two glass plates and gap of 1 mm. ITO electrode (top) and replaceable aluminum electrode (bottom) are put outside the glass. (b) Four electrodes in shape of circle, hexagon, square, and triangle. All the diameter of the circumcircles is of 20 mm.

40×25 mm glass plates by the Key Laboratory for Physical Electronics and Devices of the Ministry of Education, Xi'an Jiaotong University. The planar electrodes are placed outside the vessel, on the 40×25 mm plates. The upper electrode is made of transparent indium-tin-oxide (ITO), in diameter of $D=20$ mm, which makes it possible to record the light emission from top view. The bottom electrode is of aluminum foil, which is easy to be changed in both shape and dimension. Four shapes [i.e., circle, hexagon, square, and triangle, shown in Fig. 1(b)] were employed in our experiments and their circumcircle is the same in diameter of 20 mm.

A square-wave voltage is applied between the two electrodes with frequency of $f=50$ Hz ~50 kHz and amplitude up to 300 V. A noninductive resistor R is connected in series with the cell to sample the discharge current. The applied voltage and the current are measured by an oscilloscope (Tektronix TDS-3054B). An intensified charge-coupled device (ICCD) digital camera (Roper Scientific PI-MAX 1k) was used to record the time-dependent light emission from top view (i.e., the ITO electrode). Since the stable discharge is reproduced at each cycle of the voltage pulse, the ICCD images were recorded by integrating the light emitted by the discharge over a large number of cycles during a time interval (gate), which was swept over the entire duration of the current pulse. A CCD camera (Canon A640) was used to record the time-averaged images of the discharge emission.

III. EXPERIMENTAL RESULT

A. Circular electrode

1. Time-averaged patterns

First, we tested the electrode in shape of circle which is also the typical configuration used in planar DBD researches. We found that the breakdown voltage is about $V_{br}\approx110$ V for the present DBD cell. The breakdown voltage does not change obviously with the frequency ranged from 50 Hz to 50 kHz under our conditions. The margin of this cell (defined as the difference of the breakdown and the minimum sustain voltage [18]), however, is not large and of 10 V. The amplitude of voltage supply V_S is therefore higher than V_{br} in our experiments to ensure a stable discharge.

At a given frequency, stable discharge may sustain at the applied voltage higher than V_{br} and the discharge becomes stronger as V_S increasing. Patterns may form over the electrode surface under appropriate conditions (suitable voltage and frequency). All the patterns, once forming, are stationary and repeatable. The driving frequency should not be too low to achieve the patterns. In our experiment, the critical frequency is about $f_C=2$ kHz, below which the discharge is almost uniform and no pattern appears in the voltage range of the power source. Above f_C, the plasma patterns are observed and their structures depend strongly on voltage V_S. The tendency of the formed patterns changing with the applied voltage is very similar for all the frequency, although at different frequency the patterns at a given voltage are not exactly the same. Figure 2 shows an example of the time-averaged images of plasma patterns for $f=10$ kHz at different voltages.

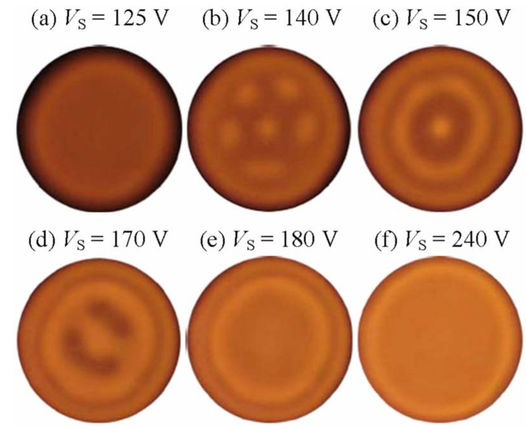

FIG. 2. (Color online). Time-averaged images of plasma patterns with symmetric electrode (circle, in diameter of 20 mm) at different V_S. The frequency is $f=10$ kHz and the CCD exposure time is 0.6 s.

It is seen in Fig. 2 that at low voltage, the discharge is weak with an edge of the discharge area (near the boundary of electrode) shaped in ring [$V_S=125$ V, see Fig. 2(a)]. As V_S increasing, a few luminous spots appear in the center and in an outer ring-like orbit [$V_S=140$ V, see Fig. 2(b)]. These spots join into a real ring at higher voltage [$V_S=150$ V, shown in Fig. 2(c)]. Further increase in voltage results in connection of the ring and the central spot [shown in Fig. 2(d)] and increase in the diameter of ring. Finally a uniform discharge appears inside the ring without pattern at 180 V or above [see Fig. 2(e)]. When the voltage goes up to 240 V or more, the discharge becomes uniform over the whole electrode [see Fig. 2(f)].

We noticed that all the patterns at different voltages show a symmetrical structure, i.e., the edge and the inner ring are shaped in a circle which is similar to the electrode boundary. The self-organized spots, appearing at lower voltage, are also located in a ring-like area.

2. Time-dependent light emission

It is too difficult to trigger the discharge in one single period of voltage supply by using ICCD and we did not try to record the discharge process from the turn on of the power source. Instead, we focused on the thereafter stable discharge which is repeatable and allows us to accumulate the light emission at the same time of current pulse but in different periods and obtain a full image of one period when the gate swept over the current pulse with gate of ~30 ns.

The discharge in the present DBD system is typical glow with one pulse on the current waveform. Figure 3 shows the waveform of the current and voltage together with the light emission at $V_S=150$ V/$f=10$ kHz after the discharge being stable. The light emission at each time was obtained from top view by ICCD camera with exposure time of 30 ns. The intensity of light emission has been normalized.

One sees in Fig. 3 that the time-dependent light emission has the same character as the current, i.e., the same rising and decay. This is also the typical characteristic of discharge in glow DBD or PDP [18].They start to increase and reach

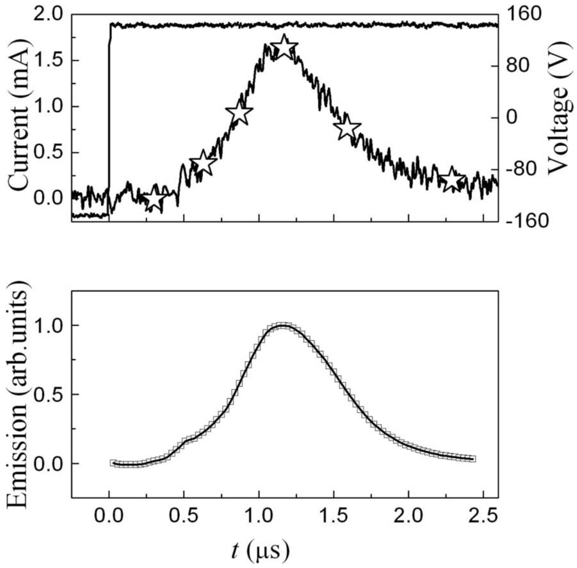

FIG. 3. (a) The waveform of discharge current and the applied square-wave voltage and the "☆" is corresponding to the ICCD images in Fig. 4. (b) The light emission at voltage of $V_S = 150$ V/$f = 10$ kHz.

the maximum synchronously during each half period, with the same duration about 2.5 μs.

The images of the light emission at different times are shown in Fig. 4. The times (i.e., $t = 0.3$, 0.63, 0.87, 1.17, 1.59, and 2.28 μs) correspond to the points noted as "stars" in Fig. 3(a). The intensity has been normalized.

One sees that the discharge starts at separated areas, i.e., a central spot and a ring [see Fig. 4(a)]. The ring-like area is just the same as that we have observed in the time-averaged image [see Fig. 2(c)] and similar to the electrode boundary.

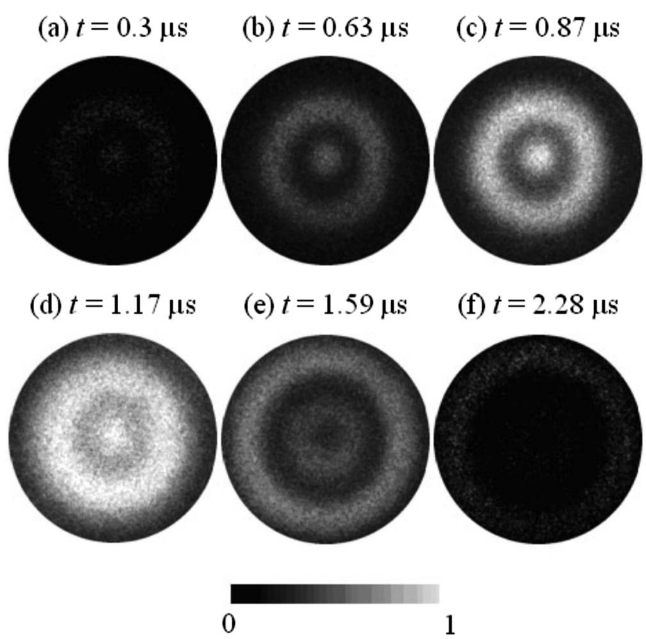

FIG. 4. ICCD images of light emission during current pulse at different times with circle boundary at voltage of $V_S = 150$ V/$f = 10$ kHz.

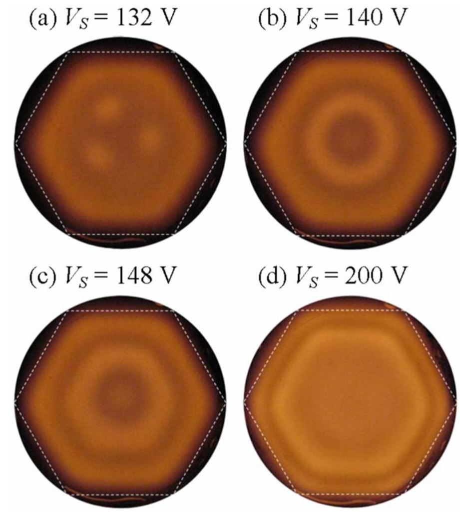

FIG. 5. (Color online). Time-averaged images of plasma patterns generated with hexagon boundary. The CCD exposure time is 0.6 s.

The discharge emission becomes stronger and stronger until reaches maximum at the current peak $t = 1.17$ μs, while the discharge area extends outwards nearby [see Figs. 4(b)–4(d)]. During the decay of discharge the bright area (where the discharge is initialed from) becomes weaker and stops emitting at $t = 1.59$ μs, while the other places (where there is no breakdown at the very beginning) have a weak emission longer, so that it seems to be a reversed pattern appearing [shown in Fig 4(e)]. Later, the light emission fades away gradually and disappears when the discharge current stops [see Fig. 4(f)].

From the results above, it is seen that the plasma patterns form at the very beginning of the discharge and have the same structure as the time-averaged image (i.e., a central spot and a circular ring). The formed patterns become intense during the rising of the discharge current and reaches maximum at the current peak. Then the discharge starts to weaken and extinguishes completely at the initial positions. The rest places also have some emission due to the expansion of the main discharge from the initial positions and may keep for a longer time so that a reversed pattern appears during the decay of discharge, but the intensity is lower than the original one. We found in experiments that although the patterns may be in various shapes at different voltages, the pattern develops in the same way as above within one half period. That is, a patterned (nonuniform) discharge would develop over the planar electrode surface in glow DBD, with breakdown and discharge areas just the same as that observed in the time-averaged images. We can use the time-averaged images of DBD to describe the plasma patterns.

B. Effect of electrode boundary

We then employed the other shaped electrode, i.e., hexagon, square, and triangle in turn.

Figure 5 shows the time-averaged images of the discharge patterns generated with hexagonal boundary at different V_S. One sees that a few luminous spots appear in the inner area

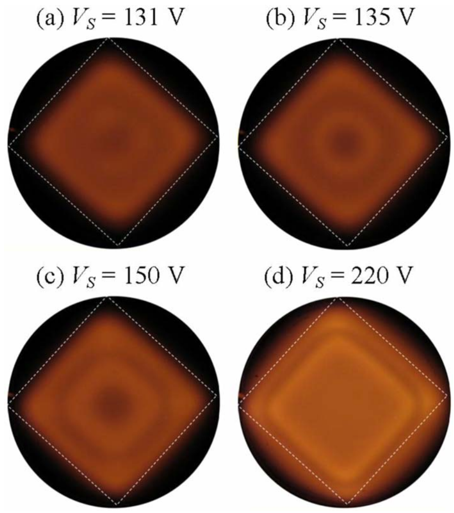

FIG. 6. (Color online). Time-averaged images of patterns with square-edged electrode.

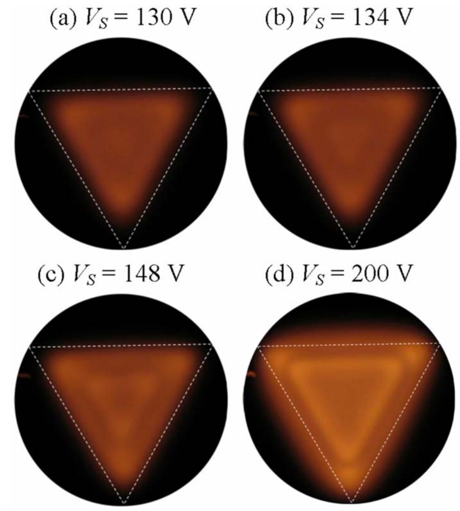

FIG. 7. (Color online). Time-averaged images of patterns with triangle-edged electrode.

of the discharge area at lower voltage (V_S=132 V). These spots connect together to form a luminous ring as the voltage increasing [see Fig. 5(b)]. The ring enlarges its radius with the voltage. At higher voltage, the ring expands to the borderline, to show a shape similar to that of electrode boundary [hexagon in this case, see Fig. 5(c)]. The bright hexagon expands close to the boundary at higher voltage (V_S =200 V) until uniform discharge is obtained at high voltage (220 V or above, not shown here). There exists a bright border in these time-averaged images, similar to that of circular electrode (see Fig. 2).

We see that the bright ring(s) in shape of the electrode boundary may form in DBD if it is near to the edge. Far from the border, the inner ring can keep a symmetrical character (in circle) at lower voltage.

When a square- or triangle-shaped electrode was used, similar tendency of pattern structure changing was observed as V_S increasing, as shown in Figs. 6 and 7. In both cases, several luminous spots appear at lower V_S and join into a ring as V_S increasing. The bright ring ultimately becomes into a luminous discharge area of square or triangle boundary at high voltage when it expands close to the electrode boundary. Similar to that in circle or hexagon electrode, the bright area is surrounded by a border in shape of electrode (square or triangle).

But different from Fig. 5, the inner bright ring is smaller and is distorted in shape of square or triangle at the very beginning and, no central spot appears at lower voltage in the two cases (see Figs. 6 and 7). Actually, the inner bright area is triangle and is very near to the electrode edge in case of triangle-shaped electrode where the discharge area is small [see Figs. 7(a) and 7(b)].

We see from above that the formed patterns [i.e., the bright ring(s)] relate to the electrode boundary when they are close to the boundary, especially at higher voltage. However, if they are far away from the electrode edge, the inner ring would keep in a symmetrical shape of circle.

C. Discussion

It is well known that the wall charge accumulated on the dielectric layer play an important role in DBD systems [2,3,19]. Immediately after the discharge develops in the gas gap, charge accumulated on the dielectric surface induces a voltage (named wall voltage) and leads to a local collapse of the electric field in the area defined by the surface charge. This self-arresting effect of the dielectric layer limits the duration of the discharge to a short time and prevents the transition of discharge into arc. The wall charge will stay on the surface for a long time (so called "memory charge") so that the field is enhanced in the next half cycle, and the DBD can sustain at a voltage supply below breakdown which has been used in PDP technology [18]. Since the glow discharge will be initialed at positions where there is higher voltage or stronger field, the distribution of the wall charge strongly affects the formation and the development of glow DBD. A uniform distribution of wall charge maybe results in a uniform discharge, while nonuniform wall charge causes a nonuniform discharge consequently. The patterned discharge should correspond to a patterned (nonuniform) distribution of wall charge.

In the present DBD, the patterned discharge may appear at moderate voltage when the frequency is not too low. This patterned (nonuniform) discharge, starts to develop at fixed places and is stationary, corresponding to the patterned distribution of wall charge. This distribution should be in agreement with the pattern observed in time-averaged images. The glow DBD is initialed at this patterned area (the bright area in the time-averaged image) where there is more wall charge. No breakdown occurs at the other places at the very beginning because of lower wall charge (hence the wall voltage), but there will also exist a discharge and light emission due to the discharge expansion from the patterned area. However, if the applied voltage is very high, the wall charge tends to be uniformized hence the discharge will tend to be uniform and, no pattern occurs in the discharge area. This is what we have seen in experiments.

We found that the pattern could not be seen in our experiments if the driving frequency is lower than a critical frequency of 2 kHz. One possible reason for the critical frequency could be related to the plasma decay during the rest time of discharge. The time interval is 1 ms (under the present condition) which might be on the order of the decay time of plasma under PDP condition and is long enough for spread of space charge and uniformization of wall charge. Actually, the change in plasma density in PDP cell might affect distinctly the discharge mode and has been observed previously [20]. But more evidence is needed for the explanation.

From Figs. 2 and 5–7, the limited size of the planar electrode plays an important role in the pattern(s). Although we did not know in experiment how patterned discharge developing from the first cycle of the applied voltage (i.e., from turn on of the voltage supply to formation of a stable pattern), the formed pattern(s) will be affected strongly by the electrode border. When the field over the surface electrode is symmetrical or uniform, the discharge is symmetrical and the patterned area, if existed, is also symmetrical. It usually shows a circular region or ring(s) in the discharge area. Far from the border, the field isn't distorted by the boundary shape and can keep symmetrical. The wall charge and the pattern may therefore distribute in symmetrical way. A high voltage may result in a larger uniform area of wall charge and extension of the discharge area, so that the discharge tends to become uniform with a border in shape of the electrode. When the field changes greatly near the boundary, the patterned area will be distorted in a shape according to the electrode edge, causing a strong boundary effect. Moreover if the initial discharge area is close to the electrode edge, the patterned shape would be just determined by the electrode boundary. From circle to triangle (i.e., the discharge areas become smaller and smaller), the boundary is closer and closer to the center and consequently, the boundary effect becomes more and more obvious. This is why the pattern has been distorted even if at low voltage in case of triangle in Fig. 7.

IV. CONCLUSIONS

We have investigated the plasma pattern in planar glow DBD experimentally. The patterns may achieve above a critical frequency and show various structures according to the applied voltage. The patterns may be in shape of separated spots, real ring, noncomplete area with a ring border or uniform area in order as the voltage increasing. At given voltage, the glow discharge is initialed synchronously in the patterned area and then extends to the other places where there is not breakdown at the very beginning. A reversed pattern will appear during the decay of current when the discharge stops at the initial positions. The limited size of planar electrode and its boundary affect strongly the plasma pattern due to the distortion of the electric field near the boundary. Consequently the formed patterns have the same shape as the electrode boundary especially when the patterns are near to the electrode edge. However, a symmetrical structure (a circular ring) may keep when the pattern is far away from the boundary. We concluded that the great change in the electric field in the space is one of the key factors to determine the pattern formation in DBD.

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