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Spatial uniformity of dielectric barrier discharge at moderate *pd* values*

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The plasma with high spatial uniformity at moderate *pd* values is achieved by using a dielectric barrier discharge reactor with two liquid electrodes. The electrical and optical characteristics of the discharge are investigated by spatiotemporally resolved measurement. Results show that the plasma with high spatial uniformity can be maintained in a wide range of applied voltages and corresponding input powers as well. The influence of wall charges on the discharge power and the spatial uniformity is discussed.

Keywords: dielectric barrier discharge, glow-like discharge, spatial uniformity, moderate *pd* values
PACC: 5280P, 5270, 0565

1. Introduction

Dielectric barrier discharges (DBDs), also referred to as silent discharges, are characterized by the presence of at least one insulating dielectric layer in contact with the discharge between two planar or cylindrical electrodes connected to an ac power supply. The discharges depend on some parameters, especially the *pd* value (the product of gas pressure p and gas gap d). Discharge mode can be divided into two modes: Townsend mode and streamer mode. The former is a diffuse discharge and generally occurs at low *pd* values, and the latter consists of a lot of discharge filaments and generally occurs at high *pd* values. DBDs are widely studied due to their numerous potential industrial applications including large-area flat plasma-display panels (PDPs), surface modification of polymers, plasma-chemical vapour deposition, excitation of CO_2 lasers, and excimer lamps.[1,2] In past years low *pd* values (less than 13.3 Pa m) discharges were well investigated.[3−5] In recent years high *pd* values (greater than 133 Pa m) discharges have been studied by many research groups.[6−11] However, the discharges at moderate *pd* values (13.3–133 Pa m) have not been extensively studied yet.

In this paper, we present a method of generating a moderate *pd* values plasma with high spatial uniformity. The spatiotemporal characteristics of the discharge are investigated. The results show that the input power increases with the increase of applied voltage. The glow-like discharge can be maintained in a wide range of applied voltages and corresponding input powers as well. The influence of wall charges on the discharge power and the spatial uniformity is discussed.

2. Experiment

A schematic diagram of the experimental set-up is shown in Fig.1. Two cylindrical containers with the same diameter 47 mm are filled with tap water. Each container has a metallic ring, which is immersed in the water of the container and connected to a power supply. Thus the water acts as a liquid electrode. Two parallel glass plates with a thickness of 1.5mm serve as the dielectric layers. An ac power supply has a maximum peak voltage of 10kV with a frequency of 26kHz. A high voltage probe (Tektronix P6015A, 1000X) is used to measure the applied voltage. A capacitor is used to measure the transported charge. The light

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emitted from the discharge is detected by two PMTs (RCA7265), and recorded with an oscilloscope (Tektronix TDS3054, 500 MHz). One of the two PMTs is used to measure the total light emission, and the other is employed in measuring the light emission of a local discharge through a lens and diaphragm. A digital camera (Canon Powershot G1: 1024×768 pixels, minimum exposure time 1ms) is applied to record images of the discharge. All investigations have been made in argon discharge.

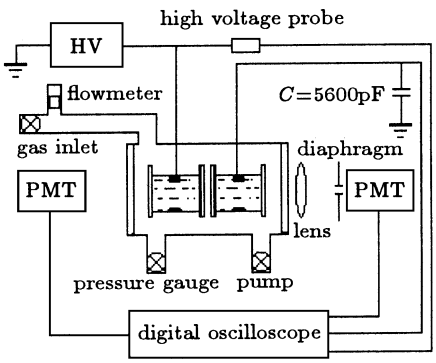


Fig.1. Schematic diagram of the experimental setup (longitudinal section view of reactor): HV—high voltage high frequency power supply, PMT—photomultiplier tube.

3. Results and discussion

The *pd* value in experiment is maintained in a range of 30.3–91 Pa m by changing pressure p and gas gap d. Townsend phase, streamer phase and glow-like discharge are observed by adjusting the applied voltage. Figure 2 shows the spatial structure of discharge as a function of applied voltage. There appear four distinct kinds of discharge: low-luminosity diffuse discharge (Fig.2(a)), filamentary discharge (Fig.2(b)), incompletely diffuse discharge (Fig.2(c)(d)), and glow-like discharge (Fig.2(e)(f)). When the gas breakdown occurs, a low-luminosity diffuse discharge takes place. As the applied voltage increases, the diffuse discharge changes into the discharge with some filaments that form a hexagon pattern. As the applied voltage increases further, the filamentary discharge gradually turns diffused. The glow-like discharge appears when the applied voltage increases up to a critical value and it can be maintained in a wide range of voltages (2.4–5.8kV) by continually increasing the applied voltage to the upper limit of the power supply.

In many applications, the plasma with high spatial uniformity is desirable. In order to ascertain the variation of spatial uniformity of the discharge, a local discharge with a diameter of 1.8mm is monitored by light emission and compared with the total discharge. The temporal behaviour, transported charges and Lissajous figure of the discharge are shown in Fig.3 for different discharges corresponding to those in Fig.2. It can be clearly seen that the discharge moment of any local discharge is the same as that of total discharge in the low-luminosity diffuse discharge. In the filamentary discharge, the synchronism in discharge still remains although the spatial uniformity of the discharge is broken. In the incompletely diffuse discharge, the spatial uniformity becomes better than that of filamentary discharge, but the synchronism is broken. As applied voltage increases, the spatial uniformity of discharge is recovered. In the glow-like discharge high spatial uniformity is achieved.

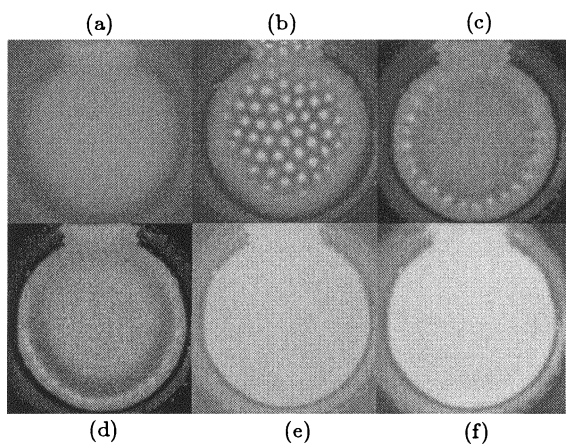


Fig.2. Spatial structure of discharge vs the applied voltage: (a) U=1.16kV, (b) U=1.67kV, (c) U=1.91kV, (d) U=2.03kV, (e) U=2.4kV, (f) U=5.8kV, with gas pressure p=30 kPa, frequency f=26kHz, gas gap d=3.0mm, and photograph exposure time: 1/50s.

An obvious characteristic of discharge is that the moment of discharge initiation shifts forward as applied voltage increases. Prior to glow-like discharge, the discharge initiation occurs during applied voltage rising. The discharge initiation of glow-like discharge happens during voltage decreasing, which is called the discharge before zero-voltage.[12] The higher the applied voltage, the more forward the discharge initiation shifts with respect to the instant of zero voltage.

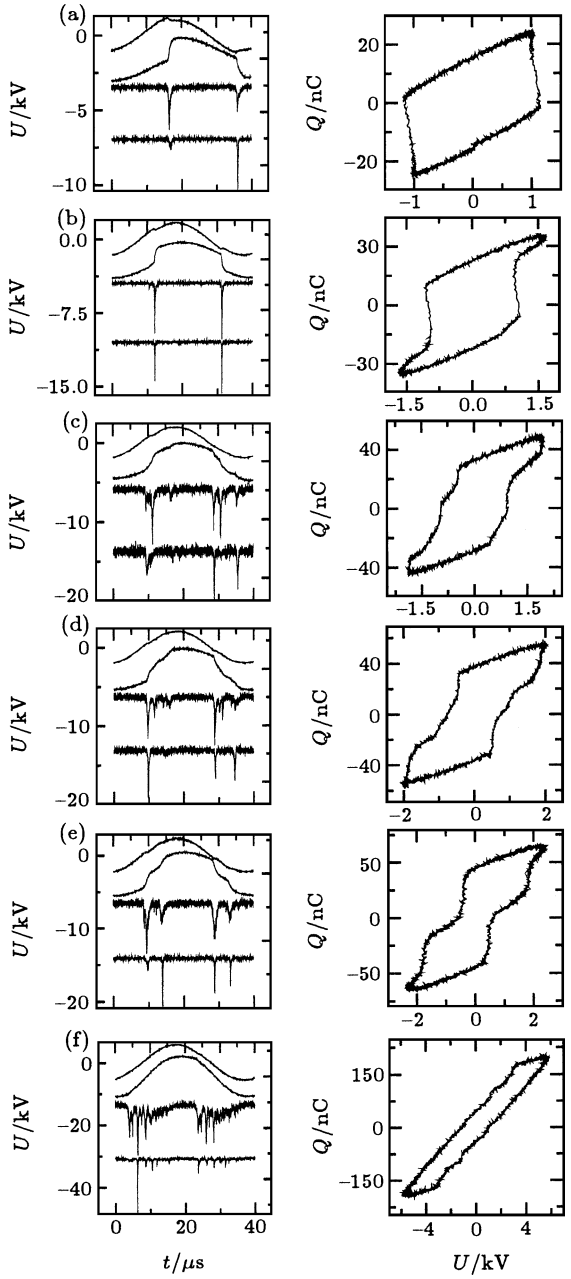


Fig.3. Waveforms (left column) of the applied voltage (the top), transported charge (the second), the total light emission (the third) and local light emission (the bottom) and measured Lissajous figures (right column) of different discharge stages (corresponding to Fig.2).

Another obvious characteristic is the variation of Lissajous figure of discharge as the applied voltage increases. When the applied voltage is low, the shape of Lissajous figure is left-leaning, which corresponds to the decrease in the applied voltage during discharge. While the applied voltage is high, the shape of Lissajous figure is right-leaning, which corresponds to the increase in the applied voltage in the discharge process. As the applied voltage increases, the transported charges increase, which indicates the increase in wall charge. The input power of discharge can be calculated from Lissajous figure of discharge. Figure 4 gives the input power as a function of applied voltage. Obviously, the input power increases with the increase of applied voltage. When the applied voltage is in a wide range of 2.4–5.8kV, the input power of glow-like discharge is in a range of 5.5–21.0W.

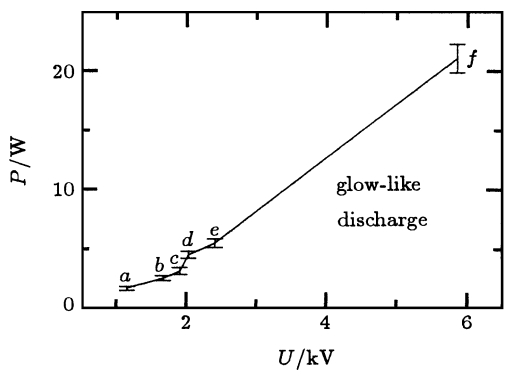


Fig.4. Input power as a function of applied voltage (corresponding to Fig.2.).

When the *pd* value is in a range of 30.3–91 Pa m, the glow-like discharge (homogeneous discharge) can be maintained in a wide range of applied voltages. For example, when the *pd* value is 30.3 Pa m, glow-like discharge can be maintained in a range of 1.1–2.5kV, and corresponding input power is in a range of 1.2–4.3W. The ranges of applied voltage and corresponding input power increase with the increase of *pd* value.

In a DBD system, the charges created in gas discharge accumulate on the surface of dielectric layer, and are called wall charges. The wall charges produced in a half cycle induce an electric field that opposes the applied field. The wall-charge-induced field reduces the net field, and the discharge is extinguished when the net field is lower than the breakdown field. However the direction of the wall-charge-induced field becomes the same as that of the applied field when the voltage polarity is changed in the next half cycle. So the wall-charge-induced field aids the applied field to initiate discharge in the next half cycle. The more the wall charges accumulate in the last discharge, the lower the applied voltage is required to initiate this discharge. When the applied voltage is sufficiently high, wall charges can be more than enough to initiate the reversed gas discharge at the falling edge of the voltage, which corresponds to the discharge before zero-voltage. This is because that the moment of discharge initiation shifts forward as applied voltage increases. Wall charges first store the energy before the discharge initiation and then release the energy

after the discharge initiation. As the applied voltage increases, more wall charges accumulate on the surface of the dielectric layer, which leads to the storage of more energies. When the discharge occurs, wall charges release more energies, resulting in the discharge power increasing.

The spatial structure of discharge is also influenced by wall charges. When the applied voltage is very low, the discharge is in the Townsend phase,[13] in which the influence of wall charges on the discharge can be neglected because there exist few wall charges. As the applied voltage increases, the discharge enters the streamer phase. The wall charges increase fast and distribute randomly on the dielectric layer. Because of the interaction of filaments and the presence of wall charges, these random filaments can form self-sustained patterns.[14] The wall charges accumulated during one half-cycle produce a field enhancement when the voltage reverses polarity. In other words, the localized site of wall charges accumulated in one half-cycle is a probable site of filament in the next half-cycle. This phenomenon is called the memory effect of wall charges. Due to the memory effect, each filament stays in nearly the same place, so that patterns can remain stationary once they are formed. The wall charges increase with the increase of applied voltage. In order to keep their balance, new wall charges accumulate on the sites where old wall charges have minimal potential. That is to say, new wall charges appear on the sites that have the least old wall charges. As the applied voltage continues to increase, new wall charges still appear on the sites of the least old wall charges, until wall charges are enough to be uniformly distributed on the dielectric surface, resulting in a homogeneous discharge.

As mentioned above, in the streamer phase, wall charges influence the spatial uniformity and temporal characteristic of discharge. Wall charges increase with the increase of applied voltage. When wall charges are very few in quantity, the discharge occurs at the rising edge of the voltage [Fig.3(b)] and spatial uniformity of the discharge is very low. As wall charges increase, the discharge initiation nearly occurs at the moment of zero-voltage [Fig.3(c), (d)] and spatial uniformity of discharge is improved. As wall charges continue to increase, wall charges are enough to form a completely diffuse discharge (glow-like discharge). This corresponds to the discharge before zero-voltage [Fig.3(e), (f)], and spatial uniformity of discharge is very high.

4. Conclusion

The plasma with high spatial uniformity at moderate *pd* values is obtained by using a dielectric barrier discharge reactor with two liquid electrodes. Townsend phase, streamer phase and glow-like discharge are observed by increasing the applied voltage. The moment of discharge initiation shifts forward as applied voltage increases. The input power increases with the increase of applied voltage. The glow-like discharge with high spatial uniformity can be maintained when the applied voltage is in a wide range of 2.4–5.8kV, and corresponding input power is in a range of 5.5–21.0W.

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