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Self-organized pattern formation of an atmospheric pressure plasma jet in a dielectric barrier discharge configuration

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This letter reports the observation of self-organized patterns formed in a 29 mm wide atmospheric pressure plasma jet. By altering the gas flow rate and/or the applied voltage, the plasma jet is seen to have at least three different modes, namely, a diffuse-looking discharge, a self-organized discharge, and an unstable discharge with randomly occurring plasma channels. The self-organized discharge mode is characterized by several bright plasma channels embedded in a diffuse and dim plasma background. These plasma channels are regularly spaced from each other and their self-organized patterns are shown to evolve abruptly. © *2007 American Institute of Physics*.
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Self-organized pattern formation is a phenomenon of an ordered macroscopic structure resulting from a nonlinear interaction between the microscopic elements of a large system.[1] Pattern formations have been observed in many nonlinear and nonequilibrium systems.[2–15] Dielectric barrier discharge (DBD) is a typical nonlinear and nonequilibrium system, in which different discharge modes, referred to as filamentary, self-organized patterned, or diffuse discharges, can be obtained at atmospheric pressure by controlling the experimental conditions. The filamentary mode is characterized by a large number of short-lived microdischarge channels with a nanosecond time scale. With the proper repetition frequency and the presence of metastables or residual-charge carriers, diffuse discharges can be obtained. The patterns are formed when a number of microdischarges or smaller diffuse discharge areas are arranged regularly under certain operating conditions.[6,7] In the past two decades, the understanding of pattern formation in DBD has been broadened with experimental observations of a large variety of self-organized patterns including hexagon, strip, spiral, and concentric ring patterns.[1,8–15] These are formed between two parallel electrodes immersed in a static atmospheric gas and their basic constituent elements tend to have a submillimeter diameter. Studies of pattern formations are important for DBDs, not only because of their intriguing similarities with those in other scientific disciplines but also because of their potential to uncover a previously uncharted operating regime that offers active plasma chemistry and stability simultaneously.[16]

In atmospheric pressure DBD systems, one solution to maintain plasma stability is to generate discharge in a confined electrode structure and flush it to a downstream point, by which a plasma jet is formed.[17,18] Self-organized patterns in atmospheric pressure glow discharge jets have been reported recently in the form of a striation pattern along the length of a single plasma jet.[19] In this letter, we report the observation of a different class of patterns formed in an atmospheric pressure plasma jet (APPJ) in which several millimeter-sized plasma channels are formed with a self-organized fashion and remain stable for many tens of minutes once formed.

The experimental apparatus is schematically shown in Fig. 1. The gas discharge is generated within a cubic quartz tube having an internal cross-sectional area of 5×29 mm^2, the open end of which is wrapped with copper wires of 10 mm wide as the powered electrode. A stainless steel plate covered with a quartz layer is placed 8 mm away from the open end of the tube and used as the grounded electrode. By applying a high voltage between the electrodes, the discharge is generated and then flushed into the ambient air by the flowing gas of helium (99.99%) to form a plasma jet. The excitation source provides a sinusoidal voltage at 45 kHz and with a peak voltage up to 10 kV. Voltage and current measurements are performed by using a high-voltage probe and a current probe via a digital oscilloscope (Tektronix

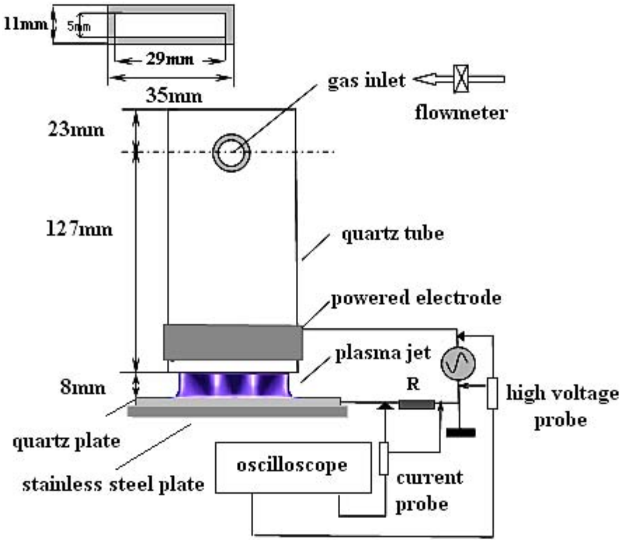

FIG. 1. (Color online) Experimental setup of the APPJ.

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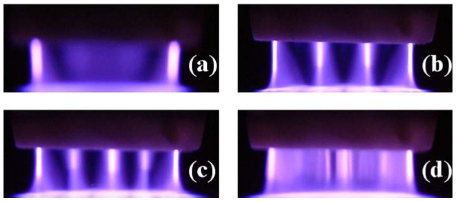

FIG. 2. (Color online) Formation process of the regular self-organized patterns with a fixed helium flow value of 0.38 m^3/h and at a peak applied voltage of (a) 2.5 kV, (b) 3.4 kV, (c) 3.7 kV, and (d) 4.0 kV.

TDS2022). The appearance of plasma patterns are imaged with a digital camera with exposure time of 40 ms.

The diffuse, self-organized, and filamentary modes of the APPJ are observed by altering the experimental conditions. The diffuse mode is shown in Fig. 2(a) in which a large diffuse discharge can be seen in the central region and its side boundaries are formed by two bright plasma sheets. With an increase of the applied voltage, this diffuse discharge mode evolves into a self-organized pattern in which additional millimeter-sized plasma channels appear abruptly, as indicated in Figs. 2(b) and 2(c). It is worth noting that the plasma channels are spatially symmetric but with different sizes and brightness. In general, the two side channels are much brighter than the middle ones, and the side channels can inhibit the expansion of the roots of the middle ones on the grounded electrode. A further increase of the applied voltage is found to eventually lead to a random-looking discharge, as indicated in Fig. 2(d).

The appearance and property of plasma jet are found to be sensitive to the helium flow rate and the applied voltage. A typical development of the jet is illustrated in Figs. 2(a)–2(d), for which the helium gas flow value is fixed at $v=0.38\ m^3/h$ and the peak applied voltage is increased up to $V_p=4.8$ kV. After the peak applied voltage is raised above the breakdown threshold at 2.5 kV, a plasma jet with a rectangular cross-sectional area of $5\times 29\ mm^2$ is ignited. Its spatial structure is dominated by a central region of a largely uniform discharge sandwiched by two bright side plasma channels, as shown in Fig. 2(a). This may be caused by the fact that the curvature of the power electrodes is sharper around the narrow face of the quartz tube than elsewhere and results in a higher local electric field. The main characters of the plasma jet at $V_p=2.5$ kV are similar to those reported before,[18] and hence it is of a spatially diffuse mode.

As the peak applied voltage is increased to 3.4 kV, two additional plasma channels appear suddenly and the appearance of the plasma jet becomes dominated by four bright channels immersed in a background of diffuse discharge, as shown in Fig. 2(b). Each of the channels has a width of a few millimeters, clearly contrasting the typical submillimeter-sized filaments observed in the previous studies.[1,8–15] The distance between two adjacent plasma channels is about 9 mm in Fig. 2(b). This self-organized pattern is stable and sustainable over quite a long time of continuous operation. As the applied voltage is increased from $V_p=3.4$ kV, the distance between the two middle plasma channels increases to 14 mm. At $V_p=3.7$ kV, the fifth plasma channel appears in the center abruptly, as shown in Fig. 2(c). The distance between two adjacent plasma channels is now about 7 mm. Again the self-organized pattern is stable over quite a long time. As the applied voltage is increased from $V_p=3.7$ kV to immediately below 4.0 kV, the plasma channels become brighter while their relative distance changes little. At $V_p=4.0$ kV, the self-organization pattern ceases to persist and the plasma jet evolves abruptly into a mode of a totally disordered appearance with randomly occurring streamers, as illustrated in Fig. 2(d). Besides this, a reduction of the applied voltage from 4.0 kV is found to result in a reversal process of mode transition from random streamers, through self-organization, to locally diffuse glow, but with the transition points occurring at different applied voltages. This hysteresis is typical for atmospheric pressure glow discharges when undergoing a mode transition.[20]

The electrical characteristics corresponding to the process of pattern formation in Figs. 2(a)–2(d) are shown in Figs. 3(a)–3(d). The discharge current shown is without the displacement current component that is determined by the property of the dielectric barriers and the internal impedance of the voltage source.[21] The typical wave forms of stable patterns are shown in Figs. 3(b) and 3(c). As shown in Figs. 3(b) and 3(c), there is only one discharge current peak per

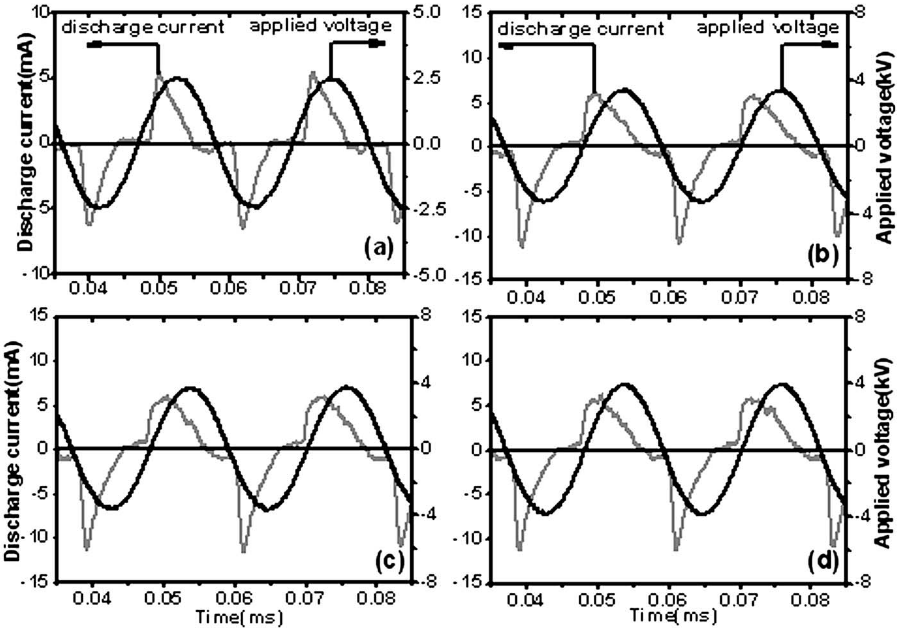

FIG. 3. Typical wave forms of the discharge voltage and current corresponding to the patterns in Fig. 2 with a fixed helium flow value of 0.38 m^3/h and at a peak applied voltage of (a) 2.5 kV, (b) 3.4 kV, (c) 3.7 kV, and (d) 4.0 kV.

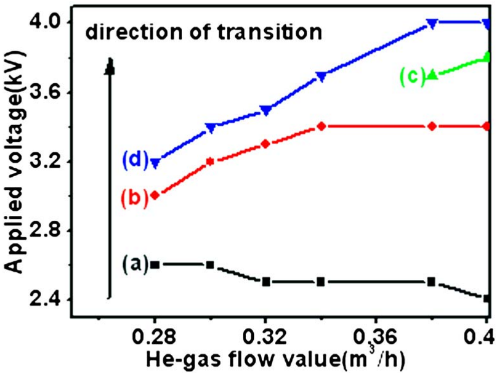

FIG. 4. (Color online) Transition curves of pattern formation over the gas flow range of $0.28\ \mathrm{m}^3/\mathrm{h} \leqslant \upsilon \leqslant 0.4\ \mathrm{m}^3/\mathrm{h}$, in which curve (a) indicates the ignition of a diffuse discharge with two side channels, curve (b) indicates the transition from the diffuse discharge to a self-organized discharge of four channels, curve (c) indicates the transition from four channels to five channels, and curve (d) indicates the transition from five channels to random streamers.

half-period of the applied voltage. The observation suggests that discharges of plasma channels in Figs. 2(b) and 2(c) occur simultaneously.

To study the voltage dependence of the pattern formation at different helium flow rates, the helium flow value is varied in the range of $0.28\ \mathrm{m}^3/\mathrm{h} \leqslant \upsilon \leqslant 0.4\ \mathrm{m}^3/\mathrm{h}$. The lower bound of this value is determined by the minimum helium flow at which the self-organized patterns occur, whereas the upper bound is limited by that of the flow controller used in our experiments. Figure 4 shows the mode transition of the jet, in which the region sandwiched by the curves marked as (a) and (b) specifies the conditions for a diffuse discharge. For a given flow value, an increase of the applied voltage generally leads to a self-organized pattern of either four or five plasma channels, as in the region between the curves marked as (b) and (d). Further increase of the applied voltage tends to become a mode of random streamers. It is worth noting that the appearance of five plasma channels occurs only after the helium flow value is in excess of $0.38\ \mathrm{m}^3/\mathrm{h}$, shown as (c).

The flow rate of gas also plays a vital role in the process of self-organization. For the same applied voltage, a similar process of pattern formation is observed to be triggered by changing the gas flow rate. Interestingly, with the increase of the helium flow rate, the number of the plasma channels contained in the pattern decreases. In addition, mode transitions of filamentary, self-organized patterned, and partly diffuse discharges can be observed. It is believed that pattern formation induced by the variation of flow field could offer a useful angle of study into the mechanism of self-organization in plasma jets. These will be reported in a future article.

A model of two-dimensional Coulomb system could be applied to explain the experimental results. Charged particles produced by discharge channels are stored on the surface of dielectric electrodes and make the channels repel each other. Besides, Lorentz force between each channel current and a parabolic potential could confine the discharge channels and balance the Coulomb repulsive force.[12,22] An alternative approach to a description of patterns observed in ac-driven DBD system could adopt the activator-inhibitor model, in which the discharge channels play the role of activator, and the wall charges act as inhibitor in the system.[13,23]

In conclusion, a hitherto unreported class of self-organized pattern is observed in the APPJ with a DBD configuration established in a helium flow. Under different experimental conditions, the plasma jet has been shown to evolve through three modes having diffuse, regularly self-organized, and completely disordered discharges, respectively. It has also been demonstrated that self-organized patterns of this APPJ are stable and their mode evolution is closely related to the applied voltage and the gas flow rate. These observations will enrich the understanding of pattern formation in DBDs and give additional information for developing a physical model of pattern formation in DBD systems.

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