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# An atmospheric-pressure plasma brush driven by sub-microsecond voltage pulses

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#### Abstract

An atmospheric-pressure room-temperature plasma brush, which can deliver uniform surface treatment effects, is reported. The plasma structure, which includes the negative glow, Faraday dark space and positive column, is clearly visible to the naked eye. The width of the Faraday dark space diminishes with decreasing gap distance and this phenomenon is different from that observed from low-pressure glow discharge plasmas. High-speed photographs taken at an exposure time of 2.5 ns show that the plasma propagates from the nozzle to the object in about 100 ns and 10 ns for gap distances of 6 mm and 2 mm, respectively, and the results are consistent with electric measurements. The emission spectra reveal  $N_2(B-A)$  bands in addition to those of O,  $N_2^+$ ,  $N_2(C-B)$  and He, indicating that the plasma source is reactive and suitable for applications such as surface modification and materials processing.

(Some figures may appear in colour only in the online journal)

# 1. Introduction

Compared with low-pressure non-equilibrium plasmas, atmospheric-pressure non-equilibrium plasmas (APNP) can be generated without an expensive vacuum system. This characteristic is very important for applications such as surface modification, materials processing, thin film deposition and biomedical decontamination [1–8]. However, owing to the relatively high breakdown voltage of gases at atmospheric pressure, the discharge gaps normally have a range between a few millimeters and several centimeters, thereby limiting the size of the materials and components that can be directly treated. If an indirect treatment is adopted, for instance, by remote exposure, some active species with a short lifetime may already disappear from the plasma before reaching the object, rendering the process inefficient.

To address these concerns, APNP jet devices have recently been attracting significant attention [9-20]. Plasma jet devices generate plasmas in an open space (surrounding air) rather than in confined discharge gaps. Hence, they can be used for direct treatment and there is also no limitation on the size

of the object. However, to the best of our knowledge, the dimensions of plasma jet nozzles that have been reported in the literature are mainly very small (sub-millimeter to several millimeters) making treatment of a large area difficult, and only a few large plasma jets have been developed [26]. One way to overcome this shortcoming is the use of plasma jet arrays [21–23]. However, since individual plasma plumes generated by these plasma jet arrays are independent and not merged, it is relatively difficult to achieve uniform treatment effects. In this paper, a novel atmospheric-pressure room-temperature uniform plasma brush is reported. The plasma brush can be operated in several different discharge modes depending on the distance between the nozzle and the sample.

## 2. Experimental setup

A schematic of the experimental setup is shown in figure 1(*a*). The device comprises two blades to guide the gas flow and also serve as the electrode. The blades are connected to a high-voltage (HV) pulsed direct current (dc) power supply (up to 10 kV with repetition rates up to 10 kHz and pulse widths variable from 200 ns to dc) through a  $60 \text{ k}\Omega$  ballast resistor *R* 

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Figure 1. (a) Schematic of the device. (b) Photograph of the plasma brush touched by a human finger (distance between the blade and finger is about 5 mm).

and a 36 pF capacitor *C*. The resistor and capacitor are used to limit the discharge current. The radius of the blade edge is about 50  $\mu$ m and the dimensions of the plasma brush nozzle are about 25 mm × 1 mm. Helium, argon or their mixtures with O<sub>2</sub> can be used. The gas flow rate is controlled by a mass-flow controller. When the HV pulsed dc voltages are applied to the blades and He is supplied at a flow rate of 1 L min<sup>-1</sup>, a homogeneous plasma brush is generated. It can be touched by a human finger as shown in figure 1(*b*) taken with a Sony digital camera (DSC-HX1) at an exposure time of 100 ms. The length of the plasma brush depends on the applied voltage, gas flow rate, nozzle dimensions, and the distance between the nozzle and the treated object. The other advantage is that both conducting and insulating materials can be treated by this plasma brush uniformly.

#### 3. Experimental results

Conducting materials to be treated are electrically connected to ground. As the distance between the brush nozzle (anode) and the object (cathode) decreases from 10 to 2 mm, the discharge mode of the plasma brush changes from a corona discharge to a glow discharge as illustrated in figures 2(a)-(d). A corona discharge occurs when the distance between the nozzle and the object is larger than 10 mm. The plasma brush extends into the surrounding air for a few millimeters, as shown in figure 2(a). Figure 2(b) shows that when the distance between the brush nozzle and the sample is reduced to 6 mm, a glow discharge emerges. Negative glow, Faraday dark space and positive column are observed from bottom to top. If the distance is further reduced to 4 mm, the plasma resembles a glow discharge, as shown in figure 2(c). The width of the Faraday dark space decreases compared with that in figure 2(b), but the length of the positive column is constant. This is different from the traditional glow discharge at a low pressure, in which the length of the positive column decreases



**Figure 2.** HV electrode made of two blades with the radius of the blade edge being about 50  $\mu$ m and the distance between the two blades about 1 mm: (*a*)–(*d*) photos of the plasma brush with the distance between the blade and the object being 10 mm, 6 mm, 4 mm and 2 mm, respectively (exposure time = 100 ms).

with decreasing discharge gap. Figure 2(d) reveals that the Faraday dark space disappears when the distance is reduced to 2 mm.

It should be emphasized that for a dielectric barrier discharge (DBD) driven by kilohertz alternative currents (ac) or radio-frequency voltages or a barrier-free discharge driven by nanosecond pulsed dc voltages, there are two well-known uniform discharge modes, namely the Townsend discharge



**Figure 3.** I-V characteristics of the plasma brush with  $V_1$  = applied voltage,  $V_2$  = voltage at the nozzle,  $I_{on}$  = total current (plasma on),  $I_{off}$  = displacement current (plasma off):  $V_1 = 7 \text{ kV}$ , pulse width = 800 ns, pulsing frequency = 5 kHz, working gas = He, He flow rate = 1.5 L min<sup>-1</sup>, discharge gap distance: (a) 6 mm and (b) 2 mm.

and the glow-like discharge [24, 25]. In order to identify the discharge modes, fast intensified charge-coupled device (ICCD) cameras with exposure times from a few nanoseconds to tens of nanoseconds are needed. If the plasma is monitored visually or by a regular CCD camera with exposure times in the millisecond range, it appears uniform and the fine structure of the plasma cannot be delineated. The plasma produced by this novel source is apparently different as it can be clearly distinguished with the naked eye.

To determine the electrical characteristics of the plasma brush, the applied voltages  $V_1$  and  $V_2$  on the blades are measured by two P6015 Tektronix HV probes. The total current  $I_{on}$  (plasma on) and displacement current  $I_{off}$  (without He flow, no plasma) are also measured by a TCP202 Tektronix current probe. The voltage and current waveforms are recorded by a Tektronix DPO7104 wide band digital oscilloscope. Figures 3(a) and (b) depict the voltage-current waveforms when the object is 6 mm and 2 mm away from the nozzle, respectively. As shown in figure 3(a) for a distance of 6 mm, before the discharge current reaches the main peak (labeled 4), there is a small current peak of about 10 mA (labeled 2). The main current pulse has an amplitude of about 70 mA and width of about 300 ns. As shown in figure 3(b) for a distance of 2 mm, only one discharge current peak with an amplitude of about 400 mA can be observed. The rise time of the discharge current is about 10 ns. The discharge current diminishes from 400 to 100 mA quickly in about 30 ns but drops slowly afterwards. It should be mentioned that the stray capacitor plays an important role during the discharge, and the main peak of the discharge current (from 1 to 3 as labeled in figure 3(b)) possibly arises from the discharge of the stray capacitance, whereas the slowly decreasing part of the discharge current (from 3 to 4 as labeled in figure 3(b)) is due to the discharge of the main circuit. Therefore, by integrating the main peak of the discharge current in figure 3(b), the total charges can be calculated to be about  $6 \times 10^{-9}$  C. The voltage drop during the main discharge is about 1 kV and according to  $C = Q/\Delta V$ , the stray capacitance is estimated to be about 6 pF.

appear for a distance of 6 mm, but only one current peak per voltage pulse occurs for a distance of 2 mm, as shown in figure 3(b). The phenomenon may be explained as follows. For a distance of 6 mm, when the plasma starts from the nozzle (anode), the positive ions in front of the blade initially weaken the electric field in the gap. Hence, the plasma is probably much thicker than the edge of the blade, and so the field enhancement effect is weakened. Afterwards, after the plasma has been initiated, although the distance between the plasma front and the object is shorter than the original gap distance, it is not enough to compensate for the first two effects for this distance of 6 mm. As the plasma propagates further into the gap, the effect of the electric field enhancement caused by decreasing the distance between the plasma front and the object starts to dominate the discharge behavior and so the plasma propagation is accelerated. This is probably the reason why there are two peaks in this case. However, when the distance is 2 mm, the third effect plays the dominant role right from the beginning and, consequently, only one fast rising current peak is observed.

Figure 3(a) shows that two current peaks per voltage pulse

To further investigate the mechanism of the plasma brush, a fast ICCD camera is used to capture the dynamics of the discharge. Figures 4 and 5 depict photographs taken at different delays for distances of 6 mm and 2 mm, respectively. The time labeled on each photograph in figures 4 and 5 corresponds to the time shown in figures 3(a) and (b), respectively. For a distance of 6 mm and as shown in figure 4(a), the plasma is initiated from the nozzle at 400 ns corresponding to 1 as labeled in figure 3(a). Then it becomes brighter as shown in figure 4(b). This corresponds to the small current peak 2 as labeled in figure 3(a). Afterwards, the plasma propagates towards the sample (cathode) leaving a dark zone near the nozzle (anode). The luminance of the plasma decreases corresponding to 3 in figure 3(a). Afterwards, the plasma propagates quickly and reaches the cathode, as shown in figure 4(d). Hence, it takes about 100 ns for the plasma to cross the 6 mm gap. Figure 4(e) illustrates a stable glow



**Figure 4.** High-speed photographs of the plasma brush for an exposure time of 2.5 ns. The time labels in each photograph correspond to the times shown in figure 3(a). The discharge gap distance is 6 mm.

discharge. The negative glow, Faraday dark space and positive column can be readily discerned from bottom to top and finally, the glow discharge reaches a steady state and the luminance of the plasma starts to decrease.

As shown in figures 5(a) and (c) corresponding to 1 and 2 in figure 3(b) for a distance of 2 mm, the plasma resembles a cathode-directed streamer-like discharge propagating from the nozzle to the sample in about 10 ns. The light intensity of the plasma increases dramatically as soon as it reaches the sample, and afterwards the intensity decreases.

The plasma gas temperature is very important for applications such as treatment of temperature-sensitive materials and plasma medicine. The rotational temperature that characterizes the gas temperature of the plasma and vibrational temperature of the plasma are estimated based on the best fit of the simulated spectra of the  $C^{3}\Pi_{u}-B^{3}\Pi_{g}$  ( $\Delta v = -2$ ) band transition of nitrogen and the experimentally recorded spectra. Figure 6 shows that the gas plasma is at room temperature while the vibrational temperature is about 2950 K, implying that the plasma is under extremely non-equilibrium conditions.

Optical emission spectroscopy (OES) enables analysis of the radiation emitted from atoms, ions, molecules and radicals



**Figure 5.** High-speed photographs of the plasma brush. The exposure time is fixed at 2.5 ns. The time labels in each photograph correspond to the times shown in figure 3(b). The discharge gap distance is 2 mm.



Figure 6. Experimental and simulated spectra of  $N_2$  second positive system 0-2 transition.

when they are excited by an electric field or by collisions with other particles. These emission lines and bands are very useful for diagnostic purposes because they impart important information about the plasma. Figures 7(a) and (b) display the emission spectra from 250 nm to 500 nm and from 500 nm to 800 nm, respectively, and clearly disclose the existence of excited O, N<sub>2</sub>, N<sub>2</sub><sup>+</sup> and He in the plasma plume. It is noted that the emission bands of N<sub>2</sub>(*B*–*A*) are not observed from most room-temperature plasma jet devices, suggesting that the concentration of the excited N<sub>2</sub>(*B*) state is quite high in the plasma brush. The results suggest that the plasma is very reactive.

### 4. Conclusion

A glow-like room-temperature plasma brush producing visibly discernible negative glow, Faraday dark space and positive column is described. The plasma brush can be touched by a human finger without harm. When the distance between the



Figure 7. Emission spectra of the plasma plume: (a) 200–500 nm and (b) 500–800 nm.

brush nozzle and the object is reduced, the width of the Faraday dark space decreases, but the length of the positive column remains constant. This is different from what is observed from a traditional glow discharge. When the gap between the nozzle and the object is 6 mm, the discharge current has two peaks. The main current pulse has a width of about 300 ns. On the other hand, when the gap distance is reduced to 2 mm, there is only one current pulse with a width of about 40 ns. High-speed photographs show that it takes about 100 ns for the plasma to traverse the distance of 6 mm from the nozzle to the object. For a distance of 2 mm, the time is reduced to about 10 ns. The electric characteristics are consistent with the high-speed photographs.

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