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Thin Solid Films 506–507 (2006) 404 – 408
thin solid films
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A novel cold plasma jet generated by atmospheric dielectric barrier capillary discharge

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Abstract

In the paper, an easy-operated scheme is presented to generate a novel kind of atmospheric cold plasma millimeter jet. The jet is achieved in several kinds of gases at atmosphere pressure, such as Ar, He and N_2, in a capillary quartz dielectric barrier discharge (DBD) system powered by a pulsed power source with a frequency of 15 kHz. Via an CCD camera, the initial discharge filaments in the DBD gap are found to be transited into diffusion discharges or glow-like discharges by the flowing gas through the DBD gap and a plasma jet is formed in the outlet of the capillary simultaneously. The critical gas flow velocity for the plasma jet formation is determined to be 3–8 m/s for different gases by a well-designed Pitot tube probe. The jet range for a special gas can be changed by varying the gas flow velocity, while the jet range for different gases varies a lot and the Helium jet takes the longest range of about 44 mm when the helium flows at a velocity of about 20 m/s. Beyond the velocity limit of 20 m/s for laminar helium flow, the jet of helium plasma becomes torrent and unstable and its range turns shorter.

Keywords: Plasma jet; Dielectric barrier capillary discharge; Pitot tube

1. Introduction

In recent years, atmospheric cold microplasmas and their jets, which exhibit some features of the low-pressure glow discharges, have attracted more and more attention in both scientific and engineering field because of its merits of small size, low temperature, low electric power cost and high density of more than 10^{13} cm^{-3} [1]. Cold microplasma jets and their array sources are suitable for various material processing applications, one of which is maskless pattern transfer [2]. Otherwise, microplasma jets open a novel scheme for plasma generation against the Schottky's theory [3] and presents an innovative device in many application fields [4–7].

Various techniques have been proposed to generate microplasmas and microplasma jets. Atmospheric cold microplasmas and their arrays can be generated in microhollow cathode arrays electrically supplied by a DC power source [8] due to Pandel effect [9] or in parallel-plate microgaps capacitively powered by an RF power source [10]. Nevertheless, cold microplasma jets are often generated by RF capacitively powered quartz barrier capillary discharge [11] or RF inductively powered single capillary tube barrier discharge [1]. However, some disadvantages in operation have been found in all the proposed techniques. On one hand, generally speaking, the electrodes used to generate microplasmas in DC microhollow cathode arrays are usually sputtered [5], and eventually, their life ceases when the electrode structures are damaged by the sputtering. On the other hand, those RF-powered microplasmas and their jets are easily changed into arcing [12] when the RF power input is raised to some extent. Otherwise, discharges are difficult to sustain in a small cavity, due to the much more loss of electrons at the walls, especially the plasmas driven by RF power, for which a RF driving potential higher than 10^3 V is needed [13,14].

Based on the idea that an RF-driven micrometer-scale plasma jet is proved to be easier triggered and sustained with an auxiliary pulsed high-voltage (HV) ignition electrode [15], a pulsed supply, which is commonly used to generate dielectric barrier discharge (DBD), should be

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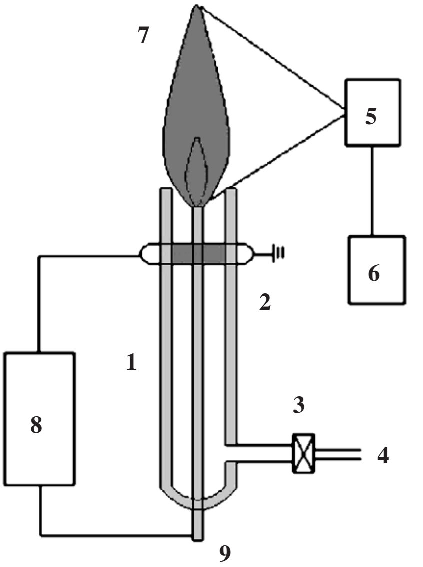
doi:10.1016/j.tsf.2005.08.088

able to be used to produce atmospheric plasma jet more easily. In this paper, an easy scheme to generate a novel kind of atmospheric cold plasma jet in a millimeter capillary is presented. The jet has been achieved with some kinds of working gas at atmosphere pressure, such as argon, nitrogen, helium and their mixtures, in a capillary quartz DBD system powered by a pulsed power source with a frequency of 15 kHz.

2. Experimental setup design

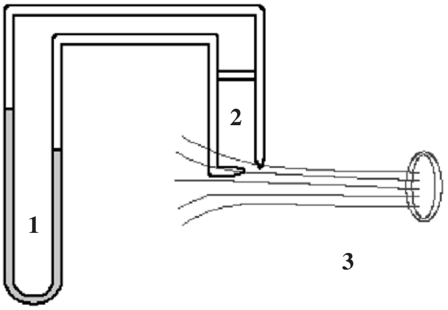
Fig. 1 shows schematically the quartz capillary DBD plasma jet generator. The main part of the setup is a capillary quartz tube with one closed end, which is 4 mm in inner diameter, 7 mm in outer diameter and 120 mm in length. A grounded two turn coil surrounds tightly on the outer wall of the capillary and a Φ 0.4-mm tungsten rod is centered at the axis of the capillary as the power electrode. The tungsten rod surface is electro-chemically polished in a 0.1 M KOH solution and its one end is sharpened into a tapered tip before being fixed to the capillary in such a direction that the tip end is inside the capillary. The tip is 15 mm away from the opening of the capillary

The generator is powered by a self-built HV source operated at a fixed frequency of 15 kHz and an adjustable amplitude voltage of 1 kV–15 kV. An HV probe of model TEK P6015A is used to monitor the voltage waveform of the power output and to ensure the plasma jet generator works properly during experiments. The output waveform of the power source is something of a sequence of asymmetric triangles because the circuit principle is the same as that of the line scan unit in TV set. Although a current probe of model TCP202 is tried to detect the discharge current, no credible current waveform can be recorded because of the small current amplitude and the very strong electrical noise produced by the open discharge scheme.



1. Quartz capillary (ϕ7mm) 2. Grounded coil
3. Mass flow rate controller 4. Gas inlet
5. CCD camera 6. Computer 7. Plasma jet
8. HV power source 9. Tungsten electrode

Fig. 1. The schematic of the DBD plasma jet generator and imaging system.



1. **U pressure-meter filled with dye solution in alcohol**
2. **Crossed capillary Pitot tubes**
3. **Plasma jet field**

Fig. 2. The schematic of the capillary Pitot tube probe.

Ar, He and N_2 gases are chosen to be the working gases of the plasma jet formation because all of the three gases produce no harm to the atmospheric environment and the human body when they are operated in an open manner. Gas flow velocity has been measured by many researchers via many kinds of different principles, such as tracer [16], hot wire method [17], time of flight [18], sonic Doppler effect [19], interferometer [20], and laser Doppler effect [21]. But the most useful method is still the oldest Pitot tube [22,23] for common gas and liquid flow. The gas flow velocities here are measured via a well-designed Pitot tube, whose schematic is show in Fig. 2, in which the U-shaped pressure meter is partially filled with dilute red solution of rhodamine in alcohol and the two probing heads with diameter of 1 mm are directed perpendicularly to each other.

According to the Bernouilli's law, the following is true for a laminar flow system:

$$P + \rho v^2/2 + h = \text{Constant}. \tag{1}$$

P is the static pressure of flowing medium; ρ is the mass density of the medium; v is the flow velocity, and h is the specific enthalpy. Because the cold plasma jet can be regarded isothermal, its specific enthalpy, h, is reasonably considered to a constant everywhere in the flowing field, and therefore, the flowing velocity v of the jet is expressed to be:

$$v = [2(P_0 - P)/\rho]^{1/2} = (2\Delta P/\rho)^{1/2} \tag{2}$$

where P_0 is the stagnation pressure of the flowing jet.

A commercially available CCD camera is used to record the images of the plasma jets in all cases. Based on the