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A large-area diffuse air discharge plasma excited by nanosecond pulse under a double hexagon needle-array electrode

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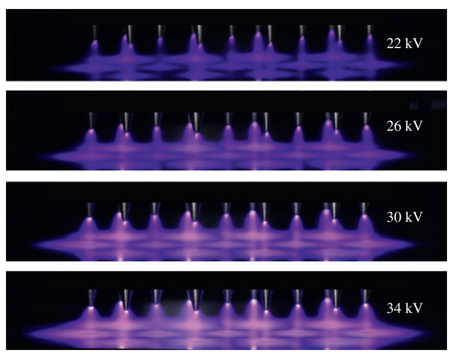
HIGHLIGHTS

- A diffuse and large area discharge plasma was generated by bipolar nanosecond pulse voltage.
- The electric and optical characteristics of the diffuse discharge are discussed.
- The T_{rot} and T_{vib} are determined at $T_{rot} = 365 \pm 5$ K and $T_{vib} = 2300 \pm 50$ K.
- The effects of discharge parameters on the pulsed DBD were investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

A large-area diffuse air discharge plasma excited by bipolar nanosecond pulse is generated under a double hexagon needle-array electrode at atmospheric pressure. The images of the diffuse discharge, electric characteristics, and the optical emission spectra emitted from the diffuse air discharge plasma are obtained. Based on the waveforms of pulse voltage and current, the power consumption, and the power density of the diffuse air discharge plasma are investigated under different pulse peak voltages. The electron density and the electron temperature of the diffuse plasma are estimated to be approximately 1.42×10^{11} cm^{-3} and 4.4 eV, respectively. The optical emission spectra are arranged to determine the rotational and vibrational temperatures by comparing experimental with simulated spectra. Meanwhile, the rotational and vibrational temperatures of the diffuse discharge plasma are also discussed under different pulse peak voltages and pulse repetition rates, respectively. In addition, the diffuse air discharge plasma can form an area of about 70×50 mm^2 on the surface of dielectric layer and can be scaled up to the required size.

Introduction

Diffuse plasma with large area, generated by dielectric barrier discharge (DBD) at atmospheric pressure (AP), has recently attracted considerable interest in diversified industrial applications, such as surface treatment [1,2], thin-film deposition [3–5], and sterilization of biomedical samples [6,7]. As we know, DBD can be realized in two major operating modes, i.e., the filament DBD mode and the diffuse DBD mode at AP. In most cases, due to the instability of the plasma, the discharge easily transforms from the diffuse DBD to the filament DBD even when the operation conditions slightly change, because where numerous microdischarges are stochastically distributed and energy is distribution of non-uniform in space and in time. These discharges result in inhomogeneous treatment and are less suitable for applications like surface treatments where uniformity is the main aspect [8,9]. Compared with the filamentary DBD, the low gas temperature, moderate power density, and uniform energy distribution of the diffuse DBD highly recommend them for applications in which

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it is important to have uniformity of effect and avoid damaging or heating the surface of the workpiece. However, at AP, the diffuse DBD plasma can be only achieved in specific conditions, because the diffuse discharge in air easily transition into spark discharge that significantly heat the gas and the control of the operation conditions in the diffuse mode are rather difficult especially at AP, what's more, the dimensions of generated plasma reported in the literature are very small, which is problematic for practical application in many industrial areas [10].

Considering the above concerns, much attention recently has been devoted to research on diffuse DBD plasma [7–17]. As an effective method with optimization of the ionization efficiency, nanosecond high-voltage pulsed discharge has unique advantages in achieving diffuse DBD plasma. Because the nanosecond high-voltage pulsed discharge is characterized by a fast rising time of pulse voltage, which makes that the electrical energy delivered in discharge is mainly deposited in the energetic electrons instead of heating the heavy particles. Also, the fast rising time of pulse voltage can also improve the energy distribution and make it possible to obtain uniform discharge plasma [10–12]. Dozens of nanoseconds pulse duration can avoid effectively the glow-to-arc transition [8,9,13]. Therefore, it is an ideal actuator to obtain diffuse pulsed DBD plasma in air at AP. Meanwhile, to address the small dimensions of generated plasma, a double hexagon needle-array electrode instead of conventional electrode, such as single needle-plate, test-tube, and plate-plate [7,8,14–17], is used to generate diffuse and large area discharge plasma between the electrodes and to keep the diffuse discharge stable for long duration. Obviously, increasing the needle electrode number is an effective method to generate much larger area discharge plasma. Also, the needles array electrode triggered simultaneously is a significant advantage of nanosecond pulse discharge.

Compared with a high voltage unipolar pulse, a high voltage bipolar pulse in which a positive pulse is followed by a negative pulse alternately and when the bipolar pulse is applied to generate a plasma discharge, the charges accumulated on the surface of the dielectric plate can participate in the subsequent pulse discharge, which is beneficial to the excitation of the discharge. In this article, we employ a double hexagon needle-array electrode as the electrode configuration excited by a bipolar pulsed power supply to produce air plasma at AP. The diffuse plasma can form an area of approximately 70 × 50 mm^2 on the surface of dielectric layer and can be scaled up to the required size. In addition, the electric and optical characteristics of the diffuse discharge are presented and discussed.

Experimental setup

The experimental setup of pulsed DBD is illustrated schematically in Fig. 1(a). It is composed of a bipolar pulsed power supply, a discharge reactor, and an optical detection system. The home-made bipolar high-voltage pulse power can supply a high voltage pulse with a rising time approximate 20 ns, a pulse width about 40 ns, and an adjustable repetition rate in range of 0–400 Hz. The pulsed DBD plasma is generated between the needle array and the plate electrode, the vertical view of the double hexagon needle-array electrode is shown in Fig. 1(b). The needle electrode is made of stainless-steel and the electrode distance from the needle to needle is 10 mm. The tip of the needle is rounded with a diameter of 0.8 mm. The plate electrode is made of a stainless-steel plate with a diameter of 80 mm and covered by a 1 mm thick quartz dielectric layer with a diameter of 100 mm. In order to reduce the interferences of discharge pulses on the detection system and other instruments, the high-voltage pulse power supply is placed in a two-layer shielding box, which is connected to the ground. The discharge voltage and discharge current are measured with a 1:1000 high-voltage probe (Tektronix P6015A 1000 × 3.0 pF 100 MΩ) and a current probe (Tektronix TCP312 Bandwidth 100 MHz). Both the waveforms are recorded and displayed in an oscilloscope (Tektronix TDS5054B 500 MHz). Optical emission spectra (OES) emitted from the plasma region are also recorded by an Andor SR-750i grating monochromator (grating groove is 2400 lines/mm, glancing wavelength is 300 nm).

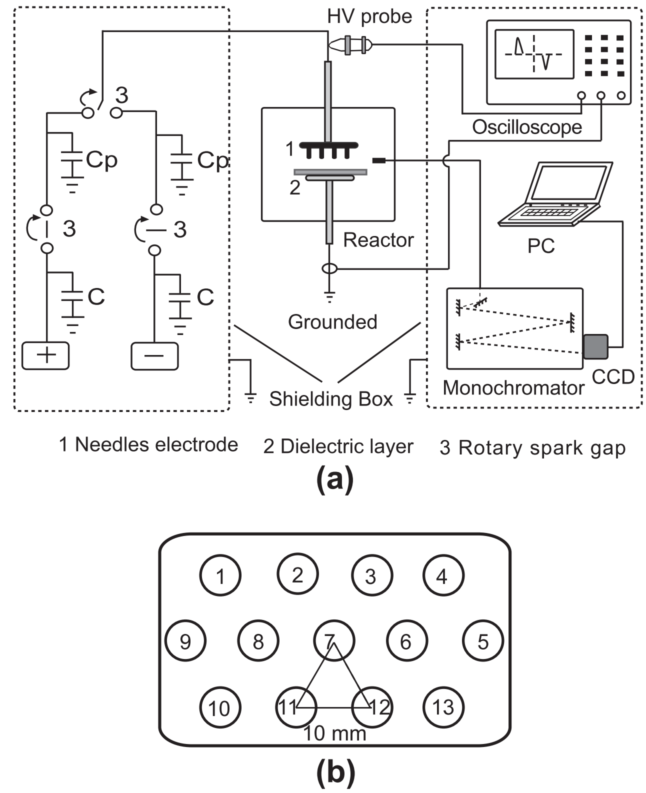

Fig. 1. (a) The experimental setup of DBD excited by bipolar nanosecond pulse power supply. (b) The vertical view of the double hexagon needle-array electrode.

Results and discussion

The visualization of the diffuse pulsed DBD in air at AP

Fig. 2(a) shows the image of a hexagon needle-array electrode diffuse DBD captured by a Canon 550D digital camera with an

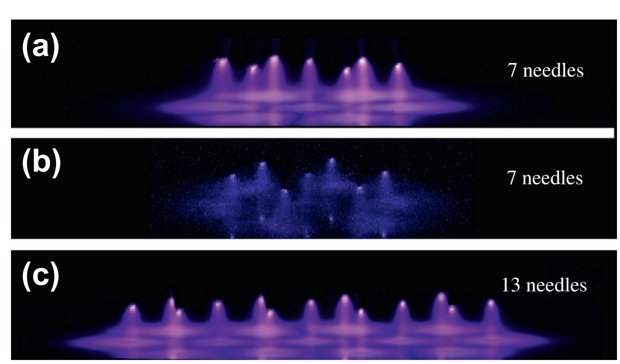

Fig. 2. The discharge images of pulsed DBD under the condition of 30 kV pulse peak voltage, 150 Hz pulse repetition rate, and 5 mm gas gap distance. (a) Image with an exposure time of 1000 ms under a hexagon needle-array electrode. (b) Image with an exposure time of 2.5 ms under a hexagon needle-array electrode. (c) Image with an exposure time of 1000 ms under a double hexagon needle-array electrode.