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Room-Temperature Atmospheric Pressure Plasma For Biomedical Applications

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Room-temperature atmospheric pressure plasma plume for biomedical applications

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As low-temperature nonequilibrium plasmas come to play an increasing role in biomedical applications, reliable and user-friendly sources need to be developed. These plasma sources have to meet stringent requirements such as low temperature (at or near room temperature), no risk of arcing, operation at atmospheric pressure, preferably hand-held operation, low concentration of ozone generation, etc. In this letter, we present a device that meets exactly such requirements. This device is capable of generating a cold plasma plume several centimeters in length. It exhibits low power requirements as shown by its current-voltage characteristics. Using helium as a carrier gas, very little ozone is generated and the gas temperature, as measured by emission spectroscopy, remains at room temperature even after hours of operations. The plasma plume can be touched by bare hands and can be directed manually by a user to come in contact with delicate objects and materials including skin and dental gum without causing any heating or painful sensation. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2045549]

One of the attractive characteristics of nonequilibrium plasmas is their enhanced plasma chemistry without the need for elevated gas temperatures. This is because the plasma chemistry is driven by the electrons, while the heavy particles remain at low energy. To enhance the gas chemistry, the electron energy distribution function can be controlled in a way to shift it towards the high-energy tail. Lu and Neiger[1] and Laroussi *et al.*[2] have demonstrated that by applying narrow voltage pulses (submicrosecond wide) to reduced-pressure and atmospheric-pressure plasmas, respectively, more applied energy is coupled to the plasma and enhanced chemistry is achieved. In this letter, submicrosecond high voltage pulses at repetition rates in the 1–10 kHz range are applied between two specially designed electrodes through which helium gas is flowing (flow rates in the 1–10 l/min range). Each of the two electrodes is made of a thin copper ring attached to the surface of a centrally perforated glass disk. The hole in the center of the glass disk is about 3 mm in diameter, while the diameter of the disk is about 2.5 cm. The diameter of the copper ring is greater than that of the hole but smaller than that of the disk. The two electrodes are inserted in a dielectric cylindrical tube of about the same diameter as the glass disks and are separated by a gap the distance of which can be varied in the 0.5–1 cm range. Figure 1 is a schematic of the device. When helium is injected at the opposite end of the dielectric tube and the high voltage pulses are applied to the electrodes, a discharge is ignited in the gap between the electrodes and a plasma plume reaching lengths up to 5 cm is launched through the hole of the outer electrode and in the surrounding room air. Figure 2 is a photograph of the plasma plume. The length of the plume depends on the helium flow rate and the magnitude of the applied voltage pulses. The plasma plume remains at low temperature and can be touched by bare hands without any harm. The device, being basically a 1-in.-diam dielectric tube (about 5 in. long) can be hand held and the plume directed at will towards a surface to be treated including human skin or dental gums. Unlike other known plasma "jet" devices, which generate very short plumes in the millimeter range, and at temperatures that can reach several tens of degrees above room temperature, this device is capable of producing and maintaining room-temperature plasma plumes more than an order of magnitude in size. Also unlike devices such as the plasma needle,[3,4] which generates 2–3-mm-long plasma at the tip of a sharp wire (needle), this device contains no sharp metal objects and since narrow submicrosecond voltage pulses are used, as opposed to rf power, the risk of arcing and device heating for long operation periods (hours) is avoided.

The gas temperature was determined by analyzing the rotational structure of the N_2 second positive system emission. This rotational structure contains information on the rotational temperature. Because of the low energies needed for rotational excitation and the short transition times, molecules in the rotational states and the neutral gas molecules are in equilibrium. Therefore, the gas temperature can be directly inferred from the rotational temperature.[5] To determine the gas temperature of the plasma plume, we compared

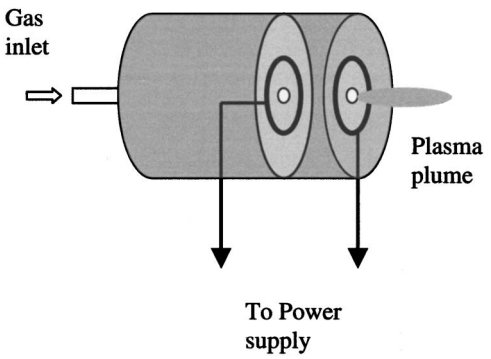

FIG. 1. Schematic of the plasma pencil.

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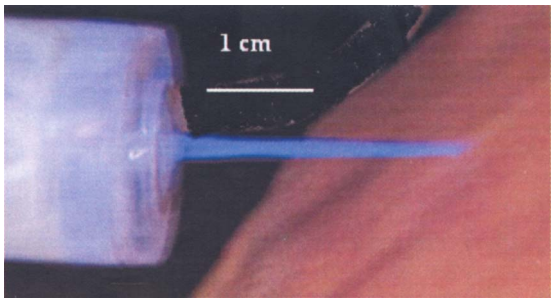

FIG. 2. (Color online) Photograph of the plasma plume in contact with human skin.

the experimentally measured spectra with simulated spectra of the 0-0 band of the second positive system of nitrogen at different temperatures. The experimental spectra were recorded by a Spectra-Pro 0.5 m imaging spectrometer. The helium flow rate is 4 l/min, the voltage magnitude is 6 kV, the pulse width is 500 ns, and the repetition rate is 3 kHz. Figure 3 shows the recorded experimental spectrum and simulated spectra at different gas temperatures. The spectral resolution is 0.02 nm (grating: 3600 g/mm, slit width: 50 μm). The curves are intentionally shifted vertically for clear comparison. It is clear from Fig. 3 that the simulated spectrum at $T=290$ K gives the best fit to the experimental spectrum. Therefore, the gas temperature is practically room temperature. This is easily verified by a simple touch of the plasma plume. The above measurements were repeated for different helium flow rates without any measurable change in temperature. Some of the measurements were carried out a significant time after the discharge was turned on. Therefore, extended operation time does not lead to an increase in temperature. This stable low-temperature operation is of the utmost importance in biomedical applications where burns or even relatively small temperature rises can negatively affect the biological samples (cells, tissue, etc.)

The electrical power is supplied to the electrodes of the device via a high voltage pulser. The high voltage is supplied to the pulser by a dc voltage supply with variable output voltage. At typical operating parameters of the plasma plume, about 15 W of power is supplied by the dc supply to the pulser. For 500-ns-wide monopolar pulses, the average power supplied to the plasma is in the 1–3 W range. Since treatment times are typically in the minute range, the maximum total energy transferred to the plasma is in the 60–180 J range. Most of this energy goes into sustaining the discharge and only a small portion is transferred to the biological sample under treatment. Assuming that the specific heat of biological matter is similar to that of water (4186 J/kg K), a maximum temperature increase of less than 1 K/ml/min is expected.

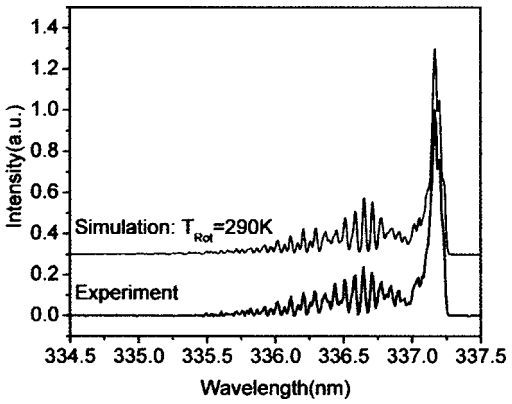

FIG. 3. Experimental and simulated emission spectra of N_2 second positive system. The curves are shifted intentionally for better comparison.

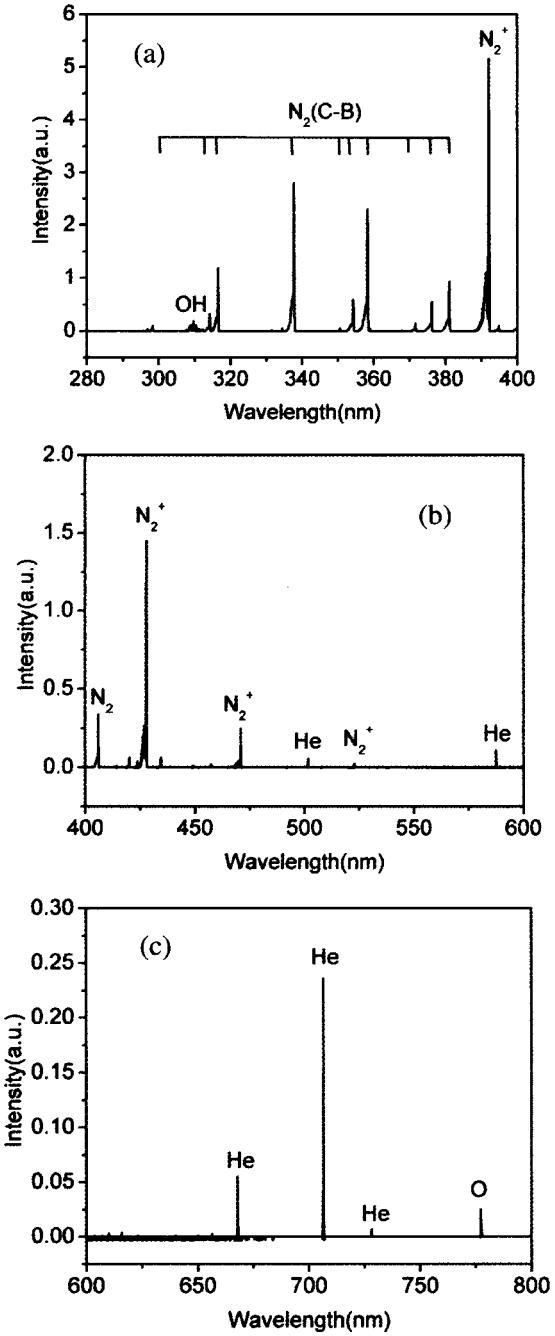

FIG. 4. Emission spectra: (a) 280–400 nm range showing OH, N_2, and N_2^+ emission lines; (b) 400–600 nm showing N_2, N_2^+ and He lines; (c) 600–800 nm range showing He and O lines.

To identify the various reactive species generated by the plasma plume, optical emission spectroscopy is applied in the 200–800 nm wavelength range. For this task a half-meter spectrometer (Acton Research SpectraPro 500i) equipped with a photomultiplier (Hamamatsu R928) is used. No line emission was detected in the 200–280 nm range. Figures 4(a), 4(b), and 4(c) show that the emission spectra

are dominated by the presence of excited nitrogen, helium, and nitrogen ions. In addition highly reactive radicals such as hydroxyl (OH) and atomic oxygen are detected. These radicals play important roles in all plasma-surface interactions. Their highly oxidative nature allows them to change important surface properties such as hydrophobicity. Their contact with organic matter (such as cells) leads to interesting processes such as oxidation of membrane lipids and proteins. In the case of bacteria (prokaryotes) this oxidation can lead to cell inactivation and even to cell lysis.[6] In the case of mammalian cells (eukaryotes), other processes such as cell detachment or cell apoptosis can result.[7]

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