

## Microplasma jet at atmospheric pressure

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A nitrogen microplasma jet operated at atmospheric pressure was developed for treating thermally sensitive materials. For example, the plasma sources in treatment of vulnerable biological materials must operate near the room temperature at the atmospheric pressure, without any risk of arcing or electrical shock. The microplasma jet device operated by an electrical power less than 10 W exhibited a long plasma jet of about 6.5 cm with temperature near 300 K, not causing any harm to human skin. Optical emission measured at the wide range of 280–800 nm indicated various reactive species produced by the plasma jet. © 2006 American Institute of Physics.

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Nonthermal plasmas generated at reduced pressure have well established for broad applications in material science. Nonthermal atmospheric plasmas get much attention lately because they can provide a cheaper and more convenient alternative in comparison with low-pressure plasmas.<sup>1</sup> Various configurations and applications of nonthermal plasmas have been extensively investigated nowadays. Capacitively coupled radio-frequency (rf) discharges are studied in connection with material surface processing<sup>2,3</sup> and plasma display panels,<sup>4</sup> dc microhollow cathode discharges can serve as efficient sources of vacuum UV radiation,<sup>5,6</sup> and dielectric barrier discharges have been turned out to be useful in surface modification and gas conversion.<sup>7,8</sup> More recently, much effort is endowed in creating an appropriate plasma source for biomedical applications.<sup>9–11</sup> Particularly, Stoffels *et al.*<sup>12</sup> developed a nondestructive atmospheric plasma source, so called rf plasma needle, for the study of the plasma interactions with living cells and tissues. Such a source has to meet many requirements to be suitable in applications for treating thermally sensitive materials. For instance, the plasma source for biomedical applications must provide truly nonthermal plasma working at atmospheric pressure and near the room temperature without any electrical and chemical risks. The microhollow discharge occurs by applying external dc or time-varying voltage electrodes. Tens or hundreds of micro-sized cathode cavity is then formed in reduced pressure, confining the glow discharge in inert gases.<sup>5,6,13,14</sup> Meanwhile, we present a microplasma jet device operated at the atmospheric pressure, which can produce a long cold plasma jet of several centimeters in nitrogen gas and which might be useful in treating thermally sensitive materials.

Figure 1 is a schematic presentation of the microplasma jet device at atmospheric pressure. The ac power supplier is a commercially available transformer for neon light operated at 20 kHz. The applied voltage is connected to two electrodes with a hole of 500  $\mu\text{m}$  diameter, through which nitrogen gas is flowing. Each of the two electrodes is made of an aluminum disk with 20 mm diameter and 3 mm thickness attached to the surface of a centrally perforated dielectric disk with 1.5 mm thickness. The hole in the center of the dielectric disk has the same diameter with the electrodes. The

dielectric disk can be made of glass, quartz, Teflon, etc. The assembled electrodes and dielectric disks are inserted in a dielectric case of the same diameter as that of the dielectric disk. To prevent an electrical shock and damage caused from electrode by accidental contact to human body, the front electrode is also covered with the cylindrical dielectric case, as shown in Fig. 1. The dielectric case has the same size of hole as that of the electrode. Once nitrogen is introduced through the aligned holes of the electrodes and dielectric disks, and ac high voltage is applied, a discharge is fired in the gap between the electrodes and a long plasma jet reaching lengths up to 6.5 cm is ejected to open air through the front electrode, as shown in the inset of Fig. 1. Therefore, the device can be handheld, and the long and narrow plasma jet of the device can be directed towards a target surface.

Because the nitrogen microplasma jet in Fig. 1 remains near the room temperature, it can be touched by bare hands or scanned on human skin without establishing any conductive pathway. As one example for treating a vulnerable target, Fig. 2 reveals a photograph of the microplasma jet in contact with bare hand. From the measurement of gas temperature by a thermocouple, it was shown that the temperature of the plasma jet at 2 cm from the dielectric case was below 300 K. In Fig. 2, the plasma operated at 6.3 lpm (liters per minute) nitrogen was ejected at the speed of approximately 535 m/s, producing afterglow at high pressure and cooling down to the room temperature. The microplasma device can also produce a short plasma less than 5 mm in

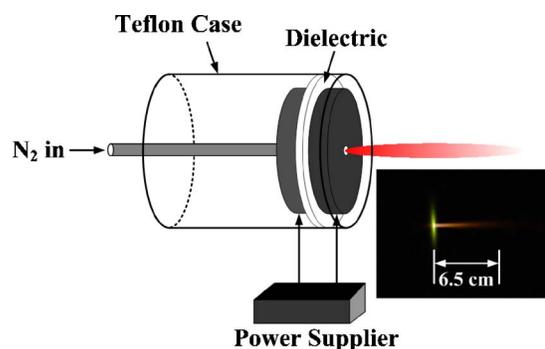


FIG. 1. (Color online) Schematic presentation of a simple nitrogen microplasma jet device at atmospheric pressure. The inset is the photograph of the microplasma jet at 6.3 lpm  $\text{N}_2$ .

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FIG. 2. (Color online) Photograph of the  $N_2$  microplasma jet in contact with human skin.

length such as the device known as the plasma needle<sup>9,12</sup> by controlling gas flow rate and applied voltage.

The measured voltage and the discharge current characteristic to the present microplasma jet device are shown in Fig. 3, when 3 lpm nitrogen was injected. The length of the plasma jet for this flow rate was about 3.3 cm. The black and gray lines represent the measured voltage and discharge current, respectively. The peak-to-peak voltage and current were 1.92 kV (0.28 kV in rms) and 1.02 A (0.038 A in rms), respectively. The discharge pattern showed sharp current pulses occurred mainly at a steep voltage gradient, though the peak current value varied. This is more apparent from a close-up in the inset of the part marked with dotted line in Fig. 3. This seems to be similar to that in atmospheric-pressure glow discharge sustained between two parallel-plate electrodes.<sup>15</sup> The typical operational power of the plasma jet is about 10 W. The electron temperature  $T_e$  can be roughly calculated from swarm parameters of electrons in nitrogen as well-known Einstein's equation,  $k_B T_e / e \approx D_e / \mu_e$ , where  $\mu_e$ ,  $k_B$ , and  $D_e$  are drift mobility, Boltzmann constant ( $1.38 \times 10^{-23}$  J/K), and the diffusion constant, which is expressed as a function of  $E/N$ . From Fig. 3, the electric field  $E$  is estimated to be 12.8 kV/cm, which is consistent to  $5.1 \times 10^{-16}$  V cm<sup>2</sup> [ $\approx 51$  Td (tomosecond)] in reduced electric field  $E/N$ .<sup>16</sup> According to Nakamura,<sup>17</sup> the ratio of the diffusion coefficient to the electron mobility is given by  $D_e / \mu_e = 0.53$  V for  $E/N = 51$  Td. As the results, the electron temperature is predicted to be 0.56 eV from the Einstein equation. The averaged electron density ( $n_e$ ) can also be estimated from the electrical parameters of the discharge, the

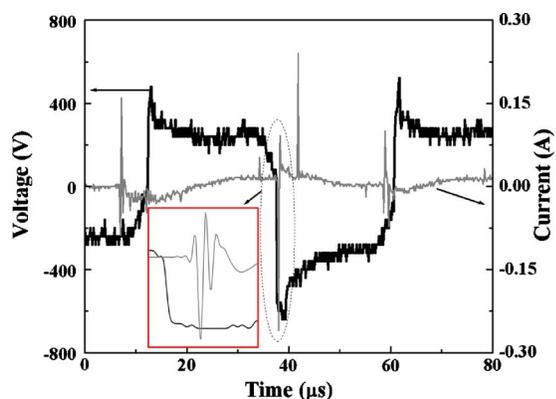


FIG. 3. (Color online) Measured voltage and discharge current of the  $N_2$  microplasma jet of Fig. 1 with applied voltage with a sine wave form. The inset is a magnified view of the part marked with dotted line.

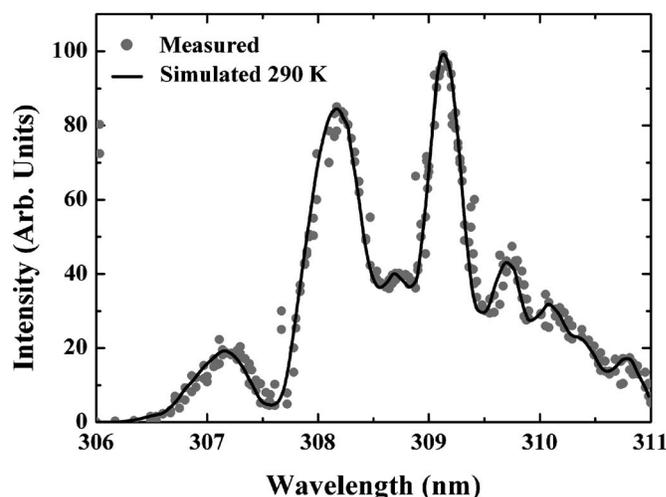


FIG. 4. Gas temperature estimated from measured and simulated optical emissions of OH molecules near 309 nm with a spectral resolution of 0.3 nm for the  $N_2$  microplasma jet at atmospheric pressure.

electric field  $E$ , the current density  $J$ , and the electron mobility  $\mu_e$ . The electron density is defined as  $n_e = J / (E \mu_e e)$ . As an example, we consider nitrogen plasma at 1 atm. The reduced electric field ( $E/P$ ) is estimated to be 16.84 (V/cm Torr), which gives a value of  $\mu_e P$  for nitrogen gas as  $0.42 \times 10^6$  cm<sup>2</sup> Torr/V s.<sup>16</sup> The current density was obtained from Figs. 1 and 3 to be 19.38 A/cm<sup>2</sup> by considering the effective discharge radius between the two electrodes. Eventually, the electron density is estimated to be  $1.71 \times 10^{13}$ /cm<sup>3</sup> at the midplane in the diode where the discharge occurs.

The gas temperature was estimated by making use of an optical spectroscopy, as shown in Fig. 4. The rotational structure of diatomic gases provides information of the rotational temperature. Molecules in the rotational states and the neutral gas molecules are in equilibrium due to the low energies needed for rotational excitation and the short transition times. Therefore, the gas temperature can be obtained from the rotational temperature.<sup>3</sup> The experimental spectrum in Fig. 4 was obtained at the same experimental parameters as that of Fig. 3. By comparing measured and simulated optical emissions of OH radicals around 309 nm with a spectral resolution of 0.3 nm,<sup>18</sup> gas temperature was found to be approximately 290 K in a good agreement with measured data by a thermocouple, as mentioned earlier, revealing low-temperature operation, the most important parameter in biomedical applications. This is similar to the observation from a pulsed cold atmospheric plasma jet.<sup>19</sup>

To identify various excited plasma species generated by the microplasma jet device, optical emission spectroscopy was applied in a wide range of 280–800 nm wavelengths. Figure 5 shows the optical emissions of the microplasma jet, when 3 lpm nitrogen gas was injected. The emission spectrum was mainly dominated by the presence of excited nitrogen species, containing  $N_2$  second and first positive systems.<sup>20</sup> In addition, highly reactive radicals such as hydroxyl (OH) at 308.9 nm and atomic oxygen at 616 and 777.1 nm were detected due to the opening to the ambient air. These radicals can play important roles in plasma-surface interactions in applications.

In summary, the nitrogen microplasma jet device powered by a commercially available power supplier showed a

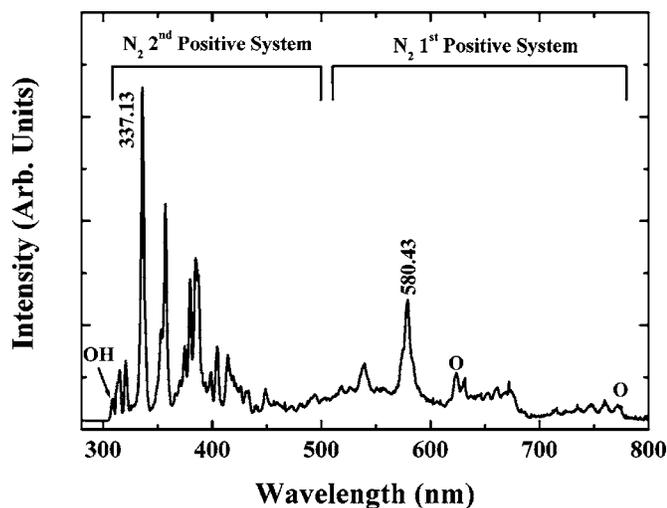


FIG. 5. Wide-range optical emission from 280 to 800 nm of the  $N_2$  microplasma jet at atmospheric pressure.  $N_2$  first and second positive systems are dominant.

long cold plasma jet reaching up to 6.5 cm, which may be suitable for treating thermally sensitive materials including human skin. The electron temperature and density using swarm parameters of electron were estimated to be 0.56 eV and  $1.71 \times 10^{13}/\text{cm}^3$ , respectively. Also, the gas temperature remained near the room temperature. From the characteristics of the microplasma jet, it is expected that the microplasma jet device can be applicable to delicate objects, vulnerable biological materials, dental gums, etc., in addition to human skin.

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- <sup>1</sup>J. Park, I. Henins, H. W. Herrman, G. S. Selwyn, and R. F. Hicks, *J. Appl. Phys.* **89**, 20 (2001).
- <sup>2</sup>Y. M. Chung, M. J. Jung, J. G. Han, M. W. Lee, and Y. M. Kim, *Thin Solid Films* **447-448**, 354 (2004).
- <sup>3</sup>S. Y. Moon, W. Choe, and B. K. Kang, *Appl. Phys. Lett.* **84**, 188 (2004).
- <sup>4</sup>H. Yoshiki and Y. Horiike, *Jpn. J. Appl. Phys., Part 2* **40**, L360 (2001).
- <sup>5</sup>S. J. Park, T. M. Spinka, and J. G. Eden, *Appl. Phys. Lett.* **89**, 031502 (2006).
- <sup>6</sup>T. I. Lee, K. W. Park, H. S. Hwang, J. P. Jegal, and H. K. Baik, *Appl. Phys. Lett.* **88**, 211502 (2006).
- <sup>7</sup>Y. Kim, M. S. Cha, W. H. Shin, and Y. H. Song, *J. Korean Phys. Soc.* **43**, 732 (2003).
- <sup>8</sup>M. B. Chang and J. S. Chang, *Ind. Eng. Chem. Res.* **45**, 4101 (2006).
- <sup>9</sup>R. E. J. Sladek, E. Stoffels, R. Walraven, P. J. A. Tielbeek, and R. A. Koolhoven, *IEEE Trans. Plasma Sci.* **32**, 1540 (2004).
- <sup>10</sup>W. J. M. Brok, M. D. Bowden, J. van Dijk, J. J. A. M. van der Mullen, and G. M. W. Kroesen, *J. Appl. Phys.* **98**, 013302 (2005).
- <sup>11</sup>T. Namihira, S. Tsukamoto, D. Wang, S. Katsuki, R. Hackam, K. Okamoto, and H. Akiyama, *IEEE Trans. Plasma Sci.* **28**, 109 (2000).
- <sup>12</sup>E. Stoffels, A. J. Flikweert, W. W. Stoffels, and G. M. Kroesen, *Plasma Sources Sci. Technol.* **11**, 383 (2002).
- <sup>13</sup>K. H. Becker, P. F. Kurunczi, and K. H. Schoenbach, *Phys. Plasmas* **9**, 2399 (2002).
- <sup>14</sup>H. Baránková and L. Bárdoš, *Surf. Coat. Technol.* **163-164**, 649 (2003).
- <sup>15</sup>E. Kunhardt, *IEEE Trans. Plasma Sci.* **28**, 189 (2001).
- <sup>16</sup>Y. P. Raizer, *Gas Discharge Physics* (Springer, New York, 1991), p. 11.
- <sup>17</sup>Y. Nakamura, *J. Phys. D* **20**, 933 (1987).
- <sup>18</sup>S. Y. Moon and W. Choe, *Spectrochim. Acta, Part B* **58**, 249 (2003).
- <sup>19</sup>J. L. Walsh, J. J. Shi, and M. G. Kong, *Appl. Phys. Lett.* **88**, 171501 (2006).
- <sup>20</sup>R. W. B. Pearse and A. G. Gaydon, *The Identification of Molecular Spectra* (Wiley, New York, 1950), p. 169.