Operating Modes of an Atmospheric Pressure Radio Frequency Plasma

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***Abstract*—The physics of an atmospheric pressure, radio frequency plasma has been investigated. The discharge is generated with helium and 0.4 vol.% nitrogen passing between two metal electrodes with a 3.0-mm gap. It was discovered that at a critical power density of 2.1 kW/cm^3, the plasma undergoes sheath breakdown and transitions from the α- to the γ-mode. Photographs are presented showing the unique distribution of excited-state species under these conditions.**

***Index Terms*—Atmospheric pressure plasma, radio frequency, α-mode, γ-mode.**

RECENTLY, there has been increased interest and development in plasma processes at atmospheric pressure. Operating at reduced pressures requires vacuum chambers that limit the size and shape of the objects to be treated. Atmospheric plasmas overcome this restriction. Moreover, they allow for continuous in-line processing of materials. We have developed an atmospheric plasma that is stabilized by helium or argon and operates at temperatures below 100 °C [1]. This source utilizes perforated metal electrodes that are coupled to radio-frequency power at 13.56 MHz.

Shown in Fig. 1 is a photograph of the low-temperature, ambient pressure plasma source. Light emission is from metastable nitrogen molecules that are produced from the recombination of N atoms in the flowing afterglow. Depending on the gas molecules fed to the plasma, it will generate a uniform density of atoms and radicals at concentrations near 1×10^{16} cm^{-3} and is well suitable for processing materials [2].

The physics of the helium-stablized, ambient pressure plasma has been investigated in an alternative design, consisting of two aluminum rods with faces parallel to each other and separated by a 3.0-mm gap [3]. The powered electrode was 9.0 mm in diameter, while the grounded electrode was 40.0 mm in diameter. The plasma was housed in a cylindrical plastic container with quartz windows. Shown in Fig. 2 are photographs of a helium and 0.4 vol.% nitrogen plasma operating in two different modes. Fig. 2 (a) and (b) were collected with a Canon S30 Digital Camera at exposure times of $1/160$ and $1/1000$ of a second, respectively. The white lines indicate the boundaries of the electrodes. The discharge presented in Fig. 2(a) was struck at a voltage and current of 229 V and 0.26 A. One sees a fairly uniform pink glow that fills the entire gap space between the two electrodes. However, note that next to the electrodes and in the center of the gap the plasma is relatively dim, while a bright region exists 0.25 mm away from the electrodes.

Fig. 1. Low-temperature, atmospheric pressure plasma (Courtesy of Surfx Technologies LLC).

With increasing power, the voltage rises monotonically with the current, until at 317 V and 0.41 A, a sharp transition occurs in the operation of the plasma. When this point is reached, the voltage and current drop to 201 V and 0.35 A, respectively, and the input power surges from 2.3 to 50.0 W. In addition, the glow discharge takes on a barbell shape as shown in Fig. 2(b). Here, bright circular disks 5.0 mm in diameter by 0.6 mm thick are centered at the electrode surfaces. These disks are connected by a dimmer column of light 1.7 mm in diameter. Note that in the picture, the glow appears to extend beyond the boundaries of the electrodes. This is an optical effect due to dispersion of the intense light being emitted by the plasma. As the power input is reduced, the current decreases, but the discharge voltage remains relatively constant at 200 V. Then at about 0.27 A, the

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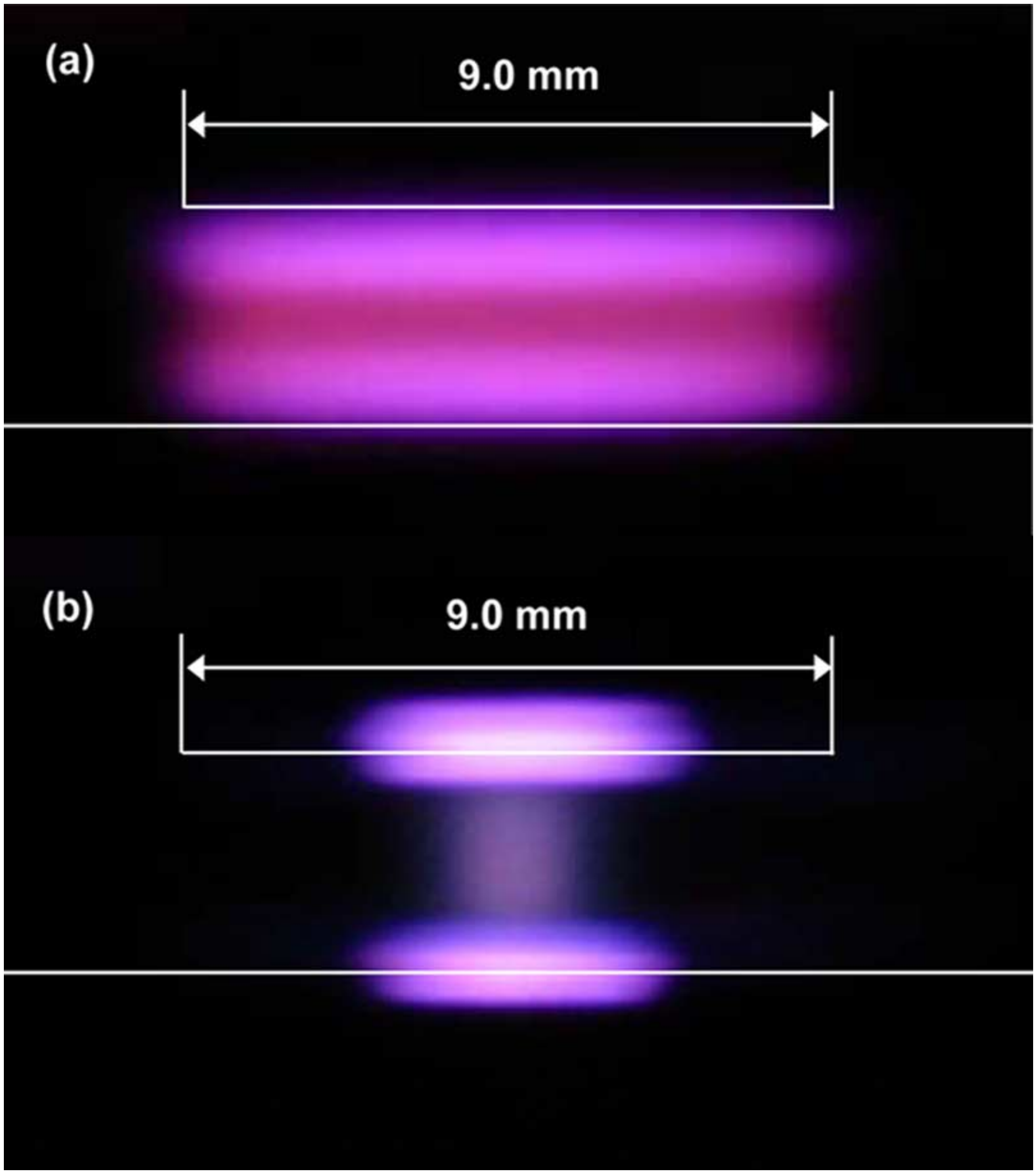

Fig. 2. Atmospheric helium-nitrogen discharge operating in (a) the α-mode and (b) the γ-mode.

plasma reverts to the previous mode of operation with the glow filling the entire volume between the electrodes [cf. Fig. 2(a)].

The photographs in Fig. 2 document the occurrence of α- and γ-mode discharges for atmospheric pressure helium plasmas driven with radio-frequency power [3]. The α-mode is associated with bulk ionization of the gas, and a sheath that is depleted of charged species near the electrodes. This is consistent with a maximum in the $N_2(B)$ emission intensity 0.25 mm away from the electrodes, and a relatively low intensity in the center of the gap. On the other hand, the γ-mode is due to secondary electron emission from the surface of the electrodes, which causes the $N_2(B)$ emission intensity to be centered there. The transition from the α to the γ-mode may be ascribed to sheath breakdown. Using the equations developed by Raizer *et al.* [4], it is predicted that the critical plasma and current densities for sheath breakdown are 6.4×10^{12} cm^{-3} and 0.76 A/cm^2, respectively [3]. These values agree well with the electron and current densities recorded immediately prior to the α-γ transition, which equal 5.7×10^{12} cm^{-3} and 0.71 A/cm^2.

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