Development of the RF plasma source at atmospheric pressure

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Abstract

A radio frequency (RF) plasma source operates by feeding helium or argon gas through two coaxial electrodes driven by a 13.56 MHz RF source. In order to prevent an arc discharge, a dielectric material is loaded outside the center electrode. A stable, arc-free discharge is produced at a flow rate of 1.5 l/min of helium gas. The temperature of the gas flame varies from 100 to 150 °C depending on the RF power. The breakdown voltage also changes when the flow rate varies. The plasma generation in a hot chamber is much more efficient than that in a cold chamber. The plasma characteristics are diagnosed by using optical emission spectroscopy. One of the applications of the RF plasma source is the printed circuit board (PCB) cleaning process, needed for environmental protection. The PCB cleaning device forms an asymmetric biaxial reactor.

Keywords: RF plasma; Atmospheric; Dielectric; Asymmetric biaxial reactor

1. Introduction

The atmospheric pressure plasmas, which overcome the disadvantages of a vacuum operation, can be used in a variety of materials processes [1–6]. The gas temperatures in arc plasma torches are very high, exceeding more than 3000 °C, and the density of the charged species range from $10^{16}$ to $10^{19}$/cm$^3$. Corona discharge, which often generates ozone in air, produces nonequilibrium plasma with gas temperatures between 50 and 400 °C, and the density of the charged species is typically approximately $10^{12}$/cm$^3$ [7]. However, their use in materials processing is limited due to the non-uniformity of the plasma. A low temperature radio frequency (RF) plasma source at atmospheric pressure, that exhibits many characteristics of a low-pressure glow discharge [8–10], has been developed. Over the last several years, we have also developed an RF plasma source at atmospheric pressure. Since the atmospheric plasma source operates under atmospheric pressure, it can be implemented in existing manufacturing facilities for high-speed, continuous plasma processing. Plasma, which is highly energized and extremely active, has the inherent tendency to create radicals, easily reacting with other molecules. Thus, the plasmas eliminate organic contaminants and improve material surfaces at low temperatures.

2. RF plasma source operated at atmospheric pressure

Fig. 1 is a schematic presentation of the RF plasma source at atmospheric pressure. It consists of an inner-powered electrode and an outer-grounded electrode. The plasma is exposed to the ambient air. We also use a matching network for minimum power reflection between the power source and reactor. A water-cooling system is connected to the outer-grounded electrode. The RF plasma source operates by feeding helium or argon gas through two coaxial electrodes driven by a 13.56 MHz RF source of power ranging from 40 to 300 W. Initially, at a low RF power of approximately 40 W, which depends on its geometry and electrode size, the discharge starts around the inner tip of the cylindrical electrode. This is because the electric field intensity is strongest at this region, where the radius of curvature is small. If the RF power increases, the discharge current increases due to the expansion of the discharge region from the tip to the base of the inner electrode. However, the measured input voltage does not increase as the power increases. Electric field intensity $E(r)$ of the coaxial capacitor from Gauss’s law is given by

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Fig. 1. Schematic presentation of the RF plasma source at atmospheric pressure.

$$E(r) = \frac{V}{b} \frac{r \ln \frac{b}{a}}{a}$$  \hspace{1cm} (1)

where \( r \) is the radial distance from the center and \( a \) and \( b \) are the inner and outer electrode radii, respectively. The maximum electric field occurs at the inner electrode surface or inner dielectric surface, in coaxial symmetry [11]. Therefore, we estimate the breakdown voltage from the \( E/V \) value, which was calculated for the given reactor size. Fig. 2 presents theoretical and experimental data of breakdown voltage vs. inner electrode radius, ranging from 0.05 to 0.25 cm. Whenever the inner electrode radius increases, the breakdown voltage tends to increase. Every experiment shows uniform glow discharge around the inner electrode. Fig. 3 presents experimental data for the helium flow rate vs. applied power. Helium glow discharge stays in the range of the applied power between the discharge-ignition and arcing power. If the power exceeds approximately 140 W, or the flow rate is too low, arc discharge occurs at the end of the inner electrode. Flow rate alone cannot completely prevent an arc discharge at high power in our case. Therefore, in order to prevent an arc discharge, a dielectric material such as quartz is loaded between the electrodes. Then, we can produce a stable, homogeneous, arc-free discharge at an RF power above 140 W and at a flow rate below 1.5 l/min of helium gas. Electric field intensities of the coaxial capacitor with the loaded dielectric material are given by

$$E(r) = \frac{V}{\varepsilon_{air} r \left( \frac{1}{\varepsilon_{air}} + \frac{1}{\varepsilon_{Q}} \right) \frac{a'}{a} + \left( \frac{1}{\varepsilon_{air}} + \frac{1}{\varepsilon_{Q}} \right) \frac{b'}{b}}$$  \hspace{1cm} (2)

for the case of the dielectric loaded over the inner electrode,

$$E(r) = \frac{V}{\varepsilon_{air} r \left( \frac{1}{\varepsilon_{air}} + \frac{1}{\varepsilon_{Q}} \right) \frac{b'}{b} + \left( \frac{1}{\varepsilon_{air}} + \frac{1}{\varepsilon_{Q}} \right) \frac{a'}{a}}$$  \hspace{1cm} (3)

for the case of the dielectric loaded over the outer electrode, and

$$E(r) = \frac{V}{\varepsilon_{air} r \left( \frac{1}{\varepsilon_{air}} + \frac{1}{\varepsilon_{Q}} \right) \left( \frac{1}{\varepsilon_{air} a} + \frac{1}{\varepsilon_{air} b} + \frac{1}{\varepsilon_{Q} a} + \frac{1}{\varepsilon_{Q} b} \right)}$$  \hspace{1cm} (4)

for the case of the dielectric loaded over the inner and outer electrodes, where \( a' \) and \( b' \) are inner and outer dielectric radii, respectively. \( \varepsilon_{air} \) and \( \varepsilon_{Q} \) are the dielectric constants of air and quartz, respectively. As expected, arc discharge does not occur while using a dielectric.

Optical emission spectroscopy (OES) has been used to observe the excited species generated by the helium plasma. Fig. 4 shows an emission spectrum from the discharge plasma between the electrodes. Axial OES data has been taken at the end of the RF plasma source. Examination of the spectrum reveals helium lines at 706.5 nm (1s2p–1s3s) and 728.1 nm (1s2p–1s3s), an
atomic oxygen line at 777.1 nm. We obtain more helium lines at 501.6, 587.6 and 667.8 nm and additional atomic oxygen lines at 533.1, 615.8, 645.6 and 844.6 nm. There are obviously not only excited helium lines, but also excited oxygen lines, which exist in air. Remember that the plasma source is open to the ambient air.

One of the important issues of the RF plasma source at atmospheric pressure is the influence of the ambient chamber temperature on breakdown properties. If the gas temperature is high enough, the mean free path of electrons will be longer than that in room temperature gas. For this reason, the RF plasma source in high temperature gas acts like a pressure-reduced chamber. Therefore, we expect that the breakdown voltage may be reduced as the gas temperature increases. The breakdown field for hot gas in the flame is given by [12,13]

\[
\frac{E}{p} = \frac{E_c}{T} \left( \frac{T_i}{T_g} \right)
\]

(5)
where $E_c$ is the critical electric field for a given gas, $T_r=300$ K is the room temperature and $T_g$ is the gas temperature in the flame. We note from Eqs. (1) and (5) that the breakdown voltage $V_b(T)$ is related to the gas temperature $T_g$ by

$$V_b(T)=E_c \frac{T_r}{T_g} \alpha \ln \frac{b}{a}$$

(6)

The required electrical voltage for breakdown is inversely proportional to the gas temperature. When the dielectric is loaded on the electrode, Eqs. (2)–(4) can be modified by the gas temperature. That is

$$V_b(T)=E_c \frac{T_r}{T_g} \varepsilon_{air} \alpha \left( \frac{1}{\varepsilon_q} \ln \frac{a'}{a} + \frac{1}{\varepsilon_{air}} \ln \frac{b'}{b} \right)$$

(7)

for the inner dielectric loaded,

$$V_b(T)=E_c \frac{T_r}{T_g} \varepsilon_{air} \alpha \left( \frac{1}{\varepsilon_{air}} \ln \frac{b'}{b} \right)$$

(8)
for the outer dielectric loaded, and

$$V_B(T) = E_e \frac{T_g}{T} \epsilon_{air} a \left( \frac{1}{\epsilon_Q a'} + \frac{1}{\epsilon_{air} a'} + \frac{1}{\epsilon_Q b'} \right)$$

(9)

for both the inner and outer dielectric loaded.

Fig. 5 shows that the experimental data agree reasonably well with the theoretical predictions. It indicates that if the gas temperature is doubled, the breakdown voltage decreases to half. Fig. 5 demonstrates clearly that the electrical breakdown voltage is inversely proportional to the gas temperature. It may be one of the ways to produce atmospheric plasma in a raised temperature.

One of the applications of the RF plasma source is the printed circuit board (PCB) cleaning process, which is needed for environmental protection. Fig. 6 is a cross-sectional view of a RF plasma-cleaning device at atmospheric pressure. The device forms an asymmetric biaxial reactor, which can ignite plasma at a low breakdown voltage, less than that of the symmetric coaxial reactor. The gas supplied to the RF cleaning device is a mixture of helium and oxygen. The surface of the PCB sample is effectively treated by using this device. Helium and oxygen plasma are used for the removal of organic compounds on the contact points of the PCB to improve surface conditions and to boost the adhesion strength of resin substrates before sealing. In contrast to conventional, low-pressure plasmas, the atmospheric RF plasma source produces an abundance of radical species, so it achieves very high selectivity with negligible damage to the surface.

3. Conclusions

We have developed an RF plasma source at atmospheric pressure that may be used in various applications, including medical sterilizers, PCB or semiconductor wafer cleaning devices, deposition of ceramic on plastics, etc. Stable and uniform plasma was produced in helium gas. It exhibits many characteristics of a low-pressure glow discharge. We developed a theoretical simple scaling law to estimate the breakdown voltage of the atmospheric pressure discharge in a coaxial reactor. Experimental results agree reasonably well with theoretical predictions. The breakdown voltage $V_B(T)$ for the RF plasma in Eq. (6) is inversely proportional to the gas temperature $T_g$ and is therefore reduced as the gas temperature increases. RF plasma is applied to clean the surface of a PCB, and treats it effectively. However, more diagnostics are required for atmospheric plasma phenomena and their applications.

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References