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Stability improvement of nonthermal atmospheric-pressure plasma jet using electric field dispersion

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ABSTRACT

A nonthermal atmospheric-pressure plasma jet device based on electric-field dispersion was proposed, fabricated and tested. The device has nickel electrodes with micro-size holes fabricated via micromachining process. It was confirmed from the optical emission spectrum (OES) of the plasma jet that the generated reactive species depend on the gas and the intensities of the species depend on the hole size. Also, we measured the concentration of NO in plasma jet as well as the concentration of ozone dissolved in typical cell culture media for biomedical applications. For the characterization, the electron density and electron temperature of the plasma were calculated from the voltage and the current measured during the plasma discharge. Above all, we observed that the electrodes of the proposed device stands long and generate plasma stably compared to the previous devices without electric-field dispersion.

1. Introduction

Atmospheric plasma is classified into arc plasma, corona plasma, dielectric barrier discharge, and hollow discharge. Arc plasma and corona plasma are unsuitable for biomedical applications because they occur at high temperatures. Recently, studies regarding dielectric barrier discharge and hollow cathode discharge have being actively carried out with low-temperature plasma [1–3].

Plasma has been used in various industrial fields. In particular, studies in environmental purification and biomedical applications have been actively carried out by expanding on existing applied fields such as displays, semiconductor processes, and surface treatment [4,5]. The representative biomedical applications of plasma reported recently are blood coagulation, cancer cell apoptosis, dental cavity treatment, healing of wounded skin, and sterilization of microbes [6–14]. The plasma must satisfy some requirements in order to be applied to biomedical treatments. Firstly, the plasma must not heat the target subject over the temperature of the cell damage. Secondly, it must be generated at atmospheric pressure to avoid the cell rupture. Given these conditions, glow-discharge, nonthermal atmospheric-pressure plasma is the most suitable type of plasma. Existing glow-discharge plasma devices can generate plasma discharge using tubes or needles that were manufactured through mechanical processes. The mechanical processes are limited in order to reduce the size of the device and to treat large areas; thus, the range of applications is limited. To overcome these limits, micromachining has been utilized in fabrication.

Glow discharge astatically occurs at atmospheric pressure, and it leads to a glow-to-arc transition (GAT) that is converted into high-temperature plasma, i.e., arc plasma [15]. The plasma is converted from nonthermal plasma into thermal plasma. And the current density may be increased to its uppermost limit as the pressure increases. This phenomenon causes arc discharge. In order to avoid GAT, we need to prevent heating the electrodes during plasma discharge. The micro hollow cathode discharge (MHCD) mode is effective as a method to prevent heating of the electrodes. MHCD moves gas through a micro hole in the electrodes. By using gas to induce a natural cooling of the electrodes, MHCD helps to prevent plasma from converting into an arc without a cooling device [16]. This mode is characterized by a decrease in voltage when the current increases [17].

Recently, Al-Bataineh et al. [18] and Kim et al. [19] reported particularly on the microplasma devices to generate a stable glow discharge. These devices are difficult to treat convex or concave surfaces. In addition, the treatment is limited to proximal distance of a few milimeters. To overcome this drawback, Kim et al. developed an atmospheric plasma jet device having micro holes fabricated by micromachining [20,21]. Developed the hand-held type plasma jet system is successfully operated at atmospheric pressure using Ar, He, N_2, and air gas. The developed plasma jet device was applied to bio-medical experiments, thereby the potential employment in biomedical field has been confirmed [22,23]. However, the

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device could not maintain uniform glow discharge for a long time. The plasma jet device developed in a previous study used a stainless steel tube as a cathode. Because the shapes of the tubes used as electrodes were not uniform, the lifespan of the electrodes was short because of current channeling which occurred during the plasma generation. This is a serious weakness in the previous plasma device to be useful for biomedical applications; therefore, this study was performed to overcome the problem.

In this study, we developed an atmospheric-pressure plasma jet device based on electric field dispersion. The proposed plasma jet device has the symmetrical cathode and anode fabricated by a micromachining process to ensure uniformity. We tested and characterized the plasma device for several gases to ensure the feasibility and improvement.

2. Device structure and fabrication

Fig. 1 shows a cross-sectional diagram of a plasma jet nozzle. The nozzle is composed of two electrode substrates, two ring electrodes, and a module case. The electrode substrates have nickel electrode layers on glass substrates. The two substrates were arranged so that each hole in the substrate was in the same position with an interval of 1 mm. Each substrate was connected to an AC bias through ring electrodes, and each electrode is insulated using plastic module cases.

Fig. 2 shows the fabrication process for the electrode substrates of plasma jet nozzles. Glass wafers were used for the substrates. Cr/Au film was deposited on the glass wafers to form seed layers for electroplating. In order to manufacture electroplating molds, THB-151N photoresist (JSR), a negative photoresist, was spin-coated with a thickness of 100 μm on the Cr/Au-deposited plane, and patterned by photolithography. A nickel layer was placed on the glass wafers by electroplating, and a chemical and mechanical polishing (CMP) process was performed to planarize the nickel surface. Photoresist used as a mold was removed, and electrode substrates with micro holes were fabricated as processing glasses by sandblasting.

Fig. 3-(a) shows the fabricated electrode substrates. The electrode substrates are circular glass substrates of 10 mm in diameter. Each substrate has 25 holes. The thickness of the glass substrate is 500 μm, and the thickness of the nickel layer is 100 μm. The holes were fabricated with diameters of 300, 400, and 500 μm. Fig. 3-(b) shows the scanning electron microscope (SEM) images of the fabricated electrode, and shows that the Ni layer of the electrode and the glass substrate (an insulation layer) were effectively processed.

3. Measurement setup

Fig. 4 shows a schematic view of the experimental setup for the discharge experiment. The discharge experiment was performed at atmospheric pressure and room temperature. In order to generate the plasma, we used air, argon, and nitrogen gas. The gas flow rate, input voltage, and frequency were maintained at 10 L/min, 15 kVp–p, and 15 kHz, respectively. 10 L/min is proper to cool

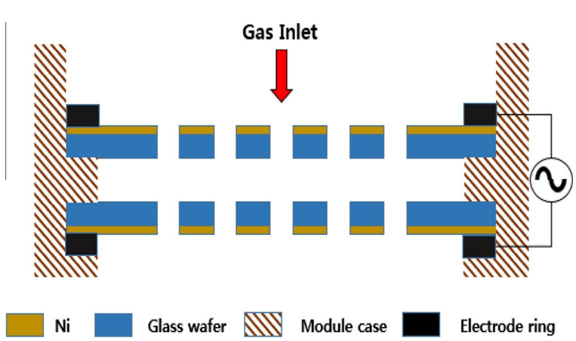

Fig. 1. Cross-sectional schematic view of the plasma jet nozzle.

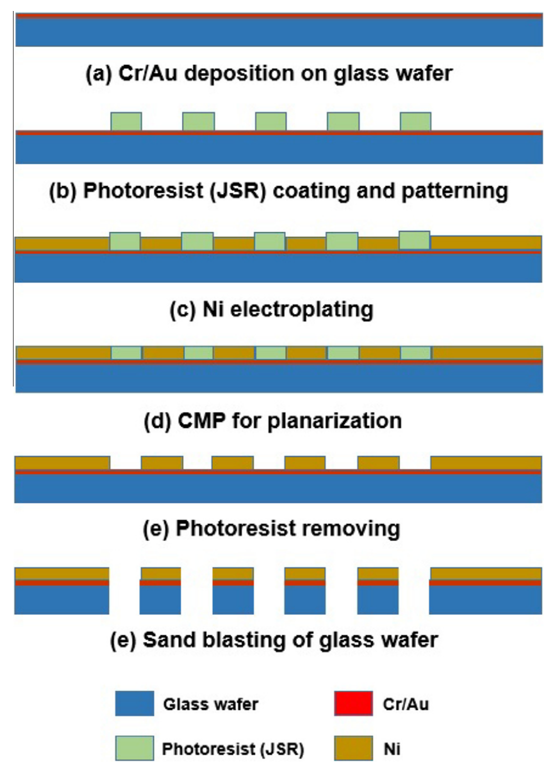

Fig. 2. Fabrication process of the electrode substrate.

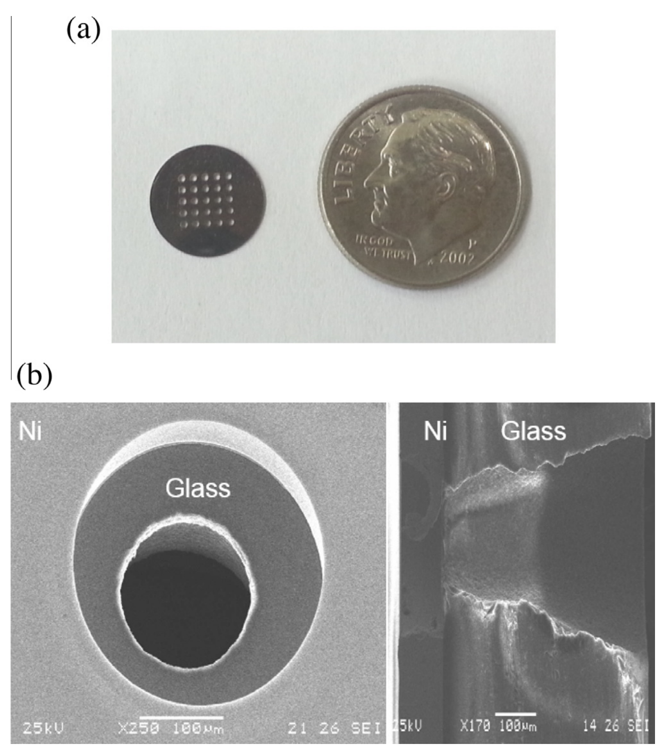

Fig. 3. Fabricated substrate: (a) photograph of electrode substrate, (b) SEM images of a hole.