

Review Paper

Flexible Plasma Sheets

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Abstract With respect to the electrode structure and the discharge characteristics, the atmospheric pressure plasma sheet of a thin polyimide film is introduced in this study; here, the flexible plasma device of a dielectric-barrier discharge with the ground electrode and the high-voltage electrode formulated on each surface of a polyimide film whose thickness is approximately 100 μm , that is operated with a sinusoidal voltage at a frequency of 25 kHz and a low voltage from 1 kV to 2 kV is used. The streamer discharge is appeared along the cross-sectional boundary line between two electrodes at the ignition stage, and the plasma is diffused on the dielectric-layer surface over the high-voltage electrode. In the development of a plasma sheet with thin dielectric films, the avoidance of the insulation breakdown and the reduction of the leakage current have a direct influence on the low-voltage operation.

Keywords: Plasma, Discharge, Atmospheric-pressure non-thermal plasma, Plasma sheet.

During the last two decades, atmospheric-pressure non-thermal plasmas have attracted considerable attention in terms of the biomedical applications [1-4], whereby the effects of these plasmas on bio-cell activation, cell extinction [5-8], sterilization [9-11], and blood coagulation [12] are the main considerations. Those effects are relevant for the treatment practices in a variety of medical fields including dermatology and cosmetology regarding the plasma skin-regeneration (PSR) technology that is for skin rejuvenation and wrinkles treatment [13-16], trichology (hair-loss prevention), oncology, surgery, and dentistry [17-20].

The focus of most of the plasma devices in terms of the bio-medical applications has been the development of the plasma-jets form with a gas injection and the dielectric-barrier discharges (DBDs) [21-24]. Recently, various types of wearable plasma devices have been presented in the forms of the plasma pad, the plasma bandage, plasma socks, and the plasma cap [25]; however, unlike the conventional plasma jets or DBD devices, attention has been garnered due to the variety of applications and the convenience of the wearable devices. While the limitations of the plasma jets and the DBD devices affect the treatment time that is taken by the professional, plasma pads can be conveniently used following only the fulfillment of a prescription; furthermore, a wide range of usages is expected because these pads can be made in varieties of types and shapes for new applications such as large treatment sizes and emergency treatments.

In this report, a plasma sheet that was developed through the completion of a pioneering wearable-plasma-pad investigation is suggested. In terms of wearable plasma pads for the biomedical applications, thinning, flexibility, portability, large-area coverage, and plasma uniformity on

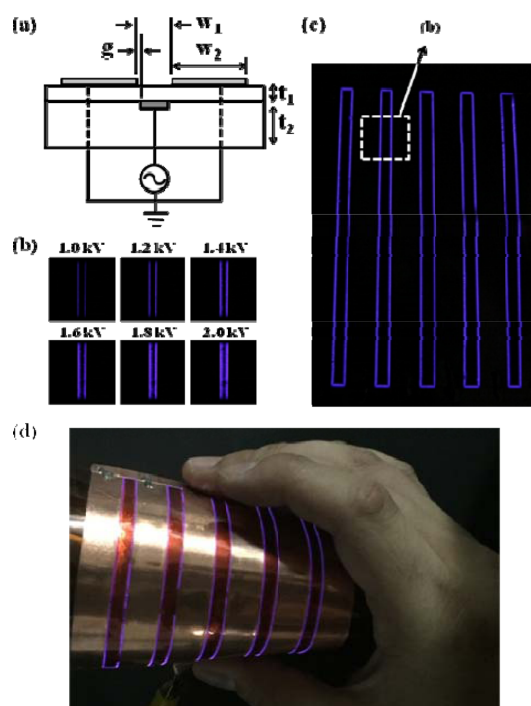


Figure 1. The thin-film plasma sheet of a stripe-type discharge: (a) schematic of the cross-sectional film structure with two electrodes, (b) magnified picture of stripe discharge with the applied voltage from 1 kV to 2 kV, (c) a stripe-discharge picture on the plasma sheet, and (d) picture of flexible plasma sheet.

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the film surface are the key considerations for the design of a reliable low-voltage-operation device where protections against insulation breakdown and current leakage are ensured.

For the thin plasma sheet, a particular polyimide films (trademarked as “Kapton” by DuPont) with a film thickness from several tens to several hundreds of μm was used. The polyimide film is advantageous as it retains excellent physical and electrical properties, as follows: a high dielectric-breakdown voltage of 5 kV, a sound solvent, and a high thermal resistance (200°C to 250°C).

Figure 1(a) shows the cross-sectional structure of the plasma sheet that is suggested in this study. The copper ground electrode (width = w_2) is on the polyimide-film surface (thickness = t_1), and the copper high-voltage electrode (width = w_1) that is attached beneath the film is covered with a base polyimide film (thickness = t_2). The gap g between the two electrodes in the cross-section is optimized as $g < 1$ mm because the operation voltage is high for a long gap. To minimize any leakage current from the high-voltage electrode, the high-voltage electrode is placed between the ground electrodes, and the width (w_1) of high-voltage electrode is smaller than that (w_2) of the ground electrode. A high voltage is applied through a dc-ac inverter that generates a sinusoidal voltage that is of a 25 kHz frequency.

Figure 1(b) shows the pictures of the stripe-type discharges on the thin plasma sheet with the applied voltage that is from 1 kV to 2 kV, and for which the following polyimide-film values apply: $w_1 = 5$ mm, $w_2 = 10$ mm, $g = 0$ mm, and $t_1 = 75$ μm . The plasma is formulated only on the polyimide-film surface that corresponds to the surface of the high-voltage electrode. At the low voltage of 1 kV, the discharge is ignited at the high-voltage-electrode side along the boundary lines between the two electrodes and the plasma diffuses into the center of the high-voltage electrode as the voltage is increased to 2 kV. Even if the insulation-breakdown voltage is approximately 5 kV with a thickness of approximately 100 μm for the polyimide film, the low-voltage operation is best, as it reduces the power leakage from the thin plasma sheet while enhancing the reliability of the plasma panel. The other important parameter is the width (w_1) of the high-voltage electrode that should be of a proper size for a high-efficiency plasma sheet. Figure 1(c) is a picture of the discharge sheet that comprises an area of 10 cm \times 10 cm. Figure 1(d) shows the plasma-sheet flexibility. The entire thickness of the plasma sheet that comprises two polyimide layers, an upper layer of 75 μm , and a lower layer of 200 μm that covers the high-voltage electrode is approximately 275 μm . Because the ground electrode is on the polyimide surface, an electric shock is avoided, and the plasma is sufficiently cold so that the panel surface can be touched without the incurrence of any thermal damage.

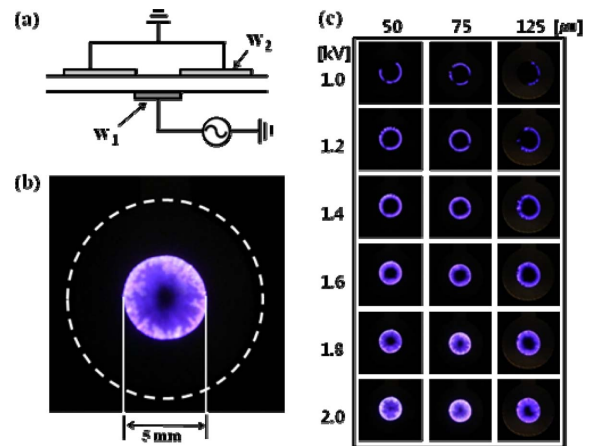


Figure 2. Circle-shape discharge on the thin-film plasma sheet: (a) Schematic of cross-sectional electrode structure, (b) magnified picture of the discharge, and (c) pictures of the circular discharge for the three different thickness of the polyimide film with an operation voltage from 1 kV to 2 kV.

A variety of electrode-structure types besides the stripe shapes that are shown in Fig. 1 exist. Figure 2 shows the circular shape of a high-voltage electrode that is surrounded by the ground electrode, and Figure 2(a) shows a diameter of $w_1 = 5$ mm for the former, and a width of $w_2 = 5$ mm for the circular-shape ground electrode. The discharge voltage and the discharge shape were investigated for the following three different polyimide-film thicknesses: 50 μm , 75 μm , and 125 μm . Figure 2(b) is a discharge picture for the 75 μm thickness with a voltage of 1.8 kV; here, the plasma is generated over the dielectric-film surface that corresponds to the high-voltage surface, as shown in Fig. 1. With the applied voltage that is from 1 kV to 2 kV, the corresponding discharge pictures are represented in Fig. 2(c) for the three polymer-film thicknesses. At the ignition stage, the plasma appears at the edge of the high-voltage side along the boundary line between the high-voltage electrode and the ground electrode. The plasma expands to the center of the circle as the voltage increases, whereby the thinner the film, the lower the ignition voltage. As the pictures are shown with film thicknesses from 50 μm to 125 μm , the plasma is generated on the whole circular surface that is of a 5 mm diameter at a voltage below 2.0 kV.

Through the experiments of this study a flexible thin-film plasma sheet is made from the polyimide film of an approximate 100 μm thickness; here, the plasma is generated by the DBD on the polyimide film where two electrodes are formulated on each surface. The operation voltage with the 25 kHz frequency is as low as 1 kV to 2 kV. The plasma begins to formulate at the boundary line between two electrodes, and it diffuses toward the center surface of the high-voltage electrode on the dielectric film.

The main issues regarding the development of a thin-film plasma sheet are the avoidance of the high-voltage insulation breakdown of the dielectric film and the

minimization of the leakage current from the high-voltage electrode. The best solution for a plasma sheet with respect to the polyimide film that was used in this experiment is therefore a low-voltage operation that is as low as 1 kV to 2 kV, even if the dielectric-breakdown voltage is as high as 5 kV. The second-best solution is the development of optimal electrode structures, as follows: (i) The optimal width value for a high-voltage electrode should be considered. The narrow electrode is more effective regarding the consideration of a plasma-diffusion area that becomes wider as the voltage is increased; in this experiment, a 5 mm-width high-voltage electrode is used for the operation-voltage 2 kV. (ii) The best arrangement of the two electrodes comprises a high-voltage electrode that is surrounded by a ground electrode, as it minimizes the electric-power loss that is caused by the leakage current from the high-voltage electrode.

So far, plasma-jet or DBD-device experiments form the focus of the studies of atmospheric-pressure non-thermal plasmas for biomedical applications. For the present study, however, a wide range of usages regarding the plasma sheets and the wearable plasma pads is expected.

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