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Design and fabrication of an electrode for low-actuation-voltage electrowetting-on-dielectric devices

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Abstract

This paper presents the design and fabrication of an electrode for low-actuation-voltage electrowetting-on-dielectric (EWOD) devices. The electrode which takes advantage of a novel shape is used to develop an EWOD device. The fabrication process for the electrode and the device development includes laser exposure, wet developing, etching, and stripping. A dielectric layer of 5% (wt. /wt.) Polyvinylidene difluoride (PVDF) is used for the electrode insulation. In addition, a very thin (50 nm) layer of Teflon is coated on the EWOD surface to provide hydrophobicity. It is observed that a thin and high dielectric-constant layer can reduce the actuation voltage in the EWOD device. An actuation voltage of 14.8 V was achieved by the EWOD device.

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Keywords: electrowetting on dielectic (EWOD); electrode; actuation voltage; photolithography; dielectric layer; hydrophobic layer.

1. Introduction

Electrowetting-on-dielectric (EWOD) is a method that is used to manipulate microliter volumes of fluids in microfluidic devices. An EWOD device consists of a base substrate, a conducting electrode array, a dielectric layer, and a hydrophobic surface. In this device, a conducting droplet on the hydrophobic surface is manipulated by applying an actuation voltage across the surface interface between the solid and the liquid. The applied voltage

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generates electric charges which creates a driving force and change the droplet contact angle resulting in a movement of the droplet on the EWOD surface [1].

EWOD devices have been employed in such applications as lab-on-a-chip systems [2], multi-analytic-sensing [3], tuneable lenses [4], fiber optics switching [5], chip cooling [6], drug delivery [7], and display technology [8]. However, it is observed from the reported applications that a high actuation voltage is required to operate the droplet. Usually, a high-actuation-voltage EWOD device faces some difficulties for instance, it induces unexpected heat which evaporates the droplet. Therefore, lowering the actuation voltage of EWOD device can improve the use of the devices.

Various sizes and shapes of electrodes including square [9], interdigitated [10], crescent [11], interlocking [12] and wedge [13] have been developed to reduce the actuation voltage of EWOD devices. Among the wide range of published works, a low voltage reversible EWOD structure with lubricated (silicon or castor oil) honeycomb polycarbonate surfaces was reported by Bormashenko et al. [14]. They achieved a minimum actuation voltage of 80 V for Si oil and 120 V for castor oil. In our previous simulation study, we showed that both droplet mixing and splitting operations of an EWOD device work at a low actuation voltage of 30 V for 2 µm of Parylene C and 50 nm of Teflon layers [3]. Moreover, a EWOD device having SiO_2 dielectric and Parylene C hydrophobic layers obtained the movement of 1M KCL droplet in air medium for the voltage of 25 V [1]. Chen and Fu [15] fabricated an EWOD device using niobium pentoxide (Nb_2O_5) dielectric layer. Their fabricated EWOD device operated at low actuation voltage because of having a high-dielectric-constant (approximately 25.5) dielectric layer. It was reported that a 1% sodium dodecyl sulphate (SDS) droplet achieves 120° to 70º changes of contact angle at 9 V. However, in most of the published papers, different dielectric layers can be also employed to reduce the actuation voltage. Nonetheless, this research focuses on the shape of the electrodes to reduce the actuation voltage. Accordingly, the paper presents the design and evaluation of an electrode for EWOD devices.

2. Mechanism of EWOD

The concept of EWOD concerns the interfacial surface tension of solid-liquid by the applied electric potential between a conductive droplet and insulated underlying electrodes. Fig. 1(a) demonstrates an EWOD device consisting of a base substrate with an array of electrodes placed on insulating layers (a dielectric layer and a hydrophobic layer). In an EWOD device, if a droplet is placed on the hydrophobic surface, three interfacial surface tension vectors at the three-phase contact lines of the droplet are generated with a contact angle θ_0 (see Fig. 1(b)). Where γ_{df} is the interfacial surface tension between the droplet and the filler medium, γ_{if} is the interfacial surface tension between the insulating layers and the filler medium, and γ_{id} is the interfacial surface tension between the insulating layers and the droplet [1].

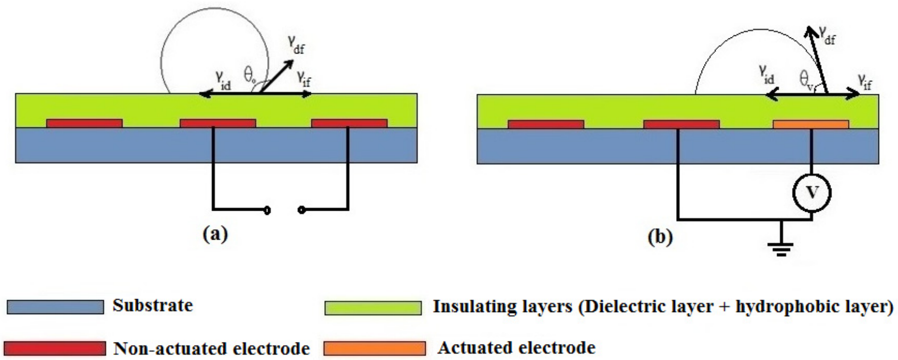

Fig. 1. Characteristics of the droplet in the EWOD device: (a) before the applied voltage, and (b) after the applied voltage.

When a neighboring electrode is connected to a voltage source, the droplet will be moved to that electrode, resulting in a change of the contact angle θ_v, which is described by the Lippmann-Young equation (Fig. 1(b)):

$$\cos\theta_v = \cos\theta_0 + \frac{\varepsilon_0 \varepsilon_{rd} \varepsilon_{rh} V^2}{2\gamma_{df}\left(t_d \varepsilon_{rh} + t_h \varepsilon_{rd}\right)} \tag{1}$$

3. Design and fabrication of the EWOD device

3.1 Design of the electrode

The performance of the EWOD device will depend on its electrode array. A mask is designed for the electrode array using a layout editor software. For the electrode design, some parameters including shape, size, inter-electrode gap distance, connecting line, and contact pad can be considered to achieve a low actuation voltage. However, in this work only the shape of the electrode is focused on while other electrode parameters are kept constant. A novel shape for the electrode is designed as shown in Fig. 2. The electrode array consists of seven control and seven ground electrodes. The dimension of each electrode is 1.4 mm^2 and the inter-electrode gap is 50 µm.

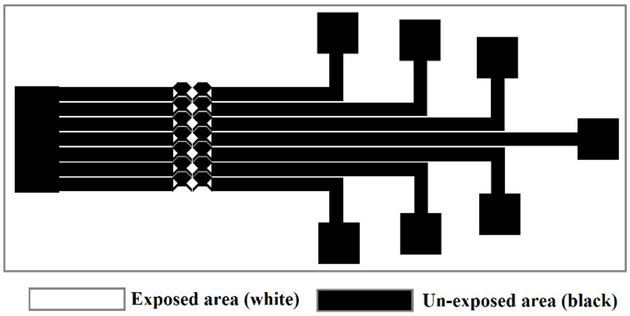

Fig. 2. Mask of the EWOD device with incorporating a novel electrode shape.

3.2 Fabrication process of EWOD

To fabricate the EWOD device, a soda-lime glass substrate with a thickness of 1.1 mm was chosen. On the top of the substrate, a thin Chromium (Cr) film of 250 nm is deposited to work as the conducting layer. The Cr deposition is carried out by electron-beam evaporation machine by Clean Surface Technology in Japan. To transfer the geometric pattern on the conducting Cr layer, a photoresist coating is required. Initially, a pre-bake of the substrate is conducted on the hot-plate at 115 ºC and followed by a cool down. Then, a liquid positive photoresist of AZ 1500 is spin-coated at a speed of 3000 rpm for 30 seconds on top of the Cr layer, and then post baked at 95 ºC for 30 minutes. The achieved thickness of the photoresist on top of Cr is 500 nm.

The next step involves photolithography. It is initiated through a laser lithography µPG10 machine. The laser lithography machine exposes the AZ 1500 layer. The mask designed in layout editor software is exported into µPG101 PC software. The µPG10 machine exposes the substrate. The duration of the laser exposure depends on the size of the EWOD design. The laser exposure time for the device was approximately 4 hours. After the laser light exposure, the wet etching process is required to achieve the desired design on the glass substrate. The wet etching process includes three stages: development, etching, and photoresist stripping. In the development stage, 1:4 dilution AZ 351B developer solution is used. The AZ 351B developer removes the photoresist from the exposed area of the substrate. In the second stage of the wet etching processes, the unwanted Cr from the exposed area is removed by immersing the substrate in a Chromium etchant. Finally, the substrate is immersed into AZ 100 remover to remove the remaining photoresist from the un-exposed area. As a result, the clear glass appears in the exposed region while, the un-exposed region retains Cr according to the designed conducting pattern of EWOD device. The entire fabrication process of the EWOD device is illustrated in Fig. 3.

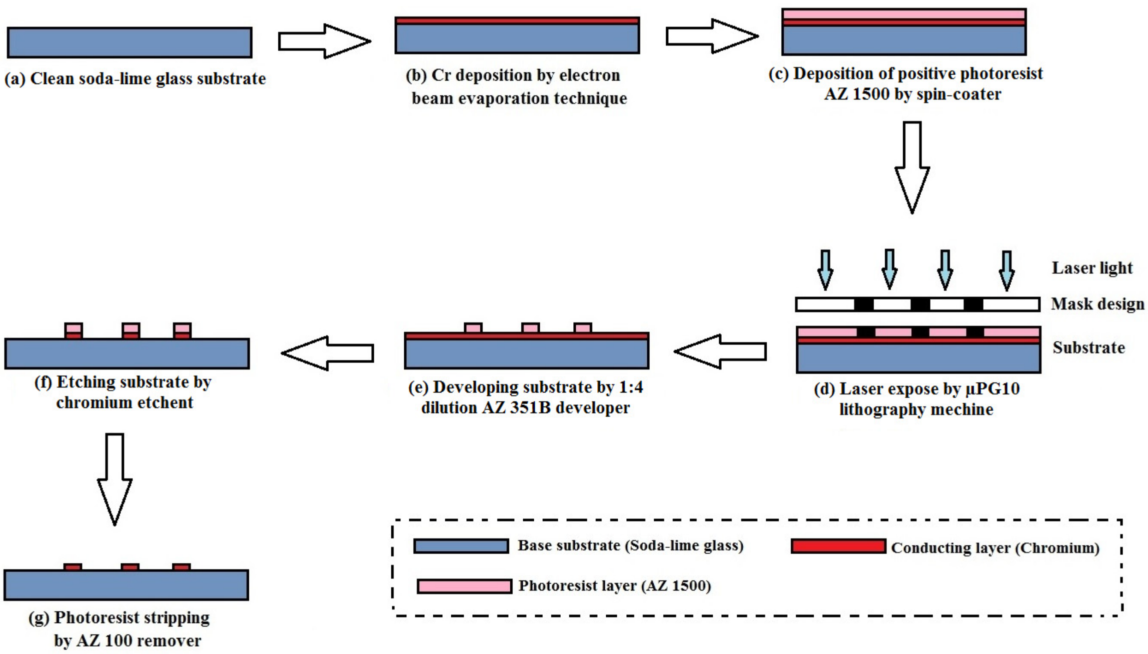

Fig. 3. The fabrication process of the Chromium (Cr) coated EWOD device.

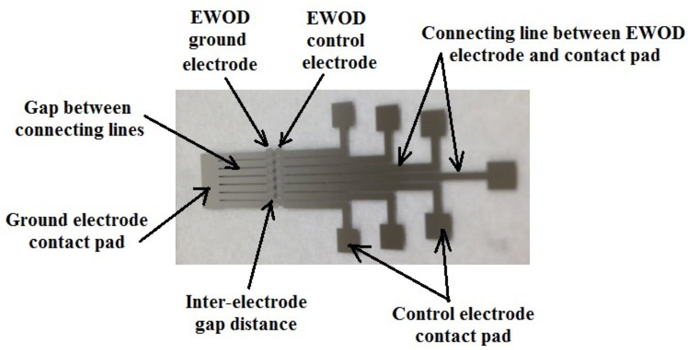

Fig. 4. Specifications of the Cr patterned single plate EWOD (open system).

The parameters associated with Cr coated EWOD design are displayed in Fig. 4. This is a single plate EWOD design where a novel shaped control electrodes and ground electrodes are located on the same glass substrate. The gap distance between both electrodes is known as inter-electrode gap. During the droplet actuation, the electrodes will need to be activated by a supply voltage. To apply the voltage to the electrode, the contact pads including connecting lines are used. In this design, the voltage is applied into individual control electrodes for manipulating the droplet from one electrode to another. Conversely, all ground electrodes are joined together and connected with the ground port of the supply voltage.

3.3 Electrode insulation: dielectric and hydrophobic layers

Electrode insulation is required to isolate the conducting electrode from the droplet. The electrode insulation involves two layers including a dielectric layer, and a hydrophobic layer. Both insulating layers are placed on top of the EWOD electrodes. Before electrode insulation, Kapton polyimide tape is used to cover the contact pads of the EWOD design. Thus, the contact pads are not insulated during the deposition of the insulating materials. In the electrode insulation process, Polyvinylidene difluoride (PVDF) dielectric material is used as a dielectric layer. The dielectric constant of PVDF is 8.4. The PVDF is in powder form. A 5 % (wt. /wt.) PVDF solution is prepared by dissolving PVDF powder in Tetrahydrofuran (THF) and N, N-Dimethylformamide (DMF) solvents. The thickness of the dielectric layer made by PVDF can be adjusted by varying the speed of spin-coater. The PVDF solution is spread on the Cr coated substrate at a speed of 500 rpm for 15 seconds, followed by 2000 rpm for 2 mins. The sample is then placed on a hot-plate at 80 ºC for 30 minutes to cure it completely. A PVDF layer with 1.8 µm thickness is thus obtained. Then, a hydrophobic layer of Teflon- AF is used to provide surface hydrophobicity. To get this layer, the Teflon- AF (1% wt. /wt. Fluorinert FC-40) is deposited at the speed of 2000 rpm for 60 seconds and baked at 80 ºC for 25 minutes. The thickness of the deposited Teflon layer is 50 nm.

4. Result and discussion

A conducting droplet made of 1M KCL with di-ionized water (DI water) was used to evaluate the actuation voltage of the fabricated EWOD device. The droplet was placed between a control electrode and ground electrode, and the initial contact angle of the droplet of 123 º was measured. When a voltage was applied to the neighboring EWOD electrode, the droplet changed its contact angle and moved to that actuated electrode. The minimum applied voltage required to initiate droplet movement is called the actuation voltage. The proposed EWOD device with the novel electrode shape and high dielectric constant-based PVDF coating achieved minimum actuation voltage of 14.78 V. In addition, electrolysis and bubble generation were observed under the applied potential of 16.2 V. This voltage is called as dielectric breakdown voltage. Fig. 5 shows the experimental setup of the proposed EWOD device for which actuation voltage was 14.78 V.

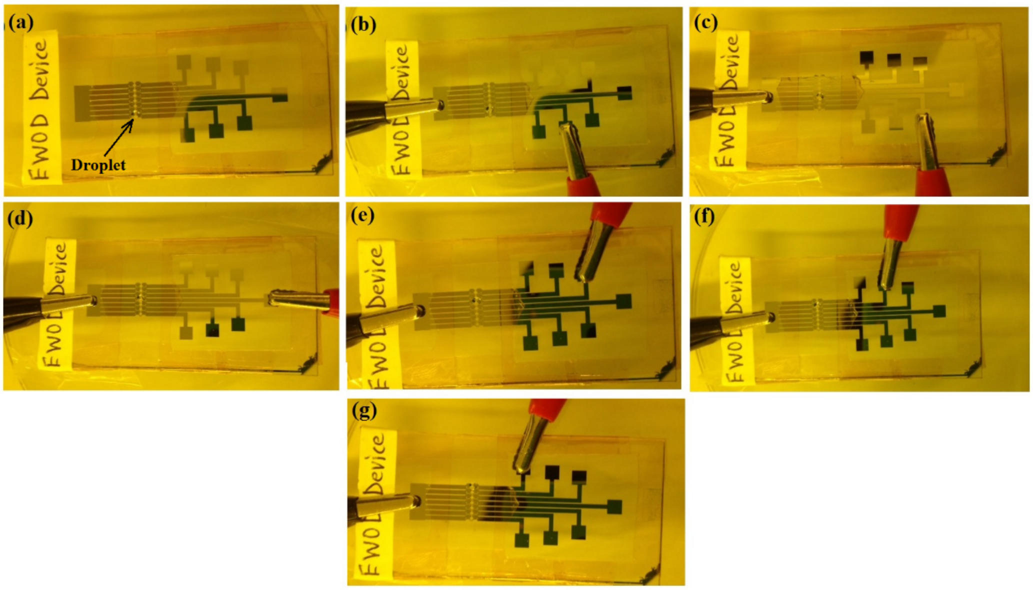

Fig. 5. EWOD droplet movement at a voltage of 14.78 V: (a) initial, and (b-g) position changes.

To compare the achieved actuation voltage with other devices, two types of EWOD electrodes shape including square and circular with PVDF dielectric and Teflon hydrophobic layers were used. Table 1 presents the minimum actuation voltages for different shapes of the electrodes. It is clear from Table 1 that the proposed electrode shape achieved lower actuation voltage than the square and circular shapes.

Table 1. Minimum actuation voltages for different shape of EWOD electrodes

Shape of EWOD electrode	Dielectric and Hydrophobic layer	Achieved minimum actuation voltage
Square electrode	PVDF and Teflon- AF	19 V
Circular electrode	PVDF and Teflon- AF	17.3 V
Proposed electrode	PVDF and Teflon- AF	14.78 V

The reason of the required lower actuation voltage for the proposed electrode is that such electrodes are placed one after the other to minimize the gap between the two adjacent electrodes in an electrode array where the droplet easily move by overlapping the adjacent electrodes.

5. Conclusion

The paper presented the design and fabrication of a novel EWOD device operating at low actuation voltage. The main contribution of this work was to design the electrodes with a novel shape so that it can manipulate the droplet on a EWOD device at low actuation voltage. The experimental results demonstrated that the minimum actuation voltage of 14.78 V was needed to initiate droplet movement for the proposed optimum electrode. The proposed electrodes for EWOD device were obtained by optimizing the shape of the electrode while some other parameters including electrode size and inter-electrode gap were kept constant.

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