Development of an Electrowetting Digital Microfluidics Platform using Low-cost Materials

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Abstract— **Digital microfluidics is an emerging technology which has proved to be promising in a variety of applications including protein and cell analysis. In this technology discrete droplets of fluid are manipulated instead of continuous flow in microchannels. In this paper, an electrowetting based digital microfluidics platform using relatively low-cost materials is presented. The commercially available printed circuit board technology is used for the electrode fabrication to further decrease the costs. Silicone rubber is used as the dielectric layer and a commercially available water repellant spray is used as the hydrophobic layer instead of the relatively expensive Teflon-AF commonly used in the literature. Fabrication of the device is relatively straight forward making it suitable even for disposable applications.**

Keywords-PCB; digital microfluidics; electrode; MOSFET; dielectric; hydrophobic

I. INTRODUCTION

Microfluidics is a relatively recent technology that concerns the treatment of liquids in minute volumes (microliter or picoliter) [1].The devices that are fabricated based on this technology are used in various applications including biochemical assays [2]. Researchers have full control on reactions and the amount of reagents that is used. In this technology, stream of fluids containing the reagents is confined in pathways called microchannels. However in recent years in place of continuous stream of liquid, discrete droplets of reagents are introduced [3]. This evolving technology has immensely increased the throughput of microfluidic devices, introducing novel fields of research such as single-cell analysis [3].

Operation-wise there are two kinds of DMF devices: oil and air-based. In the former, the droplet is immersed in oil while in the latter, droplets of liquid are surrounded by air. In oil-based devices the evaporation of the droplet is prevented. However special surfactants are needed for the stabilization of the droplet [4]. Using oil-miscible droplets and droplet drying applications are also challenging in this technology [5].

Digital microfluidics (DMF) is the term referring to the discrete droplets of liquid as discussed previously. DMF is deployed in a variety of applications thanks to its reduced reagent and solvent consumption, rapid reaction time and excellent integration capabilities. The advantages of DMF include: firstly, the ability to address each reagent individually, circumventing the need to further complex networks of tubing or microvalves. Secondly, to manipulate colloidal droplets avoiding the clogging of microchannels. Thirdly, its compatibility with a wide range of volumes, making it viable for preparative-scale sample handling [6].

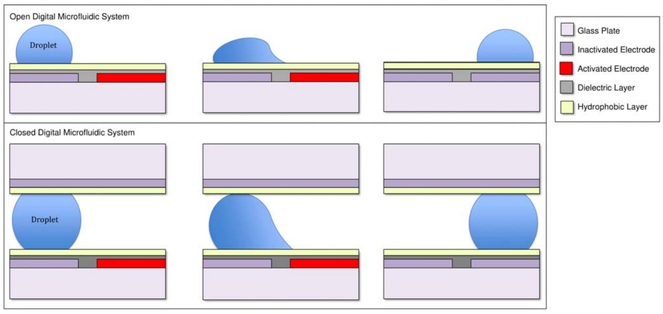

Fig. 1. A schematic diagram of the EWOD platform illustrating the movement of droplet by applied voltage. The top and bottom figures illustrate the open and closed EWOD scheme, respectively. Picture is adopted from [7].

Electrowetting on dielectrics (EWOD) refers to DMF platforms that employ an array of electrodes to manipulate a droplet position. A relatively high voltage is placed indirectly on an electrode using a dielectric spacer. The voltage decreases the contact angle of the droplet in that specific location of the electrode. By moving the voltage to the neighboring electrodes, the droplet starts to move in the direction of applied voltage (Fig. 1). In this work an array of PCB electrodes are used in order to control the droplets.

II. DESIGN

There are two kinds of EWOD devices in terms of configuration: open and closed. The former has a single plate as the substrate while in the latter, two plates are used to manipulate the droplets [8]. In the open EWOD device, the ground and the high voltage electrodes are in the same plate in contrast to the

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closed DMF where different plates are used for the this purpose. In both cases, a dielectric layer is used directly above the electrodes to insulate them from direct droplet contact avoiding water hydrolysis [5]. If the contact angle of the droplet with the surface is more than 90 degrees, the surface is called a hydrophobic surface. Changing the surface from hydrophobic to hydrophilic creates the driving force for the movement of droplet as shown in Fig. 1. Thus increasing the surface hydrophobicity is of utter importance. A hydrophobic layer is applied on the dielectric layer to increase the contact angle of the surface. EWOD devices rely on the ability to vary the contact angle of the droplet on the hydrophobic surface using an external electric field. The contact angle of the surface can be described based on the Young-Lippmann model as shown in equation (1):

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_0\varepsilon_r}{2d\gamma_{lv}}(V - V_0)^2 \quad (1)$$

where γ_{lv} is the liquid-vapor surface tension, d is the thickness of the dielectric layer, ε_0 is the permittivity of the free space, ε_r is its relative dielectric constant and V is the applied voltage. In this equation θ is the contact angle which is a function of the applied voltage V, where θ_0 is the contact angle with no voltage applied [9] [10]. When the voltage is increased, the contact angle decreases respectively and the droplet wets the electrode surface as the surface becomes more hydrophilic. In this way, the droplet moves to the next electrode array region. In order to move the droplet to the neighboring electrode, its volume should be large enough to have an adequate overlap.

Various technologies have been deployed in literature in order to fabricate the electrodes and the needed electronic circuitry including application-specific integrated circuit (ASIC). Although an ASIC can be used to fabricate electrodes and circuits simultaneously, it increases the fabrication costs unfavorably [11]. The surface area in EWOD devices can be relatively substantial which impedes the application of ASIC to a further degree. Metal deposition on the PDMS dielectric has been used in the literature as well [1]. The volume of the droplet on PDMS shrinks overtime due to the notorious porosity of PDMS. PDMS is relatively expensive in many lower end applications as well.

In this work, PCB technology is used for the EWOD electrodes besides the electrical circuitry. PCB technology is relatively inexpensive and straight forward. It is also widely commercially available which makes it a perfect choice for low cost DMF applications [12]. However other materials need to be verified to be compatible with this technology.

A dielectric and a hydrophobic layer need to be placed on the substrate of EWOD. In the literature various materials are used as the dielectric layer such as SU-8, PDMS, Parylene-C and SiO2. Hydrophobic materials that are used in literature such as Teflon-AF and CYTOP suffer from inadequate adhesion to dielectric layer [3]. They are also relatively expensive and inaccessible. Our goal was to use materials which are widely accessible and relatively cost-effective at the same time. The relatively inexpensive silicon rubber was chosen as the dielectric layer and a commercially available hydrophobic spray was used as the hydrophobic layer. Silicon rubber is being commercially produced with various viscosities in huge quantities [13].

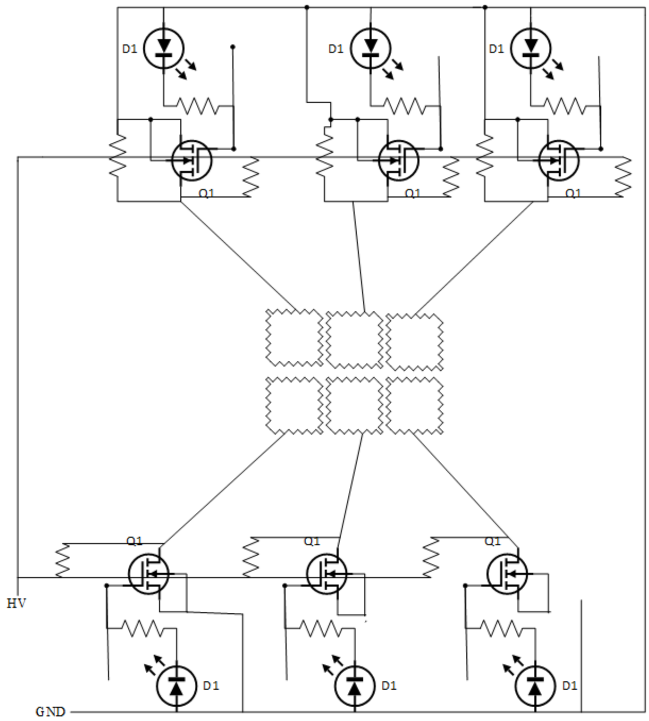

Fig. 2. The schematic diagram of the electrical driving circuitry and the EWOD electrodes that are connected together. The sawthooth-shaped electrodes are visible in the middle of the figure. The LEDs are placed for debugging purposes.

III. FABRICATION

The proposed DMF device is fabricated on a 6×8 cm^2 commercially available FR-4 PCB as described in the previous section. The schematic diagram of the device is illustrated in Fig. 2. An array of electrodes has been designed on PCB to be used as the droplet path. Each square-shaped electrode has a 6.76 mm^2 surface area. The edges of the electrodes are designed in sawtooth shape in order to maximize the overlap with the neighboring electrode. The distance between neighboring electrodes is 0.15 mm. The voltage on individual electrodes are driven by a high voltage MOSFET transistor. It enables relatively high speed switching of the voltage between electrodes. The drain and source pins of the transistors are connected to the electrodes and ground, respectively. General purpose input/output (GPIO) pins of a microcontroller address the gates of the transistors. High voltage on the GPIO pin turns on the transistor, which translates into placement of the high voltage on the electrode. By switching the high voltage on the neighboring electrodes the droplet can be manipulated.

In order to produce the relatively high voltage of 400 V for the electrodes, a voltage multiplier was designed as shown in Fig. 3. 220 V AC voltage is converted to 40 V AC using a step-down transformer. A voltage multiplier converts the 40 V AC output of transformer to 400 V DC.

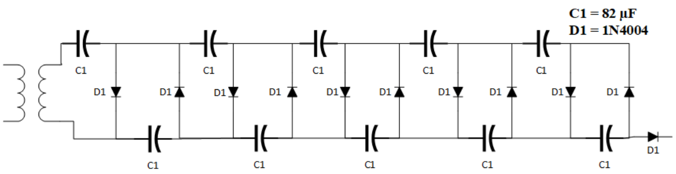

Fig.3. Schematic diagram of the 400 V high voltage generator of the PCB electrodes for EWOD platform. It consists of a step-down transformer and a 10 times capacitor-diode voltage multiplier.

For the EWOD platform a dielectric and a hydrophobic layer need to be deposited on electrodes. A schematic diagram of the fabrication process is illustrated in Fig. 4. Fig. 4a shows schematically the electrodes that are driven individually by high voltage MOSFET transistors. After thoroughly cleaning the PCB electrodes with ethanol, a 40 µm-thick layer of silicone rubber(purchased from local store) was deposited on the electrodes. The silicone rubber which is used in this work has two components that are mixed in 1:1 ratio. Since the silicone rubber viscosity was relatively high, it was diluted in a 2:1 ratio with a silicone thinner purchased from Atifam paydar™. This step is necessary otherwise, the silicone rubber thickness will be higher than expected. Please note that the silicone rubber and the silicone thinner material are both relatively inexpensive and widely accessible. The liquid silicone rubber was degassed in a vacuum desiccator for 30 min. Then it was spun on the PCB electrodes at the speed of 4500 rpm for 5 min. It was cured overnight at room temperature. A hotplate can also be used to cure it faster. However the longer curing time increases the smoothness of the silicone rubber on the surface. This process results into a layer thickness of 40 µm approximately as shown in Fig. 4b.

A commercial water repellant spray (Nanopad Sharif ™) was used as the hydrophobic material. The silicone rubber surface is sprayed until the hydrophobic material covers the surface completely. After approximately 2 min, the excess material is removed using a wipe. The surface needs to be placed intact for about 1 hour for the hydrophobic spray to reach its ultimate hydrophobicity.

The microcontroller drives the high voltage MOSFET transistors. The microcontroller is programmed using Arduino® code. The code defines the path of droplet movement by switching the high voltage on the EWOD electrodes alternately.

IV. RESULTS AND DISCUSSION

The transition of the droplet from left to right is shown in Fig. 5. Three camera shots are used in this animation to illustrate the movement of the droplet. The microcontroller is driving the electrodes in order to move the droplet. Upon applying the voltage on each electrode, the surface becomes hydrophilic and the droplet tends to move in the very direction of the electrode. Please note that the microcontroller is not shown in this image.

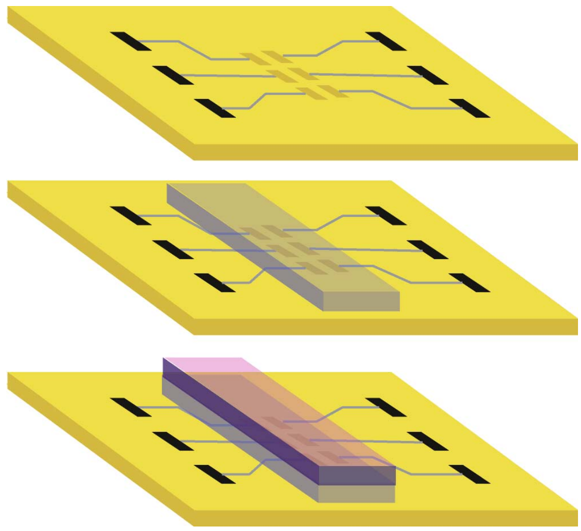

Fig.4. Fabrication process flow for the EWOD platform: (a) schematic diagram of the electrodes that are driven by high voltage MOSFET transistors. (b) A 40 µm silicone rubber layer is deposited on the electrodes. (c) A hydrophobic layer is deposited on the silicone rubber.

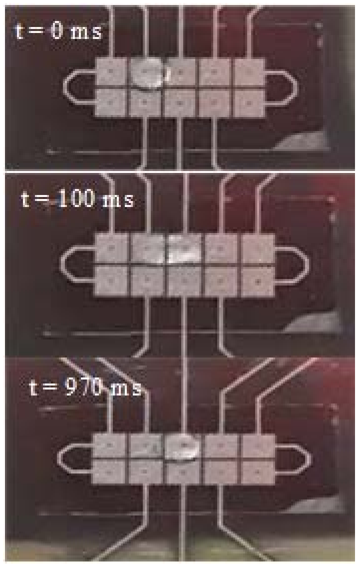

Fig. 5. The transition of the droplet from left to right is animated using three camera shots. The microcontroller which is not shown in this image is driving the electrodes to move the droplet.

Fig. 6 shows a camera image of the hydrophobic surface of the DMF platform directly above the EWOD electrode. The contact angle of the surface is measured to be approximately 100° (Fig. 6a). After applying a 400 V on the electrode the contact angle decreases to 80° (Fig. 6b). The images are fed to the ImageJ® software and the contact angles are measured. It demonstrates that the surface hydrophobicity decreases by applying voltage as expected.

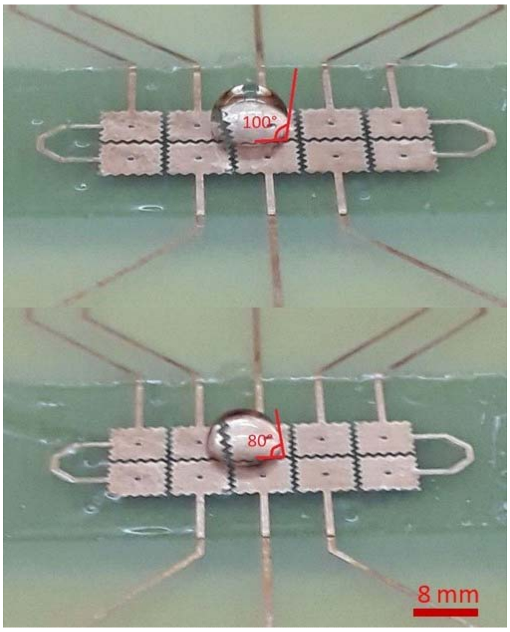

Fig. 6. The contact angle of the surface (a) before and (b) after applying the voltage on the electrode. The contact angles are measured using ImageJ® software.

In the presented EWOD platform approximately 10 μL of droplet could be moved with a speed of 3 mm/s by applying 400 V. By increasing the applied voltage the droplet could be moved faster. The droplet could even be moved diagonally. Experimental results were in good agreement with the Lippmann-Young model in equation (1). As the thickness of the dielectric layer is increased, the applied voltage should be increased as well to be able to move the droplet.

Voltages higher than 400 V can be used as well to move the droplet faster. However higher electrode voltage means higher-voltage driving circuitry, increased size of the high voltage transistors and increased power dissipation. The distance between two neighboring electrode is another factor limiting the maximum operating voltage. In this work there was a voltage breakdown at 800 V between two neighboring electrodes.

Finally, it is worth noting that hydrophobic spray is used in this work instead of PDMS as the hydrophobic layer. Although PDMS can also produce relatively high contact angles, its porosity hampers its performance in EWOD. Specifically lower viscosity liquids are absorbed in PDMS and are hydrolyzed due to direct contact with electrode.

V. CONCLUSION

In this work, a DMF platform for droplet manipulation based on electrowetting on PCB technology is presented. The electrodes were arranged in a two dimensional array to let the droplet move diagonally. The electrodes are driven by high voltage MOSFET transistors individually.

Commercially available silicone rubber and hydrophobic spray were used in this work. It should be noted that these materials are relatively inexpensive and widely accessible. Furthermore a fabrication process compatible with the FR-4 PCB substrate material was developed to decrease the costs even further. Relatively good adhesion between the dielectrics and the FR-4 is developed.

EWOD or more generally DMF is a technology targeting the lab-on-chip applications. It has several applications including the hot topic of single cell analysis in recent literature. This work may pave the way towards the widely accessible portable DMF platforms based on EWOD.

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