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Effect of electrode geometry on droplet velocity in open EWOD based device for digital microfluidics applications

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ABSTRACT

Electro wetting-on-dielectric (EWOD) is an emerging method for handling droplet motion by applying an electric field to an array of electrodes. The dependence of droplet velocities on different electrode configuration in open EWOD system has been investigated in this work. In this paper, open configured EWOD devices with different geometries of electrodes, polydimethylsiloxane (PDMS) as a base layer are designed and fabricated. The electrowetting force is computed by analytical methods as well as by numerical methods and its effect on droplet velocity is studied in detail. The velocity of the droplet is measured by using open image processing tool.

1. Introduction

As scaling in technology leads to smaller device sizes, new methods for microscale fluid control are being developed. In which more attention is drawn towards using surface tension for manipulating fluid motion, which becomes a dominant force [1]. Digital microfluidics is relatively new microscale handling technology that enables individual control over the droplets on an array of electrodes. Digital microfluidics devices allow compact fabrication, reduced reagent consumption, smaller analysis time with the efficiency, programmability, and portability, which has shown great potential for a wide range of application, such as lab-on-chip [2,3]. EWOD based digital microfluidics is explored as a most promising devices to manipulate droplet by controlling the wetting behavior of liquids on the dielectric surface using application of a voltage [4–6]. It has recently emerged as a useful tool in biomedical applications. Such as Polymer Chain Reaction (PCR) [7], glucose detection [8], enzyme assays [9], proteomics [10], DNA hybridization, and soft printing [3]. The wetting behavior of the droplet can be observed as a change in contact angle which is regulated by well known Young-Lipmann equation [11] given as

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

where γ_{lv} the solid– liquid surface tension, d is the thickness of the dielectric layer, ε_0 is the permittivity of free space, ε_r is its relative dielectric constant, V is the applied voltage and $\theta(V)$ is the contact angle with voltage, while θ_0 is the contact angle without voltage. Fig. 1 shows the basic structure of EWOD device in open configuration.

The performance of open EWOD devices fundamentally depends on a different parameter such as bottom and ground electrode configuration, dielectric material, dielectric thickness, applied voltage [12]. The effect of dielectric material including Teflon-AF, Parylene-C, Cytop and PDMS for EWOD has studied widely [13]. The effect of contact line length on droplet capillary force with square and different interdigitated pattern are investigated [14]. Utilizing an array of square electrodes has been studied [15] but this geometry is given flat surface tension profile during a transition at the edge of the electrode. To resolve this problem [16,17] has studied different electrode designed to establish the surface energy gradient between electrodes to enhance the driving force. However, despite the contributions of [12,15–17], the literature lacks a detailed experimental investigation into the role of the electrode geometry on droplets velocity in open EWOD devices. The lack of attention is given to ground wire configuration in open EWOD system, which is also one of the critical parameters for designing this system [18]. Also, very few researchers [19–21] have

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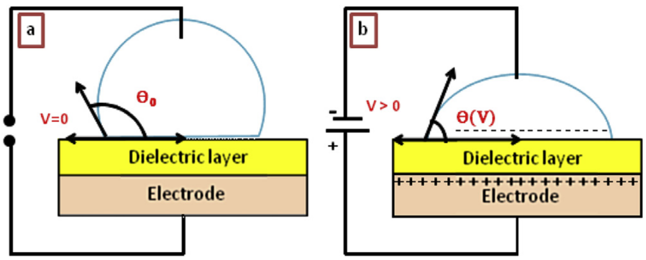

Fig. 1. The basic structure of open EWOD system **a** without and **b** with change of contact angle based on an application of a voltage between the droplet and electrode.

used PDMS as a dielectric as well as hydrophobic layer in EWOD Devices. The droplet velocity measurement is one the most important parameters for analyzing the effect of electrode geometry, dielectric pinning effect, ground wire configuration and its drag forces on droplet in open EWOD system.

In this paper velocity of the droplet is measured and compared for different electrode geometries to optimise the electrode design for EWOD devices. The contact line length and electrowetting force is measured for all electrode geometries, which is used for efficiently observing the wettability behavior of the droplet. This work also introduces a novel method for calculating droplet velocity using OpenCV, which reduces the complexity of computation without compromising the accuracy of the measurement.

2. Electrode design

2.1. Theory

In EWOD devices, droplet motion occurs as a result of capillary force which sequels an apparent wettability gradient between actuated and non-actuated electrode. The capillary line force density on a triple line (i.e. the contact line between the droplet, the substrate, and the surrounding medium) is given by Ref. [22].

$$f_w = \gamma_{lv}(\cos\theta(V) - \cos\theta_0) \tag{2}$$

From Eq. (2), it can be shown that capillary force acting on the droplet in direction x (unit vector i) is expressed as

$$F_x = \int_L \gamma_{lv}(\cos\theta(V) - \cos\theta_0)\, dl\, \vec{n}\cdot\vec{i} \tag{3}$$

where dl is the unit element of the droplet contour line and n is unit normal to the contour line. Integrating Eq. (3) to obtain the total capillary force yields [14].

$$\begin{aligned} F_x &= \gamma_{lv}(\cos\theta(V) - \cos\theta_0)\int_L dl\,\vec{n}\cdot\vec{i} \\ &= L\,\gamma_{lv}(\cos\theta(V) - \cos\theta_0) \end{aligned} \tag{4}$$

When the droplet is transported on the EWOD device, the change in the value of contact angle is given by the Lippmann-Young law through Eq. (1). Using Lippmann-Young law, we can translate that electrowetting effect into a capillary effect. So the net capillary force or electrowetting force is rewritten in the following expression [23].

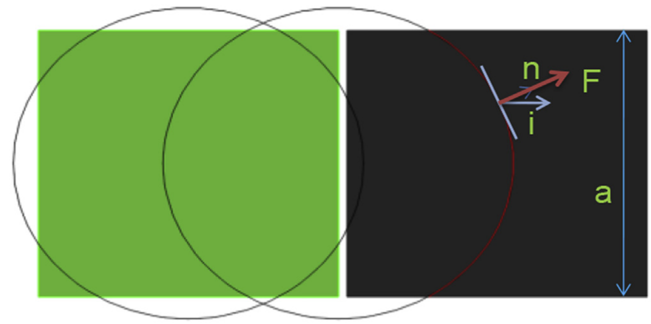

Fig. 2. The top view of the open configured EWOD device when the droplet moves from left (non-actuated-green pad) to right (actuated black pad), the contact line length (red line) is a function of droplet displacement on the electrode. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$F_x = \frac{1}{2}\frac{\varepsilon_0\varepsilon_r L}{d}V^2 \tag{5}$$

L is the effective contact line length. The contact line length L is determined by the boundary structure formation of the adjacent electrode. The contact line length of a droplet across two adjacent square electrodes varies with the droplet positions as shown in Fig. 2.

The velocity of the droplet in the open configured EWOD device is derived as explained in by Cui et al. [24]. For 110° (for PDMS) static contact angle of droplet the equation takes the form as follows.

$$U = \frac{\frac{\varepsilon_0\varepsilon_r L}{d}\cdot V^2}{\pi K_1 K_2 K_c C_V \mu R\left(5.248 + \frac{\varepsilon_0\varepsilon_r}{d\gamma_{lv}}\cdot V^2\right)} \tag{6}$$

where K_C is the damp factor caused by the pinning effect in the triangle region, K_1 is acceleration and deceleration time process factor, K_2 is the considering dragging effect due to the ground wire, R is the radius of the droplet, C_V is an empirical constant and μ is the viscosity of the fluid. In this work, following values are taken for the parameters in the Eq. (6), $\varepsilon_0 = 8.85 \times 10^{-12} c^2/N.m^2$, $\varepsilon_r = 2.75$, $L = 1.35$ *mm*, $d = 15$ *μm*, $K_1 = 2$, $K_2 = 4$, $K_C = 4$, $C_V = 12.5$, $\mu = 0.001 Ns/m^2$, $R = 1.169$ *mm* and $= 72.6$ *mN/m*^{2}.

We have modeled droplet shape with and without wire using surface evolver as shown in Fig. 3. Here we have seen that there is a surface energy change and also droplet shape does not remain a spherical cap with wire configuration. Also ground wire (catena) is providing some resistance for droplet motion. So considering all these effect in our analytical equation of droplet velocity, we have introduced K_2 parameter to take into account dragging effect due to the ground wire.

From Eq. (5) and Eq. (6), the capillary force and velocity of the droplet is directly proportional to the contact line length located on

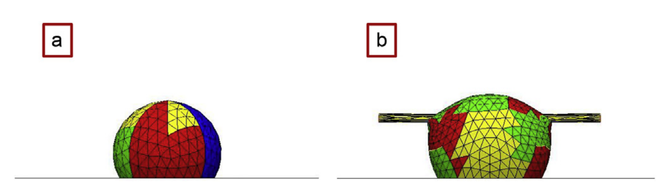

Fig. 3. **(a)** Water droplet without catena; surface energy = 3.33 × 10^{-7} J **(b)** Water droplet with catena; surface energy = 3.11 × 10^{-7} J (wire height = 700 μm).