Design and Analysis of a Low Actuation Voltage Electrowetting-on-dielectric Microvalve for Drug Delivery Applications

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Abstract— **This paper presents a low actuation voltage microvalve with optimized insulating layers that manipulates a conducting ferro-fluid droplet by the principle of electrowetting-on-dielectric (EWOD). The proposed EWOD microvalve contains an array of chromium (Cr) electrodes on the soda-lime glass substrate, covered by both dielectric and hydrophobic layers. Various dielectric layers including Su-8 2002, Polyvinylidenefluoride (PVDF) and Cyanoethyl pullulan (CEP), and thin (50 nm) hydrophobic Teflon and Cytonix are used to analyze the EWOD microvalves at different voltages. The Finite Element Method (FEM) based software, Coventorware is used to carry out the simulation analysis. It is observed that the EWOD microvalve having a CEP dielectric layer with dielectric constant of about 20 and thickness of 1 µm, and a Cytonix hydrophobic layer with thickness of 50 nm operated the conducting ferro-fluid droplet at the actuation voltage as low as 7.8 V.**

I. INTRODUCTION

Manipulation of microliter volumes of fluids in microfluidic devices are finding applications in drug delivery [1, 2]. Microvalves are the key component of a drug delivery device (DDD) which control routing, timing, and separation of drugs within a microfluidic device. Various actuation methods including electric, magnetic, piezoelectric, thermal, pneumatic, phase change, and electro-chemical have been reported in the literature for microvalve operation. Although some approaches offer good reliability and adequate accuracy, they suffer from limitations such as lack of robustness, slow response time, complex fabrication procedure, and high actuation voltage. Specifically in drug delivery applications where low actuation voltage is required, conventional approaches are less suitable.

This paper focuses on a type of microvalve known as electrowetting on dielectric (EWOD) microvalve. It offers various advantages such as flexibility, small size, fast switching, low cost, etc. EWOD is the voltage manipulation of the wettability of a liquid on a solid surface. The EWOD microvalve uses a conducting droplet on the hydrophobic planer substrate with the electrodes buried underneath. When the voltage is applied to the driving electrode, an imbalance net force is imposed on the droplet which drives the droplet.

The existing EWOD microvalves, however, require high actuation voltages. A high actuation voltage induces unexpected heat, and evaporates the droplet instead of moving it. In addition, a high actuation voltage operated EWOD microvalve increases the risk of the high voltage operation. Therefore, the main objective of this paper is to reduce the actuation voltage of the EWOD microvalve for the drug delivery applications.

It has been reported that the choice of the insulating (dielectric and hydrophobic) layers for EWOD devices determine their actuation voltage and reliability. For instance, Huang et al. [3] developed a low actuation voltage EWOD device using a 500 nm anodized tantalum pentoxide (Ta_2O_5) dielectric layer with a thin top Cytop coating. Although the dielectric material of anodized Ta_2O_5 reduces the EWOD actuation voltage, the working performance of the EWOD device declines in the presence of positive DC voltage. To overcome this, a Ta_2O_5 layer is prepared by anodizing a sputtered Ta_2O_5 film which works at low actuation voltage both for positive (+) and negative (-) DC signals. In addition, a EWOD device constructed with SiO_2 dielectric and Parylene C hydrophobic layers actuated 1M KCL droplet in air medium using 25 V minimum voltage [4]. In another study, Chen and Fu [5] fabricated a EWOD device having a high dielectric constant (approximately 25.5) of the niobium pentoxide (Nb_2O_5) layer to reduce the actuation voltage. They showed that a 1% sodium dodecyl sulphate (SDS) droplet obtains a change in contact angle (120° to 70º) at 9 V operating voltage. However, their fabrication method was complicated because of the requirement to RF reactive magnetron sputtering. Furthermore, a low actuation voltage EWOD device based on a 127 nm aluminum oxide (Al_2O_3) layer with high dielectric constant of ~ 10 was proposed by Chang et al. [6]. This device obtained the movement of 2 µl water droplet under 15 V and the dielectric breakdown voltage of 54 V. Although this EWOD device with thin insulating coatings work at low actuation voltage, sometime the dielectric breakdown occurs before archiving a significant change in contact angle of the droplet. To overcome this problem, silicon oil was used on the surface of the EWOD microvalve to reduce the actuation voltage and contact angle hysteresis.

In this paper, a EWOD based microvalve is proposed, and simulated at different voltages using different combinations of insulating layers. It is observed that the contact angle for a ferro-fluid droplet can be changed from 127° to 80° in silicon oil medium with the applied voltage of 7.8 V when a 1 µm thin CEP dielectric and 50 nm Cytonix hydrophobic surface coatings are used. The paper is organized as follows. Section II explains the theory for EWOD droplet actuation. Section III describes the design and operation of the proposed EWOD microvalve. Section IV gives the simulation results and associated discussions. Finally, Section V gives the concluding remarks.

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II. THEORY OF EWOD DROPLET ACTUATION

A. Actuating Force on the Droplet

EWOD is a complex phenomenon where an electric field creates electric charges in the conducting droplet, resulting in a driving force for the droplet movement due to the interfacial surface tension between the droplet and an insulating layer. EWOD has three interfacial surface tension vectors at the three-phase contact line, 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 layer and the filler medium, and γ_{id} is the interfacial surface tension between the insulating layer and the droplet (see Fig. 1). The volume of the EWOD droplet is chosen such that the droplet footprint is slightly larger than the electrode size ensuring that the droplet easily overlaps the neighboring electrode. When the neighboring electrode is connected to a voltage source, the droplet is moved to that electrode exceeding the threshold voltage, resulting in an apparent change of the contact angle which is described by the Lippmann-Young equation:

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

where θ_0 is the initial contact angle, θ_v is the new contact angle after applied voltage, ε_0 is the permittivity of the free space, ε_{rd} is the dielectric constant of the dielectric layer, ε_{rh} is the dielectric constant of the hydrophobic layer, V is the applied voltage, t_d is the thickness of the dielectric layer and t_h is the thickness of the hydrophobic layer.

If the conducting droplet is in contact with the insulating surface, the driving force per unit length, f_m can be calculated from the actuating and non-actuating electrode net forces [7]. It is found that contact angle hysteresis α, caused by the resisting forces, generates two edges droplet deformations, and resulting in an imbalance contact angle. The maximum value generated to increase the contact angle is known as advancing contact angle hysteresis. Conversely, the minimum value is called as receding contact angle hysteresis. The analysis of the contact angle hysteresis is shown in Fig. 2(a). It is observed that the advancing contact angle increases and the receding contact angle decrease as a function of the droplet velocity on the three-phase contact line. Hence, an equation of the driving force per unit length, f_m upon the droplet can be presented as a function of the advancing $(\theta_v + \alpha)$ and the receding $(\theta_0 - \alpha)$ contact angles, by:

$$f_m = \gamma_{df}[\cos(\theta_v + \alpha) - \cos(\theta_0 - \alpha)] \tag{2}$$

Integrating the driving force per unit length f_m over the diameter of the droplet L, produces the total force F_m on the EWOD droplet:

$$F_m = f_m L \sin\phi \tag{3}$$

The advancement angle ϕ is referenced from the center of the moving droplet where the contact line intersects the adjacent electrode (Fig. 2 (b)). The angle of advancement ϕ varies from 0 to π as the droplet transfers to the neighboring electrode. Thus, the driving force for the droplet changes as it traverses [7].

Using (1), a relationship is made of the driving force per unit length f_m from (2), including contact angle hysteresis, and the properties of the substrate, droplet, and the filler medium. Thus, the total force on an actuated droplet can be expressed from (3):

$$F_m = L\sin\phi\left\{\cos\alpha\frac{\varepsilon_0\varepsilon_{rd}\varepsilon_{rh}\mathrm{V}^2}{2\left(t_d\varepsilon_{rh} + t_h\varepsilon_{rd}\right)} - \gamma_{df}\sin\alpha\left[\sin\theta_v + \sin\theta_0\right]\right\} \tag{4}$$

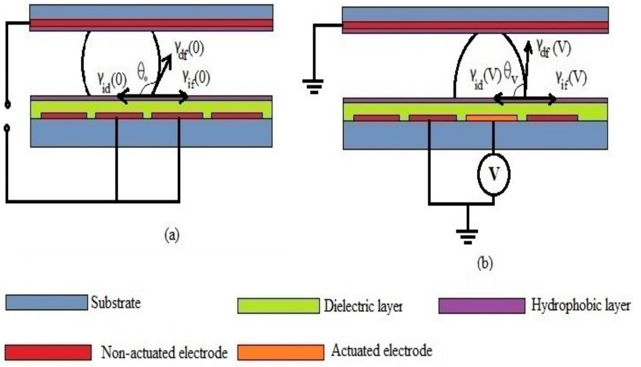

Figure 1. Characteristics of the droplet in the EWOD device: (a) without applied voltage, and (b) with applied voltage.

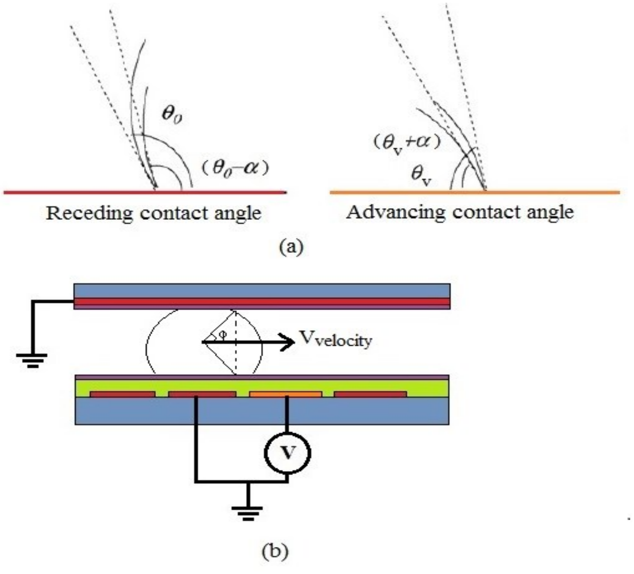

Figure 2. (a) Contact angle hysteresis. (b) EWOD force making a velocity $v_{velocity}$ to move the droplet on the right side actuated electrode.

B. *Drag Force from the Filler Medium and the Two Substrate Plates*

The movement of a droplet is resisted by the force from the top and bottom substrate plates and the viscous drag from the filler medium (air or oil). For a parallel-plate configuration [4], if the droplet is placed between two plates separated by h, then the drag force for the two plates can be expressed as:

$$F_{dtp} = 2C_v \frac{\mu_d v_{velocity}}{h} L^2 \tag{5}$$

Furthermore, the drag force for the filler medium is estimated by [7, 8]:

$$F_{dfm} = 12\mu_0 h v_{velocity} \tag{6}$$

where C_v is an empirical constant (10-15), μ_d is the droplet viscosity, $v_{velocity}$ is the droplet velocity, and μ_0 is the viscosity of the filler medium.

C. *Force Balance*

The EWOD force is balanced by equaling the droplet actuation force F_m, with the sum of the drag force from the filler medium F_{dfm} and the two substrates plate F_{dtp}. As a result, a new equation for droplet velocity can be expressed:

$$v_{velocity} = \frac{\sin\phi\left[\cos\alpha \dfrac{\varepsilon_0 \varepsilon_{rd} \varepsilon_{rh} \mathrm{V}^2}{2(t_d \varepsilon_{rh} + t_h \varepsilon_{rd})} - \gamma_{df} \sin\alpha(\sin\theta_v + \sin\theta_0)\right]}{12\mu_0 \dfrac{h}{L} + 2C_v \dfrac{\mu_d}{h} L} \tag{7}$$

D. *Calculation of the Threshold Voltage*

The threshold voltage of the EWOD can be calculated when $V = V_T$ and velocity of the droplet $(v_{velocity} = 0)$. The threshold voltage V_T for the droplet actuation [8] is:

$$V_T = \sqrt{\frac{2\gamma_{df}(t_d \varepsilon_{rh} + t_h \varepsilon_{rd})}{\varepsilon_0 \varepsilon_{rd} \varepsilon_{rh}} \left[\tan\alpha(\sin\theta_{v_T} + \sin\theta_0)\right]} \tag{8}$$

III. DESIGN AND OPERATION OF THE EWOD MICROVALVE

The design of the EWOD microvalve is shown in Fig. 3. It has three chambers: (i) EWOD fluid reservoir which stores conducting ferro-fluid, (ii) EWOD channel which is the parallel configuration where the bottom plate has three electrodes (e1, e2, and e3) on the soda-lime glass substrate, embedding them in both dielectric and hydrophobic layers, and the top plate is the 250 nm ITO coated glass with a thin hydrophobic layer only, and (iii) drug flow channel involving one EWOD electrode (e4) including a hallow long channel for drug flow. The microvalve contains two gates: (i) gate 1 is placed between the reservoir and the EWOD channel, and (ii) gate 2 is positioned between the EWOD main channel and the drug flow channel.

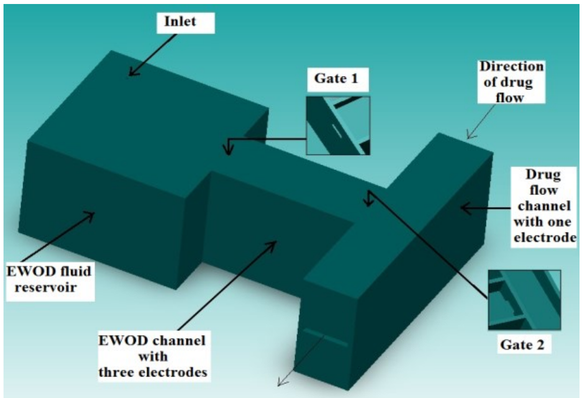

Figure 3. 3-D view of the proposed EWOD microvalve.

The bottom electrode of the EWOD microvalve is made of 250 nm of Chromium (Cr) coating with a dimension of 1.4 mm × 1.4 mm. Moreover, the gap distance between the bottom electrodes is 10 μm, and the spacer between two substrate plates is 100 μm. The top ITO glass is used for ground substrate for the EWOD actuation. The cross-section view of the proposed EWOD micorvalve is shown in Fig. 4.

Normally this microvalve is an open-state microvalve. When the electric potential is applied on the electrode (e1), a defined volume of ferro-fluid droplet is generated from the EWOD fluid reservoir whose footprint is slightly larger than the electrode size. In the 2$^{\text{n}}$ step, the first droplet is moved to the e2 electrode and another droplet is produced and placed on the e1 electrode after applying voltage on e2 and e1 electrodes at the same time. In the 3$^{\text{rd}}$ step, both of the droplet are moved to their next electrode. And in the final step, the first droplet moves to the e4 electrode in the drug flow channel which blocks the drug flow and closes the EWOD microvalve. On the other hand, the second droplet is positioned on e3 to prevent the leakage of drug. Thus, the microvalve goes on closed position, if the voltage is applied on e4. Fig. 5 shows the operation of the EWOD microvalve. In this microvalve, the ferro-fluid is chosen such that it follows the channel shape, providing very good seals, prevent droplet evaporation. Additionally, it is observed that the static contact angle of the ferro-fluid droplet immersed in silicone oil on the Teflon or cytonix surface is 127°. Therefore, the microvalve can perform as a leakage free operation.

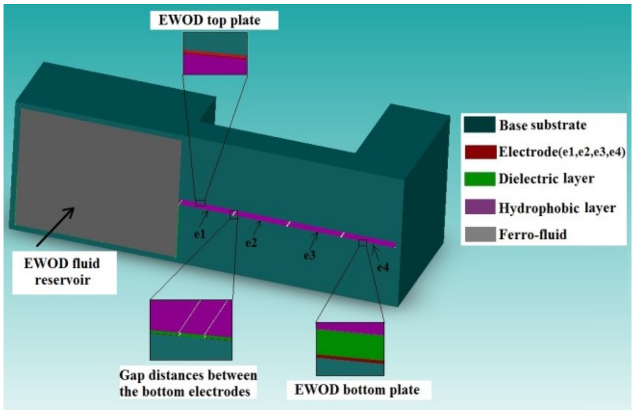

Figure 4. Cross-section view of the EWOD microvalve.

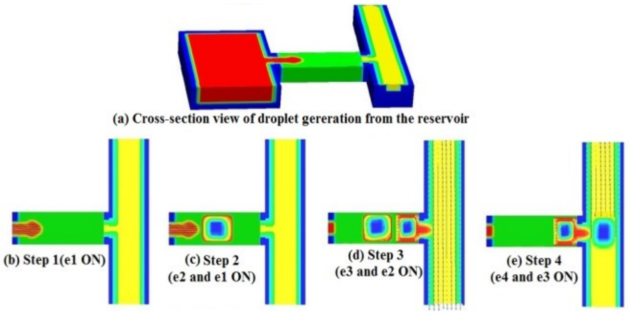

Figure 5. Operation of the EWOD microvalve.

IV. SIMULATED RESULTS AND DISCUSSIONS

To achieve minimum actuation voltage, different dielectric layers such as 2 µm of Su-8 2002; 1.23 µm and 1 µm of Polyvinylidenefluoride (PVDF); and 1.23 µm and 1 µm of Cyanoethyl pullulan (CEP) with 50 nm of Teflon and Cytonix hydrophobic layers combinations are analyzed. Table I presents the low actuation simulated voltages using different combinations of the insulating layers for the proposed EWOD microvalve.

The simulations show that if 2 µm of Su-8 2002 is used as a dielectric layer with 50 nm of Teflon, the droplet movement is occurred at 17.64 V. On the other hand, the microvalve with Su-8 2002 and 50 nm of Cytonix operates the droplet using 16.8 V. Secondly, the experiment with thin PVDF works at 10.58-9.5 V. In addition, an excellent movement is observed at 8.9-7.8 V using thin CEP. It is observed from the simulations that the EWOD microvalve having thin and high dielectric constant of insulating layers performs at lower actuation voltages. It is known that the dielectric constant (ε_{rd}) of Su-8 2002, PVDF and CEP is 3.2, 8.4, and 20 respectively. Although Teflon ($\varepsilon_{rh} = 2$) and Cytonix ($\varepsilon_{rh} = 2.25$) having different dielectric constants, the simulated actuation voltage for them is approximately the same. Therefore, the experiments show that 1 µm of very thin CEP with 50 nm of hydrophobic layer enable the microvalve to operate at 7.8 V which is the minimum actuation voltage for the proposed EWOD microvalve. Fig. 6 shows the changes of the ferro-fluid contact angle vs the applied voltage based on various simulations. It is observed that the graph follows the Lippmann-Young concept of EWOD.

TABLE I. ACHIVED LOW ACTAUATION VOLATEGES AT DIFFERENET COMBINATION OF INSULATING LAYERS

Experiments	Dielectric layers	Hydrophobic layers	Simulated voltage (V)
1.	2 µm of Su-8 2002	50 nm of Teflon	17.64
2.		50 nm of Cytonix	16.8
3.	1.23 µm of PVDF	50 nm of Teflon	10.58
4.		50 nm of Cytonix	10.51
5.	1µm of PVDF	50 nm of Teflon	9.7
6.		50 nm of Cytonix	9.5
7.	1.23 µm of CEP	50 nm of Teflon	8.9
8.		50 nm of Cytonix	8.87
9.	1µm of CEP	50 nm of Teflon	8
10.		50 nm of Cytonix	7.8

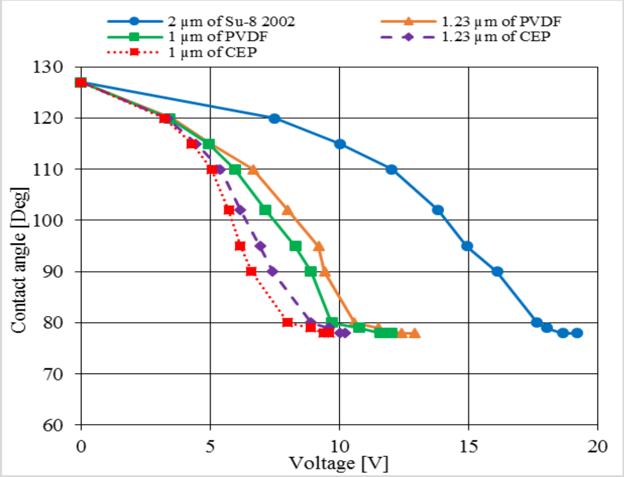

Figure 6. Contact angle change with applied voltage.

V. CONCLUSION

The paper presented the design and simulation of a low actuation voltage EWOD microvalve for drug delivery applications. The microvalve was modelled with different combinations of insulating layers materials to improve the performance of the microvalve with respect to its actuation voltage. The simulation results show that the contact angle change of the ferro-fluid droplet from 127° to 80° on the hydrophobic surface is obtained with only 7.8 V using thin CEP ($\varepsilon_{rd} = 20$) dielectric layer. Although based on the simulation results the EWOD microvalve works as a low actuation voltage microvalve, an experimental evaluation is also needed to verify the simulation results and demonstrate the operation of the proposed microvalve.

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