ELECTROWETTING-BASED MICROFLUIDIC DEVICES: DESIGN ISSUES

Chao-Yi Chen, Eve F. Fabrizio, Ali Nadim, James D. Sterling

Keck Graduate Institute of Applied Life Sciences
Claremont, CA

INTRODUCTION

Although Lippmann first explored the phenomenon in 1875, electrocapillarity has only recently generated substantial interest in the context of its application to electrowetting [1,2]. Electrowetting-based droplet systems have been proposed for biological sample actuation and manipulation [2]. Recent advances utilizing a thin dielectric layer between an electrode and a liquid electrolyte are referred to as Electrowetting on Dielectric (EWOD) methods which demonstrate more stable and reproducible electrical characteristics than direct electrolyte/electrode contact systems [3,4]. The principle of operation is shown Figure 1 in which a liquid droplet is sandwiched between two hydrophobicly-coated dielectric glass plates with embedded electrodes. The droplet is made to electrowet the surface preferentially at one end by applying an electric potential across the ground electrode and the control electrode at that end. The resulting hydrodynamic pressure gradient inside the droplet forces the droplet towards the more wetting end until the entire drop covers the energized control electrode.

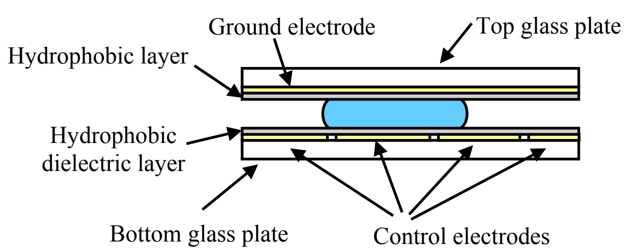


Figure 1. Electrowetting-based actuation of a droplet sandwiched between two plates.

Voltages on the order of ~100V have typically been required for the chosen dielectric materials and thicknesses. Droplet motion under these voltages has often shown hysteresis effects due to surface chemical modifications that occur at the higher field strengths. Moon, et al. [5] have successfully manipulated droplets with voltages as low as 15 V_{DC} by reducing the thickness of the dielectric layer, increasing the permittivity of the dielectric material, and treating the dielectric surface to reduce the hysteresis effect [5]. There has been little focus, however, on reducing the viscous drag forces at the fluid-solid interface because grounding of the droplet has been through the upper electrode. In this work, we describe designs that reduce the viscous drag forces significantly by removing the top glass plate. These designs utilize either (a) alternating electrode potentials with a floating droplet potential or (b) ground electrode wires or small electrodes that are embedded into the bottom plate.

DESIGN CHARACTERISTICS

In the design of Figure 1, the top glass plate was for the purpose of grounding the droplet. Since the drag on the drop resulting from the liquid-top plate interface increases the driving voltage required to obtain a particular velocity, an improved design involves removing the upper plate. A novel approach for grounding the drop is to use thin gold wires embedded in the Teflon coating layer (Figure 2). In the absence of grounding, the droplet may also be allowed to float with alternating potential applied to the control electrodes to prevent long-time charging of the droplet. Arrays of electrodes with serrated/ interdigitated edges have been used to ensure that a drop can move from one electrode to another.

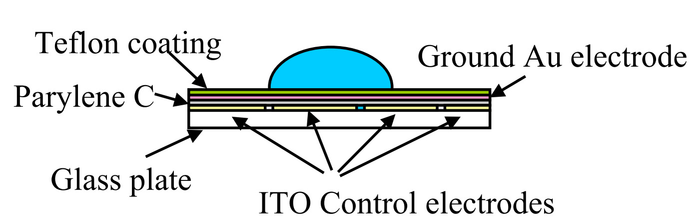


Figure 2. Electrowetting-based actuation of a droplet with single plate design.

Our designs begin with a 1200 Å indium-tin-oxide (ITO) pre-coated glass substrate from Delta Technologies to ensure optical transparency required for many fluorescence-based bioassays. The ITO is patterned to form the control electrodes using wet-etch micro-fabrication. Once electrically isolated electrodes have been formed, Parylene C or silicon dioxide is deposited as the insulating dielectric layer. For the grounding wires, gold is deposited in a 500 Å thick and 50 μm wide band using a standard lift-off technique. The dielectric and ground wires are then covered by a ~300 Å layer of Teflon AF 1611. The Teflon coating is thin enough that it provides only the requisite hydrophobicity of the surface but does not insulate the droplet from the ground gold electrode. The droplet is thus grounded through this gold wire without using the top plate.

Experiments are performed using a Keithley 2400 source meter as the voltage source and a 40–channel Keithley 2700 to independently control the electrode potentials.

ESTIMATES OF DROPLET VELOCITY

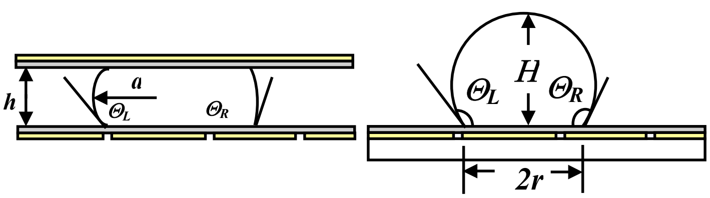
In an effort to characterize the motion of droplets in electrowetting, consider a liquid droplet of volume V sandwiched between two plates with a channel depth of h shown in Figure 3a. Taking the contact angle for the left half of the droplet to be θ_L and that of the right half to be θ_R, we estimate the droplet speed U_d by balancing the surface tension and the viscous wall-shear forces (neglecting any contact line friction or other motion-resisting forces):

$$F_{viscous} = 2\tau_w \pi a^2 = \frac{12\ \mu U_d V}{h^2}$$

$$F_{surf} = 2a\gamma_{LV}(\cos\theta_R - \cos\theta_L)$$

where μ is the viscosity and γ_{LV} is the surface tension of the liquid-air interface and V is the volume of the droplet. The shear stress at the surfaces is taken to be $6\mu U_d/h$ based on a plane Poiseuille flow. The droplet speed U_d is obtained by equating the above two equations:

$$U_d = \frac{\gamma_{LV} h}{6\pi\mu a}(\cos\theta_R - \cos\theta_L)$$



3(a) 3(b)

Figure 3. Relevant dimensions and angles of electrowetting designs. (a) A liquid droplet sandwiched between two plates. (b) A liquid droplet sitting on top of a single-plate chip.

The fastest velocity reported in the literature is ~24 cm/sec using optimized alternating electrode potentials (f~6-10kHz) with parameters of h=120μm and a~0.7mm[6]. According to the above equation, this velocity would require θ_R =69° if θ_L=90°, values which are indeed in the range of contact angle changes that are used in electrowetting devices.

Figure 3b shows a liquid droplet, with volume V, sitting on the single-plate chip. By the same argument but using the estimated shear stress as $5\mu U_s/2H$ (based on the peak velocity located near 2/5 of droplet height that has been observed in some numerical simulations) we estimate the droplet velocity U_s by the following:

$$U_s = \frac{4H\gamma_{LV}}{5\pi\mu r}(\cos\theta_R - \cos\theta_L)$$

giving

$$U_s / U_d = \frac{24Ha}{5rh}$$

For contact angles near perpendicular, $H \sim r$ and for fixed volume, V, and two-plate spacing, h, and equivalent electrowetting properties, we can expect an increase in droplet speed by utilizing a single-plate design that is approximately given by

$$U_s / U_d = \frac{24}{5}\sqrt{\frac{V}{\pi h^3}}$$

Clearly, a small plate spacing, h, results in large surface to volume ratios and high viscous drag so that large increases in droplet speed can be achieved by utilizing a single plate design.

CONCLUSIONS

A number of design issues associated with electrowetting microfluidic devices for liquid droplet actuation have been described. There are three major advantages in the use of single-plate electrowetting microfluidic designs. First, the manufacturing process can be simplified because steps required for maintaining uniform gap spacing can be eliminated. Secondly, the sample injection process would be much easier and the system can be readily integrated with existing microarray, liquid-handling and other laboratory automation systems. Thirdly, viscous drag can be reduced significantly resulting in increased droplet speed or reduced voltage requirements. These benefits indicate that a single-plate design approach has great potential for biological sample preparation and for integration with existing microarray spotting systems and other automated laboratory equipment.

ACKNOWLEDGEMENTS

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