Fast and reliable droplet transport on single-plate electrowetting on dielectrics using nonfloating switching method
Jun Kwon Park, Seung Jun Lee, and Kwan Hyoung Kang

Citation: Biomicrofluidics 4, 024102 (2010); doi: 10.1063/1.3398258
View online: http://dx.doi.org/10.1063/1.3398258
View Table of Contents: http://scitation.aip.org/content/aip/journal/bmf/4/2?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Coplanar electrowetting-induced stirring as a tool to manipulate biological samples in lubricated digital microfluidics. Impact of ambient phase on drop internal flow patterns
Biomicrofluidics 7, 044104 (2013); 10.1063/1.4817006

Sample preconcentration inside sessile droplets using electrowetting
Biomicrofluidics 7, 044102 (2013); 10.1063/1.4815931

Electrowetting on dielectric driven droplet resonance and mixing enhancement in parallel-plate configuration
Biomicrofluidics 6, 012814 (2012); 10.1063/1.3673258

Handling of artificial membranes using electrowetting-actuated droplets on a microfluidic device combined with integrated pA-measurements
Biomicrofluidics 6, 012813 (2012); 10.1063/1.3665719

A novel actuation method of transporting droplets by using electrical charging of droplet in a dielectric fluid
Biomicrofluidics 3, 022402 (2009); 10.1063/1.3122299
Fast and reliable droplet transport on single-plate electrowetting on dielectrics using nonfloating switching method

Jun Kwon Park, Seung Jun Lee, and Kwan Hyoung Kang

Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang 790-784, South Korea

(Received 2 February 2010; accepted 26 March 2010; published online 21 April 2010)

In a droplet transport based on electrowetting on dielectrics, the parallel-plate configuration is more popular than the single-plate one because the droplet transport becomes increasingly difficult without cover plate. In spite of the improved transport performance, the parallel-plate configuration often limits the access to the peripheral components, requesting the removal of the cover plate, the single-plate configuration. We investigated the fundamental features of droplet transport for the single-plate configuration. We compared the performance of several switching methods with respect to maximum speed of successive transport without failure and suggested nonfloating switching method which is inherently free from the charge-residue problem and exerts greater force on a droplet than conventional switching methods. A simple theory is provided to understand the different results for the switching methods. © 2010 American Institute of Physics. [doi:10.1063/1.3398258]

I. INTRODUCTION

Electrowetting, or electrowetting on dielectrics (EWOD), is a phenomenon in which the wettability of a droplet on an insulator-coated electrode surface is electrically changed to produce a motion. (See comprehensive review in Ref. 1 and references therein.) The electrowetting phenomenon is caused by the electrical force concentrated at the three-phase contact line.2–5 The concentrated electrical force (i.e., the electrical wetting tension) induces a change in contact angle which seems, to an external observer, to be a result of a surface-energy change in a substrate. Since the transport of an aqueous droplet based on EWOD was first demonstrated,6,7 successful developments of more complicated microfluidic operations such as creating, transporting, cutting, and merging of liquid droplets8 allowed EWOD to be adopted in many miniaturized biochemical applications.9–18 Today, electrowetting forms the backbone of digital microfluidics19–24 and many applications have been developed, including liquid lenses,25 switches,26 and reflective displays.27,28

There are two kinds of configurations in EWOD, the parallel-plate configuration7,8,29 and the single-plate configuration (Fig. 1).30–37 The parallel-plate configuration has a base plate patterned with an array of discrete electrodes and a cover plate in a parallel configuration. Droplets are sandwiched between the two plates, normally surrounded by a nonpolar liquid such as silicone oil to prevent evaporation and to reduce the contact angle hysteresis.34 A reference voltage is applied to the cover-plate electrode, and successive transport of a droplet is induced by sequentially applying electrical signals to base-plate electrodes just beneath or nearby the droplet. In the single-plate configuration, however, the cover plate is removed, and both actuation and reference voltages are applied to base-plate electrodes. In this case, the droplet is in an electrically floating...
state, and the electrostatic potential of the droplet is between the actuation voltage and reference voltage. In coplanar electrode designs, both buried activation electrodes and exposed ground electrodes to maintain the droplet grounded are located on the base plate of multiple conducting layers.\textsuperscript{35–38} Removal of the cover plate is preferable in many applications to enhance flexibilities in interfacing with liquid-handling instruments, including liquid handlers, contact and noncontact dispensing systems, surface-analytical equipment, etc. The lab-automation equipment designed for high-throughput drug screening consists of liquid handling systems that typically dispense microliter volumes into multiwell plates and can be easily adapted to be used in conjunction with electrowetting systems of single-plate configuration.\textsuperscript{37}

Compared with a droplet in oil, a droplet surrounded by air requires higher driving voltages to produce a motion. This is because of the absence of the lubrication effect of the thin oil film formed beneath the droplet which reduces the contact angle hysteresis. In previous works, the effects of device formats, electrode shapes, and actuation physics on droplet transport are investigated, which facilitates fundamental operations of digital microfluidics. However, the effect of switching method on droplet transport is not yet considered. In this work, we aim at understanding the basic features of the droplet transport in the single-plate configuration and enhancing the stability and transport speed of the single-plate configuration in air. We compare the performance of several switching methods with respect to maximum speed of successive transport without failure and suggest nonfloating switching method. We provide a theoretical explanation for the different behaviors of droplets according to the switching methods.

II. THEORY OF OPERATION

In EWOD, when an electrical potential is applied to a droplet, the insulator region just beneath the droplet stores the capacitive energy (Fig. 2). If stray capacitance is neglected, the stored electrostatic energy is $W = CV^2/2$, where $C$ represents the capacitance, $V$ the applied voltage, and $A$ the base (or contact) area of the droplet.\textsuperscript{39} After electrowetting occurs, the net electrostatic energy of the system $U_{el}$ reduces by $-W$, while the capillary (surface) energy $U_{cap}$ increases as the surface area increases. As a result, the total free energy of system $U = U_{el} + U_{cap}$ is minimized. For fixed $C$ and $V$, therefore, the increase in $A$ leads to the decrease in $U_{el}$ and thus $U$ (Fig. 2). That is why a droplet spreads in EWOD when a voltage is applied. The same is true for a digitized electrode pattern in which electrodes have different electrical potentials. A droplet tends to move...
to a position or configuration in which $A$ can be maximized (without too much increase in surface energy), thereby maximizing the electrostatic energy stored in the capacitor.

To determine the equilibrium configuration of a droplet (Fig. 3), we assume that the contact area with substrate is circular. The electrostatic energy of the system is

$$U_{el} = \varepsilon \left[ A_h (V_{drop} - V_h)^2 + A_g (V_{drop} - V_g)^2 \right],$$

where $\varepsilon$ and $d$ are the electrical permittivity and thickness of insulating layer, $V_{drop}$, $V_h$, and $V_g$ are the voltages of droplet, control electrode, and grounded electrode, and $A_h$ and $A_g$ are the contact area of the droplet with the control electrode and the grounded electrode, respectively (Fig. 3). The voltage inside the droplet is obtained by minimizing the total electrostatic energy with respect to $V_{drop}$ as

$$V_{drop} = \frac{A_h V_h + A_g V_g}{A_h + A_g}.$$  

Then, Eq. (1) becomes

$$U_{el} = \frac{\varepsilon (V_h - V_g)^2 A_h (A - A_h)}{2d A}.$$  

At equilibrium, $\partial U_{el}/\partial A_h = 0$, which leads to

$$A_h = A_g.$$  

This means that at equilibrium the contact areas of the droplet with the high voltage and ground electrodes are the same. Equations (2) and (4) give $V_{drop} = (V_h + V_g)/2$. It follows then that the wetting tension is the same around the periphery of the droplet. Accordingly, the contact angle of the droplet is the same, which in turn means that the contact area should be circular shaped as postulated before.

### III. SWITCHING METHODS

This work experimentally compared the transport performance of the five different switching methods depicted in Fig. 4. Methods A and B in Figs. 4(a) and 4(b) show the typical switching methods in previous works. In methods A and B, voltage difference is applied between the two adjacent electrodes around a droplet, in which other electrodes are in a floating state. Then, a droplet center moves to the center (interface) region of the two electrodes because this position minimizes the net free energy of the system by maximizing the contact area with the electrode region. For continuous movement, the next electrode pair is activated sequentially.

When the activated electrode pair is turned to floating state, in methods A and B, the electrical charges remain on the surface of the base plate of previously activated electrode [Fig. 5(a)]. This charge residue may exert a kind of resisting force to the movement of the droplet. When ac voltage is applied, charges are stored and released periodically according to alternating voltage. If a switching signal is applied to the next pair of electrode when charge is absent on the present pair...
of electrode, the droplet can be transported to the position of next electrode pair. In contrast, if the next electrode pair is switched on, with the present electrodes being fully charged, the droplet may not move. As a consequence, in our experiment, the droplet transport for methods A and B was possible irregularly. Therefore, complete transport for the full path was not possible. To solve this remained charge problem, in methods C and D, an intermediate step is introduced to methods A and B, respectively. That is, after a droplet moves to the activated electrode pair, the activated electrodes are briefly grounded. This step is to remove residual electrical charge on the polymer surface coated on electrodes.

Finally, we suggest a nonfloating switching method (method E), as depicted in Fig. 4(e). In the nonfloating switching method, the charges are automatically removed by grounding all the electrodes except the one activated electrode [Fig. 5(b)]. In addition, the nonfloating switching method has advantages in switch controller. In methods A–D, two switches should be connected to each
electrode in order to change the electrical status to high, ground, or floating states [Fig. 6(a)]. However, method E requires only one switch to toggle high and ground voltages. This can be achieved either by using one switch and one resistor in parallel connection [Fig. 6(b)] or by using a single three-way switch [Fig. 6(c)]. Accordingly, the number of switches and switch controllers are half of those of methods A–D. Moreover, method E does not require the intermediate step for charge removal, which makes control more convenient and efficient.

IV. FABRICATION AND EXPERIMENT

Continuous transport of a droplet is possible only when the droplet is in contact with the surface of the next electrode. Therefore, we designed electrodes to have branches overlapping with adjacent electrodes (Fig. 7). Two types of electrode array were fabricated. Pyrex 7740 glass wafer was coated with 200 Å thick layer of chromium as an adhesion layer and 2000 Å thick layer of gold as an electrode by electron beam deposition. AZ5214 photoresist was patterned on the gold by photolithography. The gold and chromium were patterned by wet etching in sequence. After removing the remaining photoresist, parylene-C was deposited in 5 μm thickness by vapor deposition using a parylene coating system (Parylene Korea Co., Ltd., PDS 2010). On the top of that, Teflon® AF1600 (DuPont) was spin coated in 100 nm thickness to make the surface hydrophobic.

A droplet of 10⁻³ M NaCl and 8 μl in volume was placed on the 4×4 electrode array, and electrical voltages of 150 and 200 Vrms were applied. A resonant signal of 100 Hz was applied to minimize the effect of contact angle hysteresis utilizing the oscillation of droplet [Fig. 8]. Application of ac signal enabled more stable operation; successive transport was seldom achieved using dc signal. The contact angle hysteresis at the electrode surface is an obstacle for the successive transport. The shape oscillation of the droplet caused by ac voltage reduces the effect of the contact angle hysteresis, which may lead to the enhanced transport performance compared with that of dc voltage. In methods A and C, a droplet was transported following the route shown in Figs. 9(a) through 11 switching times. In methods B, D, and E, a droplet was transported

FIG. 6. Electrode connections: (a) with two switches; (b) with one switch and one resistor; (c) with single three-way switch.

FIG. 7. Patterns of electrode arrays: (a) pattern 1; (b) pattern 2. 4×4 electrode arrays are made; the dimension of an electrode is 1.5×1.5 mm² and the gap between two electrodes is 60 μm in width.
following the 15-step path in Fig. 9(b). A test was considered a failure when a droplet stopped during one transport stage. We compared the maximum speed under which a stable transport was possible.

V. COMPARISON OF PERFORMANCE

As a preliminary test, we measured the maximum transport speed during the first three steps of the transport path in Fig. 9. The maximum transport speed at 200 V\text{rms} was about 30, 10, and 50 mm/s for methods A, B, and E, respectively. In relatively short path, methods A and B as well as method E could achieve successful transport, which is consistent with the results of previous works.\textsuperscript{30,31}

The performance of each switching method was tested and compared for the full path depicted in Fig. 9. At 150 V\text{rms}, only the nonfloating switching method (method E) achieved a stable transport without failure with a maximum speed of 25 mm/s. At 200 V\text{rms}, a stable transport was possible for methods C–E. The maximum transport speed at 200 V\text{rms} was 15, 4, and 44 mm/s for methods C–E, respectively (Fig. 10). The linked online video clip illustrates droplet transport using the nonfloating method at the speed of 44 mm/s.\textsuperscript{44} In contrast to the results of preliminary test, methods A and B could not achieve a complete transport for the full path due to the aforementioned charge-residue problem. Method E had the best transport speed, stability, and simplicity of system for both electrode patterns. In all experimental conditions, electrode pattern 2 showed better performance than pattern 1. However, relative performance between the switching methods was independent of electrode patterns. We compared our result with the parallel-plate configuration in Pollack\textit{ et al.}\textsuperscript{7} with respect to electrowetting number \( \eta = \varepsilon_0 \varepsilon_r U^2 / (2d \sigma_\theta) \) (see, for the meaning of electrowetting number, Ref. 1). Pollack\textit{ et al.} attained transport speed of 30 mm/s with a driving voltage of 80 V and the threshold voltage of about 40 V. They used 0.7 \( \mu \text{m} \) thick parylene-C as a dielectric layer followed by 0.2 \( \mu \text{m} \) thick AF1600 coating, while we used 5 \( \mu \text{m} \) thick parylene-C as a dielectric layer followed by 0.1 \( \mu \text{m} \) thick AF1600 coating. The driving voltages of 80 and 40 V in the setup of Pollack\textit{ et al.} correspond to electrowetting number of 1.34 and 0.34, respectively, while 200 and 150 V in our setup correspond to electrowetting number of 1.48 and 0.83, respectively. The electrowetting number in our experiment was comparable with that of Pollack\textit{ et al.}, and the transport speed was also comparable. We expect that the driving voltage of single-plate EWOD using nonfloating switching method would become lower if we use thinner dielectric layer.

\[ \]
In order to determine why method E was more stable and faster than methods C and D, which are also free from the charge-residue problem, we performed a theoretical analysis with regard to the force acting on a droplet and the equilibrium position. The net forces acting on a droplet in $x$ and $y$ directions [see Fig. 11(a) for the coordinate] at initial position $(F_x, F_y)$ are obtained by differentiating the energy of the system with respect to $x$ and $y$, as shown in Eq. (5),

$$ F_x = \frac{\partial U_{el}}{\partial x}; \quad F_y = \frac{\partial U_{el}}{\partial y}. $$

Assuming that relative performance between switching methods is, in principle, independent of electrode shape, the calculation considered square-shaped electrode for simplicity. In Fig. 11, the equilibrium positions obtained theoretically and experimentally are shown for each switching method. In all three cases shown in Fig. 11, $A_x = A_y$ is satisfied in the equilibrium position, as predicted theoretically in Sec. II. As the transport distance of a droplet in a single step is extended, we can achieve more stable transport because the droplet attains the larger contact area with the next electrode. Forces in $x$ direction computed for each switching method are $56$ $\mu$N for methods A and C, $61$ $\mu$N for methods B and D, and $87$ $\mu$N for method E. The force and the equilibrium position are identical for methods A and C and for methods B and D. Methods A and C allow longer transports in a single step with the weaker force than method E, which result in rather worse transport performance than method E. Method E showed better performance with respect to both force and transport distance in a single step than methods B and D. Based on these results, it is conjectured that the force is crucial for the fast transport of a droplet.

In Fig. 10, the maximum speed of transport for five switching methods: (a) at 150 $V_{rms}$; (b) at 200 $V_{rms}$.

In Fig. 11, the equilibrium position obtained theoretically (up) and experimentally (down): (a) for methods A and C; (b) for methods B and D; (c) for method E.
VI. CONCLUSIONS

We compared several switching methods for the single-plate configuration of EWOD. The charge-residue problem most critically prevented a stable transport for the single-plate configuration in air. We proposed nonfloating switching method in which only one electrode is activated with adjacent electrodes by shape oscillations. This seems to be due to reduction in hysteresis and enlarged contact area than any other switching methods, resulting in the fastest transport among the switching methods considered in this work. In addition, the number of switches and controllers was reduced to half of the conventional method. No successful operation was attained with dc voltages, so the use of an ac signal was essential. This seems to be due to reduction in hysteresis and enlarged contact area with adjacent electrodes by shape oscillations.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (Grant No. R0A-2007-000-20098-0).

44. See supplementary material at http://dx.doi.org/10.1063/1.3398258 for movie of droplet transport using nonfloating method at 44 mm/s.