Fast and reliable droplet transport on single-plate electrowetting on dielectrics using nonfloating switching method

Jun Kwon Park, Seung Jun Lee, and Kwan Hyoun Kang^{a)}

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

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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 microfluidics^{19–24} 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 configuration^{7,8,29} and the single-plate configuration (Fig. 1).^{30–33} 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

^{a)} Author to whom correspondence should be addressed. Tel.: +82-54-279-2187. FAX: +82-54-279-5899. Electronic mail: khkang@postech.ac.kr.

FIG. 1. Two conventional configurations of EWOD: (a) parallel-plate configuration; (b) single-plate configuration.

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.^{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.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 $W = CV^2A/2$, where C represents the capacitance, V the applied voltage, and A the base (or contact) area of the droplet.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

FIG. 2. Change in contact angle and minimization of free energy of system: (a) before applying a voltage; (b) just after voltage is applied; (c) in equilibrium state.

FIG. 3. A droplet in contact with high voltage and grounded electrodes.

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.⁴⁰ The electrostatic energy of the system is

$$U_{el} = \frac{\epsilon}{2d} [A_h (V_{drop} - V_h)^2 + A_g (V_{drop} - V_g)^2], \quad (1)$$

where ϵ 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

$$V_{drop} = \frac{A_h V_h + A_g V_g}{A_h + A_g}. \quad (2)$$

Then, Eq. (1) becomes

$$U_{el} = \frac{\epsilon (V_h - V_g)^2 A_h (A - A_h)}{2dA}. \quad (3)$$

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

$$A_h = A_g. \quad (4)$$

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.^{2,3} 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)].⁵ 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

FIG. 4. Switching methods. (a) Method A simultaneously applies high and low voltages to a pair of electrodes located in transverse direction to the direction of movement. (b) In method B, the electrode pair is parallel to the direction of movement. In methods (c) C and (d) 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. (e) Method E is nonfloating switching method which applies a high voltage to a single electrode while grounding the rest of electrodes. Time sequence is from left to right.

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

FIG. 5. Charge distribution in electrodes. Left is for initial step and right is for next step. (a) Conventional switching method; (b) nonfloating switching method.

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

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 V_{rms} 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).^{41,42} 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,^{34,43} 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. 7. Patterns of electrode arrays: (a) pattern 1; (b) pattern 2. 4×4 electrode arrays are made; the dimension of an electrode is $1.5 \times 1.5 \text{ mm}^2$ and the gap between two electrodes is 60 μm in width.

FIG. 8. Droplet oscillation on an electrode array.

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_{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.^{30,31}

The performance of each switching method was tested and compared for the full path depicted in Fig. 9. At 150 V_{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_{rms}, a stable transport was possible for methods C–E. The maximum transport speed at 200 V_{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.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 *et al.*⁷ with respect to electrowetting number $\eta = \epsilon_0 \epsilon_r U^2 / (2d\sigma_{lv})$ (see, for the meaning of electrowetting number, Ref. 1). Pollack *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 μm thick parylene-C as a dielectric layer followed by 0.2 μm thick AF1600 coating, while we used 5 μm thick parylene-C as a dielectric layer followed by 0.1 μm thick AF1600 coating. The driving voltages of 80 and 40 V in the setup of Pollack *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 *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.

FIG. 9. Transport path: (a) for methods A and C; (b) for methods B, D, and E.

FIG. 10. Maximum speed of transport for five switching methods: (a) at 150 V_{rms} ; (b) at 200 V_{rms} .

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 ,^{3,40} as shown in Eq. (5),

$$F_x = \frac{\partial U_{el}}{\partial x}; \quad F_y = \frac{\partial U_{el}}{\partial y}. \quad (5)$$

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, $A_h = A_g$ 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 μN for methods A and C, 61 μN for methods B and D, and 87 μN 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.

FIG. 11. 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 and the rest are grounded. This simple modification dramatically stabilized the transport operation. The charge-residue problem was simply resolved, and greater force was exerted on the droplet 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.

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- ¹F. Mugele and J.-C. Baret, *J. Phys.: Condens. Matter* **17**, R705 (2005).
- ²K. H. Kang, *Langmuir* **18**, 10318 (2002).
- ³K. H. Kang, I. S. Kang, and C. M. Lee, *Langmuir* **19**, 5407 (2003).
- ⁴T. B. Jones, *J. Micromech. Microeng.* **15**, 1184 (2005).
- ⁵J. Lee, H. Moon, J. Fowler, T. Schoellhammer, and C.-J. Kim, *Sens. Actuators, A* **95**, 259 (2002).
- ⁶M. Washizu, *IEEE Trans. Ind. Appl.* **34**, 732 (1998).
- ⁷M. G. Pollack, R. B. Fair, and A. D. Shenderov, *Appl. Phys. Lett.* **77**, 1725 (2000).
- ⁸S. K. Cho, H. Moon, and C.-J. Kim, *J. Microelectromech. Syst.* **12**, 70 (2003).
- ⁹V. Srinivasan, V. K. Pamula, and R. B. Fair, *Lab Chip* **4**, 310 (2004).
- ¹⁰T. Taniguchi, T. Torii, and T. Higuchi, *Lab Chip* **2**, 19 (2002).
- ¹¹A. R. Wheeler, H. Moon, C. A. Bird, R. R. O. Loo, C.-J. Kim, J. A. Loo, and R. L. Garrell, *Anal. Chem.* **77**, 534 (2005).
- ¹²I. Barbulovic-Nad, H. Yang, P. S. Park, and A. R. Wheeler, *Lab Chip* **8**, 519 (2008).
- ¹³E. M. Miller and A. R. Wheeler, *Anal. Chem.* **80**, 1614 (2008).
- ¹⁴Y.-H. Chang, G.-B. Lee, F.-C. Huang, Y.-Y. Chen, and J.-L. Lin, *Biomed. Microdevices* **8**, 215 (2006).
- ¹⁵Y.-J. Liu, D.-J. Yao, H.-C. Lin, W.-Y. Chang, and H.-Y. Chang, *J. Micromech. Microeng.* **18**, 045017 (2008).
- ¹⁶H. Moon, A. R. Wheeler, R. L. Garrell, J. A. Loo, and C.-J. Kim, *Lab Chip* **6**, 1213 (2006).
- ¹⁷A. R. Wheeler, H. Moon, C.-J. Kim, J. A. Loo, and R. L. Garrell, *Anal. Chem.* **76**, 4833 (2004).
- ¹⁸V. N. Luk, G. C. Mo, and A. R. Wheeler, *Langmuir* **24**, 6382 (2008).
- ¹⁹J. Berthier, *Microdrops and Digital Microfluidics* (William Andrew, Norwich, NY, 2008).
- ²⁰K. Chakrabarty and F. Su, *Digital Microfluidic Biochips: Synthesis, Testing, and Reconfiguration Techniques* (Taylor & Francis, London, 2007).
- ²¹R. B. Fair, *Microfluid. Nanofluid.* **3**, 245 (2007).
- ²²H. Moon, S. K. Cho, R. L. Garrell, and C.-J. Kim, *J. Appl. Phys.* **92**, 4080 (2002).
- ²³M. Abdelgawad and A. R. Wheeler, *Adv. Mater. (Weinheim, Ger.)* **21**, 920 (2009).
- ²⁴F. Mugele, *Soft Matter* **5**, 3377 (2009).
- ²⁵S. Kuiper and B. H. W. Hendriks, *Appl. Phys. Lett.* **85**, 1128 (2004).
- ²⁶P. Sen and C.-J. Kim, *IEEE 20th International Conference on MEMS*, 2007, pp. 767.
- ²⁷R. A. Hayes and B. J. Feenstra, *Nature (London)* **425**, 383 (2003).
- ²⁸T. Roques-Carnes, R. A. Hayes, B. J. Feenstra, and L. J. M. Schlangen, *J. Appl. Phys.* **95**, 4389 (2004).
- ²⁹J. Gong and C.-J. Kim, *Lab Chip* **8**, 898 (2008).
- ³⁰U.-C. Yi and C.-J. Kim, *J. Micromech. Microeng.* **16**, 2053 (2006).
- ³¹I. Moon and J. Kim, *Sens. Actuators, A* **130**, 537 (2006).
- ³²M. Abdelgawad, S. L. S. Freire, H. Yang, and A. R. Wheeler, *Lab Chip* **8**, 672 (2008).
- ³³M. Abdelgawad, P. Park, and A. R. Wheeler, *J. Appl. Phys.* **105**, 094506 (2009).
- ³⁴F. Li and F. Mugele, *Appl. Phys. Lett.* **92**, 244108 (2008).
- ³⁵R. B. Fair, A. Khlystov, V. Srinivasan, V. K. Pamula, and K. N. Weaver, *Proc. SPIE* **5591**, 113 (2004).
- ³⁶Y. Fouillet and J.-L. Achard, *C. R. Phys.* **5**, 577 (2004).
- ³⁷C. G. Cooney, C.-Y. Chen, M. R. Emerling, A. Nadim, and J. D. Sterling, *Microfluid. Nanofluid.* **2**, 435 (2006).
- ³⁸P. Y. Paik, V. K. Pamula, and K. Chakrabarty, *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.* **16**, 432 (2008).
- ³⁹J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1998).
- ⁴⁰E. Baird, P. Young, and K. Mohseni, *Microfluid. Nanofluid.* **3**, 635 (2007).
- ⁴¹S. H. Ko, H. Lee, and K. H. Kang, *Langmuir* **24**, 1094 (2008).
- ⁴²J. M. Oh, S. H. Ko, and K. H. Kang, *Langmuir* **24**, 8379 (2008).
- ⁴³S. H. Ko, S. J. Lee, and K. H. Kang, *Appl. Phys. Lett.* **94**, 194102 (2009).
- ⁴⁴See supplementary material at <http://dx.doi.org/10.1063/1.3398258> for movie of droplet transport using nonfloating method at 44 mm/s.