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Size-variable droplet actuation by interdigitated electrowetting electrode

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We propose electrowetting on dielectric (EWOD) electrodes to actuate size-variable droplets. By using interdigitated fingers and maximizing them in optimized construction, we can control droplets in different sizes with the same electrode array automatically. We both do the theory calculation and experiment verification to study the electrode with rectangular fingers. It is found that the electrode with triangle fingers can actuate droplets as small as 1/36 of that actuated by conventional square electrode array. It can actuate large droplets more efficiently than rectangular fingers. This work provides an approach to achieve multifunctional EWOD devices in the future.
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Digital microfluidics (DMF) has recently emerged as a popular technology both for academic research and for industrial applications. Based on the principle of controlling discrete liquid, the DMF has many obvious advantages, such as no moving part or channel, extreme energy efficiency, easy control, high integration, and high speed, etc.[1] As the advanced and most promising DMF device, electrowetting on dielectric (EWOD) microfluidic device is the smart micro-device to control discrete droplets through electrowetting where the wetting property of a hydrophobic surface is modified by an external electric field. The EWOD device generally works based on the basic droplet functions such as droplet creating, transporting, splitting, and merging to realize the liquid manipulation.[2] Due to its advantages in terms of speed, simplicity, compatibility, reconfigurability, flexibility and portability, the EWOD microfluidic device has been implemented in a wide range of lab-on-a-chip applications.[3–5]

Generally, a typical EWOD device contains four components: liquid droplets as the manipulated object, conductive materials as the electrodes, insulated materials as the dielectric layer, and a hydrophobic layer providing low-energy surface.[6] Among those, the electrode is the critical part for it deciding the motion of the droplets. There have been many reported shape designs of EWOD electrode, such as square,[7] rectangular,[8] and crescent,[9] etc. However, no matter what kind of the electrode shape is, the EWOD device is usually a fixed-volume design, which means that when the electrodes are defined, the volume of the droplet they can drive is invariable and should be carefully controlled, leading to the reduced reliability and limited applications. Since the droplets generation cannot be very accurately created by an EWOD,[10] and there are many potential applications for manipulation of droplets in different sizes,[11–13] the EWOD device with electrodes for size-variable actuation is imperative. There are few reports about EWOD microfluidic device for size-variable droplet actuation so far, though Wang[14] has reported an EWOD device to control size-variable droplet through micro-electrode array. However, to achieve droplet manipulating in his design, huge number of electrodes are needed, the size of the droplet must be known, and the control is complicated and nonautomatic.

Here, we report EWOD electrodes that can be used to manipulate droplets of different size easily and automatically. We design the EWOD electrodes with special shapes by using interdigitated fingers. The design of electrode with fingers was introduced by Pollack *et al.*[15] and developed later to achieve smooth movement of droplet in a fixed size.[16,17] We improve the fingers' electrode to actuate size-variable droplet by maximizing the fingers. As shown in Fig. 1, each electrode consists of a vertical major electrode and minor horizontal finger electrode. Minor fingers on each major electrode interdigitate with neighboring fingers.

The working principle of our design is based on the three-phase contact line (TCL) theory.[18] The fingers are rectangular. When the diameter of the droplet is larger than the length of the major and the minor electrodes (ignoring the small space between two driving electrodes), the EWOD force acted on the small droplets can be controlled. Under the driving of the electro-capillary forces, when the neighboring electrode is actuated, the contact line of the droplet with initial electrode extends over onto the fingers of the actuated electrode. Thus, droplets of different sizes can be actuated when they touch the fingers of the neighboring electrode.

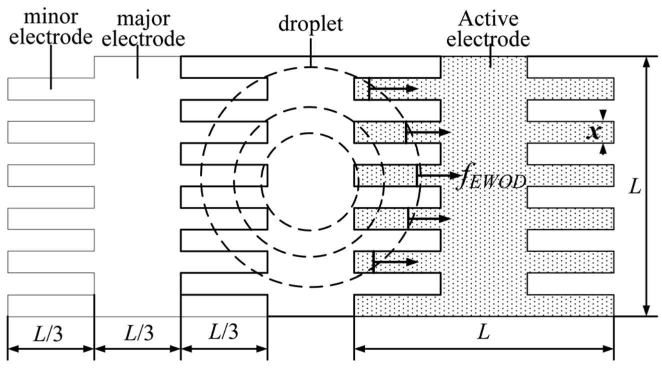

FIG. 1. EWOD electrode with rectangular fingers for size-variable droplet actuation.

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To minimize the minimum size of droplet that can be manipulate efficiently, the size of each drive electrode is set to L × L, while the length of the major electrode and minor fingers are both L/3. In this case, the diameter of the minimum droplet that can be driven is L/3. Therefore, such electrode can drive different droplets with diameters from L/3 to L (or even lager), and the minimum size of the driven droplet is one-ninth of that actuated by conventional square electrode in length of L.

To characterize our electrode design, the actuated velocity is studied. As we know, the EWOD phenomenon can be described by the Lippmann–Young equation[19]

$$\cos\theta - \cos\theta_0 = \frac{C}{2\gamma}V^2, \tag{1}$$

where θ and θ_0 are the contact angles after and before the voltage V is applied, respectively. C is the capacitance of the dielectric in the device. γ is the surface tension.

The EWOD drive force can be explained by the TCL theory[18]

$$F_{EWOD} = \int_{TCL} \gamma(\cos\theta - \cos\theta_0)dl = \frac{l}{2}CV^2, \tag{2}$$

where l is the efficient TCL on the actuated electrodes. In our electrode design, l is the sum of vertical projection of the TCL on the actuated electrode (Fig. 1).

By using the parallel plate EWOD device model and simple velocity model reported by Berthier,[20] we can obtain the actuated velocity

$$v = \frac{hl}{6\pi\mu d^2}CV^2, \tag{3}$$

where h and d are the height and the diameter of the droplet, respectively.

The velocity is proportional to the efficient TCL, which is determined by the size of electrode and droplets. In our electrode design, the lengths of the major and minor finger electrode are fixed. Therefore, the width of the finger (x in Fig. 1) and the diameter of the droplet d are critical. We demonstrate a design example to discuss the rules.

We set $L = 1.8$ mm and take $hCV^2/6\pi\mu$ as a constant to find out the effects of d and x on the velocity.

The results are shown in Fig. 2. When the width of the fingers x is smaller than 0.2 mm, the velocity reaches maximum when the diameter of droplets is about 0.9 mm, which is half of the electrode size. The velocity decreases as the diameter increases. Moreover, the velocity does not show great change along with the change of the finger width. This is consistent with the theory that when the width of fingers is small enough, the efficient TCL is half of the chord length of the TCL. For the width of fingers larger than 0.2 mm, the velocity will decrease to a minimum value and increase again, and then show vibration as the diameter increases. In general, there is no optimal value of fingers width that all size of droplets can achieve the maximum velocity as we expected. However, besides high speed, the consistency of velocity is also important because we intend to drive size-

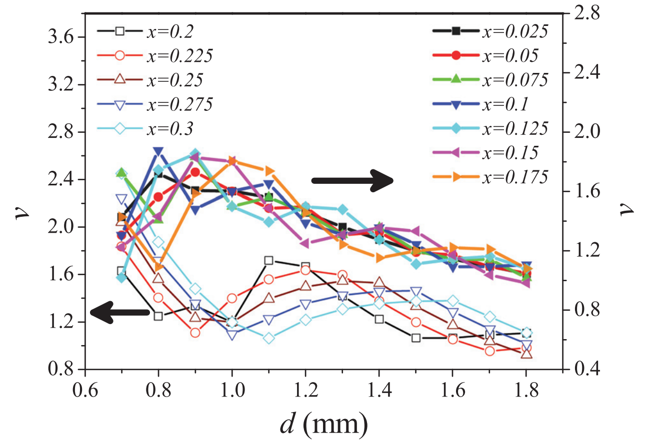

FIG. 2. Theoretical calculation of droplets velocity affected by finger width and droplet diameter.

variable droplet under consistent conditions so as to simplify the device and enhance its reliability. Through calculation, we find out that when the finger width is about 0.2 mm, electrode can actuate droplets of different sizes in acceptable velocity with smaller variation than others.

We fabricated a parallel plate EWOD device with drive electrode of 1.8 mm × 1.8 mm (Fig. 3). First, the electrodes were patterned on the bottom glass plate by wet etching of deposited aluminum. Then, a dielectric layer of 1.5 μm thick SU-8 (SU-8 2002, MicroChem) was spin-coated and cured. Finally, 80 nm thick Teflon (AF 2400, DuPont) was spin-coated as the hydrophobic layer. The top glass plate contained an unpatterned indium tin oxide (ITO) layer as the transparent common electrode and a layer of 80 nm thick Teflon (AF 2400, DuPont) as the hydrophobic layer. A double-stick tape (about 60 μm thick) was used to define the gap between the top and bottom plates.

The actuation signal was an AC signal of 80V_{RMS} with a frequency of 1 KHz. When the voltage was applied on the electrodes through the control of LABVIEW software and other components, the droplets can be transported from one electrode to another automatically. Fig. 4 shows the sequential images of the actuating droplets in different sizes by the same EWOD device under the consistent driving signal,

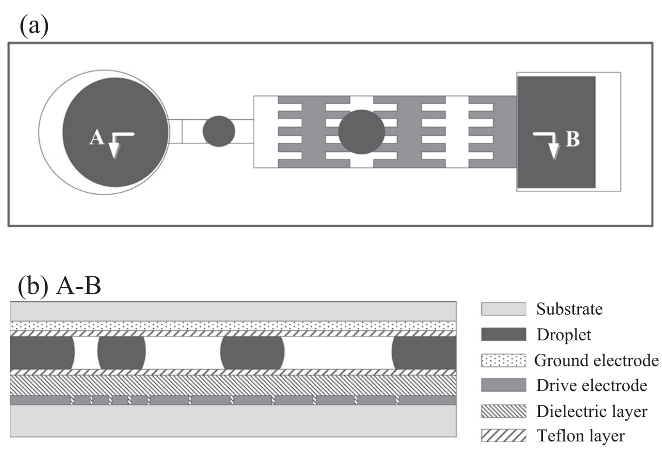

FIG. 3. Schematics of parallel plate EWOD device configuration with the EWOD electrode proposed.

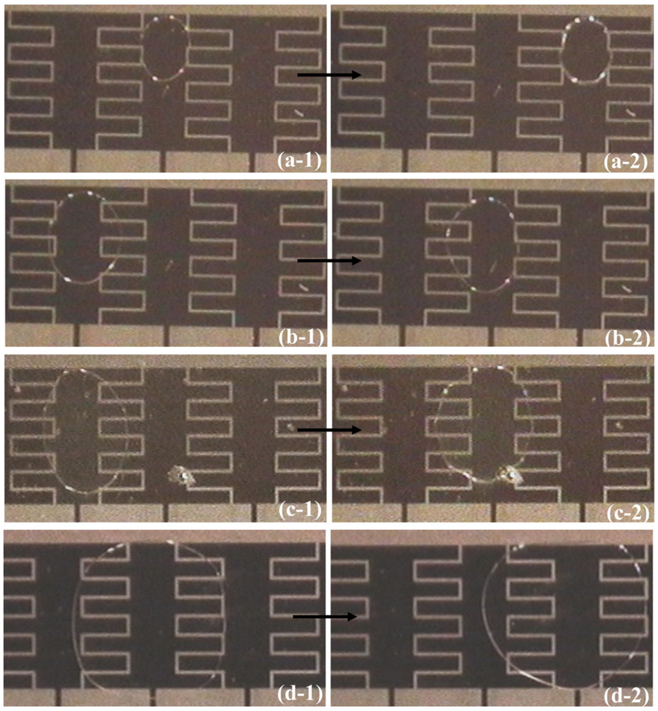

FIG. 4. Different volumes of droplets transported from left to right under same driving signal in a parallel-plate EWOD device with rectangular interdigitated fingers: (a) 27 nl, (b) 57 nl, (c) 90 nl, and (d) 190 nl.

which verifies our design for actuation of droplets from 27 nl to 190 nl. It should be pointed out that the droplets were not regular in shape and their routes were not straight during transporting, most probably because the fingers had unpredictable effects on them.

The voltage-dependent maximum velocity at which droplets could be transferred between adjacent electrodes was recorded experimentally by changing the signal switching frequency between adjacent electrodes. Fig. 5 indicates that the velocity is approximately proportional to the square of the voltage. When the droplet is 1.25 mm in diameter, the electrode with 0.2 mm wide fingers can actuate droplet faster than other electrodes do. In addition, for electrodes with finger width of 0.2 mm, the droplet of 1.25 mm in diameter can achieve highest speed actuation among them. Such

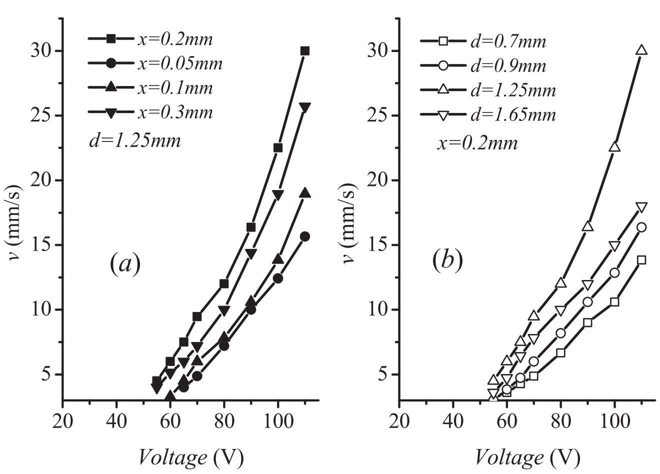

FIG. 5. Driving velocity affected by (a) rectangular fingers width and (b) diameter of droplets under different drive voltages.

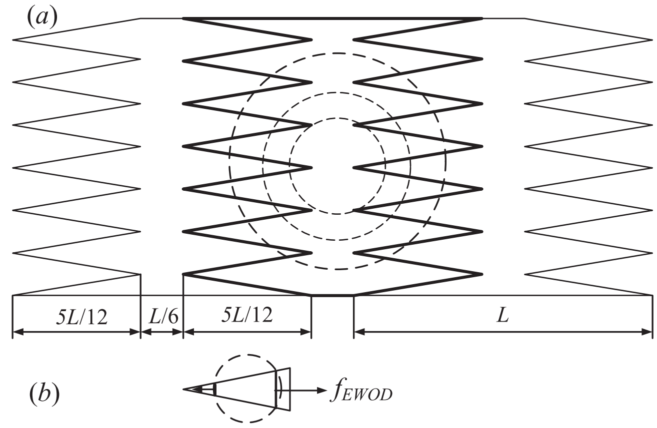

FIG. 6. (a) EWOD electrode with triangle fingers for size-variable droplet actuation, (b) the mechanics demonstration of small droplet actuated by large triangle fingers.

experimental results are both in good agreement with the theory calculation.

As discussed above, the minimum droplet that can be actuated by the electrode with rectangular fingers is limited (see Fig. 1). To actuate smaller droplet, we design electrodes with triangle fingers (see Fig. 6(a)). Because the fingers are in triangle, even the droplets are smaller than the fingers in length, the EWOD force will never be balanced (Fig. 6(b)). Thus, the minimum droplet size is decided by the major electrode and this kind of electrode can control size-variable in a lager range than the rectangular fingers did. In the design shown in Fig. 6, the diameter of the driven droplet can vary from L/6 to L. The minimum size of the driven droplet reaches 1/36 (or even smaller with a narrower major electrode) of that driven by the conventional $L \times L$ electrode.

Fig. 7 are the pictures captured from a piece of video, which shows three droplets with volume of 15 nl, 90 nl, 180 nl

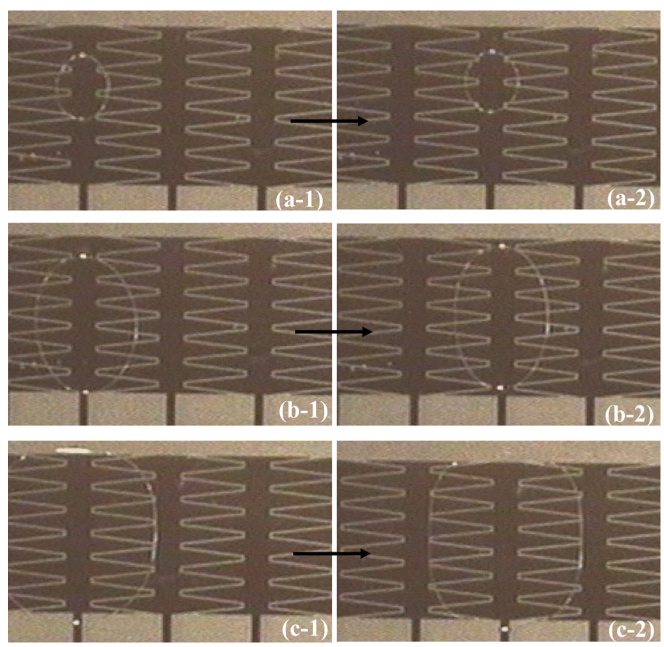

FIG. 7. Different volumes of droplets transported from left to right under same driving signal in a parallel-plate electrowetting device with triangle interdigitated fingers: (a) 15 nl, (b) 90 nl, and (c) 180 nl.[21]

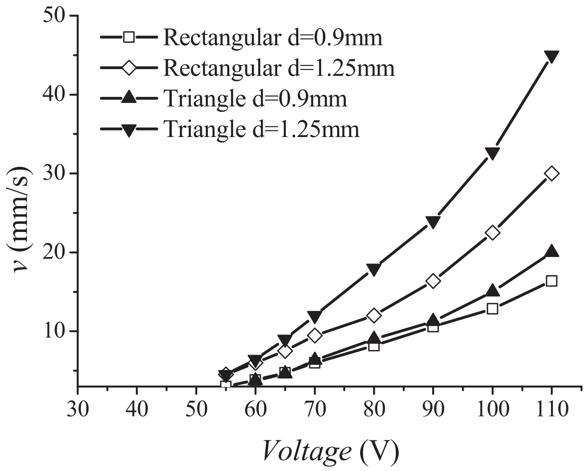

FIG. 8. Voltage-dependent velocity indicating faster transporting of electrode with triangle fingers than that with rectangular fingers for droplets in relatively large size.

are transported by the electrodes with triangle fingers under the same driving signal smoothly, continuously, and automatically.

Fig. 8 shows the velocity comparison of two droplets of 0.9 mm and 1.25 mm in diameter driven on electrodes with rectangular and triangle fingers. It is obvious that the electrode with triangle fingers can transport droplets faster than that with rectangular fingers. It can be explained as follows. When the droplet is small, the velocity difference between the two designs is not clear, because the TCL or the EWOD force is relatively small for both triangle and rectangular fingers. However, when the droplets get large enough, the efficient TCL on the triangle is more than half of the chord length of the actual TCL, which induced a more efficient actuation.

In summary, we design two types of EWOD interdigitated electrode for size-variable actuation. The electrodes with rectangular fingers and triangle fingers can be easily implemented to drive different sizes of droplets, the minimum size of which is much smaller than that driven by conventional electrode. The variable size of driven droplet ranges from 15 nl to 180 nl. The size-variable droplets can be driven automatically without knowing their exact size. Therefore, the droplet volume in EWOD device does not need to be carefully controlled and different droplets can be manipulated in one device using the same electrode structure for more smart applications.

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[21]See supplementary material at http://dx.doi.org/10.1063/1.4769433 for transportation of droplets with different sizes.