DIRECT HANDWRITING MANIPULATION OF DROPLETS BY SELF-ALIGNED MIRROR-EWOD ACROSS A DIELECTRIC SHEET
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ABSTRACT
In this paper, we demonstrate a novel approach to generate electrowetting on a dielectric sheet over a liquid electrode. A 12.5 μm-thick PVDC film (Saran wrap) was used as the dielectric sheet. Two important phenomena were found: (1) EWOD not only occurs on the manipulated droplet, but also the liquid electrode (mirror-EWOD), (2) the mirror-EWOD causes the manipulated droplet and the liquid electrode self-aligned when they are in comparable sizes. Based on these discoveries, a direct handwriting droplet manipulation platform was designed and fabricated, in which droplets can be transported by a droplet-tipped stylus across a dielectric sheet. PVDC film was also applied in conventional EWOD devices as a disposable dielectric layer.

1. INTRODUCTION
EWOD (electrowetting-on-dielectric) has been widely used in Lab-on-a-Chip, optics, and display applications for its low power consumption and ease of fabrication [1-3]. In the Lab-on-a-Chip or μ-TAS (total analysis system) applications, EWOD can be used to pump liquid droplets on dielectric coated driving electrodes. The moving path of a droplet is determined by the arrangement of driving electrodes and the sequence of electrical signals applied on the electrodes. Therefore, it is difficult to drive a droplet along an arbitrary trajectory. Researchers have demonstrated the use of light to move droplets arbitrarily by an opto-electrowetting (OEW) mechanism [4]. Nevertheless, requiring photoconductor and optical beam (laser) with proper wave length and power, the fabrication of the OEW device and the setup of the optical system are complicated in comparison to conventional EWOD devices. In this research, we study the electrowetting phenomenon across a dielectric sheet and demonstrate the direct and arbitrary manipulation of a droplet through handwriting by mirror-EWOD without pre-designed driving electrodes and control circuits.

2. PRINCIPLE
EWOD on Solid Electrodes
EWOD is an electrical means to change the surface wettability on a dielectric coated electrode. As shown in Fig. 1, a sessile drop is placed on a solid electrode coated with a hydrophobic dielectric layer. When a voltage is applied between the probe immersed in the droplet and the electrode below, the potential across the dielectric layer causes contact angle change. With proper electrode and circuit design, droplet-based digital microfluidic Lab-on-a-Chip can be achieved by EWOD actuations [5].

EWOD on Liquid Electrodes
Although EWOD has been widely applied, the EWOD phenomenon was mainly studied on dielectric-covered solid electrodes. We made our first attempt to investigate EWOD on a liquid electrode with the setup shown in Fig. 2(a). As can be seen, to conduct this experiment, a robust thin dielectric film/sheet is desirable. Several materials were tested, and a kind of Saran wrap was perfectly applicable in this test in terms of its mechanical and electrical properties.

Fig. 2(b) and (c) show the experimental result of EWOD on a liquid electrode when a 12.5 μm-thick polyvinylidene chloride (PVDC) sheet (barely noticeable on figure) was used as a dielectric layer. Teflon was spun on the both sides of the PVDC sheet. A 1.5 μL water droplet was placed on top of the PVDC sheet, while a 10 μL 1 M NaCl(aq) or water droplet was hung underneath it as a liquid electrode. Two probes were immersed into the droplets, and a voltage was applied through the probes. Similar to EWOD on a solid electrode, as shown Fig. 2(b) and (c), EWOD occurs when
replacing the solid electrode with a liquid electrode. Depending on the frequency of the applied voltage, the conductivity of the liquid droplet would cause different voltages across the dielectric sheet, resulting different contact angle change.

**Mirror-EWOD across a Dielectric Sheet**

As shown in Fig. 2(b) and (c), when the upper droplet is smaller than the liquid electrode (lower droplet) and placed in the center of the liquid electrode, EWOD occurs merely on the upper droplet. The lower larger droplet can be simply regarded as an electrode. However, when the size of the liquid electrode is shrunk to a comparable volume of the upper droplet, electrowetting was found not only on the upper droplet, but on both sides of the PVDC sheet as can be seen in Fig. 3. The electrowetting is quite different from EWOD on a solid electrode because now electrowetting also happens on the electrode. We name this phenomenon “mirror-EWOD” since EWOD occurs simultaneously across the dielectric film.

![Diagram of dielectric sheet with droplets](image)

(a) When the liquid electrode is in a comparable size of the upper droplet, electrowetting occurs on both sides of dielectric film (mirror-EWOD).

![Images of droplets](image)

(b) No voltage was applied. (c) 1 kHz, 140 Vrms applied. 

Figure 3: Two 2 μL water droplets were actuated by mirror-EWOD across a Teflon-coated 12.5 μm-thick PVDC sheet: (b) no voltage was applied, and (c) 1 kHz, 112 Vrms was applied. (d) 1 kHz, 140 Vrms was applied. (e) 1 kHz, 270 Vrms was applied.

Fig. 3(b)-(e) show the experimental result of two 2 μL water droplets actuated by mirror-EWOD across a Teflon coated 12.5 μm-thick PVDC sheet. It is noticeable that there are no electrodes on the dielectric sheet. Voltage is directly supplied through two probes immersed in droplets. An 1 kHz AC signal was applied across the PVDC sheet through two droplets above and below it. As the voltage was increased, the contact angles were decreased on both sides of the PVDC sheet. The contact angles on both sides were changed from around 101° (Fig. 3(b)) to 94° (Fig. 3(c)), 86° (Fig. 3. (d)), and 62° (Fig. 3(e)) when 1 kHz 112 Vrms, 140 Vrms, and 270 Vrms were applied respectively.

**Self-Aligned Droplets by Mirror-EWOD**

Along with mirror-EWOD, the droplets self-alignment took place as the contact lines of the upper and lower droplets overlapped. As shown in Fig. 4(a), although the original positions of the two droplets are not aligned, when voltage is applied between the probes, the mirror-EWOD force would bring the overlapped droplets to each other. Fig. 4(b) and (c) show the self-alignment of two 2 μL water droplets across a Teflon coated 12.5 μm-thick PVDC sheet, when 1kHz 140 Vrms was applied. At this moment, if we slightly move one of the droplets by the probe tip, the other droplet on the other side of the PVDC sheet would follow it.

![Diagram of droplets](image)

(a) Mirror-EWOD causes two droplets self-aligned.

![Images of droplets](image)

(b) No voltage was applied. (c) 1 kHz 140 Vrms applied.

Figure 4: Two 2 μL water droplets were self-alligned by mirror-EWOD across a 12.5 μm-thick PVDC sheet.

The beauty of the mirror-EWOD lies not only in the droplets self-alignment, but also the same applied voltage (comparing to Fig. 1(a)) now resulting in doubled EWOD phenomenon.

3. **DESIGN AND EXPERIMENTS**

**Direct Droplet Manipulation Platform**

As described above, mirror-EWOD causes EWOD on both sides of the dielectric film and droplets self-alignment. The mirror-EWOD was further applied to a droplet manipulation
platform, in which the path of the droplet can be controlled by a stylus as handwriting. Fig. 5 shows the cross-sectional view of the device. A water droplet is placed between a Teflon coated ITO (Indium Tin Oxide) glass and a PVDC sheet. On top of the PVDC sheet is a droplet-tipped stylus. When a sufficient voltage is applied on the ITO and the stylus, the droplet underneath PVDC can be dragged in an arbitrary path determined by the trajectory of the stylus. When the voltage is turned off, mirror-EWOD is not occurring; stylus can be move without changing the position of manipulated droplets. Multiple droplets can be transported by the handwriting stylus sequentially with a single switch to control the existence of mirror-EWOD.

Requiring no driving electrodes (i.e., the only driving electrode is the droplet on the stylus tip), the fabrication of the device is quite simple and needs no clean room facilities. An ITO coated glass was first cleaned and coated with 1600 Å Teflon by spinning. A 12 μm-thick PVDC sheet was also coated with 1600 Å Teflon. A 2 μL water was then placed on the Teflon coated ITO glass and covered with the PVDC sheet. The distance between PVDC and glass substrate was 1 mm, determined by the spacer thickness. 1 M NaCl (aq) was used as liquid electrode to eliminate the voltage consumption in the liquid electrode. Fig. 6 shows some video frames of a manipulated droplet (2 μL water) driven by the electrolyte droplet (liquid electrode) on the stylus tip. As can be seen in Fig. 6(a), the droplets were first misaligned to each other. When a sufficient voltage was applied between the stylus and the ITO electrode, mirror-EWOD occurred across the PVDC sheet and droplets were self-aligned. The voltage used was a 1 kHz AC signal from a function generator (Agilent 33220A) and then being amplified to 140 Vrms by an amplifier (A.A.Lab Systems A-303). When the stylus was moved by hand, the electrolyte droplet drove the manipulated water droplet in an arbitrary path (Fig. 6(b)-(d)).

Such a platform exploits EWOD without electrode patterns and greatly reduces the complexity and cost of fabrication. Since it requires no (one switch if needed) electrical control circuits and no software programs, the whole platform becomes more compact than conventional EWOD devices [5]. Therefore, mirror-EWOD is very suitable for portable devices. To achieve the portability, a battery powered mirror-EWOD system was established. The function generator was replaced by a timer/oscillator IC to provide a 1 kHz square wave signal. The signal was then be amplified by audio transformers to 140 Vrms.

Disposable Dielectric Layer EWOD Devices

Besides using PVDC as a dielectric layer on liquid electrodes, PVDC can also be applied on solid electrodes. By applying a finger pressure, PVDC was easily attached on a clean glass substrate with patterned ITO or gold electrodes. After PVDC was attached on glass substrate, 1600 Å-thick Teflon was then spun on it. Fig. 7 shows the EWOD effect of a 2 μL water droplet placed on a PVDC coated ITO electrode. EWOD occurs normally in this experiment except for some area with air bubble trapped between PVDC and the substrate. Applying little silicon oil during PVDC attachment can successfully prevent air bubbles trapping.

As shown in Fig. 8(a), PVDC was also tested in a conventional EWOD device as a dielectric layer. Fig. 8(b)-(e) show the droplet transported by applying a 1 kHz, 140 Vrms voltage on one of the patterned gold electrodes. Using PVDC as a dielectric layer does not have major differences from using other dielectric layer by more complicated fabrication processes (e.g., CVD oxide, Parylene, spun PR, etc).
the PVDC sheet tested in this research is not a thin film (12.5 µm-thick), the required EWOD voltage is higher. However, such PVDC sheet is very easy to obtain (Saran wrap) and handle.

Moreover, It was found that PVDC sheet is easily attached on or detached from the glass substrate. Therefore, PVDC can be used not only as a regular dielectric layer but also a disposable one. A new disposable concept is proposed. By only dispose part of the EWOD device, i.e., the dielectric layer, the cost of the device could be largely decreased. For example, after a bioassay, bio-particle (e.g., cells, proteins, etc.) might be adsorbed on the surface of a EWOD device. By replacing only the dielectric layer, a new bioassay can be conduct on the same device substrate without cross contaminations.

4. CONCLUSION

In this paper, we use liquid electrode in place of solid electrode in EWOD devices. A 12 µm-thick PVDC was used as a dielectric layer. We found that PVDC not only occurs on the manipulated droplet, but also the liquid electrode. Moreover, the manipulated droplet and the liquid electrode are self-aligned if they are in comparable sizes. We use this new phenomenon to design a direct handwriting droplet manipulation system. The key features of this device are:

- it requires no driving electrodes making the fabrication simple; (2) no control circuits are needed (droplets are manipulated by hand) making the whole system compact; PVDC can also be applied to conventional EWOD device as a disposable dielectric layer, which greatly reduces the cost of microfluidic chips.

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6. REFERENCES