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3D electrowetting-on-dielectric actuation

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ABSTRACT

This paper describes three-dimensional (3D) digital microfluidics based on an alternating current electrowetting-on-dielectric (AC-EWOD) principle. To achieve 3D manipulation of a droplet between two parallel plates, the horizontal and vertical actuation of a droplet is investigated separately. The dynamic behavior of a water droplet actuated by AC-EWOD in various conditions is studied using high-speed imaging. Optimum actuation parameters such as applied frequency, switching time, and the gap between the top and bottom plates are obtained. For horizontal actuation, a high frequency (1 kHz) is used for small-droplet deformation; on the other hand, for vertical actuation, a low frequency (44 Hz) is used for large-droplet deformation. Finally, as a proof of concept, 3D manipulation of a droplet with two parallel plates is demonstrated by the combination of horizontal and vertical AC-EWOD actuation, resulting in increased space for digital microfluidics.

1. Introduction

The development of reliable bio-chip and lab-on-a-chip systems is highly anticipated for biomedical and genomics applications such as cell manipulation and polymerase chain reaction (PCR) [1–4]. Bio-chip and lab-on-a-chip systems consist of microfluidic components such as extremely small channels, pumps, and sensors. These systems allow us to incorporate many biochemical laboratory functions on a single chip [5–8]. In the development of these systems, microfluidic technology is essential in the handling of small volumes of fluids (less than a picoliter).

As the size of a fluidic system decreases, the surface area to volume ratio is linearly increases. It makes the effects of viscosity on the fluidic system dominate. From a fluid mechanics perspective, the Reynolds number, the ratio of inertia forces to viscous forces, is commonly used to characterize flows and to verify governing forces in a fluidic system [8–10]. In a microfluidic system, the effect of the viscous forces is dominant, because of the small Reynolds number, which is inversely proportional to the size of the fluidic system. Therefore, the fluid driving techniques often used in macrofluidic systems may perform inadequately for pumping fluids in microfluidic systems, because of the high fluidic resistance generated by the viscous force.

As alternatives, a variety of microfluidic technologies based on capillary forces and electrokinetic forces such as electroosmosis, electrophoresis, and dielectrophoresis have been developed [11–15]. Electrowetting-on-dielectric (EWOD) is one of these microfluidic techniques based on discrete liquids (most commonly droplets) without channel networks [16,17]. This is fundamentally different from other existing techniques relying on complicated microchannels. EWOD has been established as one of the most efficient and feasible microfluidic technologies, because of its outstanding advantages such as fast response time, low power consumption, and robust operation [8,18].

There have been great strides in the development of modern EWOD technology. About a hundred years ago, Gabriel Lippmann first studied the electrocapillarity, the basis of the present EWOD principle, in which the interfacial tension of mercury in contact with electrolyte solutions could be varied by applying an electric potential between the mercury and the solution [19]. He not only established a theory of the electrocapillarity, but also developed some applications such as a sensitive electrometer and a motor [16,17]. However, electrolysis induced by the electric current flow through electrolyte solutions restricted broader applications. A century later, Berge conducted a sessile droplet experiment using an electrode covered with a thin hydrophobic dielectric layer [20]. He achieved not only a large variation in the contact angle but also a reversible droplet operation that minimized the electrolysis problem.

In 1998, Washizu demonstrated the electrostatic actuation of unconfined liquid droplets by introducing arrays of patterned

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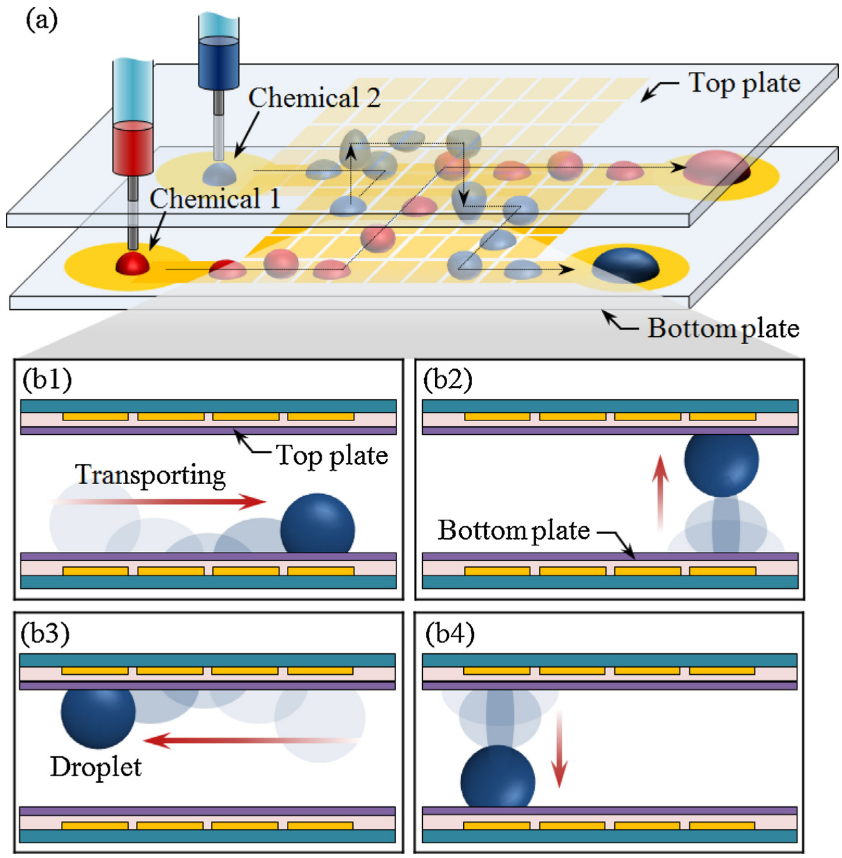

Fig. 1. Experimental schematic for the 3D manipulation of a droplet between parallel plates consisting of patterned arrays of EWOD electrodes: (a) simulated 3D rendering; (b) 2D droplet motion images.

electrodes covered by a hydrophobic layer [21]. Early in 2000, Fair and Kim's research groups achieved the two-dimensional (2D) manipulation of droplets confined with two parallel plates, which initiated the study of 2D digital microfluidics for biomedical applications [22–24]. As the popularity of bio-chip and lab-on-a-chip systems increases, new demands for improving chip density and analysis speed have arisen. Song et al. and Nelson et al. developed a scaling model for EWOD actuation and monolithic fabrication for manipulating picoliter droplets, respectively [25,26]. And Welch et al. applied EWOD actuation to DNA sequencing chemistry [27].

Nevertheless, the extension of current 2D digital microfluidic platforms to a 3D space is seen as a necessity for further enhancement of the chip density and analysis speed [28]. To realize the 3D manipulation of biological and chemical droplets, vertical actuation is essential for transporting the droplets vertically from a bottom plate to the top and vice versa in EWOD chips. Thus far, few attempts at vertical actuation have been made. Takeda et al. demonstrated droplet jumping on a super-hydrophobic surface by using strong electric fields ($\sim$1 MV m^{-1}) and potentials ($\sim$9 kV) [29]. Roux et al. also succeeded in droplet jumping by electrostatic actuation and demonstrated 3D droplet manipulation by incorporating with EWOD actuation; however, the droplet manipulation was conducted in oil circumstances, which are not preferable in many biochemical applications [30,31]. Later, Lee et al. demonstrated droplet jumping using a similar super-hydrophobic surface by EWOD actuation with relatively low potential ($\sim$100 V) [32]. However, to lift sessile droplets in air, the high energy barrier due to the interfacial and potential energy difference between the sessile and airborne states has to be overcome.

In this study, we first present the complete 3D droplet manipulation through the combination of horizontal and vertical droplet actuation between two parallel plates, based on sole alternative current electrowetting-on-dielectric (AC-EWOD) actuation, as shown in Fig. 1. In contrast to previous works, we demonstrate vertical transportation of a droplet without jumping by electrically controlling the droplet shape and the gap between the top and bottom plates. This works in current EWOD system platforms without additional actuation methods and complex microfabrication processes for the super-hydrophobic surface. We also consider the advanced 3D EWOD platform consisting of the closed and open systems connected together for future work. Hence, in the closed system, confined droplets could be split or created; whereas, in the open system, unconfined droplets could be horizontally and vertically transported for various fluidic operations. Note that a preliminary report on this work was presented at the International Conference on Solid-State Sensors, Actuators and Microsystems held in Barcelona, Spain [33].

2. Theoretical background

Electrowetting-on-dielectric (EWOD) is a prevalent method for manipulating the interfacial tension between two fluids using an external electric potential. When an electric potential is applied between a conductive droplet and an electrode covered by a hydrophobic dielectric layer, electrical current cannot flow, but electrical charges in the droplet accumulate around a triple contact line (TCL), since the dielectric layer behaves as a capacitor, as shown in Fig. 2(a). As a result, the interfacial tension is modified, which causes the apparent contact angle of the droplet to decrease, making the droplet spread out on the electrode. This phenomenon is called electrowetting-on-dielectric (EWOD) [4,16].