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RESEARCH ARTICLE

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Droplets actuating chip based on electrowetting-on-dielectric

Abstract A droplet-based actuating chip by using the method of electrowetting-on-dielectric (EWOD) was developed to manipulate the microfluidics. Here, the actuation mechanism of the sandwiched-configuration EWOD chips was carefully studied, and the movement of droplets was numerically analyzed by using the computational fluidic software, CFD-ACE+. The fabrication of the chip, including a heavily phosphorus-doped poly-silicon micro-electrode array and a thermally grown SiO_2 dielectric layer, was exploited to improve the chip stability and decrease the actuation voltage. In experiments, the transportation of a deionized droplet of about 0.5 μL is successfully achieved in air by applying the low voltage of 45 V.

Keywords microfluidic chip, EWOD, surface tension, micro-electro-mechanical systems (MEMS)

1 Introduction

As the technologies of micro-electro-mechanical systems (MEMS) advanced in recent years, much attention has been drawn to the micro total analysis system (μTAS) or lab-on-chip (LOC), which aims at the functional transformation from real-life laboratory analysis to the operations of the microchip. Owing to the advantageous characteristics of high-throughput, automation, quickness and accurateness, it promises to provide a wide range of applications in clinical diagnostics, environmental detection, drug discovery, food production, molecular biology and optical fields [1].

In LOC or μTAS, manipulating and controlling the microfluidics is the key technology. Early researches are focused on the continuous flow systems, which are mainly based on the pneumatic pressure, electrochemical force, shear force, electro-osmotic force and so on. However, due to the limitations of the traditional continuous flow systems [2], focus of research in recent years has shifted to the discrete micro-droplet systems. Besides, more attention has been paid to using surface tension for discrete droplet actuation, because surface tension becomes a dominant force on the microscale. The tension forces based on the surfactant effect [3], thermocapillarity effect [4] and the method of electrowetting-on-dielectric (EWOD) [5–7] have been proposed to manipulate discrete droplets. The method of electrowetting-on-dielectric directly changes the wettability and local contact angle of droplets on the solid surface by changing the electric potential applied to the electrode array under the hydrophobic dielectric layer, and thus results in asymmetric deformation of droplets to realize the actuation and control of droplets. Among the aforementioned surface-tension-based methods, EWOD will be considered as one of the most promising technologies for the manipulation of micro-droplets, owing to the electrochemical inertness of the surface, fast response speed, and low power consumption.

This paper presents the electrowetting phenomena and the actuation principle of the sandwiched-configuration actuator, in which controlled droplets are sandwiched between the two plates of electrodes. A numerical approach based on the finite volume of fluid is firstly used to simulate the movement of liquid droplets and optimize the configuration and process of the actuator. As a result, the manipulation of a deionized droplet is successfully achieved in air by applying the low voltage of 45 V.

2 Actuation principle and simulation

2.1 The method of electrowetting-on-dielectric

Figure 1 illustrates traditional EWOD systems, in which air is used as the surrounding of a discrete deionized droplet. Initially, all the electrodes are ground and the contact angles around the droplet are the same, and we ignore the effect of gravity on droplets. The relation between the contact angle of

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droplets on the hydrophobic solid surface θ_0 and the surface tensions is given by Young's equation

$$\cos\theta_0 = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}}$$

where γ_{sg}, γ_{sl} and γ_{lg} are the surface tensions at solid/air, solid/droplet and droplet/air, as is shown in Fig. 1(a). In general, the contact angle of deionized droplets on hydrophobic surfaces is larger than 90°.

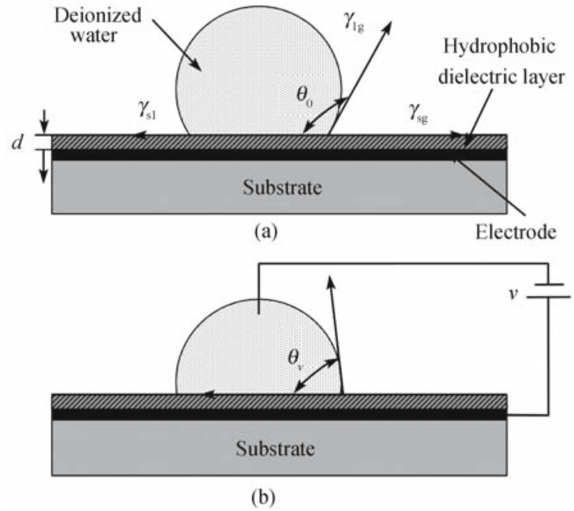

Fig. 1 Illustrations of the EWOD system
(a) With no electric potential; (b) With the external electric potential

Based on the Lippmann equation, the surface tension at solid/droplet decreases as the electric potential is applied between the electrode and the droplet

$$\gamma_{slv} = \gamma_{sl} - \frac{1}{2}\frac{\varepsilon_0\varepsilon_r}{d}v^2$$

where γ_{sl} and γ_{slv} denote the solid/droplet surface tensions with no external electric potential and an electric potential v, ε_0 the permittivity of vacuum, ε_r the effective dielectric constant of the dielectric layer and d is the effective thickness of the dielectric layer. Due to the decrease of the solid/droplet surface tension at the three-phase contact line, the contact angle decreases, as is shown in Fig. 1(b), and thus the relations between the changed contact angle θ_v and the potential v is determined by the equation of Young-Lippmann [8]

$$\cos\theta_v = \cos\theta_0 + \frac{1}{2}\frac{\varepsilon_0\varepsilon_r}{d}\frac{v^2}{\gamma_{lg}}$$

According to the Young-Lippmann equation above, the factors which affect the contact angle of the droplet, are mostly the applied electric potential, the effective thickness and the effective dielectric constant of the dielectric layer. In experiments, the contact angle decreases with the increase of the applied potential, until the contact angle becomes the smallest when the applied electric potential exceeds a certain value. It can be called the saturation of the contact angle [8], which must be carefully considered in the design of EWOD actuators.

2.2 The configuration and actuation principle of the actuator

The sandwiched configuration, where controlled droplets are sandwiched between two parallel planar plates, is usually adopted in EWOD actuators. The top plate consists of a hydrophobic layer, a transparent electrode and a glass plate. The bottom plate consists of the microelectrode array and the hydrophobic dielectric layer. Small blocks are used as the spacers between the two plates. Thus, the droplets' movement is limited between the two plates filled with air or silicon oil, as is shown in Fig. 2(a).

Figure 2(b) illustrates the cross-sectional image of the EWOD droplet actuator. As the switch k is off, no electric potential is applied and thus the contact angles of the droplet with the top and bottom plates are initial contact angles (θ_t and θ_0). As the switch k is on, the external electric potential is applied to the actuator. Because of the top thinner dielectric layer and the larger electric capacitance, the electric potential between the droplet and the top plate is very small, which results in a little change of the contact angle with the top plate [7]. Thus, the external potential is mostly applied between the droplet and the bottom electrode, which results in the great change of the contact angle of the droplet on the solid surface above the right energized electrode. However, the contact angle above the left electrode keeps constant without the potential. Thus, the asymmetric deformation of the droplet, which establishes a pressure gradient between the two ends of the droplet, appears and then gives rise to the droplet movement.

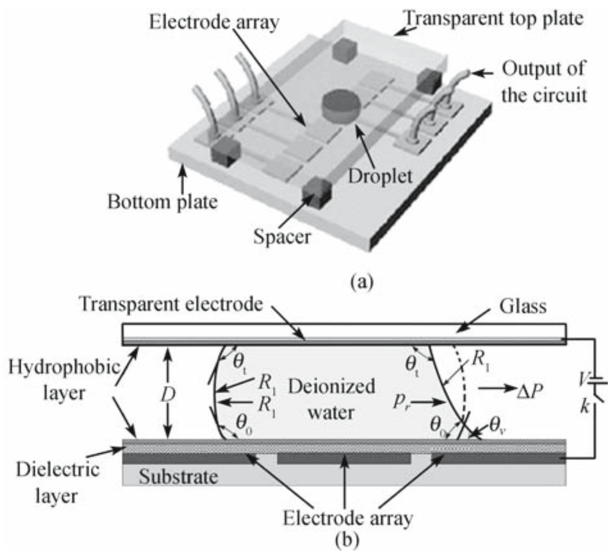

Fig. 2 Illustration of the sandwiched-configuration actuator
(a) 3-D image of the actuator; (b) The cross-sectional image of the actuator

An analytical method is also used to analyze the actuation pressure in the sandwiched configuration. Using Laplace equation, the dynamic pressures P_l and P_r on the two ends of the droplet can be described by the principal radii of curvature

$$P_\mathrm{l} - P_a = \frac{\gamma_\mathrm{lg}}{R_\mathrm{l}}$$

$$P_\mathrm{r} - P_a = \frac{\gamma_\mathrm{lg}}{R_\mathrm{r}}$$

where P_a is the atmosphere pressure, R_l and R_r are the principal radii of curvature on the left end and the right end of the droplet. Thus, the systemic horizontal pressure difference ΔP can be expressed

$$\Delta P = (P_\mathrm{l} - P_a) - (P_\mathrm{r} - P_a) = \gamma_\mathrm{lg}\left(\frac{1}{R_\mathrm{l}} - \frac{1}{R_\mathrm{r}}\right)$$

According to the geometrical relations, the radii of the meniscus curvature on the two ends of the droplet can be determined by the local contact angles and channel gap height of the two plates D

$$R_\mathrm{l} \approx -\frac{D}{\cos\theta_0 + \cos\theta_\mathrm{t}}$$

$$R_\mathrm{r} \approx -\frac{D}{\cos\theta_v + \cos\theta_\mathrm{t}}$$

Thus, the systemic horizontal pressure difference can be inferred

$$\Delta P = \frac{1}{2D}\frac{\varepsilon_0\varepsilon_\mathrm{r}}{d}v^2$$

From the equation above, the systemic pressure difference is proportional to the square of the applied voltage, the effective dielectric constant of the dielectric layer, and inversely proportional to the effective thickness of the dielectric layer. Moreover, the equation is only applicable before the saturation of the contact angle. Therefore, in order to manipulate droplets conveniently, many factors must be considered in the actuator, including the high external applied voltage and the high quality dielectric materials with the high dielectric constant, the high electric breakdown characteristic and the optimized thickness.

2.3 Numerical simulation

The method of electrowetting-on-dielectric is essentially one of the electric-controlled surface tension methods for manipulating the discrete droplets. Thus, the movement of the droplet sandwiched between the two plates can be simulated with the principle of the surface tension methods. Here, we use computational fluidic software, CFD-ACE+, in which the Free Surface Module is adopted.

During the simulation, the finite volume of fluid methodology is adopted and the surface tension, gravity and viscosity are considered. In experiments, the contact angles of the droplet with no electric potential and with a 40 V electric potential are 110° and 80° respectively. Thus, the parameters of the electrode array used in the simulation are: the size of each electrode is $1.4 \times 1.4\ \mathrm{mm}^2$ and the gap height between the two plates is 200 μm. The initial contact angle on the top hydrophobic plate is 110°, and the contact angles on the bottom electrode array depend on its excited conditions. As is shown in Fig. 3, the black block denotes the electrodes applied with electric potential (electrode V_2 at t_0 and t_1, electrode V_3 at t_2 and t_3), on which the contact angle is set to 80°, other blocks denote the electrodes with no electric potential, on which the contact angle is set to 110°. Figure 3 illustrates the movement of the droplet (ellipse strap) from the left to the right. As a result, a method by increasing the gap height is used to optimize the movement of the droplet in the sandwiched actuator.

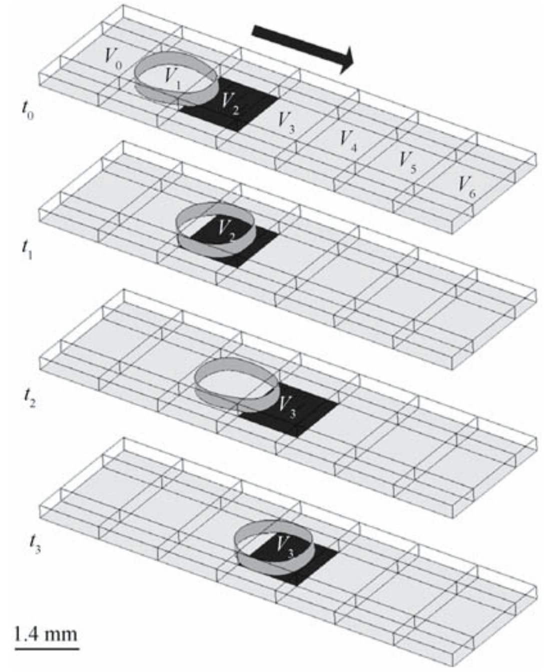

Fig. 3 Simulative results of droplet movement on the sandwiched EWOD actuator

3 Fabrication

Here, SiO_2 film thermally grown on the poly-silicon surface is used as the dielectric layer of the actuator, owing to its high quality film characteristic of a high dielectric constant, high electric breakdown and good processing compatibility. It improves the disadvantages of processing incompatibility between Ti/Pt electrode and Si_3N_4 dielectric film deposited by low pressure chemical vapor deposition (LPCVD) and the low electric breakdown of Si_3N_4 dielectric film. The film of

Teflon® AF1600 is spin-coated as the hydrophobic layer, on which the contact angle of a deionized droplet is about 110°, as is shown in Fig. 4.

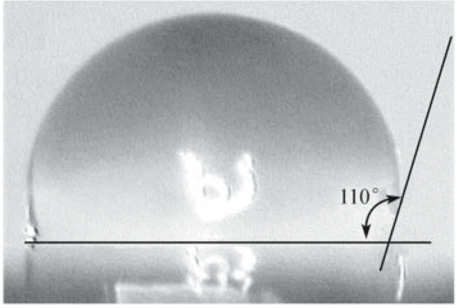

Fig. 4 Image of the contact angle of a deionized water on Teflon® AF1600 surface

The process starts with a 5 000 Å SiO_2 film thermally grown on Si substrate at 1 050°C. An 8 000 Å poly-silicon thin film is deposited by LPCVD on SiO_2. The poly-silicon film is doped with phosphorus, and patterned to form the microelectrode array. The size of each electrode is 1.4×1.4 mm^2, and the distance between two adjacent electrodes is 20 μm. Then, 1 000 Å SiO_2 is thermally grown on the surface of the poly-silicon electrodes at 950°C to serve as the high-performance dielectric layer. A 300 Å Teflon® AF1600 layer is then spin-coated on both the bottom oxide layer and the top glass plate covered with the ITO transparent electrode as the hydrophobic layer. Lastly, four blocks of 200-μm-high adhesive tapes are used as the spacers for supporting the top plate and then forming the sandwiched configuration.

4 Experiments and discussion

Before conducting the experiments, a droplet of deionized water with the volume of 0.5 μL is dispensed with a pipet onto the hydrophobic surface of the bottom electrode, and then covered with a transparent top plate to form the sandwiched configuration. To avoid electric breakdown of the dielectric layer, the voltage pulse is used as the applied potential, of which the frequency and the duty-ratio are controlled by a control system with a micro-controller. The movement of droplets is viewed with a digital microscope and captured with a charge coupled device (CCD) camera.

During the experiments, the top electrode is grounded, and a 5 Hz frequency, 1:1 duty-ratio voltage pulse is applied to the active electrodes. As the applied voltage is up to 25 V, the contact angle of the droplet becomes small and the deformation of the droplet appears. When the applied voltage increases to 45 V, the systemic horizontal pressure difference becomes sufficiently larger to quickly drive the droplet. As is shown in Fig. 5, initially, the droplet lies on the surface of two electrodes V_1 and V_2, and all the electrodes are grounded. Then, the voltage is applied on the electrode V_2, and the droplet is quickly moved to the upper electrodes by electrowetting. Finally, the droplet moves on the surface of the electrode V_4, as the voltage is applied to the electrodes V_2, V_3 and V_4 in turn. Therefore, the droplet can be accurately manipulated to any electrode.

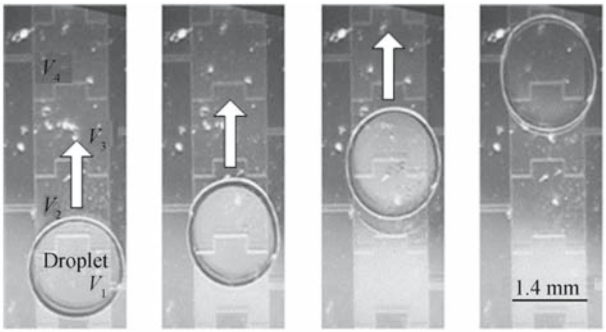

Fig. 5 Sequential frames of the droplet movement on the sandwiched EWOD actuator

Here, SiO_2 film thermally grown on poly-silicon surface is used as the dielectric layer, which avoids the appearance of the low-electric-breakdown “dots” [5] and thus improves the surface roughness and electric breakdown characteristics of the dielectric layer. Moreover, the filled surrounding is aired in our actuator. Although it brings actuation difficulty without the lubricating silicon oil, which can decrease the flow resistance, the contamination of silicon oil to the controlled droplet is avoided. In experiments, the droplet is successfully manipulated at a 45 V applied voltage in air by optimizing the height of the dielectric layer.

5 Conclusions

In this paper, the actuation mechanism of the sandwiched-configuration EWOD chips is illustrated, and a numerically computational method, for the first time, is used to simulate and optimize the dynamic characteristics of the droplet movement. To reduce the applied voltage and improve the stability of the actuator, the SiO_2 film thermally grown on the phosphorus-doped poly-silicon electrodes is used as the dielectric layer, the spin-coated Teflon® AF1600 as the hydrophobic layer. As a result, the manipulation and control of deionized droplets in air is achieved by applying a 45 V voltage.

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