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EFFECT OF APPLIED VOLTAGE ON A NEW DESIGNED LAB ON A CHIP ELECTROWETTING ACTUATION SYSTEM

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Abstract

Electrowetting on dielectric (EWOD) is known as a promising technique to manipulate liquid droplet for chemical and biomedical applications. A new EWOD platform is designed and simulated for solving the asymmetrical splitting difficulty, transporting, mixing and merging of the different volume of droplets. The electrode design expands the performance of EWOD systems, giving the high reproducibility on the volume of the droplet and dilution factors and ultimately reduces the required time for above activities. The satisfactory voltage range was applied on the electrode based on unit-square electrode shapes to move droplets. In this paper the simulation results are presented with water droplet surrounded by air in closed microchannel EWOD platform.

Keywords: Electrowetting on dielectric, Lab on a chip, Microfluidic, Symmetric splitting, Dilution factor, Electrode shape.

1. Introduction

In recent years, the liquid droplet manipulation has been widely explored to develop a fully functional digital microfluidic platform to transport the chemical or biomedical liquids on biochips also known as Lab on a chip (LoC) or micro Total Analysis Systems (μ-TAS) [1, 2]. The goals are to reduce the laboratory reactant and procedures and also miniaturizing the instruments. These systems with high throughput and minimum reagent consumption can be benefited especially in the applications of medical diagnosis, drug delivery, point of care and environmental monitoring [3, 4]. Generally microfluidic can be divided into two branches of applications, continuous flow and digital microfluidics [5, 6]. The continuous flow requires valve or pump

Nomenclatures

e	Width of electrode, μm
V_s	Splitting volts, V
V_{th}	Threshold voltage, V

Greek Symbols

δ	Gap length between each electrode, μm
λ	Dents length, μm
θ_1, θ_2	Young contact angle of non-actuated and actuated electrodes
μ-TAS	Micro Total Analysis Systems

Abbreviations

DEP	Dielectrophoresis
EWOD	Electrowetting on dielectric
GUI	graphical user interface
LoC	Lab on chip

to generate the essential external forces for liquid actuation [7, 8] while the digital microfluidic manipulates liquid in a discrete manner as unit-sized volumes of droplet which includes electrowetting on-dielectric (EWOD), dielectrophoresis (DEP) and immiscible-fluid flow (multiple-phase flow) methods [9]. Nevertheless, DEP requires relatively high voltages to direct droplets and immiscible-fluid flow still needs external pumps to push liquid into the microchannels [10, 11]. Therefore the EWOD technique is the most feasible method as it needs a reasonable value of voltage and it does not need any external mechanical systems.

2. Method

A EWOD device is a liquid droplet actuator based on controlling charges at the interface of a liquid and an insulator over buried electrodes. In addition, the droplets of microliter or nanoliter sizes can be promptly driven to the expected position, which is not achievable by any other microfluidic methods. In our method, the droplet is sandwiched between top ground and bottom actuating hydrophobic-insulated-electrodes. The start of droplet motion will occur by applying voltage to electrode adjacent to where a droplet resides while simultaneously deactivating the electrode beneath the droplet. The accumulation of charges in the overlap region of the liquid/insulator interface reduces the interfacial tension. At this interface, the droplet contact angle with solid will change the wettability of the droplet from hydrophobic to hydrophilic.

Consequently, surface tension gradients will be created across the gap between adjacent electrodes and a pressure difference will then established inside the droplet, and it will give rise to motion of droplet. Usually EWOD devices are undertaking the case of invariable electrodes shape and dimension, which result in the transporting of only the unit-sized volume droplet [12, 13].

But in the proposed has a multi-task and multi-volume transporting EWOD platform by changing the shape of hydrophobic insulated electrode referring to the conventional works that includes the square electrode shape with some indentation at their borders with another electrode [14]. The proposed consists of 4 triangle shapes, which constitute the unit square electrode shape shown in Fig. 1.

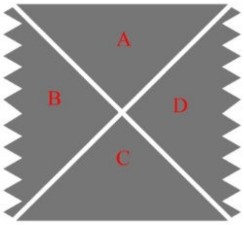

Fig. 1. Proposed Electrode Shape Design Consist of 4 Triangle Electrodes with the Names of A, B, C and D.

3. Design

The dimension of unit-sized electrode pitch is designed in 1 mm while the gap between each inner electrode is 10 μm and between each square is 25 μm. A few interlocking dents are designed between the inner electrodes and a unit-sized square electrodes to avoid droplet stranding over the electrode areas based on the analytical model proposed by Berthier and Peponnet [15] to determine a lower limit for non-dimensional ratio of the length of dents to its width.

$$G(\lambda, e, \delta, n) = \frac{\frac{\lambda}{e}}{\frac{\delta}{e} + \left[\frac{\theta_2}{\theta_1} - 1\right]\frac{1}{n\pi}} \tag{1}$$

where λ is dents length, e is width of electrode, δ is the gap length between each electrode, θ_2 and θ_1 are Young contact angle of non-actuated and actuated electrodes respectively, and n is number of dents.

Berthier and Peponnet had verified that the value of G function should be larger than 1 in order to satisfy the required condition [16]. According to our designed, the value of G function for two types of surrounding medium i.e. air is approximately 2.86 for 5 dents at the boundary unit-sized square electrodes. This is with the dents length of 140 μm , and for 5 dents at the boundary of inner triangle electrodes is 1.11 for air as filler medium and with dents length of 30 μm.

The properties of simulation was based on the real electrodes designed consist of 1mm electrode pitch with 100 μm distance to top plate and 140 μm spike length, 25 μm pad gap and 800 nm insulating layer thickness with dielectric constant of 3 [17]. This is implemented using the Surface Evolver software, EDEW 2.0, a user-friendly graphical user interface (GUI) simulation tool.

4. Results and Discussion

In the case of transporting the droplet from one unit square to adjacent electrode, the droplet is placed over the third of five electrodes with start position x= 2275e-6. An individual actuated voltage was applied over the forth electrode to induce droplet motion as shown in Fig. 2. A negligible displacement is observed with increasing voltage from 10 V to 20 V; this is because the resulting electrical field was not enough to change the contact angle leading to motion of the droplet as shown in Fig. 3, the result was in 3 dimensional, 3D, at 11 iterations.

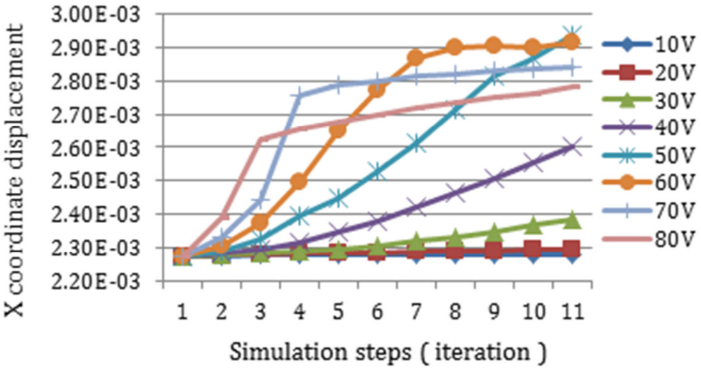

Fig. 2. Effect of Applied Voltages on the Droplet Position.

With further increasing voltage from 30 V, the amount of displacement rises dramatically and this trend continues up to 50 V. However, at 60 V the displacement declines in comparison with 50 V trend and this reduction continues obviously for 70 V and 8 0V. The main reason of these motions dropped after 60 V, is certainly related to the unnaturally expanding the droplet area over adjacent electrode instead of moving over it as shown in Fig. 3. Therefore the voltage range between 30 V and 50 V is appropriate to transport the droplet and when the applied voltage is closer to the upper limit, it will lead to higher velocity of droplet motion.

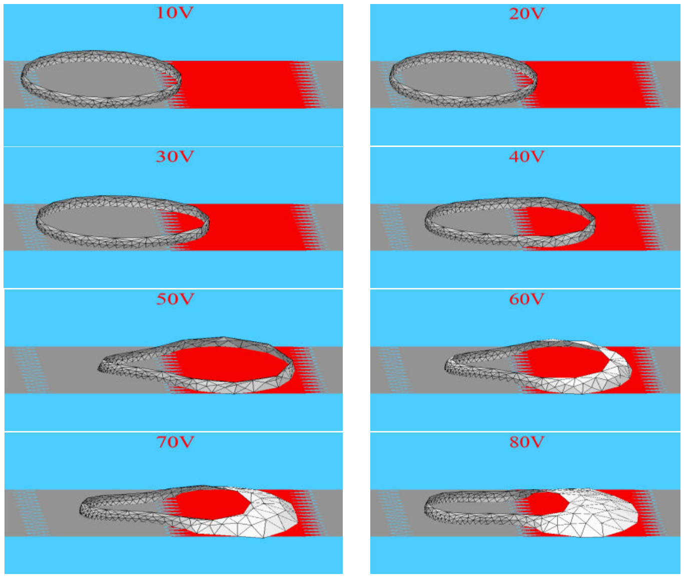

Fig. 3. Effect of Different Applied Voltages within 11 Iterations on Droplet Motion.

In the conventional electrode designs, designers and researchers have elaborated that in order to have a symmetric splitting, it will depend on some factors like time sequencing of turning on/off, alignment of droplet, electrode shape, etc. However, in our proposed electrodes shape design, since a unit-square electrode is divided into 4 parts, each part has its own electrical control unit.

The hypothesis of "pre-splitting alignment" is proposed based on the special shape of these inner electrodes. This is not only to achieve symmetrical splitting, but also to have a controllable asymmetrical splitting by adding another 4 inner electrodes in particular position of unit-square electrode.

Figure 4 shows the proposed design where a unit droplet volume is placed over the square electrode shape by applying voltage on the 4 inner electrodes. While aligning droplet for splitting it in a symmetrical way, A and C electrodes is turned off and the proper voltage is applied to B and D and the neighbouring electrodes, simultaneously. This will result in the motion of droplet from areas covered by A and C electrodes to the area over electrode B and D and neighbouring electrodes through modified interfacial tension of liquid-solid interface as shown in Fig. 4(a).

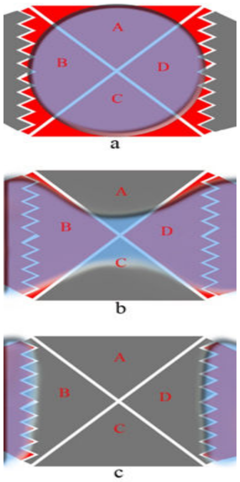

Fig. 2. In all Figures, the Red Electrodes Indicate the Actuated Electrodes while the Grey Electrodes Indicate a Non-Actuated Electrode. (a) Droplet is Placed Over the Unit-Square Electrode (b) the Electrode B, D and Neighbouring Electrodes are Turned On with Specific Voltage and (c) All Inner Electrodes are Turned Off.

For splitting mechanism, higher voltage is needed and it is called "splitting voltage", V_s. It is different from normal transporting voltage and there is a minimum required voltage to begin with. Here, in the droplet motion, it is called "Threshold Voltage", V_{th}. If the applied voltage on the electrodes B and D and neighbouring electrodes is lower than the splitting, V_s nevertheless higher than V_{th}, based on the hydrodynamic of droplet and special position of the electrodes, as shown in Fig. 4(b), the controllable alignment of aqueous droplet over inner electrodes will be provided which they can then form the pre-splitting position. When the applied voltage is not enough to split the droplet, the droplet will align as pre-splitting position. The successful splitting is done by turning off the electrodes B and D and applying V_s on the neighbouring electrodes as shown in Fig. 4(c).

Commonly, in the conventional EWOD, splitting method was only based on the hydrodynamic of droplet without any means to form proper alignment as pre-splitting position. Through this interpolating method, it will improve and provide more accurate results by achieving the symmetric splitting on chip with the dilution factor. Hence, we could obtain such individual precision amount of droplet especially in biomedical application like in the case of sample separation.

Based on the designed criteria including electrode dimensions, the distance between top and bottom electrodes, surrounding medium, its thickness and type of dielectric layer are considered. Further simulation is done to depict on the way "pre-splitting alignment" hypothesis can fit the lack of alignment based on the inner electrodes.

Table 1 shows the simulation criteria based on designed unit-square droplet shape. The simulation is done in air medium for fluid handling using EWOD. Only a unit-sized electrode is subjected to simulation and the droplet is placed at 2nd electrode then adjacent. The 1st and 3rd electrodes are actuated with the voltage range between 10 V and 60 V to observe the effect of voltage on the formation of droplet necking as to split droplet into two daughter droplets.

Figure 5 depicts the visual simulation results that give a clear concept of voltage range influence on droplet. This specifies the droplet does not show any particular motion toward actuated electrodes when 20 V is applied to the adjacent electrodes. However, by further increasing the voltages to 50 V, more droplet volume would expand over the adjacent electrodes but this range of voltage is not enough to create the required necking effect to split droplet into two daughter droplets.

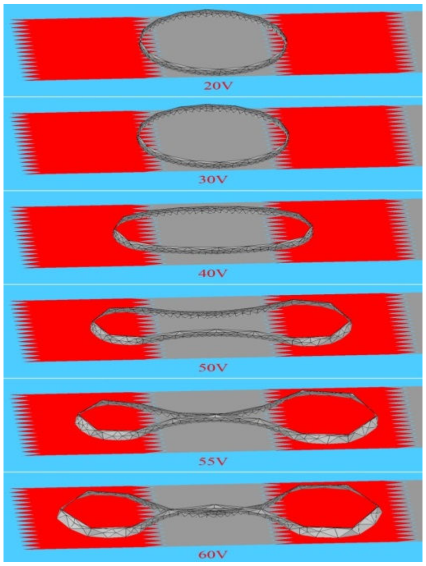

Fig. 5. 3D Visual Simulation Results in Closed Channel with Different Voltage Range Applied to Adjacent Square Electrodes at 17 Iterations for 20 V and 55 V and 11 Iterations for 60 V. The Red Electrode Illustrates the Actuated Electrodes.

Figure 6 shows the surface energy- iteration characteristic for different voltage applied. It shows that, through the applied voltage from 10 V to 40 V, the reduction of surface energy is negligible for lower range of voltage and the curve during 17 iterations would remain essentially stable.

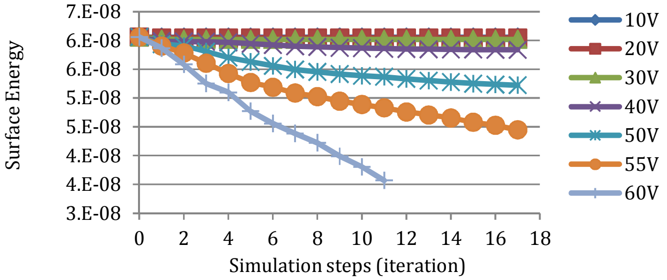

Fig. 6. The Effect of Applied Voltages on the Energy Curve.

However, further increasing the voltage will result in the dramatically drop of surface energy and formation of necking at 55 V and 60 V is observed and this occurs within 17 and 11 iterations respectively. Its visual results can be seen in Fig. 5. These results are also obvious from surface energy curve diagram plotted versus position diagram as shown in Fig. 7. It is observed that the voltage range between 30 V and 50 V do not result in splitting.

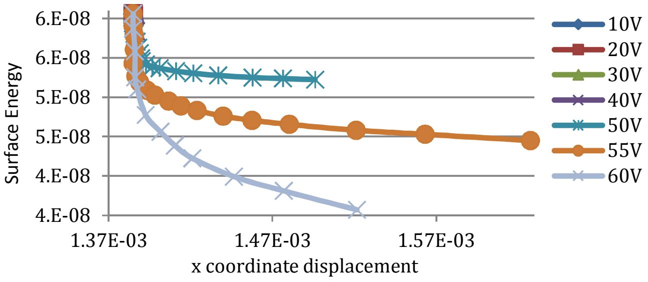

Fig. 7. The Effect of Applied Voltages on the Energy Curve versus Centroid (In X Displacement).

Therefore the droplet for lower voltage range would remain the droplet constant in its position and for higher voltage range, the whole droplet volume will move over one of electrode surface due to droplet hydrodynamic as shown in Fig. 8. Thus, the voltage range between 30 V and 50 V can be used as pre-splitting voltage and the voltage range between 55 V and 60 V is chosen as splitting voltage.

This method can be used to dispense the droplet from reservoir and provides not only the external control by means over pinch off area through inner electrodes, but it also can develop method to accurately control the volume of the droplet. Within this method, it will be possible to generate different volume of droplets on the same EWOD platform without the need of redesigning or even changing the size of unit-square electrode, provided that a set of proper voltages and frequencies are applied.

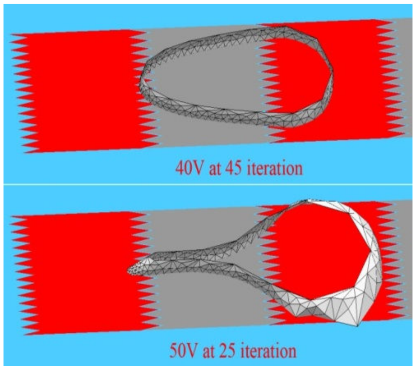

Fig. 8. 3D Visual Simulation Results in Closed Channel for 40 V and 50 V at High Iteration Steps.

Furthermore, the other process that can be performed on this EWOD system is a mixing. In the microscopic world, effective mixing becoming a technical problem because it is difficult to generate turbulence flow by mechanical actuation. The necessary inertial forces that produce turbulence and resulting large interfacial surface areas to promote mixing are usually absent. Thus in this system, mixing mainly depends on diffusion through limited interfacial areas.

The effect of the unit-divided-square electrode in mixing area inside the EWOD devices can be excellent by providing internal diffusion inside the unit-electrode. This can be done via turning on/off of the inner electrodes or even by providing the clockwise motion inside EWOD devices with all neighbouring electrodes contributing to reach the lowest required time in order to obtain the complete mixing. The process will obviously reduce the mixing time required as compared to the conventional device.

Another advantage of using a unit-square-divided electrode is related to the pining problem of smaller droplet volume than a unit-volume. In the conventional method, there is a separating gap between each electrode to avoid droplet pining during its motion from one electrode to another. The whole hydrophobic region is introduced to the imposed gap between each electrode. The crenellated edge is designed to remedy the stranded droplet over electrode by extending the droplet contact line over the dents of the next electrode. However in conventional EWOD method, if the smaller volume of droplet is generated and placed over the unit-square electrode, it will create another pining problem.

Therefore by utilizing the unit-square-divided electrode, a smaller droplet volume can be controlled and handled based on the inner electrodes that inherently crenellated edge with bigger dents length, which used in boundary for each electrode. Thus, by actuating this unit-square-divided electrode (inner electrodes), even the smaller droplet volume can be controlled. Hence, make this system as an ideal design for application of logic gates LoC or digital microfluidic.

Table 1. The Value of Parameters for Confined Droplet Mode used in EDEW.

Parameter	Value
Liquid	Water
Surface tension	Surface tension
Contact angle at top and bottom	110 [Deg]
Distance to top	100e-6 $[m]$
Droplet volume	78e-12 $[m^3]$
Layer thickness	800e-9 $[m]$
Rel dielectric constant	3
Pad size x and y	1000e-6 $[m]$
Pad gap	25e-6 $[m]$
Spike length	140e-6 $[m]$
Start position x	1385e-6 $[m]$
Rectangular-pulse Width	0.27

5. Conclusion

The specific range of voltage applied on the new designed LoC electrowetting (EWOD) actuation system that contains a set of electrode with several inner electrodes certainly can control the droplet motion with high degree of precision. The proposed design has improved the splitting, dispensing and mixing parts of LoC EWOD systems. It offers a high reproducibility on the volume of the droplet and dilution factors. All in one platform principle can give more flexibility and better choices for multiple applications of EWOD especially in lab on a chip (LoC).

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