Droplet mixer based on electrowetting

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Abstract. The manipulation of droplets on the microscale is a growing area of research for Lab-on-a-chip applications. The droplet represents a controlled reproducible volume for studying fast chemical reactions and performing parallel studies. One technique for manipulating droplets on a surface is electrowetting: a technique which uses applied electrical potentials to exert stress on the droplet and to produce deformation or movement. This paper presents a new design of an electrowetting based mixer intended to demonstrate a method for rapidly bringing together two droplets and mixing them. Preliminary measurements of mixing are also presented.

1. Introduction:
Manipulating and mixing of small volumes of liquid in microfluidic devices is important for the use of chemical and biological protocols in Lab-on-a-Chip or Micro Total Analysis systems. Mixing could be used for preprocessing, performing controlled sample dilution or controlled reactions between different ratios of reagents. Mixing of droplets can be through diffusion (passive mixing) or an external force may be used to create dispersed multi-laminates or turbulence in the liquid (active mixing). The application of electrical potentials to generate movement and deformation of a droplet through the action of electrowetting and dielectrophoresis \cite{1-3} can be used both to bring droplets together and induce internal motion to improve mixing.

2. Background and theory
Electrowetting refers to the fact that when an electrical potential is applied to a droplet in contact with an isolated electrode, a change in the contact angle between the droplet and the surface is observed at the three phase point. As such, this physical phenomena produces a change in the wetting of the droplet on the surface, decreasing the contact angle and resulting in a spreading of the droplet on the surface \cite{4}. Different designs of device have been used to produce movement of small droplets and then mixing \cite{1-3,5}.

The change in the wetting of the surface is related to the contact angle change but also to a change in the centre of mass of the droplet. If the electrical potential is applied using a patterned structure of electrodes, the pattern can be used to produce an asymmetric shift in the centre of mass and therefore translational motion of the droplet. The change in contact angle $\theta$ is given by \cite{6}

$$\cos \theta = \cos \theta_0 + \frac{\varepsilon_r \varepsilon_0 V^2}{2d\sigma_{lv}}$$
where $\theta_0$ is the static contact angle without the voltage applied, $\varepsilon_d$ and $\varepsilon_0$ are the dielectric constant and the permittivity of free space, respectively, $d$ is the thickness of the dielectric layer used to insulate the electrodes and $\sigma_{lv}$ is the liquid-air surface tension. It is generally considered that movement of the centre of mass and the change in contact angle changes are considered as independent observables[7,8]. The change in contact angle is due to overcoming the vertical component of electrostatic force [9].

As a result, typical movements that have been observed, such as the “inch-worm” translational motion of the droplet presented previously [5], involve other effects to produce the motion. In this case, the droplet exhibits an oscillating behaviour arising from the AC potential applied, with the droplet elongating and returning to a spherical shape periodically. Throughout the elongation, the advancing side of the droplet shifts forward while the trailing side remains virtually pinned. During the restoring cycle, the trailing side is pulled forward while the advancing side remains virtually pinned. This motion is sustained until the droplet reaches the end of the structure [5]. The initial direction arises from instabilities in the wetting on each side of the droplet.

The electrode array presented in this paper is intended to produce deliberate motion of the droplet in a particular direction through the use of a specific design.

3. Electrode design and experimental set up

3.1 Electrode design

Figure 1 shows the design of the chip as well as illustrating the principle of operation in the application of AC electrical potentials. A droplet is placed at point A on either side of the device and a signal is applied between the pair of electrodes on either side. The triangular shape of the electrodes produces a increasing capacitance per unit length towards the centre of the chip, since the area (width of the electrode) increases and the separation between the electrodes decreases. One way of considering electrowetting is to consider the fluid as moving up gradients in capacitance since the energy in the system then decreases as a result. Therefore, by placing the droplet at point A and applying the voltage, the droplet will move toward point B. At this point the droplet will remain stationary if the interdigitated sections are in phase (i.e. upper pair are in phase and the same for the lower pair). When the phase of, for example, the left pair is then switched, strong electric fields are then generated in the interdigitated area, rapidly pulling both droplets into the centre, where they will mix.

![Figure 1](image_url)  

**Figure 1** Schematic diagram of the electrowetting chip design. On either side are a pair of microelectrodes, the separation of which decreases towards the centre of the chip. In the central area, the structure of the electrodes is broken into a region of interdigitated fingers for mixing. The droplets move from position A to B under the application of an electrical potential between the pair of electrodes on left and right, as indicated by the schematic power supplies. The droplets can be held at point B if the electrodes which are interdigitated (i.e. the upper or lower pairs) are in phase. Switching them to out of phase then pulls the droplets into the central interdigitated area for mixing.
3.2 Device fabrication

The electrode arrays were fabricated in layers of titanium and platinum using photolithography and ion beam milling. The insulating dielectric layer was deposited using a combination of two different materials. A photoresist was used: SU-8, which is a chemically amplified epoxy based negative resist, used in a wide range of film thicknesses (1µm to 200µm) in MEMS applications. SU-8 resists have high functionality, high optical transparency and are sensitive to UV radiation.

The thinnest available grade of SU-8 (MicroChem SU-8 2000.5, 14% in cyclopentanone) was used to coat the electrodes. First, the device was cleaned with acetone and IPA, put on a hotplate at temperature of 150°C for 15 minutes to remove adsorbed water from the device surface. The device was then spin coated with Ti Prime at 3000 RPM for 20 seconds, and baked at 120°C for 2 minutes on a hotplate. SU-8 was then deposited by spin coating at 500 RPM for 5s then 6000 RPM for 30s followed by soft-baking on a hot plate at 105°C for 1 min. Following exposure for 1 min, the device was post-baked at 125°C for 60s and developed in ethyl lactate (Shipley Microposit EC Solvent-11) for 30s, rinsed with IPA and blow dried with nitrogen gas.

Finally, the devices were coated with a thin layer of Cytop to produce a hydrophobic surface: the measured contact angle of droplets on the device was 105°.

3.3 Experimental setup

The signals were applied to the electrodes using a signal generator and broadband amplifier (KH Krohn-Hite Corporation). The signals were routed through a switched multiplexor which allowed up to nine pairs of individual electrodes to be powered as well as handling the inverting of the phases. A programme was developed in Labview to control the polarity and timing of the electrodes throughout the experiment. The experiments were observed using a black and white Fast-Vision-13 high speed camera since the velocities in electrowetting experiments is too fast to be observed using standard cameras.

Liquid droplets of deionised water (DI water) and black ink solution with a PH=7.2 and conductivity 5.4mS/m were positioned using pipette dispensers.

4. Results and discussion

Figure 2 shows a captured video frame following the application of an electrical potential. The volume of the dispensed droplets was approximately 4µl, with an ink droplet placed at position A₁ and a water droplet at A₂. The initial applied voltage was 60V at 1.5 kHz between the two electrode pairs, 1&2 and 3&4, with electrodes 1 and 3 in phase (similarly 2 and 4).

After the voltage was applied, the contact angle of two droplets decreased and the droplets spread across the electrode pair at points A. This voltage, however, was not sufficient to induce a lateral movement. Increasing the voltage to 80V resulted in the two droplets moving to points B as shown in the figure. This position was stable.

Mixing was then achieved by changing the polarity of electrodes 1 and 2 and increasing the voltage to 130V. With the electrodes in the interdigitated region between electrodes 1&3 (and also 2&4) out of phase, strong electric fields were generated over the entire area, rapidly pulling the droplets into the centre. Figure 3 shows captured video frames over a 1 second period following the switching of the voltages. Droplet merging was observed to occur in
0.02 seconds: within the first 10 frames of the high speed camera. Following the merging, internal rotational flow and mixing by diffusion was observed until a uniform distribution of the ink was observed at 0.9 seconds.

![Series of images](image)

**Figure 3** Series of images 0.2 second intervals showing the internal diffusion of the ink and movement of the two droplets under an applied voltage of 130V at 1.5kHz.

5. **Conclusion**

An electrowetting chip was designed and fabricated for the controlled mixing of two droplets. The movement of the droplets in a controlled manner from the dispensing position to the centre of the device was demonstrated. The subsequent mixing by altering the applied potentials in the central interdigitated area was then demonstrated, with the two droplets mixing in approximately 0.9 seconds.

6. **Acknowledgments**

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7. **References**

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