A Fast Fabricating Electro-wetting Platform to Implement Large Droplet Manipulation

Yiyan Li[1], Roger Chen[2], and R. Jacob Baker[1]
[1] Department of Electrical and Computer Engineering, University of Nevada, Las Vegas and [2] Genia Corporation
liy10@unlv.nevada.edu

Abstract— Droplet actuation, merging, and splitting using controlled electro-wetting are implemented on the top of a standard printed circuit board (PCB) resulting in a fast prototyping microfluidic platform for biological experiments. In the system reported here the PCB is used as a substrate and is covered with Saran Wrap. The Saran Wrap can then be coated, or not, with a commercial water repellent liquid. The resulting hydrophobic surface is used as a supporting dielectric layer for the experiments. Results show that lower actuation voltages and frequencies are achieved, than previously reported, to move larger droplets (30 microliter). Single-plate and dual-plate techniques are compared showing that a single-plate system can utilize lower voltages while at the same time being simpler to construct. The platform is designed for tissue immunohistochemistry staining experiments.

Keywords—electro-wetting; immunohistochemistry; low voltage; printed circuit board (PCB) microfluidics

I. INTRODUCTION

Reliable batch processing of rat brain samples is a critical and difficult issue in immunohistochemistry experiments. Conventionally, in tissue immune staining experiments, the neurologists use tweezers or hooks to move the micro-meter thick brain sections, which contain important data, from one Petri dish to another. This process is repeated several times to complete the process steps present in an immunohistochemistry experiment. The brain sections are very easily cracked along the boundary of the cortex and the mesencephalon during this process due to the hard dragging and frequently movements by the metal handling instruments. In many experiments, the result is a loss of data from, for example, a monthly prepared tissue sample. Current lab-automation techniques implemented by Electro-wetting [1, 2] and Dielectrophoresis [3, 4] are providing promising solutions to automate the experimental procedures and reduce the tissue damage. However, very few studies have tried to modify a platform specifically suitable for a rat's brain section immunohistochemistry staining. Because areas of tyrosine hydroxylase cells are in a range of about 4 mm, the conventional electro-wetting platforms are too small to wet the tissues efficiently. Further, fabricating an electro-wetting system using photolithographic techniques requires clean room facilities and expensive prototyping masks. To simplify the procedures this work develops a low-cost electro-wetting platform on a printed-circuit board (PCB) with large electrodes. The specific goal of this platform is for applications in rats' brain sections staining. The post-processed PCB array presented here can move large droplets (~30 μL) with a much smaller voltage and frequency than previously reported [5]. Voltage / frequency related performance and limitations of the PCB microfluidic system are also investigated. Result shows that it is a promising technique to assist neurologists in conducting tissue staining experiments.

II. MATERIALS AND METHODS

A. High Voltage Supply

A standard (FR-4, glass epoxy) double-sided PCB board (Advanced Circuits, Tempe, AZ, USA) is used for the substrate material. A PIC24FJ96 microcontroller (Microchip, USA) is used to control the operation of the circuit. The droplet operation can be pre-programed as self-running or it can be controlled in real-time with keyboard commands. The high-voltage module (EMCO F40, EMCO, Schweiz, Switzerland) is capable of supplying a DC voltage from 0 to 2000 V.

A high-voltage square wave is created at the drains, B0-B17, of NMOS transistors (VN2460) seen below in Fig. 1. P0-P17 are connected to the I/O ports of the microcontroller. For example, if P0 goes high then B0 goes low. If P0 goes low then B0 is pulled to the High DC Voltage through a resistor.

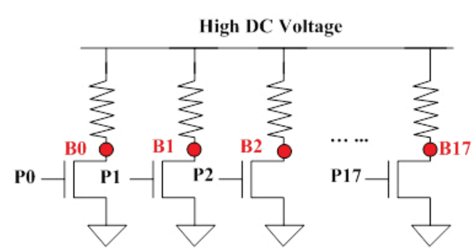

Figure 1 – Schematic of the voltage supply circuit.

B. Post-fabrication of the Substrate

The electrodes are made using bare copper rectangles on the top of the PCB. A plastic sheet (Saran Wrap, 15 μm thick polyethylene) [5] is cut in suitable size and coated on the top of the electrodes. Before the Saran Wrap is put on the top of the copper electrodes, a tissue is used to dampen a thin layer of peanut oil (or any other kitchen oil) on the top of the electrodes to help repel air bubbles that form on top of the electrodes. Peanut oil is also placed on top of Saran Wrap to create a hydrophobic surface. We did not use a commercial water-repellant liquid, such as Rain-X [5] to create the hydrophobic surface for our experiments. Peanut oil is used instead due to the capability of creating a larger contact angle than possible with Rain-X, Fig. 5.

C. Single-Plate and Dual-Plate Operations

Both single- and dual-plate operation were investigated in the work reported here. For single-plate operation the droplet must bridge two adjacent electrodes, Fig. 2a. To move the droplet one plate (colored gold in Fig. 2) is activated (driven to a high voltage) while the other plate is grounded. The droplet moves towards the activated plate. In a dual-plate operation topology the top plate is grounded so the droplet does not have to bridge two electrodes for movement to occur. In our dual plate experiments the top plate is made by ITO glasses (Adafruit, NYC, USA) and coated with a layer of Saran Wrap.

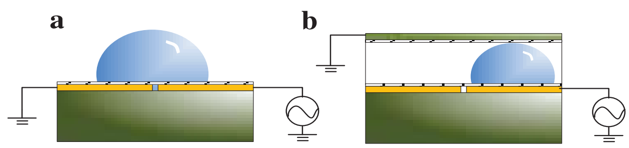

Figure 2 – Diagram of single plate operation (a), and dual plate operation (b).

A diagram showing the electro-wetting system is seen in Fig. 3. The control section of the system is a separate board, with display and keyboard. The electrode array is placed along with the high-voltage supply on its own board. A cable is used to connect the control board to the array board.

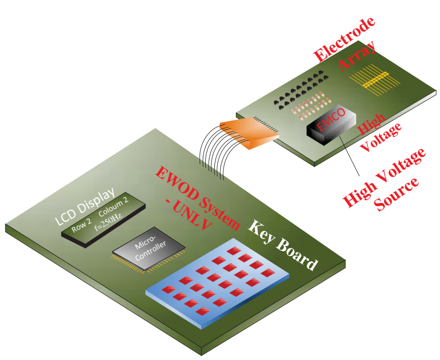

Figure 3 – Diagram of the electro-wetting system.

D. Contact Angle Calculation

The contact angle is modeled (Fig. 4) and calculated as following:

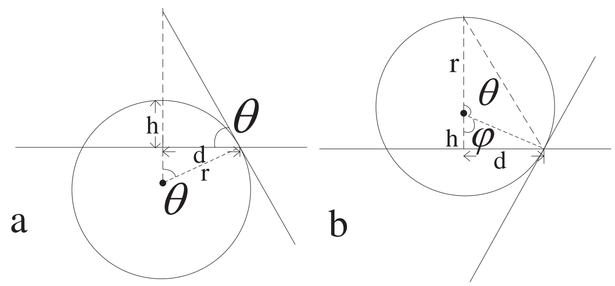

Figure 4 – (a) Diagram showing how the contact angle is calculated if the contact angle is less than 90° and (b) how it's calculated if it is larger than 90°.

Assuming θ is the contact angle, and that d and h are known, then for (a),

$$\tan\theta = \frac{d}{r-h},\ d^2 + (r-h)^2 = r^2$$

$$d^2 + r^2 + h^2 - 2rh = r^2,\ r = \frac{d^2+h^2}{2h}$$

$$\tan\theta = \frac{2hd}{d^2-h^2},\ \theta = \arctan\frac{2hd}{d^2-h^2}$$

and for (b)

$$\tan\theta = -\tan\varphi,\ \tan\varphi = \frac{r+h}{d}$$

$$d^2 + (h-r)^2 = r^2,\ r = \frac{d^2+h^2}{2h}$$

$$\tan\varphi = \frac{d^2+3h^2}{2hd},\ \theta = \pi - \arctan\frac{d^2+3h^2}{2hd}$$

Figure 5 shows varying contact angles between a droplet of water and different surfaces. An actuation voltage of 500 V at 18 kHz was previously reported when using Rain-X [6]. But, in our experiments, the lowest actuation voltage is around 200 V at DC to 1 kHz. This may be attributed to the hydrophobic oil applied to the surface. The peanut oil coated surface can increase the contact angle to 98°, Fig. 5d.

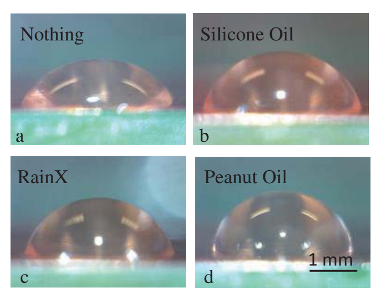

Figure 5 – Differences in contact angles of pure water droplet on different coated Saran Wrap surfaces. No voltages applied. a. Nothing coated on the Saran Wrap; b. With silicone oil coated on the Saran Wrap. c. With RainX coated on the Saran Wrap. d. With Peanut Oil coated on the Saran Wrap.

III. RESULTS

A. Comparison of the Contact Angle on Different Surfaces

Ideally, the droplet's contact angle is large with no voltage applied and becomes small with the application of a voltage (electric field). When this occurs the droplet can be moved quickly from one position to another. The contact angles of pure water droplets were compared on four different surfaces, Fig. 6. The surface coated with peanut oil, Fig. 5d, shows the largest contact angle with no applied electric field.

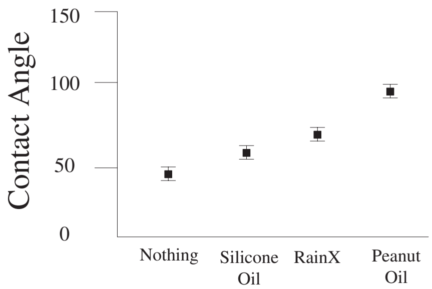

Figure 6 – Diagram of the average contact angles of the four surfaces, and standard deviations (SD) of the contact angle of different surfaces

B. Voltage and Freqency Based Contact Angle Changes

The contact angle is more sensitive to changes in voltages than changes in frequencies, Figs. 7-8. The result is that the first choice, when trying to move large droplet, is to increase the voltage but not change the frequency.

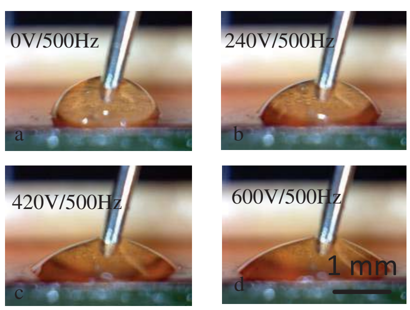

Figure 7 – On a peanut oil coated surface, measuring the contact angle change with voltages. Voltages are supplied at the surface. The stainless steel needle penetrating the droplet is grounded.

The actuation (threshold) voltage (at 500 Hz) to move the droplet in single-plate platform is much smaller than in the dual-plate platform, as seen in Fig. 9. In the dual plate platform, the grounded electrode (the top ITO glass) is less conductive than metal, and the dielectric layer (Saran Wrap) is too thick (15 μm).

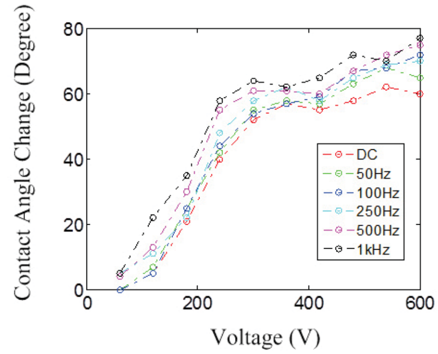

Figure 8 – Contact angle change with frequencies and voltages again using a pure water droplet on a peanut oil surface.

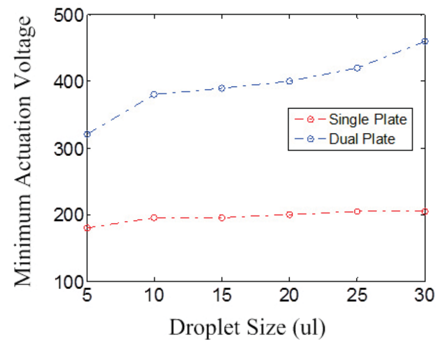

Figure 9 – Minimum actuation voltage at 500 Hz in single-plate and dual-plate platforms.

Figures 10-12 show actuation, merging, and splitting (respectively) of coffee droplets on both the single-plate (a) and the dual-plate platforms (b).

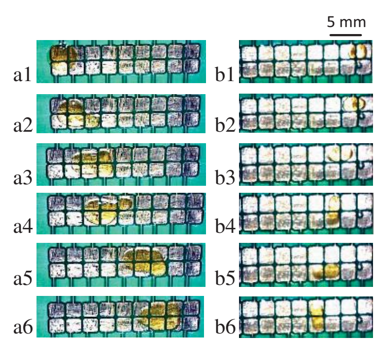

Figure 10 – Actuation of coffee droplets in single plate platform (a1-a6), and dual plate platform (b1-b6).

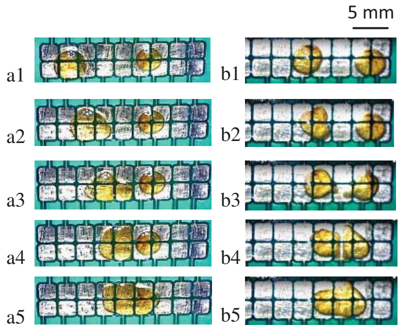

Figure 11 – Merge of coffee droplets in single plate platform (a1-a5), and dual plate platform (b1-b5).

It was previously reported, [5], that a single-plate platform is incapable of splitting droplets. However, we were able to split droplets as can be seen in Fig. 12a. As seen in this figure, the right-most electrodes are held at a constant voltage. The electrodes are then sequentially activated to move portions of the coffee droplets towards the left.

Note that the dual-plate images seen on the right side of Figs. 10-12 are less clear and lighter colored than the single-plate images on the left side of the figures because of the reflection from the cover (top plate).

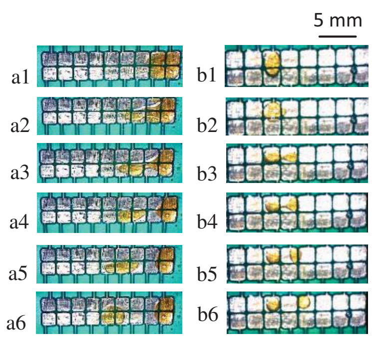

Figure 12 – Split of coffee droplets in single plate platform (a1-a6), and dual plate platform (b1-b6).

IV. Conclusion

A platform for the manipulation of droplets has been developed and characterized. In the dual-plate design the size of the droplet is more flexible. The droplet can be scaled down to the same size as the electrode (Fig. 10b and Fig. 12b). In the single-plate design the droplet should be no smaller than 2 electrodes (4 mm when a 2 mm electrode is used) to ensure reliable movement. The droplet size is one limitation of the standard PCB prototyping. When designing the PCB board, the gap between the electrodes should be no less than 75 μm, so it is hard to make intersectional electrodes which will ease the movements of smaller droplets. A razor blade can be used to create the gap between electrodes as described in other studies [5, 6]. Even with these shortcomings, this technique is still attractive for neurological experiments due to the absence of mechanical components and the resulting reduction in damage to the tissue being tested.

The single-plate electro-wetting platform developed in this study is able to move 30 μL (5-6 mm in diameter) droplets with an actuation AC voltage of around 200 V. Prototyping this microfluidic system is fast and efficient requiring no clean room facilities or special semiconductor-fabrication related skills. This technique can be a good candidate for assisting neurologists in the reliable and efficient batch processing of immunochemistry and H&E [8] staining of rats' brain sections.

Future work will investigate how electrode geometry and the size of the gaps between the electrodes influence the actuation voltages. Further, scaling to smaller geometries, perhaps using integrated circuit (IC) technology, will be explored. The use of the thinner dielectrics in ICs under the electrodes, for example, should result in smaller actuation voltages.

References

[1] M. S. Kim, T. Kim, S. Kong, S. Kwon, C. Y. Bae, J. Choi, C.H. Kim, E.S. Lee and J. Park, "Breast cancer diagnosis using a microfluidic multiplexed immunohistochemistry platform," PloS one, vol. 5, no. 5, pp. e10441, May. 2010.

[2] M. G. Pollack, R. B. Fair and A. D. Shenderov, "Electrowetting-based actuation of liquid droplets for microfluidic applications," Appl. Phys. Lett., vol. 77, no. 11, pp. 1725-1726, Jul. 2000.

[3] H. Zhao, "Role of hydrodynamic behavior of DNA molecules in dielectrophoretic polarization under the action of an electric field," Physical Review E, vol. 84, no. 2, pp. 021910, Aug. 2011.

[4] G. Medoro, N. Manaresi, A. Leonardi, L. Altomare, M. Tartagni and R. Guerrieri, "A lab-on-a-chip for cell detection and manipulation," Sensors Journal, IEEE, vol. 3, no. 3, pp. 317-325, Jun. 2003.

[5] M. Abdelgawad and A. R. Wheeler, "Low-cost, rapid-prototyping of digital microfluidics devices," Microfluidics and Nanofluidics, vol. 4, no. 4, pp. 349-355, Apr. 2008.

[6] M. Abdelgawad and A. R. Wheeler, "Rapid prototyping in copper substrates for digital microfluidics," Adv Mater, vol. 19, no. 1, pp. 133-137, Jan. 2007.

[7] J. Gong and C. Kim, "Direct-referencing two-dimensional-array digital microfluidics using multilayer printed circuit board," Microelectromechanical Systems, Journal of, vol. 17, no. 2, pp. 257-264, Apr. 2008.

[8] Y. Li, X. Tian, L. Qian, X. Yu, and W. Jiang, "Anodal transcranial direct current stimulation relieves the unilateral bias of a rat model of Parkinson's disease," Engineering in Medicine and Biology Society, pp. 765-768, Sep. 2011.