Multiplexed Localization in Bi-Layer Digital Microfluidic Systems

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ABSTRACT

This paper reports a new protocol for digital microfluidic (DMF) systems. The DMF multiplexer is based on a cross-referenced architecture and makes use of bi-polar voltage activation and threshold effects to overcome addressability limitations. This eliminates inter-droplet actuation interference. The threshold voltage phenomenon is studied in this paper theoretically and experimentally. The numerical results of a 2-D COMSOL simulation of a closed DMF structure are shown. Experimental results verify the operation of the proposed DMF multiplexer, as the independent motion of a single microdroplet in a multi-microdroplet system is presented.

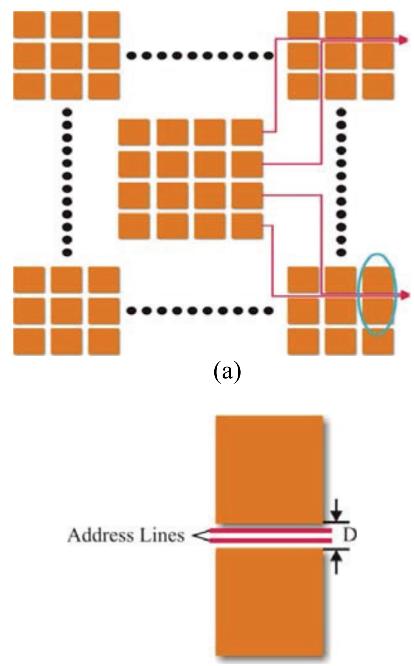
Keywords: Digital microfluidics, multiplexer, bi-polar, threshold voltage

1 INTRODUCTION

Electrowetting (EW) is a desirable actuation mechanism for microdroplet control in digital microfluidic (DMF) devices. The first generation of DMF systems [1, 2] made use of a catena wire inside a microdroplet that is placed on top of hydrophobic/dielectric layers and a metal electrode. The second generation of DMF systems became far more practical, however, because it made use of closed DMF structures [3, 4]. The closed geometry reduced evaporation and allowed for the actuation of multiple microdroplets.

The greatest challenge remaining for the afore-mentioned closed DMF architectures is the addressability of the inner electrodes. As is shown in Fig. 1, addressing of underlying electrodes in a DMF system with individually addressed electrodes in a 2-D electrode grid has severe limitations. Electrical address lines (i.e. wires) must be patterned from the contact pads at the edges of the chip to each metal electrode, and these address lines cannot short, overlap or cross each other. Scalability to large 2-D structures is therefore virtually impossible. With this in mind, Fan et al. [5] introduced an innovative bi-layer structure, with x and y electrode arrays placed orthogonally to each other on either side of the microfluidic control region. This configuration is called cross-referencing and is shown in Fig. 2.

The complexity of the cross-referenced DMF structure is greatly reduced compared to the 2-D individually-addressed electrode arrays. In fact, the only remaining major limitation to this newest generation of DMF systems relates to the simultaneous motion of multiple microdroplets [6]. The desire to actuate only one microdroplet becomes difficult in a multiple microdroplet system, as all microdroplets in the presence of a net applied voltage will start to move. (For example, a voltage applied to a top row electrode with two microdroplets positioned below it will simultaneously actuate both microdroplets– even if the simultaneous motion of both microdroplets is not desired.)



(a)

(b)

Figure 1: Addressability issues are shown for a 2-D DMF system with (a) a schematic of the overall structure and (b) the gap size, D, limitations between the inner electrodes.

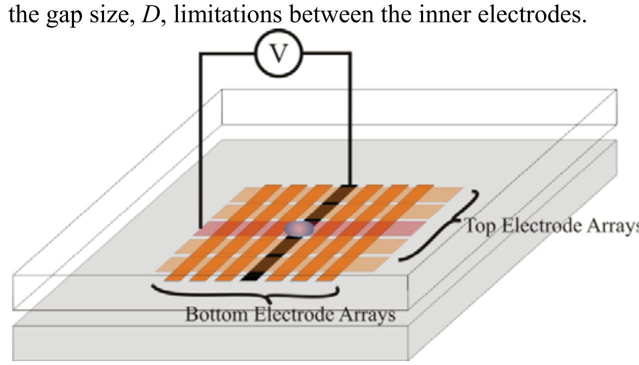


Figure 2: The voltage activation process for a cross-referenced structure is shown.

This paper introduces a novel DMF multiplexer protocol that overcomes the aforementioned limitations of cross-referencing systems. The fundamental operation of these DMF multiplexers makes use of a cross-referencing architecture and bi-polar voltage activation. The bi-polar electrode activation is important, as it is used to create a localized above-threshold-voltage condition and actuate an individual microdroplet. The DMF multiplexers are designed such that motion is induced only in regions where the overlying top electrodes (with $+V_{app}$) overlap the underlying bottom electrodes (with $-V_{app}$). A threshold condition is used to ensure that only the $2V_{app}$ voltage difference in this location can cause the microdroplet motion. Regions experiencing only $\pm V_{app}$ voltage differences will not overcome the threshold voltage condition and will not induce motion. This technique, being the first of its kind, is expected to allow for enhanced $m \times n$ addressability with multiple microdroplets using only $m+n$ electrodes.

The two requirements of the DMF multiplexer system–being based upon a cross-referencing architecture and bi-polar voltage activation–are studied numerically and described in the following two sections.

2 THRESHOLD VOLTAGE ACTUATION

In the numerical analysis of the proposed DMF multiplexer structure, the nonlinear relationship between the applied voltage and the contact angle change in the Lippmann-Young equation is the main cause of the threshold effect. At voltages below this threshold, V_{th}, contact angle changes of the microdroplet are negligible, while at voltages beyond this magnitude the contact angle changes become significant.

The threshold-voltage phenomenon can be studied through a simultaneous 2-D analysis of hydrodynamics and electrostatic field conditons in a closed DMF system. This is accomplished with a COMSOL multiphysics simulation providing coupling of the Level-Set method and a quasi-static field solver. The nonlinear relation between the contact angle and applied voltage is a function of many parameters (such as the dielectric thickness, surface roughness, droplet size, and gap distances between the electrodes). In this simulation the Level-Set method for two-phase laminar flow solves the Navier-Stokes equation with surface tension introduced as an external force.

The hydrodynamic and electrostatic modules of the simulation are related to each other through the defining of the contact angle θ with the Lippmann-Young equation:

$$\cos\theta = \cos\theta_0 + \frac{C}{2\gamma_{LV}} V_{diff}^2 , \tag{1}$$

where θ_0 is the initial contact angle, C is the capacitance per unit area, and γ_{LV} is the liquid-vapor surface tension.

In order to study the threshold voltage phenomenon, the COMSOL simulation is analyzed for a variety of applied voltages to find the exact voltage in which the microdroplet starts to move. The range of the applied voltage can be divided into three parts: lower than the threshold voltage, at the threshold voltage and greater than the threshold voltage. In the first part (i.e. $V_{app} < V_{th}$) the microdroplet contact angle change is very small, and the microdroplet does not start to move due to the lack of sufficiently large electrowetting on a dielectric (EWOD) forces. In the second part (i.e. $V_{app} = V_{th}$) there is a noticeable change in contact angle, and the microdroplet starts to move towards the activated electrode. In the third part (i.e. $V_{app} > V_{th}$), the threshold voltage is surpassed, and the contact angle change increases considerably. The microdroplet exhibits rapid motion.

Numerical results for the threshold-based effects are shown in Figs. 3-5. Fig. 3 shows the microdroplet with negligible actuation for $V_{app} < V_{th}$. The contact angle change becomes apparent in Fig. 4, where $V_{app} = V_{th}$. Here, the threshold voltage initiates the contact angle change of the right edge of the microdroplet. The change becomes noticeable, compared to the previous case, and surface tension forces are large enough to initiate the microdroplet motion. The contact angle change of the microdroplet at the voltages beyond the threshold voltage is shown in Fig. 5.

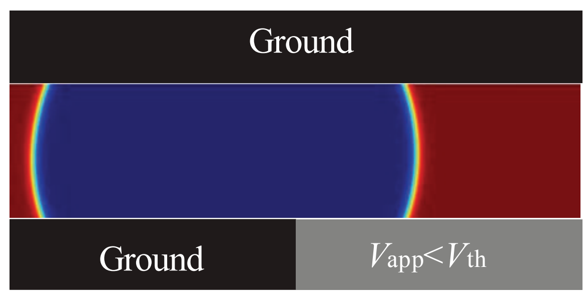


Figure 3: COMSOL results are shown for a 2-D closed DMF system before the threshold voltage, $V_{app}<V_{th}$.

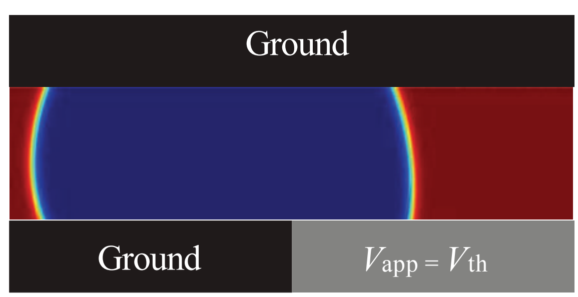


Figure 4: COMSOL results are shown for a 2-D closed DMF system at the threshold voltage, $V_{app}=V_{th}$.

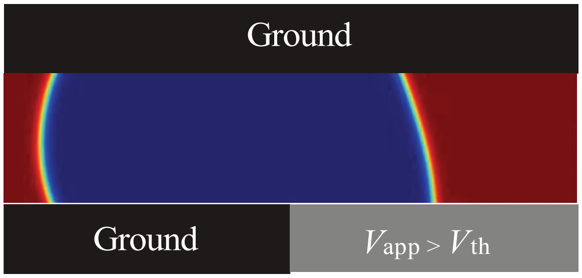


Figure 5: COMSOL results are shown for a 2-D closed DMF system after the threshold voltage, $V_{app}>V_{th}$.

3 BI-POLAR VOLTAGE ACTIVATION

To study the field effects of the proposed bi-polar voltage activation scheme, a 3-D simulation of a DMF multiplexer system with bi-polar activation is carried out using COMSOL. This simulation has only one electrostatic component, and similar to the electrostatic part of the 2-D closed DMF system, the conductive media DC application mode of COMSOL is used. The boundary conditions of this simulation are selected in a way that only the second top (m = 2) and bottom (n = 2) electrodes experience electric potentials of $+V_{app}$ and $-V_{app}$, respectively. In this simulation the applied voltage to the bottom and top electrodes are selected by considering the threshold voltage of the DMF system described in section 2. The magnitude of V_{app} is selected such that, by itself, it is smaller than the threshold voltage, and when doubled in the overlapped electric region to $2V_{app}$, it is greater than V_{th}.

As shown in Fig. 6, the normalized electric field at the intersection of the two activated electrodes is higher than the threshold electric field required for initiating microdroplet motion. At the same time, the electric fields in other regions (e.g., m = 2 and n = 4) are below the threshold electric field and thus cannot initiate microdroplet motion. Given microdroplets placed in the same row (i.e. m = 3), only the one at the position m = 2 and n = 2 will move to the left. This satisfies our requirements for complete $m\times n$ addressability in the 2-D plane.

4 FABRICATION AND EXPERIMENT

To test the operation of the DMF multiplexer, two rectangular electrode arrays are designed and fabricated in our UBC DMF Laboratory (see Fig. 7). These two electrode arrays are oriented as orthogonal top and bottom electrodes. The multiplexer is patterned via photolithography from 45 nm thick copper films (EMF corporation, Ithaca, NY). The electrodes have a 500 µm width and 600 µm pitch. A PDMS (Dow Corning corporation, Midland, MI) layer is then spin-coated and baked over top of the electrode arrays to act as both the hydrophobic and dielectric layers [7, 8]. The structure is mounted on an xyz translation stage for testing.

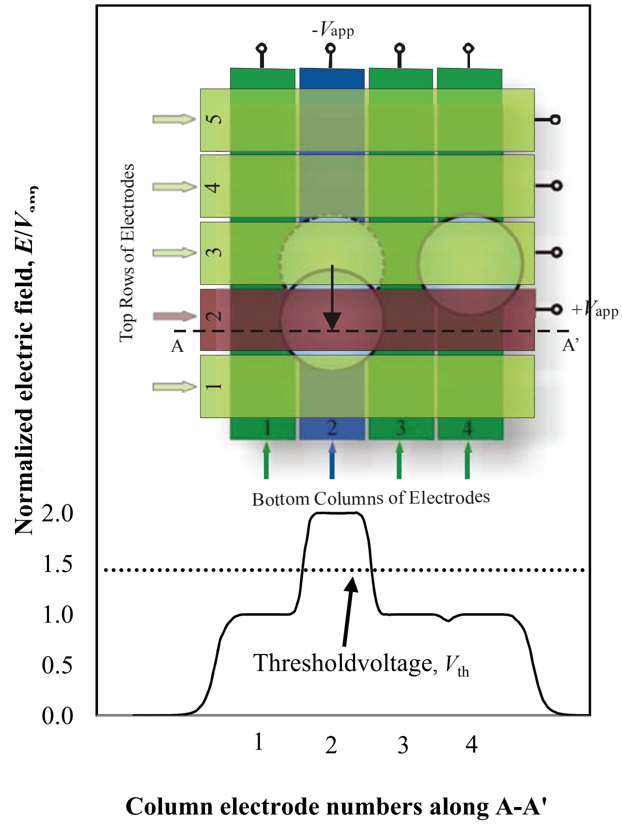
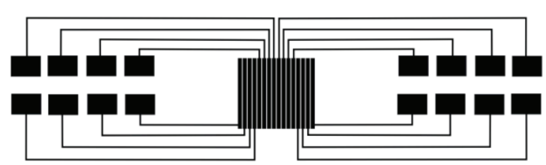


Figure 6: The electric field within the 3-D DMF multiplexer system is stimulated in COMSOL and shown here.

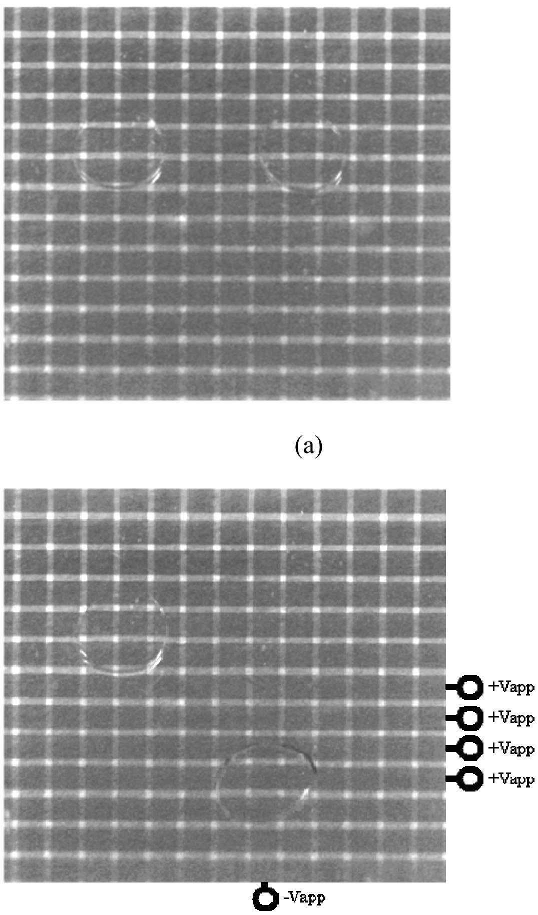
(a)



(b)

Figure 7: A fabricated electrode array for the DMF multiplexer is shown in this figure: (a) pre-coated copper microscope slide and the patterned electrode array, and (b) the photolithography mask used for device fabrication.

A high-resolution camera (LEICA APO Z6) is used to acquire the image of microdroplets within the DMF multiplexer during bi-polar voltage activation. The onset of the motion, being of relevance to the threshold-based voltage actuation, is recorded by this camera. The results are shown in Fig. 8. The desired motion for the unactivated conditions shown in Fig. 8(a) is downward for the right microdroplet (and only the right microdroplet). To accomplish this, $-V_{app}$ is applied to the column electrode shown in Fig. 8(b), and $+V_{app}$ is applied to the row-electrodes shown in the same figure. Note how the combination of these two applied voltages will create a localized high-field region at the lower edge of the right microdroplet. This high field region overcomes the threshold electric field and droplet motion is induced. The resulting motion of the right microdroplet is shown in Fig. 8(b). The left microdroplet remains stationary.



(a) (b)

Figure 8: Microdroplet motion in a DMF multiplexer system is shown in this figure: (a) two 0.5 μL microdroplets are sandwiched between the top and bottom electrode plates; (b) the right microdroplet moves downwards due to its experiencing of a $2V_{app}$ electric potential (while the left microdroplet remains stationary).

5 CONCLUSION

Independent motion of microdroplets in a cross-referenced architecture was achieved for systems incorporating multiple microdroplets. To accomplish this motion, a multiplexing format was introduced to satisfy threshold-based voltage actuation and bi-polar voltage activation in a cross-referenced architecture. The device met the two requirements for enhanced $m \times n$ addressability in a two-dimensional grid, and the numerical results were experimentally verified with the fabrication and testing of a DMF multiplexer device.

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