DETERMINISTIC SPLITTING OF ELECTROWETTING MICROCHANNELS

Ananda Banerjee, Yuguang Liu, Jason Heikenfeld and Ian Papautsky*

School of Electronic and Computing Systems, University of Cincinnati, Cincinnati, OH USA

ABSTRACT

In digital microfluidics, droplet generation approaches show ~10% variation in droplet volumes. In this work, we demonstrate a new approach for splitting sample volumes precisely by gradually ramping down voltage. This allows us to eliminate hydrodynamic instabilities responsible for variations in droplet volume. A simple visual method was developed for measuring sample volumes created on chip. Our results show that generating and measuring arbitrary sample volumes accurately, with <1% variation is possible in electrowetting based devices. This approach can be easily extended to existing digital microfluidic systems, and can potentially improve the performance applications requiring precise sample metering, such as immunoassays or DNA amplification.

KEYWORDS

Electrowetting, splitting, fluid dispensing, programmable channels, virtual channels

INTRODUCTION

Digital microfluidics relies on controlled sample volumes in the form of droplets, yet conventional droplet generation approaches show ~10% variation in droplet volumes and are restricted to creating only small volumes [1, 2]. Splitting a droplet typically involves abrupt de-activation of an energized electrode and thus de-wetting migration of fluid to the adjoining energized electrodes. Variations in the generated droplet volume have been attributed to hydrodynamic instabilities arising in the splitting region and decrease in volume of the source reservoir. [1] More precise methods of volume control involve feedback loops and require complex signal processing.

In this work, for the first time, we demonstrate deterministic splitting of precise sample volumes in electrowetting (EWOD) microfluidic devices. We show that instabilities can be eliminated by ramping potential at the splitting electrode with a simple open loop system, thus enabling precise control of sample volumes without complex signal processing. We recently demonstrated programmable microfluidic channels capable of sustaining pressure driven flows and on-demand reconfiguration in an electrowetting-based platform [3, 4]. That work merged the paradigms of digital and continuous microfluidics for the first time. Now, we incorporate deterministic splitting for generating microfluidic channels or droplets of precise volumes (< 1% error). The concept of ramped splitting for dispensing finite sample volumes is a readily adaptable and can potentially benefit electrowetting applications requiring accurate sample dispensing.

METHODS

Devices were fabricated with insulated gold electrodes patterned on a glass substrate. A patterned spacer layer defined the height of the channel and the inlet and outlet reservoirs (Fig.1). A "virtual" microchannel was formed over voltage-activated (70V) insulated electrodes with aqueous fluid (PBS) in an oil-ambient. The electrode at the center formed the splitting region and was connected to the power supply through a resistance network for controlling the applied voltage.

When potential was ramped down, fluid occupying the splitting region migrated to the adjoining voltage-activated segments causing them to bulge. This bulging in the fluid segments is accompanied by an increase in the area of cross-section and a consequent change in the sidewall radius of curvature R_s and apparent bottom contact angle θ_s (Fig. 2a).
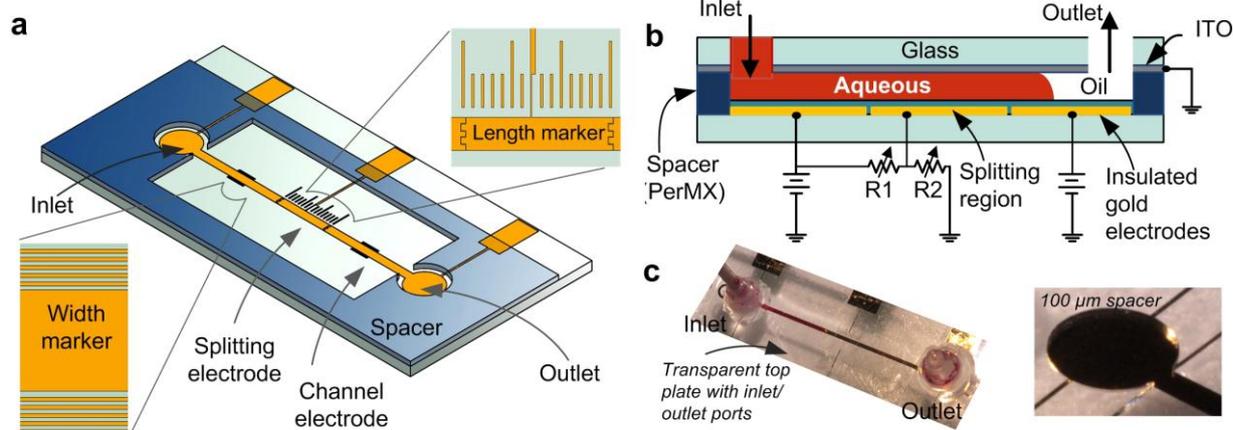
Figure 1: *(a) Electrowetting device for demonstrating deterministic splitting. Width and length markers can be used for determining volume and position of splitting. (b) Cross-section of electrowetting device. The voltage applied to the splitting electrode is controlled by suitably varying the resistances R1 and R2 connected to it. (c) Virtual microfluidic channel formation and magnified image of inlet/outlet reservoir patterned in the spacer layer.*

$$w_P = 2R_s \, sin^2 \left(\frac{\theta_s - 90}{2} \right)$$

$$Area = hw - R_s Sin\theta(h + R_s) + \frac{\theta}{180} \pi R_s^2$$
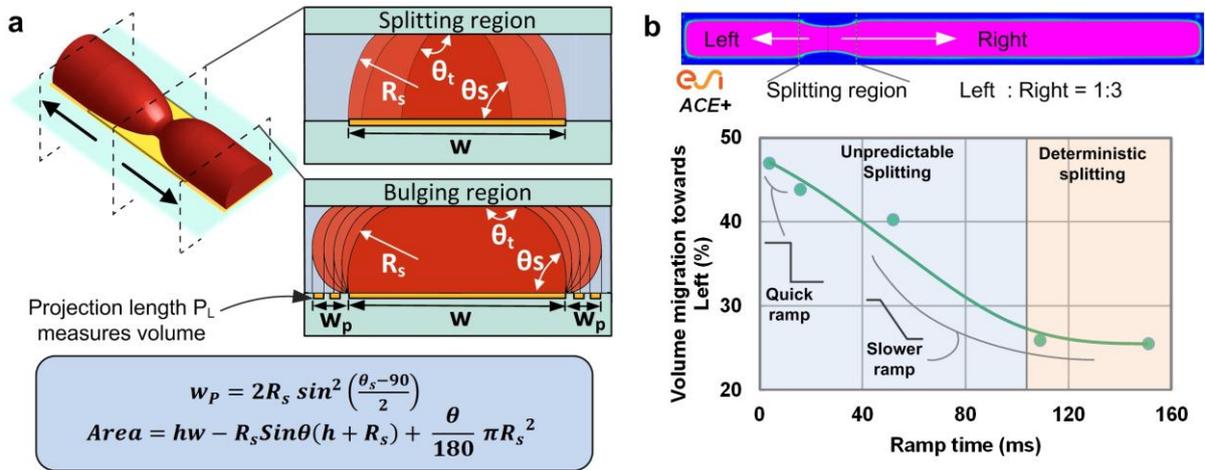
Figure 2: *(a) Splitting and bulging in virtual channels. The projection of the bulge w_p can be used to determine the area of cross section and volume of the bulged segments. (b) CFD ACE+ model of splitting. Graph shows that deterministic splitting is achieved when voltage is gradually ramped.*

When seen from the top the sidewalls of the bulge in the sidewalls appear to be a uniformly advancing front. The projection of bulge w_p can be expressed in terms of R_s and θ_s. The precise volume of fluid segments of known length created by the process of splitting can be calculated by measuring the projection length experimentally and finding the corresponding value of the bottom contact angle and the associated area of cross-section. The process of visual volume measurement was aided by the width markers lining the channel electrodes (Fig.1). Length markers patterned lining the splitting region indicated the position of splitting.

Under equilibrium conditions, migration of fluid should be governed by the maintenance of uniform Laplace pressures at all regions of the oil-water interface. This implies that fluid migration to either side of the splitting region would be proportional to the lengths of the voltage-activated regions. This is consistent with the mechanisms of droplet splitting described in literature [1, 5]. However, if voltage is switched off abruptly at the splitting electrode, the fluid volume occupying this region becomes hydrodynamically unstable without any confining forces to hold it in place. The migration of fluid from this region to the adjoining voltage-activated segments becomes unpredictable. The nature of the unpredictability lies in the proportion of fluid migrating to either side. This is the cause for deviation in volume of droplets in electro-wetting digital microfluidic devices.

Fluid migration from the splitting region to the adjacently-located existing fluid can be controlled in a more predictable manner if the voltage applied at the splitting electrode is gradually reduced. This would allow time for mass transfer from the splitting region to proceed under near-equilibrium conditions. The excess fluid accommodated at the hydrophilic regions on either side causes an equal bulging such that the Laplace pressure is the same at all regions along the oil-aqueous interface.

RESULTS AND DISCUSSION

Fluid redistribution from the splitting region is governed by hydrodynamic instabilities. We developed a numerical model in CFD-ACE+ (ESI Inc.) to understand and reduce the effects of instabilities (Fig.2b). Our numerical results show that fluid redistribution from the splitting region is proportional to the length of the adjoining segments when potential is reduced gradually (>120 ms). We successfully demonstrated this experimentally. The experiments involved splitting a 25mm long fluid segment at the center, over a splitting electrode 3 mm in length. The volume of the entire microchannel was 1.12 µL. In the first set of experiments we gradually ramped down the voltage applied to the splitting electrode by changing the resistance of the network through which the splitting electrode was connected. In the later set, the same experiment was repeated by abruptly grounding the splitting electrode. The volume of the split segments on both sides of the splitting region was observed in both cases. Under ideal conditions, the volume of the segments on both sides of the splitting region should be equal. The volume of both segments was calculated by measuring the projection length of the bulge on either side of the splitting region.

When voltage was abruptly turned off at the splitting electrode, we observed that the fluid migration to either side of the splitting region was unpredictable. The projection lengths on both sides of the splitting region were unequal. A representative result is shown in Fig.3, illustrating that most of the volume over the splitting region migrated to one side causing it to bulge more. In this case, the projection length was ~26 µm on one side and ~5µm on the other. The volume of the segment was calculated to be ~0.586 µL, with the volume of the other segment ~0.534 µL. This is a deviation of +/- 5% from the targeted volume of 0.558 µL. Gradually decreasing voltage at the splitting electrode yielded two split fluid segments of equal volume, as illustrated in Fig. 3b,c. The splitting progressed with the formation of symmetric radii of curvature on the sidewalls over the splitting electrode. Fluid migrated to the adjoining voltage-activated regions causing them to bulge. When splitting was completed, the projection length of the bulged segments was measured using the 10 µm
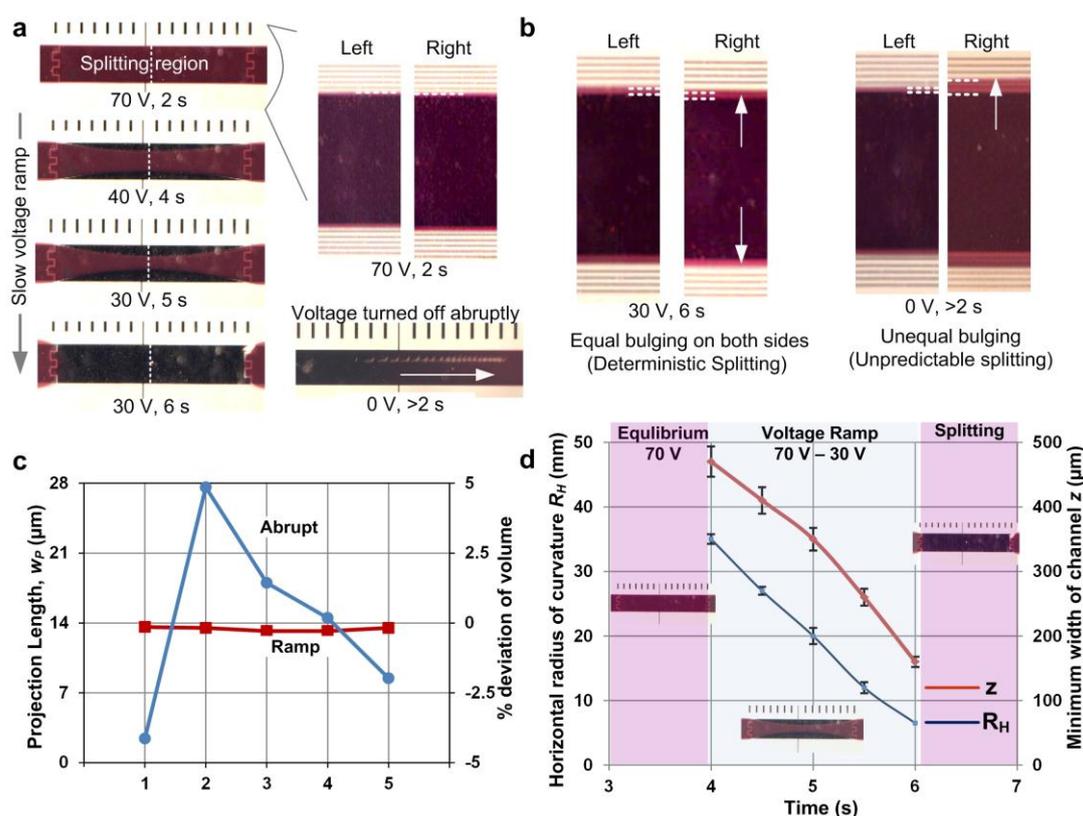
Figure 3: (a) Experimental results showing both deterministic and unpredictable splitting at centered electrode. For the gradual voltage ramp, a symmetric radius of curvature is observed. (b) The final bulge on both sides is equal (w_p ~13.5 μm) for gradually ramped splitting. Abruptly turning off voltage leads to unequal bulging on two sides.(c) 5 sets of experiments each with ramped splitting (red) and abrupt splitting (blue) are shown. The volume variations from the target ranged < **1%** for ramped splitting and +/-5% for abrupt splitting.(d) Radius of curvature and minimum width of channel at the splitting region during ramped splitting. Gradually reducing voltage from 70V to 30V over 2 seconds.

width markers patterned on either side. The projection length was found to be ~13.5 μm on either side of the splitting region yielding a volume of ~ 0.558 μL on either side. The experiments were repeated 5 times and the measurements were found to be within 1% maximum variation (Fig. 3c). We also measured the radius of curvature in the splitting region and the minimum channel width at the splitting region for all experiments to confirm that the process of splitting proceeds in a deterministic manner (Fig. 3d).

CONCLUSIONS

In summary, for the first time, we demonstrate precise deterministic splitting of volumes in electrowetting, overcoming the well-accepted ~10% variability. Using the ramping strategy described herein, it is possible to generate a wide range of sample volumes with improved precision (< 1% error). We envision that this would benefit applications requiring precise reagent volumes in both droplet and microchannel EWOD platforms. Ultimately, this work moves us closer to the ability of forming EWOD fluid networks 'on-demand', which we expect would have a wide range of applications in medical diagnostics, environmental monitoring, and agriculture.

REFERENCES:

[1] J. Gong and "CJ" Kim, *Lab. Chip*, 2008, **8**, 898.
[2] R. B. Fair, *Microfluid. Nanofluid.*, 2007, **3**, 245.
[3] A. Banerjee, E. Kreit, Y. Liu, J. Heikenfeld and I. Papautsky, *Lab. Chip*, 2012, **12**, 758.
[4] M. Dhindsa, J. Heikenfeld, S. Kwon, J. Park, P. D. Rack and I. Papautsky, *Lab. Chip*, 2010, **10**, 832.
[5] J. Berthier et al., *Sens Actuators A ,* 2006, **127**, 283-294.

CONTACT
***Ian Papautsky, Tel: +1-513-556-2347; ian.papautsky@uc.edu