

LIGHT-ACTUATED DIGITAL MICROFLUIDICS FOR LARGE-SCALE, PARALLEL MANIPULATION OF ARBITRARILY SIZED DROPLETS

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ABSTRACT

We report on a new light-actuated digital microfluidics device which is capable of using on demand, ‘virtual’ electrodes formed by a data projector to enable large-scale, parallel manipulation of arbitrarily sized droplets. The device features a thin, high-quality Al₂O₃ film deposited via atomic layer deposition (ALD) which allows aggressive scaling of the dielectric thickness, while maintaining high device reliability. We demonstrate the splitting, merging and parallel manipulation of droplets at high actuation speeds (2 cm/s). Due to the thin ALD dielectric layer, this high actuation speed is achieved at 85x lower optical power and 5x lower voltage than our previous device.

INTRODUCTION

The ability to quickly perform large numbers of chemical reactions in parallel using low reagent volumes is a field well addressed by digital microfluidics. Compared to continuous flow-based techniques, digital microfluidics offers the advantage of individual sample addressing, reagent isolation, and compatibility with array-based techniques used in chemistry and biology [1,2]. Several biological and non-biological applications, such as DNA amplification with polymerase chain reaction [3], purification of peptides and proteins from heterogeneous mixtures [4], and chemical synthesis [5], have been demonstrated using digital microfluidics.

Digital microfluidics is generally realized by sandwiching a liquid droplet between two layers of electrodes. One layer has a grounding electrode over its entire surface while the other contains an array of lithographically defined, individually addressable electrodes. The spacing of these electrodes is such that the droplet covers more than one electrode at a time so that a voltage may be applied to only part of the droplet [1,2]. The droplet is moved towards the region of high electric potential through a combination of electromechanical forces. A caveat to this technique, however, is that when multiple droplets need to be manipulated simultaneously, a large and complex electrode network must be created. Additionally, since the electrode size determines the minimum droplet

volume that can be actuated, as electrodes scale to smaller sizes, interconnect and addressing of these electrodes grows proportionally. Consequently, large scale droplet manipulation requires complex addressing schemes and multi-layer metal deposition [6].

In 2003, we reported a device which removed the need for individual electrode addressing imposed by current techniques. Instead of lithographically defined interconnects, photo-sensitive interconnects were used to selectively address electrodes [7]. While this device removed the constraint of complex addressing schemes, the size of the manipulated droplet was still governed by the size of the patterned electrodes. We subsequently reported a device which utilized a continuous photosensitive film which replaced both the electrodes and interconnects to achieve droplet manipulation [8]. Since the electrode size was now defined by the size of the optical pattern, instead of the physical size of the electrode, we could manipulate picoliter to microliter scale droplets on the same device without the need to change the electrode spacing.

The force used to manipulate the droplets in digital microfluidics is proportional to the capacitive energy per unit area stored in the oxide layer [9].

$$F_{net} \sim \frac{\epsilon_{ox}}{d_{ox}} V_{ox}^2 \quad (1)$$

where F_{net} , ϵ_{ox} , d_{ox} , V_{ox} are the net force per unit length, electrical permittivity, oxide thickness, and voltage across the oxide layer, respectively. As is evident from Eq. 1, in order to achieve low voltage actuation, it is necessary to reduce the oxide thickness so that similar forces may be obtained. However, creating thin oxide layers is difficult in practice as the low thermal budget (~500 °C (dependant on the electrode material)) of these devices traditionally requires the use of low temperature processes (e.g. PECVD) which are not as conformal (i.e. not pin-hole free) as other high-temperature process (e.g. thermal oxidation). Atomic Layer Deposition (ALD) lends itself well to this issue. As a low temperature process that has near perfect conformality, it is a natural choice to address the aforementioned problem. ALD allows for the aggressive scaling of the oxide layer, enabling lower voltage actuation, without the quality

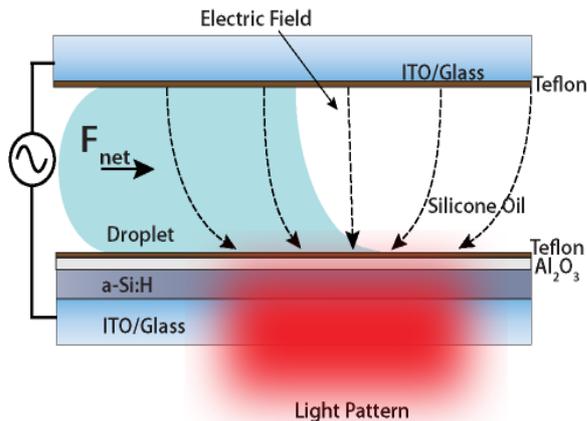


Figure 1: Device schematic showing incident light creates localized areas of high conductivity in the a-Si:H film. This creates localized electric field concentration in the illuminated region resulting in a net electro-mechanical force on the droplet.

issues associated with other low-temperature thin oxides [10].

In this paper, we use ALD deposited Al₂O₃ as the oxide layer in order to realize a new low-power, large format (> 1 cm x 1 cm) light-actuated digital microfluidics (LADM) device. Not only can the applied bias be reduced, but considerable lower optical power is necessary for virtual electrode creation. This enables the use of a simple data projector (instead of a laser) to control a large number of droplets at the same time.

DEVICE FABRICATION AND OPERATION

The LADM device concept and design is depicted in Fig. 1. The device consists of an indium-tin-oxide (ITO) (300nm) coated glass substrate, a 1-μm thick photosensitive a-Si:H layer deposited via plasma-enhanced chemical vapor deposition (PECVD) (Oxford Plasmalab 80plus), a 100-nm film of Al₂O₃ deposited by ALD (Picosun Sunale R150) and a 25 nm film of spin coated 0.2%-Teflon (1500rpm, 30s).

The top substrate is formed from another Teflon-coated ITO glass wafer. It should be noted that the entire fabrication process does not require any photolithographic steps.

The two substrates are then placed on top of one another separated by a 300-μm spacer of double-sided tape forming the microfluidic manipulation chamber. AC bias is applied to the top and bottom ITO substrates. A commercially available projector (Dell 4210X DLP) is focused onto the light-actuated digital microfluidics substrate (Fig. 2). Optical patterns are generated on an external computer and sent to the projector. The total manipulation area on-chip is 1.5 cm x 1.1 cm. Bright-field illumination and a CCD camera (Dinolite, AM413T) are used for visualization and recording.

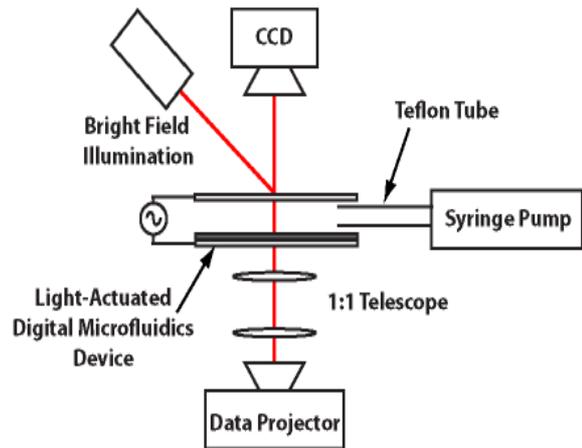


Figure 2: Experimental setup. A standard data projector (spatial light modulator) is focused onto the light-actuated digital microfluidics substrate with a 1:1 telescope. Bright-field illumination and a CCD camera allow for droplet visualization.

Fig. 1 also demonstrates the physical mechanism of the LADM device. In the absence of light, the externally applied voltage exists primarily across the highly resistive a-Si:H layer. However, upon illumination, the conductivity of the a-Si:H increases by more than 100x. This causes the externally applied voltage to now drop across the electrically insulating layers (oxide, Teflon). In turn, this causes the droplet to translate toward the illuminated region. As a result, the illuminated area acts as a virtual electrode.

METHODS

The fluidic chamber is first flooded with silicone oil (1.0 cSt DMS Trimethylsiloxy terminated Polydimethylsiloxane, Celest Inc. Morrisville, PA). Aqueous droplets with a conductivity of 10 mS/m are introduced into the fluidic chamber via a syringe pump (KD Scientific, 780210) and Teflon tube (Fig. 2).

The optical pattern of interest is drawn, in real-time, on a computer and sent to the data projector. The projector provides a maximum optical intensity of 3 W/cm² at the device surface. Simply by changing the size, shape and number of the optical patterns, droplets with a wide range of volumes can be manipulated on the same chip. We have successfully manipulated droplet volumes ranging from 5 nL to 2 μL on the LADM device.

RESULTS

Droplet Transport

To investigate droplet speed dependence on applied voltage, a square light pattern (1.05 mm x 1.05 mm) was projected onto the substrate near a 200 nL droplet. The resulting maximum velocity was recorded for various applied voltages (Fig. 3) at a frequency of 10 kHz. A maximum speed of 2 cm/s was achieved at 52 Vppk. Compared with prior work [8], the current

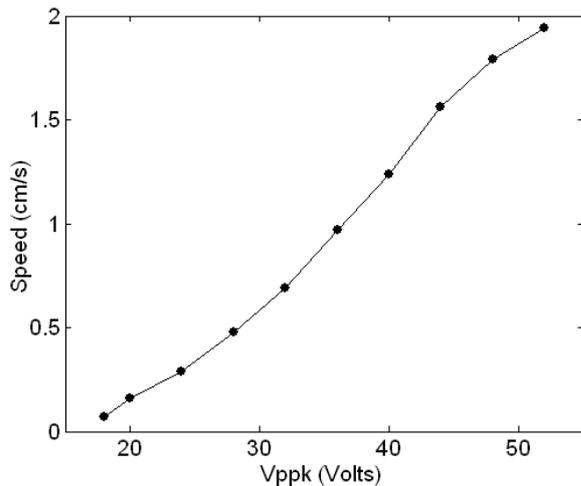


Figure 3: Maximum droplet speed versus voltage for a 200 nL droplet at 10 kHz frequency.

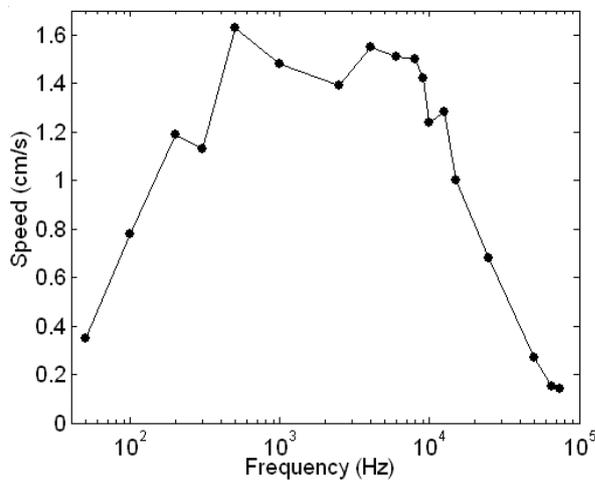


Figure 4: Maximum droplet speed versus frequency for a 200 nL droplet. Bias voltage is 40 Vppk).

device has 20x faster manipulation speed while using 5x lower voltage and 85x lower optical intensity. The droplet can be actuated with lower voltage bias, though at somewhat reduced speed. Voltages as low as 16 Vppk have been achieved and are amongst the lowest reported for digital microfluidics [10].

Fig. 4 demonstrates the frequency dependence of the LADM device. A square light pattern (1.05 mm x 1.05 mm) was projected onto the substrate near a 200 nL droplet and the maximum velocity was recorded for various applied frequencies (Fig. 4). For a 40 Vppk bias, actuation speeds > 1.5 cm/s are observed over a broad frequency range (500 Hz to 10 kHz).

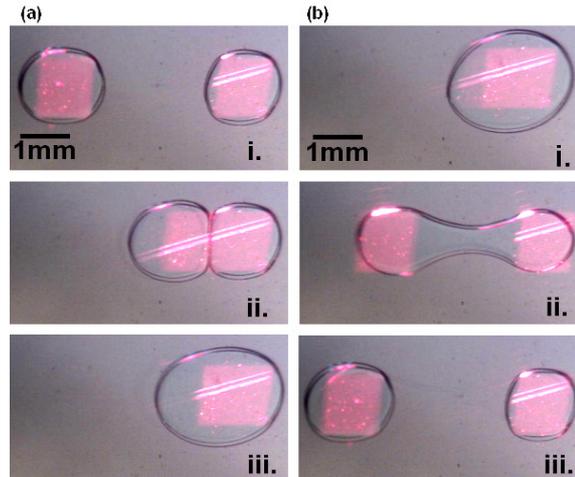


Figure 5(a): Droplet Merging - Two distinct 900 nL droplets (i) are merged (ii) by moving one light pattern towards the other resulting in a single droplet (iii) (50 Vppk, 10 kHz). (b) Droplet splitting - A single 1800 nL droplet (i) is pulled apart using two light patterns, with one pattern moving towards the left (ii), resulting in two distinct droplets (iii) (50 Vppk, 10 kHz).

Droplet Merging and Separation

The ability to merge and separate droplets is a critical component of any digital microfluidic system. In Fig. 5.a, two light patterns (1.15 mm x 1.30 mm) move two individual 900 nL droplets towards each other until they merge into one large droplet (1800 nL). Fig. 5.b demonstrates the splitting of an 1800 nL droplet into two 900 nL droplets. This is achieved by moving two light patterns in opposite directions. The voltage and frequency used for both merging and splitting was 50 Vppk and 10 kHz, respectively.

Multi-droplet Manipulation and Array Formation

The ability to create droplet arrays is important for many high throughput assay applications. This is a task well suited by LADM as parallel manipulation is achieved simply by altering the projected optical patterns.

Fig. 6 demonstrates LADM's ability to effect real-time, reconfigurable droplet manipulation. The simultaneous movement of 7 droplets is demonstrated. The 4 outer droplets move clockwise in a circular manner, whilst the 3 inner droplets move anti-clockwise (50 Vppk, 10 kHz).

Fig. 7 shows a 7x7 droplet array formed using the LADM device. Light patterns extract droplets dispensed from a Teflon tube and arrange the droplets into a vertical column of 7 droplets before transporting them into an array (50 Vppk, 10 kHz).

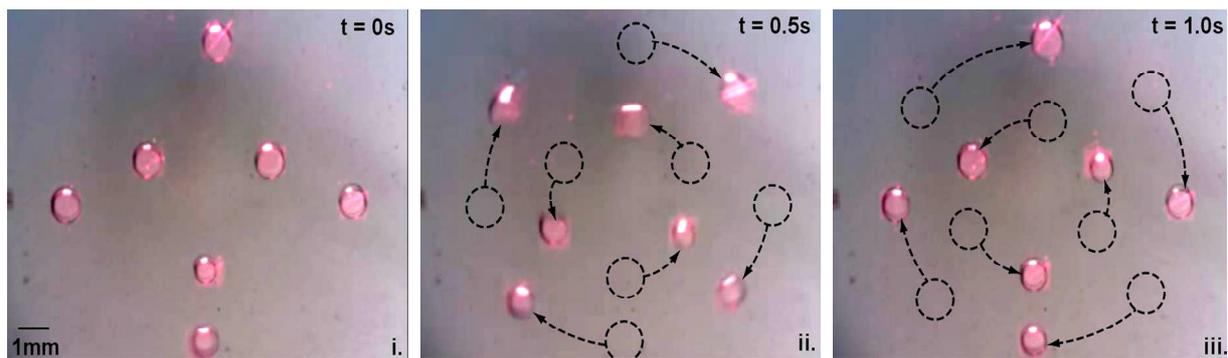


Figure 6: Parallel movement of droplets. 7 droplets undergo simultaneous movement. 4 outer droplets moves clockwise in a circular manner, whilst 3 inner droplets move anti-clockwise in a circular manner (50 Vppk, 10 kHz).



Figure 7: On-demand formation of a parallel array of droplets. Projected light patterns pull seven 200 nL droplets dispensed from a Teflon tube and arrange the droplets into a vertical column before transporting the droplets into a 7x7 array (50 Vppk, 10 kHz).

CONCLUSION

We have presented a Light-Actuated Digital Microfluidics device. This technique provides many advantages over current droplet manipulation methods including ease of fabrication and the ability for real-time, parallel, reconfigurable control. The use of an ALD oxide layer allows one to aggressively scale oxide thickness which subsequently reduces the required voltage and optical power necessary to achieve high speed actuation (2 cm/s). By reducing the optical power demands, a simple data projector can be used to pattern the virtual electrodes on the LADM surface. Using this technique, we have successfully demonstrated the translation, splitting, merging, and large-scale manipulation of droplets.

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