LIGHT ACTUATED MICROFLUIDIC DEVICES

Pei Yu Chiou, Zehao Chang, Ming C. Wu

Department of Electrical Engineering, University of California at Los Angeles,
420 Westwood Plaza, Los Angeles, CA 90095-1594, USA
TEL: (310) 8257338, FAX: (310) 7945513, Email: peiyu@icsl.ucla.edu

ABSTRACT

A light-actuated microfluidic device has been successfully fabricated to inject, move, separate, and merge liquid droplets with nano-liter volumes. Light actuation is realized by sandwiching the liquid droplets between two photosensitive surfaces whose wettability can be changed by light. By integrating a photoconductor with an electrowetting electrode, the surface tension at the liquid/solid interface above the electrode can be modified by shining an optical beam on the photoconductor. The surface tension change is reversible and has a fast response time (~ millisecond). The liquid droplets follow the optical beam path up to a speed of 78 mm/sec. All optical actuation for complete liquid droplet functions has been achieved. Simultaneous manipulation of multiple droplets is also demonstrated.

INTRODUCTION

Microfluidic devices have been widely used in chemical and bio-medical applications. Compared with macro scale devices, the microfluidic devices offer many advantages, including small sample volume requirement for expensive or hazardous reagents and short diagnosis time with reduced device size. There are two types of microfluidic systems: (1) continuous flow systems with pumps, valves, and channels; and (2) liquid droplet-based system actuated by surface tension force. The latter is called digital fluidic system. It has attracted much attention recently because it eliminates the need for pumps and valves, minimizes the risks of cross-contamination, and reduces the samples volume requirement [1-4]. It uses surface tension gradient to move, combine, and mix liquid droplets. Surface tension is the dominant force in microscale and has been used widely in actuating microfluid and controlling the liquid morphologies [5]. Several mechanisms have been proposed to control the surface tension, including electrowetting [6], thermocapillary [7], and electrochemical processes [8].

Controlling surface tension by light is an intriguing concept. It would enable a flexible and reconfigurable microfluidic system that are defined and actuated by light. The conceptual design of an optically controlled microfluidic system is illustrated in Fig. 1(A). Droplets of samples and reagents from input reservoirs are injected and mixed by optical beams. The mixed samples can be detected optically (e.g., fluorescent detection) and then sorted at the output using optical beams again. Ichimura *et al.* reported light-induced motion of liquid droplets on surface modified with a monolayer of photoisomerizable azobenzene [9]. However, its response time (> 20 seconds) is too long for real time actuation. Furthermore, it cannot move water droplets, the most important liquid for bio-systems. Recently, we proposed a new mechanism called opto-electrowetting (OEW) to change surface wettability by light [10]. The change is reversible, i.e., the surface changes from hydrophobic to hydrophilic when illuminated by light, and it returns to hydrophilic when light is removed. The OEW surface has a very fast response time (on the order of milliseconds). Compared with electrowetting technique, the OEW device requires only one common bias voltage for all electrodes. Since the

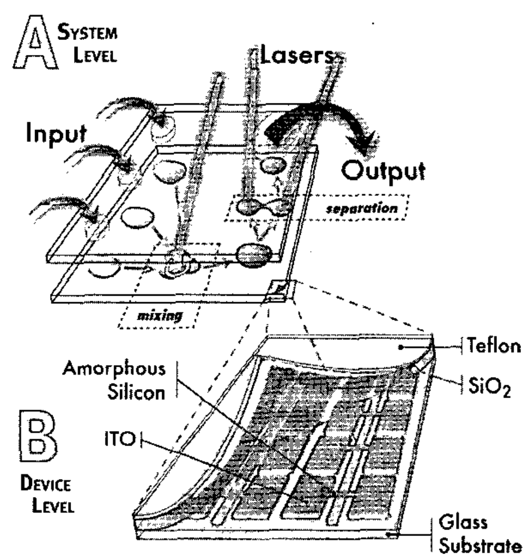

Fig.1(A) Schematic illustration of liquid droplets manipulation in opto-electrowetting (OEW) device. (B) Schematic of the OEW surface electrodes are addressed optically, a large number (hundreds of thousands or millions) of electrodes can be integrated on the same chip without running into wiring problem. The electrode area can also be scaled down to manipulate nano-liter or smaller liquid droplets. In this paper, we report on a novel light-actuated microfluidic system. Injection, transport, merging, and separation of nano-liter water droplets actuated by scanning optical beams are demonstrated for the first time. Simultaneous manipulation of multiple water droplets is also achieved.

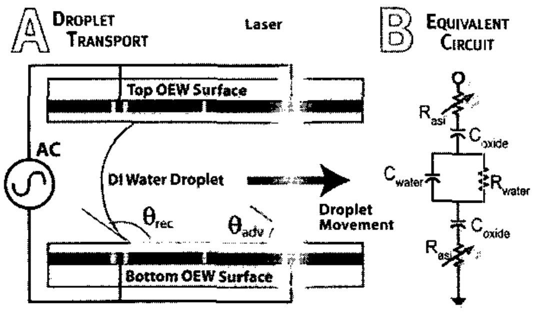

Fig.2 (A) Illustration of contact angle change on OEW surface. (B) Equivalent circuit for one unit cell of the OEW device. R_{asi} is the resistance of the amorphous silicon photoconductor under light illumination; C_{oxide} is the capacitance of the SiO_2 insulator; C_{water} and R_{water} are the capacitance and resistance of water layer between the two OEW surfaces.

DESIGN AND FABRIATION

It is well known that contact angle of a liquid-solid interface can be modified by electric potential:

$$\cos[\theta(V_i)] = \cos[\theta(0)] + \frac{1}{2}\frac{\varepsilon}{d\gamma_{LV}} V_i^2 \qquad (1)$$

where V_i , d , ε , and γ_{LV} are voltage across the insulator, thickness of insulation layer, dielectric constant of the insulating layer and the interfacial tension between liquid and vapor, respectively. This is called electrowetting effect. By integrating a photoconductor in series with the electrowetting electrode, the voltage drop, V_i, across the insulator can be controlled optically. This mechanism is called Opto-Electrowetting (OEW).

The cross section of the OEW device is shown in Fig. 2(A). The liquid droplet is sandwiched between two OEW surfaces. Each OEW surface consists of a two-dimensional (2D) array of floating electrodes. The electrodes are connected to a common bias line through photoconductive bridges (Fig. 1(B)). The OEW electrode can be modeled as a serial combination of a variable resistor (the photoconductor) and a capacitor (the insulator). The liquid itself is a parallel combination of capacitance and conductance. The equivalent circuit of the OEW devices over one unit cell is shown in Fig. 2(B). An AC voltage is applied between the two OEW surfaces. The operation principle is explained as follows: in the absence of light, most of the voltage drops across the photoconductors because of their high resistance. With light illumination, the resistance of the photoconductors decreases by several orders of magnitudes and most of the voltage now drops across the oxide. This changes the surface from hydrophobic to hydrophilic through electrowetting effect. The change of surface tension is reversible. Its response time depends on the RC charging time of the capacitor and the recombination time of the electron-hole pairs. It is on the order of a millisecond.

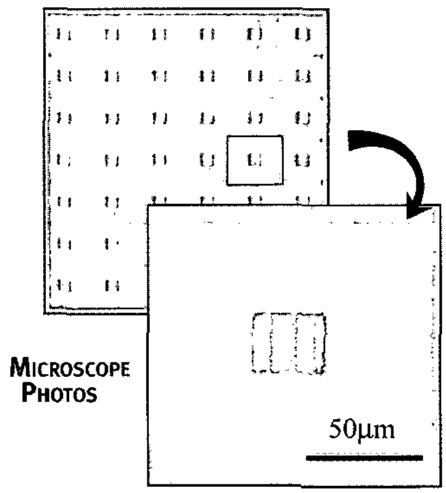

Fig.3 Microscope picture of the device.

We use a 100-μm-thick spacer to precisely define the gap between the two OEW chips. The OEW structure is fabricated on a glass substrate. It consists of five layers of materials: a 2-μm-thick indium-tin oxide (ITO) electrode layer, a 0.5-μm-thick amorphous silicon photoconductive layer, a 20-nm-thick aluminum Ohmic contact layer, a 0.5-μm-thick silicon dioxide insulator, and a thin Teflon coating (50 nm thick) on the surface (Fig. 1(B)). The ITO layer is patterned into a 2D array of electrodes with interleaving wires in one direction. All the wires are connected together and have the same electric potential. Each electrode (50μm x 100μm) is connected to the adjacent wire (5 μm wide) through a narrow strip (5μm x 30 μm) of amorphous silicon photoconductor. We choose amorphous silicon because of its high dark resistance and visible light response. The microscopic picture of a finished OEW surface is shown in Fig. 3.

The optimum frequency of the AC bias depends on the dimensions of the photoconductors, the thickness and the dielectric constant of the insulator, the area of the electrodes, and the conductivity of the liquid. We simulate the response of the equivalent circuit using a SPICE simulator, and found the optimum frequency to be between 100 Hz to 700 Hz for devices with dimensions mentioned earlier and de-ionized (DI) water. In that frequency range, more than 90% of voltage drop switches between the photoconductor and the insulator.

RESULT AND DISCUSSION

Droplet Transport

Transport of liquid droplet is realized by shining a light beam on one edge of the droplet (Fig. 2(A)). Since all the materials are transparent (except for the small areas covered by amorphous silicon), a single light beam is sufficient to control both OEW surfaces. We used a 5mW green laser with a wavelength of 532 nm and a beam diameter of 1 mm for our experiment. Several hundreds of electrodes are actuated simultaneously. The contact angle of the droplet in the illuminated area decreases, as shown in Fig. 2(A). To move the droplet, the decrease of the contact angle needs to be larger than the contact angle hysteresis, i.e., the difference between the advancing and receding angles. The contact angle difference between the two sides of the droplet induces an unbalanced pressure to move the droplet. As the light beam moves, the droplet follows the trace of the light beam spot. Figure 4 shows the snap shots from the video recording of the droplet when the laser light is scanned towards the left. The maximum speed observed for the 1mm-diameter droplet is 78 mm/s.

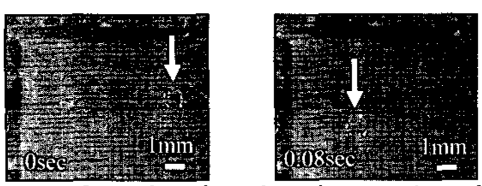

Fig. 4 Snap shots from the video recording of the transport of a 0.1μl liquid droplet actuated by a 5 mW green (532nm) laser beam.

Droplet Separation

Liquid droplet separation is an important function to control liquid volumes in biochemical and chemical applications. In our device, we achieved the droplet separation by shining two laser beams on the opposite edges of the droplet (Fig. 5A). The liquid meniscus shape at these two local areas becomes concave, resulting in a pressure to elongate the droplet. Meanwhile, at the center part of the droplet, the meniscus shape in the vertical cross section remains convex due to the hydrophobic property of the Teflon surface. This forces the center part of the droplet to narrow and produce a neck, which creates a pushing force to cut the droplet. The separation process completes when the two edges of the neck merge (Fig. 5B). For more detailed analysis, the shape and size of the droplet also need to be considered [4].

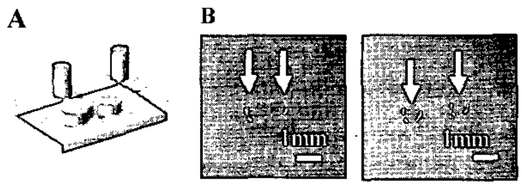

Fig. 5(A) Schematic illustrating the process of liquid droplet separation (B) Snap shots of video recording showing liquid droplet separation.

Droplet Injection

The liquid droplets in the OEW device are injected from the reservoirs integrated on the chip. The liquid reservoir is formed by two large ITO electrodes with matching shapes on both top and bottom surfaces (Fig. 6A). These electrodes are directly connected to the bias lines. The surfaces become hydrophilic and confine the liquid within the reservoir. The injection process is similar to that of droplet separation except only one light beam is needed. The light beam is initially positioned at the edge of the reservoir. As the light beam moves away from the reservoir, a droplet with diameter similar to the light spot is created (Fig. 6B). The injected volume is controlled by the beam spot size. We are able to inject droplets with volumes of 10 nl to 1 μl.

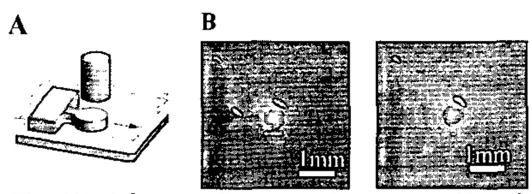

Fig. 6(A) Schematic illustrating the process of liquid droplet injection. The reservoir is formed between two large electrodes with fixed bias. A laser beam pulls a droplet from the reservoir. (B) Snap shots of video recording showing injection of a droplet.

The smallest volume is limited by the size of the OEW electrode, which is 50 μm x 100 μm in our current device. It is possible to further scale down the electrode size and the gap spacing to attain smaller droplet volume.

Multidroplet Transport

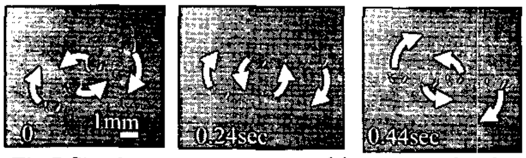

Fig. 7 Simultaneous movement of four water droplets actuated by two time-multiplexed laser beams. Since optical beams cross freely in space, arbitrary moving patterns can be achieved. In this experiment, the two outer droplets rotate in clockwise direction while the two inner droplets rotate in counterclockwise direction.

Manipulation of multiple droplets at the same time is useful for parallel detection and combinatorial analysis in lab-on-a-chip applications. In OEW device, one optical beam can control multiple droplets by time multiplexing. More optical beams can be employed to increase the throughput of the microfluidic systems. Since light beams cross freely in space, the OEW microfluidic device is particularly suitable for manipulating multiple droplets in any desired moving pattern. We have successfully transported four liquid droplets in continuous circular motions using two optical beams (Fig. 7). Each optical beam is time-multiplexed to control two droplets. Several liquid droplet functions, including transport, separation, combination, and injection, can be performed simultaneously on the same chip.

CONCLUSION

The light-actuated OEW mechanism offers several advantages for microfluidic systems. First, complete microfluidic functions (injection, transport, separation, combination, and mixing) can be integrated on the same chip with simple optical control. Second, the OEW device is scalable since only two bias wires are needed for the whole chip, independent of the number of electrodes. The 1 cm x 1 cm chip used in our experiments has 20,000 electrodes. Scaling of the chips to a million electrodes and/or larger active areas will be straightforward. Third, it is scalable to very small liquid volume. Ultimately, the size of OEW electrode, the gap spacing between OEW surfaces, and the focused spot size of the actuating light limit the volume of the droplet. Lastly, other optical tools such as optical tweezers can be integrated with the device to manipulate particles or cells. A powerful all optical lab-on-a-chip system capable of manipulating microfluid and micro particles by light is possible.

ACKNOWLEDGEMENT

The authors would like to thank Professor C. J. Kim for the valuable suggestion in droplet separation. This project is supported in part by DARPA Optoelectronics Center through CHIPS (Center for Heterogeneously Integrated Photonics) under contract # MDA972-00-1-0019.

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