Thermocapillary Actuation of Liquids Using Patterned Microheater Arrays

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ABSTRACT

We demonstrate a microfluidic actuation technique capable of directing nanoliter liquid samples on the surface of a glass substrate through the use of both electronically addressable heater arrays and chemical patterning. Pathways for liquid movement are delineated by the arrangement of microheaters, which also provide the thermocapillary actuating force. The drops are confined to these pathways by a selectively deposited fluorinated monolayer, which defines the channel edges. Operating voltages in the range of 2-3 V is used to move, split, and trap liquids. This fluid transportation technique enables direct access to liquid samples for handling and diagnostic purposes and offers a low power alternative to existing microfluidic systems.

INTRODUCTION

Recent progress in the development of microfluidic analysis systems has the potential to revolutionize the fields of chemical, biological, and material science. By reducing sample size, advantages such as improved response times, reduced cost per analysis, and increased experimental throughput are made possible. In these devices, various fluid actuation techniques have been implemented for liquid flow in closed channels [1,2,3] and on open surfaces [4,5,6]. We present a microfluidic actuation technique that utilizes programmable surface temperature distributions in combination with a patterned non-wetting monolayer to control the direction and flow rate of nanoliter volumes of liquids on a free surface [7]. This system takes advantage of the increased role of surface tension in fluids with large surface area to volume ratios, by allowing one to induce flow via the manipulation of liquid-gas surface energy. Benefits of this fluidic actuation method include low voltage operation and the ability to handle polar and non-polar liquids.

EXPERIMENTS

Theory

A liquid film which is heated locally at some position $\mathbf{x}$ reduces the surface tension, $\gamma(\mathbf{x})$, at that point and gives rise to a gradient in surface tension across the liquid. A thermocapillary shear stress is induced which pulls the liquid away from the heated region,

$$\tau = d\gamma/d\mathbf{x} = (d\gamma/dT)(dT/d\mathbf{x}) \qquad (1)$$

where τ is the shear stress, and T is temperature [8,9,10]. For a thin flat liquid film, the flow speed is given by

$$v(\mathbf{x}) = h(\mathbf{x},t)\,\tau/2\mu(\mathbf{x}) \qquad (2)$$

where $h(\mathbf{x},t)$ is the film thickness, $\mu(\mathbf{x})$ is the local viscosity, and t is time.

Sample Fabrication

A cross-section through one micro-heater of the completed device is shown in Fig. 1(b). The heaters are fabricated over a 6.25 cm^2 area of 0.7 mm thick glass slides. Organic contaminants are first removed from the slides by placing them in a solution of 1:1 H_2SO_4:H_2O_2 for 30 min. Ti (50 nm), Au (300 nm), and Cr (3nm) are then deposited onto the substrate *via* electron beam evaporation, and are patterned into resistive heating elements and contacts using a lift-off procedure. Both the Cr and Au are removed from the central portion to increase the heater resistance and therefore concentrate the power dissipation in the channel. Constrictive patterns in the resistors slightly increase local heating and help center the moving drops. To provide low contact resistance, the Cr is etched away in the contact regions at the edges of the glass slide. With the contact regions masked, a 400 nm layer of SiO$_2$ is then deposited using plasma enhanced chemical vapor deposition at 250 °C to provide electrical insulation. A hydrophobic monolayer is then formed on the surface by placing the samples in a solution of 1,1,2,2- perfluoroctyltrichlorosilane (PFOTS), and is defined using photolithography [11,12]. This monolayer makes the surface outside of the channel non-wetting and therefore provides confinement of liquid streams and drops. The microheaters are 3 mm wide by 0.8 mm long and the average resistance is 155 Ω. A top-view of a single microheater is shown in Fig. 1(a).
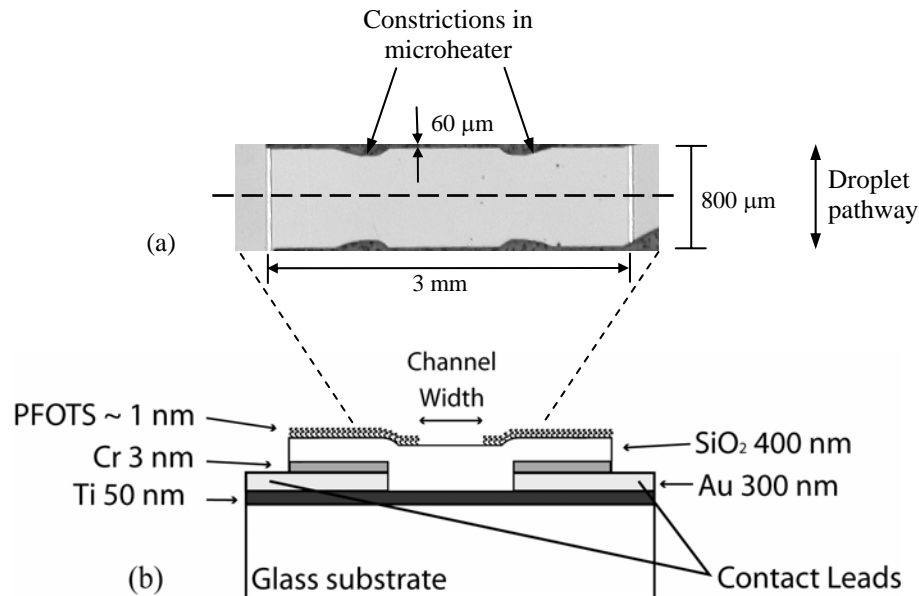

Figure 1. (a) Top-view of a single Ti microheater. Constrictions in the heater slightly increase local resistive power dissipation and help center the drops. Resistors are separated by 60 µm gap. (Note: contact leads are not shown). (b) Cross-section of thermocapillary actuation device. Maximum power is dissipated in the center region of the titanium layer where both Cr and Au have been removed. The low surface energy of the PFOTS monolayer serves to confine liquids over the microheater and defines the width of each droplet. Card edge connectors contact the Au film at both ends.
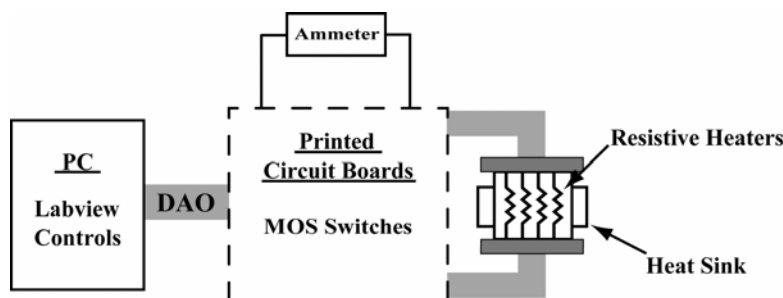
Figure 2. Experimental layout showing the microfluidic device on top of a heat sink at the right, the switching and measurement electronics in the center, and the computer with the digital-to-analog boards at the left.

Experimental Setup

The array is controlled and powered as shown in Fig. 2. The resistive heaters are addressed via a LabView control program from a PC. The power supply for the heaters comes from two digital to analog output (DAO) boards (United Electronic Industries PD2-AO-32) housed in the PC. The boards provide a total of 64 output channels, each with a maximum allowed voltage and current of 10 V and 90 mA, respectively. Each voltage supply channel of the DAO is connected to a set of MOSFET switches (Analog Devices ADG452) located on a printed circuit board (PCB). The switches enable each heating resistor to be connected directly to the voltage supply or in series with a Keithley ammeter. By measuring the change in resistance, the ammeter can detect the presence and thickness of a liquid on the surface of the chip. Both sides of the slide are connected to the PCB by card edge connectors with a 1.54 mm connector spacing.

The glass slide is held by vacuum on top of a brass block fixed at room temperature. This heat sink reduces thermal cross-talk between adjacent heating elements and also provides a constant baseline temperature to prevent the device from heating up continuously.

EXPERIMENTAL RESULTS AND DISCUSSION

The actuation and splitting of discrete dodecane droplets is shown in Fig. 3. As seen in Fig. 3(a)-3(e), localized heating can split a single droplet drop of approximately 150 nL of dodecane into two separate drops. Any small satellite drops left behind by the action of splitting (such as the one shown in Fig. 3(e)) can be swept up by moving one of the larger drops over it.
The power used to split and move a drop of dodecane was typically less than 40 mW per resistor, which provides a thermal gradient of 5 °C/mm. Thermocapillary actuation of discrete drops is demonstrated in Fig. 4. Figures 4(a)-4(d) depict a dodecane drop moving from right to left through an intersection of two 1000-μm wide partially wetting stripes defined by the monolayer patterning. Figures 4(e)-4(g) show another dodecane drop turning a corner at the same intersection.
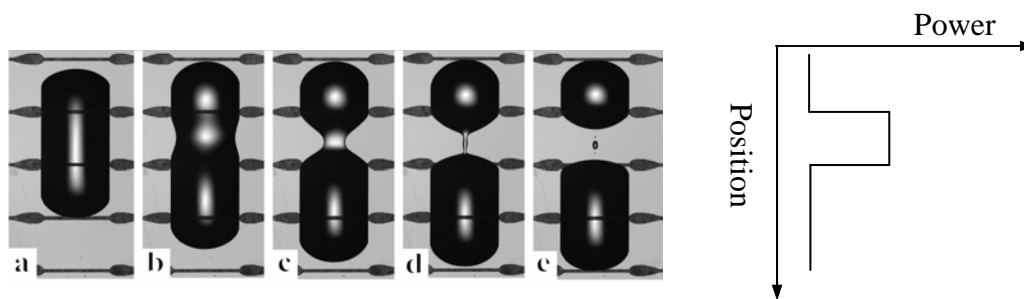
Figure 3. (a)-(e) Thermally induced splitting of a dodecane drop on a partially wetting stripe (droplet width = 1000 μm). The voltage applied to the resistor was 2.5 V. The images were recorded at t = 0, 6.0, 7.5, 8.0, and 8.5s.
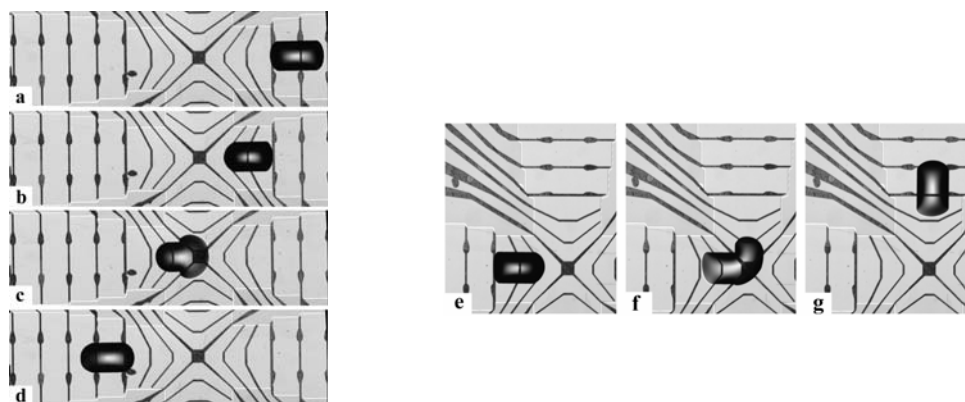

Figure 4. (a)-(d) Thermocapillary actuation of dodecane drop through intersection (droplet width = 1000 μm, total time lapse = 104 s). **(e)-(g)** Dodecane drop turning 90° corner. (Total time lapse = 164 s).

The sequential addressing of resistors is shown in a diagram in Fig. 5. By heating resistors 1 and 3, the position of the drop is then known to a precision equivalent to the length of one microheater. Resistor 3 is then turned off as resistor 4 is simultaneously turned on. The drop then moves away from its initial position, as it is no longer tightly confined by thermal gradients. Finally, as seen in Fig. 5(c), resistor 2 is turned on and resistor 1 is switched off, and the droplet is now positioned above resistor 3. The average droplet speed, v_d, can then be controlled by heater switching times, i.e. varying the time between each step in power. For the droplet in Figs. 4(a)-4(d), v_d = 56 μm/s and, v_d = 26 μm/s for the droplet in Figs. 4(e)-4(g). A voltage of 2.36 V was applied to the heaters in these series of images.

Glycerol, polyethylene glycols (having molecular weights between 100 and 1000), and polydimethylsiloxane silicone oil have also been transported using thermocapillary actuation, in addition to dodecane. The power required for splitting and transporting liquid drops can be reduced by at least one order of magnitude by using a polymeric substrate of low thermal conductivity instead of glass [13]. Battery powered operation of this microfluidic device then becomes practicable.
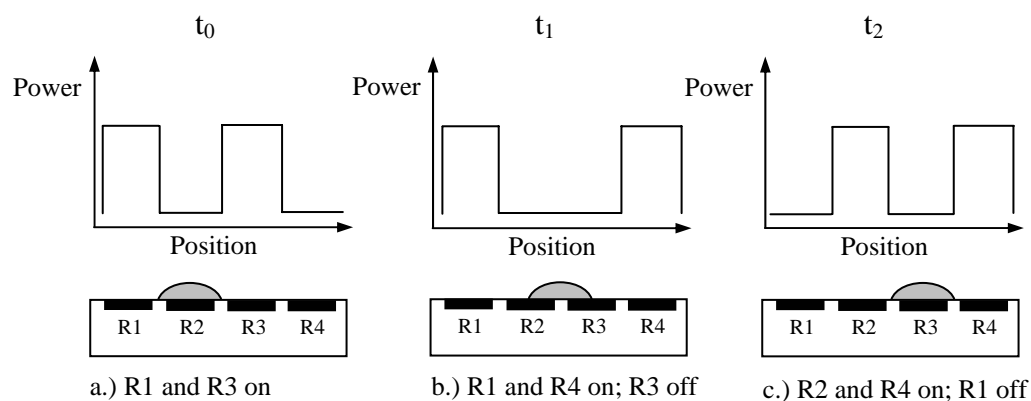
Figure 5. Cross-section of device showing sequential heating of resistors, R1, R2, R3, R4 at different times, t, where $t_2 > t_1 > t_0$: a.) Voltage applied to R1 and R3: the drop is confined on top of R2. b.) Turn off R3 and apply voltage to R4: drop moves away from R1. c.) Apply voltage to R2 and turn off R1: drop is positioned above R3.

CONCLUSIONS

We have demonstrated an electronically addressable heating array of microheaters to split, actuate, and direct liquid drops on a free surface. Electronic control of the heating elements allows merging or dividing of liquids into specified volumes, establishing transport with a predetermined velocity, and trapping drops at fixed locations, for eventual analysis and synthesis. These results demonstrate the feasibility of thermocapillary flow as an actuation method for droplet-based microfluidic systems.

ACKNOWLEDGEMENTS

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