

A 128-PIXEL DIGITALLY-PROGRAMMABLE MICROFLUIDIC PLATFORM FOR NON-CONTACT DROPLET ACTUATION USING MARANGONI FLOWS

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Abstract: A contactless programmable fluidic processor utilizing Marangoni flows is presented. Two dimensional control of microdroplets suspended in oil is achieved using a 128-pixel heater array suspended 100-500 μm above the oil layer. The heaters create surface temperature perturbations ($<7^\circ\text{C}$ simulated), resulting in local recirculating Marangoni flows which can move droplets in either a push or pull mode. Programmed movement is achieved by the sequential activation of the heaters. Addressible control of each heater is provided by digital circuitry and a graphical interface. Droplets with diameters 300-1000 μm can be manipulated and merged at speeds up to 140 $\mu\text{m/s}$. This system provides a platform for high-throughput droplet-based assays where the reagents do not contact any solid surface.

Keywords: Marangoni flow, programmable fluidic processor, droplet, microfluidics, micro-TAS.

I. INTRODUCTION

Microdroplet-based programmable fluidic processors (PFPs) provide a versatile platform for user-defined, high-throughput biochemical assays [1]. Droplets are manipulated on a 2-dimensional grid using methods such as electrowetting-on-dielectric (EWOD) [2], dielectrophoresis (DEP) [1], and magnetic fields [3]. All of these approaches, however, require a substrate patterned with electrodes or coils, and all allow some degree of contact between the droplet and the substrate, both of which raise concerns for device contamination, sample loss, and reusability.

This paper describes a scalable system for programmable droplet manipulation which does not require patterned substrates or droplet interactions with solid surfaces. Droplet actuation is accomplished using Marangoni flows, generated by a 128-pixel array of heaters held above the oil layer. Previously we have shown that a small heat source, when placed $<500 \mu\text{m}$ above a layer of oil, creates a local temperature increase on the liquid surface, accompanied by a local decrease in surface tension. This results in Marangoni flow oriented outward (away from the heat source) on the fluid surface, and inward below the surface [4-5]. The recirculating flows can trap, filter, and pump aqueous droplets in oil, and can also move the droplets if the heat source translated laterally with a scanning stage [5-7]. The present effort incorporates these concepts into a programmable system for non-contact actuation of microdroplets (Fig. 1) where the droplets are moved by the

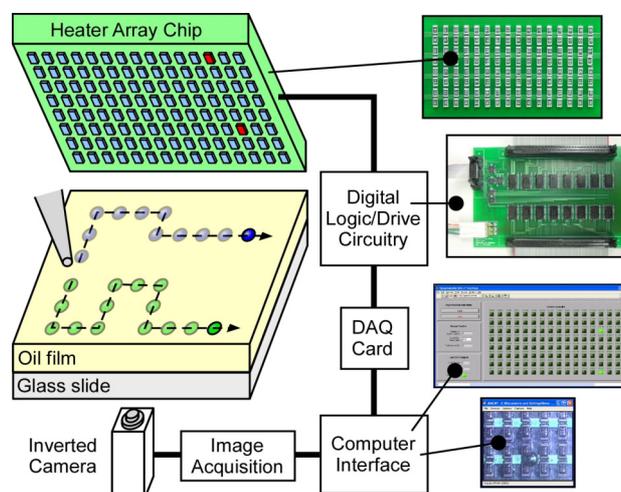


Fig. 1: A complete system for programmable, non-contact droplet actuation based on Marangoni flows, including a 128-pixel array of resistive heaters suspended above the oil layer, control circuitry, and a graphical user interface.

sequential activation of the heaters rather than translation of the heaters. Physical structures such as microchannels or electrodes are avoided, thus simplifying the fluidic substrate and reducing contamination. The favorable scaling of the Marangoni effect at small dimensions provides an opportunity for further miniaturization.

II. DEVICE CONCEPT AND DESIGN

A 128-pixel array of heaters is suspended $<500 \mu\text{m}$ above an oil layer. Each heater, when activated, creates a temperature gradient on the liquid surface which generates surface and subsurface Marangoni flows (see simulation, Fig.

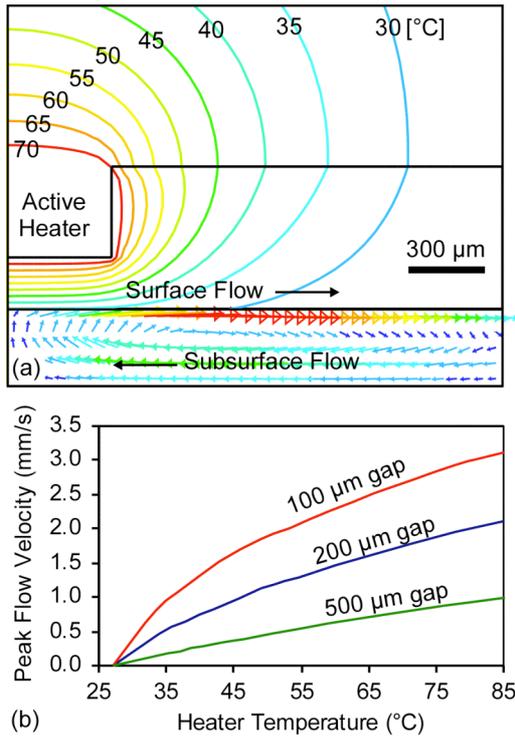


Fig. 2: CFD simulation (FLUENT 6.0). (a) Temperature contours generated by the heater and velocity vectors of the surface and subsurface Marangoni flows. (b) Flow velocity vs. heater temperature for a 100 μm, 200 μm, and 500 μm gap between the heater and liquid.

2). The heater can either push a droplet away with its surface flow (push mode actuation), or pull a droplet toward it via its subsurface flows (pull mode actuation) depending on the conditions discussed in section III. Droplet movement can be programmably controlled through the sequential activation of individual heaters.

The 16x8 heater array is implemented as #0603 surface-mount resistors (1x0.8x0.3 mm) placed at 1.9 mm pitch on a printed circuit board (Fig. 3). Heaters are individually set and reset via a graphical interface and control circuitry (Fig. 4). D-latches maintaining the state of each heater are set by serial commands from the DAQ card. The refresh rate is $\sim 10^5$ heaters/second, therefore, a

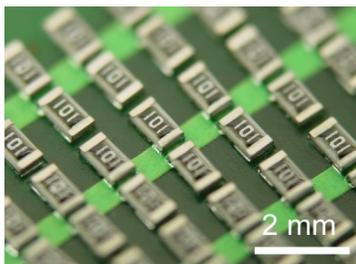


Fig. 3: Micrograph of heater array.

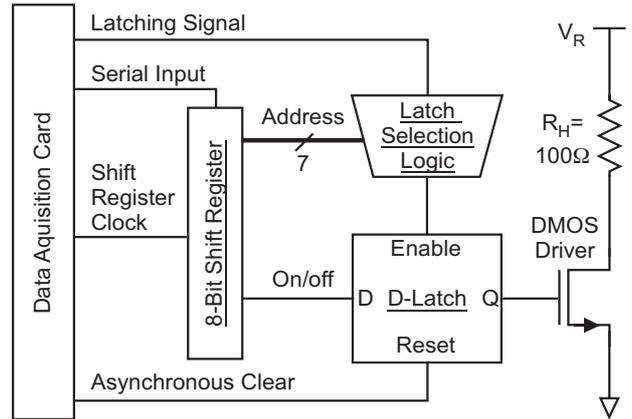


Fig. 4: Schematic of logic and driver circuitry.

128 pixel array can be set in <5 ms. The control interface includes 3 signals for setting/resetting individual pixels along with an asynchronous clear to deactivate the entire array. The heaters have 100 Ω resistance and are driven by power DMOS transistors tied to an isolated supply and ground.

Figure 5 shows the experimental setup. The oil layer is placed on a glass slide so that droplet motion can be imaged from below with a CCD camera. A high-density oil (specific gravity=1.07) is chosen so that droplets float on the oil surface with no contact to the glass slide below. Droplet samples are deposited directly into the oil using a micropipette. The heater array, with the chip resistors facing the sample, is then lowered to within 500 μm above the oil surface using a micromanipulator. Two ribbon cables provide electrical interconnect to the control circuitry.

No customized microfabrication is required in the present millimeter-scale implementation. Further miniaturization has potential to improve pumping efficiency because the Marangoni effect, like other surface phenomena, scales favorably to small dimensions. Miniaturization will, however, require additional attention to issues such as heat dissipation and thermal crosstalk.

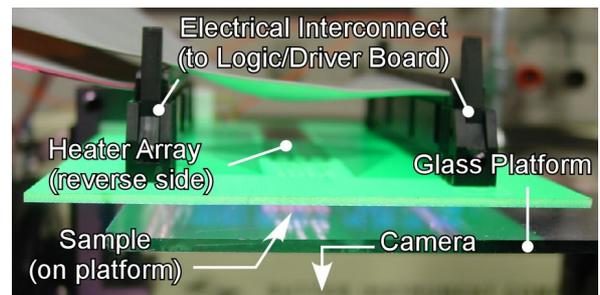


Fig. 5: Experimental setup.

III. EXPERIMENTAL RESULTS

Individual heaters were characterized for thermal efficiency and capability to produce flow. The thermal isolation of each heater is ≈ 100 K/W, and a maximum temperature of 160 °C is obtained on 1.3 W power (Fig. 6a). (Micromachined structures, by contrast, can achieve thermal isolation $>10^4$ K/W.) The parasitic temperature increase on the adjacent heater is 80 °C, roughly 50% of the increase on the first heater. The bulk substrate remains close to room temperature. Heat sinks and other thermal isolation were shown to reduce thermal crosstalk. Surface flow velocities up to 1700 $\mu\text{m/s}$ are achieved using 25 μm pollen particles as tracers. The simulated surface temperature change corresponding to these velocities is <7 °C. (A consequence of further miniaturization is that even lower temperature perturbations can achieve the same flow velocities [4]). The velocity of droplets is less compared to pollen due to their larger mass and drag (Fig. 6b). A $\Phi=300$ μm droplet, for example, moves at speeds up to 73 $\mu\text{m/s}$ in the push-mode.

The push-mode of actuation occurs in single

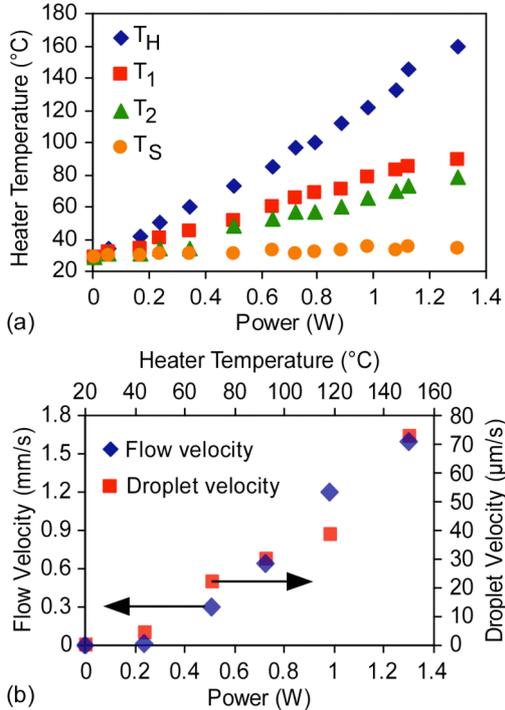


Fig 6: (a) Temperature of an active heater (T_H) vs. input power. Also shown is the temperature increase one pixel away (T_1), two pixels away (T_2), and on the substrate 2 cm away (T_S). (b) Flow velocity (25 μm pollen) and droplet velocity ($\Phi=300$ μm droplet) vs. input power and heater temperature. Gap ≈ 300 μm .

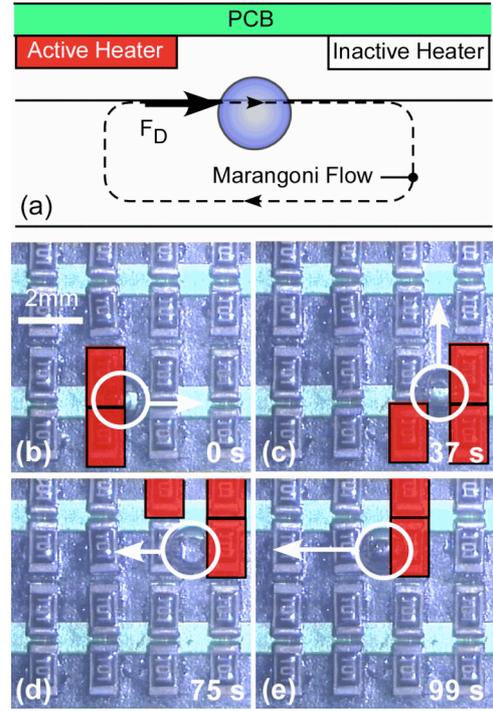


Fig 7: Push-mode actuation. (a) Surface Marangoni flows create a droplet force (F_D) oriented away from the active heater. (b-e) A $\Phi=900$ μm droplet is moved along a square path by activating multi-heater configurations sequentially. Active heaters are shaded. $P_H=1$ W/heater, gap ≈ 400 μm .

layers of oil with depth >500 μm , and when the droplets are very small ($\Phi < 100$ μm). In this mode, surface Marangoni flows drive the droplet away from the active heaters (Fig. 7). Multi-heater configurations may be used to direct a droplet in the desired direction. For example, two adjacent heaters next to a droplet push the droplet in a straight line. A right-angle turn can be accomplished using three heaters in an L-shape. Arbitrary movements can be generated with sequential activation of such configurations.

The pull-mode of actuation utilizes subsurface flows which bring the droplet toward the active heater at speeds up to 140 $\mu\text{m/s}$ (Fig. 8). This mode, which occurs in relatively thin layers of oil (<500 μm) and multilayer oil systems, is more easily controlled because only one activated pixel is necessary to trap a droplet. The sequential activation of adjacent pixels can translate the droplet along a virtual grid. Figure 9 shows the simultaneous actuation of multiple droplets.

While a surface temperature rise of <7 °C is necessary for actuation, higher temperature can be encountered in various operations. In such

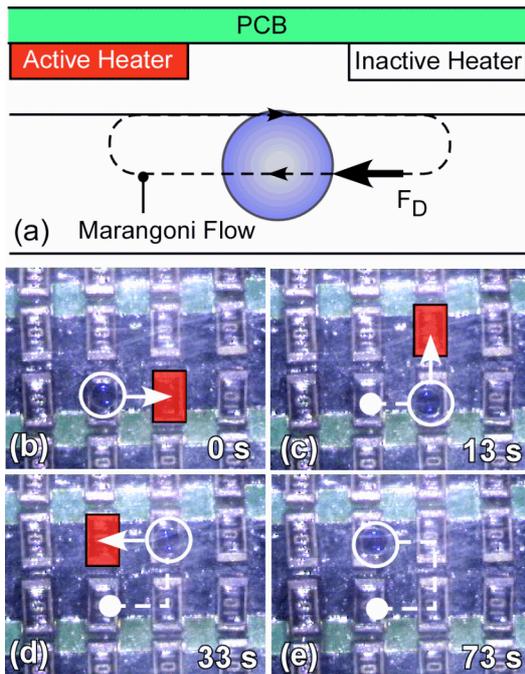


Fig 8: Pull-mode actuation. (a) Subsurface Marangoni flows create a force on the droplet (F_D) toward the active pixel. (b-e) Programmed movement of a $\Phi=600 \mu\text{m}$ droplet. Active heaters are shaded. $P_H=1 \text{ W/heater}$, $\text{gap}\approx 400 \mu\text{m}$.

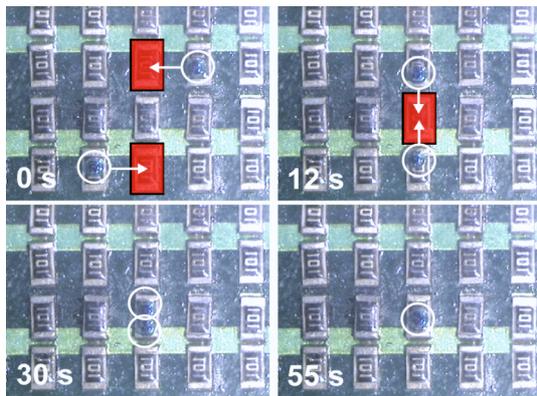


Fig 9: Droplet merging with pull-mode actuation. Two droplets ($\Phi=600 \mu\text{m}$) are merged through sequential activation of the heaters. Active heaters are shaded. $P_H=1 \text{ W/heater}$, $\text{gap}\approx 300 \mu\text{m}$.

circumstances, droplet evaporation can present a challenge. For example, 1 mm droplets floating on top of the oil layer tend to evaporate in $<2 \text{ min}$. To address this issue, two miscible oils were combined, one with density less than water (mineral oil), and the other with density greater than water (Dow Corning 550 Fluid). Aqueous droplets remain suspended between the two layers, unexposed to both the air and the glass surface below. The suspended droplets are manipulated using subsurface flows (pull mode).

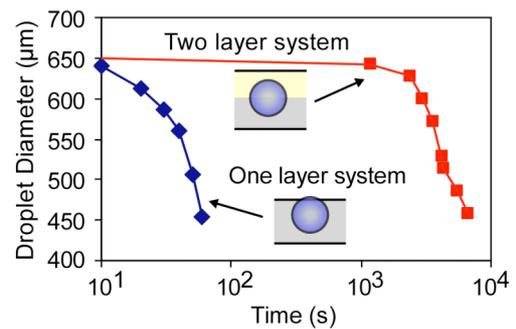


Fig 10: Preventing droplet evaporation. Droplet size is plotted vs. time (log scale) for a $\Phi=650 \mu\text{m}$ droplet in single and double layer oil systems.

Evaporation times are on the order of hours, 100x higher than the single layer oil system where the droplet is exposed (Fig. 10), thus allowing for assays which require longer incubation times.

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