DROPLET-BASED HOT SPOT COOLING USING TOPLESS DIGITAL MICROFLUIDICS ON A PRINTED CIRCUIT BOARD

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ABSTRACT

Thermal management is a critical issue in integrated circuit (IC) design. With each new IC technology generation, feature sizes decrease, operating speeds increase, and package densities increase, contributing to larger power consumption and elevated die temperatures. Higher temperatures are detrimental to circuit behavior and reliability. Furthermore, hot spots due to spatially non-uniform heat flux in integrated circuits can cause physical stress and further reduce reliability. We have demonstrated a cooling method on a "digital microfluidics" platform whereby discrete droplets are manipulated to adaptively cool simulated hotspots using microliter-sized droplets. Cooling droplets are actuated independently in user-defined patterns over an array of electrodes by electrowetting, eliminating the need for external pumps. We explore the cooling ability of these droplets by varying the temperature of the hot spot and the effective flow rate of the droplets. The results presented here suggest that digital microfluidics is an attractive platform for adaptive hot spot cooling.

KEYWORDS: microfluidics, digital microfluidics, electrowetting, coplanar electrowetting, PCB, droplet, microliter, hot spot, chip cooling, adaptive cooling, active cooling

I. INTRODUCTION

Thermal management is a critical issue in integrated circuit (IC) design. Decreasing feature sizes, increasing speeds, and increasing package densities are contributing to increased power dissipation and elevated die temperatures. Higher temperatures are detrimental to circuit behavior and reliability. It has been predicted in the 2003 International Technology Roadmap for Semiconductors (ITRS) that in 2018 the peak power consumption of high-performance desktops will jump by 100% (150W to 300W) and in lower-end desktops by 110% (80W to 168W) [1].

The resulting high die temperatures and non-uniform thermal distributions of poorly managed ICs can result in a number of problems. Electromigration, MOS transistor drive capability, and interconnect delay are all worsened with increasing die temperatures [2], resulting in performance degradation. Furthermore, hot spots due to spatially non-uniform heat flux in integrated circuits can cause physical stress and further reduce reliability.

Package-level thermal management is proving to be inadequate for the next generation chips, therefore alternative designs need to be investigated towards embedded IC-level cooling. A number of embedded cooling techniques have been reported to date. These methods can be broadly placed into one of three categories: passive, active, and active adaptive cooling methods. Passive cooling requires no external power and relies solely on conduction, natural convection, or radiation to redistribute and dissipate heat such as in metal plates, thermosyphons, and heat pipes. Active cooling, by contrast, uses external methods such as forced convection by fans, pumped microchannel loops, and refrigeration. Active cooling can further be categorized into active adaptive cooling, whereby a closed-loop feedback of the thermal profile on an IC can enable a temperature-aware adaptive cooling system that can dynamically cool hot spots to maintain an even thermal profile.

Many liquid-based cooling systems have been demonstrated in the literature. A pumpless loop has been reported by Mukherjee *et al*, where fluid density difference between two vertical, parallel tubes induces fluid motion [3]. This passive microfluidic cooling technique uses convection to redistribute the heat in an efficient closed-system manner. While this method requires little or no power, it is not suitable for applications where specific cooling of hot spots is required.

Currently, much attention has been focused on active microfluidic techniques, such as micropumps, which are capable of pumping liquids through microchannels. A closed-loop two-phase microchannel cooling system has been developed by Liang *et al*, which uses electroosmosis to transfer liquids to and from a heat exchanger [4]. A major limitation of this method is that it is limited to permanently etched channels making a reconfigurable (i.e. adaptive) active cooling system difficult to design. Alternatively, a cooling module based on piezoelectric generation of droplets has been demonstrated [5]. Secondary droplets are formed from a primary drop and then impinged on the target surface, evaporating upon impact. The momentum of the atomized droplets is sufficient to propel the droplets to penetrate through the vapor layer and spread into a thin film on the hot surface.

The cooling efficiency of these devices has been shown to be higher than traditional fan-based methods. However, their architectures are fixed and cannot be reconfigured for adaptive cooling. A more attractive solution is to use a droplet-based microfluidic device whereby droplets are independently controlled and pathways are dynamically reconfigured to address hot spots.

Electrowetting was demonstrated by Pollack *et al* [6] as a viable technique to manipulate droplets. Under a clocked-voltage control, microfluidic operations such as formation, transport, splitting, merging, and mixing of droplets have been studied, resulting in an instruction set for this "digital microfluidic" platform [6-10]. While initially intended for biological and chemical lab-on-a-chip applications, this platform has been under development for applications to chip cooling [11-12]†.

The discretization of liquids for cooling on this platform has several advantages over other microfluidic systems. First, microfluidic operations can be reduced to a set of basic discrete operations, which allows the use of a hierarchical and cell-based design approach. Also, this design approach enables scalability and easy customization of microfluidic chip architectures for various cooling needs. Second, the absence of permanently etched channels allows for a planar and completely reconfigurable system. Third, cooling liquid droplets can be transported over a planar array of electrodes without the need for external pumps and valves. Fourth, we have previously demonstrated that liquid flow is inherently increased with increasing temperature [12]. Thus, local hot spots on a chip will have an inherently increased cooling rate without the need for external sensors.

In this paper, we present the first demonstration of the ability of microliter-sized droplets to cool a hot spot using a novel "topless" coplanar electrowetting scheme, which eliminates the need for a confining top plate. Using infrared imaging, the cooling efficiency of these droplets is characterized by varying transport switching frequencies (i.e. effective flow rates), as well as varying the input power supplied to hot spot-generating heaters.

II. DETAILS OF EXPERIMENTAL METHODS

Chip Fabrication

Coplanar digital microfluidic chips were made using standard PCB fabrication processes on 2-layer boards. As shown in Figure 1, 1.5 x 1.5 mm^2 electrodes spaced 3 mils apart were patterned in copper to a final thickness of ~1 mil. Via holes (6 mils in diameter) were drilled into each electrode to provide electrical contacts to the backside of the board. Grounding rails (4 mils wide) were patterned alongside all the drive electrodes, spaced 3 mils from the electrodes, to provide a continuous ground connection to the droplets. A liquid photoimageable (LPI) soldermask (~0.7 mil) was patterned to serve as an insulator, filling the vias and exposing only the ground rails. Thin-film resistive lines, aligned and contained within the footprint of target electrodes, were patterned on the backside of the board to generate hot spots. As the only PCB post-processing step, Teflon AF was brush-coated to render the surface hydrophobic.

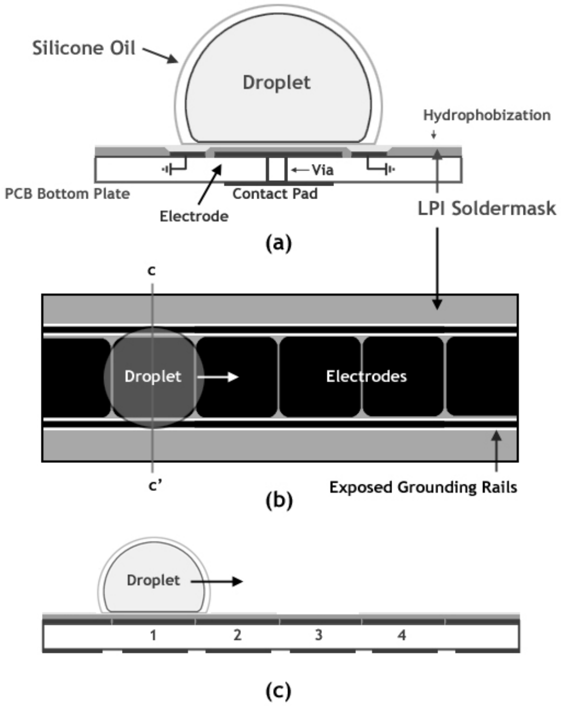

Figure 1. Schematic of a coplanar digital microfluidic chip on PCB. The side view (a) represents the cross section c-c' as specified in the top view (b). Droplet transport is shown from the side (c) and top (b) view of the electrowetting chip. A droplet is held onto electrode 1 by applying a voltage (240V) at that electrode. Droplet transport to the right is achieved by deactivating electrode 1 and activating electrode 2 simultaneously. This creates a reduction in interfacial tension on the leading edge of the droplet, causing the droplet to move until it is aligned onto the center of the new electrode.

Droplet Actuation by Electrowetting

Droplets were actuated electrostatically by modulating the interfacial tension between a liquid droplet and a solid surface through a phenomenon known as electrowetting [7]. A polarizable and conducting liquid droplet (1M KCl) was manually dispensed on the digital microfluidic chip. In all the experiments, the volume of each droplet was 6μl, with a

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† Further information and videos can be found at http://www.ee.duke.edu/research/microfluidics.

footprint large enough to overlap the adjacent electrodes. In order to prevent evaporation of the droplets and maintain a constant volume, 2μl of 1cSt immiscible silicone oil (DMS-T01, Gelest, Morrisville, Pennsylvania, USA) was added to the droplet, creating a thin surrounding oil layer. The use of oil also reduces the minimum actuation voltages required for transport of the droplets.

Electrical connections to the chip were made through an array of spring-loaded probes contacting the backside of the PCB (G095 Series, Qualmax America, State College, PA, USA). A custom electronic controller was built and a software program written, to address and switch each electrode independently and automatically. The basic scheme for droplet actuation is explained in Figure 1.

Experimental Setup

An experimental chip was designed to characterize the cooling efficiency of hot spots using droplets. As shown in Figure 2, the chip consists of linear arrays of nine electrodes. A 1.5 x 1.5 mm^2 thin-film heater, patterned on the backside of the PCB, was aligned with the center electrode. The input power to the heater was controlled using a constant-power supply.

A single droplet was shuttled back and forth across all nine electrodes at various switching frequencies of the electrodes. The switching frequency denotes the rate at which an electrode is switched which translates to transfer of droplets across two electrodes, thus it is a measure of effective flow rates. An infrared camera (JTL1 Infrared Imager, Edmund Optics, Barrington, NJ, USA) was used to capture the thermal profile of both the droplet and the chip. The video was recorded digitally and the images were processed using a custom-written MATLAB program, where the temperature of the hot spot was obtained for each frame. The IR camera was calibrated with a thermocouple.

III. RESULTS AND DISCUSSION

Simple Hot Spot Cooling

The feasibility of the droplets to cool hot spots was tested by applying 660mW to the thin-film heater (equivalent to a heat flux of 30 W/cm^2), upon which a single droplet was transported across the nine-electrode linear array. The switching frequency of the electrodes was varied from 18 to 32 Hz which translates to droplet residence times on each electrode from 55ms to 31ms. The droplet was shuttled back and forth on the 9-electrode linear array for 10s at 32 Hz switching frequency and held away from the hot spot stationarily on an electrode for 5s. The shuttling of the droplets again resumed for 10s at the next frequency and held stationary for 5s and this process continued through all the switching frequencies. Storing the droplets away from the heat source for 5s allowed any heat stored in the droplet to dissipate before being transported at the next switching frequency. Figure 3 shows a sequence of time-lapsed images of the droplet cooling the hot spot, in both the infrared and visible spectrum, as it traverses across the linear array. At t = 0s in Figure 3, the temperature at the hot spot is 70°C and from image processing yielded a temperature decrease of 23°C at the hot spot after a quarter of a second of shuttling the droplet at a 32 Hz switching frequency.

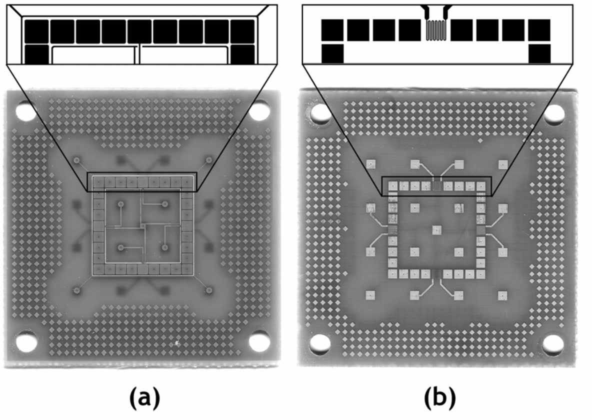

Figure 2. Photographs of the PCB chip viewed from the top-side (a) and bottom-side (b). The schematic shows the region where hot spot characterization was performed.

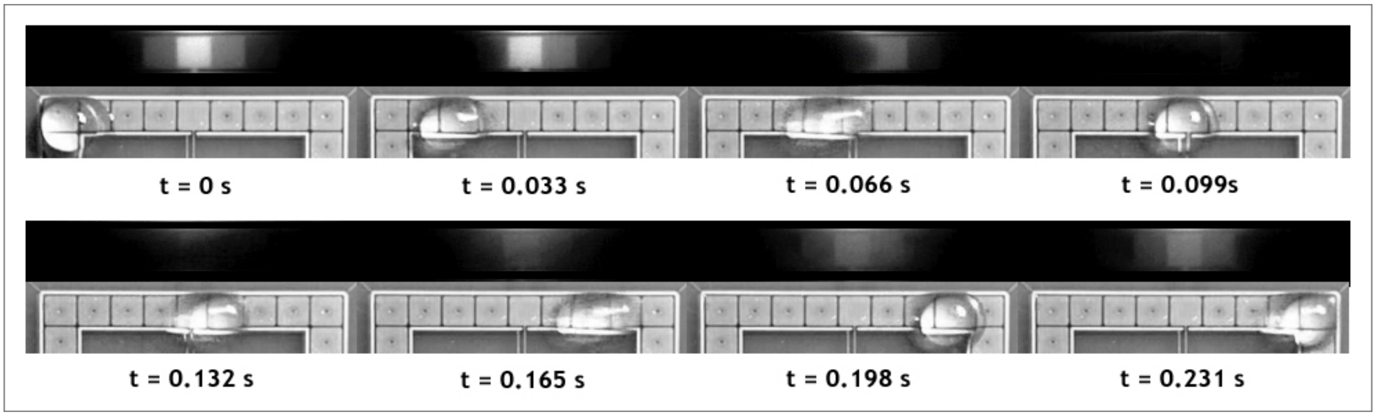

Figure 3. Top view of droplet transport as viewed from an infrared camera (top image in each frame, white = hot) and regular camera (bottom image). A droplet volume of volume 6μl is transported across the hot spot (65ºC) at a switching frequency of 32 Hz. The hot spot is cooled by 20ºC at t = 0.231s.

The temperature of the hot spot as a function of time at different switching frequencies is shown in Figure 4 for the duration of the experiment. The data shown was captured every 1/30th seconds. At each switching frequency, the temperature of the hot spot varied between low and high temperature values. The lower value corresponds to the temperature of the droplet as it passes over the hot spot, and the higher value is the maximum temperature of the hot spot when the droplet is at either of the far ends of the linear array. It should be noted that the temperature of the hot spots is lower at higher switching frequencies which is an expected result since a droplet shuttling at higher speeds corresponds to higher flow rates and therefore would remove heat faster. The time-averaged temperature of the droplet increased at a rate of approximately 0.22°C/s, while the average cooling rate of the hot spot is 5.5°C/s at 32 Hz.

Due to the interference of the droplet during infrared imaging, the lowest temperature of the hot spot could not be obtained as the water droplet does not transmit IR. Therefore, the "coolability" (i.e. temperature drop) due to the shuttling droplet is calculated as the difference between the higher values at each frequency and the steady-state value of the hot spot obtained at the end of the experiment. It is important to note that this represents a worst-case scenario, as it is likely that the hot spot is actually cooled to a much lower temperature.

The coolability of the droplets with switching frequencies from 18 to 32 Hz was obtained for heater input power ranging from 360mW to 660mW. As shown in Figure 5, the effectiveness of cooling by the droplets improves as the input power to the hot spot increases at higher frequencies. For example, at a switching frequency of 32 Hz, there is a 150% increase in the "temperature drop" for an 83% increase in heater power from 360mW to 660 mW. This suggests that cooling performance is greatly improved as the power densities in the hot spot are increased. It should be noted that below the switching frequency of 22 Hz, the temperature drop for input power of 560mW and 660mW is the same but the temperature drop increases at higher switching frequencies for 660mW of input power. This shows that the heat removal of the droplets saturate at a particular switching frequency and any increase in input power would not change the heat removal while decrease in input power would lead to a smaller temperature drop. Due to the power limitations of the thin-film heater, the upper limit of this trend could not be obtained. The copper traces of the heaters would open at input power beyond 660mW so experiments were not performed at higher input power. Another limitation of this method is that water droplets evaporate at 100°C and therefore liquids with higher boiling point have to be used to cool higher temperatures.

Figure 6 shows the relative heat transfer coefficients, defined by Newton's law of cooling, as calculated from the data obtained in Figure 5. Because the heat input from the hot spot to the droplet, dQ/dt, was difficult to obtain experimentally, the heat transfer coefficients were normalized to the best-case scenario (heater power = 660mW, switching frequency = 32

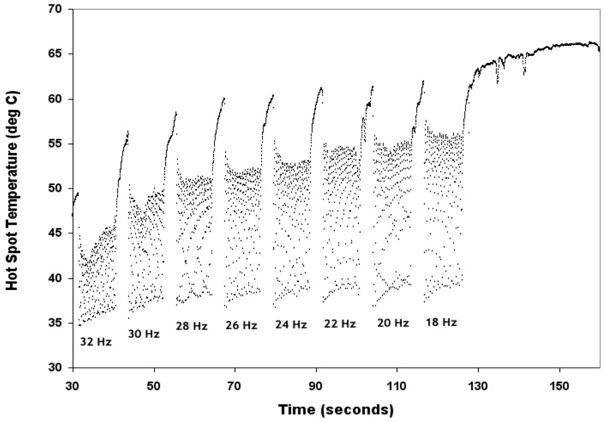

Figure 4. Variation in the temperature of the hot spot with the droplet shuttling at various frequencies. At each frequency, the droplet was shuttled back and forth the linear array for 10s, and stationarily held away from the hot spot for 5s to allow any heat stored in the droplet to dissipate. At the end of the experiment, the hot spot was allowed to reach a steady-state temperature.

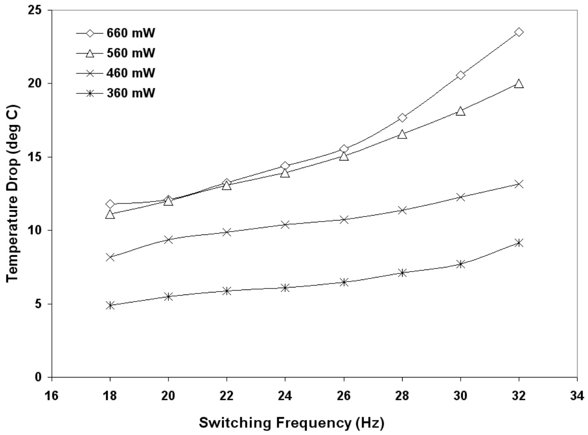

Figure 5. Temperature drop at the hot spot with respect to switching frequency of a shuttling droplet as a function of input power.

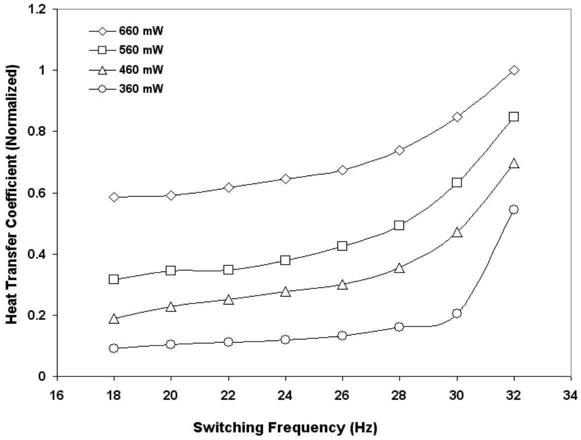

Figure 6. Heat transfer coefficients between the droplet and hot spot at various heater powers (360 to 660 mW) and droplet transport frequencies (18 to 32 Hz).

Hz) and it was also assumed that the power delivered to the hot spot in contact with the droplet was linearly proportional to the input power delivered to the heater on the back-side of the PCB.

At low frequencies, the change in heat transfer coefficients of the droplets was observed to be almost linear, while at higher frequencies the increase in heat transfer coefficient is more rapid. Cooling is therefore significantly enhanced at higher effective flow rates of the droplet. Although only a single droplet was studied here, up to four additional droplets could be simultaneously transported across the 9-electrode linear array, thus increasing the effective flow rate by 5× given the same switching frequency (i.e. the flow rate of five droplets transported at 32 Hz across the linear array has the same effective flow rate as a single droplet transported at 160 Hz). The feasibility of simultaneously transporting multiple droplets has been demonstrated by us earlier [10].

IV. TOWARD ADAPTIVE CHIP COOLING

The digital microfluidic platform is an attractive solution toward IC cooling, and has been demonstrated to possess a number of advantages over other microfluidic designs. First, low-power solid-state actuation, reconfigurable and independent addressing, and high flow rate of droplets makes digital microfluidics an ideal platform for IC-level active cooling. Second, we have previously shown that the increased flow rates of droplets due to the temperature-induced low viscosities of the surrounding silicone oil create an inherently temperature-aware system [12]. Coupled with the ability to redirect flow on-the-fly, a truly adaptive hot spot cooling solution can be realized. Third, as we have demonstrated here, special fabrication techniques, typically a requisite for microfluidic devices, are not required in our system. Using a standard PCB process, we have successfully transported droplets and shown their ability to cool hot spots. Finally, the coplanar structure developed here not only allows us to create a topless, open system, but it also simplifies any IC integration problems by confining the entire microfluidic device to one plane.

An embedded closed-loop device is thus now feasible, whereby a self-contained and self-regulated microfluidic chip can be integrated with the IC die itself. Droplets are formed from larger actively cooled reservoirs, then carried across the IC with velocities and flow paths programmed, and re-adjusted based on the change in flow rates due to the presence of hot spots, and returned to the reservoir where they can be recycled. In this way, cooling and thermal uniformity on the IC can be achieved from this constant digitization, transport, and cooling of liquid droplets.

V. CONCLUSIONS AND FUTURE WORK

As integrated circuits experience larger power densities and elevated die temperatures with every technology generation, package-level thermal management is rapidly becoming inadequate. Alternative designs therefore need to be investigated towards embedded IC-level cooling. A number of embedded cooling techniques have been reported to date; however, limitations in their architectures render them unsuitable for adaptive hot spot cooling.

A more attractive solution uses a digital microfluidic platform whereby droplets are independently controlled and pathways can be dynamically reconfigured to address hot spots. In this paper, we demonstrate for the first time the ability to program these microliter-sized droplets to cool hot spots via a novel “topless” coplanar electrowetting scheme. Using infrared imaging, we have shown that a single droplet is able to cool a simulated hot spot on a PCB substrate, and that cooling is significantly improved upon increasing switching frequencies (i.e. effective flow rates), as well as larger power densities inducing the hot spot. While this study has been shown using only a single droplet, it can easily be extended to employ multiple droplets. The increased effective flow rates resulting from multiple droplets would allow for improved cooling performance and should therefore be studied. Furthermore, the effect of the presence of a top plate, as well as volume scaling into sub-microliter volumes, can potentially improve cooling rates and should also be investigated.

ACKNOWLEDGEMENTS

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