THERMAL EFFECTS ON DROPLET TRANSPORT IN DIGITIAL MICROFLUIDICS WITH APPLICATIONS TO CHIP COOLING

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ABSTRACT

Thermal management has emerged as a critical issue in the design of integrated circuits (ICs). As feature sizes decrease and package densities increase, current package-level cooling techniques will soon become inadequate. While a number of MEMS-based cooling solutions have been proposed to address cooling at the IC level, many are not equipped to address the problem of real-time active and "smart" cooling, where hotter thermal regions (i.e., hot areas) are detected and subsequently cooled at an increased rate. We describe an alternative cooling method, on a platform we call "digital microfluidics," where nanoliter-sized discrete liquid droplets immersed in oil are manipulated. Cooling droplets are actuated independently in user-defined patterns over an array of electrodes by electrowetting, eliminating the need for external pumps. This paper presents the effects of temperature-dependent system parameters on droplet transport in this digital microfluidic platform. We demonstrate experimentally that under a fixed frequency, the minimum voltage required to oscillate a microliter-sized droplet across a linear electrode array decreases as much as 30% for a 50°C temperature increase. The effect of two temperature-dependent parameters, interfacial tension and oil viscosity, are investigated as possible mechanisms. The results presented here suggest that digital microfluidics is an attractive platform for smart, active cooling.

KEY WORDS: microfluidics, digital microfluidics, electrowetting, droplet, nanoliter, thermal effects, chip cooling, smart cooling, active cooling

I. INTRODUCTION

Thermal management is an increasingly important issue in integrated circuit (IC) design. Decreasing feature sizes, increasing frequencies, and increasing package densities of ICs will soon render current package-level cooling techniques inadequate. Poor thermal design and management often results in overheating, which, according to recent statistics, accounts for a large portion of field failures. In addition, it has been predicted in the 2001 International Technology Roadmap for Semiconductors (ITRS) that the peak power consumption of high-performance desktops will jump by 92% (150W to 288W) in 2014, and by 95% (81W to 158W) in lower-end desktops in 2016 [1].

High die temperatures and non-uniform thermal distributions of poorly managed ICs can result in a number of problems. For example, the mean-time-to-failure due to electromigration decreases exponentially with increasing temperatures. MOS transistor drive capability is found to decrease almost 4% for every 10°C rise in temperature, whereas interconnect delay increases at the same rate [2], resulting in performance degradation. Furthermore, an uneven thermal distribution (i.e., hot-areas) within the die can result in chip failure due to physical stress.

Various techniques have been explored to reduce power consumption, and thus heat dissipation, in ICs [3,4]. However, power consumption for these ICs continues to increase, despite their lower supply voltages. Designers must thus resort to alternative techniques to address heat transfer and dissipation. Since current package-level designs are becoming inadequate, new techniques are needed to develop embedded IC-level cooling methods.

A number of cooling techniques based on micro-electro-mechanical systems (MEMS) have been reported to date [5-9]. These methods can be broadly placed into one of two categories, passive and active cooling methods. Passive cooling requires no external power and just relies on conduction, natural convection, or radiation to redistribute and dissipate heat. Active cooling, by contrast, requires an input power source, using external methods such as forced convection, pumped loops, and refrigeration. Active cooling can further be categorized into "smart" active cooling, whereby a closed-loop feedback of the thermal profile in an IC can create a temperature-aware adaptive cooling system that can dynamically cool hot areas, maintaining an even thermal map.

Go *et al* have reported an active MEMS-based air cooling device that employs an array of microfabricated membranes

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actuated electromagnetically to produce microjets of air [5]. Microcantilevers then hydrodynamically dissipate the hot air faster than a plain-wall heat sink. A pumpless loop has been reported by Mukhrjee *et al*, where fluid density difference between two vertical, parallel tubes induces fluid motion [6]. This passive microfluidic cooling technique uses convection to redistribute the heat in an efficient closed-system manner. While these methods require little or no power, they are not suitable for applications where specific cooling of hot areas is required.

Currently, much attention has been focused on active microfluidic techniques, such as micropumps which are capable of pumping liquids quickly through microchannels. For example, 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 [7]. Similarly, a MEMS-based microcapillary pumped loop has been reported in which an evaporator, condenser, reservoir, and liquid lines have all been integrated on a silicon wafer [8].

The problem with current microfluidic devices is that they often require large pressure gradients to transport liquids, and are often limited to permanently etched channels, making a reconfigurable (i.e. smart) active cooler difficult to design. A more attractive alternative is to use a droplet-based microfluidic device, rather than a continuous-flow based device, whereby droplets are independently controlled and pathways are dynamically reconfigured to address hot areas.

Electrowetting was demonstrated in both oil and air as a viable technique to manipulate droplets by Pollack *et al* [10]. Under clocked-voltage control, microfluidic operations such as transport, splitting, merging, mixing, and formation of droplets have been studied, resulting in an instruction set for this "digital microfluidic" platform [10-14]. While initially intended for biological and chemical labs-on-a-chip applications, this platform can be easily extended for applications to chip cooling.

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 for a hierarchical and cell-based design approach to be used. Second, the absence of permanently etched channels allows for a completely reconfigurable system. Third, cooling liquid droplets can be transported over a 2D-array of electrodes without the need for external pumps and valves. Fourth, liquid flow has been shown to inherently increase with increasing temperature. Thus, local hot areas on a chip will have an inherently increased cooling rate without the need for external sensors.

Pamula and Chakrabarty have proposed utilizing such an electrowetting-based "digital microfluidic" platform for cooling ICs [15]. In this paper, we investigate the thermal effects on droplet transport by specifying minimum energies required to move a droplet at a given temperature. In order to understand these thermal effects affecting the droplet transport, we then present the temperature-dependency of two system parameters, interfacial tension and oil viscosity,.

II. DETAILS OF EXPERIMENTAL METHODS

Chip Fabrication

The digital microfluidic platform consists of a chrome-patterned glass bottom plate and a transparent conducting top plate, between which a droplet is sandwiched, as shown in the side view of Figure 1. The bottom plates were fabricated using standard microfabrication techniques and consists of an array of independently addressable control electrodes patterned using a 200 nm thick chrome layer. An 800 nm layer of Parylene C was then coated to serve as an insulating layer. The top plates consist of a thin layer of transparent indium tin oxide (ITO) coated on glass, forming a continuous ground contact. Both the top and bottom plates are hydrophobized with a thin layer (~50 nm) of Teflon AF 1600. The top and bottom plates are separated using a glass spacer, yielding a fixed gap height.

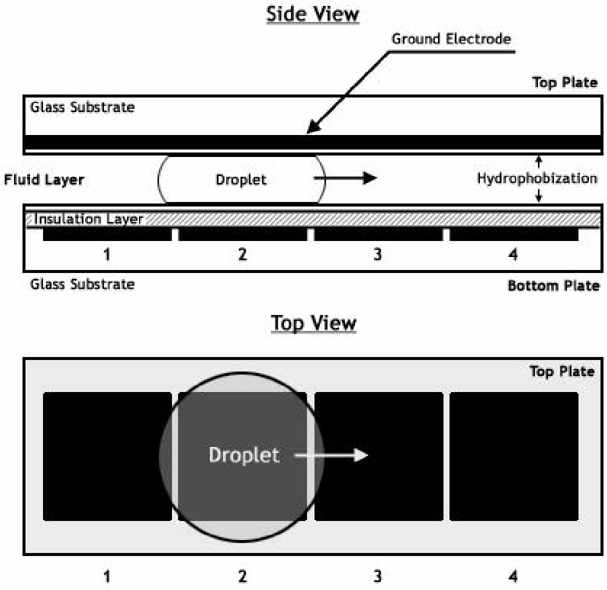

Figure 1. Schematic side and top views of the electrowetting chip. A droplet is held onto electrode 2 by applying a voltage at that electrode. Droplet transport to the right is achieved by deactivating electrode 2 and activating electrode 3. This creates a reduction in interfacial tension on the leading 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 are actuated electrostatically in which the interfacial tension of a liquid droplet and a solid surface are modulated, a phenomenon known as electrowetting [11]. A polarizable and conducting liquid droplet is sandwiched between the two planar plates described above. Droplets typically consist of 1M KCl in de-ionized water unless otherwise specified. The volume of each droplet is chosen such that its footprint is slightly larger than the electrode pitch, ensuring overlap between the droplet and adjacent electrodes. Such an overlap is necessary for the droplets to respond to the applied voltages. In the experiments performed here, the volume of each droplet is 1.4 µl, which provides sufficient overlap on 1.5 mm pitch square electrodes using a 600µm gap height. A customized electronic controller and software program were built and written to address and switch each electrode independently and automatically. The basic scheme for droplet actuation is explained in Figure 1.

In order to prevent evaporation of the droplets , a filler fluid of immiscible silicone oil is used. The use of oil also reduces the minimum actuation voltages required for transport of the droplets. Based on our earlier observations [16], we also assume the presence of a very thin oil film encapsulating the droplet on top and bottom While typical electrowetting-based systems consist of a solid-liquid interface, the presence of an oil film in our system suggests the existence of a liquid-liquid interface. Thus, the interfacial tension between the droplet and oil is an important parameter to be studied.

Experimental Setup

A number of parameters were varied to investigate the thermal effects on droplet transport, including system temperature, interfacial tension, oil viscosities, and actuation voltages. For temperature-controlled experiments, heaters were provided off the chip using an ITO-coated glass slide affixed to the bottom of the chip. A thermocouple-based PID controller was used to ensure that the chip, droplet, and surrounding silicone oil were maintained at the desired temperatures.

The surface tensions of the liquid droplets were modified using a nonionic surfactant (Triton-X 100). Since silicone oil is used to surround the droplets, values were measured as the interfacial tension with silicone oil using a surface tensiometer (Fisher Tensiomat Model 21). Each measurement was made by resting a platinum-iridium ring between the interface of silicone oil and the desired liquid. The tensiometer was zeroed, and an upward force was slowly applied until the ring broke through the surface of the oil, at which point the surface tension value was obtained.

Silicone oil with a viscosity of 1 cSt was used for all initial experiments (Gelest, Inc., PA). However, the viscosity temperature coefficient (v.t.c.) [1] of 0.37 suggested that viscosity changes with temperature were significant in the ranges studied (10°C to 100°C). Thus, additional viscosities of 0.65, 2, 5, and 10 cSt were obtained to study the effects of viscosity only on droplet transport.

Experiments were visually observed using a CCD microscope and recorded digitally for further analysis.

III. RESULTS AND DISCUSSION

Successful transport of a droplet in a digital microfluidic chip is contingent upon a number of parameters, including actuation voltage, droplet dimension, filler fluid viscosity, and droplet-oil interfacial tension among others. While the impact of these parameters on droplet transport has been established in experiments performed at room temperature, their effects at higher temperatures have not yet been studied in detail [10-14].

To determine the viability of our platform for chip-cooling, the effect of temperature on minimum actuation voltages, interfacial tension, and oil viscosities must be primarily studied.

System-Global Temperature Effects on V_{th}

Threshold voltages (V_{th}), defined as the minimum voltage required to oscillate a droplet among a set of electrodes at a specific switching frequency, were determined at various system-global temperatures. An off-chip heater was used to raise the temperature of the entire system uniformly to 75°C, during which period droplets were oscillated among four electrodes using 4, 8, and 16 Hz switching frequencies.

We observe up to a 30% decrease in V_{th} for a 50°C temperature increase, as shown in Figure 2. As much as a 17V reduction in actuation voltage was observed. Since linear droplet velocity increases with voltage, these results suggest that droplet velocity increases as temperature increases for a given voltage. This inherent increase of the droplet flow rate at higher temperatures makes this system an attractive approach for smart active cooling, since hotter regions on an IC would result in faster cooling rates.

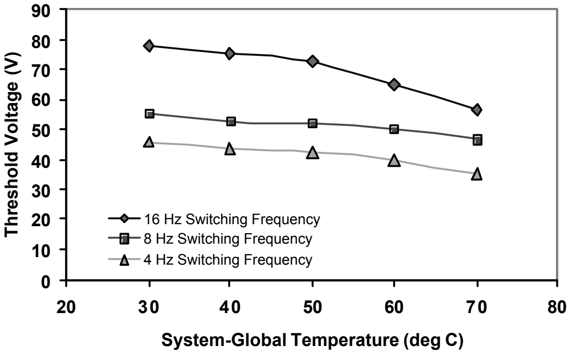

Figure 2. Temperature effects on threshold voltage, V_{th}. 1.5 mm square electrodes and a 600µm gap was used. The volume of each droplet was 1.4 µl.

In order to identify the mechanism by which droplet transport is facilitated at higher temperatures, two temperature-dependent parameters were investigated: interfacial tension and oil viscosity.

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[1] v.t.c. = 1 - (viscosity @ 99° C/viscosity @ 38° C).

Interfacial Tension Effects on V_{th}

Since electrowetting is a phenomenon whereby the surface tension of the droplet with a surface is modulated, it is important to study the effects of temperature on this parameter. However, since there is evidence to suggest the presence of a thin oil film between the droplet and the solid surface in our system [16], a more relevant parameter to investigate is the interfacial tension of the droplet with the surrounding oil. Interfacial tension measurements between the droplet liquid and 1 cSt oil at various temperatures are shown in Figure 3.

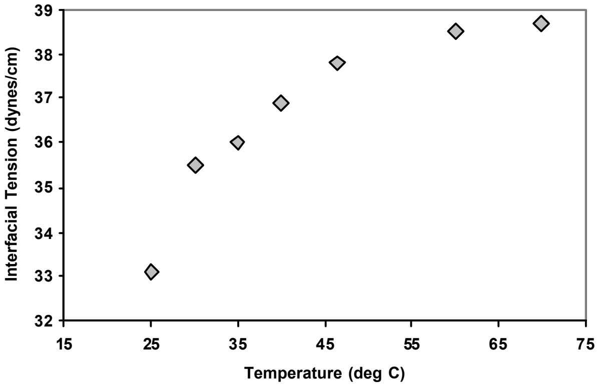

Figure 3. Variation in the oil-water interfacial tension for a 1 cSt silicone oil and de-ionized water at various temperatures.

Over a 50°C temperature range, we observe a 14% (5.7 dyne/cm) increase in interfacial tension, which appears to asymptote near 75°C. This behavior suggests that at higher temperatures, interfacial tension alone no longer has a significant impact in the threshold voltage reductions shown in Figure 2, which exhibit a linear decrease past 60°C.

We verify this behavior by exploring the threshold voltage dependency on interfacial tension in the absence of temperature variation, as shown in Figure 4. Various concentrations of Triton-X were added to water to reduce its interfacial tension, and V_{th} was obtained at each concentration for 4, 8 and 16 Hz switching frequencies.

The results from Figure 4 suggest that there exists an optimal interfacial tension near 10 dynes/cm for transport. Below this value, the droplet deforms due to lower surface tension such that the leading edge of the droplet responds faster in moving towards to an activated electrode compared to the lagging edge. Therefore, these droplets need larger threshold voltages to transport. Typically, we observe a discrete motion of a droplet at higher surface tensions. Above 10 dynes/cm, however, the threshold voltage response is nearly linear, with, at most, a slope of +0.5V per every dyne/cm. This suggests that, over the interfacial tension ranges observed in Figure 4, the temperature-induced interfacial tension effect on V_{th} accounts for only a 2.85V increase. Thus, while interfacial tension may partially reduce the speed of droplet at higher temperatures, other mechanisms are at play, which we investigate next.

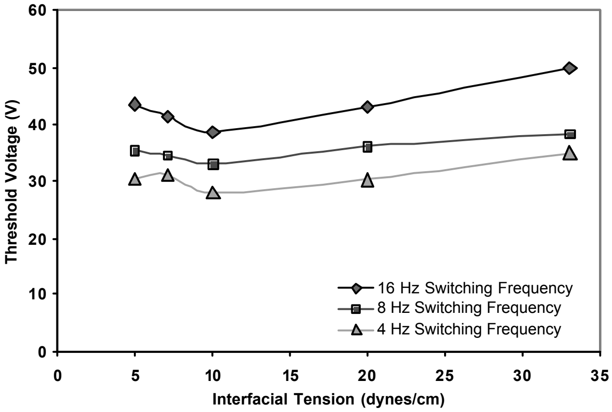

Figure 4. Threshold voltage (V_{th}) dependency on Interfacial tension @ 25°C. Note: Because it is impossible to chemically increase the surface tension of de-ionized water, the interfacial tension values beyond 33.1 dynes/cm (0% Triton-X) were unobtainable. Data-fitting curves are included for visualization purposes only.

Oil Viscosity Effects on V_{th}

The viscosity of the surrounding silicone oil plays a significant role in droplet transport. It has been previously reported that V_{th} increases with increasing viscosities of the oil and the droplet [17]. The viscosity temperature coefficient (v.t.c.) of 0.37 cSt for 1 cSt silicone oil suggests that there exist significant reductions in oil viscosity at elevated temperatures. Assuming linearity, the calculated viscosity of 1cSt silicone oil is 0.71 cSt at 70°C.

Threshold voltages were obtained for 4, 8, and 16 Hz switching frequencies for 0.65 cSt silicone oil at 25°C, and compared to values obtained using 1 cSt oil at both 25°C and 70°C. Values were normalized to 1 cSt oil at room temperature, as shown in Figure 5.

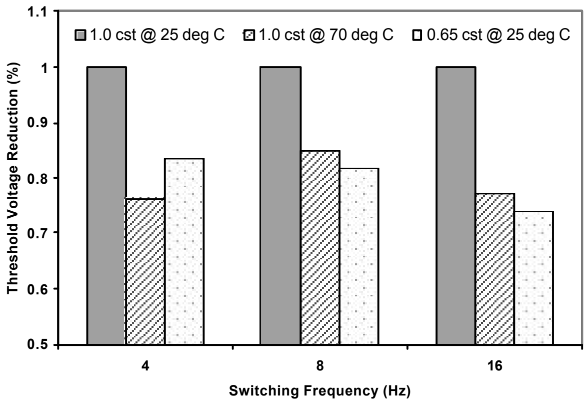

Figure 5. Percent reductions in threshold voltages (V_{th}) for droplet transport in 0.65 cSt oil at 25°C and 1.0 cSt oil at 75°C, as compared to values obtained in 1.0 cSt oil at 25°C.

We observe that the threshold voltage reductions for both 1.0 cSt at 70°C and 0.65 cSt at room temperature are similar. The largest voltage drop was observed for droplets oscillating at 16 Hz in 0.65 cSt oil, with a value of 17.6V. This is consistent with the 17V drop shown in Figure 2, suggesting that oil viscosity is the primary mechanism in facilitating droplet transport at higher temperatures.

IV. APPLICATIONS TO CHIP COOLING

The digital microfluidic approach to chip cooling has a number of advantages over other microfluidic methods. First, the 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, as presented here, the increased flow rates of droplets due to the temperature-induced lowered viscosities of the surrounding oil create an inherently temperature-aware system for smart cooling. Third, special fabrication techniques, typically a requisite for microfluidic devices, are minimally, if at all, required in our system. Although we have performed experiments here using microfabricated glass chips, we have recently demonstrated the transport of droplets using the more commonly available PCB (printed circuit board) design techniques. Using the copper layer for the electrodes, the solder mask as the insulator, and a Teflon AF coating for hydrophobicity, simultaneous and independent droplet transport in multiple 1D arrays has been demonstrated. An embedded closed-loop device is therefore feasible using a number of existing fabrication techniques, reducing the overhead in design and manufacturing costs.

Two-dimensional *m* x *n* arrays have been fabricated and tested on both glass and PCB chips. Droplet formation using electrowetting only has also been demonstrated [14]. A self-contained and self-regulated microfluidic device can thus be realized onto the IC itself, where droplets are formed (i.e., digitized) from larger actively cooled reservoirs, carried across a heated region with velocities proportional to temperature, and returned. Cooling and thermal uniformity on the IC can thus be achieved from this constant digitization, transport, and cooling of liquid droplets, as shown in Figure 6.

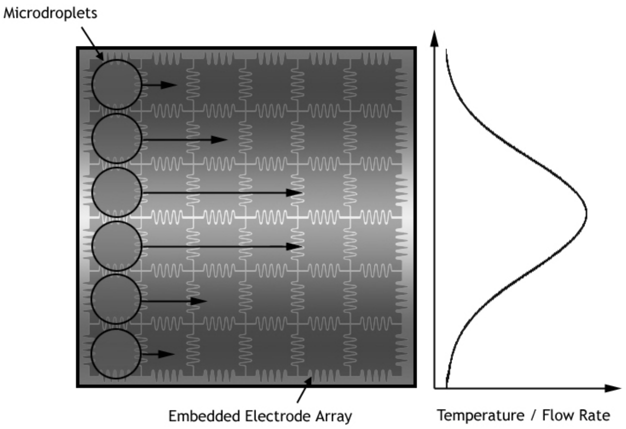

Figure 6. Top view schematic of cooling on a one-dimensional heat problem. Droplets are transported across a two-dimensional electrode array embedded on the surface of an IC. Since flow rate is proportional to temperature, droplets toward the hotter, middle region travel and cool more rapidly.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we study for the first time thermal effects on droplet transport in a digital microfluidic platform. A significant drop in minimum threshold voltages (V_{th}) required for the oscillation of microdroplets was observed at elevated temperatures, which, given a constant actuation voltage, is synonymous to increased droplet velocities. This increased flow at higher temperature makes this platform ideal for active and smart chip-cooling applications. Interfacial tension and oil viscosities were investigated as possible mechanisms for this behavior. The reduction of interfacial tension alone with elevated temperatures plays a minor role in the reduction of V_{th}, while the lowered viscosity of the surrounding oil accounts for nearly all the changes observed. Hence, the surrounding temperature-dependent silicone oil plays a significant role in enabling the "smart" aspect of chip cooling without the need for external sensors.

In this paper, we have established the effects of system-global temperature changes on droplet transport. However, the effects of local temperature changes on viscosity need to be studied. A more precise relationship between temperature and flow rates also needs to be established. Thermocapillary effects in this platform are yet unknown, and must be investigated. As a method to sense and meter droplets for smart, dynamic cooling, a feedback mechanism using capacitance measurements should also be studied [17].

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