A Digital-Microfluidic Approach to Chip Cooling

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Thermal management is an increasingly important aspect of IC design. After reviewing several chip-cooling techniques proposed in the literature, this article presents an alternative approach based on a recently invented digital-microfluidic platform. Originally developed for a biological and chemical lab on a chip, this technology can be adapted for use as a fully reconfigurable, adaptive cooling platform.

OVERHEATING IS A major cause of IC failure during system operation. Although the semiconductor industry continues to double transistor density every two years (as Moore's law predicted), the power dissipation associated with this performance gain is also increasing. This is not a new or surprising trend, but ICs are quickly reaching temperatures that current cooling techniques are hard-pressed to keep up with. The 2006 *International Technology Roadmap for Semiconductors* predicts that the peak power consumption of high-performance desktops will jump by 18% (167 W to 198 W) in 2013, and by 51% (91 W to 137 W) in lower-end desktops in 2013. If cooling methods don't improve, elevated die temperatures in tomorrow's ICs could result in catastrophic failures.[1] Furthermore, as uneven thermal distributions across the substrate become more pronounced, failures due to physical stress will increase. Researchers have proposed chip-cooling techniques to improve heat transfer, but most of these solutions fail to address the problems caused by a nonuniform thermal profile.

In this article, we provide an overview of today's chip-cooling solutions. We then present an alternative approach based on the recently invented digital-microfluidic platform. This new fluid-handling platform enables a vast array of microliter- to nanoliter-size droplets to move independently along a substrate. Unprecedented flexibility allows the system to reconfigure flows, and therefore cooling rates, to match the chip's thermal profile. We earlier presented an implementation of this approach that uses aqueous-based droplets to collect, carry, and dissipate heat away from the substrate.[2] Here, we present a different approach, which uses liquid-metal droplets to create an adaptive thermal-interface material (TIM).

IC-cooling techniques

There has been considerable developmental effort to improve chip cooling, particularly in recent years. Researchers have proposed a wide range of approaches, many leaning toward the microfluidic platform. Although these techniques have relied on fundamentally different technologies, they share several characteristics. We have classified these common characteristics into two categories, each with its own advantages in performance, complexity, and cost.

Passive versus active cooling

Cooling methods are either passive or active. Passive methods include thermal conduction (pastes, metal lines, and vias), natural convection (finned heat sinks and ventilation slots), and radiation (coatings and paints). Heat pipes and thermosyphons are also passive methods, but they offer higher performance. Passive devices are generally inexpensive to implement because they have no active component, and they are relatively simple in design. Passive-cooling devices typically perform worse than active-cooling devices.

Active cooling requires input power. Thus, active methods require external components such as forced-

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convection devices (fans and nozzles), pumped loops (heat exchangers and cold plates), and refrigerators (Peltier thermoelectric and vapor-compression-based).

Adaptive versus nonadaptive cooling

We further categorize active-cooling devices with the notion of adaptability to varying temperatures. An adaptive cooling system incorporates closed-loop feedback of the chip's temperature (from either direct or indirect measurement). The temperature-aware system can dynamically cool different chip areas. The ability to selectively cool different areas is important because thermal nonuniformity can cause detrimental stresses on the IC substrate. Thermal nonuniformities, or hot spots, arise from varying power distributions on the IC substrate and can reach power densities of 300 W/cm^2 or more. A nonadaptive cooling system lacks a temperature feedback mechanism and thus cannot respond to hot spots.

Underlying technologies

Commercial and academic cooling systems use five general technologies: heat-sink fans, macrofluidics, microelectromechanical systems (MEMS), refrigeration, and microfluidics.

Fan-based cooling. The most widespread technique for cooling chips uses a heat spreader and forced convection. A metal-finned heat sink is typically mounted on the chip's packaging, and a fan coupled to the heat sink circulates air through the fins to dissipate the heat. Air is usually directly available, and the cooling device doesn't require any additional complex or expensive packaging. Although small improvements in heat-sink design and in chip interfaces have been made recently, this technology has remained largely unchanged for many years.

Macrofluidics-based cooling. A second class of cooling technologies is based on macrofluidics. These liquid-cooling methods work at the macroscale (greater than microliters) and fall into two categories: direct and indirect. Direct methods involve the immersion of electronic chips in a pool of inert dielectric liquid. Indirect methods usually use a two-phase flow. Examples of indirect-cooling devices include thermosyphons and heat pipes. In thermosyphons, a liquid evaporates with applied heat and condenses, dissipating the heat elsewhere in a closed system. Typically, gravity returns the condensed liquid to the hot area. A heat pipe is a sealed and evacuated vacuum-tight container partially filled with a fluid. When heat is applied locally, the fluid in that part of the pipe vaporizes, travels to the low-pressure areas, and condenses. The condensate reaches the hot area through wick structures lining the heat pipe, ensuring uniform heat distribution. Heat pipes are passive-cooling devices and are used in many notebook and quiet desktop computers such as Apple's Power Mac G5.

MEMS-based cooling. A third class of cooling technologies is MEMS-based devices. Using today's microfabrication techniques, manufacturers can develop complex structures on a substrate to promote heat conduction and dissipation. These devices replace traditional plain-wall heat sinks, and although they can be designed to work with either air or liquid, air is usually preferred for cost-effective implementation and simple assembly. Examples of proposed MEMS-based air-cooling methods include air-impinging jet heat exchangers and arrays of microfabricated membranes actuated electromagnetically to produce air microjets.[3] These methods work on the principle of injecting small streams of air through the MEMS device onto the IC substrate's surface to create flow patterns that help redistribute and therefore dissipate heat. Another example of a MEMS-based device is a bulk-micromachined microfin array heat sink, which enhances hydrodynamic mixing. The array consists of warped bimorph microcantilevers that vibrate when an air jet impinges on them, creating vortices and dissipating heat faster than a plain-wall heat sink.

Refrigeration-based cooling. Another type of IC-cooling technology is refrigeration systems using vapor compression, gas compression, or thermoelectric devices. These systems can generate a subzero effective thermal resistance, and require only that the evaporator attached to the chip package have a contact temperature less than the cooling-air temperature. The result is a substantial increase in heat dissipation from the chip.

Traditional refrigeration units require large amounts of input power to operate, and their compressors are large and bulky. Engineers have developed compact vapor compression refrigeration units, but focus has shifted toward solid-state refrigeration. Solid-state refrigeration uses thermoelectric coolers (TECs) to provide thermal resistance at or below 0°C/W. TECs depend on the Peltier effect, by which DC current applied across two dissimilar materials causes a temperature differential. In a typical system, the TECs lie between the heat source (the IC die or packaging) and the heat sink.[4] Because one side of the TEC is hot, the heat sink must dissipate power on the hot side. This extra energy can cause higher ambient temperatures at the heat sink, and if the heat sink cannot dissipate the heat, the cold side of the TEC might heat up as well. As a result, researchers are looking for ways to increase the efficiency of TEC devices.

Microfluidics-based cooling. Originally proposed in the early 1980s, microfluidic cooling devices push small volumes of liquids (less than microliters) across an IC's surface to conduct and dissipate heat downstream. Owing to limitations in microfluidic-handling technologies, this method has yet to be realized in a practical commercial system. However, as chip power consumption continues to rise and microfluidic pumping technology matures, microfluidics-based cooling is receiving renewed attention.

The first microfluidic cooling device was the microchannel heat sink.[5] Microchannel heat sinks are minute flow channels fabricated on the back of a thin silicon chip substrate. With hydraulic diameters ranging from 10 to 30 microns, these heat sinks have an extremely high surface area per unit volume of working fluid, and a low thermal resistance. However, because they required a large external supply of pressurized cooling liquid, commercialization of these devices was not economically or practically feasible. Furthermore, an external pressure source for a liquid supply is inherently unsuitable for compact, embedded systems. Thus, there remained a technology void and a pressing need for IC cooling in compact packages.

Over the past decade, microchannel devices have been developed to miniaturize cooling hardware. Microchannel cooling loops now have high cooling performance, large heat-transfer coefficients, small channel volumes, and a small cooling inventory. Heat transfer in these systems depends on heat convection between a solid and a moving liquid. Given a solid surface at temperature T_b and an adjacent moving liquid at temperature T_f, where $T_b > T_f$, the rate of energy transfer from the surface of the solid to the liquid is quantified as $dQ_c/dt = hA(T_b - T_f)$. This is Newton's law of cooling. A is the surface area and h is a proportionality factor called the heat-transfer coefficient. The heat-transfer coefficient is an empirical parameter that incorporates the flow pattern's nature near the surface, the fluid properties, and the geometry into the heat-transfer relationship. For example, in a forced-convection system using fans blowing across the chip, the heat-transfer coefficient's value is far higher than in a free-convection system, because new flow patterns are introduced to the otherwise slow, buoyancy-induced air motion.

Researchers have developed a pumpless loop with microchannel surfaces for cooling.[6] It relies on fluid density differences between two vertical, parallel tubes to induce fluid motion. This method requires no external pumps, and as the temperature increases, the flow becomes faster. It is a passive-cooling method with no external power requirements. However, it cannot be used in applications that need specific hot-spot cooling.

Recently, much attention has focused on developing reliable micropumps that can pump liquids through microchannels. To increase the heat flux from a microchannel with single-phase cooling, it is necessary to increase the heat-transfer coefficient either by increasing the liquid flow rate or by decreasing the hydraulic diameter. In two-phase regimes, the evolution of the phase change from liquid to vapor in microsystems is different than in macrosystems. Stanford researchers developed a closed-loop, two-phase microchannel cooling system based on electro-osmotic pumping of liquids.[7] The electro-osmotic pump is connected to a microchannel heat exchanger, which in turn is connected to a heat rejecter. This pump has removed 38 W with a pump power of 2 W. This was the first demonstration of a hermetically sealed electro-osmotic cooling system.

A MEMS-based microcapillary pumped loop (micro-CPL) has been fabricated on a silicon wafer, integrating an evaporator, a condenser, a reservoir, and liquid lines.[8] Micro-CPLs offer greater geometric freedom than heat pipes. They also carry greater heat loads because of the simultaneous flow of vapor and liquid, in contrast to the countercurrent flows in conventional heat pipes.

Georgia Tech researchers have developed a cooling module based on piezoelectric droplet generation.[9] In this structure, secondary droplets form from a primary drop and then impinge on the hot surface. Unlike a heat pipe, the structure doesn't need wicks to continuously supply liquid to the chip's hot area. Upon impinging on the hot surface, the droplets evaporate and don't form an insulating vapor blanket as occurs with pool boiling. The atomized droplets have sufficient momentum to penetrate through the vapor layer and spread into a thin film on the hot surface.

Digital-microfluidic cooling platforms

Although many of the newer cooling techniques just reviewed can transfer heat at a significantly higher rate than current practices do, they lack the flexibility to accommodate dynamic cooling of hot spots that cause nonuniform thermal profiles. This is because these techniques cannot alter cooling rates, either spatially or temporally, and thus are inadequate for adaptive cooling. Hence, designers address, in advance, any thermal variations in the IC by aggressively designing for higher cooling rates near the regions of high heat flux.

An alternative technique, which enables adaptive cooling, uses digital microfludics technology. Duke University researchers have developed a micropump that uses electrowetting to form and manipulate discrete droplets electrostatically.[10] Dividing liquids into independently controlled liquid packets for manipulation provides several important advantages over continuous-flow or mist-based systems:

- Microfluidic operations can be reduced to a set of basic discrete operations (moving one unit of liquid one unit step), allowing a hierarchical, cell-based design approach.
- The absence of permanently etched structures allows a completely reconfigurable system. The only active component, an actuating electrode, is embedded in a planar surface of the device, requiring no additional components or structures such as pumps and valves.
- Given a 2D array of actuating electrodes, the device can manipulate liquid droplets laterally in any arbitrary path without external pumps and valves. Without the fixed structures found in continuous-flow devices, the digital-microfluidic system can be completely virtual and reconfigurable.
- Liquid flow inherently increases with increasing temperature. Thus, local hot spots on a chip can potentially have an inherently increased cooling rate without requiring external sensors.

Electrowetting-based droplet actuation

A digital-microfluidic device typically consists of a substrate patterned with an array of electrodes. There are several ways to pattern the substrate, ranging from microfabrication vacuum processes to less expensive printed circuit board (PCB) processes. An insulator separates the electrodes from the conductive droplets. The insulator is coated with a hydrophobic material that prevents the droplet from wetting the surface. An upper plate provides a channel in which the droplets can move. The upper plate is coated with a conductive material, usually indium tin oxide, to keep the droplet at a ground potential. A spacer material maintains a gap between the lower substrate and the upper plate, and the entire channel contains an immiscible fluid (usually silicone oil) to facilitate droplet movement. Figure 1a shows a schematic of the assembled glass-based chip.

The digital-microfluidic device achieves droplet motion through the electrowetting effect. Applying a potential to an underlying electrode controls a droplet's ability to wet the surface. Applying this electric field increases the droplet's surface energy, and therefore the droplet wets the surface. This results in a decrease in the contact angle, causing the droplet to spread onto the electrode. Placing a droplet on top of an array of electrodes initiates lateral motion. Figure 1b illustrates the method. Pollack, Shenderov, and Fair provide experimental details and protocols.[10]

Unlike continuous-flow microfluidic devices, which allow only unidirectional flow induced by an external pump, a digital-microfluidic device under software control can drive droplets in any arbitrary direction. The user can programmatically manipulate many droplets using a set of fundamental fluidic operations: transport, dispense, merge, and split.[11]

Flow-through adaptive cooling

Although digital-microfluidic devices have traditionally functioned in biological or chemical labs on chips, we propose implementing the same architecture and droplet-based operations for IC cooling applications. One method, flow-through adaptive cooling, would use aqueous droplets continuously dispensed from an actively cooled reservoir and transported over an IC's surface. The droplets would transfer, store, and carry heat away from the IC substrate back to the cooling reservoir. Many droplets could therefore move in reconfigurable flow paths and flow rates to eliminate thermal nonuniformities. The

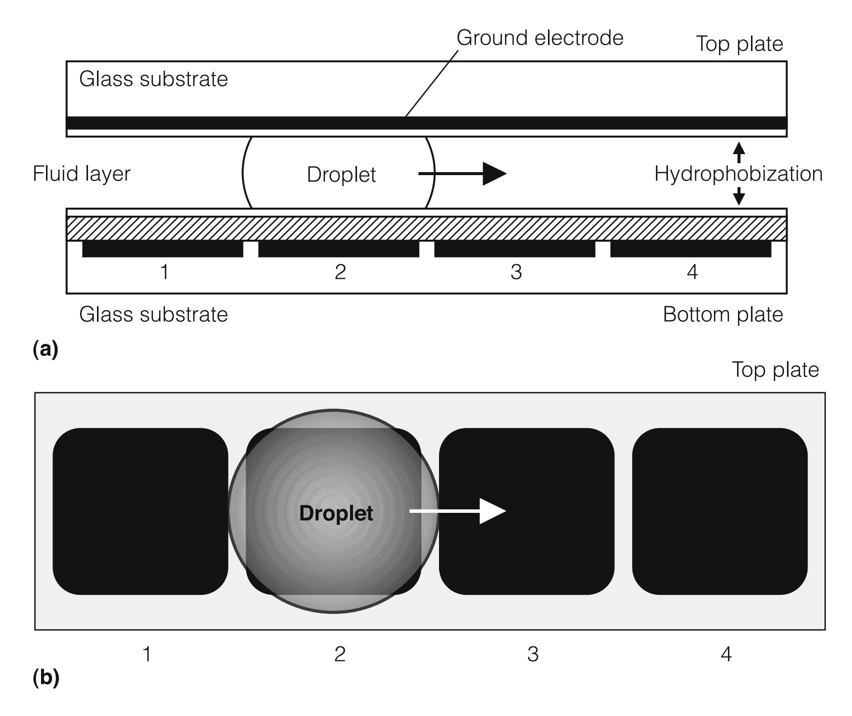

Figure 1. An assembled digital-microfluidic chip during droplet actuation: side view (a), and top view (b). Applying a voltage to electrode 2 beneath the droplet charges the droplet, and increased surface energy causes the droplet to change its interfacial tension with the surrounding oil (if present), thus wetting the electrode's surface. Turning off the voltage under electrode 2 and applying it to adjacent electrode 3 creates an interfacial tension gradient. This causes the droplet to move until the interfacial tension equilibrates when the droplet moves completely onto the activated electrode. This method is the basis of all microfluidic operations.

microfluidic device would interface with the target IC at either the package level or the substrate level. Figure 2 illustrates this technique. (We present further details elsewhere.[2])

Programmable thermal switching

An alternative and fundamentally different approach to adaptive cooling uses electrowetting to create a programmable thermal switch. This method manipulates a liquid-metal droplet to selectively switch an area in the cooling device from a high thermal-conductivity mode to a higher thermal-conductivity mode. The result is a programmable TIM that can reconfigure itself in response to the nonuniform heat flux in the target IC substrate. This programmable TIM interfaces the target IC substrate with an active-cooling device, thus providing a method to eliminate hot spots. Although this method cannot obtain maximum cooling, it can prevent physical stress due to temperature variation within the die.

To illustrate programmable thermal switching, Figure 3 shows a digital-microfluidic chip that contains an array of cells covering the entire area of a target IC chip. Each cell contains a single electrode with a droplet of liquid metal on top. Above the microfluidic chip is the IC substrate. Beneath each droplet is a metal via that travels to the chip's back side. The back side is attached to an existing (thermoelectric) cooling device.

The liquid-metal droplet acts as a conduit between the IC substrate and the heat sink. By default, the device turns all the electrodes on, detaching the droplet from the top surface of the IC substrate. The thermal resistance between the IC substrate and the microfluidic chip now matches that of the oil. When the device detects a hot spot over a cell, the electrode in the cell is turned off, causing the droplet to relax and subsequently come into contact with the top plate. This reduces thermal resistance between the hot spot and the heat sink by several orders of magnitude, and heat can then pass more efficiently from the hot spot to the heat sink.

Next, we present several studies conducted to establish the feasibility of the programmable thermal-switching method. The liquid metal chosen for these studies was mercury because of its established record as an electrowettable material.

Mercury droplet transportability. We tested mercury's transportability with our own digital-microfluidic devices. Using PCB-based digital-microfluidic chips, we demonstrated successful transport of mercury for a system with and without a filler fluid (1.5-centistoke silicone oil). The maximum transport switching frequencies were higher in oil than in air, and the droplet motion was more repeatable in the absence of a top plate.

Steady-state heat transfer of mercury. Typically, a microprocessor operates with a nominal level of background heat, and it produces localized hot spots when a functional unit is turned on (for example, a floating-point unit). The functional unit operates for a given period of time, and the hot spot ceases to exist when the functional unit is no longer running. Thus, it is important to study the steady-state effects of heat transfer when a mercury droplet is conducting heat away from a hot spot, because a functional unit's turn-on time can vary depending on the CPU's workload.

In one set of experiments, we placed a mercury droplet between a hot spot and a conductive via in a PCB-based microfluidic chip and filled the rest of the chip with silicone oil. We turned on the hot spot at a specified power density and measured its temperature as a function of time. We performed this experiment for hot-spot power densities of 100, 333, 500, and 750 W/cm^2. For comparison, we obtained the hot spot's steady-state temperature in oil and in air. An on-chip resistance temperature detector (RTD), intertwined with the heater, recorded the droplet's temperature at a 100-ms sampling interval. We investigated mercury's steady-state heat-transfer characteristics for a 1-mm diameter droplet with a gap height of 100 microns. We obtained steady-state temperatures for the hot spot in air, in oil, and in the presence of a mercury droplet. Figure 4 shows the results. We observed that for each hot-spot power density, the steady-state temperature for a system filled with oil was far lower than for one filled with air. We observed further cooling when a mercury droplet was placed underneath the hot spot. In these systems, adding oil and mercury reduced thermal resistance between the hot spot and the bottom microfluidic chip, which acted as a heat sink because of its large thermal mass.

We also observed that as hot-spot power density increased, each system's steady-state temperature increased. However, in air and in oil, the rate of increase is higher than in mercury, suggesting that the system will perform no worse (and will most likely perform better) if this trend continues for higher power densities.

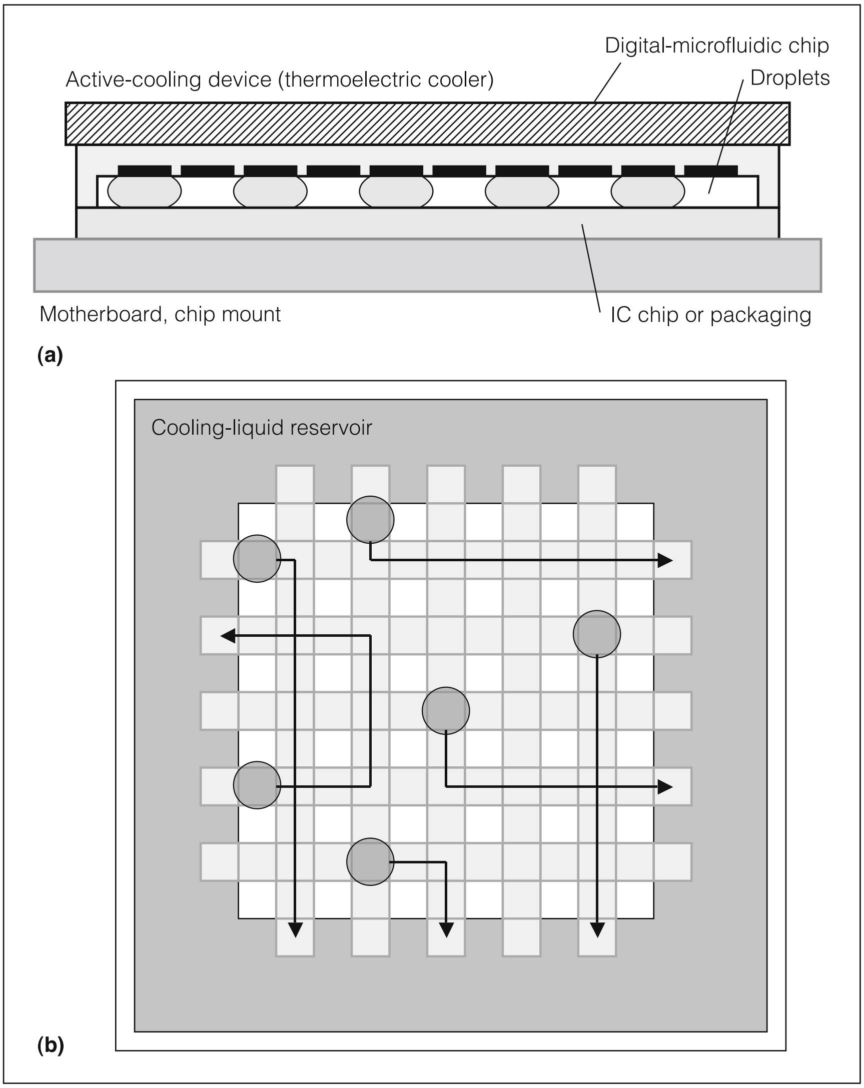

Figure 2. Proposed digital-microfluidic flow-through cooling architecture: As the side view (a) shows, droplets are sandwiched between the IC or IC packaging and the digital-microfluidic chip. Attached to the digital-microfluidic chip is an active-cooling device (such as a thermoelectric cooler or a heat-sink fan), which dissipates heat from the system. As the top view (b) shows, droplets form from reservoirs of cooling liquid and move in reconfigurable flow paths back to the reservoirs, where they are recycled. The remainder of the chip contains oil.

Transient heat transfer of mercury. We performed an experiment to demonstrate the feasibility of using a liquid-metal switch to selectively control the conduction of heat away from a hot spot. A mercury droplet in oil, initially removed from a hot spot, was delivered to the hot spot for a period of time and then again removed from the hot spot. As a control, we observed a similar system in which droplets consisted of water rather than mercury. As an additional

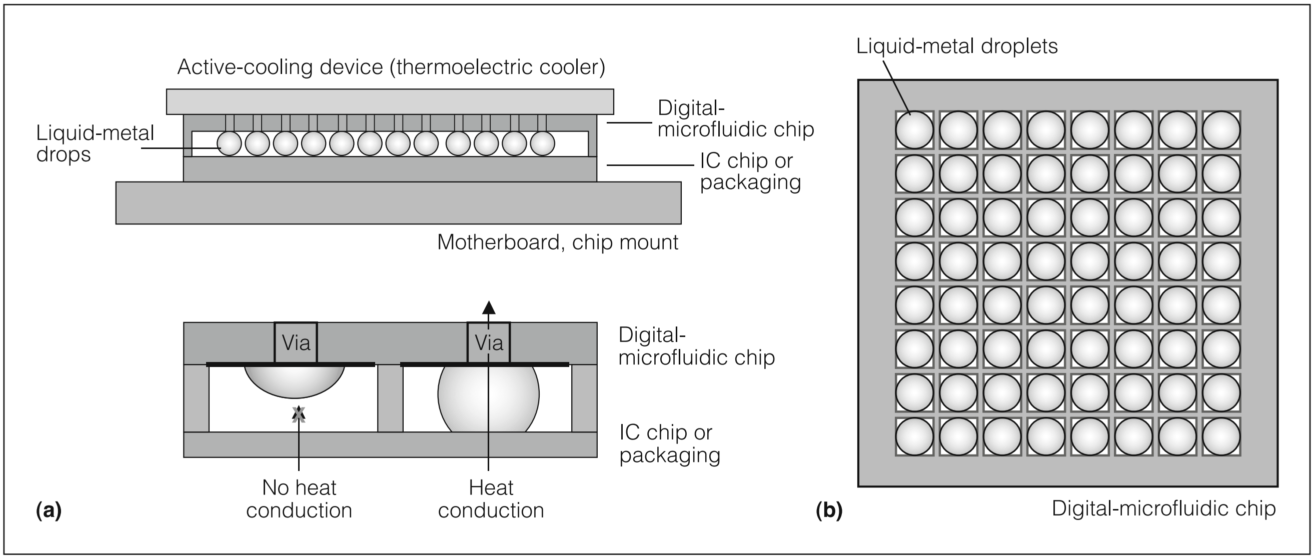

Figure 3. An array of liquid-metal droplets on a digital-microfluidic chip: top view (a), and side view (b). Droplets interface with the IC chip or package. The device switches between low and high thermal conduction by switching an electrode on and off. If an electrode or the device fails, the default position is off, so that maximum heat transfer can occur.

variable, we observed heat conduction both when an electrical via was present and when it was absent beneath the mercury droplet. This let us determine the via's effect on cooling. An on-chip resistive temperature device (RTD), intertwined with the heater, recorded the droplet's temperature at a sampling interval of 100 ms. Figures 5 and 6 show the results.

Figure 5 shows temperature data obtained at a hot spot when we delivered a mercury droplet for 20 seconds and then removed it. The hot spot had a heat flux density of 500 W/cm^2. We observed that the hot spot had an initial steady-state temperature of 89°C, which dropped by 9°C when the mercury droplet moved to it. The hot spot returned to its initial steady-state value when the mercury droplet moved away. We repeated this experiment for both a mercury droplet and a water droplet, with and without a via beneath the droplet. As Figure 6 shows, there was a significantly greater increase in temperature drop with the mercury droplet than with the water droplet.

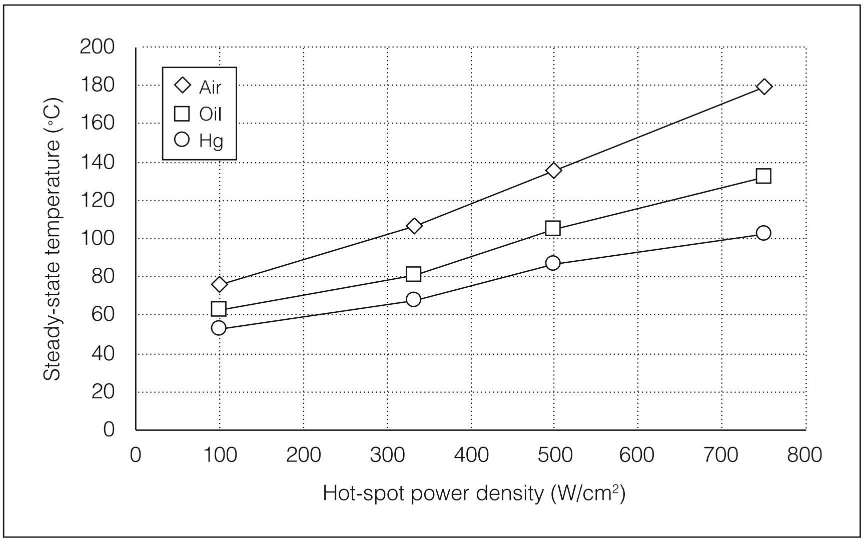

Figure 4. Steady-state temperature of a hot spot in air, oil, and in the presence of a mercury droplet with respect to hot-spot heat flux density.

The presence of the via also promoted cooling. Because of its higher thermal conductivity, mercury was more effective in cooling the hot spot than water, and the via allowed greater heat conduction through the PCB, and thus greater cooling. The via in our system was epoxy filled and copper plated, but a thermally conductive filled via is commercially available and would significantly improve cooling.

We also studied the relationship between the mercury droplet's heat transfer and the hot spot's power density (W/cm^2). We applied power densities as high as 500 W/cm^2 to a 500-micron × 500-micron thin-film heater. The resulting steady-state hot-spot temperatures ranged from 110°C to 557°C in air, 76°C to 466°C in oil, and 73°C to 373°C for a mercury droplet of about 1 mm^2 in area. Figure 7 shows the results. At 500 W/cm^2, the hot-spot temperature drop from the uncooled system (air to oil) to the system cooled by the mercury droplet (air to mercury) was as great as 184°C, twice as large as that observed for the hot spot cooled by oil only. This is a significant improvement over the 11% increase in temperature drop observed for the hot spot with a heat flux density of 133 W/cm^2.

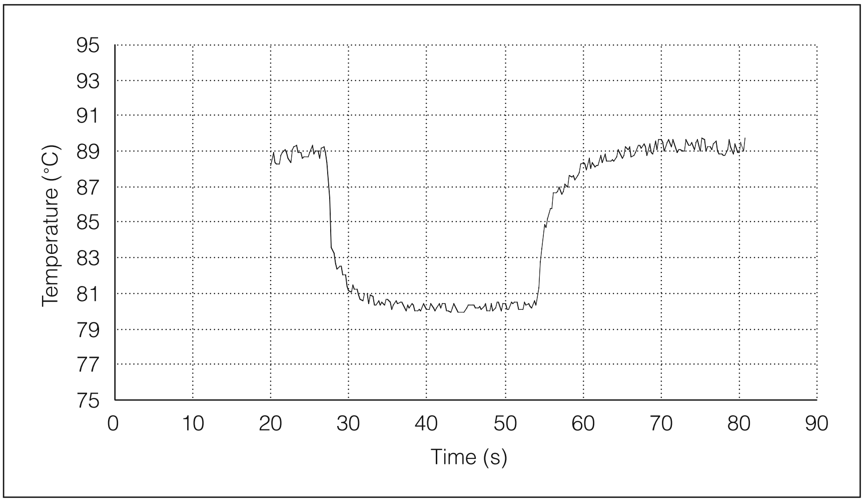

Figure 5. Temperature profile of a hot spot as a mercury droplet passes over it.

Table 1 compares heat flux density with relative heat-transfer coefficients, defined by Newton's law of cooling, as calculated from the data shown in Figure 7. We observed a linear increase in the heat-transfer coefficient for increasing hot-spot power densities. This suggests that the addition of mercury droplets in oil results in improved heat transfer, which further improves as the hot spot becomes more intense.

Throughout this article, we have demonstrated the feasibility of using the concept of digital microfluidics for applications in chip cooling. The benefits of using aqueous or liquid-metal droplets to rapidly respond to changing cooling demands are exclusive to this type of microfluidic platform. These benefits promise a cost-effective way to handle potentially devastating overheating side effects such as hot spots. Several challenges remain, however, before adaptive hot-spot cooling is possible in a real system. These include scaling the platform's physical dimensions to transition from microliter- to nanoliter-size droplets, exploring alternative liquids to achieve even higher thermal conductivities, and implementing alternative dielectric materials to insulate the electrodes from the droplet in order to achieve even faster droplet transport speeds. All three areas aim to both improve cooling performance and facilitate the packaging of this technology with current and future IC devices. ■

Acknowledgments

This research was supported by the National Science Foundation under grant CCR-0306349.

■ References

1. S.H. Tsai and S.M. Kang, "Cell-Level Placement for Improving Substrate Thermal Distribution," *IEEE Trans.*

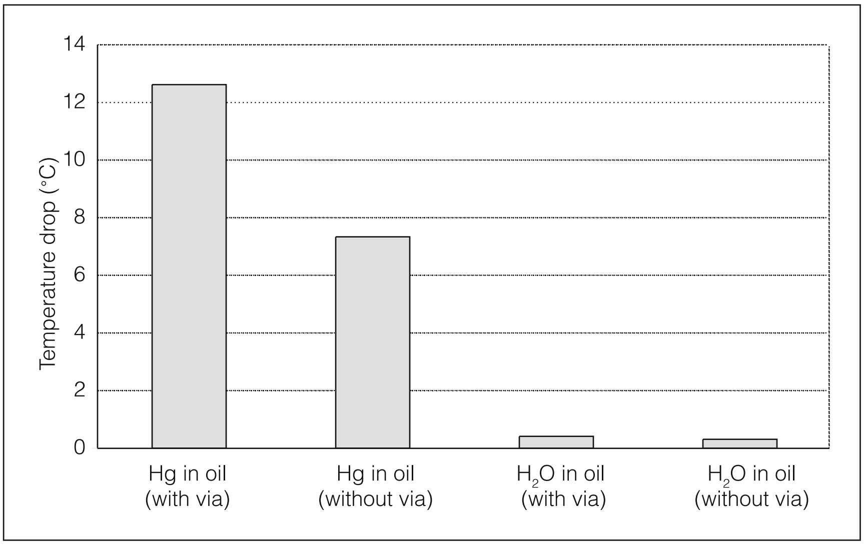

Figure 6. Temperature drop of a hot spot when a mercury (Hg) droplet in oil or a water (H_2O) droplet in oil passes over it, with and without a via beneath the droplet.

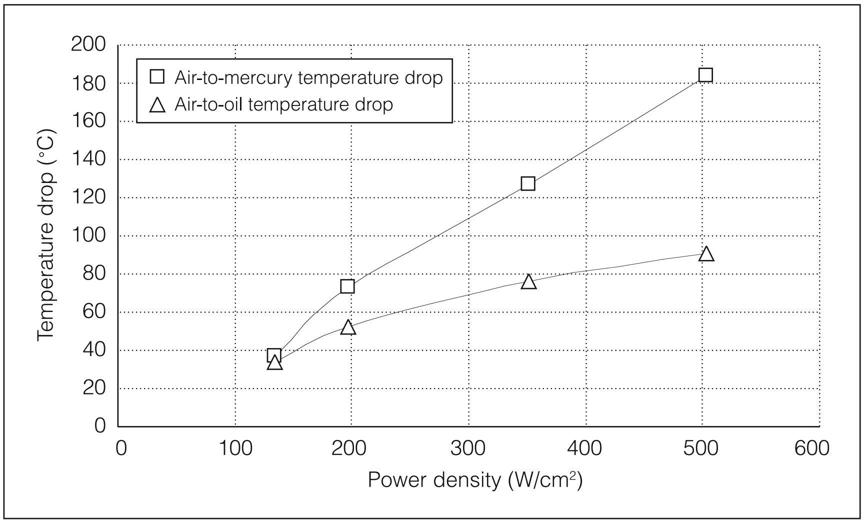

Figure 7. Temperature drop for the hot spot (air-to-oil and air-to-mercury) versus heat flux density.

Computer-Aided Design of Integrated Circuits and Systems, vol. 19, no. 2, Feb. 2000, pp. 253-266.

2. P.Y. Paik, V.K. Pamula, and K. Chakrabarty, "Adaptive Cooling of Integrated Circuits Using Digital Microfluidics," *IEEE Trans. Very Large Scale Integration (VLSI) Systems*, vol. 16, no. 4, Apr. 2008, pp. 432-443.
3. S.J. Campbell Jr. et al., "Thermal Management of a Laptop Computer with Synthetic Air Microjets," *Proc. 6th Intersociety Conf. Thermal and Thermomechanical Phenomena in Electronic Systems* (ITherm 98), IEEE Press, 1998, pp. 43-50.
4. I. Sauciuc et al., "Thermal Devices Integrated with Thermoelectric Modules with Applications to CPU Cooling," *Proc. InterPack 05*, American Soc. Mechanical Engineers, 2005, article 73243.
5. D.B. Tuckerman and R.F.W. Pease, "High-Performance Heat Sinking for VLSI," *IEEE Electron Device Letters*, vol. 2, no. 5, May 1981, pp. 126-129.
6. S. Mukherjee and I. Mudawar, "Smart Pumpless Loop for Micro-Channel Electronic Cooling Using Flat and Enhanced Surfaces," *IEEE Trans. Components and Packaging Technologies*, vol. 26, no. 1, Mar. 2003, pp. 99-109.
7. L. Jiang et al., "Closed-Loop Electroosmotic Microchannel Cooling System for VLSI Circuits," *IEEE Trans. Components and Packaging Technologies*, vol. 25, no. 3, Sept. 2002, pp. 347-355.
8. K. Pettigrew et al., "Performance of a MEMS Based Micro Capillary Pumped Loop for Chip-Level Temperature Control," *Proc. 14th IEEE Int'l Conf. Micro Electro Mechanical Systems* (MEMS 01), IEEE Press, 2001, pp. 427-430.
9. S.N. Heffington, W.Z. Black, and A. Glezer, "Vibration-Induced Droplet Atomization Heat Transfer Cell for High-Heat Flux Applications," *Proc. 8th Intersociety Conf. Thermal and Thermomechanical Phenomena in Electronic Systems* (ITherm 02), IEEE Press, 2002, pp. 408-412.
10. M.G. Pollack, A.D. Shenderov, and R.B. Fair, "Electrowetting-Based Actuation of Liquid Droplets for Microfluidic Applications," *Lab on a Chip*, vol. 2, no. 2, 2002, pp. 96-101.
11. S.K. Cho et al., "Toward Digital Microfluidic Circuits: Creating, Transporting, Cutting and Merging Liquid Droplets by Electrowetting-Based Actuation," *Proc. 15th IEEE Int'l Conf. Micro Electro Mechanical Systems* (MEMS 02), IEEE Press, 2002, pp. 32-52.
12. H. Zeng et al., "Piston-Motion Micro-Mirror Based on Electrowetting of Liquid Metals," *J. Microelectromechanical Systems*, vol. 14, no. 2, 2005, pp. 285-294.

Table 1. Heat-transfer coefficient relative to heat flux density.

Heat flux density (W/cm^2)	134.6	197.5	351.4	504.0
Relative heat-transfer coefficient	1.11	1.40	1.67	2.02

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