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Small-Scale Solutions to Grand Challenges in Thermal Management

Suresh V. Garimella
Birck Nanotechnology Center, Purdue University, sureshg@purdue.edu

SMALL-SCALE SOLUTIONS TO GRAND CHALLENGES IN THERMAL MANAGEMENT

Suresh V. Garimella
Cooling Technologies Research Center, an NSF IUCRC
School of Mechanical Engineering and Birck Nanotechnology Center
Purdue University, West Lafayette, IN 47907 USA
sureshg@purdue.edu

Abstract: Research needs in the field of thermal management of microelectronics and microsystems are identified, followed by a brief discussion of recent advances in solution approaches. These include novel solutions that rely on two-phase flow at the microscale, micropumps, droplet actuation on structured surfaces, passive transport in wick structures, ion-driven and piezoelectrically driven airflow, nanostructured thermal materials, and novel diagnostic tools.

Keywords: thermal management, cooling, nanotechnology, challenges, recent advances

INTRODUCTION

The continued evolution of electronics – from the breath-taking pace of the past few decades into the 21st century – requires a fundamental shift in perspective, coupled with major technical innovations at all scales, to manage the power dissipated in the form of heat. On the other end of the spectrum, large computing systems such as data centers are facing an energy crisis caused by this increasing power demand, which is aggravated by the energy consumed by cooling systems. Tens of megawatts of power consumed by data centers stress the energy supply infrastructure and cause environmental concerns as well. The many scales and the large ranges of heat fluxes and power levels encountered, as well as the need for energy efficiency and reduction of power usage, raise this problem to a grand challenge from a technical point of view. At the same time, the ubiquity and continued rapid growth and penetration of electronics into all aspects of life, from healthcare to education to security and beyond, demand that suitable solutions be urgently pursued.

Electro-thermal co-design at the micro- and nano-scales is critical for achieving desired performance and reliability in microelectronic circuits and other microsystems. Emerging solutions based on innovations at the small scale to address these grand challenges in thermal management will be discussed, with specific examples including novel droplet actuation on structured surfaces and micropumps, ion-driven and piezoelectrically driven airflow, and nanostructured thermal materials.

RESEARCH NEEDS

Research needs in thermal management have tracked the technologies used for the building-block of most electronics, *i.e.*, the transistor. While the switch from bipolar to CMOS transistors was expected to solve the problem of heat generation, the continued growth of the number and density of transistors in microelectronic chips has ensured that thermal management remains a critical bottleneck in the design of these systems. One important change over the last decade has been the shift from a focus on managing ever higher heat fluxes to a platform-based approach, where a more holistic approach to the entire system, including energy efficiency considerations, has emerged. Research needs in this area include:

- Models, materials and characterization of interfaces for improved contact conductance and heat spreading
- Novel high-conductivity packaging materials
- Embedded thermoelectrics for site-specific thermal management and energy recovery
- Passive liquid-based approaches
- Integrated, active microfluidic approaches
- Development of new fluids (the 'holy grail' of finding a fluid that exhibits properties similar to those of water but is not water!)
- Improved ultimate heat rejection – novel approaches to air cooling (ion-driven flows, piezoelectric fans, synthetic jets,…)
- Reduction of power consumed by active cooling solutions
- Energy (waste-heat) recovery
- Micro- and nano-scale sensing and control

For any given application, it is important to evaluate a variety of solutions; a hybrid approach may often be the best for a given application.

RECENT ADVANCES

While there are different ways to categorize the constraints and cooling needs in thermal management, some recent novel solutions (chosen primarily based on the scope of research in the author's group) are discussed in the following, based loosely on the coolant, the heat flux level, and on whether active fluidic actuation is employed.

High-Flux Active Liquid Cooling

With the rapid progress in high-performance computers, telecommunications, automotive electronics (IGBTs in hybrid/electric vehicles) and military applications that demand high-performance computation, heat flux levels in the range from 100 to 1000 W/cm^2 (and even higher in localized areas in some cases) are not uncommon. These high heat fluxes need aggressive, active cooling approaches such as microchannels, impinging jets, and sprays.

There is consensus in the literature that single-phase flow and heat transfer in microchannels is now quite well-understood, and that adequate predictive capabilities are available for practical designs of microchannel heat sinks [1]. Flow boiling offers significantly higher heat transfer rates while maintaining much better temperature uniformity. Although flow boiling in microchannels has received much attention in recent years, the implementation of microchannel heat sinks operating in the two-phase regime in practical applications has lagged due to the complexity of boiling phenomena at the microscale. This has led to difficulties in predicting the heat transfer rates that can be achieved as a function of the governing parameters.

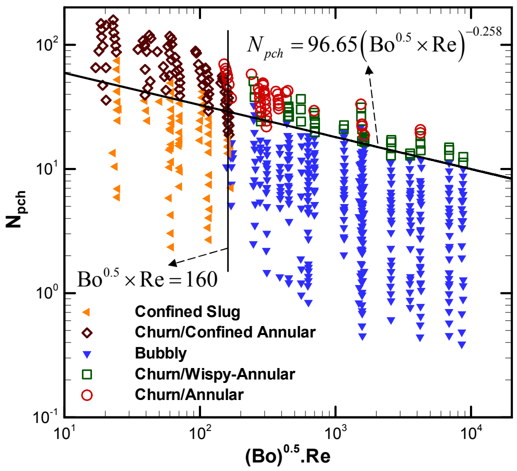

Fig. 1. Comprehensive flow regime map for flow boiling in microchannels, in terms of the Bond number ($Bo = g(\rho_f - \rho_g)D^2/\sigma$), Reynolds number ($Re = GD/\mu$), and Phase Change number ($N_{pch} = \frac{q''_w}{Gh_{fg}}\frac{L_H}{D_{hH}}\frac{\rho_f - \rho_g}{\rho_g}$).

From extensive experimental work and analysis conducted in recent years in the authors' group, a clear picture has emerged that promises to enable prediction of flow boiling heat transfer over a wide parameter space. Experiments have been conducted to determine the effects of important geometric parameters such as channel width, depth, and cross-sectional area, operating conditions such as mass flux, heat flux and vapor quality, as well as fluid properties, on flow regimes, pressure drops and heat transfer coefficients in microchannels. High-speed flow visualizations have led to a detailed mapping of flow regimes occurring under different conditions, as shown in Fig. 1. Given a particular set of geometric, flow and operating conditions, this map allows for the flow regime to be determined, so that an appropriate predictive model may be applied. Quantitative criteria for the transition between macro- and micro-scale boiling behavior have also been identified. These recent advances towards a comprehensive understanding of flow boiling in microchannels are summarized in [2].

Impinging microjets of water have recently been demonstrated to support heat fluxes as high as 420 W/cm^2 in single-phase operation, using ten thousand jets per square cm with distributed return channels in a microfabricated double-branching hierarchical manifold [3]. Applications in electronics cooling typically necessitate operation as confined jets. While heat transfer and pressure drop in single-phase confined jets (single and multiple jets, with a variety of liquids) is now quite well understood [4], and predictive correlations are available [5], two-phase operation of impinging jets is still not well understood. Studies such as [6] demonstrate the potential heat transfer capabilities of boiling under jet impingement, but the operating and geometric conditions have yet to be systematically optimized.

The capabilities of active liquid cooling techniques can be enhanced if the coolant is refrigerated. In particular, for operation at high ambient temperature and humidity conditions, refrigeration becomes critical for the viability of liquid-cooled solutions. It has been demonstrated that negative thermal resistances can be achieved by this means [7], which allows for the available thermal resistance budget to be effectively expanded. One of the more challenging aspects to miniaturizing vapor compression systems for use in the small form factors typical of electronic systems is reduction in the size of compressors; recent efforts have targeted the design of compressors that can fit in the available space inside laptops [8].

The typically high pressure drops that are encountered in active liquid cooling demand novel approaches to fluidic actuation with micropumps as reviewed in [9,10].

High-Flux Passive Liquid Cooling

Heat pipes are among the most widely used devices for passive heat transport and heat spreading. While a two-phase liquid flow loop operates within heat pipes, no external pumping is needed. Instead, a capillary wick structure imbedded inside the sealed heat pipe structure provides the necessary means for liquid return to the evaporator side from the condenser side. Heat pipes offer one or two orders of magnitude of increase in the thermal conductivity over that of solid copper with the same form factor due to their two-phase transport mechanisms. However, heat pipe and vapor chamber operation has generally been limited to local heat fluxes at the evaporator in the range of 50 W/cm^2. Recent work aimed at a better understanding of high flux operation of heat pipes and optimization of conventional wick microstructures has demonstrated that local heat fluxes as high as 500 W/cm^2 or more can be handled [11,12]. Additionally, nanoengineering the wick structure inside the heat pipe and optimizing the shape of the wick to maximize capillary feeding (see Fig. 2) shows the potential for even greater heat fluxes to be managed [13].

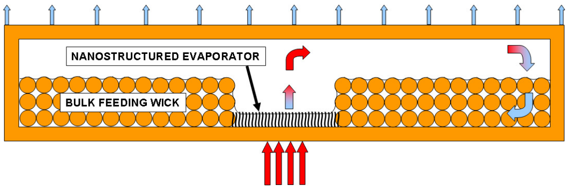

Fig. 2. Schematic illustration of a vapor chamber with an integrated nanostructured wicking material in the evaporator section.

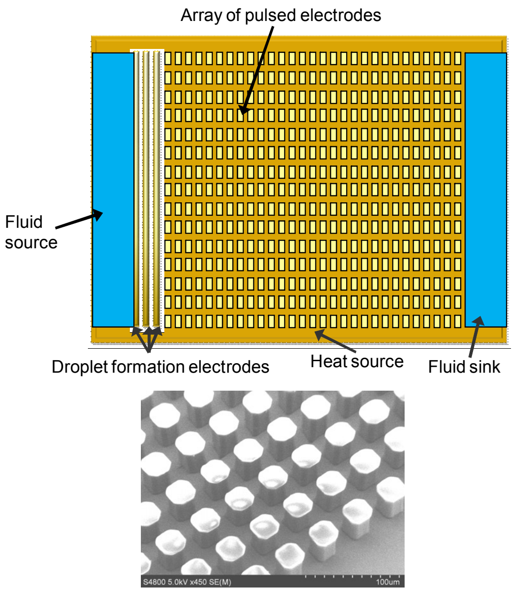

Fig. 3. Conceptual diagram of an EW-based droplet actuation scheme for site-specific thermal management; a sample superhydrophobic surface shown in the lower panel (with SU-8 pillars) provides enhanced control of droplet wetting/non-wetting.

Electrowetting (EW) can be used to actuate the motion of droplets of a wide range of fluids. Besides allowing for droplets to be manipulated for lab-on-a-chip applications, this also offers the possibility of managing "hot spots" on electronic chips. Droplets can be made to oscillate around hot spots, pick up heat, and then be directed off the chip for secondary cooling. This concept can also be used to enhance the performance of heat spreaders, as an alternative to vapor chamber-like operation [14]. The operation of droplet-based cooling systems can be further controlled and optimized by employing superhydrophobic surfaces, such as those shown in Fig. 3 [15]. Such surfaces allow droplets to be transported with low friction (in the so-called unwetting Cassie state) until the hot spots are encountered, at which time, electrowetting is used to wet the surface (taking the droplet into the Wenzel state) for effective heat transport. The heated droplet can again be withdrawn into a Cassie state and moved away. Surface engineering of this kind can play a significant role in enhancing the performance of novel, passive liquid-cooling devices.

Air Cooling for Mobile Products

Mobile platforms including portable computers, game controllers and cellular phones pose a unique set of challenges for thermal management. While the power consumption in these devices is typically lower than those considered in the previous sections, the cooling solutions must be low-cost and light-weight, besides fitting into the very small form factors available. Significant advances have been made by fan manufacturers in terms of noise reduction, reduced power consumption, and increased volume flow rates in ever smaller form factors. Alternative air-movement schemes have also been investigated.

Piezoelectrically driven cantilevers [16,17] (Fig. 4) can be used under resonant operation to drive air in mobile products with negligible noise production, and very low power consumption; moreover, piezofans can be produced at very reasonable cost. Significant enhancements in heat transfer over the case of natural convection have been demonstrated. Synthetic jets also hold promise for efficient air movement [18].

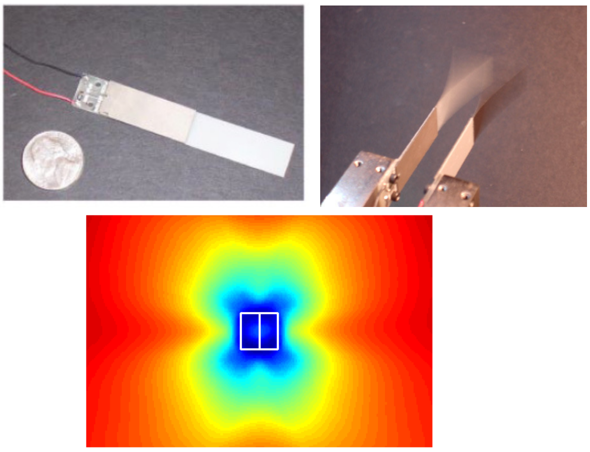

Fig. 4. Piezoelectrically actuated fan (a mylar cantilever with a piezoelectric patch is shown on top left, two cantilevers in motion are shown on top right), and the measured heat transfer coefficient contours on a surface under the action of a piezofan.

Ionic wind generation [19,20] offers the exciting possibility of generating air movement with almost zero added volume. An ionic wind is formed when air ions are accelerated by an electric field (between two electrodes on or close to the surface) and exchange momentum with neutral air molecules, causing air flow. Because ionic winds can generate flow with no moving parts and have low power consumption, they offer an attractive method for cooling portable electronic products. The local heat transfer coefficients have been shown to increase by more than 200% above those obtained from bulk flow alone (see infrared images in Fig. 5, where the collecting electrode is visible as the black stripe). Challenges include neutralization of the air molecules and damage to the electrodes; the latter can be alleviated by coating the electrodes with hard materials like nanostructured diamond.

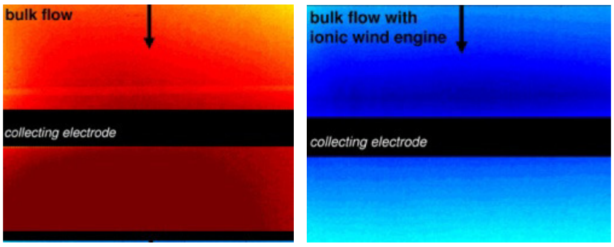

Fig. 5. Temperature of a flat heated surface under bulk flow alone (left) and after the ionic wind is turned on (right).

The performance of air cooling can also be enhanced by entraining liquid droplets into the air stream as a mist [21]. A two-phase mist, consisting of finely dispersed water droplets in an airstream, flowing through a longitudinally-finned heat sink, was shown to reduce the heat sink thermal resistance by up to 97% relative to dry air flow. The latent heat absorbed by the evaporating droplets significantly reduces the sensible heating of the air inside the heat sink which translates into higher heat-dissipation capacities. The diameter of the mist droplets and the loading fraction of the misting fluid at the inlet are key parameters that influence thermal performance.

Passive Approaches

It is noted that the first choice for a thermal management solution would always be natural convection from heat sinks due to the passive nature of this approach and the ready availability of ambient air. Performance in such designs can be improved by careful design of enclosures and orientation. One clever example exploited the higher heat transfer coefficients for an isothermal boundary condition as compared to that of constant heat flux by employing a thermal spreader into the design space of a television screen [22]. Similarly, order-of-magnitude improvements in thermal performance have been made in the commercial heat sinks available today. Research is also ongoing into more conductive composite materials for spreading and lowered thermal interface resistances. Another area of significant research is in solid-state approaches using thermoelectric coolers. A discussion of these approaches is beyond the scope of this article.

Microscale Diagnostics

Since many of the new advances in thermal management technologies have exploited transport mechanisms at the small scale, it is vital that scale-appropriate diagnostic tools be developed to allow for detailed experimental measurements. For example, much of the two-phase transport in these applications is dominated by the flow field and heat and mass transfer in very thin evaporating liquid films. Recent advances in microscale particle image velocimetry (μPIV) [23 , 24] and infrared measurements with microscale spatial resolution [25] have facilitated the development of predictive models [26]. Similarly, temperature measurement at small scales is best served by non-intrusive methods, such as those that relate the observed Brownian motion in a fluid [27] to temperature, or utilize laser-induced fluorescence for thermography [28]. Infrared particle image velocimetry (IR PIV) offers a means for velocity measurements to be made in through-silicon vias and channels without optical access [29]. Further development of such non-intrusive techniques with microscale temporal and spatial resolutions is necessary for the continued development of cooling solutions engineered at the micro and nano scales.

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