

ADVANCED COOLING TECHNOLOGIES FOR MICROPROCESSORS

THOMAS W. KENNY, KENNETH E. GOODSON, JUAN G SANTIAGO, EVELYN WANG, JAE-MO KOO,
LINAN JIANG, ERIC POP, SANJIV SINHA, LIAN ZHANG, DAVID FOGG, SHUHUAI YAO, ROGER
FLYNN, CHING-HSIANG CHANG, CARLOS H. HIDROVO

*Department of Mechanical Engineering, Stanford University,
Stanford, CA 94305 USA
Kenny@cdr.stanford.edu*

Received (2 May, 2005)

Revised (8 July, 2005)

Accepted (9 July, 2005)

Recent trends in processor power for the next generation devices point clearly to significant increase in processor heat dissipation over the coming years. In the desktop system design space, the tendency has been to minimize system enclosure size while maximizing performance, which in turn leads to high power densities in future generation systems. The current thermal solutions used today consist of advanced heat sink designs and heat pipe designs with forced air cooling to cool high power processors. However, these techniques are already reaching their limits to handle high heat flux, and there is a strong need for development of more efficient cooling systems which are scalable to handle the high heat flux generated by the future products.

To meet this challenge, there has been research in academia and in industry to explore alternative methods for extracting heat from high-density power sources in electronic systems. This talk will discuss the issues surrounding device cooling, from the transistor level to the system level, and describe system-level solutions being developed for desktop computer applications developed in our group at Stanford University.

Keywords: cooling, microchannel,

1. Background

Microprocessor packaging requirements include a need to provide many electrical interconnects, deliver high current and stable voltage, operate over extended periods with variable mechanical and thermal loads without mechanical interconnect failure, and must also provide the first step of the heat removal from the microprocessor to the surroundings. In recent years, there has been steady increases in the need for interconnects (hundreds are now common), current (100 W processors at 3V require 30 A of current), and heat removal (100W is now common). At the same time, the heat removal requirements have imposed a need for placement of large heatsinks at the backside of the processor. These heatsinks must efficiently spread the 100W over large surface areas so that the heat can be carried away by air moving through a desktop computer chassis. A recent example heatsink is shown in Fig. 1. Here, a copper base block is clamped into contact with the microprocessor package, and heatpipes capture heat from the block and carry it to the outer areas of the fins. This entire structure

occupies a volume of more than 100 in³ inside the chassis, costs more than \$20, and weighs several hundred grams.

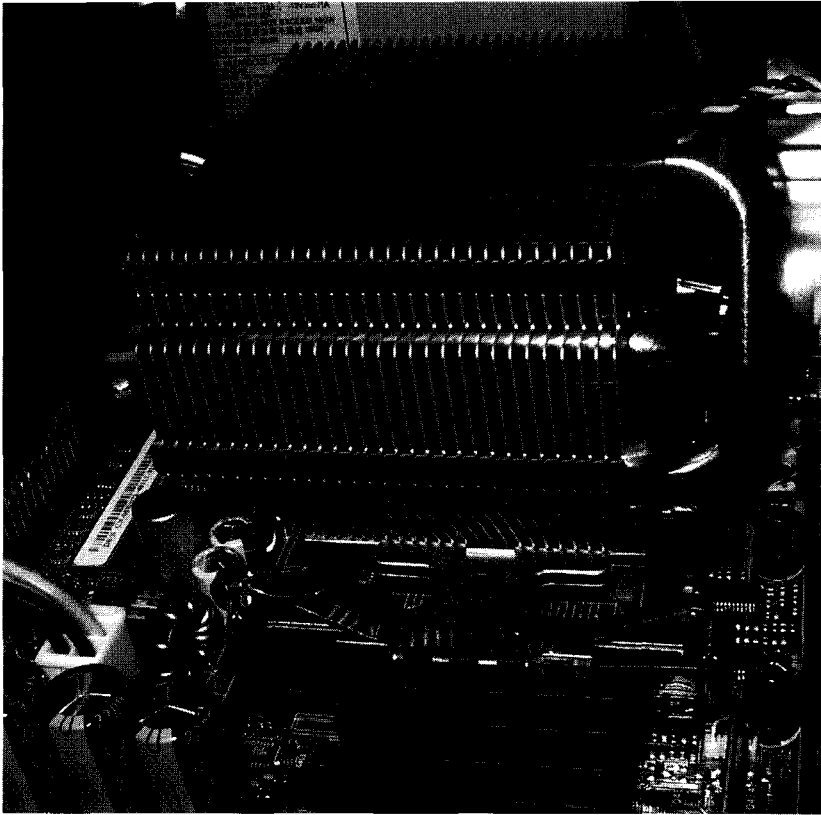


Fig. 1. Photograph of heatsink in a Dell Precision 3500 Computer, purchased in 2003. Clamps (shown near the bottom) apply a constant force between a copper block at the bottom of the heatsink and the microprocessor package. Nickel-plated copper fins extend up from the base. A pair of copper heatpipes reach from the base out the right side, and back into the upper edge of the fins, to help spread heat from the base to the entire surface area of the fins. This entire heatsink is about 6" x 6" x 6" in dimension, and weighs more than 400 gm.[1]

The size of this heatsink is a consequence of the need to transmit the heat to the moving air without requiring high air velocities, which would lead to uncomfortable levels of noise. The placement of this large volume element at the microprocessor creates many other problems for the computer system designer – primarily associated with the need to provide access to memory, graphics processors, and other electronic devices, as well as power conditioning elements and other I/O. The convergence of all these needs on the same volume makes it inconvenient and expensive to utilize so much of this volume for air cooling.

The mass of this heatsink raises other concerns. Because the system must operate in all orientations, the force exerted by the spring-loaded clamps must be significantly greater than the weight of the heatsink. Since all this force must be exerted on the microprocessor package, it is important for this package to be mechanically stiff. Since the system must be assembled and then shipped and handled, the entire force of the heatsink mass times any handling accelerations must be carried by the mounting structures and the package. These problems all increase in proportion to the mass of the heatsink, and are becoming a significant problem for the mechanical design of the microprocessor package and the neighboring circuit board support structure. Failures in these areas of the system are becoming more and more common.

Trends in the industry suggest that these problems are going to continue growing. The semiconductor association roadmaps all point towards another doubling of processor power consumption within the next 4 years [2]. As processor power increases, the volume and mass of conventional heatsinks must more than double, leading to even greater challenges in packaging and cooling of microprocessors.

To overcome these challenges, researchers have been exploring the thermal management problem at all levels. Figure 2 shows a thermal resistance model for the microprocessor cooling problem, including the heat transfer from the transistor through the interconnects within the device, all the way to the transfer to the ambient.

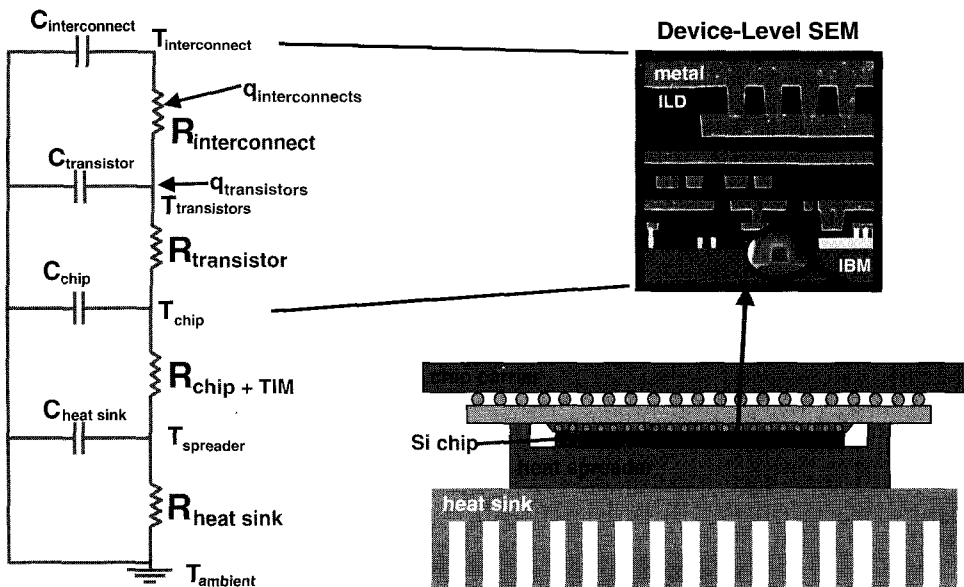


Figure 2 Illustration of the thermal model for heat transport from the transistor to the ambient. Included are thermal resistances for the path through the interconnects, through the backside of the die, through the thermal

interface material (TIM), through the spreader and heat sink, and to the air. Improvements are needed at every level of this system to address the needs for future computer system design.

Figure 2 provides an outline for the remainder of this paper. We will present recent work on the modeling of thermal transport within the electronic device, research on the use of microchannel heat exchangers for capture of the heat at the package level, and recent developments related to the use of closed-loop cooling to carry heat from the package to a remote heat rejector. The introduction of closed-loop liquid cooling is seen as an approach that can overcome some of the scaling barriers in conventional cooling system design, and may allow continued increases in microprocessor power density.

2. Device-Level Heat Propagation Challenges

Generation of heat at the transistor level in modern microprocessors is a complicated phenomenon. Simplistic ohmic dissipation models do not capture the important details of the energy transport. Dissipation begins with interactions between ballistic electrons and the surrounding phonons within a transistor, and continues through a combination of ballistic phonon transport and scattering to the thermal phonon spectra. This decay process can include transitions directly to longer-wavelength acoustic phonons which thermalize more rapidly in a small volume, or through an intermediate optical phonon path which may propagate some distances before scattering to acoustic phonons and thermalizing [sinha]. Figure 3 illustrates these parallel pathways.

Detailed monte-carlo models of the scattering process between individual electrons and the available spectra of acoustic and optical phonons have been constructed. These models allow determination of the spatial distribution of the energy dissipation, and have begun to show that the more conventional continuum electrical and thermal models overestimate the spreading of the heat dissipation in high-speed CMOS transistors. Copies of the monte carlo computational code are available for download at : <http://nanoheat.stanford.edu>, and are described elsewhere [3]

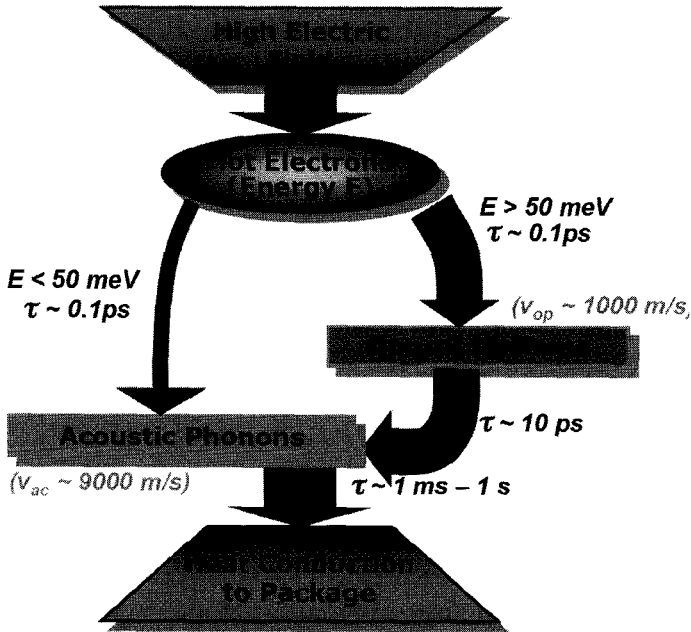


Figure 3 Illustration of the processes for thermalization of energy present in high-speed CMOS transistors. Energy may be dissipated through scattering of phonons by the electrons. Acoustic phonons are well-known participants in this process, but optical phonons can be active at the energy levels of high-speed electronic devices, and can contribute a slower pathway that dissipates energy over a larger volume.

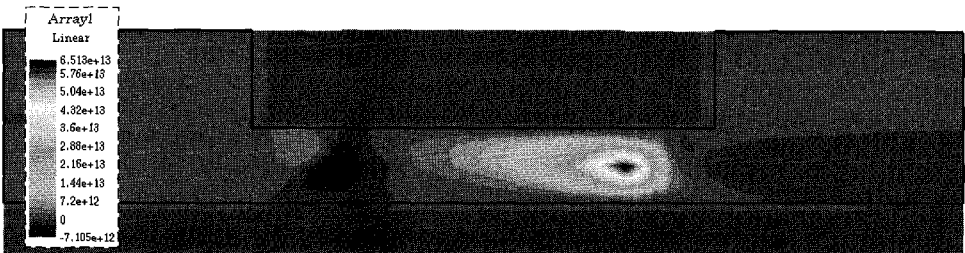


Figure 4 Illustration of heat dissipation within the gate of an 18 nm thin-body SOI transistor. Detailed Monte-Carlo modeling of scattering between electrons and phonons shows that the heat dissipation is concentrated in a small volume within the transistor, leading to greatly enhanced temperature rises at the local scale, and increased risk of device failure, relative to continuum models. [3]

3. Microfluidic Heat Exchanger Modeling and Measurements

Once the heat has traveled to the surface on the backside of the microprocessor, there are many options for the capture and removal of the heat. The conventional approaches

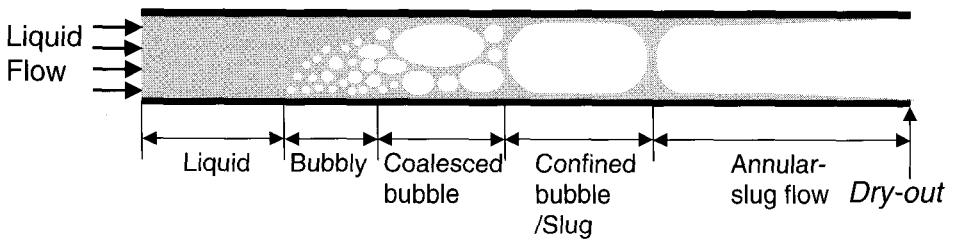
have used a thermal interface grease and a copper heat spreader to distribute the heat over a larger area, and then usually through a solder interface to a large metal heat sink. There are inefficiencies in this solution, related to the thermal resistance of all these interfaces, and the thermal resistance associated with the conduction to the ends of the fins in a conventional heat sink. Recently, heat pipes have been used to enhance this spreading, as shown in Fig. 1, but it is possible to do even better. In this section, we discuss the opportunities and challenges associated with the use of microchannel heat exchangers to capture the heat in a moving fluid as close to the microprocessor as possible.

The main motivation for the use of fluids in a cooling system is that they are capable of absorbing heat at the microscale close to the heat generating regions, and can then be moved arbitrary distances to locations where the rejection of heat to the surrounding environment is more convenient. This allows the volume around the microprocessor to be used for electronic system needs, and greatly reduces the local mass of the rejection system. The system optimization challenges are transformed into pump optimization, microchannel geometric optimization, and 2-phase fluid management. By shifting the challenges of cooling system design in to this new regime of microchannels, fluids, and pumps, we can avoid the significant roadblocks that have begun to constrain the cooling system design of conventional computer systems, and we open new opportunities for system optimization.

In order to design microchannel heat exchangers for these applications, it is important to develop accurate models for fluid and heat transport in these sub-mm channel geometries. For simple single-phase fluid transport, conventional models of fluid flow and heat transfer are adequate, but 2-phase flow presents significant added challenges. There are complications with the overlap between the dimensions of the channels and the diameters of bubbles, leading to a complicated series of fluidic phenomena that are all dependent on temperature, viscosity, flow velocity, heat flux, and many other parameters. Figure 5 illustrates the difference between observations of the 2-phase behavior of macroscopic heat exchangers and what is expected in microchannel heat exchangers. The formation of bubbles with diameters sufficient to fill the channel can cause blockage of the flow, and diversion of the fluid into other parallel pathways, leading to greatly-reduced heat capture, and thermal runaway. This “dryout” phenomena is commonly observed in 2-phase microchannel heat exchangers, and is a significant obstacle to their use in real applications.

To address this challenge, our team has been working to construct detailed models of fluid behavior in microchannels during boiling, and has also developed experimental capabilities for local measurement of temperature, pressure, flow, as well as detailed observations of bubble growth and departure.

Macro-/Mini-Channel



Microchannel ($D_h \leq 100 \mu\text{m}$)

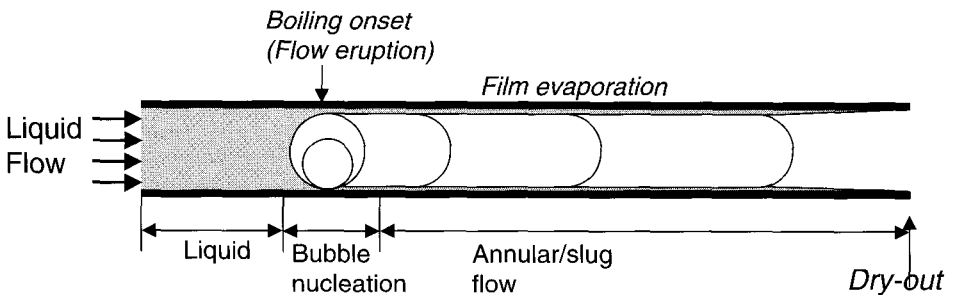


Figure 5 Illustrations of 2-phase fluid behavior in macroscopic and microscopic systems. In a macroscopic system, vapor bubbles form and detach from the heated surface, gradually coalescing into slugs. In a microchannel system, the bubbles can grow to fill the channel before detachment, leading to complete blockage and early dryout of the channels.

3.1. Microchannel modeling

To understand heat transfer during 2-phase flow in microchannels, a series of models have been constructed that represent the fluids using various approximations for the liquid/vapor mixture, approximations for the heat transfer coefficients at the liquid/solid interfaces, and conventional conduction for transport in the solid structures of the microchannel devices. All of these models incorporate detailed representations of the temperature and pressure dependencies of the thermal conduction, viscosity, latent heat, and density of the liquid and vapor constituents of the fluid [4]. The regions of the channel are discretized as shown in figure 5, allowing use of conservation equations in each region of the solid or fluid, and detailed models for the fluid behavior and heat transport in each flow regime.

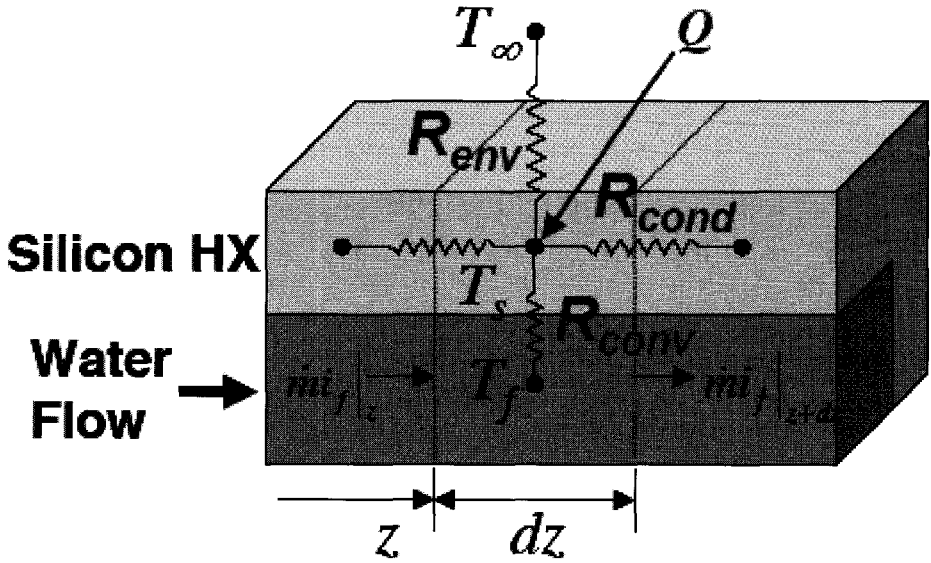


Figure 6. Drawing of the discretized models for heat transport in a microchannel structure, including the conduction from the solids through the interfaces and into the fluids, as well as all the phenomena within the fluids that can effect heat transport (flow, viscosity, latent heat,...).

Complications arise in all of these 2-phase situations because the nucleation temperature is a strong function of pressure, and the pressure is a function of position, flow velocity, and flow regime everywhere in the channel. The formation of a bubble within the channel partly blocks the flow, leading to changes in the pressure upstream of the bubble location, and it also displaces fluid, leading to increased movement of fluid elsewhere, which can also alter the pressure distribution in throughout the channel. The liquid is incompressible, but the bubbles are compressible, so the appearance of bubbles leads to complicated dynamical behaviors including oscillations in pressure, flow, and temperature. All of these phenomena are being captured in the models being explored in our group, and these models are being used to design systems that are resistant to unwanted dynamical behavior, or which maximize heat capture and transport in the presence of these behaviors.

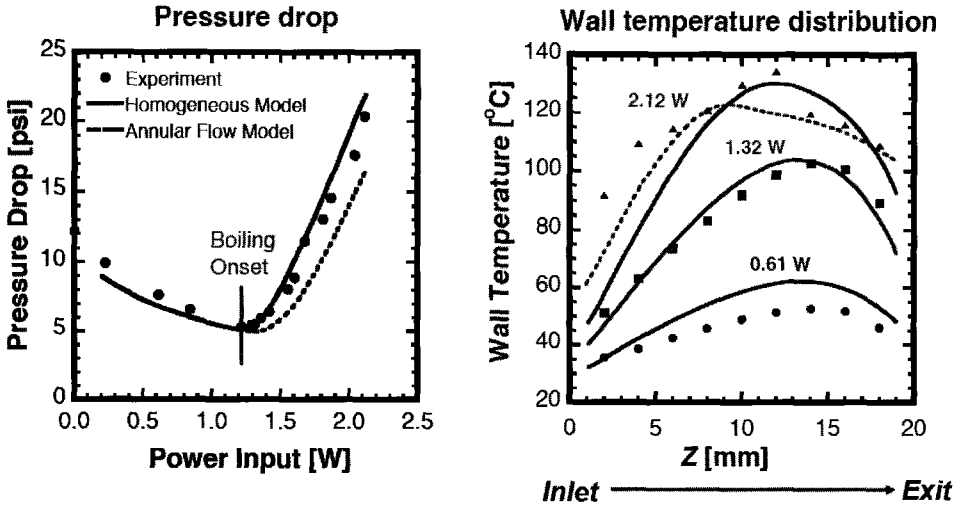


Figure 7. Plots showing comparisons between models and measurements of pressure and temperature in microchannels during the transition between single-phase and 2-phase. These plots show good agreement throughout the transition between single-phase and 2-phase domains. [4]

3.2. Microchannel Measurements

Experimental observations and heat transfer measurements were carried out to complement the modeling effort. These experiments were intended to determine the behavior of the boiling in the microchannels, and to extract heat transfer coefficients that could be used in microchannel heatsink design.

To build these microchannel experimental structures, we have relied on MEMS fabrication methods. This provides several advantages over other possible approaches, including :

- Silicon has thermal conductivity similar to the materials that would probably be used for a microchannel heat exchanger, such as Copper, SiC, Si, and Al. Measurements in silicon test structures will be relevant to the design of real heat exchangers.
- Silicon can be patterned using deep reactive ion etching to form many complicated channel geometries. Wafer bonding, sacrificial materials, and other MEMS techniques allow a very broad variety of design flexibility for test structures, including the opportunity to incorporate thermal isolation.
- Silicon may be doped by diffusion and implantation to form heaters and thermistors, to allow integrated, localized heat transfer measurements, or to mimic hot spot heat sources.

The high thermal conductivity of silicon makes heat flux measurements challenging, because thermal conduction away from the heated region can overwhelm the heat transfer into the fluid in the microchannel. To overcome this, we have developed microchannel designs that consist of a single channel suspended within a narrow beam, bonded to a glass coverslip for support and to seal the microchannel. Figure 8 illustrates such a device, with the inlet and outlet reservoirs, and the placement of the resistors for heating and temperature measurement.

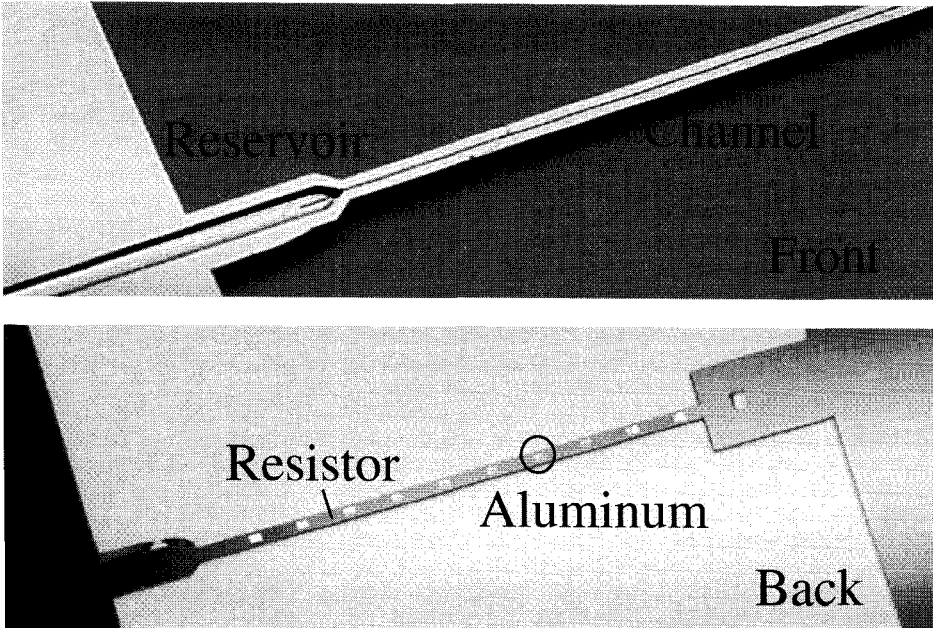


Figure 8. Photograph of isolated silicon microchannel for heat transfer experiments. The channel is formed on the front side by plasma etching, and doped silicon resistors are formed on the backside to act as heaters and thermometers. Aluminum contacts are included to allow wirebond connections to an external circuit.

We were also interested in experimental studies of cooling by microjet impingement, and this required the design and fabrication of enclosed microjet structures – test devices that included heaters and thermometers formed around an array of jets that would impinge on an internal surface within the structure. Figure 9 Shows the design and a photograph of an isolated jet test structure.

These structures were build, calibrated, and then filled with fluid and used for heat transfer measurements. These measurements have been extensive, and published elsewhere, but the summary of the results is as follows :

- Heat transfer in microchannels is a sensitive function of the character of the boiling throughout the microchannel. Formation of bubbles in one part of a single channel can cause changes in the flow, leading to changes in the pressure distribution along the channel. Since the boiling temperature is a function of static pressure, this coupled phenomena can lead to significant instabilities.
- Roughening structures in these microchannels can help nucleate the boiling in a specific location, leading to improved stability in the two-phase behavior.
- Heat flux in excess of 200 W/cm^2 can be achieved in microchannel and microjet heat exchangers.
- Microjet heat exchangers have the advantage of localizing most of the pressure drop within the jet, leading to opportunities for more stable boiling in the chamber of an enclosed device.

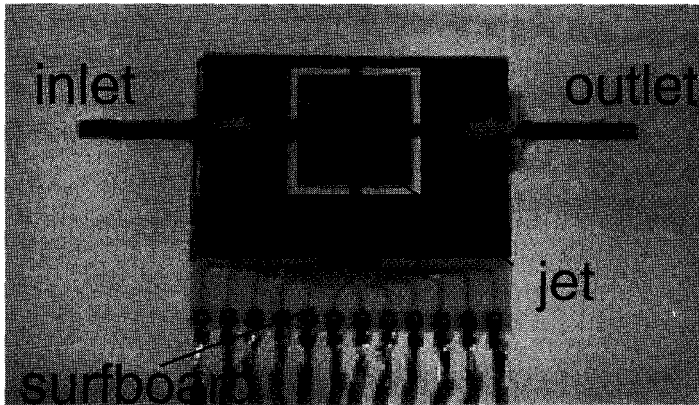


Figure 9. Drawing and photograph of a thermally isolated jet test structure. The illustration shows a side view, and shows the fluid path and the location of the heaters and thermometers. The photograph shows a top view with the inlet and outlet labeled. The center square region is the test structure, and it is isolated and supported only by 4 thin beams. [6]

Figure 10 shows a comparison between the behavior of a channel and a jet in a miniature heat exchanger. In this figure a single channel structure is compared with a single jet structure at comparable fluid flow rates. In the channel, the temperature rises linearly through the single phase region, and then flattens slightly as boiling begins. The expected flat plateau in the temperature as a function of power for the microchannel does not occur in this case because the onset of boiling causes vapor bubble displacement of fluid in the channel, and a corresponding pressure increase that suppresses boiling in some parts of the channel. In contrast, the jet structure has stable pressure in the boiling chamber independent of the onset of boiling, and achieves a much flatter plateau and more efficient conversion of liquid to vapor. [6]

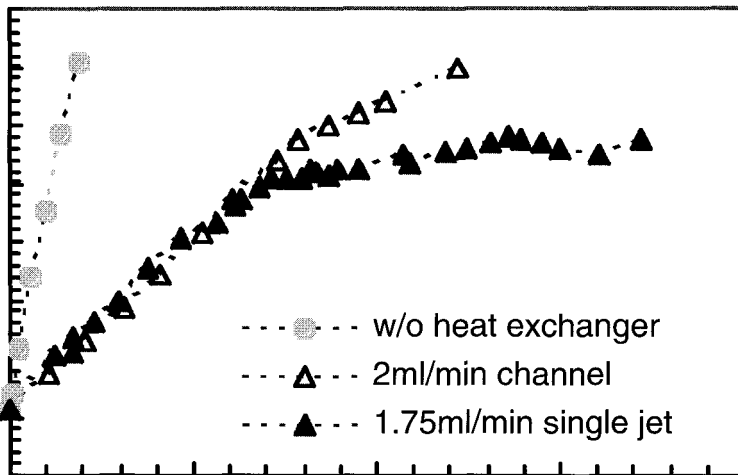


Figure 10 Comparison plot of the surface temperatures of 3 devices as a function of input heater power. The first example is a conventional heatsink without a heat exchanger, showing a linear increase in temperature with power. The second example is a single microchannel heat sink, showing a linear increase in the single-phase region and a transition to a second linear region after the onset of boiling. The 3rd example is a single-jet enclosed heatsink. This example also displays a linear temperature increase through the single-phase region, and then a transition to a power-independent plateau in the 2-phase region. This comparison shows that microjet structures can be more stable in the 2-phase region and provide broader power-independent plateaus. [6]

4. Conclusions

This paper has presented an overview of the increasing challenge for heat removal from microprocessors. Ongoing research at many institutions is focused on developing better

understanding of miniature heat exchangers and methodologies for measurement and design of products. This paper has focused on recent research at Stanford on these topics, including efforts on modeling of the heat transfer from the transistor level all the way to the full system, and experiments on heat transfer in microchannel heat exchangers. The combination of these experiments and models can be used to design optimized 2-phase heat exchangers that can capture and transfer heat flux in excess of 200 W/cm².

5. Acknowledgements

This work has been supported by many sources, including DARPA HERETIC (F33615-99-C-1442), Intel, AMD, and Apple, and numerous NSF and NDSEG Fellowships. The authors wish to acknowledge Dr. Elias Towe for early support of the DARPA HERETIC program, and Ravi Prasher at Intel for support. The project made use of the National Nanofabrication Users Network facilities funded by the National Science Foundation under award number ECS-9731294.

References

1. Dell Precision 3500 Computer Chassis, Dell Computer Corp, 2002. Photograph of Heatsink by T. Kenny.
2. ITRS 2002 Roadmap.
3. E. Pop, K. E. Goodson, R. W. Dutton, "Analytic Band Monte Carlo Model for Electron Transport in Si Including Acoustic and Optical Phonon Dispersion," *J. Appl. Phys.*, vol. 96, no. 7, 2004.
4. Koo, J.M., Im, S., Jiang, L., and Goodson, K.E., "Integrated Microchannel Cooling for Three-Dimensional Circuit Architectures," *ASME Journal of Heat Transfer*, in press.
5. L. Zhang, J. Koo, L. Jiang, K. E. Goodson, J. G. Santiago, T. W. Kenny, "Measurements and Modeling of Two-phase Flow in Microchannels with Nearly-constant Heat Flux Boundary Conditions", *Journal of Microelectromechanical Systems*, Vol. 11, No. 1, Feb. 2002, pp. 12-19.
6. E.N. Wang, L. Zhang, L. Jiang J.M. Koo, J.G. Maveety E.A. Sanchez, K.E. Goodson, and T.W. Kenny, "Micromachined Jets for Liquid Impingement Cooling of VLSI Chips", *JMEMS* 13, 833 (2004).

Copyright of International Journal of High Speed Electronics & Systems is the property of World Scientific Publishing Company and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.