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Cool applications for hot technologies

Increasing microelectronic density and processing speeds imply more heat. Small tech offers next-gen solutions

By Richard Gaughan

Perhaps classifying Gordon Moore's famous 1965 prediction-that the economically producible number of discrete components in a single IC was to double every two years-as a "Law" has given it a sense of inexorability. In fact, though, Moore's observation was a quantification of the effects of human ingenuity in the face of a technical challenge.

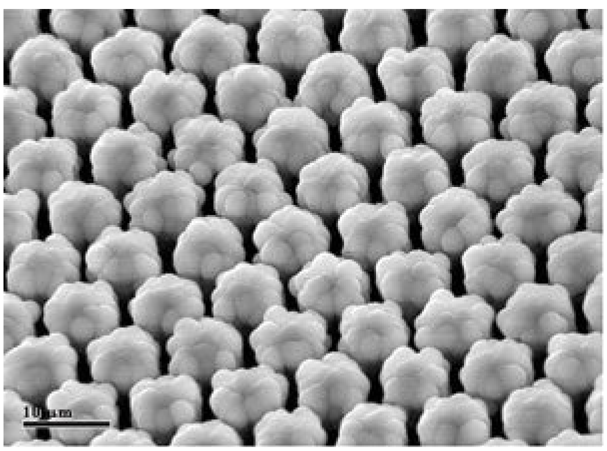
And there are challenges ahead.

The average power density of advanced microcircuits is heading to several hundred Watts/cm^2, creating a more difficult heat dissipation problem at the same time as small circuit dimensions lead to greater consequences of overheating. Power requirements are also an exponentially increasing function of processing speed.

If microelectronics are to continue to follow the trend of increasing density and improved processing speed, then innovative methods of dissipating heat are needed. Micro- and nano-cooling approaches are poised to meet that need.

The task of a thermal management system is to get heat out of a sensitive area and dissipate it in a large heatsink. For example, a microprocessor may be mounted with an integral radiator so that heat conducts from the electronic chip through the device to the radiator base and then radiates into the surrounding air. A circulating fan will exchange the air within the case with air from the room, which then becomes the final heatsink.

The first step is simply to get the heat from the chip to the radiator base, and the effectiveness of heat transfer depends upon the quality of the surface contact. Thermal grease is often used to ensure uniform thermal contact between the two surfaces. The better the thermal grease, the better the heat transfer.



An array of vertically aligned carbon nanotubes grown using plasma enhanced chemical vapor deposition is intercalated with copper to create a composite that exhibits good thermal properties ideal for chip cooling. (Image courtesy of NASA)

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Carbon nanotubes are the most thermally conductive material known, so what better material for enhancing thermal conductivity? That is the reasoning of Professor Minoru Taya of the University of Washington. He developed a material blend that takes advantage of both the thermal conductivity of CNTs and the mechanical flexibility of phase changeable polymer (http://depts.washington.edu/cims/research/electronic.htm). Using chloroform as an environmentally friendly solvent, the CNTs are dispersed in the polymer matrix. With the material under compression, when the polymer changes to liquid, at its specific critical temperature, the thickness decreases. Combined with the high conductivity of the CNTs, the resistance of the thermal interface material is a factor of five smaller than traditional thermal interface material.

Good thermal interfaces are useful in other places as well. For example, the Hubble Space Telescope's Imaging Spectrograph suffered from high operating temperatures, which degraded the data quality. The problem is that surface roughness in the conductive path decreases the thermal conductivity, raising the instrument's temperature. That may change during a proposed Hubble servicing mission next year. If approved, the material, a carpet of 40-micron-long carbon nanotubes on a copper pad, will be inserted between the two surfaces. The nanotubes, intercalated with copper, retain their structural integrity even at pressures up to 60psi. The nanotubes will conform to the rough surface, providing good thermal contact.

The intercalated CNT/copper material is also suitable for chip cooling, for which NASA has licensed the technology to a commercial partner. Meyya Meyyappan is the chief scientist for exploration at NASA's Ames Research Center (www.ipt.arc.nasa.gov/). He spoke at NSTI's Nanotech 2007 conference, held May 21-24 in Santa Clara, Calif., about the status of a variety of carbon nanotube applications.

This example, like all he spoke of, relies on the properties of nanomaterials to provide unique capability, but, he said, "the system itself needs a seamless integration to micro/macro for a technically feasible and commercially viable product."

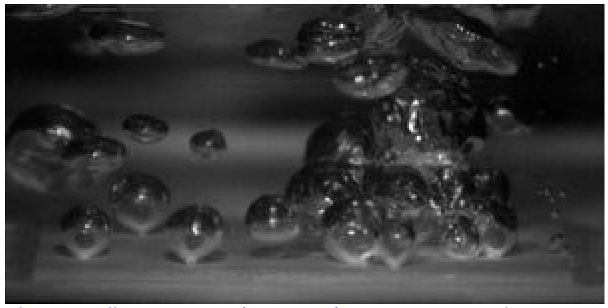
To the macro world, and beyond!

Thermal management systems are a perfect example of Meyyappan's point. Heat may be transferred through highly conductive nanomaterial, but eventually large amounts of heat must be dissipated into the environment, the "thermal bath," and that takes macro-scale hardware. Cooligy (www.cooligy.com), a company based in Mountain View, Calif., has developed a microstructured heat exchanger as the heart of an integrated liquid cooling system for advanced microelectronics. The company's system approach considers not only such factors as workability of the heat exchanger material and low thermal resistance of the exchanger design, but also macroscopic factors such as efficiency of the radiator design, thermal conductivity of the cooling liquid, and even resistance to bacterial growth within the cooling loop.

Effective heat transfer in a cooling system requires the cooling fluid to be in contact with as much surface area as possible of the material that is designed to extract the heat. Fabrication of a reliable and efficient high surface-to-volume ratio microstructure (HSVRM) is therefore extremely critical for developing an effective microheat exchanger. For microchannels of the same shape, the heat transfer coefficient is inversely proportional to the hydraulic diameter. HSVRMs with very fine features in a microheat exchanger should significantly enhance heat transfer.

HSVR microstructures that are applicable in microheat exchangers can be classified into two types: microchannel and microporous. Silicon microchannels are commonly used in liquid cooling systems, although metallic materials with higher thermal conductivity are preferable for more-effective heat transfer. Folded fins are another class of microchannel HSVRMs that are used as heat exchanger structures.

Microporous types of HSVR structures provide higher values of surface area per unit volume than commonly used micro/minichannels. Mesh and woven mesh structures are ordered porous structures, while metallic foams are the most common form of unordered microporous structures. They are formed by sintering a polymeric foam substrate that is coated with slurry of metallic particles. Metal foams can also be created by electrodeposition accompanied by hydrogen evolution where metallic deposition takes place around hydrogen bubbles. The surface area of this electrochemically formed porous foam structure is several orders of magnitude higher than the other types of foams because of dendrites that form within the pores.



This image illustrates part of a series of experiments at Purdue University designed to quantify the effects of surface roughness on heat transfer. In general, increased roughness appears to offer increased heat extraction. (Image courtesy of Suresh Garimella, Purdue University)

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The problem is that small features, while they enhance the heat transfer, increase the pressure drop, levying additional requirements on the pumping system. Cooligy circumvented this problem by incorporating a manifold into the side of the heat exchanger away from the microelectronics and retaining the microstructure adjacent to the surface to be cooled. But, as Madhav Datta, Cooligy's chief scientist, said at the recent Electrochemical Society Meeting in Chicago, "development of microheat exchangers with high heat transfer rate and minimized pressure drop is a challenging task." Depending upon the application and required performance, the active microstructure heat exchanger design can be the porous material or the microchannel design. Coupled with a high-pressure compact mechanical pump or other pump technology, the system can maintain consistent die temperature in the presence of local hot spot zones of 1 to $2mm^2$, with power densities of $500W/cm^2$ or above. According to Fred Rebarber, director of sales and marketing, Cooligy's process is compatible with high-volume manufacturing techniques, so costs are kept low for a technology that "offers maximized performance and reliability in a system concept that is available today for a wide range of high-end thermal management needs."

Other commercial solutions are coming from companies such as ALD Nanosolutions, IBM, Celsia, and CoolChips (see "Aiming for a cool market," p. 15).

Two-phase is best

The Cooling Technologies Research Center (CTRC, http://meweb.ecn.pur due.edu/~CTRC/), founded in 2002 at Purdue University, is one of the National Science Foundation's industry/university cooperative research centers. The center's mission is to improve the understanding and technology of high-performance heat removal from compact spaces. Air-cooled and passive heat pipe approaches generally available in commercial equipment, according to Suresh Garimella, the CTRC's director, "have a limited ability for heat removal, and acoustic noise and space restrictions may prevent air cooling solutions from continuing. New solutions are already being called for, and a wide variety are being investigated both in the industry and universities."

Garimella's academic investigations into liquid cooling systems have reached the conclusion that a two-phase cooling cycle is the optimum system design for high-performance applications. In a two-phase system, the confined liquid is heated to the boiling point and then condensed, cooled, and recirculated. The latent heat of the phase transition provides a larger, well-defined heat transfer that functions at lower flow rates and smaller temperature differentials than a single-phase liquid cooling system. But the thermal performance can be influenced by several factors, including exactly where in the system the phase transition takes place, the liquid flow rate, and other conditions. The pressure requirements vary as a function of flow conditions, so design constraints on the microchannel heat exchanger, the tubing interconnections, and the pump are likely to be tighter than necessary for single-phase systems.

Several pump technologies are available, but to reach the full potential and full economic competitiveness, Garimella believes micropumps must be incorporated within the microchannel structure of the heat exchanger. No current technology is effective at that scale, but he is encouraged by the prospects for integration of electrohydrodynamic injection micropumps.

More hot technologies for cooling

Garimella noted, “We consider a wide range of approaches that span the spectrum from very high flux techniques to those that are very quiet, consume very little power, and can be incorporated into portable devices.” Other technologies that have shown promise for cooling microelectronics are piezoelectrically driven resonant fans, immersive jet-impingement cooling, and advanced heat pipe designs.

For some of these technologies, the fundamental physics is not yet well understood. But, Garimella said, “even in cases where the operational principles are understood and demonstrated, there are a lot of implementation issues, including reliability, cost, and supplier availability.” Although the addition of thermal control capabilities introduces additional design considerations, Garimella believes it is now time for thermal management to be considered simultaneously with electrical considerations in designing the next generation of electronics.

He’s encouraged by the trend within industry to use that co-design approach. “With combined electrical and thermal design, the power efficiency and self-heating problems are likely to be kept at bay for the coming decades.”

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