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Editorial

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The requirements for thermal management of electronic devices have changed significantly over the last 40 years. In the beginning, thermal management was mostly an issue at the systems level, for example, the sophisticated water cooling systems of early high-power computers. It has steadily developed to a problem on the device and component level as miniaturization and, thus, heat-dissipation density has progressed in power requirements and feature size in microelectronics. The general public became aware of the problem when Intel declared in 1994 to have "hit the thermal wall" in the development of their central processing units (Markoff, 2004).

Since the efficiency of active cooling methods, for example, pumped circulating fluid coolers (single phase and two phase) and heat pipes, is length scale dependent by the governing laws of fluid mechanics, and they require additional space, these systems encounter some difficulties to keep up with the miniaturization in electronics. Therefore, before active cooling can be used, there is often a need to spread the heat generated in a very small footprint to a larger surface. A further bottleneck is the heat transfer from the power-dissipating device to the cooling system. Pressed contacts and thermal paste used for decades are increasingly becoming an important, if not the main, thermal resistance from the device to the heat exchanger. Brazed contacts perform much better in this regard; yet, they have the disadvantage to generate stresses and suffer from fatigue failure on large number of active and/or passive temperature cycles of the device. Therefore, the heat spreaders, in direct contact with the heat-dissipating element, must have a coefficient of thermal expansion (CTE) that can be adapted to that of the heat source.

In an early review by Zweben (Zweben, 1992) on the subject of materials for thermal management, the choice of materials having high thermal conductivity and low CTE in the range between 4 and 8 ppm/K was rather limited. Apart from molybdenum and tungsten, most of the materials were metal matrix composites. The best candidates were the Cu/Mo, Cu/W and Al/SiC composites together with some Be/BeO composites; the latter had considerable health-hazard potential. Thermal conductivity was limited to roughly 200 W/mK, that is, half of the value for pure copper, a material of choice as long as the thermal mismatch constraints were neglected.

Over the last two decades, development of materials for thermal management has come a long way. This development has mainly been enabled by using fillers in metal matrix composites with high thermal conductivity and low CTE. Virtually all of these new composite materials are using carbon-based fillers, ranging from graphite flakes over carbon fibers and (nano-) filaments to diamond particles. The use of the latter has largely been enabled by the availability of diamond of decent quality at low price and produced in China.

In this special issue of *Emerging Materials Research*, various types of carbonaceous reinforcements have been reported. These include the following: graphite flakes (Hutsch *et al*. (107–114)), carbon fibers and filaments (Silvain *et al*. (75–88)), and diamond particles (Xue and Yu (99–106); Tavangar and Weber (67–74)). The work presented in this issue is based on some of the talks that were presented at the Materials for Thermal Management session at the EuroMat 2011 conference held from September 11 to 15 in Montpellier, France. This highlights the fact that, with such carbonaceous reinforcements, the thermal conductivity well beyond that of pure copper in one, two, or three dimensions can be achieved. The current upper limit is an isotropic conductivity of around 1000 W/mK but there is considerable optimism that composites having even higher thermal conductivity can be produced in the near future (Tavangar and Weber, 2012).

Despite the fact that the past two decades have seen an improvement in thermal conductivity of thermal management materials by a factor of 2 to 5, these materials have not yet been utilized in thermal management applications on a large scale. One of the reasons for this is their price. On a price per volume basis of the raw materials, diamond composites are currently comparable to molybdenum metal: a cubic centimeter of an Al/diamond composite containing 60 volume% of diamond costs roughly USD0.4 compared to USD0.35 of the same volume of molybdenum. Obviously, as diamond quality and the matrix metal is changed from aluminium to silver, as in the contribution by Tavangar and Weber (2012), raw material prices are increasing to USD3–4 per centimeter cube, mainly due to the historically high silver price. For other forms of carbon, especially high thermal conductivity fibers and filaments, prices are currently high because of the limited production capacity and the difficulties to produce these at consistently high thermal conductivity. However, as time goes by and manufacturing of the raw materials becomes a standard industrial process, this problem may be solved eventually.

Although the price range indicated above would not be prohibitive, it does not include the cost related to the manufacturing process, the tooling and the machining which accounts for the lion's share of the price at which such advanced composites are currently offered. Reducing the manufacturing cost of these composites is therefore a challenge for the years to come.

A second important issue is the homogeneity of the composites at small length scale. Indeed, to maximize thermal conductivity, the characteristic size of the dispersed phase needs to be large to minimize the effect of thermal resistance at interfaces of dissimilar materials, that is, the carbon phase and the metal matrix. For diamond particles and graphite flakes of several hundreds of micrometers in diameter, this entails a limitation of the minimum feature size of the substrate. In the case of diamond particles, machinability and surface quality of the substrates will also be affected. At the other end of the size spectrum of dispersed phases, that is, for carbon short fibers and carbon nanofilaments, the intrinsic thermal resistance at the interface is limiting the gain in thermal conductivity. The contributions by Sylvain *et al*. and Monachon and Weber, in this issue, have described methods to reduce the interface thermal resistance at the microscale by proper engineering of the interface, opening a window to the use of smaller dispersed particles and fibers without sacrificing thermal conductivity.

However, feedback from potential industrial clients suggests that the price premium is not covered by a concomitant improvement in overall performance on the device level. Although the recent developments on materials, covered in this issue, have significantly reduced the thermal resistance in the heat spreader or thermal substrate, the bottleneck has shifted to other places on the device level limiting the overall gain in thermal management performance. This highlights the fact that thermal management should not be considered as a question of the material performance of the substrate alone but should rather be an approach in which improvements in various fields, for example, fluid mechanics (microchannel cooling, two-phase flow), micromachining, and materials science (thermal contact materials, high thermal conductivity materials), should be combined to provide performing solutions on the device or even the system level. Although historically, these fields have been covered by distinct scientific communities, it is high time that the forces of these various fields are coordinated to face the current and future challenges in thermal management to come up with real breakthrough solutions.

REFERENCES

Markoff J (2004) Intel's big shift after hitting technical wall. *The New York Times*, 17 May.

Tavangar R and Weber L (2012) Silver-based diamond composites with highest thermal conductivity. *Emerging Materials Research* **1**: 67–74.

Zweben C (1992) Metal-Matrix composites for electronic packaging. *Journal of Metals* **44(7)**: 15–23.