Thermal Materials Solve Power Electronics Challenges

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The thermal properties of advanced materials used in heat spreaders and heatsinks provide new options for power system designers.

Thermal management deals with problems arising from heat dissipation, thermal stresses and warping. It is critical in the packaging of power semiconductors and other microelectronic and optoelectronic devices, including microprocessors, high-power RF devices, laser diodes and light-emitting diodes (LEDs).[1-2] Intel's acknowledgement that it has hit a "thermal wall" highlights the severity of the problem.[2] Laptop heating has increased to the point where, in one case, medical treatment was required.[3] Further evidence of the thermal problem is Apple's new Computer Power Mac G5 desktop, which has an automotive-like pumped liquid-cooling system. Replacing convection cooling with liquid cooling requires the addition of new manufacturing and servicing infrastructures, and raises significant reliability and cost issues. Heat dissipation is currently the key factor-limiting power levels. It will have to be solved in order to meet the well-publicized heat flux goal of 1000 W/cm^2 required for future military systems like the all-electric ship.

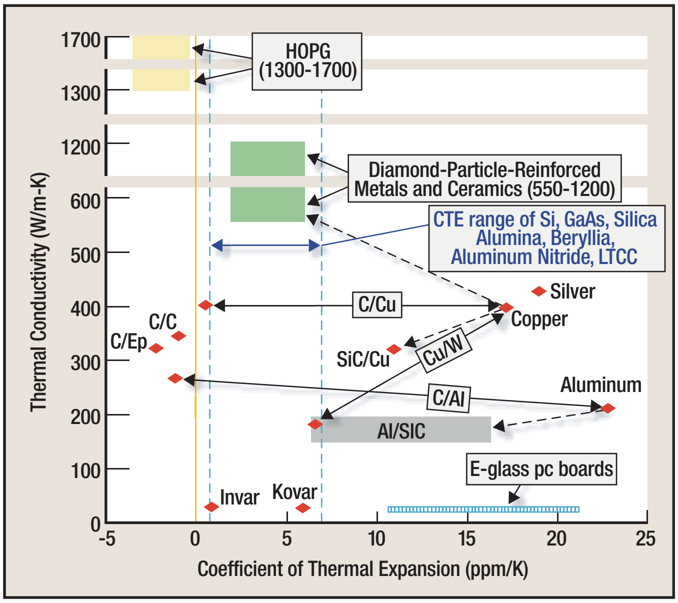

Fig. 1. *When selecting thermal materials, the ideal solutions have high thermal conductivity and closely matched CTEs.*

Thermal stresses and warpage in electronic components arise primarily from different coefficients of thermal expansion (CTEs). The increasing use of lead-free solders, which have much higher processing temperatures than lead-tin types, exacerbates the problem. Note that even when liquid cooling is used, thermal stresses caused by CTE mismatches are still important. Semiconductors and ceramics have CTEs in the range of 2 ppm/K to 7 ppm/K. The CTEs of copper, aluminum and glass fiber-reinforced polymer pc boards are much higher. Decades-old traditional low-CTE materials like copper/tungsten (Cu/W), copper/molybdenum (Cu/Mo), copper-Invar-copper (Cu/I/Cu) and copper-molybdenum-copper (Cu/Mo/Cu) have high densities and thermal conductivities that are little or no better than that of aluminum (**Table 1**). We call these first-generation thermal management materials.

Table 1 also shows an improved first-generation material, a laminate consisting of Cu-Mo bonded to outer copper layers (Cu/Cu-Mo/Cu). When both weight and thermal conductivity are important, a useful figure of merit is specific thermal conductivity (thermal conductivity divided by density or, in this case, specific gravity, which is dimensionless), as introduced by me and K.A. Schmidt many years ago.[4] All of the tables in this article include this property, which can provide a good estimate of potential weight reduction (higher is better).

When aluminum and copper are used for heat dissipation, significant design compromises are typically required, which can significantly reduce cooling efficiency. For example, to minimize thermal stresses, it is common to use compliant polymeric thermal interface materials (TIMs) to attach high-

Reinforcement	Matrix	Thermal Conductivity k (W/m-K)	CTE (ppm/K)	Density (g/cm³)	Specific Thermal Conductivity (W/m-K)
—	Aluminum	218	23	2.7	81
—	Copper	400	17	8.9	45
—	Invar	11	1.3	8.1	1.4
—	Kovar	17	5.9	8.3	2.0
—	Cu/I/Cu	164	8.4	8.4	20
—	Cu/Mo/Cu	182	6.0	9.9	18
—	Cu/Mo-Cu/Cu	245 to 280	6 to 10	9.4	26 to 30
—	Titanium	7.2	9.5	4.4	1.6
Copper	Tungsten	157 to 190	5.7 to 8.3	15 to 17	9 to 13
Copper	Molybdenum	184 to 197	7.0 to 7.1	9.9 to 10.0	18 to 20
—	Solder – Sn63/Pb37	50	25	8.4	6.0
—	Epoxy	1.7	54	1.2	1.4
E-glass Fibers	Epoxy	0.16 to 0.26	11 to 20	2.1	0.1

Table 1. *Properties of traditional first-generation thermal management materials.*

CTE heatsinks. It is widely recognized that TIMs increasingly account for most of the system total thermal resistance.[5]

The high thermal resistance of TIMs can be overcome by direct solder attach, but this can result in high thermal

Reinforcement	Matrix	Inplane Thermal Conductivity (W/m-K)	Through-Thickness Thermal Conductivity (W/m-K)	Inplane CTE (ppm/K)	Density (g/cm^3)	Specific Inplane Thermal Conductivity (W/m-K)
Natural Graphite	Epoxy	370	6.5	-2.4	1.94	190
Continuous Carbon Fibers	Polymer	330	10	-1	1.8	183
Discontinuous Carbon Fibers	Copper	300	200	6.5 to 9.5	6.8	44
SiC Particles	Copper	320	320	7 to 10.9	6.6	48
Continuous Carbon Fibers	SiC	370	38	2.5	2.2	170
Carbon Foam	Copper	350	350	7.4	5.7	61

Table 2. *Properties of advanced second-generation thermal management materials with high thermal conductivities and low coefficients of thermal expansion ($300 \le k < 400$).*

stresses. At present, the key way to work around this issue is to employ "soft" solders, typically Indium based, which have low yield stresses. However, these solders also have poor thermal fatigue and metallurgical characteristics. Use of materials with matching CTEs allows the packaging design engineer to select from a wider range of solders. Low-CTE solders, now under development, will further alleviate the thermal stress problem.

Weight is a key consideration in most portable systems, including notebook computers, cell phones, hybrid automobile electronics and avionics. Even if system weight is not important, low-density materials are needed for components like heatsinks to minimize shock-load stresses during shipping. New high-performance third-generation materials developed in the last few years have ultrahigh thermal conductivities, low CTEs and low densities that can solve key packaging problems, including reducing the CTE and increasing thermal conductivity of pc boards. When the low-CTE solders under development are commercialized, it will be possible to match the CTEs of virtually all packaging materials.

High-Performance Thermal Materials

In response to the well-documented needs previously described, an increasing number of high-performance advanced materials that offer significant improvements have been and are continuing to be developed. Advantages include thermal conductivities up to more than four times that of copper, CTEs that are tailorable from –2 to +60 ppm/K and a wide range of electrical resistivities. They also have extremely high strengths and rigidity, low densities, and low-cost, net-shape fabrication processes. Demonstrated payoffs include the following: improved and simplified thermal design, elimination of heat pipes, fans and pumped fluid loops, heat dissipation through pc boards, weight savings up to 90%, size reductions up to 65%, reduced cooling power, reduced thermal stresses, direct attach with hard solders, increased reliability, improved performance, increased pc board natural frequency, increased manufacturing yield, and part and system cost reductions. These materials are being used in a rapidly increasing number of commercial, aerospace and defense applications.

High-performance thermal materials, which are at various stages of development, fall into five main categories: monolithic carbonaceous materials, metal matrix composites (MMCs), carbon/carbon composites (CCCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs).[4, 6-9] A composite material is two or more materials bonded together. They are nothing new in electronic packaging. For example, E-glass fiber-reinforced polymer (E-glass/polymer) pc boards are PMCs. Cu-W and Cu-Mo are MMCs, rather than alloys. The numerous ceramic particle-reinforced and metal particle-reinforced polymers used for TIMs, underfills, encapsulants and electrically conductive adhesives are all PMCs.

The first second-generation thermal management material, silicon carbide particle-reinforced aluminum, commonly called Al/SiC in the packaging industry, is an MMC that was first used in microelectronic and optoelectronic packaging by me and my colleagues at GE in the early 1980s.[9] The first parts cost hundreds to thousands of dollars. As the processing technology matured and use increased, component cost dropped by several orders of magnitude. Microprocessor lids using this material now sell for $2 to $5 each in large volumes. Al/SiC has been used for some time in high-volume commercial and aerospace microelectronics and optoelectronic packaging applications, demonstrating the potential of advanced thermal management materials.

At present, we are in the early stage of the third generation of packaging materials. Several of the new high-performance materials discussed in this article are being used in production applications, including servers, notebook computers, plasma displays, aircraft and spacecraft electronics, and optoelectronic systems. Considering that these materials were only commercialized in the last few years, this is remarkable progress.

Fig. 1, which plots thermal conductivity as a function of CTE, compares traditional and advanced thermal materials. Ideal materials have high thermal conductivities and CTEs that match those of semiconductors and ceramics like Si, GaAs, alumina, aluminum nitride and low-temperature cofired ceramics (LTCCs). As the figure shows, by combining matrices of metals, ceramics and carbon with thermally conductive reinforcements like special carbon fibers (abbreviated C), SiC particles and diamond particles, it is possible to create new materials with high thermal conductivities and a wide range of CTEs.

Materials presented include monolithic metals, highly oriented pyrolytic graphite (HOPG) and a number of composites. The composites include carbon fiber-reinforced

Reinforcement	Matrix	Inplane Thermal Conductivity (W/m-K)	Through-Thickness Thermal Conductivity (W/m-K)	Inplane CTE (ppm/K)	Density (g/cm^3)	Specific Inplane Thermal Conductivity (W/m-K)
—	CVD Diamond	1100 to 1800	1100 to 1800	1 to 2	3.52	310 to 510
—	HOPG	1300 to 1700	10 to 25	-1.0	2.3	565 to 740
—	Natural Graphite	150 to 500	6 to 10	—	—	—
Continuous Carbon Fibers	Copper	400 to 420	200	0.5 to 16	5.3 to 8.2	49 to 79
Continuous Carbon Fibers	Carbon	400	40	-1.0	1.9	210
Graphite Flake	Aluminum	400 to 600	80-110	4.5 to 5.0	2.3	174 to 260
Diamond Particles	Aluminum	550 to 600	550 to 600	7.0 to 7.5	3.1	177 to 194
Diamond and SiC Particles	Aluminum	575	575	5.5	—	—
Diamond Particles	Copper	600 to 1200	600 to 1200	5.8	5.9	102 to 203
Diamond Particles	Cobalt	>600	>600	3.0	4.12	>145
Diamond Particles	Silver	400 to >600	400 to >600	5.8	5.8	69 to >103
Diamond Particles	Magnesium	550	550	8	—	—
Diamond Particles	Silicon	525	525	4.5	—	—
Diamond Particles	SiC	600	600	1.8	3.3	182

Table 3. *Properties of advanced third-generation thermal management materials with ultrahigh thermal conductivities and low coefficients of thermal expansion ($k \geq 400$).*

carbon (C/C), carbon fiber-reinforced epoxy (C/Ep), carbon fiber-reinforced copper (C/Cu), silicon carbide particle-reinforced copper (SiC/Cu) and traditional Cu-W. HOPG, also called thermal pyrolytic graphite and annealed pyrolytic graphite by various manufacturers, and diamond particle-reinforced metals and ceramics have the highest thermal conductivities.

Tables 2 and **3** present properties of several dozen selected second-generation and third-generation high-performance materials, respectively. **Table 3** includes diamond made by chemical vapor deposition (CVD) for reference. For anisotropic materials, inplane isotropic and through-thickness thermal conductivity (k) values are presented. The absolute and specific thermal conductivities of the advanced materials in **Table 2** and especially in **Table 3** are significantly higher than those of the traditional materials in **Table 1**.

Applications

A number of second- and third-generation advanced thermal materials are now in commercial and aerospace production systems, including power systems, servers, plasma displays, notebook computers, aircraft, spacecraft and defense electronics, and a variety of optoelectronic products. These materials include natural graphite; natural graphite/epoxy; HOPG; C/Ep; C/C; diamond particle-reinforced copper (diamond/Cu), an MMC; and diamond particle-reinforced silicon carbide (diamond/SiC), a CMC.

Al/SiC has been used in insulated gate bipolar transistor (IGBT) module bases for some time. **Fig. 2** shows an IGBT module that is widely used in traction applications. Because the CTE mismatch between Al/SiC and ceramic substrates is small compared to that of copper, the Al/SiC modules last many times longer under thermal cycling.

Fig. 3 shows a liquid-cooled Al/SiC power module base used in aircraft applications.

HOPG, a brittle, highly anisotropic material, is typically encapsulated with aluminum, Al/SiC or C/Ep. The CTE of the encapsulant tends to dominate. **Fig. 4** shows an aluminum-encapsulated HOPG aircraft VME format power supply housing that is conduction cooled and dissipates 235 W. The effective inplane thermal conductivity reportedly is 1160 W/m-K.

A key limitation of Al/SiC is that its thermal conductivity is only in the range of aluminum. However, it can be enhanced

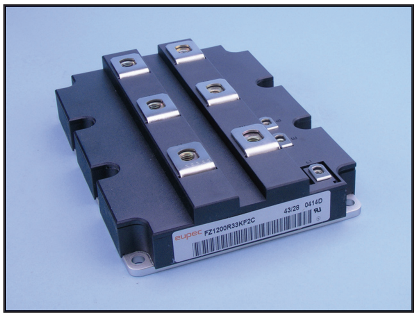

Fig. 2. *This traction IGBT module has an Al/SiC metal matrix composite base, enabling it to undergo many more thermal cycles compared to copper. (Courtesy of Eupec.)*

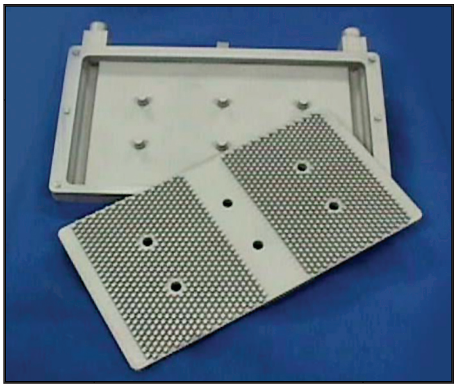

Fig. 3. *Al/SiC metal matrix composites have many applications, including this liquid-cooled aircraft power module base. (Courtesy of Ceramics Process Systems.)*

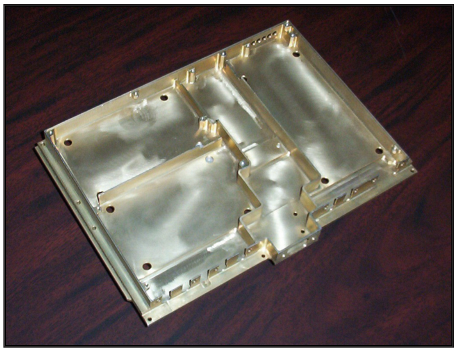

Fig. 4. *This conduction-cooled, aluminum-encapsulated highly oriented pyrolytic graphite VME format aircraft power supply housing dissipates 235 W. (Courtesy of k Technology Corp.)*

by insertion of HOPG, as it is for the VME housing in **Fig. 4**, while closely maintaining the CTE of Al/SiC. The thermoelectric cooler base in **Fig. 5** is another good example.

The need for lightweight, high-thermal-conductivity materials in notebook computers has led to the increased use of natural graphite heat spreaders. The lightweight laptop in **Fig. 6** has no heat pipes or fans.

In what I consider to be an historic milestone, diamond/SiC CMC heat spreaders are now in IBM servers. **Fig. 7** shows a diamond/SiC heat spreader coated with silicon to improve surface roughness.

As previously discussed, the high CTE of pc boards is a key source of thermal stresses and warping. A traditional solution has been the use of Cu/I/Cu constraining layers to reduce CTE. A new lightweight approach uses thermally conductive carbon fibers that, in addition to reducing CTE, increase pc board effective thermal conductivity. The high stiffness of these fibers also reduces warping and increases natural vibration frequency. Thermally conductive carbon fibers also are being used in high-performance TIMs and thermal straps.

Solving Manufacturing Problems

CTE mismatches cause thermal stresses and warping that can result in failures during processing, greatly reducing yield. The increased use of lead-free solders, which have much higher processing temperatures, is exacerbating the situa-

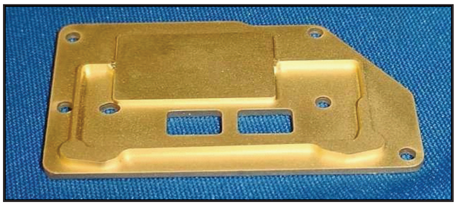

Fig. 5. *This thermoelectric cooler base uses Al/SiC-encapsulated highly oriented pyrolytic graphite (HOPG), which can have greater thermal conductivity than Al/SiC while maintaining its approximate CTE. (Courtesy of Ceramics Process Systems.)*

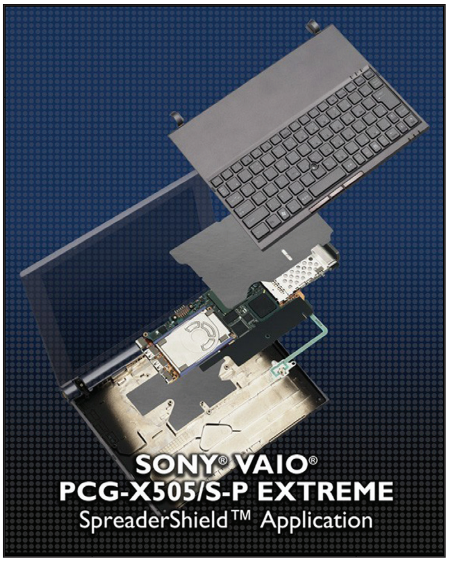

Fig. 6. *This lightweight laptop computer with natural graphite heat spreaders uses no heat pipes or fans. (Courtesy of GrafTech.)*

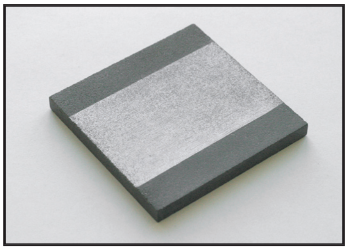

Fig. 7. *This diamond particle-reinforced silicon carbide ceramic matrix composite heat spreader uses a silicon coating to improve surface roughness. (Courtesy of Skeleton Technologies.)*

tion. I was asked to solve such a problem. In that particular case, the yield of a complex and expensive ceramic package was less than 5%. Modeling the many process steps using finite element analysis enabled definition of the base plate CTE required to produce an acceptable level of warping. This increased the yield to more than 99%, saving more than $60 million.

Cost is a complex issue involving many factors, and component and system costs are both important considerations. For example, an expensive material may well be cheaper than a pumped liquid-cooling system when all costs, including component, manufacturing, servicing and warranty, are included. If we adopt the approach that the proof of the pudding is in the eating, we find that, as discussed previously, several high-performance materials are being used in commercial and aerospace applications, demonstrating their cost-effectiveness.

The Future

We are in the early stages of a thermal management materials revolution. Al/SiC, the first second-generation thermal material, was only developed about two decades ago. Historically speaking, this is barely the blink of an eye. Most of the new high-performance third-generation materials have been commercialized within the last few years. Based on this perspective, it seems reasonable to expect that in the future there will be significant developments in both materials and processes, leading to improved thermal properties and reduced costs.

Decreasing cost will stimulate further use of these materials in an increasing number of microelectronic, optoelectronic and MEMS applications. One significant barrier is the general lack of awareness of advanced materials among packaging engineers. However, the successful use of diamond particle-reinforced SiC composites in commercial servers suggests that other diamond-reinforced composites merit consideration.

One intriguing area of interest is nanocomposites. Estimates of carbon nanotube thermal conductivity run as high as 6600 W/m-K. Values more than 3000 W/m-K have been measured. Graphite nanoplatelets, which are much cheaper than nanotubes, are another candidate for nanoscale reinforcement, as are nanoparticles of diamond and other thermally conductive materials. While the small size of nanoscale reinforcements results in a large number of interfaces that reduce thermal efficiency, they are certainly worth exploring. It may well be that nanoreinforcements can be used with other reinforcements, such as thermally conductive carbon fibers, to produce hybrid composites with attractive properties. Other potential advantages of nanocomposites are reduced CTE and increased stiffness.

As previously discussed, composite solders with low CTEs are now under development. Combined with the materials discussed in this article, the packaging engineer will have the ability to match thermal expansions throughout the package, improving manufacturing yield, reliability and performance. Because of the unique ability of this and other advanced thermal management materials to meet future packaging requirements, I anticipate that they will play an increasingly important role in the 21st century. **PETech**

Acknowledgements

Some of the data in this paper were taken from the following publications, and appear courtesy of the publishers: Kelly, A., and Zweben, C., Editors-in-Chief. *Comprehensive Composite Materials*, Pergamon Press, Oxford, 2000; Zweben, C. "Composite Materials And Mechanical Design," *Mechanical Engineers' Handbook, Book 1: Materials and Mechanical Design*, Third Edition, Myer Kutz, Ed, John Wiley & Sons Inc., New York, 2005.

Zweben, C. "Metal Matrix Composites, Ceramic Matrix Composites, Carbon Matrix Composites and Thermally Conductive Polymer Matrix Composites," Chapter 5, *Handbook of Plastics, Elastomers and Composites*, Fourth Edition, A. Harper, Editor-in-Chief, McGraw-Hill, New York, 2002.

References

1. Strand, S.D. "Future Technology in the Global Market," Power Systems World, Oct. 23-27, 2005.
2. Markoff, J. "Intel's Big Shift After Hitting Technical Wall," *New York Times*, May 17, 2004.
3. "Burned Groin Blamed on Laptop," *BBC News World Edition*, Nov. 22, 2002.
4. Zweben, C. and Schmidt, K.A. "Advanced Composite Packaging Materials," *Electronic Materials Handbook,* ASM International, 1989.
5. Lasance, C. J. M. "Problems with Thermal Interface Material Measurements: Suggestions for Improvement," Electronics Cooling, November 2003.
6. Fleming, T.F.; Levan, C.D.; and Riley, W.C. "Applications for Ultra-High Thermal Conductivity Fibers," Proceedings of the 1995 International Electronic Packaging Conference, International Electronic Packaging Society, pp. 493-503.
7. Norley, J. "Natural Graphite Based Materials for Electronics Cooling," Proceedings of the IMAPS Advanced Technology Workshop on Thermal Management, Oct. 25-27, 2004.
8. Zweben, C. "Electronic Packaging: Heat Sink Materials," *Encyclopedia of Materials: Science and Technology*, Vol. 3, 2001, pp. 2676-83.
9. Thaw, J.; Zemany, J.; and Zweben, C. "Metal Matrix Composites for Microwave Packaging Components," Electronic Packaging and Production, August 1987, pp. 27-29.