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Heat Sinks

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THERMAL MANAGEMENT is one of the critical aspects of packaging design. To ensure reliable operation of electronic and microwave components, junction temperatures must be kept within specified limits. As a rule, the problem is one of cooling, because failure rates increase dramatically with increasing temperature. For every 10 °C (18 °F) increase in temperature, silicon and gallium arsenide lifetime drops by a factor of 2.5 to 3. Heat sinks, also called cold plates, are commonly used to transport heat dissipated by devices to a heat exchanger or to spread it over a larger surface area to facilitate cooling by radiation or convection. To minimize thermal impedance, the heat sink typically is adhesively bonded or soldered to the component it supports, which generally is one or more devices, a ceramic substrate supporting the devices, or a multilayer printed wiring board (PWB).

Another critical packaging design problem is minimizing thermal stresses in the assembly. Thermal stresses can cause mechanical failures of devices, circuit solder joints, substrates, or the adhesive or solder used to hold the assembly together. Failure of the heat sink is also possible, especially if it is a ceramic material like beryllia or aluminum nitride. To minimize thermal stresses, it is important that all of the components in the assembly have similar coefficients of thermal expansion (CTEs).

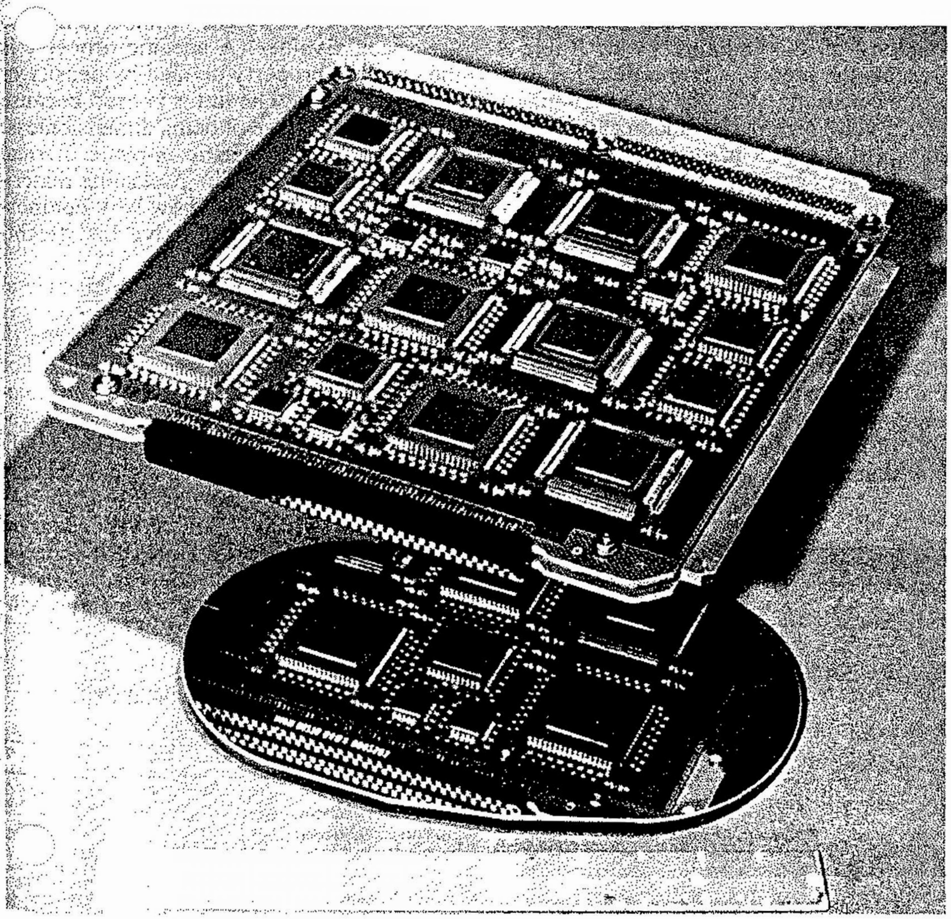

Fig. 1 Printed wiring board assembly consisting of two PWBs bonded to a central heat sink

Therefore, the key requirements for heat sinks is that they have high thermal conductivities and low CTEs to match those of other components in the assembly. Typically devices are silicon or gallium arsenide, which have low CTEs, as do ceramic substrates like alumina, beryllia, and aluminum nitride.

Printed wiring boards merit special consideration. Traditionally, these have been made of E-glass fabric reinforced epoxy and other polymers. In the past, chips were mounted in packages attached to the board by relatively flexible leads that acted like expansion joints, so that it was not necessary to have a close CTE match between the package and PWB. (In fact, the CTE of glass-epoxy is significantly higher than that of most chips and ceramics.) The development of ceramic (typically alumina) leadless chip carriers (LCCs), which are soldered directly to the surface of the board, changed all that, because significant differences in the CTEs of the PWB and LCC can cause failure of the solder joints. In fact, this has turned out to be a serious problem.

To be more precise, it is actually the CTEs of the assembly of the PWB and the heat sink that must match that of the ceramic LCC. Because of this, several approaches have been developed. One is to use a glass-epoxy PWB in conjunction with a low CTE, stiff heat sink that constrains the PWB. Another strategy is to use a PWB and heat sink that both have CTEs that match or approximate that of the ceramic LCC. In both approaches, low-CTE heat sinks are required. Figure 1 shows an assembly consisting of two PWBs bonded to a central heat sink.

At present, the most widely used heat sinks are laminated metal sandwiches consisting of two layers of copper bonded to a central constraining layer of Invar or molybdenum. The laminates provide low CTEs

Table 1 In-plane properties of heat sinks

Material	Reinforcement, vol%	Density, g/cm³	Density, lb/in.³	Coefficient of thermal expansion, 10^{-6}/K	Coefficient of thermal expansion, 10^{-6}/°F	Thermal conductivity, W/m · K	Thermal conductivity, Btu/h · ft · °F	Elastic moduli, GPa	Elastic moduli, 10^6 psi
Carbon fiber-epoxy	60	1.8	0.065	−1.1	−0.6	310	180	186	27
Carbon fiber-aluminum	28	2.5	0.092	6.5	3.6	290	168	131	19
Carbon fiber-copper	28	7.2	0.26	6.5	3.6	400	230	158	23
Boron fiber-aluminum	20	2.6	0.095	12.7	7.1	180	103	...	...
C-Ep and aluminum laminate	...	2.3	0.084	6.5	3.6	230	132	118	17
SiC particle-aluminum	...	2.9	0.104	10.3	5.7	180	103	172	25
Copper-clad Invar	...	8.4	0.30	5.5	3.1	164	95	131	19
Copper-clad molybdenum	...	9.9	0.36	6.0	3.3	182	105	230	33

and thermal conductivities in the range of aluminum alloys. For simplicity, these heat sinks are referred to as copper-clad Invar (CCI) and copper-clad molybdenum (CCM). The CTEs of these laminates can be controlled by adjusting the relative thicknesses of the copper and constraining layers. Table 1 presents effective mechanical and thermal properties of CCM and CCI.

Both CCI and CCM are finding increasing use in heat sinks. However, they have two major limitations: First, they have high effective densities and, second, their thermal conductivities are in the range of aluminum alloys, which, although relatively good, may not be high enough for some applications. To overcome these deficiencies, a number of other composite materials are either in production or being evaluated, including boron fiber reinforced aluminum (B-Al) (Ref 1), carbon fiber reinforced aluminum (C-Al) (Ref 2), carbon fiber reinforced copper (C-Cu) (Ref 3), and silicon carbide particle reinforced aluminum (SiC_p-Al) (Ref 4). Another approach under development combines layers of aluminum and carbon fiber reinforced epoxy (Ref 5).

As discussed in the article "Reinforcements and Matrix Materials" in this Volume, there are numerous kinds of carbon fibers available with a wide range of properties. For packaging applications, the most attractive ones at this time are ultrahigh-modulus, high thermal conductivity fibers derived from a pitch precursor material. Table 1 presents predicted properties of C-Al and C-Cu composites reinforced with pitch-base fibers that have a modulus of 895 GPa (130×10^6 psi). Fibers are oriented so that in-plane properties are isotropic. As discussed in the article "Composite Packaging Materials," a wide range of CTEs can be achieved by varying the fiber volume fraction. The properties presented correspond to a material having an isotropic in-plane CTE of 6.5×10^{-6}/K, a typical value for alumina. Table 1 also presents the properties of carbon fiber reinforced epoxy. This composite has high conductivity, but its slightly negative CTE is not a good match for alumina.

Boron fiber reinforced aluminum is also a candidate heat sink material. However, although boron fibers have a relatively low CTE, they are poor thermal conductors. As a consequence, increasing the fiber volume fraction (vol%) to lower the CTE has the undesirable effect of reducing thermal conductivity. Therefore, it is necessary to trade off CTE and conductivity. In Ref 1, a fiber volume fraction of 20% was selected. Table 1 presents the properties of such a heat sink. Fibers are oriented at 0° and 90°.

Properties of silicon carbide particle reinforced aluminum are discussed in the article "Composite Packaging Materials." Because the CTE of SiC particles is lower than that of aluminum, composite thermal expansion decreases with increasing particle volume fraction. At this time, 55 vol% appears to be an upper limit for material that can be readily fabricated. Because the thermal conductivity of high-purity silicon carbide particles is high, there is no thermal conductivity penalty for using high volume fractions of this reinforcement. Table 1 presents the predicted properties of a composite consisting of 45 vol% 6063 aluminum and 55 vol% high-purity silicon carbide particles. Although the predicted CTE is not as low as that of alumina, it is somewhat lower than the value for B-Al. Additional work may succeed in further reducing the CTE of SiC_p-Al.

The last type of composite heat sink considered is a laminate consisting of layers of carbon fiber reinforced epoxy (C-Ep) oriented at 0° and 90°, or at 0°, +45°, −45°, and 90°, bonded to layers of monolithic (unreinforced) aluminum. By selecting the type of fiber and relative amounts of C-Ep and aluminum, it is possible to tailor the thermal expansivity of the laminate over a wide range (Ref 5). Table 1 presents predicted properties of a laminated heat sink that combines layers of aluminum and ultrahigh-modulus carbon fiber reinforced epoxy. The fiber selected has a modulus of 895 GPa (130×10^6 psi). The volume ratio of fiber to epoxy is 60%. Figure 2 shows PWB heat sinks that were fabricated using this approach.

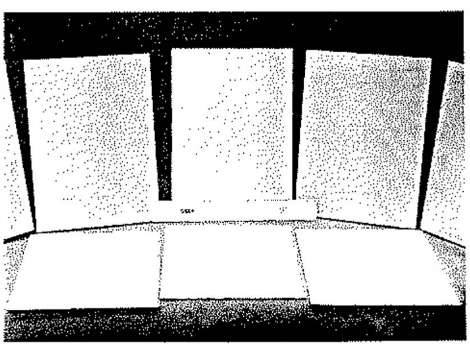

Fig. 2 Laminated heat sinks consisting of layers of ultrahigh modulus pitch-base carbon-epoxy and aluminum

Table 1 shows that composites offer significant potential advantages over CCM and CCI heat sinks. First, carbon fiber reinforced copper has the potential for both significantly higher thermal conductivity and lower density. Second, for applications for which thermal conductivities in the range of aluminum are acceptable, a number of composites offer density reductions.

A widely used method for comparing properties when weight is important is to use specific values. A specific property is the absolute property divided by density or specific gravity. The latter is used because it has the advantage of being dimensionless. Table 2 presents specific in-plane thermal conductivities of various packaging materials. The values clearly show why composites are particularly attractive for weight-sensitive applications.

An important consideration for clad metal and fiber-reinforced composite heat sinks is that their properties are anisotropic. (Particle-reinforced materials are isotropic.) For CCI and the carbon fiber reinforced composites discussed in this article, through-thickness conductivities are significantly lower than in-plane values. The relative importance of in-plane and through-thickness conductivities is largely dependent on the particular configuration and, as a rule, requires finite-element analysis to determine. For applications in which through-

Table 2 Specific in-plane conductivities of heat sinks

Material	W/m · K	Btu/h · ft · °F
Carbon fiber-epoxy	172	100
Carbon fiber-aluminum	116	67
Carbon fiber-copper	55	32
Boron fiber-aluminum	69	41
C-Ep and aluminum laminate	100	60
SiC particle-aluminum	62	36
Copper-clad Invar	20	12
Copper-clad molybdenum	18	10

thickness conductivity is important, C-Cu is an attractive material, especially when weight is a consideration.

In this article, low-expansivity heat sinks have been evaluated. Candidates include copper-clad Invar and copper-clad molybdenum, a variety of fiber-reinforced materials, and silicon carbide particle reinforced aluminum. Composites offer significant potential for weight reduction over clad metals. In addition, predicted values for carbon fiber reinforced copper show that they present opportunities for conductivities substantially higher than those of any other material identified to date.

Most of the composite property values presented in this article are based on analytical predictions, and further development of these materials is required to translate their considerable potential into production hardware. However, because the payoff for success is very significant, a considerable effort is now underway.

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