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Performance of Isotropic and Anisotropic Heat Spreaders

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Anisotropic heat spreaders (flexible graphite and continuous carbon fiber polymer-matrix composite) and isotropic heat spreaders (copper and aluminum) have been evaluated numerically in terms of thermal resistance. Anisotropic ones are attractive for their through-thickness thermal insulation ability. Flexible graphite is superior to carbon fiber composite in providing lower thermal resistance. Carbon fiber composite is advantageous in its superior through-thickness thermal insulation ability and its smaller critical thickness (the optimal thickness for maximizing heat spreading while minimizing thickness). The isotropic heat spreaders are superior to the anisotropic ones in providing low thermal resistance, provided that the thickness is large, but they do not have the through-thickness thermal insulation ability. A higher value of the in-plane thermal conductivity enhances the effectiveness of flexible graphite. As the heat source area decreases, the thermal resistance increases while the critical thickness decreases. For the same heat source area, a greater in-plane dimension of the heat source perpendicular to the intended heat spreading direction decreases the thermal resistance and critical thickness. Flexible graphite is comparatively more advantageous when the thickness is smaller and when the heat source area is larger. For the same thickness below 2 mm, flexible graphite with in-plane conductivity of 1500 W/(m K) is superior to copper and that with in-plane conductivity of 600 W/(m K) is superior to aluminum. The highest thermal conductance obtained is 6.1×10^4 W/(m^2 K) when the thermal interfacial resistance is neglected and 5.1×10^4 W/(m^2 K) when this resistance is included. The conductance increases with decreasing heat source area and with decreasing heat spreader length.

Key words: Heat spreader, thermal conduction, flexible graphite, carbon fiber polymer-matrix composite, copper, aluminum

INTRODUCTION

Overheating limits the performance and reliability of microelectronics and solid-state lighting (light-emitting diodes). Heat spreaders are used for directing heat away from the heat source. If the heat source and heat sink are separated from one another, as necessitated by the configuration of the electronic package, a heat spreader can serve to direct heat from the heat source to the heat sink. Heat spreaders function by thermal conduction. Methods involving convection include use of fans and heat pipes, but these methods tend to have more complex implementation.

Isotropic thermal conductors, such as copper,[1,2] aluminum,[3] tungsten-copper,[4] and diamond copper-matrix composite,[5] are used for heat spreading. However, anisotropic thermal conductors with high in-plane thermal conductivity and low through-thickness thermal conductivity are increasingly being used, because (i) high in-plane thermal conductivity is considered to be more important for heat spreading than high through-thickness thermal conductivity, and (ii) a very low through-thickness thermal conductivity enables the heat spreader to

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serve, to a degree, as a thermal insulator in the through-thickness direction, thus avoiding heat flow to nearby components in the electronic package.

Anisotropic thermal conductors that exhibit high in-plane thermal conductivity and do not exhibit very low through-thickness thermal conductivity include copper–diamond–copper sandwich composites[6,7] and diamond-coated silicon carbide.[8] Anisotropic thermal conductors that exhibit high in-plane thermal conductivity and very low through-thickness thermal conductivity include flexible graphite[9] and continuous carbon fiber polymer-matrix composites.[10,11]

Continuous carbon fiber polymer-matrix composites with fibers at least partly in the direction of the intended heat spreading have high in-plane thermal conductivity and low through-thickness thermal conductivity, since the carbon fibers are conductive whereas the polymer matrix is not. These composites are typically in the form of a laminate that consists of laminae (or plies) of continuous carbon fibers that are oriented in the plane of the laminate. The fibers in each lamina can be aligned or woven. Flexible graphite refers to exfoliated graphite (made by exfoliation of intercalated graphite flakes) that has been compressed in the absence of a binder.[9,12] Due to the accordion-like microstructure of exfoliated graphite, mechanical interlocking between adjacent pieces of exfoliated graphite occurs during the above-mentioned compression, resulting in a sheet. The sheet is resilient in the through-thickness direction, due to the accordion-like microstructure of exfoliated graphite and the preferred orientation of the graphite layers in the plane of the sheet. This preferred orientation results in high in-plane thermal conductivity but relatively low through-thickness thermal conductivity. This resiliency allows the sheet to conform to the topography of the surface against which it is pressed. This conformability is advantageous for forming a good thermal contact between flexible graphite and the surface against which it is pressed. Thus, flexible graphite can be used as a thermal interface material for enhancing thermal contacts.[13–19] However, such conformability is also valuable for the use of flexible graphite as a heat spreader.[20,21] In contrast, continuous carbon fiber polymer-matrix composites do not exhibit resilience or conformability.

In spite of the technological importance of heat spreaders, little attention has been given to the science behind the heat spreader function. The science pertains to how various parameters (such as the thermal conductivity and its anisotropy) affect the effectiveness of the heat spreading, particularly in relation to the effectiveness limit (i.e., the minimum thermal resistance) and the dependence of the effectiveness on the thickness of the heat spreader and on the in-plane dimensions of the heat source. Such understanding is valuable for the design, implementation, and further development of heat spreader materials.

Prior work has addressed the science behind thermal interface materials,[18] which involve a heat transfer configuration that is quite different from that associated with heat spreaders. Thermal interface materials pertain to heat flow in the direction perpendicular to the plane of the thermal interface, whereas heat spreaders pertain to heat flow from the heat source surface to the adjoining heat spreader surface and heat flow away from the heat source along the heat spreader. In other words, the heat flow associated with the use of a heat spreader is in two directions (i.e., in the through-thickness direction followed by the in-plane direction), whereas that associated with the use of a thermal interface material is in a single direction.

This paper addresses isotropic and anisotropic heat spreaders. Anisotropic heat spreaders exhibit high in-plane thermal conductivity and low through-thickness thermal conductivity. In addition, this paper provides a comparison of anisotropic heat spreaders (i.e., flexible graphite and continuous carbon fiber polymer-matrix composite) and isotropic heat spreaders (i.e., copper and aluminum). The approach involves calculation of the thermal resistance of the heat conduction path. This resistance depends on the thermal conductivity of the heat spreader in both through-thickness and in-plane directions, in addition to depending on the dimensions of the heat source surface and the thickness of the heat spreader. As is typically the case in practice, the in-plane dimensions of the heat spreader are larger than those of the heat source surface.

Thermal management is needed not only for cooling of microelectronics and solid-state lighting, but also for aircraft cooling[11] and radiant heating (as for buildings).[20] Carbon-based materials are particularly suitable for aircraft and lightweight electronics, due to their low density. Although the sizes of the heat spreaders are much larger for aircraft cooling and radiant heating than for cooling of microelectronics and solid-state lighting, there is considerable commonality in the science behind these types of thermal management.

The objectives of this paper are (i) to provide guidelines for the design of anisotropic heat spreaders for effective heat spreading, (ii) to investigate the effects of the thermal conductivity, the thermal conductivity anisotropy, and the dimensions on the performance of a heat spreader, (iii) to investigate the performance limit of heat spreader materials, and (iv) to provide a comparative evaluation of the performance of anisotropic and isotropic heat spreaders of various representative compositions.

METHODS

Consider a rectangular heat source surface of dimensions u and w in contact with a heat spreader. The length of the heat spreader l is taken to be the

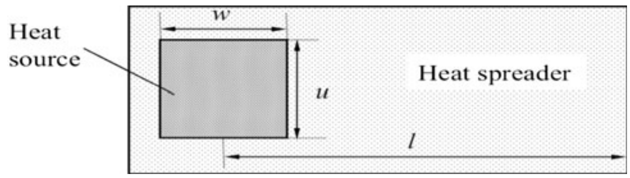

Fig. 1. Geometric configuration of the heat spreading.

distance from the center of this rectangle to the far end of the heat spreader in the direction of the intended heat spreading, as illustrated in Fig. 1. The average depth of heat penetration along the thickness of the heat spreader is t. Due to the heat flow in the through-thickness direction of the heat spreader, the depth of heat penetration increases as the heat spreads. The quantity t is the average value over the length of the heat spreader. Hence, the center of the cross-section of the longitudinal heat path (i.e., the path in the direction of the intended heat spreading) is at an average depth of $t/2$. Since the heat path involves a change in direction from the through-thickness direction of the heat spreader to the longitudinal (in-plane) direction of the heat spreader, the average distance of heat penetration in the through-thickness direction of the heat spreader is taken as $t/2$.

Consider an anisotropic heat spreader. Let the thermal conductivity of the heat spreader be κ_1 and κ_2 in the through-thickness and longitudinal directions, respectively. The anisotropy is such that $\kappa_2 > \kappa_1$. The thermal conduction from the heat source involves the path in the through-thickness direction followed by that in the longitudinal direction. The thermal resistance of the part of the heat conduction path in the through-thickness direction is given by

$$R_1 = (t/2)/(\kappa_1 uw), \quad (1)$$

and the thermal resistance of the heat conduction path in the longitudinal direction is given by

$$R_2 = l/(\kappa_2 ut). \quad (2)$$

The total thermal resistance is given by

$$R = R_1 + R_2. \quad (3)$$

R depends on t. The value of t at which R is minimum is referred to as the critical thickness (t_c) of the heat spreader. When the thickness is below t_c, the heat spreading is below the maximum capability of the material. When the thickness is above t_c, a part of the thickness of the heat spreader contributes little to the heat spreading. Thus, t_c can be considered the optimal thickness for maximizing the heat spreading while minimizing the thickness. The critical thickness is obtained by differentiating R with respect to t and setting the differential to zero. Hence,

$$t_c = \sqrt{(2wl/\alpha)}, \quad (4)$$

where

$$\alpha = \kappa_2/\kappa_1. \quad (5)$$

The total thermal resistance R at the critical thickness is roughly the minimum thermal resistance that the particular heat spreader material can provide. In other words, it relates to the performance limit of the heat spreader material. The thermal resistance R decreases with increasing thickness. When the thickness exceeds the critical thickness, the further reduction in R is relatively small. In other words, the curve of R versus thickness starts to level off when the thickness reaches the critical thickness.

For an isotropic heat spreader, $\kappa_1 = \kappa_2 = \kappa$ and Eq. 4 becomes

$$t_c = \sqrt{(2wl)}. \quad (6)$$

The above model neglects the thermal resistance associated with the interface between the heat source and the heat spreader. This interfacial resistance is reduced when the heat spreader is conformable, so that the air pockets at the interface are at least partially filled with the heat spreader material. The air pockets are present due to the fact that the surfaces of the heat spreader and heat source are not perfectly smooth. Hence, a conformable heat spreader is preferred. In general, the interfacial resistance is reduced when the heat source and heat spreader surfaces are smoother and when there is a highly conformable and very thin thermal interface material between the heat source and the heat spreader for displacing the air at the interface.[16–18] The interfacial resistance is neglected in the model calculation in this paper. However, the interfacial resistance corresponding to the lowest measured interfacial resistance reported in the literature is added to the resistance calculated based on the model in order to obtain a more accurate value of the overall resistance.

The above model is applied to a number of anisotropic and isotropic heat spreaders. The anisotropic heat spreaders include commercial flexible graphite sheets (with in-plane thermal conductivity ranging from 300 W/(m K) to 1500 W/(m K)[22]) that are specifically for heat spreading, namely SPREADERSHIELD of GrafTech International, Lakewood, OH. Three grades of SPREADERSHIELD are used in this study: SS300, SS600, and SS1500. The in-plane and through-thickness thermal conductivity values of SS300 are 300 W/(m K) and 4.5 W/(m K), those of SS600 are 600 W/(m K) and 3.5 W/(m K), and those of SS1500 are 1500 W/(m K) and 3.4 W/(m K). Hence, the thermal conductivity anisotropy (α) is 67, 170, and 440 for SS300, SS600, and SS1500, respectively.

The anisotropic heat spreaders studied also include continuous carbon fiber epoxy-matrix composite, with unidirectional fibers being made from mesophase pitch, with diameter of 10 μm, density of

2.2 g/cm^3, and thermal conductivity of 900 W/(m K) to 1000 W/(m K), as manufactured by Cytec Industries, Inc. (Woodland Park, NJ). Taking the fiber thermal conductivity to be 1000 W/(m K) and considering that the fiber volume fraction is 60% (a typical fiber content), the in-plane thermal conductivity of this unidirectional composite was calculated to be 600 W/(m K), which can be considered to be at the high end of what can be expected of continuous carbon fiber polymer-matrix composites. The through-thickness thermal conductivity of the composite is taken to be 0.73 W/(m K), which is the measured value for a crossply continuous carbon fiber epoxy-matrix composite.[10] Hence, the thermal conductivity anisotropy (α) is 823 for the composite—greater than any of the grades of flexible graphite.

The isotropic heat spreaders studied include aluminum (alloy 1100, annealed, with thermal conductivity of 222 W/(m K)[23]) and copper (alloy C11000, electrolytic tough pitch, with thermal conductivity of 388 W/(m K)[23]). Aluminum and copper are among the most common materials used as heat spreaders.

For each material combination, the heat spreader length in the direction of the intended heat spreading (l), the heat source dimensions (u and w in the plane of the interface between the heat source and the heat spreader), the critical thickness (t_c), the total thermal resistance (R when the heat spreader thickness equals t_c), and the variation of the total thermal resistance with the thickness are calculated using the above equations.

RESULTS AND DISCUSSION

As shown in Table I, for the same dimensions, the total thermal resistance is lower for flexible graphite than for continuous carbon fiber polymer-matrix composite and decreases with increasing in-plane thermal conductivity of the flexible graphite. This is because of the strong positive influence of high in-plane thermal conductivity. The through-thickness thermal conductivity also helps, as shown by the high value of the total thermal resistance of the carbon fiber composite compared with the flexible graphite with the same in-plane thermal conductivity of 600 W/(m K).

For the same dimensions, the total thermal resistance is much lower for the metals (aluminum and copper) than for any of the anisotropic materials. This is due to the high through-thickness thermal conductivity of the metals, even though the in-plane thermal conductivity of the metals is not high compared with the anisotropic materials.

For the same dimensions, the critical thickness is lower for the carbon fiber composite than for flexible graphite and decreases with increasing thermal conductivity anisotropy (α) of the flexible graphite. Among the anisotropic materials, greater

Table I. Performance of various heat spreader materials

	Thermal Conductivity (W/(m K))				$u = w =$ 5 mm		$u = w =$ 3 mm		$u = w =$ 2 mm		u = 1 mm w = 2 mm		u = 2 mm w = 1 mm	
Material	κ_1	κ_2	α	l (mm)	R (K/W)	t_c (mm)	R (K/W)	t_c (mm)	R (K/W)	t_c (mm)	R (K/W)	t_c (mm)	R (K/W)	t_c (mm)
FG	4.5	300	67	10	10.9	1.22	23.4	0.95	43.0	0.77	86.1	0.77	60.86	0.55
SS300				50	24.3	2.74	52.4	2.12	96.2	1.73	192	1.73	136.1	1.22
				100	34.4	3.87	74.1	3.00	136	2.45	272	2.45	192	1.73
FG	3.5	600	170	10	8.73	0.76	18.8	0.59	34.5	0.48	69.0	0.48	48.8	0.34
SS600				50	19.5	1.71	42.0	1.32	77.2	1.08	154	1.08	109	0.76
				100	27.6	2.42	59.4	1.87	109	1.53	218	1.53	154	1.08
FG	3.4	1500	440	10	5.60	0.48	12.1	0.37	22.1	0.30	44.3	0.30	31.3	0.21
SS1500				50	12.5	1.06	27.0	0.82	49.5	0.67	99.0	0.67	70.0	0.48
				100	17.7	1.51	38.1	1.17	70.0	0.95	140	0.95	99.0	0.67
CC	0.73	600	823	10	19.1	0.35	41.2	0.27	75.6	0.22	151	0.22	107	0.16
				50	42.8	0.78	92.0	0.60	169	0.49	338	0.49	239	0.35
				100	60.5	1.10	130	0.85	239	0.70	478	0.70	338	0.49
Al	222	222	1.00	10	1.80	10.0	3.88	7.75	7.12	6.32	14.2	6.32	10.1	4.47
				50	4.03	22.4	8.67	17.3	15.9	14.1	31.9	14.1	22.5	10.0
				100	5.70	31.6	12.3	24.5	22.5	20.0	45.1	20.0	31.9	14.1
Cu	388	388	1.00	10	1.03	10.0	2.22	7.75	4.08	6.32	8.15	6.32	5.76	4.47
				50	2.31	22.4	4.96	17.3	9.11	14.1	18.2	14.1	12.9	10.0
				100	3.26	31.6	7.01	24.5	12.9	20.0	25.8	20.0	18.2	14.1

FG flexible graphite, *CC* carbon fiber polymer-matrix composite.

anisotropy and lower through-thickness thermal conductivity contribute to giving a lower critical thickness. The critical thickness is much higher for the isotropic materials than for the anisotropic materials, in spite of the isotropy of the isotropic materials, due to the relatively high through-thickness thermal conductivity of the isotropic materials. The values of the critical thickness for the isotropic materials are, in most cases, too large to be practical for microelectronics. When comparing the anisotropic and isotropic materials at comparable thicknesses (Table II), the difference in thermal resistance is not as large as in the case of comparison at the corresponding critical thickness values.

The critical thickness values given in Table I for flexible graphite are all large compared with the commercially available thicknesses for SPREADERSHIELD;[22] For example, the available thickness for SS1500 is 0.025 mm, whereas the critical thickness for SS1500 ranges from 0.21 mm to 1.51 mm (Table I).

For all the materials, whether isotropic or anisotropic, and for the same heat source dimensions, both the thermal resistance and the critical thickness increase with increasing heat spreader length (l), as expected. For all the materials, at the same l, the thermal resistance increases while the critical thickness decreases with decreasing heat source dimensions ($u = w$). The decrease in the critical thickness is because a smaller heat source results in a smaller through-thickness conduction path area and hence less heat penetration in the through-thickness direction. This result means that a more concentrated heat source makes heat spreading more demanding, but the thickness of the heat spreader can be smaller. For all the materials, for the same heat source area (uw), both the thermal resistance and the critical thickness increase with increasing ratio w/u, because a higher ratio corresponds to a smaller u, which results in a narrower conduction path in the in-plane direction.

Table II presents the effect of heat spreader thickness on the total thermal resistance R for each type of heat spreader studied. For thicknesses exceeding the critical thickness, R is calculated for thickness equal to the critical thickness. Figure 2 shows plots of R versus thickness for the various heat spreader materials, as obtained by using the above equations when the thickness is up to the critical thickness and assuming that R is fixed at the value at the critical thickness when the thickness exceeds the critical thickness. This assumption is reasonable, since the part of the thickness beyond the critical thickness contributes relatively little to the thermal conduction. For any of the materials, R decreases monotonically with increasing thickness, such that it starts to level off when the thickness reaches the critical thickness.

Table II shows the dependence of the performance on the heat spreader material, heat spreader thickness, and heat source area. For the same heat spreader thickness and for heat source area of 5 mm × 5 mm, the performance of the various

Table II. Relationship between thermal resistance and thickness for three values of $u = w$, namely 5 mm, 3 mm, and 2 mm, for $l = 50$ mm

Material	Thickness (mm)	R (K/W)		
		$u = w = 5$ mm	$u = w = 3$ mm	$u = w = 2$ mm
FG SS300	1.00	37.8	67.9	111
	2.00	25.6	52.5	96.2
	3.00	24.3	52.4	96.2
FG SS600	1.00	22.4	43.7	77.4
	2.00	19.5	42.0	77.2
	3.00	19.5	42.0	77.2
FG SS1500	1.00	12.6	27.0	49.5
	2.00	12.5	27.0	49.5
	3.00	12.5	27.0	49.5
CC	1.00	42.8	92.0	169
	2.00	42.8	92.0	169
	3.00	42.8	92.0	169
Al	1.00	45.1	75.3	113
	2.00	22.7	38.0	57.4
	3.00	15.3	25.8	39.2
Cu	1.00	25.8	43.1	64.8
	2.00	13.0	21.8	32.9
	3.00	8.75	14.8	22.4

FG flexible graphite, *CC* carbon fiber polymer-matrix composite.

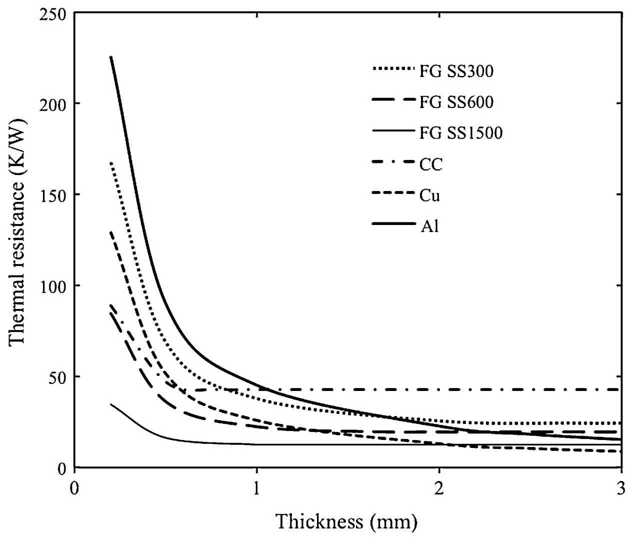

Fig. 2. Variation of total thermal resistance with heat spreader thickness for various heat spreader materials, heat source area of 5 mm × 5 mm, and l = 50 mm.

materials, as indicated by the thermal resistance R, decreases in the order:

(i) Cu, SS1500, Al, SS600, SS300, CC when the thickness is 3 mm,
(ii) SS1500, Cu, SS600, Al, SS300, CC when the thickness is 2 mm, and
(iii) SS1500, SS600, Cu, SS300, CC, Al when the thickness is 1 mm,

where SS1500, SS600, and SS300 are the three grades of flexible graphite investigated and CC refers to the carbon fiber composite investigated.

The above ranking means that, for the same heat spreader thickness and for the heat source area of 5 mm × 5 mm, flexible graphites SS1500 and SS600 are superior to Cu only when the thickness is below 2 mm. It further means that, for the same thickness and for heat source area of 5 mm × 5 mm, SS1500 and SS600 are superior to Al only when the thickness is below 3 mm. When the thickness is 3 mm, Cu is superior to SS1500, SS600, and SS300, and Al is superior to SS600 and SS300. For any thickness, SS1500, SS600, and SS300 are superior to CC.

When all three heat source areas are considered together, for the same thickness, SS1500 is superior to Cu and SS600 is superior to Al when the thickness is below 2 mm. Hence, a smaller thickness helps the relative effectiveness of flexible graphite.

The ranking also depends on the heat source area. For thickness of 1 mm, the ranking is shown below in decreasing order of performance for various heat source areas (in parentheses):

(i) SS1500, SS600, Cu, SS300, CC, Al (5 mm × 5 mm)
(ii) SS1500, Cu, SS600, SS300, Al, CC (3 mm × 3 mm)
(iii) SS1500, Cu, SS600, SS300, Al, CC (2 mm × 2 mm)

The above ranking is the same for heat source areas of 3 mm × 3 mm and 2 mm × 2 mm, but is different for heat source area of 5 mm × 5 mm. Flexible graphite SS1500 is superior to Cu for any of the heat source areas. However, SS600 and Cu are close in performance, such that SS600 is superior to Cu for heat source area of 5 mm × 5 mm but is inferior to Cu for heat source areas of 3 mm × 3 mm and 2 mm × 2 mm. Flexible graphite materials SS1500, SS600, and SS300 are all superior to Al and CC for any of the three heat source areas. CC and Al are close in performance, such that CC is superior to Al for heat source area of 5 mm × 5 mm but inferior for heat source areas of 3 mm × 3 mm and 2 mm × 2 mm.

For thickness of 2 mm, the ranking is shown below in decreasing order of performance for various heat source areas (in parentheses):

(i) SS1500, Cu, SS600, Al, SS300, CC (5 mm × 5 mm)
(ii) Cu, SS1500, Al, SS600, SS300, CC (3 mm × 3 mm)
(iii) Cu, SS1500, Al, SS600, SS300, CC (2 mm × 2 mm)

As in the case of thickness of 1 mm, the ranking is the same for heat source areas of 3 mm × 3 mm and 2 mm × 2 mm, but is different for heat source area of 5 mm × 5 mm. For thickness of 2 mm, Cu is more effective than all the other materials investigated for heat source areas of 3 mm × 3 mm and 2 mm × 2 mm. For heat source areas of 3 mm × 3 mm and 2 mm × 2 mm, both Cu and Al are superior to SS600, SS300, and CC. Hence, the advantage of flexible graphite is greater for the larger heat source area of 5 mm × 5 mm. Comparison of the ranking for thicknesses of 1 mm and 2 mm shows that flexible graphite is more advantageous when the thickness is smaller.

The thermal conductance associated with removal of heat from the heat source is given by $1/RA$, where R is the thermal resistance and A is the heat source area. The lowest value of R for each value of the heat source area is given by Cu as the heat spreader material, as shown in Table I for the case of l = 10 mm and heat spreader thickness of 10 mm. In this case, when the heat source area is 5 mm × 5 mm, the thermal conductance is 3.9×10^4 W/(m^2 K); when the heat source area is 2 mm × 2 mm, the thermal conductance is 6.1×10^4 W/(m^2 K). The conductance increases with decreasing heat source area. In addition, the conductance decreases with increasing l and decreases with decreasing thickness. The highest conductance obtained in this work (for l = 10 mm) is 6.1×10^4 W/(m^2 K). This value is actually an overestimate, because the thermal resistance associated with the interface between the heat source and the heat spreader is neglected in the model. For a 10 K temperature difference between the heat source and the heat spreader, this highest conductance corresponds to heat flux of 6.1×10^5 W/m^2, which is smaller than the value of 1×10^6 W/m^2 required for cooling of light-emitting diodes.

For heat removal from the heat source to the heat sink, with heat flowing only in the direction perpendicular to the thermal interface, the thermal conductance is up to 3×10^5 W/(m^2 K), which is the highest value reported so far.[24,25] This value can be considered the highest thermal conductance that can be reasonably expected for the interface between the heat source and the heat spreader. For a heat source area of 2 mm $\times$ 2 mm, this highest interfacial conductance corresponds to the lowest interfacial thermal resistance (equal to the reciprocal of the conductance divided by the area) of 0.833 K/W. With the lowest interfacial thermal resistance added to the lowest value of 4.08 K/W (Table I) for the total thermal resistance obtained from the above model for the case of heat source area of 2 mm $\times$ 2 mm, the lowest value of the grand total of the thermal resistance is 4.91 K/W. Hence, the highest value of the thermal conductance (equal to the reciprocal of the thermal resistance divided by the area) is 5.1×10^4 W/(m^2 K). This value is lower than the value of 6.1×10^4 W/(m^2 K) obtained above with the interfacial resistance being neglected.

Table III presents the thermal resistance with and without the interfacial thermal resistance included. The difference between these values is small enough for it not to affect the ranking mentioned above.

Compared with metallic heat spreaders, flexible graphite is attractive for its conformability, low coefficient of thermal expansion (valuable for reducing the tendency for thermal fatigue), chemical resistance, and low density. Compared with carbon fiber composite heat spreaders, flexible graphite is attractive for its conformability and chemical resistance. Due to its conformability, which decreases the thermal resistance associated with the interface between the heat spreader and the heat source, flexible graphite is more advantageous than the above results may indicate.

Although isotropic heat spreaders do not have thermal insulation ability in the through-thickness direction, such insulation ability may be rendered by coating the heat spreader with a thermal insulator at surfaces other than the surface that is in contact with the heat source. An example of a thermal insulation material is a nanoporous ceramic thick film.

Table III. Thermal resistance without and with the interfacial thermal resistance included

Material	Thickness (mm)	Thermal Resistance (K/W): Interfacial Resistance Excluded[a]	Thermal Resistance (K/W): Interfacial Resistance Included[b]
FG SS300	1.00	111	112
	2.00	96.2	97.0
	3.00	96.2	97.0
FG SS600	1.00	77.4	78.2
	2.00	77.2	78.0
	3.00	77.2	78.0
FG SS1500	1.00	49.5	50.3
	2.00	49.5	50.3
	3.00	49.5	50.3
CC	1.00	169	170
	2.00	169	170
	3.00	169	170
Al	1.00	113	114
	2.00	57.4	58.2
	3.00	39.2	40.0
Cu	1.00	64.8	65.6
	2.00	32.9	33.7
	3.00	22.4	23.2

The lowest interfacial thermal resistance is 0.833 K/W. $u = w = 2$ mm; $l = 50$ mm
[a]Based on the model
[b]The value based on the model plus 0.833 K/W.

CONCLUSIONS

Anisotropic heat spreaders (flexible graphite and continuous carbon fiber polymer-matrix composite) and isotropic heat spreaders (copper and aluminum) have been evaluated comparatively in this paper in terms of the thermal resistance. The main findings are summarized below:

1. Flexible graphite is superior to continuous carbon fiber polymer-matrix composite as an anisotropic heat spreader material in that it gives lower thermal resistance. The conformability of flexible graphite adds to its attractiveness. However, carbon fiber composite is advantageous in its better through-thickness thermal insulation ability and its smaller critical thickness.
2. Metallic isotropic heat spreaders are more effective than anisotropic heat spreaders in that they give lower thermal resistance, provided that the thickness of the isotropic heat spreaders are large compared with the anisotropic ones. However, isotropic heat spreaders do not have the through-thickness thermal insulation ability.
3. A higher value of the in-plane thermal conductivity enhances the effectiveness of flexible graphite as a heat spreader in that it decreases both the thermal resistance and the critical thickness.
4. As the heat source area decreases, the thermal resistance increases while the critical thickness decreases.
5. For the same heat source area, a greater in-plane dimension of the heat source in the direction perpendicular to the direction of intended heat spreading helps to decrease both the thermal resistance and the critical thickness.

6. The advantage of flexible graphite is greater when the thickness is smaller and when the heat source area is larger.
7. For the same thickness, flexible graphite SS1500 is superior to Cu and SS600 is superior to Al when the thickness is below 2 mm.
8. The highest thermal conductance obtained in this work (for a copper heat spreader of length 10 mm and thickness 10 mm with a heat source area of 2 mm × 2 mm) is 6.1×10^4 W/(m^2 K) when the thermal resistance associated with the interface between the heat source and the heat sink is neglected and is 5.1×10^4 W/(m^2 K) when the interfacial resistance is considered. The conductance increases with decreasing heat source area and with decreasing heat spreader length.

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