Recent Developments in CTE-Matched Composite Thermal Materials

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Introduction

A surprisingly large number of engineered materials are available to the module and system packaging engineer that have been designed for a target coefficient of thermal expansion (CTE, stated both at room temperature and across a specified range of temperatures) and possessing bulk thermal conductivity values useful for device heat dissipation. There are continuing research and development programs for new forms and variations of such materials, intended to meet continuing demands for improvement on a spectrum of requirements. These requirements include higher bulk isothermal conductivity values, lower cost, lower CTE values, reduced density and weight, and, for certain types of applications, a target CTE and highly anisotropic property.

This discussion seeks to identify both existing and common materials (for comparison purposes) and new developments that are being brought to market and/or are in production today. The purpose is to add to the design engineer's tool kit for available materials of these types. In addition, high temperature effects on selected materials are illustrated.

Function and Goals

Designed operating temperatures continue to rise for electronic systems incorporated into an expanding variety of applications, including ground vehicles, space platforms, computing, geothermal exploration and monitoring, and for many power components, diode lasers, RF components, and integrated circuits that are applied in systems that include solar inverters, military systems, new types of weapons, as examples.

Challenging circumstances apply in such cases to those system designs that have, for example, only conduction cooling available or very limited convection. Typical examples are found in missiles and airborne and high-power RF-driven systems, as well as commercial electronic systems such as downhole oil/gas/geothermal exploration tools. For systems that require electronics to operate in harsh environments (including temperature, g-forces, high moisture, vibration and shock, and similar), all of the packaging materials used for the module or system must meet environmental requirements, in addition to normal electrical, thermal, and packaging specifications.

A general statement regarding primary market drivers for thermal management is the continuing effort to miniaturize semiconductors and the associated packaging while at the same time increasing device overall functionality. While heat flux (power dissipated per unit area) for a semiconductor may be possible to maintain at a similar level for a succeeding generation of wafer design, with increased understanding of wafer layout and feature size reduction, the use of increasing functionality in successive designs is a contributor to overall increases in total die heat flux. These are well-documented characteristics that are continuing over decades of semiconductor design and manufacturing, as shown in the number of transistors per unit area and per die, device operating frequency, and trends documenting increasing number and types of functionality.

An important factor that is the primary driver for the selection and implementation of a rigid CTE-matched material as a packaging component is the use of a solid joining material between a substrate and carrier or between a device and substrate. This solid joining material can be a reflowed solder or a sintering paste or film, typically used to provide the highest level of electrical and thermal conductivity between the device and substrate. The solid joint is commonly between a copper (or metallized) surface, the solder or other joining material, and the adjoining surface; each is a rigid material, typically possessing a different CTE value. Heat generation during operation, leading to temperature change, can trigger potentially serious expansion mismatch between materials, leading to cracking or voiding over time and cycling.

In summary, the use of a CTE-matched rigid packaging material is only found where temperature-induced expansion mismatch occurs between rigid materials applied with solid joining materials. If no such thermal expansion mismatch exists, the materials described in this presentation will not be selected, especially given cost differences compared to solid copper. Relatively high bulk thermal conductivity is a highly desirable additional attribute, but is not relevant to this discussion when no serious CTE mismatch exists. An exception to this statement is found in niche applications where very high thermal stability is desired, measured as bulk thermal conductivity divided by the coefficient of thermal expansion. Primary examples of this attribute may be found in certain optical applications, such as highly-specialized mirrors and semiconductor wafer production system platforms.

Applications

Rigid joining systems that include reflowed solders, silver sintering films and pastes, other sintering pastes, and similar, are typically found where primary objectives are minimizing electrical resistance, thermal resistance, or both. Where heat dissipation is significant, the rigid joint therefore is typically subjected to careful examination for relative CTE values between the joined materials. Another application area is where elimination of packaging materials is required to allow the most efficient heat transfer, by eliminating thermal resistance of individual materials and through interfaces between materials. The use of high thermal conductivity and well-performing electrical interconnects, such as are found with soldered joints, is the primary path to eliminate polymeric materials in the material stack for the purpose of maximizing heat transfer efficiency.

Solder attachment of a high-power RF device directly to a thermal plane within a circuit carrier is a primary example of how efficient heat transfer can be achieved with direct attach, specifically for those systems which must operate with natural convection and conduction through the PCB or assembly, and this approach will be discussed further, below.

Role of Heat Flux versus Total Heat Dissipation

A market driver that is focusing the interest on development of high thermal conductivity materials and those with both high thermal conductivity and specific CTE values is the impact of rising heat fluxes found in many critical market segments. Heat flux (amount of power to be dissipated per unit area) is the critical factor. Note that it is possible for total power (heat) dissipated from a die or component to rise without an increase in heat flux; this is accomplished by introduction of mitigating factors in the die or package design. One solution would be to increase the die area proportionately; however, this is frequently heavily constrained by other factors such as module design, associated internal component placement, and limitations on semiconductor die cost increases.

Another solution for high performance semiconductors is the introduction of a reflowed solder as a metallic TIM1 (the thermal interface material placed between the backside of a processor or ASIC die within a module and the underside of the lid that provides mechanical protection for the die). The very significant gain in *effective* thermal conductivity achieved with this transition to a metallic TIM (e.g., with an effective thermal conductivity of 20-40W/mK or greater) compared to the previous polymeric TIM1 (with, as an example, an effective thermal conductivity of 3-5W/mK) will allow an increase in total power dissipated from the die. The large improvement in effective conductivity reduces thermal resistance attributable to the internal package layers and allows a more efficient transfer of heat to the copper lid, which in total can allow more efficient transfer through the external heat sink or liquid cooling assembly. The net result may be an increase in die heat flux and total power dissipated, with an improvement in efficiency of the complete thermal stack to remove the additional heat load generated.

Increases in heat flux can be highly detrimental, increasing stress due to temperature change on the package materials. Systems with high rates of power cycling (such as may be found in many power semiconductor systems during operation) and in radar and other pulsed RF systems are also subject to mechanical stresses due to temperature. Continuing reductions in die size and/or increased power dissipation that result in higher heat flux exacerbate this potential failure mechanism at the die-to-substrate level. This can be worsened in other harsh environment (i.e., vibration, shock, rotation, high moisture) and/or high operating temperature conditions.

Impact of Temperature

CTE-matched materials are subject to variation in bulk thermal conductivity and CTE value in low and high temperature operation. The impact of high temperature can be more severe for certain types of materials; engineered composites as an example may show greater thermal conductivity variation with temperature than will an element such as silver, copper, or diamond. When designing electronic systems for high temperature operation, the design engineer must evaluate performance characteristics over the expected use temperature range.

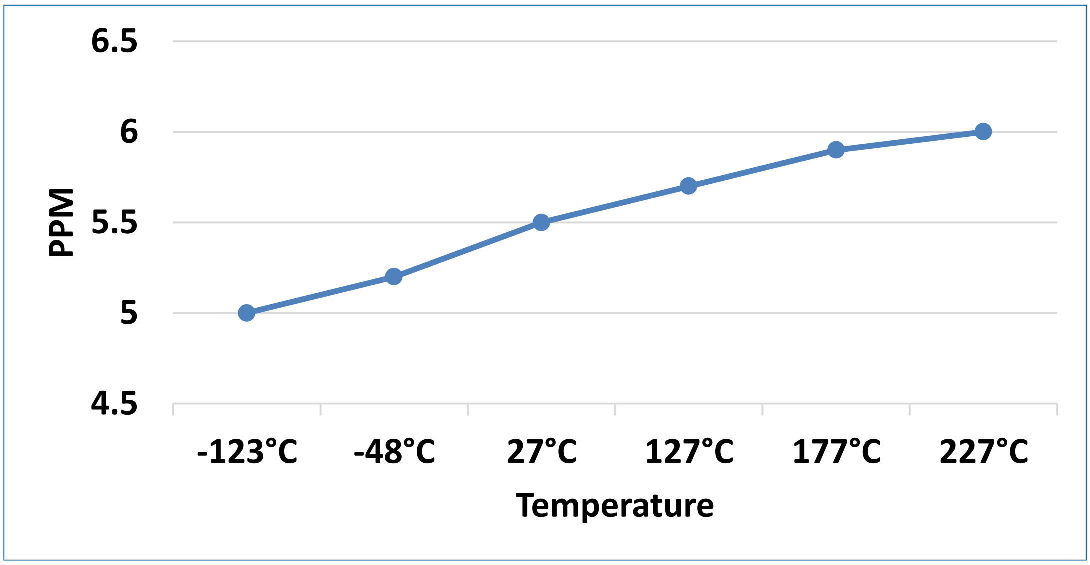

Figure 1. Coefficient of Thermal Expansion versus Temperature. Vendor data: Silver-diamond Composite. [1]

Performance characteristics of materials can be affected by low temperature operation; although low temperature is not the focus of this conference presentation, evaluation of heat spreading materials for low temperature operation may be required for applications in space, airborne systems, ground vehicles, and certain types of sensors and LED devices (such as marine warning systems). Systems designed for cryogenic operation are at the low temperature extreme; embrittlement and significant changes in thermal conductivity occur in operation for many but not all materials**.**

Data from another manufacturer illustrates a second example of the impact of temperature on thermal composites; this is shown in Figure 2, below, for thermal conductivity values (-50°C to 350°C)..

[Note: This graph purports to show vendor test data for bulk thermal conductivity versus temperature for a commercialized silver-diamond composite. (The graph is included to illustrate the point of the impact of temperature on material thermal conductivity at each test point. The specific data points illustrated are subject to interpretation, depending on exactly how a sensor was placed and the testing performed.)]

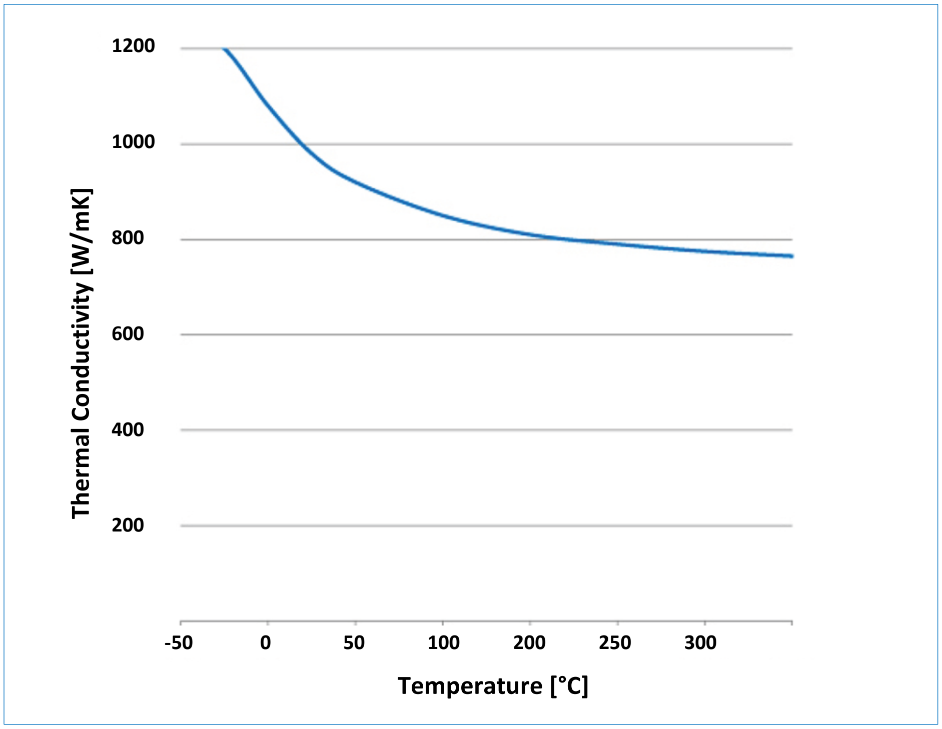

Figure 2. Thermal Conductivity versus Temperature. Vendor data: Silver-diamond composite. [2]

The same vendor also publishes a statement for thermal conductivity following heat treatment at 800°C.. A graph showing bake testing to 150°C in a liquid bath (full test description not given) illustrates an initial four per cent decline in thermal conductivity with subsequent stable values through one thousand cycles. This type of data, when made available including test methodology by a manufacturer, can be useful during the evaluation and selection process.

Material Categories

CTE-matched semiconductor packaging materials as a broad category include many well-known, well-characterized legacy materials. Primary examples are CuW (in actuality, typically W-Cu), Cu-Mo (Mo-Cu) in many versions, Kovar, and many different closely related materials identified by terms such as CMC (Cu-Mo-Cu), Super CMC, and similar. These are metal laminates and alloys, primary packaging materials for RF components. As a general description, these are typically dense materials that are primarily copper-based, offer selectable CTE values and thermal conductivity values (based on the ratio of constituents selected), and generally may be machined and can be brazed (with notable exceptions) to add package sidewalls and other features. Examples of material properties of these types are given below; a relative statement of CTE and conductivity is that these laminates and composites fall generally into the 6-7ppm/°C CTE range and 160-220W/mK range for bulk thermal conductivity. Depending on the specific type selected, these can be generally isothermal materials; some laminates are anisotropic, so care must be taken to select a specific variation for a given task and combination of requirements.

The continuing development of semiconductors with higher heat fluxes has raised requirement for bulk thermal conductivity (ideally, isotropic or near-isotropic) above the moderate thermal conductivity value range for the CuW, CuMo, and similar laminates.

Discussion of CTE-matched composites must also include comparisons with other material categories that also offer a specific CTE value for use as a semiconductor packaging material. Primary examples are metals and metal alloys, diamond, and graphite films, sheets, and plates.

There are also combinations of materials such as CPC™, a CuW composite with copper metal applied to both surfaces, useful for enhancing thermal conductivity and surface machining and metallization. [3, 4] Another example is the use of composite casting methods such as are used for production of AlSiC components, with in-situ casting of diamond pins, pyrolytic graphite, and other materials to enhance heat transfer in specific directions (i.e., through-plane, in-plane), as has been described elsewhere in the literature. Another variant is termed as SuperCMC® manufactured with multiple layers of molybdenum foil (to 10% by volume percentage) laminated between copper layers. [3, 5] This material achieves a CTE value reported as 9.5ppm/°C (at R.T. – 800°C) and bulk thermal conductivity reported of approximately 360W/mK, although current commercial availability is not known. This laminate structure has been produced with up to eight layers; however, five is more typical. As with similar laminates, varying the number of Mo foil layers and copper layers (and therefore, the volume percentage of Mo, up to 40%) alters the final CTE and conductivity values for a specific structure. These types of materials are targeted primarily for applications for RF flanges, for example, achieving improved performance values as compared to the legacy CuMo baseplates.

All such combination material concepts increase manufacturing cost, a trade-off between thermal performance achieved and acceptable tooling and final component cost.

Manufacturing Methods

Composite materials are manufactured by commercial vendors utilizing different manufacturing methods. Evaluation of characteristics and capabilities offered by different manufacturing processes within a given composite material category is important. The manufacturing process used by a vendor can impact not only CTE value for the resulting composite, but also the relative isotropicity and, very importantly, the types of features that can be applied to a component design and the resulting cost trade-offs between tooling cost (if any), process cost, and machining and other post-processing costs. Within the confines of a broad review of new material developments such as this, it is not possible to include extended detail on each material category, but identifying the important factors for material evaluation for a design project is important and can be undertaken here.

Common high volume materials such as AlSiC are produced in near-net-shape casting, ingot casting and machining, and sheet casting processes. The term "near-net-shape" is applied to a precision two-step casting process that has very important advantages for in-situ casting of design features, "aluminium-rich" regions as required, and an aluminum "skin" of pre-determined thickness on all surfaces of the as-cast component when removed from the final mold; the only machining step required is removal of the casting sprue in one casting port location. This two-step casting process also allows for the insertion of other materials, such as an in-plane layer of pyrolytic graphite, within the final cast component. Designed-in "aluminium-rich" zones are a key feature to minimize machining time and cost for through-holes and other physical features, without penetrating into the AlSiC composite core.

Variation of the constituent percentages (silicon carbide powder and aluminium metal) allows production of composites with standard CTE values of approximately 8.0ppm/°C (37% Al356/63% silicon carbide by volume) and 11.7ppm/°C (63% Al356/37% silicon carbide by volume). Bulk thermal conductivity value varies accordingly with constituent percentages: 190W/mK (63% SiC), 170WmK (37% SiC), at room temperature. [6]

Sheet casting of AlSiC composites, by comparison, yields a CTE value of 11.9ppm/°C and bulk thermal conductivity value of 155W/mK (45% SiC by volume). Sheet casting by the nature of the process does not allow for features such as pedestals, sidewalls, wells, or similar; component production is generally limited to flat baseplates and lids.

Manufacturing of AlSiC and diamond composites in ingot form, requiring machining of all surfaces to create component shapes and features, is undesirable given the specialized cutting tools required for aggressive composites. Machining of certain other composites, such as the common aluminum-graphite and coppergraphites composites, can be accomplished easily and at relatively high speed, not requiring diamond cutting tools, which is highly advantageous for both prototyping and volume production.

An important note for electronic package component manufacturing processes and requirements for aluminum metal matrix composites (such as AlSiC and Si-Al) is that brazing temperatures are not compatible with such composites for addition of package sidewalls and seals and related components. AlSiC, Si-Al, and other aluminium composites must not be designed into applications where operating temperatures will approach the melting temperature of aluminium metal.

Silver-diamond and copper-diamond composites will withstand such brazing temperatures, although these are considerably higher cost solutions. Copper-graphite composites will withstand these temperatures and are available at much lower cost.

Legacy electronic package component materials such as CuW, CuMo, and Kovar, with low bulk thermal conductivity values, are frequently selected for replacement with net-shape cast components such as AlSiC. An important design consideration is that, in order to effect the transition from a machined CuW package component to a net-shape cast AlSiC component, design modification will be required to adapt sidewall, step, and internal pedestal design to accommodate minimum angle requirements for the casting process (as compared to the existing machining specifications).

Surface Roughness, Flatness, and Machining Qualities

A distinguishing feature of certain of these CTE-matched materials may be the machining characteristics of different types. Machining characteristics are important given the need to specify surface flatness and roughness for next-level assembly *and* to determine whether or not a given material type will accept features that are either to be drilled, tapped, cast in place, or brazed or otherwise included in the finished component.

Certain composites are difficult and costly to machine, as mentioned, requiring diamond tools and machining time; this is important for volume production throughput and cost. For composites of this type, selecting a vendor with a near-net-shape casting process will typically yield the lowest production cost and dimensionally-accurate features. More importantly, certain types of composite *casting* manufacturing processes are designed purposefully to yield an external so-called "skin" on all surfaces of the finished component. The most practical and cost-effective processes yield this skin of a given constituent metal during the manufacturing process to provide the most uniform appearance and surface finish for post-processing metallizations. This is important as metallization for a significant percentage of designs globally is a critical requirement for many package components across a wide range of market segments.

Bulk Thermal Conductivity Value

Considerable market demand exists for package materials with specified CTE value combined with even higher bulk thermal conductivity value. This statement does not suggest that this requirement eclipses the importance of the target CTE value; if only a high bulk thermal conductivity value (exceeding 700W/mK) is necessary, the package design engineer will turn to a CVD diamond component offering conductivity between 900 and 2200W/mK (depending on the grade and type of synthetic diamond selected), if cost is not a principal driver.

(An additional note applies to those semiconductor package requirements requiring an exceptionally low CTE value, such as 2ppm/C. For such applications, a CVD diamond component may be the only practical selection.)

CTE-matched composites with higher bulk thermal conductivity are the subject of numerous industry development programs. The tables below illustrate recent commercialized materials and published thermal performance values. The latest Ag-diamond composite introduction in 2022 is shown as having tested CTE values in the range 5-6ppm/°C and bulk thermal conductivity of 690-720W/mK. [1.]

Selection Criteria

In general industry usage, the selection of a packaging material with a targeted CTE value will also include evaluation of the bulk thermal conductivity value of candidate materials. Given that the primary selection criterion is the targeted CTE value, certain additional material attributes that are considered (in relative order of importance) are shown in Table 3, below. Please note that the relative prioritization will change for a specific design project based on individual project requirements; this is intended as a broad generalization only.

Selection Criteria: CTE-Matched Rigid Packaging Materials Generalized Prioritization of Materials Characteristics for Common Applications
Required coefficient of thermal expansion (CTE) value
Feature capability and process (net-shape casting, machining, other)
Bulk thermal conductivity value (including relative isotropicity)
Metallization capability
Surface roughness, finish, flatness tolerances
Production unit cost
Tooling cost (If any)
Temperature range
Environmental tolerance (moisture, embrittlement, other)

Table 1. Generalized selection prioritization, CTE-matched rigid packaging materials.

Manufacturers of CTE-matched packaging materials typically offer different types of materials and multiple products of varying CTE, conductivity, density, and configurations. Products from one vendor are shown in Table 2.

Example: Vendor Data, Legacy Materials
CTE-Matched Semiconductor Packaging Material Choices
(Selected Materials; All CTE Values @ Room Temperature)

Material	**Material Description**	**Bulk Thermal Conductivity (W/mK)**	**CTE (ppm/ °C)**	**Specific Resistance (ohm.m)**	**Edge Quality**	**Roughness (Ra)**	**Flatness**
A	Diamond/Cu	600	4.0	3.5×10^{-4}	30µm (Chipping)	<0.1µm	<20µm/10mm
B	Diamond/Cu	550	6.0	2.6×10^{-4}	30µm (Chipping)	<0.2µm	<20µm/10mm
C	Cu-W	180	6.5	5.3×10^{-8}	15µm (Round)	<0.2µm	<10µm/10mm
D	Cu-W	200	8.3	4.0×10^{-8}	15µm (Round)	<0.2µm	<10µm/10mm
E	CVD Diamond	1000	2.3	5.0×10^{-7}	30µm (Chipping)	<0.1µm	<30µm/10mm

Note: CTE, thermal conductivity presumed to be measured at room temperature; thermal conductivity presumed to be bulk (not stated). Source: Manufacturer data sheets.

Table 2. CTE-matched semiconductor packaging materials: An example of vendor data for legacy materials. [4]

A cross-section of current engineered thermal materials across the electronics packaging industry is shown below, illustrating traditional and most recent developments from a number of vendors.

CTE-Matched Semiconductor Packaging Material Choices
(Selected Materials; All CTE Values @ Room Temperature)

Material Type	Material Description *© DS&A LLC 2022*	CTE [Typ., ppm/°C] (R.T.)	Bulk Thermal Conductivity (Typ., W/mK)
Diamond	Diamond, hexagonal MBD6	**1.0 – 2.2**	1,000 – 1,200
Diamond	Monocrystalline	**2.3**	2,000
SiC	Silicon carbide, monocrystalline	**3.7**	425
SiC	Silicon carbide, polycrystalline	**3.8**	300
Al-graphite	Al/graphite composite, anisotropic	**4**	230
CuD	Copper diamond composite	**4.0 – 6.0**	550- 600
SiC	Silicon carbide, monocrystalline	**4.7**	370
AgD	Silver diamond composite w/Ag skin	**5.6**	690
AgD	Silver diamond composite w/Ag skin	**5.8 – 6.4**	550-720
W-Cu	90W10Cu composite	**6.2**	201
Si-Al	Si/aluminum	**6.5**	125
Mo-Gr	Molybdenum-Titanium-Graphite	**6.5***	650 (X-Y) / 45 (Z)
CuD	Cu/diamond composite	**6.7**	470
W-Mo	85Mo15Cu	**6.9**	154
Cu-graphite	Cu/graphite composite, near-isotropic	**7**	287 (X-Y) / 225 (Z)
MgSiC	Magnesium-silicon carbide	**7**	230
CuD	Copper diamond composite w/Cu skin	**7**	500
AlD	Al/diamond composite	**7.0 – 9.0**	440-530
AlSiC	AlSiC w/Al skin	**8**	190
SuperCMC®	Cu/Mo (multiple layers)	**9.5**	370
CuD	Cu/diamond	**11-12**	400
AlSiC	AlSiC composite, isotropic	**11.7**	170
CuD	Cu/40%D composite	**12**	475
Cu (Reference)		**17**	360

*Note: * Volumetric percentage. Sources: Respective manufacturer data sheets.*

Table 3. CTE-Matched Semiconductor Packaging Material Choices: Selected materials and properties.

Anisotropic Material Developments

Isotropic or near-isotropic thermal conductivity typically provides the simplest and most common design conception, before a selection is made of an identified material. It should be noted that there are also certain materials which offer highly anisotropic characteristics that may be very desirable for very narrowly-defined types of applications.

An example of a rigid and highly anisotropic CTE-matched composite that was designed to offer excellent in-plane thermal conductivity with limited through-plane heat transfer is a molybdenum-titanium-graphite material, developed within the European Union to meet specifications for components for CERN. Material properties and test methods are illustrated in Table 5.

Anisotropic Rigid CTE-Matched Composite: Mo-Ti-Gr (Selected Material, Commercialized)					
Parameter	**Orientation**		**Units**	Test Method	Notes
	X-Y	**Z**			
Density	2.57		g/cm^3	--	--
Flexural Strength	102.1	16.9	Mpa	ASTM D 7972	3-point bending
Flexural strain to rupture	2580	5900	µm/m	ASTM D 7972	3-point bending
Young's Modulus	69.7	5.5	Gpa	ASTM E 1876	Impulse excitation technique
Thermal conductivity @20°C	650	45	W/m-K	Inferred from equation: λ= ρ • Cp • a	
Thermal conductivity @ 300°C	310	23	W/m-K	Inferred from equation: λ= ρ • Cp • a	
Thermal diffusivity @ 20°C (a)	390	27	mm^2/s	ASTM E 1461	Laser flash
Specific heat	0.65		J/gK		Laser flash
CTE (20-1000°C)	2.4	14.7	10^{-6} K^{-1}	ASTM E 228	Dilatometry
CTE average (20-1000°C)	6.5		10^{-6} K^{-1}	(2 • CTE_IP + CTE_TP)/3	
Electrical conductivity	0.8		MS/m	ASTM E 1004	Electromagnetic method (Sigmascope SMP 350)
Dimensional stability	0	0.1	%	Dilatometry	

Table 5. CTE-matched semiconductor packaging material development: Anisotropic rigid material properties. [7.]

The highest unit volumes in production usage of more traditional highly anisotropic thermal materials are the many graphite films and sheets in production for mobile and handheld devices such as smart phones, notebook PCs, subnotebooks, and tablets. Within mobile devices of these general types, a highly anisotropic material is critically important, to provide in-plane heat spreading of heat dissipated from specific components without transferring the same heat load to the glass keyboard surface or to the backside of the system case. Many of these types of graphite films and sheets are now in production from multiple manufacturers globally as this concept has proven to be very successful, easily modelled during design, and manufactured to provide high-volume, low cost heat spreaders with very low CTE values in a bewildering array of shapes and forms. In addition, these films and sheets may be specified with a range of pressure-sensitive adhesives and polyimide films to provide simple, rapid adhesion for high volume assembly and electrical isolation, as needed. These types of graphite film developments were brought to high-volume manufacturing in the last seven years, reflecting the increased functionality and power dissipation of many types of ICs, RF devices, and power devices in a multitude of packaging configurations in extremely small system volumes.

These same material concepts are therefore now available for high temperature applications in more specialized industry segments, where similar types of components (ICs, RF, power) with increasing heat fluxes can be applied in significantly higher-temperature environments. Graphite materials of this type are typically able to withstand operating temperatures of 400°C, with a number of materials tested to 700°C and in some circumstances to 2,000°C. [The use of graphite blocks and carriers for non-electronic operations at extremely high temperatures is well known, such as in nuclear power generation, steel making, and for metalworking ovens, as examples.]

Graphite has a very low CTE value that is typically stated as very similar to silicon, in the range of 2-4ppm°C. Engineered graphite films, sheets, and blocks may have CTE values that are slightly negative in the in-plane orientation (e.g., -0.4ppm°C) and relatively high in the through-plane orientation (to as high as 23-27ppm°C). [8.]

Similar applications are used in space platforms and on an increasing basis, leading to new material developments to meet differentiated requirements. Novel adaptations of graphite film and sheet materials, highly anisotropic, utilize manufacturing techniques developed to stack such films, rotating the plane to create block (or “brick”) forms that utilize the very high in-plane (X-Y) thermal conductivity of the planar films. This concept is therefore referred to as offering very high “X-Z” thermal conductivity. These “brick” and flexible “strap” material concepts have been subjected to cyclical flexing and bending tests as well as outgassing test per ASTM E 595; meeting JAXA and NASA outgassing requirements. Careful design can utilize these material concepts (recognizing the relatively high rate of thermal expansion in one plane) to advantage for system design. [9.]

The same manufacturer that has developed these “brick” forms of X-Z graphite for satellite applications, exposed to very low and very high ambient temperatures in space during operation, has also developed aluminized polyimide films and ITO-coated polyimide films that are applied for certain of these satellite applications. Certain of these materials are limited in operating temperature capability, depending on the specific combination of graphite forms, adhesives, and polyimides. Vendor test data demonstrates that the temperature dependence of the material specific heat is similar to that found with other graphite materials. Thermal diffusivity (in-plane and out of plane) was measured over a temperature range from 100K to 300K; a laser heating method was used. Space applications include thermal control, heat transfer via the flexible “thermal straps” between components and radiation surfaces, and similar. Advantages include the relatively high in-plane thermal conductivity, very low CTE, very low density, as well as the excellent flexibility and durability of the thermal straps and films. [10.]

CTE-matched PCB Thermal Planes

Development of lightweight, CTE-matching thermal plane composites with high relative bulk thermal conductivity for use within complex multilayer PCBs to mount and remove heat from high-heat flux GaN and SiC RF power devices was the target of a multiyear materials development program managed by the US Navy. Intended applications focused on radar system multilayer PCBs in missile systems, where only conductive cooling was available and no forced convection or liquid cooling systems could be implemented. [11.]

While this concept has been the source of extensive university and industry development programs over more than two decades, satisfactory material solutions were required to meet industry-standard IPC PCB manufacturing processes, equipment design, and handling and drilling and similar production steps. [12.]

Selection of a copper-graphite composite followed extensive testing of candidate material concepts. The primary barrier to implementation was the requirement to manufacture large sheets of the candidate Cu-graphite composite in thicknesses of 40micron and 20micron. The necessary manufacturing processes were ultimately developed and this high-performance, low-CTE, PCB composite thermal ground plane material concept is now in volume production for the targeted missile system GaN RF PCBs for several programs, as discussed elsewhere in the literature. [13.] This development and manufacturing program illustrates the continuing developments of novel composite material solutions to high heat flux, low stress electronics systems requirements.

Summary

Significant research and development effort globally continues to produce improvements in thermal and packaging material sets that meet lower and more specialized CTE targets and higher bulk thermal conductivity values, reflecting more specialized requirements across industry segments. While the primary selection criteria for these material types is based on matching a very specific CTE requirement, continual increases in heat flux and total power dissipation for IC, RF, and power semiconductors also requires new materials with higher bulk thermal conductivity characteristics. Temperature is a determinant of both CTE and bulk thermal conductivity for many materials and designing for in high temperature conditions must therefore require evaluation of test data for packaging and thermal materials under exacting conditions.

For extreme temperature environments, certain material sets capable of operation in ambient temperatures above 200°C, especially graphite- and diamond-based material types, are showing promise. Graphite-based metal matrix composite such as Cu-graphite are lower cost than diamond-based composites. Cu-graphite is now used as a solution for high performance missile radar system applications for GaN RF devices; graphite sheet and film materials are utilized in space and airborne high and low temperature applications and in high unit volume mobile and handheld devices. CVD diamond and diamond-based composites are highly specialized CTE-matched materials that serve different industry application types. Developments in diamond composite materials add new materials to the packaging engineer's tool kit.

These many different types of materials offer a range of different CTE values, bulk thermal conductivity values, manufacturing and feature capabilities, and cost. As silicon carbide and gallium nitride semiconductors allow higher device operating temperatures, packaging and thermal materials must be identified which also function at higher temperatures.

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