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ABSTRACT

Novel techniques are described for fabricating a new thermal management structure (TMS), in the form of rigid low-mass structures with extremely high in-plane thermal conductivity. The core materials can be forms of thermally anisotropically conducting pyrolytic graphite that are directly encapsulated in a new thin-layering process.

The structures can be used in a large variety of applications, including:

(a) Efficient interfacing with ceramic materials and metals to provide new thermal management technologies.

(b) Providing the source for a new hybrid technology where low-mass custom-designed multilayer thin-film circuits can be directly processed onto such structures. Alternatively, having been pre-fabricated on an independent substrate, hybrids can be efficiently interfaced to such thermal management structures.

(c) Providing electrical connectivity between both sides of a TMS board through a new feedthrough technology that allows the fabrication of both single-sided and double-sided hybrids.

These thermal management techniques and their applications are the subject of an International Patent Application Number PCT/GB99/02180, filed in the names of the European Organization for Nuclear Research and Queen Mary & Westfield College, London.

1 INTRODUCTION

Electronic and electrical devices are all sources of heat and their stable operation under controlled temperatures, particularly within complex high density systems, needs the best possible thermal management. Increasing miniaturisation of individual semiconductor components, higher operating speeds and improved packaging density within electronic system design lead to the requirement of improved thermal management schemes wherever possible. Typically the thermal management devices are adjacent to, and in contact with, the electronics or their mother-board, and should be designed to combine the highest possible thermal conductivity with efficient connectivity and appropriate mechanical strength. It is particularly beneficial for such requirements to be achieved with minimium-mass structures at an acceptable cost. The new thermal management structure (TMS) [1] described here achieves these goals, and has a variety of ancilliary applications, also described, that solve specific needs in related areas of electrical circuit boards, heat-transfer interfacing and novel hybrid structures.

Some existing devices encapsulate high thermal conductivity materials into composite structures [2] in order to provide thermal sinks. However the fabrication process of such devices often results in a significant reduction in the effective thermal conductivity of the core material as well as an increase in mass and bulk. The best thermal systems available at present have in-plane conductivities that are around 1000 W/mK.

Thermal management systems are often also used for supporting hybrid electronic circuits. Beryllia is an example of a substrate used in such applications as a heat sink, and has a thermal conductivity around 280 W/mK at room temperature. Dielectric layers with, for example, gold contacts can be processed onto the beryllia to make electrical connection to surface-mounted devices. However, beryllia is a hazardous and toxic material and is carcinogenic. It is difficult to process and the dielectric layers tend to be thick, and hence contribute to overall bulky structures, while the use of gold as a contact material can be expensive.

In contrast, the new TMS presented here is non-toxic and safe to handle, and provides high thermal conductivity, with a structure that has low mass, volume and thickness.

A wide range of pyrolytic graphite materials can be used as a core in producing these new structures. The material has been available for some time, in the form of plates which have excellent in-plane thermal conductivities. At room temperature these can typically be in the region of 300 to 400 W/mK for high conductivity pyrolytic graphites (HCPG) and from 1500 to 1900 W/mK for very high conductivity pyrolytic graphites (VHCPG) that are thermally enhanced. Graphite material with both higher and intermediate values of thermal conductivity is also available. HCPG substrates have in-plane thermal conductivity temperature coefficients close to zero, while VHCPG substrates have a negative temperature coeffient of around -0.4%/K, and hence increase their thermal conductivity by around 70 W/mK for every 10°C reduction in operating environment temperature. Both forms typically have transverse thermal conductivities in the region of 2 to 20 W/mK. The HCPG materials are machinable with care, while those of VHCPG are friable, of low bending modulus and are easily fractured and delaminated.

In current thermal management products some forms of these graphite substrates are encapsulated either through enclosure techniques or by fibre adherence. The former improves mechanical modulus properties at the expense of large increases in enclosed volume and mass, and hence drops in thermal conductivity of typically 40%. The latter again results in significant reduction in thermal performance, with even optimised devices suffering up to 50% reduction of the initial core conductivity.

The structures described here can all be fabricated using the wide range of pyrolytic graphites that have been specified above. The central feature of the new thermal management structures (TMS) is the process of encapsulation, which achieves significant increases in mechanical rigidity of the substrates through direct coatings of only a few microns or few tens of microns in thickness of polyimide or other selected polymers that include resins of epoxy, acrylic, polyurethane or polyester materials. The high intrinsic in-plane thermal conductivity is essentially preserved in the final TMS through a combination of excellent surface adherence and minimal decrease in volume fraction for the core plate, for all applications with substrate thickness of 350μm or larger.

Examples of all the new structures described in this paper have been successfully fabricated as prototypes within the development phase of a future high energy physics experiment at CERN, and details of their specific applications and instrumentation performance will be reported elsewhere.

2 THE ENCAPSULATION OF GRAPHITE PLATES

The key ingredient for producing the devices described here comes from the new technique in which the high or very high thermal conductivity pyrolytic graphite plates are incorporated into extremely thin, low-mass structures by direct encapsulation. The encapsulating materials listed in Section 1 have properties that promote adhesion to the graphite surface and allow the encapsulation to be achieved with a negligible increase in volume and minimal decrease of effective thermal conductivity. However, the resulting structures benefit from increased tensile strength and much improved surface properties. The encapsulated devices can be of any geometry constructed from planar elements. They can include individual holes, or matrix structures of fine holes that can be implemented where the overall mechanical integrity needs to be optimised. Hence devices can be custom-designed for use in each particular application.

2.1 The Encapsulation with Polyimide

The technique is generally applicable to graphite plates greater than 100μm in thickness, with the polyimide applied in layers typically 8μm thick, and built up by multiple applications to form an integral polyimide encapsulation of the required thickness. The plates can be profiled to any geometry before coating and all edges, both inner and outer can be uniformly covered. The resulting boards can maintain an in-plane thermal conductivity very close to that of the initial graphite plate. Substrates with surface flatness in the region of $\pm 5\mu$m have been prepared from plates with typical dimensions of 100mm$\times$100mm, provided by Advanced Ceramics Corporation [2] and Atomgraph [3], and this has be maintained after encapsulation. Depending on the specific value of the initial substrate thermal conductivity, the thermal conductivities of TMS boards are typically 350 W/mK for HCPG-type and 1700–1800 W/mk for VHCPG-type substrates at room temperature, and the VHCPG TMS boards have a similar negative temperature coefficient to that of the uncoated core.

The details of the encapsulation processes are protected by an International Patent Application [1]. However, it should be noted that the preparation of the graphite plate for encapsulation can require heating, polishing and surface cleaning prior to applying the initial polyimide layer.

Any number of layers can then subsequently be added until the required thickness of polyimide is achieved. The steps are carried out in a way that preserves the flatness of the core material, and can also result in all inner and outer edges being covered in a controlled manner. The process is completed by a heat-curing sequence before final cooling.

2.2 The Encapsulation with Other Resins

The general procedures for preparing the substrate prior to encapsulation are the same as given in Section 2.1. However, the techniques for application with the resins epoxy, acrylic, polyurethane or polyester can be different. There are also alternative procedures for the subsequent processing. Combinations of processing steps can be selected to optimse the properties of each particular thermal management structure depending upon its geometry, and the flatness and coating specifications that are required.

It is possible to apply the resins to each surface in a single layer of the required thickness, or in multiple layers if necessary. The encapsulation can be as thin as a few microns, or alternatively many tens of microns or thicker. By combining as appropriate, the use of high pressure and low vacuum, dependent upon the temperature of the curing process, it is possible to achieve surface encapsulations with micron-level tolerances in both thickness and flatness. The resulting TMS has all inner and outer surfaces covered and has the same wide variety of potential applications as in the case with polyimide encapsulation.

3 FEED-THROUGH ELECTRICAL INTERCONNECTIONS

The TMS can also be made into new low-mass printed circuit boards with extremely high thermal conductivities, and also provide the option of electrical interconnections between the upper and lower faces, using an adaptation of the above polyimide encapsulation process. This can provide significant improvements in the case of structures that currently incorporate thermal management devices sandwiched between layers of printed circuit boards, with the need for electrical interconnections between opposite sides.

3.1 Producing the Electrical Feed-throughs

The pattern of required interconnections can be custom-designed to suit any planar geometry. The graphite plate is then drilled with the hole pattern required for interconnections. The holes should each be at least $200\mu m$ larger than their required final diameter, which would typically itself be at least $100\mu m$. The plate is then processed for complete encapsulation in polyimide, or in some applications solid components may be added to the polyimide to improve the uniformity of the hole encapsulation, prior to covering the surface of the substrate. In the subsequent operation the original pattern of holes is re-drilled, now with their desired final diameters. This leaves the internal surface of the holes electrically insulated from the electrically conducting graphite substrate core. Thin-film layer processing, with custom-designed tracking, typically with aluminium, can then be applied to both sides of the TMS, and as part of the process the necessary inter-surface electrical connections can be made.

4 Interfaced Thermal Management Structures

In the process of producing the TMS other planar forms, of for example polyimide, alumina, beryllia, beryllium or aluminium nitride can be directly fused into the coated surface. Such fused items will subsequently be referred to as "facing structures". In addition the TMS boards, either as bare structures or with electrical surface tracking or electrical feed-through connectivity, can be further interfaced to other assemblies which themselves may be heat sources, and which have substrate materials such as polyimide various metals or ceramics. The overall system can then act as a low-mass heat transfer link with high thermal efficiency.

4.1 Producing the TMS Interface

Two methods have been developed: the first is more applicable to balanced stuctures with overall top-bottom symmetrical geometry, while the second allows excellent interfacing to be achieved when the components of the top and bottom surfaces are different in shape or material.

4.1.1 Method 1

The facing structure is first coated with a liquid epoxy glue, which is heated to a temperature producing partial polymerisation. It is then positioned on the TMS and a low vacuum compression is carried out at a higher temperature to produce a bubble-free interface with a thickness that can be only a few microns if desired. The TMS and the facing structures can be relatively positioned to high spatial precision and if necessary rigid facings can be positioned to precisions of around 20 to 30μm using custom-designed and prepared template jigs.

4.1.2 Method 2

The facing structure is prepared as in Method 1 with a coating of a liquid epoxy, and similarly positioned with respect to the TMS. In this case, however, the bubble-free interface is produced by allowing the liquid epoxy to polymerise under compression and low vacuum at room temperature. For composite structures that are to be used at, or around, room temperature, this procedure minimises the internal mechanical stresses without the need for compensating layers of encapsulation that may be required in structures processed at the higher temperatures of Method 1. The process hence allows devices to have minimal mass and thickness.

Composite structures produced by both methods have been temperature-cycled over the range +100°C to -25°C with no observable changes to their mechanical structure. Such assemblies have also been subjected to very high doses of charged particle irradiation up to 3×10^{14} p.cm^{-2} 24 GeV/c protons, again with no observed changes.

5 A NEW HYBRID TECHNOLOGY

The concept of the TMS described here has been combined with techniques of thin-film multilayer circuitry to produce a new hybrid technology in which HCPG or VHCPG substrates have been directly interfaced to low mass, custom-designed thin-film circuits.

The thin-film multilayer circuits can be fabricated directly onto the graphite substrates using alternating layers of vacuum deposited aluminium and polyimide or epoxy resin. The thin-film layers of aluminium are typically 5μm thick, and using initial graphite substrates with flatness tolerances also of a few microns it is possible to achieve micron-level resolution in the lithography of the deposited aluminium. This means that fine (micron scale) features can be readily defined on the hybrid surface, and in the thin-film metal layers, so as to result in new connectivity applications. Examples of such are fan-in/fan-out structures integrated into hybrids to interface custom-designed ASIC chips to silicon microstrip detectors. Centre-to-centre spacings of wire-bond pads of less than 50μm have been achieved in single and double layer processes for hybrids prototyped for a future high energy physics experiment. Previously such features were conventionally made using metal structures on thin glass or ceramic substrates, and hence resulted in the device needing additional pieces, with more material, complexity and increased cost.

During the multilayering sequence the polyimide(or other resin) can be applied over the custom-designed aluminium circuit layers, with the same techniques as used for coating the TMS described in Section 2. This involves layers typically around 8μm thick, but down to a few microns thickness if necessary. Such processing can be done on both sides of the board to produce, if required, a double-sided electrical device with high intrinsic thermal management capability, and feed-through connectivity can be introduced through the techniques described in Section 3.

An alternative technique has also been developed that can be particularly appropriate if the most efficient thermal management is required. In this the thin-film hybrid circuits are interfaced directly to substrates of HCPG, or preferably of VHCPG. In this process custom-designed multilayer structures can be fabricated on, for example, an aluminium substrate and subsequently separated by a chemical peel-off procedure to provide access to the under-surface of the initial polyimide layer. The thin-film hybrid can then be fused to the graphite substrate using either of the techniques described in 4.1.1 or 4.1.2. Other types of custom-designed multilayer circuits which are fabricated on polyimide or epoxy resin layers can also be interfaced to the graphite substrates using either of the processes described in 4.1.1 or 4.1.2.

6 EXTENDING THE APPLICATIONS

Many extended applications can be implemented by combining the techniques used to produce the TMS with the various new interface fusing processes. For example, to provide additional rigidity to the TMS-hybrid structure, as well as giving protection to the edges against impact or delamination, a thin surrounding frame can also be incorporated around the perimeter of the device. Preferably this should have the same coefficient of thermal expansion as the structure, and be for example carbon fibre. The structure can then be constructed to provide a single flat surface which can be coated and attached to the multilayer circuit, again using either of the techniques given in 4.1.1 or 4.1.2

Also more generally, using the techniques of 4.1.1 and 4.1.2, all forms of pyrolytic graphite can be fused into appropriate boards of carbon or PCB-type materials, to produce custom-designed inserts for regions where it is needed to have enhanced performance in thermal transfer. Again, in prototypes for a high energy physics experiment, such applications have been successfully demonstrated by electrically interfacing two of the new technology hybrids via a thin and flexible, metal-tracked interconnect cable to produce a new flex-rigid device. These devices have much better thermal performance than any hybrids previously used in this area of research, are remarkably rigid and require minimal material. They can also be produced at acceptable cost.

There are also possibilities of using the TMS processing techniques to produce extremely thin layers of coated pyrolytic graphite substrates in sheet form. These could provide alternatives to thermal grease in the thermo-mechanical interfaces between elements of multi-component thermal management systems.

7 SUMMARY AND OUTLOOK

Novel techniques have been described for encapsulating graphite substrates of high thermal conductivity, including HCPG and VHCPG in a manner that substantially preserves their thermal conductivity properties while producing rigid low-mass thermal management structures of minimum volume, that are safe to handle, and can be manufactured at acceptable cost. The resulting devices can be operated over a wide temperature range, are highly radiation hard and can be interfaced directly to a wide variety of other materials. They provide a basis for new technologies for the design and fabrication of thermal transfer schemes and electronic hybrids.

The intrinsic features of these new devices make them particularly relevant when minimum mass and bulk are of the highest priority. This can be particularly relevant in the general area of electronic assemblies that combine high-speed operation with high component-density. Specific applications have already been demonstrated with prototype projects for experimental particle physics, and it is foreseen that these can be adapted to meet similar instrumentation needs in satellite and space-borne experiments.

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