IMAPS 2014 Proceedings | Oct. 13-16, 2014 | San Diego, CA USA (ISBN: 978-0-9909028-0-5)

How Can Millions of Aligned Graphene Layers Cool High Power Microelectronics?

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Abstract

Thermal management is an increasingly critical problem in today's microelectronics industry. As power requirements increase and size requirements decrease, innovative materials with high thermal conductivity (TC), light weight, and many times low coefficient of thermal expansion (CTE) are desired to solve these thermal challenges. Thermal Pyrolytic Graphite (TPG*), a unique synthetic material produced by Momentive via chemical vapor deposition, contains millions of layers with highly-oriented stacked graphene planes and exhibits excellent in-plane thermal conductivity (>1500 W/m-K) and very low density (2.25g/cm3). In order to take advantage of its superior properties for thermal management, various forms of TPG-metal composite products were developed in the past few years. TPG composite with metal encapsulation simultaneously achieves high thermal conductivity from the TPG core and high mechanical strength from the metal shell. Momentive's proprietary bonding technology enables an intimate and strong joint between TPG and dissimilar metals, including Al, Cu, Sn, WCu, MoCu, AlSiC, and AlBe. In addition, the variety of compatible metals adds new functionalities to the TPG composite, such as platability and solderability for direct die attachment, CTE matching to semiconductor, and flexibility for off-plane connectivity. Also in this paper, three TPG composite categories, i.e.: TC1050* Heat Spreader, TPG Heat Sink and TPG Laminate, will be discussed in detail. Individually, their design guidance, performance, reliability, and application examples will be shared with the reader. With these three TPG composite products, Momentive has translated our extensive experience and success in thermal management at the system level, with TC1050 Heat Spreaders, to the device level, with TPG Heat Sinks and TPG Laminates.

Key words

Graphene, pyrolytic graphite, thermal conductivity, thermal expansion, thermal management

I. Introduction

New electronic devices are constantly becoming more powerful and compact. These electronics generate heat that must be dissipated, or else the electronics can be damaged by heat buildup. New capabilities are constrained by the ability of designers to remove heat in a cost-effective manner. Generally, every 10 degrees Celsius increase in chip junction temperature decreases the lifespan of the device by half. The U.S. Air Force estimates that 70 percent of its electronics equipment failures are due to thermal effects. Conventional thermal management products are typically constructed of either copper or aluminum. Copper and aluminum have very high coefficients of thermal expansion (CTE), compared with the semiconductor materials from which electronic components are constructed. A mismatch in CTE with electronic components causes thermal stress in the mounted electronic devices at an elevated temperature. This stress can cause unreliable operation and eventually lead to component failure.

To combat this problem, heat sinks with direct contact with semiconductor dies have been made from low-CTE materials such as aluminum silicon carbide (AlSiC), molybdenum-copper (MoCu), tungsten-copper (WCu), or copper-molybdenum laminates. However, these materials sacrifice thermal performance in exchange for better CTE matching with the electronic components. A comparison of thermal expansion and thermal conductivity of various materials is illustrated in Fig. 1.

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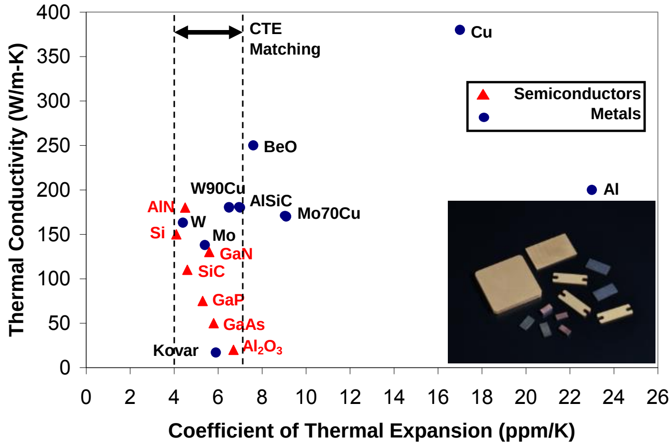

Fig. 1. Materials map for thermal expansion and thermal conductivity.

II. TPG and TPG-Metal Composites

Thermal pyrolytic graphite (TPG*) is an advance thermal management material discovered more than half century ago by Dr. Arthur Moore, a pioneer in graphite research at Momentive [1]. In Momentive's current process, the graphene planes are first laid on heated substrates in a high temperature chemical vapor deposition (CVD) process by pyrolysis of hydrocarbon gas. As illustrated in Fig. 2, the as-deposited pyrolytic graphite (PG) boards have a turbostratic, partially disordered structure and are further annealed into fully dense, highly ordered TPG at above 3000 degrees Celsius. The well-aligned graphene planes created through this two-step process provide superior thermal conductivity (>1500 W/m-K). Compared to copper, which is commonly used in passive cooling, TPG enables four times higher cooling power with one-fourth the weight.

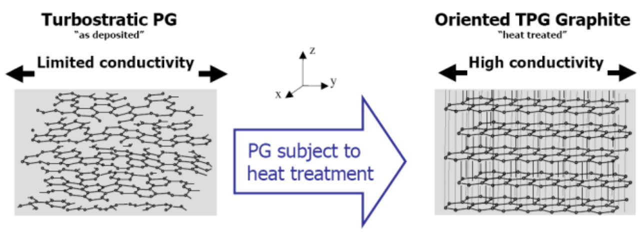

Fig. 2. As-deposited PG showing turbostratic structure (left), and annealed TPG material with highly oriented graphene stacks (right).

TPG is a relatively soft material, due to the weak Van der Waals force between the graphene layers. Also, the inertness of graphite prevents it from joining to other metals or ceramics through regular plating, soldering and brazing processes. A few novel bonding processes have been developed to encapsulate TPG into metal casing, such as aluminum and copper [2]. The TPG-metal composites behave like solid metal and can be further machined, plated or bonded to other components to meet various requirements. Implementation of TPG composite products, such as TC1050* heat spreaders and TPG thermal straps, into the heat path can quickly conduct the heat away from the sources and, therefore, greatly increases the electronics' efficiency and life. Momentive's TPG composite products have been successfully deployed in the cooling systems of satellites, avionics and phased array radars, which can take full advantage of its high thermal performance, high durability and light weight.

Fig. 3. TPG composites are made by encapsulating TPG in metal cladding. The composites can be machined for specific applications. Steps from left to right are a) cutting TPG and inserting into metal clad; b) bonding; c) post-bonding machining.

To address CTE-matching, Momentive recently introduced the TPG heat sinks, which contain TPG material in various CTE-matched alloys. Bonding TPG with CTE-matched alloys such as WCu, MoCu and AlSiC, simultaneously achieves high TC (>900 W/m-K) from the TPG core and low CTE (<$9\text{x}10^{-6}/^{o}C$) from the metal encapsulation. This TPG composite heat sink provides high thermal conductivity, CTE matching, long reliability and low density. This combination significantly outperforms the traditional monolithic incumbents using Al, Cu, WCu, MoCu, or AlSiC.

The following two sections of this paper will focus on the discussion of thermal and mechanical properties as well as reliability of the TPG heat sink technology specifically. Among Momentive's TPG portfolio, TPG heat sinks offer the widest array of advanced functionality and meet the strictest packaging standards.

III. Properties

High thermal conductivity and low density are two important properties of these novel TPG-metal composites, including TC1050 heat spreader, TPG heat sink and TPG laminate. A near-zero thermal interface resistance at the metal-TPG bond line is the key to realize the overall high thermal conductivity. The low composite CTE of the TPG heat sink is determined by the exceptionally high modulus of elasticity of these low CTE alloys. A comparison of the modulus and CTE values among typical heat sink metals and TPG is shown in Table I.

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TABLE I
PROPERTY COMPARISON OF
TYPICAL HEAT SINK METALS AND TPG

Material	Modulus (GPa)	CTE ($10^{-6}/^{o}C$)
Al	68	23.6
Cu	110	16.9
Mo	330	5.4
W	400	4.4
Mo70Cu	240	9.1
TPG-in plane	30	0
TPG-thru plane	11	24

Note: Test data. Actual results may vary. Typical data are average data and are not to be used as or to develop specifications.

In one Momentive study, TPG composites with Mo70Cu/TPG/Mo70Cu sandwich structure were prepared using Momentive's proprietary bonding technique. The TPG* plates were cut in a way that all the graphene planes were aligned vertically to the metal substrates. The TPG loading varied from 20 to 87 percent in thickness (volume). The composite through-plane thermal conductivities were measured by using Netzsch NanoFlash LFA 447. As shown in Fig. 4, the measured through-plane thermal conductivity with various TPG loading matched the calculated value, indicating an exceptionally low thermal interface resistance was achieved with this bonding method. A thermal conductivity as high as 900 W/m-K was demonstrated at the TPG volume loading of 87 percent.

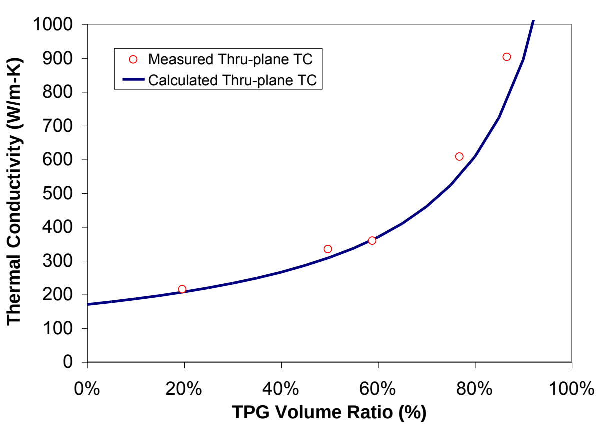

Fig. 4. The thermal conductivity of TPG-Mo70Cu composites at different graphite loadings.

In addition, the CTE values of this TPG composite were characterized by using dilatometer Anter Unitherm 1251. The study also confirmed that the TPG composites maintained the CTE of the metal shell in both lateral directions and its thermal expansion is independent of TPG loadings (Fig. 5) and temperature (Fig. 6).

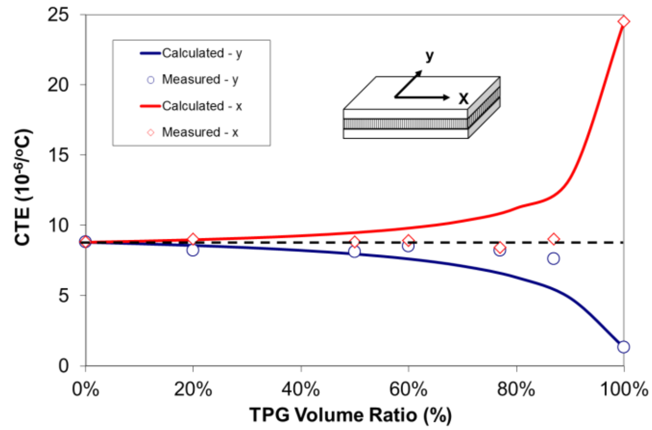

Fig. 5. The CTE of TPG-Mo70Cu composites in two in-plane directions at different graphite loadings.

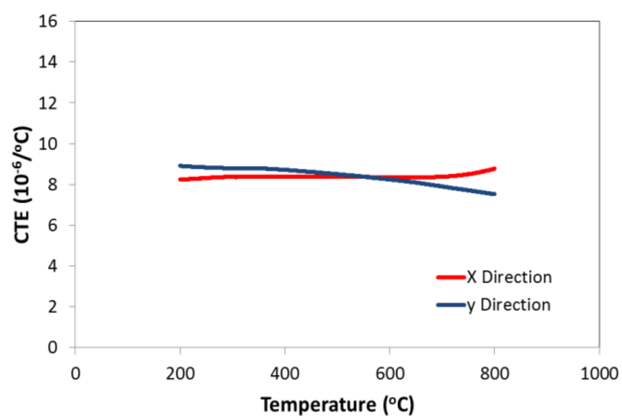

Fig. 6. The CTE of TPG-Mo70Cu composites in two in-plane directions at different temperature.

IV. Reliability

In addition to the excellent TPG-metal bonding, shear strength of the metal-metal joint in the TPG heat sink exceeds the ultimate yield strength of Cu and Mo70Cu and on par with the one of W85Cu (450 MPa). The exceptionally strong mechanical bond ensures the reliability for years of service in harsh environments. Fig. 7 shows the thermal conductivities of 20 pieces of TPG heat sinks before and after a series of thermal cycling, vibration and shock tests, following military microelectronics packaging standard MIL-STD-883H. As demonstrated in Fig. 7, no degradation in thermal characteristics of TPG heat sinks was observed after each test. Furthermore, the TPG heat sink regularly passed the strict hermeticity standard (helium leak rate $< 10^{-8}$ atm-cc/sec), guaranteeing no outgassing or graphite exposure in downstream processes.

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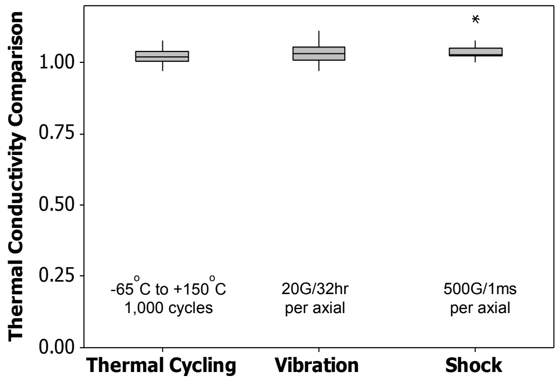

Fig. 7. Through-plane thermal conductivities comparison before and after thermal cycling, vibration and shock tests.

V. Applications

All three categories of TPG* composites, i.e.: TC1050 heat spreader, TPG heat sink and TPG laminate, inherit high thermal conductivity and light weight from the TPG core. Individually, however, they were developed carrying different forms and properties to address different thermal management applications.

A. TC1050 Heat Spreader

TC1050* heat spreader with its large format and high strength is commonly used for system level thermal management and can bear weight load. Typical applications include thermal cores for printed wire boards (PWB), avionic and satellite traveling wave tube (TWT) mounts, electronic chassis, and cold plates in radar systems. In a demonstration shown in Fig. 8, heat load of 45 watt was added to the left side of each heat spreader and the right side was chilled with cooling liquid maintained at 20 degrees Celsius. TC1050 heat spreader delivered 64 percent temperature reduction over its aluminum incumbent due to its exceptionally high thermal conductivity.

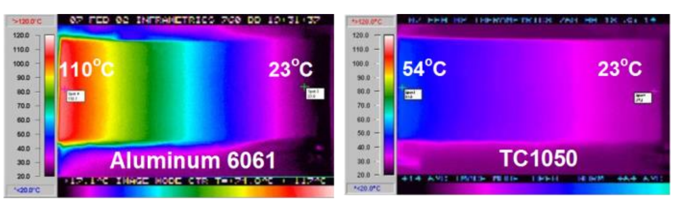

Fig. 8. Infrared image of aluminum (left) and TC1050 (right) heat spreaders with 45 watt heat loading and 20 degrees Celsius cooling.

B. TPG Heat Sink

The TPG heat sink is mainly developed for advanced thermal management of high power RF/microwave microelectronics, laser diodes and LEDs. Common die attach layouts can be categorized into two configurations, i.e.: center-mounted and edge-mounted as illustrated in Fig. 9. Most high power RF and microwave devices are soldered onto the center of the CTE matched heat sinks. In some optoelectronics applications, laser diodes are mounted on the edge of the heat sink to maximize light extraction. In Momentive's product design, TPG is strategically placed into the composite to efficiently conduct heat away from the source. Fig. 9 presents a comparison of thermal performance between TPG heat sinks and their monolithic incumbents for both die attach configurations. Due to its superior thermal conductivity, TPG heat sink exhibits a much more uniform temperature profile, as well as lower absolute device temperature. The typical benefit of temperature reduction by using TPG heat sink is from 30 to 50 percent. In some extreme designs, 60 percent temperature reduction can be expected. The significant thermal resistance reduction and superior heat spreading power in the heat sink can be also translated to up to 80 percent more operating power from the electronic device without impacting operating temperature.

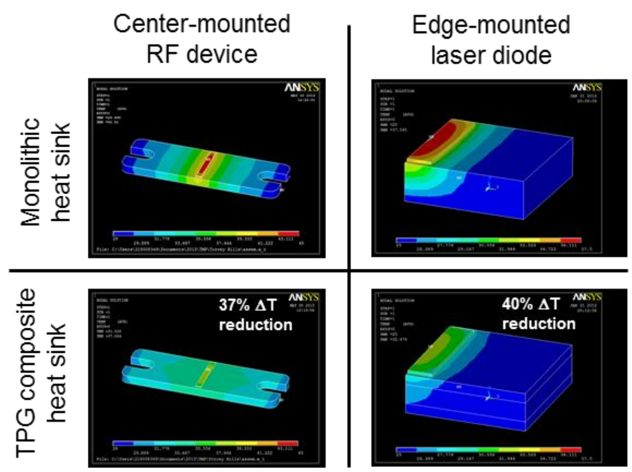

Fig. 9. Temperature profile comparison between monolithic and TPG composite heat sinks via thermal simulation.

In an independent validation test, power transistors were attached to a ceramic substrate which was brazed onto a TPG heat sink and an incumbent WCu heat sink. The transistor temperature was determined via infrared imaging. As shown in Fig. 10, the TPG heat sink exhibited 30 percent less thermal resistance than the monolithic WCu heat sink. As a result of the high heat conduction from TPG, the TPG heat sink enabled 60 percent more power loading to the transistors without increasing the junction temperature. The heat reduction observed in this bench test also matched thermal simulation result.

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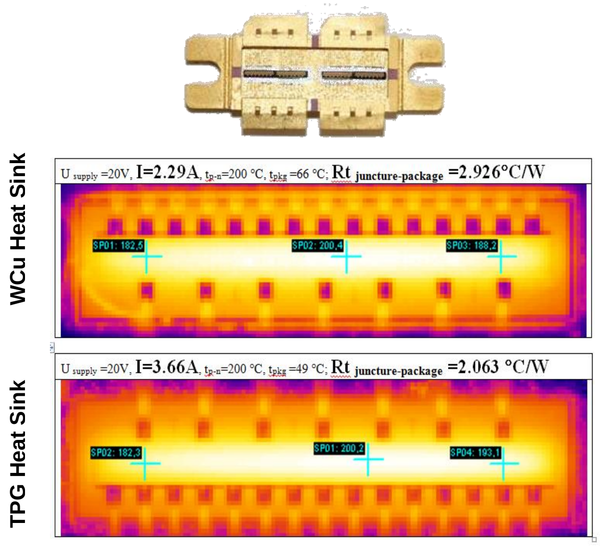

Fig. 10. Top - Power transistors attached to TPG heat sink; Bottom - Temperature profiles of power transistors using WCu heat sink and TPG heat sink, respectively. (Courtesy of Syntez Microelectronics Ltd.)

C. TPG Laminate

TPG laminate consists of TPG sheet sandwiched by very thin metal foils such as aluminum, copper or tin. In addition to high thermal conductivity and low weight, the laminate also presents low profile, flexibility, formability and solderability, which make it an excellent candidate as a heat spreader, thermal strap and heat sink fin. In a similar test demonstrated in Fig. 8, TPG laminate reduced the heat source temperature by 80 percent. When used as heat sink fins, the high heat spreading power of TPG laminate also improves the efficiency of finned heat sinks. As shown in Fig. 11, air-cooled heat sinks were able to dissipate 13 to 20 percent more power when the aluminum fins were replaced by TPG laminate.

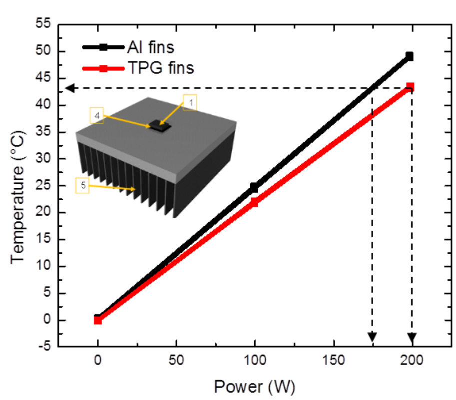

Fig. 11. A comparison of device temperatures using aluminum and TPG laminate fins.

VI. Conclusion

As a summary, the properties of TPG and its composites are compared to conventional thermal management materials in Table II. Bonding TPG with CTE-matched alloys, such as WCu, MoCu and AlSiC, simultaneously achieved high thermal conductivity, which is contributed by the TPG core, and low CTE, which is dictated by the stiff metal enclosure. An excellent thermal and mechanical bonding between the TPG and metal is the key to ensure the desired thermal and mechanical properties, as well as long term reliability. High power microelectronics can benefit from the superior performances of TPG based composite products.

TABLE II
A COMPARISON OF THERMAL MANAGEMENT MATERIALS

Material	In-Plane TC(1) (W/m-K)	Thru-Plane TC(1)(2) (W/m-K)	Density(1) (gm/cm³)
Aluminum	210	210	2.7
TPG + Aluminum	1073	507	2.4
Copper	400	400	8.9
TPG + Copper	1133	783	4.5
AlSiC12	180	180	3.0
TPG + AlSiC12	1060	435	2.5
W85Cu	190	190	15.6
TPG + W85Cu	1063	455	6.7
Mo70Cu	170	170	9.8
TPG + Mo70Cu	1057	416	4.8

(1) Estimation is based on 67% of TPG loading.
(2) TPG graphene plane is perpendicular to the metal surface for this estimation.

Note: Typical data are average data and are not to be used as or to develop specifications

Acknowledgement

The authors would like to acknowledge the support provided by the State of Ohio, Department of Development under the Ohio Third Frontier Advanced Materials Program.

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