

Heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets

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Abstract

The thermal interface material technologies used for electronic packages encompass several classes of materials. However, there is still a need for thermal interface materials and methods for making thermal interface materials having improved thermal conductivity property by maximizing the anisotropic benefit of exfoliated graphite platelets to the fullest extent. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the material performance. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets. The results indicate that polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink. Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact. The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal and exhibit a relatively high ratio of thermal conductivity to weight. Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material. Reducing the strain on the thermal interface material may reduce the potential for pump-out and the associated increase in thermal resistance due to loss of material from the interface. Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the matrix. Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface. The thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect.

Keywords: Interface materials; Thermoplastic materials; Smooth surfaces; Rough surfaces; Graphite platelets; Carbon black

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1. Introduction

In an electronic device, a thermal interface material is a material that is disposed between a heat generating component of an electronic device and a heat dissipating component in order to facilitate efficient heat transfer between the heat generating component and the heat dissipating component [1, 2]. The powering up or powering down of the electronic device may cause temperature changes which may cause a relative motion between the heat generating component and the heat dissipating component, including in-plane motion and out-of-plane motion due to coefficient of thermal expansion mismatch [3, 4]. With the development of more sophisticated electronic components, including those capable of increasing processing speeds and higher frequencies, having smaller size and more complicated power requirements, and exhibiting other technological advances, such as microprocessors and integrated circuits in electronic and electrical components and systems as well as in other devices such as high-power optical devices, relatively extreme temperatures can be generated [5, 6]. However, microprocessors, integrated circuits, and other sophisticated electronic components typically operate efficiently only under a certain range of threshold temperatures. The excessive heat generated during operation of these components can not only harm their own performance, but can also degrade the performance and reliability of the overall system and can even cause system failure [7, 8]. The increasingly wide range of environmental conditions, including temperature extremes, in which electronic systems are expected to operate, exacerbates these negative effects.

With the increased need for heat dissipation from microelectronic devices caused by these conditions, thermal management becomes an increasingly important element of the design of electronic products [9, 10]. As noted, both performance reliability and life expectancy of electronic equipment are inversely related to the component temperature of the equipment [11, 12]. For instance, a reduction in the operating temperature of a device such as a typical silicon semiconductor can correspond to an exponential increase in the reliability and life expectancy of the device [13, 14]. Therefore, to maximize the life-span and reliability of a component, controlling the device operating temperature within the limits set by the designers is of paramount importance. A thermal management system is designed to assist with this objective. One element of a thermal management system is a thermal interface material [15, 16]. A typical use for a thermal interface

material is to thermally connect a computer chip to a cooling module to overcome contact resistance and lack of surface conformity between the heat sink, or the cooling module and the chip or other heat source. Typically, thermal interfaces consist of thermal greases, phase change materials, and tapes [17, 18]. Flexible graphite is readily applicable to such applications because of its low thermal resistance and its ability to conform to the surfaces to be interfaced, especially when either or both surfaces are not completely flat [19, 20]. Such characteristics are important in a thermal management system because reducing the thermal resistance as much as possible is of paramount importance.

The process for manufacturing the flexible graphite used in the thermal interface is well-known [21, 22]. In general, flakes of natural graphite are intercalated in an acid solution. After the flakes are intercalated, they are washed and dried and then exfoliated by exposure to a high temperature for a short period of time. This causes the flakes to expand or exfoliate in a direction perpendicular to the crystalline planes of the graphite [23, 24]. The exfoliated graphite flakes are vermiform in appearance and are therefore commonly referred to as worms. The worms may be compressed into sheets or foils with a density approaching theoretical density although a density of about 1.1 grams per cubic centimeter is considered typical for most applications. The sheets of flexible graphite can be cut into any desired configuration to suit a particular application. Graphite is made up of layer planes of hexagonal arrays or networks of carbon atoms. These layer planes of hexagonally arranged carbon atoms are substantially flat and are oriented or ordered so as to be substantially parallel and equidistant to one another [25, 26]. The substantially flat, parallel equidistant sheets or layers of carbon atoms, usually referred to as graphene layers or basal planes, are linked or bonded together and groups thereof are arranged in crystallites. Highly ordered graphite consists of crystallites of considerable size: the crystallites being highly aligned or oriented with respect to each other and having well-ordered carbon layers. In other words, highly ordered graphite has a high degree of preferred crystallite orientation [27, 28]. It should be noted that graphite possesses anisotropic structures and consequently exhibit or possess many properties that are highly directional such as thermal and electrical conductivity.

The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the thermal interface material performance. The method includes preparing the graphite nanofibers in a herringbone configuration, and dispersing the graphite nanofibers in the herringbone configuration into the thermal interface material. The method further includes applying a magnetic field of sufficient intensity to align the graphite nanofibers in the thermal interface material. Thermal materials are used in packaging as interfaces between devices to dissipate heat from these devices. One typical thermal interface material typically includes a polymer matrix and a thermally conductive filler. As electronic components have become smaller and more densely packed on integrated boards and chips, designers and manufacturers now are faced with the challenge of how to dissipate the heat which is generated by these components. The thermal interface material technologies used for electronic packages encompass several classes of materials, such as phase change materials, epoxies, greases, and gels. However, there is still a need for thermal interface materials and methods for making thermal interface materials having improved thermal conductivity property by maximizing the anisotropic benefit of exfoliated graphite platelets to the fullest extent. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets.

2. Methods

The present study includes a system for aligning graphite nanofibers to enhance thermal interface material performance. The system includes the graphite nanofibers configured in a herringbone configuration and a means for dispersing the graphite nanofibers in the herringbone configuration into the thermal interface material. The system further includes a means for applying a magnetic field of sufficient intensity to align the graphite nanofibers in the thermal interface material. Nanofibers can be produced by interfacial polymerization and electrospinning. Carbon nanofibers are graphitized fibers produced by catalytic synthesis

around a catalytic core. The catalytic core around which graphite platelets are formed is called a metal seed or a catalytic metal seed, wherein the catalytic metal seed is a material having magnetic properties such as iron, cobalt, or nickel. Metal-core graphite nanofibers can be grown in numerous shapes around a catalytic metal seed. The metal-core graphite nanofibers comprise of graphite platelets arranged in various orientations with respect to the long axis of the fiber, giving rise to assorted conformations. A magnetic field is applied to the metal catalyst prior to deposition of the graphite nanofibers on the metal-core. With the application of a magnetic field, the magnetic poles of the seed are aligned with the magnetic field and will subsequently carry the attached graphite nanofibers along with them as they rotate in the applied field following deposition.

Conventional manufacture of expanded graphite requires thermal and chemical treatment in order to expand the interlayers without completely breaking or separating the layers between the basal planes. Typically, the expansion is conducted by treating particles of graphite, such as natural graphite flakes, with an intercalant, for example, a solution of sulfuric and nitric acid, such that the crystal structure of the graphite reacts with the acid to form a compound of graphite and the intercalant. Upon exposure to elevated temperatures the particles of intercalated graphite expand in an accordion-like fashion in the direction perpendicular to the crystalline planes of the graphite flakes. The resulting expanded, or exfoliated, graphite particles are vermiform in appearance and are commonly referred to as worms. This expansion of the particles into worms, rather than separation into separate platelets, occurs as a result of the Van der Waals forces securing together the basal planes of the graphite structure. The Van der Waals forces between the basal planes of the graphite prevent complete separation of the leaflets. Expanded graphite structures may be used as particulate in composite materials, such as polymers, to provide reinforcement and add stiffness, strength and other properties. Attractive benefits of the use of such particulate-filled polymers in materials-intensive industries include low cost, weight reduction, styling potential, superior acoustic characteristics, reduced maintenance and corrosion resistance.

With a diamond shaped catalytic metal seed, the majority of the graphite platelets will align along the fiber axis as dictated by an external magnetic field, so that the catalytic metal seed may have its poles aligned perpendicular to or parallel to the external magnetic field. The seed particles are not limited to elongated diamonds, so that the deposited metal-core graphite nanofiber forms the chevrons. The graphite platelets can assume any of a myriad of shapes. If the catalytic metal seeds are rectangular plates, then the graphite platelets are deposited as plates. If the catalytic metal seeds are cylindrical, then the graphite platelets are deposited as cylindrical plates. If the catalytic metal seeds are little bars, then the graphite platelets are deposited as rectangular solids along the long axis of the rectangular bar. The graphite platelets assume the geometry of the catalytic metal seed surface. A magnetic field of sufficient strength to cause the domains within the catalytic metal seeds to align along the external field is applied. Application of an external magnetic field pre-aligns the magnetic poles of the catalytic metal seed by applying a magnetic field to the catalytic metal seed prior to deposition of the graphite platelets on the metal-core. The chamber is charged with the reactive gas mixture. By judicious choice of the catalytic metal seeds catalyst, the ratio of the hydrocarbon-hydrogen reactant mixture, and reaction conditions, it is possible to tailor the morphological characteristics, the degree of crystallinity, and the orientation of the precipitated graphite crystallites with regard to the fiber axis. The gas mixture thermally decomposes onto the catalytic metal seed to generate the metal-core graphite nanofibers. The metal-core graphite nanofibers can be dispersed in silicone-based gels or pastes that are used as thermal interface materials that are eventually cured into pads.

The thermal interface material having a thickness between a first surface and a second surface opposite the first surface. The thermal interface material further includes a plurality of carbon nanofibers, wherein a majority of the carbon nanofibers are oriented orthogonal to a plane of the first surface and wherein the carbon nanofibers comprise a magnetic catalytic seed. Graphite nanofibers have received considerable attention in the electronics field due to their remarkable thermal conductivity [29, 30]. Moreover, the thermal conductivity of graphite nanofibers is anisotropic [31, 32]. Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies homogeneity in all directions. Therefore, the present study takes advantage of the anisotropic nature of the graphite nanofibers by effectively aligning them along the

conductive axis, thereby generating a thermal interface material with exceptional thermal conductivity at comparatively low loading levels. A thermal interface material is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heatsinks, in order to increase thermal transfer efficiency [33, 34]. These gaps are normally filled with air, which is a very poor conductor [35, 36]. A thermal interface material may take on many forms [37, 38]. The most common is the white-colored paste or thermal grease [39, 40]. Some brands of thermal interface materials use micronized or pulverized silver [41, 42]. Another type of thermal interface materials are the phase-change materials [43, 44]. The phase change materials are solid at room temperature, but liquefy and behave like grease at operating temperatures.

A phase change material is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; consequently, phase change materials are classified as latent heat storage units. Phase change materials latent heat storage can be achieved through solid-solid, solid-liquid, solid-gas and liquid-gas phase change. However, the only phase change used for phase change materials is the solid-liquid change. Liquid-gas phase changes are not practical for use as thermal storage due to the large volumes or high pressures required to store the materials when in their gas phase. Liquid-gas transitions do have a higher heat of transformation than solid-liquid transitions. Solid-solid phase changes are typically very slow and have a rather low heat of transformation. Initially, the solid-liquid phase change materials behave like sensible heat storage materials; their temperature rises as they absorb heat. Unlike conventional sensible heat storage, however, when phase change materials reach the temperature at which they change phase they absorb large amounts of heat at an almost constant temperature. The phase change material continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid-material falls, the phase change material solidifies, releasing its stored latent heat. A large number of phase change materials are available in any required temperature range from -8 up to 200 °C. Within the temperature range of 20 to 60 °C, some phase change materials are very effective.

Graphite starting materials for the flexible sheets suitable for use in the present study include highly graphitic carbonaceous materials capable of intercalating organic and inorganic acids as well as halogens and then expanding when exposed to heat. Examples of highly graphitic carbonaceous materials include natural graphite from various sources, as well as other carbonaceous materials such as carbons prepared by chemical vapor deposition and the like. Natural graphite is most preferred. The graphite starting materials for the flexible sheets used in the present study may contain non-carbon components so long as the crystal structure of the starting materials maintains the required degree of graphitization and they are capable of exfoliation. Generally, any carbon-containing material, the crystal structure of which possesses the required degree of graphitization and which can be exfoliated, is suitable for use with the present study. Natural graphite flakes are intercalated by dispersing the flakes in a solution containing, for example, a mixture of nitric and sulfuric acid, advantageously at a level of about 20 to about 300 parts by weight of intercalant solution per 100 parts by weight of graphite flakes. The intercalation solution contains oxidizing and other intercalating agents. Examples include those containing oxidizing agents and oxidizing mixtures. Alternatively, an electric potential can be used to bring about oxidation of the graphite. Chemical species that can be introduced into the graphite crystal using electrolytic oxidation include sulfuric acid as well as other acids. The quantity of intercalation solution may range from about 20 to about 200 parts per hundred. After the flakes are intercalated, any excess solution is drained from the flakes and the flakes are water-washed.

The particles of graphite flake treated with intercalation solution can optionally be contacted by blending, with a reducing organic agent selected from alcohols, aldehydes, and esters, which are reactive with the surface film of oxidizing intercalating solution at temperatures in the range of 25 °C and 125 °C. The organic reducing agent increases the expanded volume upon exfoliation and is referred to as an expansion aid. The amount of organic reducing agent is suitably from about 0.8 to 8 percent by weight of the particles of graphite flake. Another class of expansion aids that can be added to the intercalating solution, or to the graphite flake prior to intercalation, and work synergistically with the above-described organic reducing agents are carboxylic acids. An expansion aid in this context will advantageously be sufficiently soluble in

the intercalation solution to achieve an improvement in expansion. More narrowly, organic materials of this type that contain carbon, hydrogen and oxygen, preferably exclusively, may be employed. Suitable organic solvents can be employed to improve solubility of an organic expansion aid in the intercalation solution. Sulfuric acid, nitric acid and other known aqueous intercalants have the ability to decompose formic acid, ultimately to water and carbon dioxide. Because of this, formic acid and other sensitive expansion aids are advantageously contacted with the graphite flake prior to immersion of the flake in aqueous intercalant. The intercalation solution will be aqueous and will preferably contain an amount of carboxylic acid expansion aid of from about 0.2 percent to about 8 percent, the amount being effective to enhance exfoliation. Formic acid is contacted with the graphite flake prior to immersing in the aqueous intercalation solution, it can be admixed with the graphite by suitable means, typically in an amount of from about 0.2 percent to about 8 percent by weight of the graphite flake.

3. Results and discussion

The low-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 1 for the production of the thermal interface material. Metal heat spring thermal interface materials can be made to preferentially release from a desired surface by adding a metal clad aluminum foil, but require a high pressure in order to provide effective contact, minimize thermal resistance, and fill any interface gaps [45, 46]. Typically, some form of mechanical retention hardware is used to ensure adequate contact and optimal performance [47, 48]. Unfortunately, clamping forces of the mechanical retention hardware can damage the semiconductor component [49, 50]. The metal spring thermal interface materials also suffer from low elasticity, poor gap filling, and the potential for micro motion induced oxidation over time [51, 52]. Furthermore, the aluminum foil release layer can negatively affect thermal performance. Polymeric elastomer materials may be used as a thermal interface material [53, 54]. The thermal properties of polymeric elastomer materials can be modified with the addition of various forms of carbon, for example graphene layers, graphite flake, carbon fibers, or carbon nanotubes [55, 56]. Polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink. However, like the metal heat spring thermal interface materials, polymeric elastomer materials also require high pressures in order to adequately fill interface gaps. Also like the metal heat spring thermal interface materials, excess pressure can cause damage to the semiconductor component, for example, cracking. Polymeric elastomer materials adhesively bond to surface of both the semiconductor component and the heat sink. If future removal of the heat sink is required, the risk of damaging the semiconductor component or the thermal interface material is high due to the adhesive properties, for example the inherent tackiness, of polymeric elastomer materials. Although conventional release layers, such as, for example, non-stick polymers or aluminum foil, can be applied to polymeric elastomer materials, they create an insulative barrier and degrade thermal performance. Expanded graphite materials may be used as a thermal interface material. Expanded graphite materials are available at relatively low cost, have good thermal performance and excellent dimensional compliance or gap filling capability, and release cleanly from device surfaces for easy reuse during semiconductor component repair or replacement. However, expanded graphite materials have limited elasticity and are not easily reusable for different surface topologies. Carbon nanotube materials may be used as a thermal interface material. Carbon nanotube materials include sheets of densely packed, generally vertically aligned and intertwined. Carbon nanotube materials offer extremely high thermal conductivity and thus excellent thermal performance. Carbon nanotube materials are durable and reusable, but have extremely limited elasticity and gap filling capabilities and require high mechanical loads to enable good thermal performance. Carbon nanotube materials are also relatively expensive to manufacture, and as such, are typically used as thermal beds on testers for lidded modules where high loads can be used without component damage and extremely high component test volumes are anticipated. Flexible graphite materials may also be used for their superior heat transfer properties. Flexible graphite materials generally have poor gap filling capabilities. Thermal grease or thermal gel may be used as a thermal interface material. Thermal grease or thermal gel is typically filled with various forms of thermally conductive media, such as, for example, carbon, metal particles, ceramic particles, or metal oxide particles. These materials have reasonable thermal performance and gap fill capability, but must be dispensed or printed onto surfaces. After

being applied, thermal gel must be thermally cured as they rely on adhesive bonding at device and cooling hardware surfaces to ensure stable interface performance. Neither thermal grease nor thermal gel meets suitable reuse requirements. Phase change material may be used as a thermal interface material. Phase change material is a substance which can change from a solid to liquid at a certain temperature, for example, at room temperature. The phase change material absorbs heat when changing from a solid to a liquid, and releases heat when changing from a liquid to a solid. Advantages of phase change material include superior gap filling capability and good thermal performance.

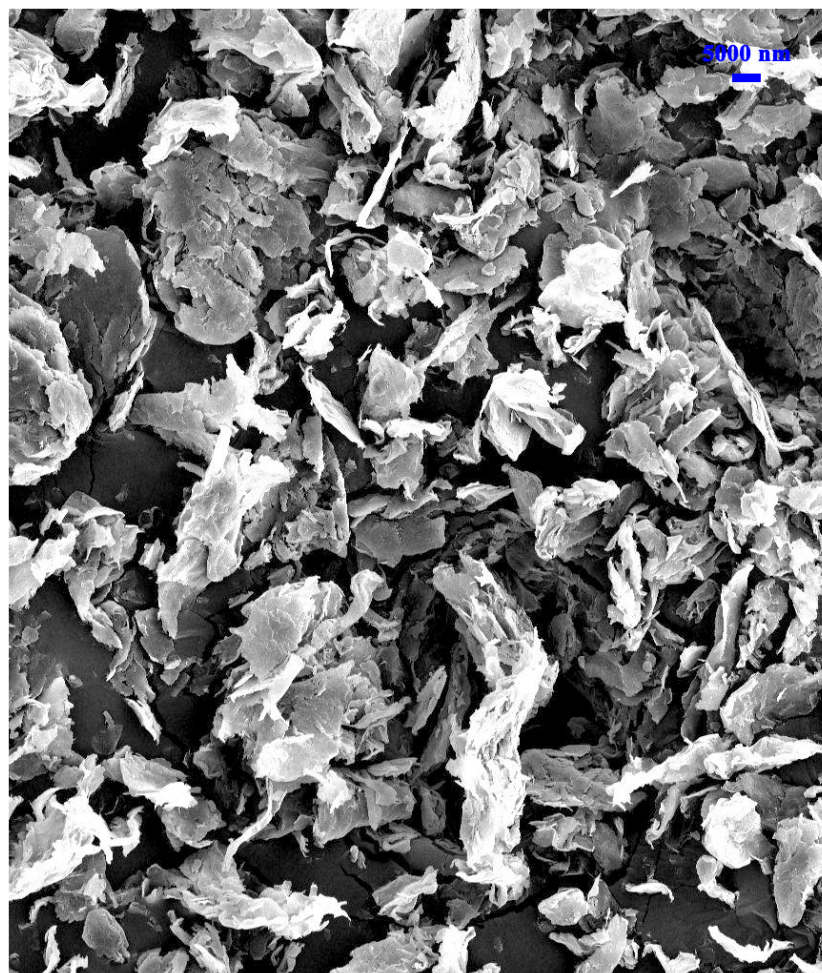


Figure 1. Low-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The moderate-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 2 for the production of the thermal interface material. It is well known that many electronic components, and especially power semiconductor components such as transistors and microprocessors, are more prone to failure or malfunction at high temperatures [57, 58]. Consequently, the ability to dissipate heat often is a limiting factor on the performance of the component. Heat dissipation may be affected by the direct mounting of the electronic component to a thermal dissipation member such as a cold plate or other heat sink or spreader. The dissipation member may be a dedicated, thermally-conductive ceramic or metal

plate or finned structure, or simply the chassis or circuit board of the device [59, 60]. However, beyond the normal temperature gradients between the electronic component and the dissipation member, an appreciable temperature gradient is developed as a thermal interfacial impedance or contact resistance at the interface between the bodies [61, 62]. The thermal interface surfaces of the component and heat sink typically are irregular, either on a gross or a microscopic scale [63, 64]. When the interfaces surfaces are mated, pockets or void spaces are developed therebetween in which air may become entrapped. These pockets reduce the overall surface area contact within the interface which, in turn, reduces the heat transfer area and the overall efficiency of the heat transfer through the interface. To improve the heat transfer efficiency through the interface, a thermal interface material may be used to fill the gap between the heat sink and electronic component to fill in any surface irregularities and eliminate air pockets. The thermal interface material may be a pad or other layer of a thermally-conductive, electrically-insulating material. Even in a direct contact, however, the processor and the attach block do not transfer heat efficiently, because the quality of contact between two non-conforming solid surfaces is typically poor. A thermal interface material may therefore be inserted between the processor and the attach block in order to enhance the thermal contact between the two surfaces. Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact. The quality of the contact between the processor and the attach block, or thermal interface material performance, depends on the quality of the thermal conduction through the thermal interface material and the quality of contact between the thermal interface material and the two surfaces. Consequently, a precise material tester capable of providing precise measurements of thermal interface material performance may be useful to improve overall thermal solution designs for notebooks and other devices.

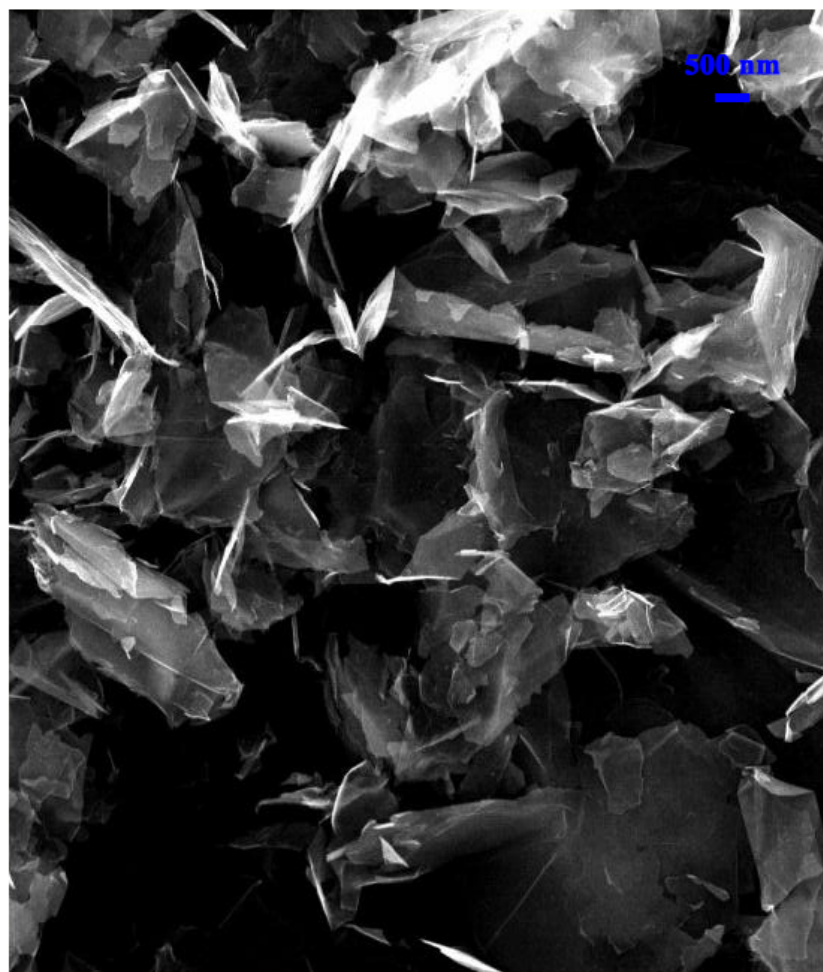


Figure 2. Moderate-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The effect of thermal interface material thickness on the thermal resistivity of the thermal contact is illustrated in Figure 3 for graphite platelets and carbon black. The heat dissipating components facilitate heat dissipation from the surface of a heat source, such as a heat-generating electronic device, to a cooler environment, usually air [65, 66]. In many typical situations, heat transfer between the solid surface of the electronic device and the air is the least efficient within the system, and the solid-air interface consequently represents the greatest barrier for heat dissipation [67, 68]. The heat dissipating components seek to increase the heat transfer efficiency between the electronic device and the ambient air primarily by increasing the surface area that is in direct contact with the air or other heat transfer media. This allows more heat to be dissipated and consequently lowers the electronic device operating temperature. The primary purpose of a heat dissipating component is to help maintain the device temperature below the maximum allowable temperature specified by its designer or manufacturer [69, 70]. Typically, the heat dissipating components are formed of a metal, especially copper or aluminum, due to the ability of metals like copper to readily absorb heat and transfer it about its entire structure. In the case of heat sinks, copper heat sinks are often formed with fins or other structures to increase the surface area of the heat sink, with air being forced across or through the fins to effect heat dissipation from the electronic component, through the copper heat sink

and then to the air [71, 72]. Limitations exist, however, with the use of metallic heat dissipating components. One limitation relates to the relative isotropy of a metal that is, the tendency of a metallic structure to distribute heat relatively evenly about the structure. The isotropy of a metal means that heat transmitted to a metallic heat dissipating component becomes distributed about the structure rather than being preferentially directed to a desired location. In addition, the use of copper or aluminum heat dissipating elements can present a problem because of the weight of the metal, particularly when the heat transmitting area of the heat dissipating component is significantly larger than that of the electronic device. For example, several heat sinks need to be arrayed on a circuit board to dissipate heat from a variety of components on the board. If metallic heat sinks are employed, the sheer weight of the metal on the board can increase the chances of the board cracking or of other equally undesirable effects, and increases the weight of the component itself. In the case of larger heat dissipating components such as for example that class of components known as heat spreaders, the weight of a pure copper heat spreader requires special mechanical features and designs to hold the heat spreader. What is desired, therefore, is a heat dissipating component effective for dissipating heat from a heat source such as an electronic device. The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal like copper or aluminum and exhibit a relatively high ratio of thermal conductivity to weight. One group of materials suitable for use in heat sinks are those materials generally known as graphite, but in particular anisotropic graphite such as those based on natural graphite and flexible graphite.

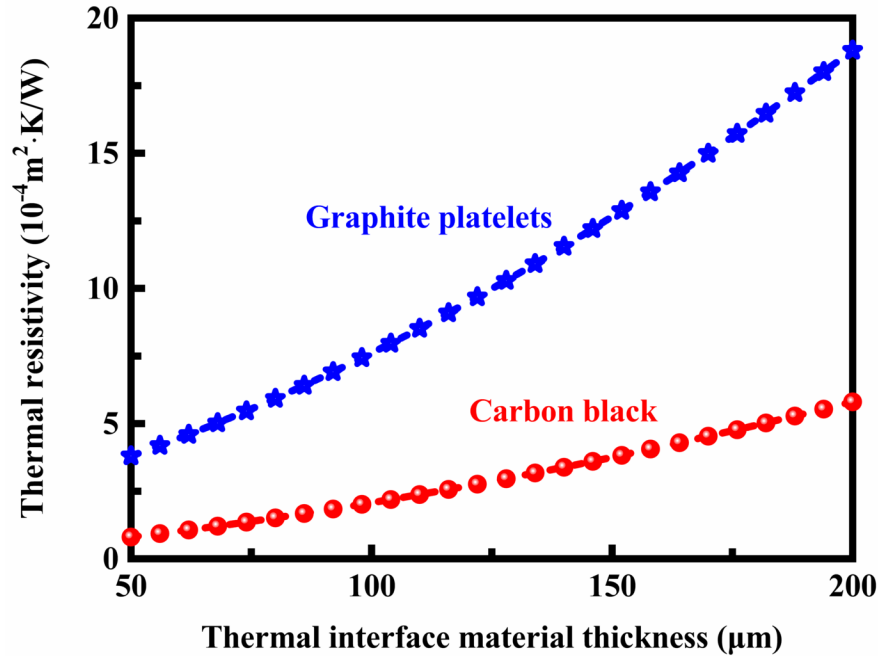


Figure 3. Effect of thermal interface material thickness on the thermal resistivity of the thermal contact for graphite platelets and carbon black.

The effect of filler volume fraction on the thermal conductivity of the thermal interface material is illustrated in Figure 4 for graphite platelets and carbon black. In most polymer composite applications, the resin system is mixed with expanded graphite, chopped fibers or other additives for processing and durability requirements and sometimes with fillers for further cost reduction. These additives are incorporated into the polymer in specific amounts in order to customize properties of the resulting composite. Additionally, thermal, electrical, and mechanical properties are all affected by the form and matter of the particulate in polymers. Desired properties can be obtained by varying filler content and process techniques. However, the orientation and accommodation of the particulate in the component may cause weak areas, susceptible

to crack initiation and propagation at sharp bends. Thermal interface materials are used between heat-generating components and heat sinks to establish heat-conduction paths therebetween. However, thermal interface materials provide a thermally conducting heat path that is substantially contained between the heat generating components and the heat sink, which results in a relative narrow heat conduction path that causes heat to be localized around the electronic component. That is, a substantial portion of heat generated by the electronic component is conducted via the path of least impedance through the thermal interface material that lies directly between the electronic component and the heat sink. This results in limited heat spreading throughout the thermal interface material and the heat sink. Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material. Flexible heat-spreading materials may generally refer to and include a wide range of materials having flexibility equal to or greater than a sheet of stamped aluminum and flexibility equal to or greater than a sheet of stamped copper. Within the flexible heat-spreading material, heat laterally spreads out such that there will be more surface area from which heat may be transferred from the flexible heat-spreading material. The greater surface area due to the laterally spreading of the heat may increase and improve the heat transfer efficiency associated with the flexible heat-spreading material and the overall thermally-conductive interface assembly. Heat may be transferred from the flexible heat-spreading material via conduction in the normal direction to an outer layer of thermal interface material, in which flexible heat-spreading material is sandwiched between, bonded to, or encapsulated within layers of thermal interface material. Heat may be transferred from the flexible heat-spreading material via convection to air or other ambient environment, in which a heat-spreading material includes thermal interface material on only one side such that other side of the heat-spreading material is exposed to air or another ambient environment. In cases in which thermal interface material is on or along only one side of a heat-spreading material, and the thickness of the thermal interface material may be greater than the thickness of the flexible heat-spreading material. Alternatively, the thickness of the thermal interface material may be about equal to or less than the thickness of the flexible heat-spreading material in other cases. In cases in which flexible heat-spreading material is sandwiched between, bonded to, or encapsulated within layers of thermal interface material, the layers of thermal interface material along one side of the flexible heat-spreading material may be thicker, thinner, or about equal to the layers of thermal interface material along the other or opposite side of the flexible heat-spreading material. For example, a flexible heat-spreading material may have inner and outer layers of thermal interface material, where the inner layer, which is intended to contact one or more electronic components, is thicker than the outer layer. Thermally-conductive interface assemblies include one or more outer layers of soft thermal interface materials that are relatively flexible, soft, and thin, for example, for good conformance with a mating surface. This, in turn, may help lower thermal impedance as thermal impedance depends upon the degree of effective surface area contact therebetween. The ability to conform to a mating surface tends to be important as the surfaces of a heat sink and a heat-generating component are typically not perfectly flat and smooth, such that air gaps or spaces tend to appear between the irregular mating surfaces.

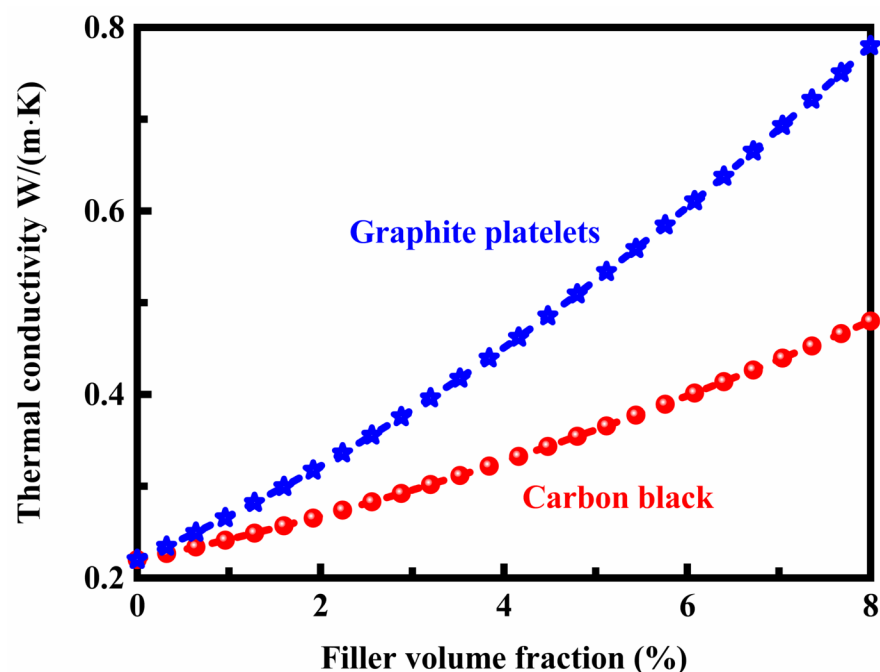


Figure 4. Effect of filler volume fraction on the thermal conductivity of the thermal interface material for graphite platelets and carbon black.

The high-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 5 for the production of the thermal interface material. Conventional polymeric thermal interface materials may be used as the thermal interface material. However, currently used polymeric thermal interface materials are typically cure in place silicone gel materials that are required to be shipped and stored frozen. They also have short pot lives upon opening, short shelf lives, and require special dispensing equipment to apply. Therefore, it is necessary to eliminate, avoid, or at least reduce these aforementioned drawbacks associated with conventional polymeric thermal interface materials. A thermal interface material in the form of a pad of self-healing, thermoplastic material may or may not be naturally tacky. The thermal interface material may have a softening or melting temperature higher than a normal operating temperature of a central processing unit, for example, normal operating temperature from about 60 °C to about 100 °C or from about 30 °C to about 40 °C. Consequently, the pad of thermoplastic material will soften or melt once, for example, during an adhesive curing stage or during an initial operation of the central processing unit, and then solidify. Thereafter, the pad of thermoplastic material may be used below its softening or melting temperature and remain solidified. The thermal interface material comprises a thermoplastic phase change material having a softening or melting point temperature that falls within a range from about 80 °C to about 200 °C or about 100 °C to about 180 °C. Or, for example, the thermal interface material may have a softening or melting temperature of about 40 °C, 60 °C, or 80 °C. The thermal interface material may have a thermal conductivity of about 0.8 Watts per meter per Kelvin or more, or 2.0 Watts per meter per Kelvin or more, which thermal conductivity may be enhanced by incorporating thermally-conductive filler into the thermoplastic material. The thermal interface material may comprise a low melting alloy having a melting temperature of about 200 °C or less. The surface features protrude from the mating surface of the particular heat transfer component into selected areas of the interface. The protruding features may limit the relative movement of the mating surfaces in the selected areas of the interface during thermal cycling due to coefficient of thermal expansion mismatch. Limiting the relative movement may reduce strain on the thermal interface material in areas of the interface proximate to the protruding features. Reducing the strain on the thermal interface material may reduce the potential for thermal interface material pump-out and the associated increase in thermal

resistance due to loss of material from the interface. The protruding features are incorporated onto the heat sink and protrude out from the heat sink mating surface into selected areas of the interface between the heat sink mating surface and the module lid mating surface. The protruding features may be incorporated onto the heat sink through a forming process during manufacturing of the heat sink. Channels may be machined or otherwise incorporated into the heat sink, and the channels may be filled with a material that is appropriate for the heat sink in order to form the protruding features. In some cases, the heat sink may be formed from a heat sink material, such as an aluminum-based material or a copper-based material, among other alternative materials. When the heat sink is formed from an aluminum-based material, the channels may be filled with an aluminum-based material that is the same as the aluminum-based material of the heat sink or that is substantially similar to the aluminum-based material of the heat sink. Alternatively, with respect to the example in which the heat sink is formed from an aluminum-based material, the channels may be filled with other materials compatible with the aluminum-based material for efficient transfer of heat to the heat sink.

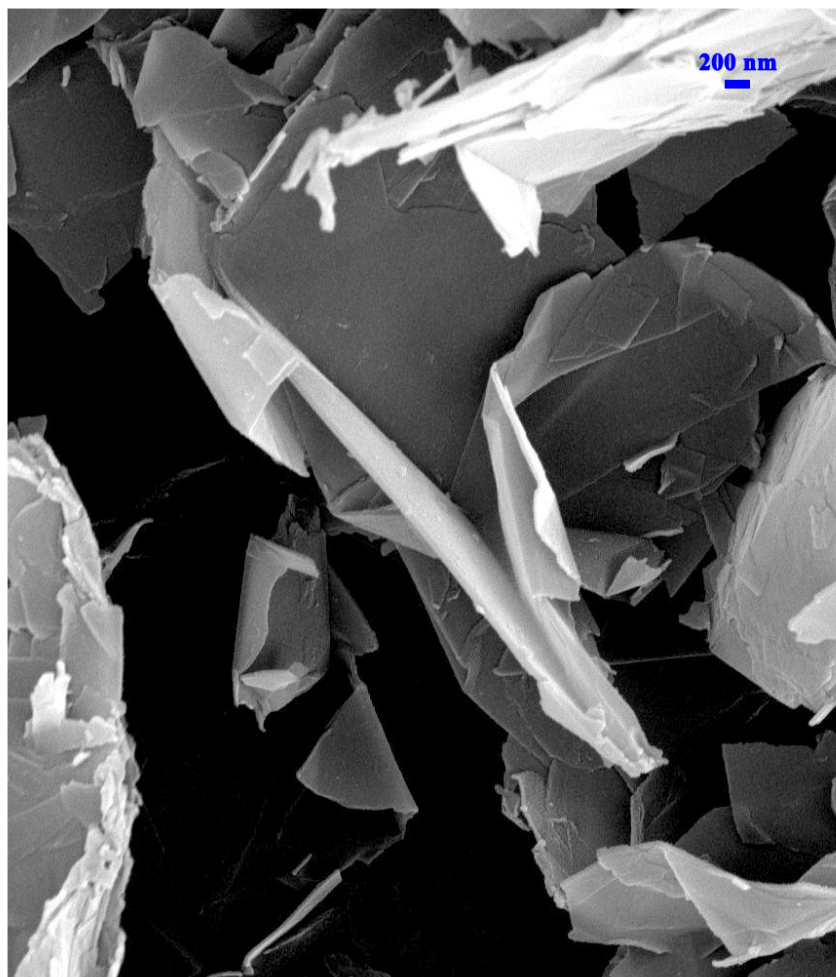


Figure 5. High-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The transmission electron micrographs of the exfoliated graphite platelets are illustrated in Figure 6 for the production of the thermal interface material. Some of particulate-filled polymers are conductive polymers. Although almost all plastics, whether thermoplastic polymers or thermosetting polymers, are intrinsically

good electrical insulators, introduction of graphitic and other carbonaceous materials into the polymers can create electrical conduction paths in the insulating polymer matrix when these particles contact each other above a certain content, or critical volume fraction. Graphite, in general, can be used along with specially-processed electroconductive carbon black as a filler to provide electrical and thermal conductivity to normally non-conducting or poorly conducting polymeric materials. However, the size and morphological characteristics of conventional graphite particles limit the extent that the properties of a polymer composite can be improved. A first thermal interface material or layers may be used between an integrated heat spreader or lid and the heat generating components or device to reduce hot spots and generally reduce the temperature of the heat generating components or device. A second thermal interface material or layers may be used between the integrated heat spreader and the heat sink to increase thermal transfer efficiency from the heat spreader to the heat sink. One or more thermally conductive fillers may be added to create a thermally conductive interface material in which one or more thermally conductive fillers will be suspended in, added to, and mixed into, the thermally reversible gel. For example, at least one thermally conductive filler may be added to a mixture including gellable fluid and gelling agent before the gellable fluid and gelling agent have gelled or form the thermally reversible gel [73, 74]. At least one thermally conductive filler may be added to the gellable fluid and then gelling agent may be added to the mixture containing gellable fluid and thermally conductive filler [75, 76]. At least one thermally conductive filler may be added to the gelling agent and then gellable fluid may be added to the mixture containing gelling agent and thermally conductive filler [77, 78]. At least one thermally conductive filler may be added after the gellable fluid and gelling agent have gelled [79, 80]. For example, at least one thermally conductive filler may be added to the gel when the gel may be cooled and be loosely networked such that filler can be added. The amount of thermally conductive filler in the thermally reversible gel may vary in different cases. A thermal interface material may include not less than 8 percent but not more than 80 percent by weight of at least one thermally conductive filler. Thermal interface materials are typically composed of an organic matrix highly loaded with a thermally conductive filler. Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the organic matrix. Commonly used fillers exhibit isotropic thermal conductivity and thermal interface materials utilizing these fillers must be highly loaded to achieve the desired thermal conductivity. Unfortunately, these loading levels degrade the properties of the base matrix material, such as flow, cohesion, and interfacial adhesion. Consequently, the thermal interface material formulator must balance matrix performance with thermal conductivity with the net result being a material with less than optimum thermal conductivity. It is desirable to formulate a thermal interface material with as high a thermal conductivity as possible without sacrificing other physical properties. The protruding features may prevent excessive relative movement of the module lid and the heat sink during power or thermal cycling. The protruding features are positioned in a central area of the interface separating the module lid and the heat sink. During thermal cycling, the module lid may bow upward into the central area of the interface, and the heat sink may bow downward into the central area of the interface. This may result in a significant reduction of interface thickness in the central area. By positioning the protruding features in the central area of the interface, the potential reduction of interface thickness in the central area is limited by a distance that the protruding features extend into the interface from the heat sink mating surface. The protruding features include three protruding features that are distributed substantially uniformly along the heat sink mating surface in the central area of the interface. Each of the protruding features has a substantially similar shape. The number of protruding features, the position or distribution of protruding features on the heat sink mating surface, the size or shape of each of the protruding features, or a combination thereof, may vary. As an example, in some cases, the protruding features may be strategically patterned based on characteristics of the individual components of the electronic component cooling assembly, such as characteristics of the heat sink and characteristics of the module lid, among other possible factors.



Figure 6. Transmission electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The effect of pressure on the bond line thickness of the thermal interface material for smooth surfaces is illustrated in Figure 7 for graphite platelets and carbon black. The thermal interface material structures include protruding surface features to reduce thermal interface material migration. The thermal interface material structures incorporate surface features onto a particular mating surface, such that the features protrude into selected areas of an interface separating the particular mating surface from another mating surface. In some cases, the protruding features may be incorporated onto a mating surface of a heat spreader that surrounds an electronic component and distributes heat away from the electronic component [81, 82]. In other cases, the protruding features may be incorporated onto a mating surface of a heat sink that overlies the module lid and is separated from the module lid by the interface [83, 84]. During thermal cycling, a coefficient of thermal expansion mismatch between the module lid and the heat sink may cause relative motion between the module lid and the heat sink [85, 86]. By incorporating surface features that protrude from a mating surface into selected areas of the interface, the potential relative movement of the mating surfaces in the selected areas may be limited [87, 88]. Limiting the relative movement may reduce strain on the thermal interface material in areas of the interface proximate to the protruding features. Reducing the strain on the thermal interface material may reduce the potential for thermal interface material pump-out and the associated increase in thermal resistance due to loss of material from the interface. A heat source dissipates heat using a heat sink that is joined to the heat source by a thermal interface material, such as a thermal grease or a thermal putty. Compressing the thermal interface material between the heat source and

the heat sink may fill an interface gap between a mating surface of the heat source and a mating surface of the heat sink in order to form an interface for efficient removal of heat from the heat source via the heat sink. The heat source and the heat sink may correspond to different materials that have different coefficient values of thermal expansion. Due to the coefficient of thermal expansion mismatch between the heat source and the heat sink, thermal changes associated with thermal cycling cause relative movement of the heat source and the heat sink. To illustrate, during thermal cycling, the heat source may bow upward into a central area of the interface, and the heat sink may bow downward into the central area of the interface, resulting in a significant reduction of interface thickness between the heat source and the heat sink in the central area of the interface. The resulting strain may cause the thermal interface material to migrate away from the central area of the interface over time. Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface. By contrast, the thermal interface material structures incorporate surface features onto a mating surface of a particular heat transfer component of an electronic component cooling assembly that includes two heat transfer components separated by an interface that includes a thermal interface material. The heat spreader surrounds an electronic component and distributes heat away from the electronic component. In some cases, the surface features may be incorporated onto a mating surface of the heat spreader. In other cases, the surface features may be incorporated onto a mating surface of the heat sink.

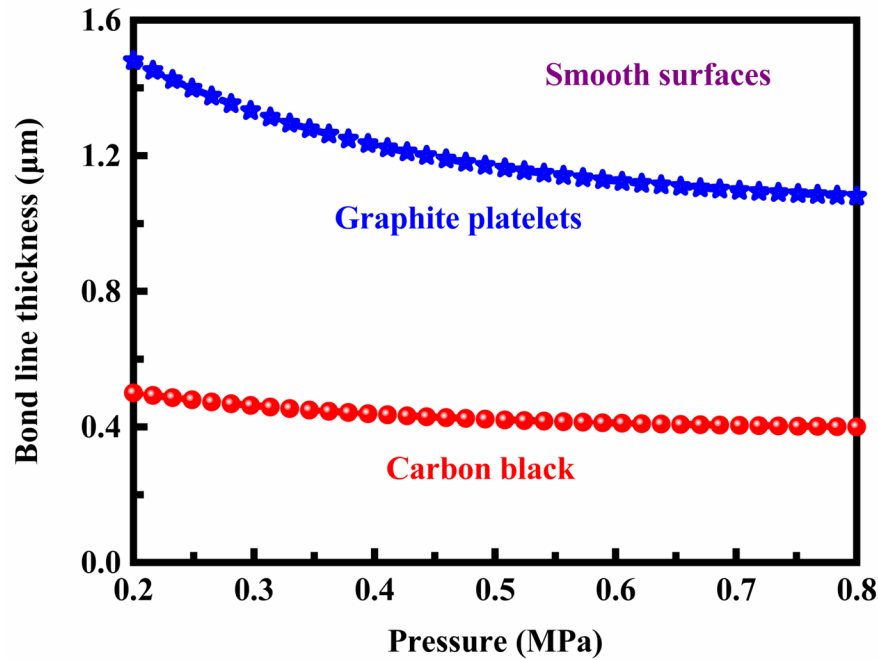


Figure 7. Effect of pressure on the bond line thickness of the thermal interface material for smooth surfaces for graphite platelets and carbon black.

The effect of pressure on the bond line thickness of the thermal interface material for rough surfaces is illustrated in Figure 8 for graphite platelets and carbon black. Typically, information handling systems include a plurality of thermal conducting members such as, for example, processors, integrated heat spreaders, heat sinks, heat transfer dies, and a variety of other thermal conducting materials. As the heat production of thermal conducting members, for example, processors, increases, the transfer of heat between thermal conducting members, for example, the processor, an integrated heat spreader, a heat transfer die, and a heat sink, raises a number of issues. Conventionally, a thermal interface material such as, for example, a thermal grease, a phase change thermal interface material, and a variety of other thermal interface materials, is used between a plurality of thermal conducting members such as, for example, a processor and a heat sink, an

integrated heat spreader and a heat sink, a heat transfer die and a heat sink, and a pair of heat sinks, in order to fill air gaps in the thermal conduction path between the two thermal conducting members. It is optimum to apply an amount of thermal interface material to the interface surfaces between the thermal conducting members such that the thermal interface material engages approximately 100 percent of the interfaces surfaces between the thermal conducting members and completely occupies an interface volume between the thermal conducting members. However, when pressure is applied to engage the thermal conducting members the thermal interface material and then heat is transferred between the thermal conducting members, the thermal interface material thins and spreads across the interface surfaces between the thermal conducting members. This can cause the thermal interface material to flow out of the interface volume between the thermal conducting members and migrate onto, for example, a silicon substrate or a printed circuit board that the thermal conducting members are coupled to. This phenomenon is known as pump out and is accelerated by expansion and contraction of the thermal conducting members during heating and cooling cycles, which results in the loss of the thermal interface material from the interface volume between the thermal conducting members. This can be particularly problematic in some chipsets and processors that include power input pads located adjacent the chipset or processor on the base substrate, as the thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect. As the thermal interface material spreads in the volume between the first thermal conducting member and the second thermal conducting member, the excess of thermal interface material becomes housed in the channel, preventing the excess of thermal interface material from migrating off of the first thermal transfer surface and onto the sensitive top surface and the electrical contacts. The method then proceeds to the step where heat is dissipated from the heat producing component. The heat producing component is operated and produces heat, which is conducted through the first thermal conducting member, the thermal interface material, and the second thermal conducting member. The fins on the second thermal conducting member allow the heat to be dissipated to the ambient. Consequently, an apparatus and method are provided that allow excess thermal interface material being used to help dissipate heat from a heat producing component to be housed such that the excess thermal interface material does not engage sensitive surfaces in the system that could cause failure in the system.

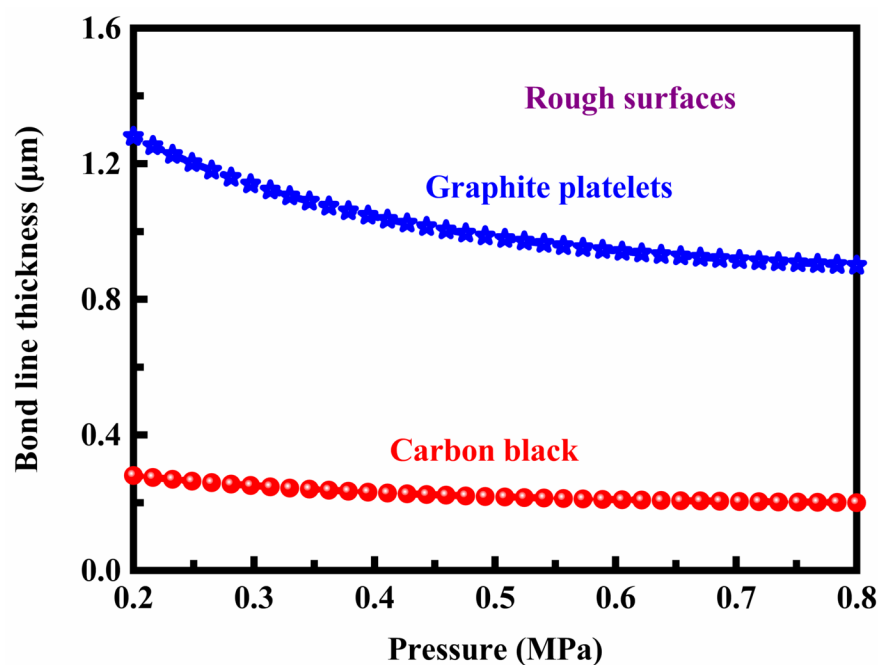


Figure 8. Effect of pressure on the bond line thickness of the thermal interface material for rough surfaces for graphite platelets and carbon black.

4. Conclusions

The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the thermal interface material performance. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets. The major conclusions are summarized as follows:

- Polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink.
- Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact.
- The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal like copper or aluminum and exhibit a relatively high ratio of thermal conductivity to weight.
- Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material.
- Reducing the strain on the thermal interface material may reduce the potential for pump-out and the associated increase in thermal resistance due to loss of material from the interface.
- Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the organic matrix.
- Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface.
- The thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect.

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Heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets

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Abstract

The thermal interface material technologies used for electronic packages encompass several classes of materials. However, there is still a need for thermal interface materials and methods for making thermal interface materials having improved thermal conductivity property by maximizing the anisotropic benefit of exfoliated graphite platelets to the fullest extent. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the material performance. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets. The results indicate that polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink. Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact. The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal and exhibit a relatively high ratio of thermal conductivity to weight. Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material. Reducing the strain on the thermal interface material may reduce the potential for pump-out and the associated increase in thermal resistance due to loss of material from the interface. Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the matrix. Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface. The thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect.

Keywords: Interface materials; Thermoplastic materials; Smooth surfaces; Rough surfaces; Graphite platelets; Carbon black

1. Introduction

In an electronic device, a thermal interface material is a material that is disposed between a heat generating component of an electronic device and a heat dissipating component in order to facilitate efficient heat transfer between the heat generating component and the heat dissipating component [1, 2]. The powering up or powering down of the electronic device may cause temperature changes which may cause a relative motion between the heat generating component and the heat dissipating

component, including in-plane motion and out-of-plane motion due to coefficient of thermal expansion mismatch [3, 4]. With the development of more sophisticated electronic components, including those capable of increasing processing speeds and higher frequencies, having smaller size and more complicated power requirements, and exhibiting other technological advances, such as microprocessors and integrated circuits in electronic and electrical components and systems as well as in other devices such as high-power optical devices, relatively extreme temperatures can be generated [5, 6]. However, microprocessors, integrated circuits, and other sophisticated electronic components typically operate efficiently only under a certain range of threshold temperatures. The excessive heat generated during operation of these components can not only harm their own performance, but can also degrade the performance and reliability of the overall system and can even cause system failure [7, 8]. The increasingly wide range of environmental conditions, including temperature extremes, in which electronic systems are expected to operate, exacerbates these negative effects.

With the increased need for heat dissipation from microelectronic devices caused by these conditions, thermal management becomes an increasingly important element of the design of electronic products [9, 10]. As noted, both performance reliability and life expectancy of electronic equipment are inversely related to the component temperature of the equipment [11, 12]. For instance, a reduction in the operating temperature of a device such as a typical silicon semiconductor can correspond to an exponential increase in the reliability and life expectancy of the device [13, 14]. Therefore, to maximize the life-span and reliability of a component, controlling the device operating temperature within the limits set by the designers is of paramount importance. A thermal management system is designed to assist with this objective. One element of a thermal management system is a thermal interface material [15, 16]. A typical use for a thermal interface material is to thermally connect a computer chip to a cooling module to overcome contact resistance and lack of surface conformity between the heat sink, or the cooling module and the chip or other heat source. Typically, thermal interfaces consist of thermal greases, phase change materials, and tapes [17, 18]. Flexible graphite is readily applicable to such applications because of its low thermal resistance and its ability to conform to the surfaces to be interfaced, especially when either or both surfaces are not completely flat [19, 20]. Such characteristics are important in a thermal management system because reducing the thermal resistance as much as possible is of paramount importance.

The process for manufacturing the flexible graphite used in the thermal interface is well-known [21, 22]. In general, flakes of natural graphite are intercalated in an acid solution. After the flakes are intercalated, they are washed and dried and then exfoliated by exposure to a high temperature for a short period of time. This causes the flakes to expand or exfoliate in a direction perpendicular to the crystalline planes of the graphite [23, 24]. The exfoliated graphite flakes are vermiform in appearance and are therefore commonly referred to as worms. The worms may be compressed into sheets or foils with a density approaching theoretical density although a density of about 1.1 grams per cubic centimeter is considered typical for most applications. The sheets of flexible graphite can be cut into any desired configuration to suit a particular application. Graphite is made up of layer planes of hexagonal arrays or networks of carbon atoms. These layer planes of hexagonally arranged carbon atoms are substantially flat and are oriented or ordered so as to be substantially parallel and equidistant to one another [25, 26]. The substantially flat, parallel equidistant sheets or layers of carbon atoms, usually referred to as graphene layers or basal planes, are linked or bonded together and groups thereof are arranged in crystallites. Highly ordered graphite consists of crystallites of considerable size: the crystallites being highly aligned or oriented with respect to each other and having well-ordered carbon layers. In other words, highly ordered graphite has a high degree of preferred crystallite orientation [27, 28]. It should be noted that graphite possesses anisotropic structures and consequently exhibit or possess many properties that are highly directional such as thermal and electrical conductivity.

The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the thermal interface material performance. The method includes preparing the graphite nanofibers in a herringbone configuration, and dispersing the graphite nanofibers in the herringbone configuration into the thermal interface material. The method further includes applying a magnetic field of sufficient intensity to align the graphite nanofibers in the thermal interface material. Thermal materials are used in packaging as interfaces between devices to dissipate heat from these devices. One typical thermal interface material typically includes a polymer matrix and a thermally conductive filler. As electronic components have become smaller and more densely packed on integrated boards and chips, designers and manufacturers now are faced with the challenge of how to dissipate the heat which is generated by these components. The thermal interface material technologies used for electronic packages encompass several classes of materials, such as phase change materials, epoxies, greases, and gels. However, there is still a need for thermal interface materials and methods for making thermal interface materials having improved thermal conductivity property by maximizing the anisotropic benefit of exfoliated graphite platelets to the fullest extent. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets.

2. Methods

The present study includes a system for aligning graphite nanofibers to enhance thermal interface material performance. The system includes the graphite nanofibers configured in a herringbone configuration and a means for dispersing the graphite nanofibers in the herringbone configuration into the thermal interface material. The system further includes a means for applying a magnetic field of sufficient intensity to align the graphite nanofibers in the thermal interface material. Nanofibers can be produced by interfacial polymerization and electrospinning. Carbon nanofibers are graphitized fibers produced by catalytic synthesis around a catalytic core. The catalytic core around which graphite platelets are formed is called a metal seed or a catalytic metal seed, wherein the catalytic metal seed is a material having magnetic properties such as iron, cobalt, or nickel. Metal-core graphite nanofibers can be grown in numerous shapes around a catalytic metal seed. The metal-core graphite nanofibers comprise of graphite platelets arranged in various orientations with respect to the long axis of the fiber, giving rise to assorted conformations. A magnetic field is applied to the metal catalyst prior to deposition of the graphite nanofibers on the metal-core. With the application of a magnetic field, the magnetic poles of the seed are aligned with the magnetic field and will subsequently carry the attached graphite nanofibers along with them as they rotate in the applied field following deposition.

Conventional manufacture of expanded graphite requires thermal and chemical treatment in order to expand the interlayers without completely breaking or separating the layers between the basal planes. Typically, the expansion is conducted by treating particles of graphite, such as natural graphite flakes, with an intercalant, for example, a solution of sulfuric and nitric acid, such that the crystal structure of the graphite reacts with the acid to form a compound of graphite and the intercalant. Upon exposure to elevated temperatures the particles of intercalated graphite expand in an accordion-like fashion in the direction perpendicular to the crystalline planes of the graphite flakes. The resulting expanded, or exfoliated, graphite particles are vermiform in appearance and are commonly referred to as worms. This expansion of the particles into worms, rather than separation into separate platelets, occurs as a result of the Van der Waals forces securing together the basal planes of the graphite structure. The Van der Waals forces between the basal planes of the graphite prevent complete separation of the leaflets.

Expanded graphite structures may be used as particulate in composite materials, such as polymers, to provide reinforcement and add stiffness, strength and other properties. Attractive benefits of the use of such particulate-filled polymers in materials-intensive industries include low cost, weight reduction, styling potential, superior acoustic characteristics, reduced maintenance and corrosion resistance.

With a diamond shaped catalytic metal seed, the majority of the graphite platelets will align along the fiber axis as dictated by an external magnetic field, so that the catalytic metal seed may have its poles aligned perpendicular to or parallel to the external magnetic field. The seed particles are not limited to elongated diamonds, so that the deposited metal-core graphite nanofiber forms the chevrons. The graphite platelets can assume any of a myriad of shapes. If the catalytic metal seeds are rectangular plates, then the graphite platelets are deposited as plates. If the catalytic metal seeds are cylindrical, then the graphite platelets are deposited as cylindrical plates. If the catalytic metal seeds are little bars, then the graphite platelets are deposited as rectangular solids along the long axis of the rectangular bar. The graphite platelets assume the geometry of the catalytic metal seed surface. A magnetic field of sufficient strength to cause the domains within the catalytic metal seeds to align along the external field is applied. Application of an external magnetic field pre-aligns the magnetic poles of the catalytic metal seed by applying a magnetic field to the catalytic metal seed prior to deposition of the graphite platelets on the metal-core. The chamber is charged with the reactive gas mixture. By judicious choice of the catalytic metal seeds catalyst, the ratio of the hydrocarbon-hydrogen reactant mixture, and reaction conditions, it is possible to tailor the morphological characteristics, the degree of crystallinity, and the orientation of the precipitated graphite crystallites with regard to the fiber axis. The gas mixture thermally decomposes onto the catalytic metal seed to generate the metal-core graphite nanofibers. The metal-core graphite nanofibers can be dispersed in silicone-based gels or pastes that are used as thermal interface materials that are eventually cured into pads.

The thermal interface material having a thickness between a first surface and a second surface opposite the first surface. The thermal interface material further includes a plurality of carbon nanofibers, wherein a majority of the carbon nanofibers are oriented orthogonal to a plane of the first surface and wherein the carbon nanofibers comprise a magnetic catalytic seed. Graphite nanofibers have received considerable attention in the electronics field due to their remarkable thermal conductivity [29, 30]. Moreover, the thermal conductivity of graphite nanofibers is anisotropic [31, 32]. Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies homogeneity in all directions. Therefore, the present study takes advantage of the anisotropic nature of the graphite nanofibers by effectively aligning them along the conductive axis, thereby generating a thermal interface material with exceptional thermal conductivity at comparatively low loading levels. A thermal interface material is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heatsinks, in order to increase thermal transfer efficiency [33, 34]. These gaps are normally filled with air, which is a very poor conductor [35, 36]. A thermal interface material may take on many forms [37, 38]. The most common is the white-colored paste or thermal grease [39, 40]. Some brands of thermal interface materials use micronized or pulverized silver [41, 42]. Another type of thermal interface materials are the phase-change materials [43, 44]. The phase change materials are solid at room temperature, but liquefy and behave like grease at operating temperatures.

A phase change material is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; consequently, phase change materials are classified as latent heat storage units. Phase change materials latent heat storage can be achieved through solid-solid, solid-liquid, solid-gas and liquid-gas phase change. However, the only phase change used for phase change materials is the solid-liquid change. Liquid-gas phase changes are not practical for use as thermal storage due to the large volumes or high pressures required to store the

materials when in their gas phase. Liquid-gas transitions do have a higher heat of transformation than solid-liquid transitions. Solid-solid phase changes are typically very slow and have a rather low heat of transformation. Initially, the solid-liquid phase change materials behave like sensible heat storage materials; their temperature rises as they absorb heat. Unlike conventional sensible heat storage, however, when phase change materials reach the temperature at which they change phase they absorb large amounts of heat at an almost constant temperature. The phase change material continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid-material falls, the phase change material solidifies, releasing its stored latent heat. A large number of phase change materials are available in any required temperature range from -8 up to 200 °C. Within the temperature range of 20 to 60 °C, some phase change materials are very effective.

Graphite starting materials for the flexible sheets suitable for use in the present study include highly graphitic carbonaceous materials capable of intercalating organic and inorganic acids as well as halogens and then expanding when exposed to heat. Examples of highly graphitic carbonaceous materials include natural graphite from various sources, as well as other carbonaceous materials such as carbons prepared by chemical vapor deposition and the like. Natural graphite is most preferred. The graphite starting materials for the flexible sheets used in the present study may contain non-carbon components so long as the crystal structure of the starting materials maintains the required degree of graphitization and they are capable of exfoliation. Generally, any carbon-containing material, the crystal structure of which possesses the required degree of graphitization and which can be exfoliated, is suitable for use with the present study. Natural graphite flakes are intercalated by dispersing the flakes in a solution containing, for example, a mixture of nitric and sulfuric acid, advantageously at a level of about 20 to about 300 parts by weight of intercalant solution per 100 parts by weight of graphite flakes. The intercalation solution contains oxidizing and other intercalating agents. Examples include those containing oxidizing agents and oxidizing mixtures. Alternatively, an electric potential can be used to bring about oxidation of the graphite. Chemical species that can be introduced into the graphite crystal using electrolytic oxidation include sulfuric acid as well as other acids. The quantity of intercalation solution may range from about 20 to about 200 parts per hundred. After the flakes are intercalated, any excess solution is drained from the flakes and the flakes are water-washed.

The particles of graphite flake treated with intercalation solution can optionally be contacted by blending, with a reducing organic agent selected from alcohols, aldehydes, and esters, which are reactive with the surface film of oxidizing intercalating solution at temperatures in the range of 25 °C and 125 °C. The organic reducing agent increases the expanded volume upon exfoliation and is referred to as an expansion aid. The amount of organic reducing agent is suitably from about 0.8 to 8 percent by weight of the particles of graphite flake. Another class of expansion aids that can be added to the intercalating solution, or to the graphite flake prior to intercalation, and work synergistically with the above-described organic reducing agents are carboxylic acids. An expansion aid in this context will advantageously be sufficiently soluble in the intercalation solution to achieve an improvement in expansion. More narrowly, organic materials of this type that contain carbon, hydrogen and oxygen, preferably exclusively, may be employed. Suitable organic solvents can be employed to improve solubility of an organic expansion aid in the intercalation solution. Sulfuric acid, nitric acid and other known aqueous intercalants have the ability to decompose formic acid, ultimately to water and carbon dioxide. Because of this, formic acid and other sensitive expansion aids are advantageously contacted with the graphite flake prior to immersion of the flake in aqueous intercalant. The intercalation solution will be aqueous and will preferably contain an amount of carboxylic acid expansion aid of from about 0.2 percent to about 8 percent, the amount being effective to enhance exfoliation. Formic acid is contacted with the graphite flake prior to immersing in the aqueous intercalation solution, it can be

admixed with the graphite by suitable means, typically in an amount of from about 0.2 percent to about 8 percent by weight of the graphite flake.

3. Results and discussion

The low-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 1 for the production of the thermal interface material. Metal heat spring thermal interface materials can be made to preferentially release from a desired surface by adding a metal clad aluminum foil, but require a high pressure in order to provide effective contact, minimize thermal resistance, and fill any interface gaps [45, 46]. Typically, some form of mechanical retention hardware is used to ensure adequate contact and optimal performance [47, 48]. Unfortunately, clamping forces of the mechanical retention hardware can damage the semiconductor component [49, 50]. The metal spring thermal interface materials also suffer from low elasticity, poor gap filling, and the potential for micro motion induced oxidation over time [51, 52]. Furthermore, the aluminum foil release layer can negatively affect thermal performance. Polymeric elastomer materials may be used as a thermal interface material [53, 54]. The thermal properties of polymeric elastomer materials can be modified with the addition of various forms of carbon, for example graphene layers, graphite flake, carbon fibers, or carbon nanotubes [55, 56]. Polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink. However, like the metal heat spring thermal interface materials, polymeric elastomer materials also require high pressures in order to adequately fill interface gaps. Also like the metal heat spring thermal interface materials, excess pressure can cause damage to the semiconductor component, for example, cracking. Polymeric elastomer materials adhesively bond to surface of both the semiconductor component and the heat sink. If future removal of the heat sink is required, the risk of damaging the semiconductor component or the thermal interface material is high due to the adhesive properties, for example the inherent tackiness, of polymeric elastomer materials. Although conventional release layers, such as, for example, non-stick polymers or aluminum foil, can be applied to polymeric elastomer materials, they create an insulative barrier and degrade thermal performance. Expanded graphite materials may be used as a thermal interface material. Expanded graphite materials are available at relatively low cost, have good thermal performance and excellent dimensional compliance or gap filling capability, and release cleanly from device surfaces for easy reuse during semiconductor component repair or replacement. However, expanded graphite materials have limited elasticity and are not easily reusable for different surface topologies. Carbon nanotube materials may be used as a thermal interface material. Carbon nanotube materials include sheets of densely packed, generally vertically aligned and intertwined. Carbon nanotube materials offer extremely high thermal conductivity and thus excellent thermal performance. Carbon nanotube materials are durable and reusable, but have extremely limited elasticity and gap filling capabilities and require high mechanical loads to enable good thermal performance. Carbon nanotube materials are also relatively expensive to manufacture, and as such, are typically used as thermal beds on testers for lidded modules where high loads can be used without component damage and extremely high component test volumes are anticipated. Flexible graphite materials may also be used for their superior heat transfer properties. Flexible graphite materials generally have poor gap filling capabilities. Thermal grease or thermal gel may be used as a thermal interface material. Thermal grease or thermal gel is typically filled with various forms of thermally conductive media, such as, for example, carbon, metal particles, ceramic particles, or metal oxide particles. These materials have reasonable thermal performance and gap fill capability, but must be dispensed or printed onto surfaces. After being applied, thermal gel must be thermally cured as they rely on adhesive bonding at device and cooling hardware surfaces to ensure stable interface performance. Neither thermal grease nor thermal gel meets suitable reuse requirements.

Phase change material may be used as a thermal interface material. Phase change material is a substance which can change from a solid to liquid at a certain temperature, for example, at room temperature. The phase change material absorbs heat when changing from a solid to a liquid, and releases heat when changing from a liquid to a solid. Advantages of phase change material include superior gap filling capability and good thermal performance.

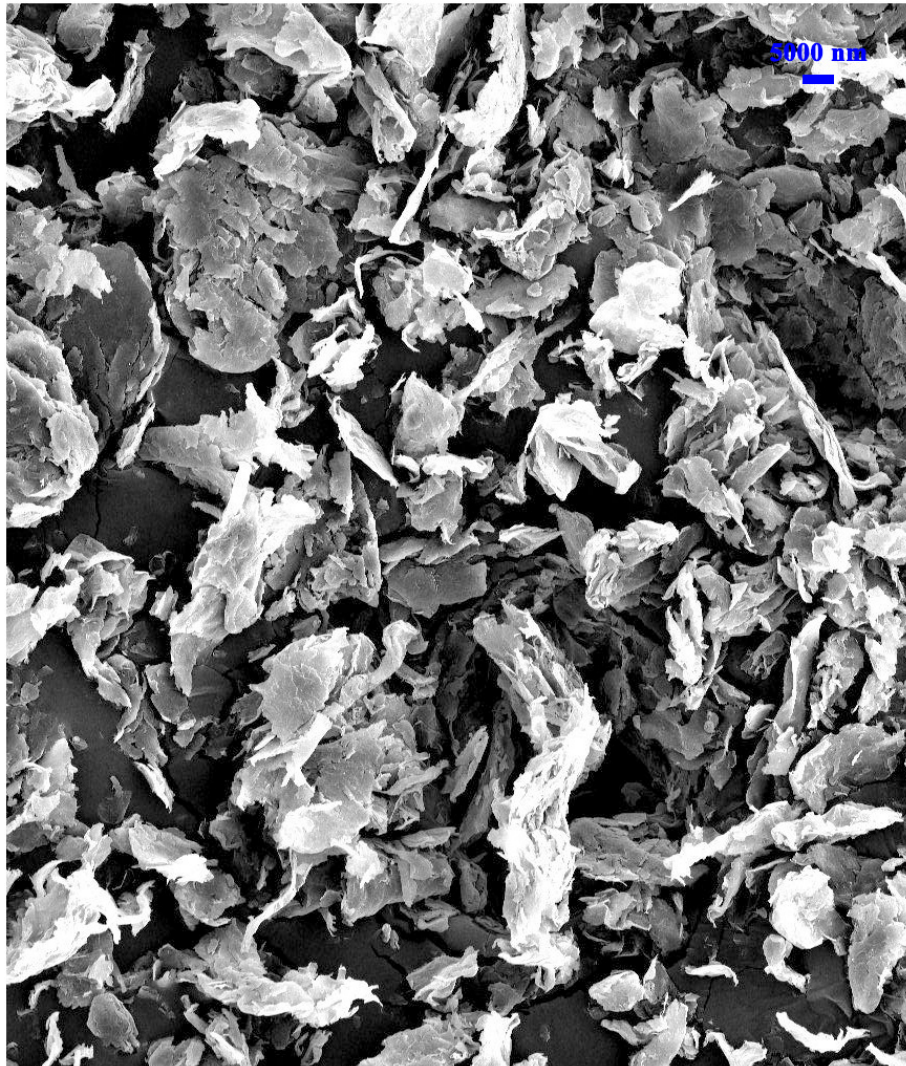


Figure 1. Low-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The moderate-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 2 for the production of the thermal interface material. It is well known that many electronic components, and especially power semiconductor components such as transistors and microprocessors, are more prone to failure or malfunction at high temperatures [57, 58]. Consequently, the ability to dissipate heat often is a limiting factor on the performance of the component. Heat dissipation may be affected by the direct mounting of the electronic component to a thermal dissipation member such as a cold plate or other heat sink or spreader. The dissipation member may be a dedicated, thermally-conductive ceramic or metal plate or finned structure, or simply the chassis or circuit board of the device [59, 60]. However, beyond the normal temperature gradients between the electronic component and the dissipation member, an appreciable temperature gradient is developed as a thermal interfacial impedance or contact resistance at the interface between the bodies [61, 62]. The thermal interface surfaces of the component and heat sink typically are irregular, either on a gross or a microscopic scale [63, 64]. When the interfaces surfaces are mated, pockets or void spaces are

developed therebetween in which air may become entrapped. These pockets reduce the overall surface area contact within the interface which, in turn, reduces the heat transfer area and the overall efficiency of the heat transfer through the interface. To improve the heat transfer efficiency through the interface, a thermal interface material may be used to fill the gap between the heat sink and electronic component to fill in any surface irregularities and eliminate air pockets. The thermal interface material may be a pad or other layer of a thermally-conductive, electrically-insulating material. Even in a direct contact, however, the processor and the attach block do not transfer heat efficiently, because the quality of contact between two non-conforming solid surfaces is typically poor. A thermal interface material may therefore be inserted between the processor and the attach block in order to enhance the thermal contact between the two surfaces. Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact. The quality of the contact between the processor and the attach block, or thermal interface material performance, depends on the quality of the thermal conduction through the thermal interface material and the quality of contact between the thermal interface material and the two surfaces. Consequently, a precise material tester capable of providing precise measurements of thermal interface material performance may be useful to improve overall thermal solution designs for notebooks and other devices.

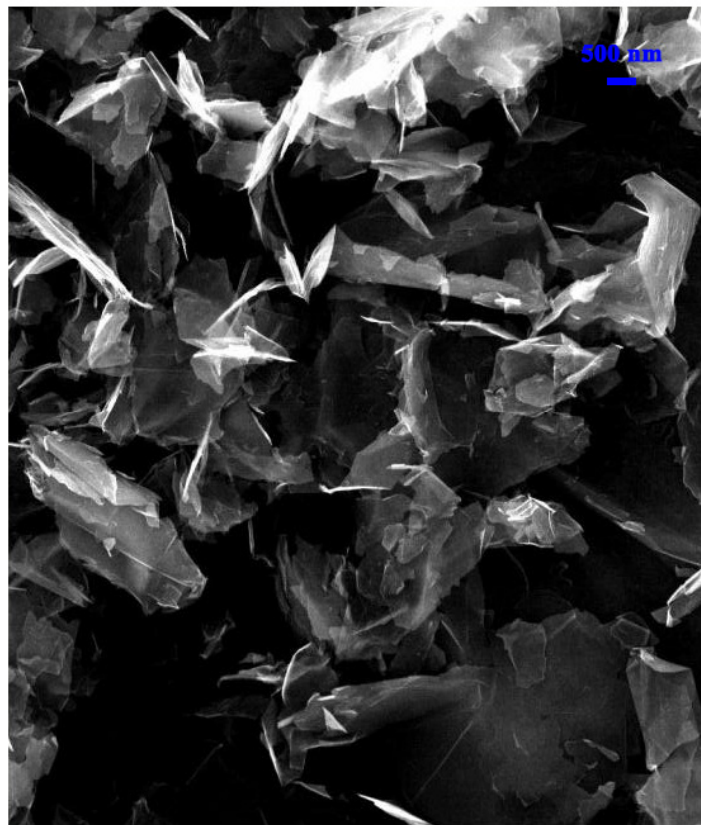


Figure 2. Moderate-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The effect of thermal interface material thickness on the thermal resistivity of the thermal contact is illustrated in Figure 3 for graphite platelets and carbon black. The heat dissipating components facilitate heat dissipation from the surface of a heat source, such as a heat-generating electronic device, to a cooler environment, usually air [65, 66]. In many typical situations, heat transfer between the solid surface of the electronic device and the air is the least efficient within the system, and the solid-air interface consequently represents the greatest barrier for heat dissipation [67, 68]. The heat dissipating

components seek to increase the heat transfer efficiency between the electronic device and the ambient air primarily by increasing the surface area that is in direct contact with the air or other heat transfer media. This allows more heat to be dissipated and consequently lowers the electronic device operating temperature. The primary purpose of a heat dissipating component is to help maintain the device temperature below the maximum allowable temperature specified by its designer or manufacturer [69, 70]. Typically, the heat dissipating components are formed of a metal, especially copper or aluminum, due to the ability of metals like copper to readily absorb heat and transfer it about its entire structure. In the case of heat sinks, copper heat sinks are often formed with fins or other structures to increase the surface area of the heat sink, with air being forced across or through the fins to effect heat dissipation from the electronic component, through the copper heat sink and then to the air [71, 72]. Limitations exist, however, with the use of metallic heat dissipating components. One limitation relates to the relative isotropy of a metal that is, the tendency of a metallic structure to distribute heat relatively evenly about the structure. The isotropy of a metal means that heat transmitted to a metallic heat dissipating component becomes distributed about the structure rather than being preferentially directed to a desired location. In addition, the use of copper or aluminum heat dissipating elements can present a problem because of the weight of the metal, particularly when the heat transmitting area of the heat dissipating component is significantly larger than that of the electronic device. For example, several heat sinks need to be arrayed on a circuit board to dissipate heat from a variety of components on the board. If metallic heat sinks are employed, the sheer weight of the metal on the board can increase the chances of the board cracking or of other equally undesirable effects, and increases the weight of the component itself. In the case of larger heat dissipating components such as for example that class of components known as heat spreaders, the weight of a pure copper heat spreader requires special mechanical features and designs to hold the heat spreader. What is desired, therefore, is a heat dissipating component effective for dissipating heat from a heat source such as an electronic device. The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal like copper or aluminum and exhibit a relatively high ratio of thermal conductivity to weight. One group of materials suitable for use in heat sinks are those materials generally known as graphite, but in particular anisotropic graphite such as those based on natural graphite and flexible graphite.

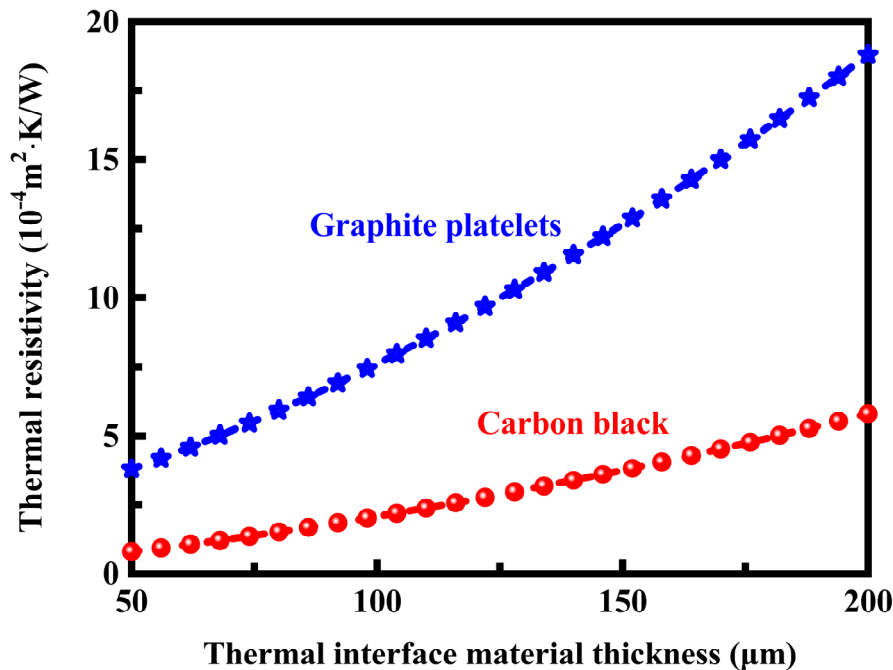


Figure 3. Effect of thermal interface material thickness on the thermal resistivity of the thermal contact for graphite platelets and carbon black.

The effect of filler volume fraction on the thermal conductivity of the thermal interface material is illustrated in Figure 4 for graphite platelets and carbon black. In most polymer composite applications, the resin system is mixed with expanded graphite, chopped fibers or other additives for processing and durability requirements and sometimes with fillers for further cost reduction. These additives are incorporated into the polymer in specific amounts in order to customize properties of the resulting composite. Additionally, thermal, electrical, and mechanical properties are all affected by the form and matter of the particulate in polymers. Desired properties can be obtained by varying filler content and process techniques. However, the orientation and accommodation of the particulate in the component may cause weak areas, susceptible to crack initiation and propagation at sharp bends. Thermal interface materials are used between heat-generating components and heat sinks to establish heat-conduction paths therebetween. However, thermal interface materials provide a thermally conducting heat path that is substantially contained between the heat generating components and the heat sink, which results in a relative narrow heat conduction path that causes heat to be localized around the electronic component. That is, a substantial portion of heat generated by the electronic component is conducted via the path of least impedance through the thermal interface material that lies directly between the electronic component and the heat sink. This results in limited heat spreading throughout the thermal interface material and the heat sink. Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material. Flexible heat-spreading materials may generally refer to and include a wide range of materials having flexibility equal to or greater than a sheet of stamped aluminum and flexibility equal to or greater than a sheet of stamped copper. Within the flexible heat-spreading material, heat laterally spreads out such that there will be more surface area from which heat may be transferred from the flexible heat-spreading material. The greater surface area due to the laterally spreading of the heat may increase and improve the heat transfer efficiency associated with the flexible heat-spreading material and the overall thermally-conductive interface assembly. Heat may be transferred from the flexible heat-spreading material via conduction in the normal direction to an outer layer of thermal interface material, in which flexible heat-spreading material is sandwiched between, bonded to, or encapsulated within layers of thermal interface material. Heat may be transferred from the flexible heat-spreading material via convection to air or other ambient environment, in which a heat-spreading material includes thermal interface material on only one side such that other side of the heat-spreading material is exposed to air or another ambient environment. In cases in which thermal interface material is on or along only one side of a heat-spreading material, and the thickness of the thermal interface material may be greater than the thickness of the flexible heat-spreading material. Alternatively, the thickness of the thermal interface material may be about equal to or less than the thickness of the flexible heat-spreading material in other cases. In cases in which flexible heat-spreading material is sandwiched between, bonded to, or encapsulated within layers of thermal interface material, the layers of thermal interface material along one side of the flexible heat-spreading material may be thicker, thinner, or about equal to the layers of thermal interface material along the other or opposite side of the flexible heat-spreading material. For example, a flexible heat-spreading material may have inner and outer layers of thermal interface material, where the inner layer, which is intended to contact one or more electronic components, is thicker than the outer layer. Thermally-conductive interface assemblies include one or more outer layers of soft thermal interface materials that are relatively flexible, soft, and thin, for example, for good conformance with a mating surface. This, in turn, may help lower thermal impedance as thermal impedance depends upon the degree of effective surface area contact therebetween. The ability to conform to a mating surface tends to be important as the surfaces of a heat sink and a heat-generating component are typically not perfectly flat and smooth, such that air gaps or spaces tend to appear between the irregular mating surfaces.

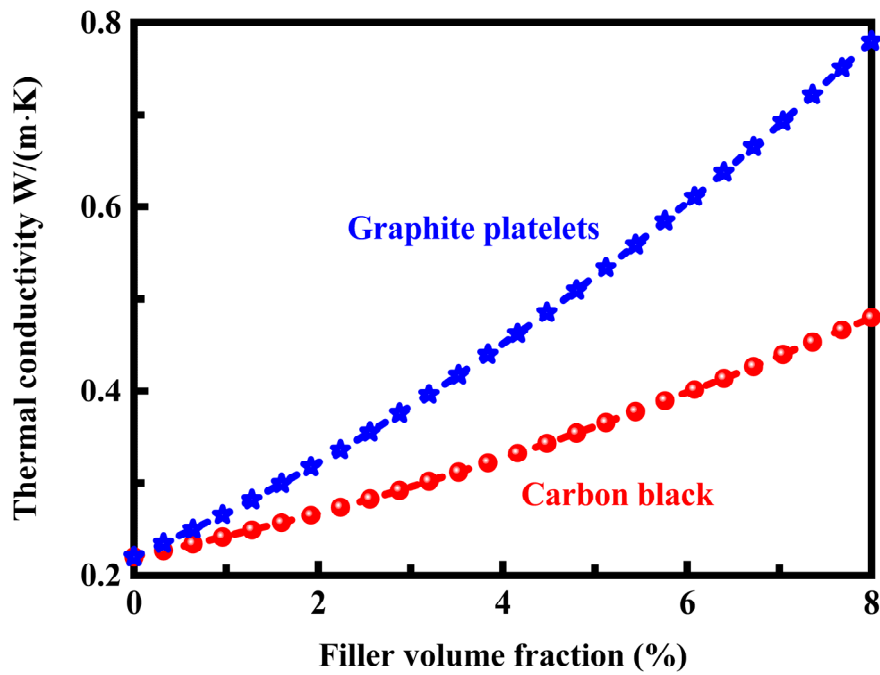


Figure 4. Effect of filler volume fraction on the thermal conductivity of the thermal interface material for graphite platelets and carbon black.

The high-resolution scanning electron micrographs of the exfoliated graphite platelets are illustrated in Figure 5 for the production of the thermal interface material. Conventional polymeric thermal interface materials may be used as the thermal interface material. However, currently used polymeric thermal interface materials are typically cure in place silicone gel materials that are required to be shipped and stored frozen. They also have short pot lives upon opening, short shelf lives, and require special dispensing equipment to apply. Therefore, it is necessary to eliminate, avoid, or at least reduce these aforementioned drawbacks associated with conventional polymeric thermal interface materials. A thermal interface material in the form of a pad of self-healing, thermoplastic material may or may not be naturally tacky. The thermal interface material may have a softening or melting temperature higher than a normal operating temperature of a central processing unit, for example, normal operating temperature from about 60 °C to about 100 °C or from about 30 °C to about 40 °C. Consequently, the pad of thermoplastic material will soften or melt once, for example, during an adhesive curing stage or during an initial operation of the central processing unit, and then solidify. Thereafter, the pad of thermoplastic material may be used below its softening or melting temperature and remain solidified. The thermal interface material comprises a thermoplastic phase change material having a softening or melting point temperature that falls within a range from about 80 °C to about 200 °C or about 100 °C to about 180 °C. Or, for example, the thermal interface material may have a softening or melting temperature of about 40 °C, 60 °C, or 80 °C. The thermal interface material may have a thermal conductivity of about 0.8 Watts per meter per Kelvin or more, or 2.0 Watts per meter per Kelvin or more, which thermal conductivity may be enhanced by incorporating thermally-conductive filler into the thermoplastic material. The thermal interface material may comprise a low melting alloy having a melting temperature of about 200 °C or less. The surface features protrude from the mating surface of the particular heat transfer component into selected areas of the interface. The protruding features may limit the relative movement of the mating surfaces in the selected areas of the interface during thermal cycling due to coefficient of thermal expansion mismatch. Limiting the relative movement may reduce strain on the thermal interface material in areas of the interface proximate to the protruding features. Reducing the strain on the thermal interface material may reduce the potential for thermal interface material pump-out and the associated increase in thermal resistance due to loss of

material from the interface. The protruding features are incorporated onto the heat sink and protrude out from the heat sink mating surface into selected areas of the interface between the heat sink mating surface and the module lid mating surface. The protruding features may be incorporated onto the heat sink through a forming process during manufacturing of the heat sink. Channels may be machined or otherwise incorporated into the heat sink, and the channels may be filled with a material that is appropriate for the heat sink in order to form the protruding features. In some cases, the heat sink may be formed from a heat sink material, such as an aluminum-based material or a copper-based material, among other alternative materials. When the heat sink is formed from an aluminum-based material, the channels may be filled with an aluminum-based material that is the same as the aluminum-based material of the heat sink or that is substantially similar to the aluminum-based material of the heat sink. Alternatively, with respect to the example in which the heat sink is formed from an aluminum-based material, the channels may be filled with other materials compatible with the aluminum-based material for efficient transfer of heat to the heat sink.

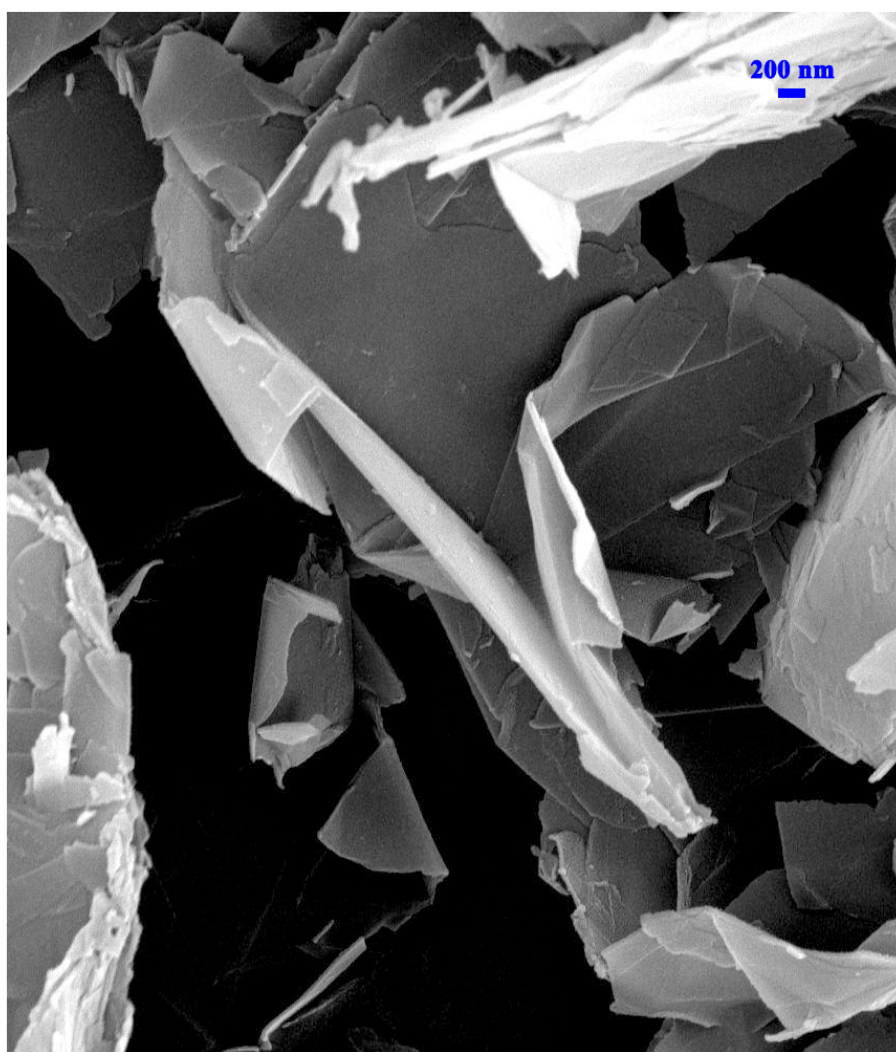


Figure 5. High-resolution scanning electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The transmission electron micrographs of the exfoliated graphite platelets are illustrated in Figure 6 for the production of the thermal interface material. Some of particulate-filled polymers are conductive polymers. Although almost all plastics, whether thermoplastic polymers or thermosetting polymers, are intrinsically good electrical insulators, introduction of graphitic and other carbonaceous materials into the polymers can create electrical conduction paths in the insulating polymer matrix

when these particles contact each other above a certain content, or critical volume fraction. Graphite, in general, can be used along with specially-processed electroconductive carbon black as a filler to provide electrical and thermal conductivity to normally non-conducting or poorly conducting polymeric materials. However, the size and morphological characteristics of conventional graphite particles limit the extent that the properties of a polymer composite can be improved. A first thermal interface material or layers may be used between an integrated heat spreader or lid and the heat generating components or device to reduce hot spots and generally reduce the temperature of the heat generating components or device. A second thermal interface material or layers may be used between the integrated heat spreader and the heat sink to increase thermal transfer efficiency from the heat spreader to the heat sink. One or more thermally conductive fillers may be added to create a thermally conductive interface material in which one or more thermally conductive fillers will be suspended in, added to, and mixed into, the thermally reversible gel. For example, at least one thermally conductive filler may be added to a mixture including gellable fluid and gelling agent before the gellable fluid and gelling agent have gelled or form the thermally reversible gel [73, 74]. At least one thermally conductive filler may be added to the gellable fluid and then gelling agent may be added to the mixture containing gellable fluid and thermally conductive filler [75, 76]. At least one thermally conductive filler may be added to the gelling agent and then gellable fluid may be added to the mixture containing gelling agent and thermally conductive filler [77, 78]. At least one thermally conductive filler may be added after the gellable fluid and gelling agent have gelled [79, 80]. For example, at least one thermally conductive filler may be added to the gel when the gel may be cooled and be loosely networked such that filler can be added. The amount of thermally conductive filler in the thermally reversible gel may vary in different cases. A thermal interface material may include not less than 8 percent but not more than 80 percent by weight of at least one thermally conductive filler. Thermal interface materials are typically composed of an organic matrix highly loaded with a thermally conductive filler. Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the organic matrix. Commonly used fillers exhibit isotropic thermal conductivity and thermal interface materials utilizing these fillers must be highly loaded to achieve the desired thermal conductivity. Unfortunately, these loading levels degrade the properties of the base matrix material, such as flow, cohesion, and interfacial adhesion. Consequently, the thermal interface material formulator must balance matrix performance with thermal conductivity with the net result being a material with less than optimum thermal conductivity. It is desirable to formulate a thermal interface material with as high a thermal conductivity as possible without sacrificing other physical properties. The protruding features may prevent excessive relative movement of the module lid and the heat sink during power or thermal cycling. The protruding features are positioned in a central area of the interface separating the module lid and the heat sink. During thermal cycling, the module lid may bow upward into the central area of the interface, and the heat sink may bow downward into the central area of the interface. This may result in a significant reduction of interface thickness in the central area. By positioning the protruding features in the central area of the interface, the potential reduction of interface thickness in the central area is limited by a distance that the protruding features extend into the interface from the heat sink mating surface. The protruding features include three protruding features that are distributed substantially uniformly along the heat sink mating surface in the central area of the interface. Each of the protruding features has a substantially similar shape. The number of protruding features, the position or distribution of protruding features on the heat sink mating surface, the size or shape of each of the protruding features, or a combination thereof, may vary. As an example, in some cases, the protruding features may be strategically patterned based on characteristics of the individual components of the electronic component cooling assembly, such as characteristics of the heat sink and characteristics of the module lid, among other possible factors.



Figure 6. Transmission electron micrographs of the exfoliated graphite platelets for the production of the thermal interface material.

The effect of pressure on the bond line thickness of the thermal interface material for smooth surfaces is illustrated in Figure 7 for graphite platelets and carbon black. The thermal interface material structures include protruding surface features to reduce thermal interface material migration. The thermal interface material structures incorporate surface features onto a particular mating surface, such that the features protrude into selected areas of an interface separating the particular mating surface from another mating surface. In some cases, the protruding features may be incorporated onto a mating surface of a heat spreader that surrounds an electronic component and distributes heat away from the electronic component [81, 82]. In other cases, the protruding features may be incorporated onto a mating surface of a heat sink that overlies the module lid and is separated from the module lid by the interface [83, 84]. During thermal cycling, a coefficient of thermal expansion mismatch between the module lid and the heat sink may cause relative motion between the module lid and the heat sink [85, 86]. By incorporating surface features that protrude from a mating surface into selected areas of the interface, the potential relative movement of the mating surfaces in the selected areas may be limited [87, 88]. Limiting the relative movement may reduce strain on the thermal interface material in areas of the interface proximate to the protruding features. Reducing the strain on the thermal interface material may reduce the potential for thermal interface material pump-out and the associated increase in thermal resistance due to loss of material from the interface. A heat source dissipates heat using a heat sink that is joined to the heat source by a thermal interface material, such as a thermal grease or a thermal putty. Compressing the thermal interface material between the heat source and the heat sink may fill an

interface gap between a mating surface of the heat source and a mating surface of the heat sink in order to form an interface for efficient removal of heat from the heat source via the heat sink. The heat source and the heat sink may correspond to different materials that have different coefficient values of thermal expansion. Due to the coefficient of thermal expansion mismatch between the heat source and the heat sink, thermal changes associated with thermal cycling cause relative movement of the heat source and the heat sink. To illustrate, during thermal cycling, the heat source may bow upward into a central area of the interface, and the heat sink may bow downward into the central area of the interface, resulting in a significant reduction of interface thickness between the heat source and the heat sink in the central area of the interface. The resulting strain may cause the thermal interface material to migrate away from the central area of the interface over time. Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface. By contrast, the thermal interface material structures incorporate surface features onto a mating surface of a particular heat transfer component of an electronic component cooling assembly that includes two heat transfer components separated by an interface that includes a thermal interface material. The heat spreader surrounds an electronic component and distributes heat away from the electronic component. In some cases, the surface features may be incorporated onto a mating surface of the heat spreader. In other cases, the surface features may be incorporated onto a mating surface of the heat sink.

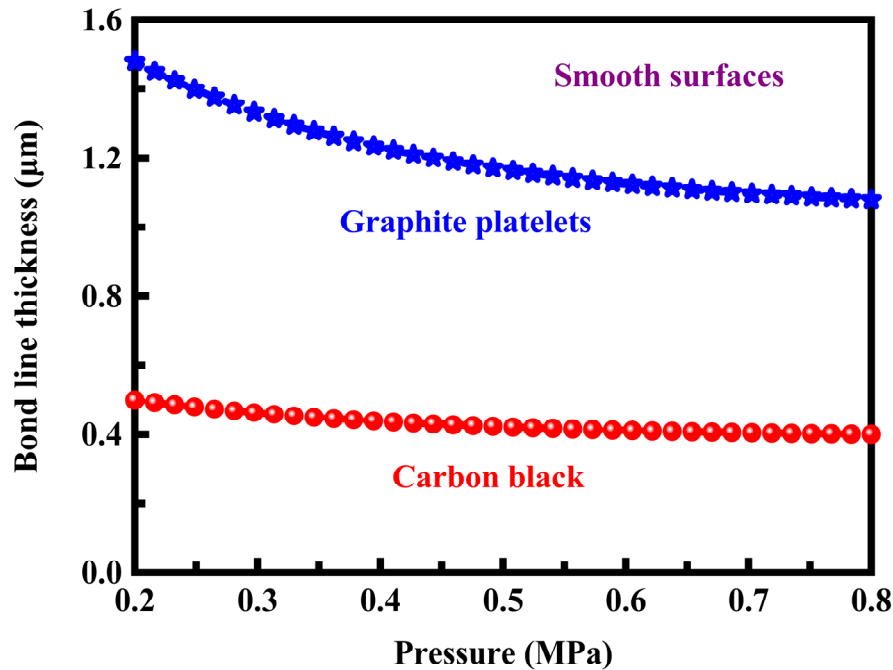


Figure 7. Effect of pressure on the bond line thickness of the thermal interface material for smooth surfaces for graphite platelets and carbon black.

The effect of pressure on the bond line thickness of the thermal interface material for rough surfaces is illustrated in Figure 8 for graphite platelets and carbon black. Typically, information handling systems include a plurality of thermal conducting members such as, for example, processors, integrated heat spreaders, heat sinks, heat transfer dies, and a variety of other thermal conducting materials. As the heat production of thermal conducting members, for example, processors, increases, the transfer of heat between thermal conducting members, for example, the processor, an integrated heat spreader, a heat transfer die, and a heat sink, raises a number of issues. Conventionally, a thermal interface material such as, for example, a thermal grease, a phase change thermal interface material, and a variety of other thermal interface materials, is used between a plurality of thermal conducting members such as, for example, a processor and a heat sink, an integrated heat spreader and a heat sink, a heat transfer die and a heat sink, and a pair of heat sinks, in order to fill air gaps in the thermal

conduction path between the two thermal conducting members. It is optimum to apply an amount of thermal interface material to the interface surfaces between the thermal conducting members such that the thermal interface material engages approximately 100 percent of the interfaces surfaces between the thermal conducting members and completely occupies an interface volume between the thermal conducting members. However, when pressure is applied to engage the thermal conducting members the thermal interface material and then heat is transferred between the thermal conducting members, the thermal interface material thins and spreads across the interface surfaces between the thermal conducting members. This can cause the thermal interface material to flow out of the interface volume between the thermal conducting members and migrate onto, for example, a silicon substrate or a printed circuit board that the thermal conducting members are coupled to. This phenomenon is known as pump out and is accelerated by expansion and contraction of the thermal conducting members during heating and cooling cycles, which results in the loss of the thermal interface material from the interface volume between the thermal conducting members. This can be particularly problematic in some chipsets and processors that include power input pads located adjacent the chipset or processor on the base substrate, as the thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect. As the thermal interface material spreads in the volume between the first thermal conducting member and the second thermal conducting member, the excess of thermal interface material becomes housed in the channel, preventing the excess of thermal interface material from migrating off of the first thermal transfer surface and onto the sensitive top surface and the electrical contacts. The method then proceeds to the step where heat is dissipated from the heat producing component. The heat producing component is operated and produces heat, which is conducted through the first thermal conducting member, the thermal interface material, and the second thermal conducting member. The fins on the second thermal conducting member allow the heat to be dissipated to the ambient. Consequently, an apparatus and method are provided that allow excess thermal interface material being used to help dissipate heat from a heat producing component to be housed such that the excess thermal interface material does not engage sensitive surfaces in the system that could cause failure in the system.

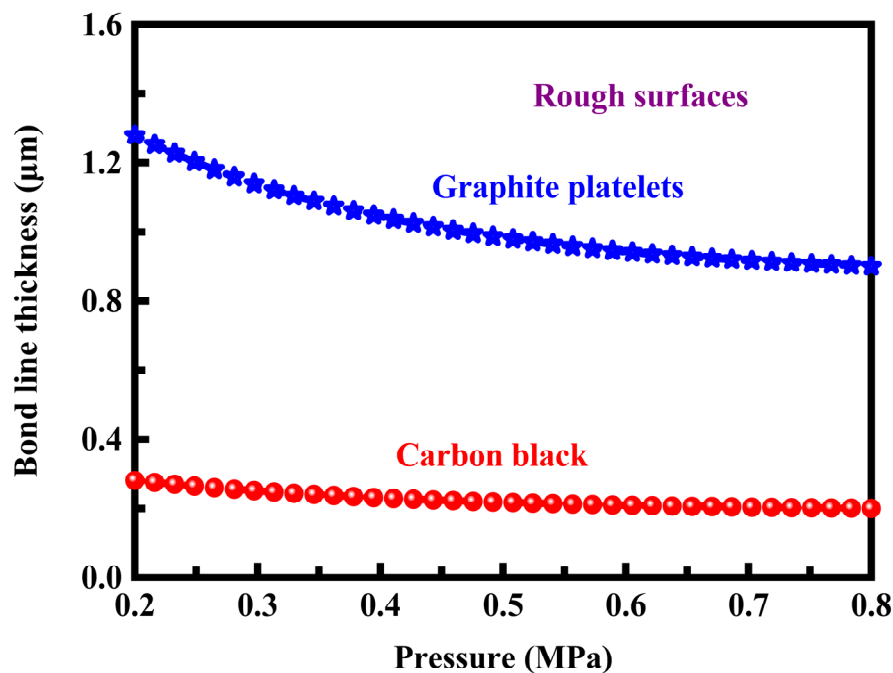


Figure 8. Effect of pressure on the bond line thickness of the thermal interface material for rough surfaces for graphite platelets and carbon black.

4. Conclusions

The present study aims to provide a thermal interface material with aligned graphite nanofibers in the thermal interface material to enhance the thermal interface material performance. The effect of filler volume fraction on the thermal resistivity of the thermal contact and the thermal conductivity of the thermal interface material is investigated for graphite platelets and carbon black. The effect of pressure on the bond line thickness of the thermal interface material is evaluated for smooth and rough surfaces. Particular emphasis is placed upon the heat conduction properties of thermally conductive interface materials with exfoliated graphite platelets. The major conclusions are summarized as follows:

- Polymeric elastomer materials offer both high thermal performance and reasonable gap filling capability to enable good contact between a semiconductor component and a heat sink.
- Under mechanical pressure, the soft thermal interface material conforms to the microscopic surface contours of the adjacent solid surfaces and increases the microscopic area of contact between the thermal solution surface and the silicon die surface and therefore reduces the temperature drop across this contact.
- The heat dissipating component should advantageously be relatively anisotropic, as compared to a metal like copper or aluminum and exhibit a relatively high ratio of thermal conductivity to weight.
- Thermal interface materials provide a limited heat-conduction path and may include flexible heat-spreading materials and one or more layers of soft thermal interface material.
- Reducing the strain on the thermal interface material may reduce the potential for pump-out and the associated increase in thermal resistance due to loss of material from the interface.
- Thermal conductivity is driven primarily by the nature of the filler, which is randomly and homogeneously distributed throughout the organic matrix.
- Pump-out of the thermal interface material results in increased thermal resistance due to loss of material from the interface.
- The thermal interface material can migrate out of the interface volume between the thermal conducting members and onto the power input pads, resulting in excessive heating and part failure at the power interconnect.

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