

HIGH PERFORMANCE THERMAL INTERFACE MATERIALS WITH LOW THERMAL IMPEDANCE

FIELD OF THE INVENTION

[0001] The present disclosure relates generally to thermal interface materials, and more particularly to thermal interface materials including a phase change material.

DESCRIPTION OF RELATED ART

[0002] Thermal interface materials are widely used to dissipate heat from electronic components, such as central processing units, video graphics arrays, servers, game consoles, smart phones, LED boards, and the like. Thermal interface materials are typically used to transfer excess heat from the electronic component to a heat spreader, then transfer heat to a heat sink.

[0003] Figure 1 schematically illustrates an electronic chip 10, including a silicon die 12, a printed circuit board 14, and a plurality of flip chip joints 16 on the printed circuit board 14. The electronic chip 10 is illustratively connected to a heat spreader 18 and a heat sink 20 by one or more first thermal interface materials (TIM) 22. As illustrated in Figure 1, a first TIM 22A connects the heat sink 20 and heat spreader 18 and a second TIM 22B connects the heat spreader 18 and silicon die 12 of electronic chip 10. One or both of thermal interface materials 22A, 22B may be a thermal interface material as described below.

[0004] TIM 22A is designated as a TIM 2 and is positioned between a heat spreader 18 and a heat sink 20, such that a first surface of TIM 22A is in contact with a surface of heat spreader 18 and a second surface of TIM 22A is in contact with a surface of heat sink 20.

[0005] TIM 22B is designated as a TIM 1 and is positioned between an electronic chip 10 and a heat spreader 18 such that a first surface of TIM 22B is in contact with a surface of electronic chip 34, such as a surface of silicon die 12, and a second surface of TIM 22B is in contact with a surface of heat spreader 18.

[0006] In some embodiments (not shown), the TIM 22 is designated as a TIM 1.5 and positioned between an electronic chip 10 and a heat sink 20, such that a first

surface of TIM 22 is in contact with a surface of electronic chip 10, such as a surface of silicon die 12, and a second surface of TIM 2 is in contact with a surface of heat sink 22.

[0007] Thermal interface materials include thermal grease, grease-like materials, elastomer tapes, and phase change materials. Traditional thermal interface materials include components such as gap pads and thermal pads. Exemplary thermal interface materials are disclosed in the following patents and applications, the disclosures of which are hereby incorporated by reference in their entirety: CN 103254647, CN 103254647, JP 0543116, U.S. 6,238,596, U.S. 6,451,422, U.S. 6,500,891, U.S. 6,605,238, U.S. 6,673,434, U.S. 6,706,219, U.S. 6,797,382, U.S. 6,811,725, U.S. 6,874,573, U.S. 7,172,711, U.S. 7,147,367, U.S. 7,244,491, U.S. 7,867,609, U.S. 8,324,313, U.S. 8,586,650, U.S. 2005/0072334, U.S. 2007/0051773, U.S. 2007/0179232, U.S. 2008/0044670, U.S. 2009/0111925, U.S. 2010/0048438, U.S. 2010/0129648, U.S. 2011/0308782, US 2013/0248163, and WO 2008/121491.

[0008] Thermal greases and phase change materials have lower thermal resistance than other types of thermal interface materials because of the ability to be spread in very thin layers and provide intimate contact between adjacent surfaces. However, a drawback of thermal grease is that thermal performance deteriorates significantly after thermal cycling, such as from 65°C to 150°C, or after power cycling when used in VLSI (“very-large-scale-integration”) chips. It has also been found that the performance of these materials deteriorates when large deviations from surface planarity causes gaps to form between the mating surfaces in the electronic devices or when large gaps between mating surfaces are present for other reasons, such as manufacturing tolerances, etc. When the heat transferability of these materials breaks down, the performance of the electronic device in which they are used is adversely affected. In addition, the silicone oil in the grease evaporate out of the grease and damage other parts of the electronic device.

[0009] In some embodiments it is also desirable for thermal interface materials to have excellent thermal performance and thermal stability.

SUMMARY OF THE INVENTION

[0010] The present disclosure provides thermal interface materials that are useful in transferring heat from heat generating electronic devices, such as computer chips, to heat dissipating structures, such as heat spreaders and heat sinks. The thermal interface materials illustratively include at least one phase change material, at least one polymer matrix material, at least one first thermally conductive filler having a first particle size, and at least one second thermally conductive filler having a second particle size, wherein the first particle size is larger than the second particle size.

[0011] In one more particular embodiment, a thermal interface material is provided. The thermal interface material includes at least one polymer, at least one phase change material, a first thermally conductive filler having a first particle size, and a second thermally conductive filler having a second particle size. In one embodiment, the first particle size is larger than the second particle size.

[0012] In one more particular embodiment of any of the above embodiments, the first thermally conductive filler comprises aluminum particles. In another more particular embodiment of any of the above embodiments, the second thermally conductive filler comprises zinc oxide particles.

[0013] In one more particular embodiment of any of the above embodiments, the first particle size is from about 1 microns to about 25 microns. In one more particular embodiment of any of the above embodiments, the first particle size is from about 3 microns to about 15 microns. In one more particular embodiment of any of the above embodiments, the first particle size is from about 3 microns to about 10 microns. In one more particular embodiment of any of the above embodiments, the second particle size is from about 0.1 microns to about 3 microns. In another more particular embodiment of any of the above embodiments, the second particle size is from about 0.1 microns to about 1 micron.

[0014] In one more particular embodiment, of any of the above embodiments, the first particle comprises aluminum and has a first particle size is from about 1 microns to about 15 microns and the second particle comprises zinc oxide and has a second particle size is from 0.1 microns to about 1 micron.

[0015] In one more particular embodiment of any of the above embodiments, the thermal interface material further includes a third thermally conductive filler having a third particle size, the second particle size being larger than the third particle size. In a still more particular embodiment, the third particle size is from about 10nm to about 100 nm.

[0016] In one more particular embodiment of any of the above embodiments, the thermal interface material further includes at least one coupling agent, such as a titanate coupling agent. In another more particular embodiment of any of the above embodiments, the thermal interface material further includes at least one antioxidant. In another more particular embodiment of any of the above embodiments, the thermal interface material further includes at least one ion scavenger. In another more particular embodiment of any of the above embodiments, the thermal interface material further includes at least one crosslinker.

[0017] In another embodiment, a formulation for forming a thermal interface material is provided. The formulation includes a solvent, at least one phase change material, at least one polymer matrix material, at least one first thermally conductive filler having a first particle size, and at least one second thermally conductive filler having a second particle size, wherein the first particle size is larger than the second particle size. In a more particular embodiment, the formulation further includes a third thermally conductive filler having a third particle size; wherein the second particle size is larger than the third particle size.

[0018] In another embodiment, an electronic component is provided. The electronic component includes a heat sink, an electronic chip, and a thermal interface material positioned between the heat sink and electronic chip, the thermal interface material including: at least one phase change material, at least one polymer matrix material, at least one first thermally conductive filler having a first particle size, and at least one second thermally conductive filler having a second particle size, wherein the first particle size is larger than the second particle size. In a more particular embodiment, a first surface of the thermal interface material is in contact with a surface of the electronic chip and a second surface of the thermal interface material is in contact with the heat sink. In another more particular embodiment, the

electronic component includes a heat spreader positioned between the heat sink and the electronic chip, wherein a first surface of the thermal interface material is in contact with a surface of the electronic chip and a second surface of the thermal interface material is in contact with the heat spreader. In still yet another more particular embodiment, the electronic component includes a heat spreader positioned between the heat sink and the electronic chip, wherein a first surface of the thermal interface material is in contact with a surface of the heat spreader and a second surface of the thermal interface material is in contact with the heat sink.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The above-mentioned and other features and advantages of this disclosure, and the manner of attaining them, will become more apparent and the invention itself will be better understood by reference to the following description of embodiments of the invention taken in conjunction with the accompanying drawings, wherein:

[0020] FIG. 1 schematically illustrates an electronic chip, a heat spreader, a heat sink, and first and second thermal interface materials.

[0021] Corresponding reference characters indicate corresponding parts throughout the several views. The exemplifications set out herein illustrate exemplary embodiments of the invention and such exemplifications are not to be construed as limiting the scope of the invention in any manner.

DETAILED DESCRIPTION

[0022] The present invention relates to thermal interface materials useful in transferring heat away from electronic components.

A. Thermal Interface Material

[0023] In one exemplary embodiment, the TIM 22 is a thermal interface material. In some exemplary embodiments, TIM 22 comprises one or more phase change materials, one or more polymer matrix materials, two or more thermally conductive fillers, and, optionally, one or more additives.

a. Thermally conductive filler

[0024] In some exemplary embodiments, the TIM 22 includes at least a first thermally conductive filler and a second thermally conductive filler.

[0025] Exemplary thermally conductive fillers include metals, alloys, nonmetals, metal oxides, metal nitrides and ceramics, and combinations thereof. Exemplary metals include but are not limited to aluminum, copper, silver, zinc, nickel, tin, indium, lead, silver coated metals such as silver coated copper or silver coated aluminum, metal coated carbon fibers, and nickel coated fibers. Exemplary nonmetals include but are not limited to carbon, carbon black, graphite, carbon nanotubes, carbon fibers, graphene, powdered diamond, glass, silica, silicon nitride, and boron coated particles. Exemplary metal oxides, metal nitrides and ceramics include but are not limited to alumina, aluminum nitride, boron nitride, zinc oxide, and tin oxide.

[0026] The TIM 22 may comprise the two or more thermally conductive fillers in an amount as little as 10 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, 80 wt.%, 85 wt.%, as great as 90 wt.%, 92 wt.%, 95 wt.%, 97 wt.%, 98 wt.%, 99 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM 22.

[0027] The thermally conductive fillers may be provided as particles. Average particle diameter (D50) is commonly used to measure particle size. Illustrative particles have average particle diameters as little as 10 nm, 20 nm, 50 nm, 0.1 microns, 0.2 microns, 0.5 microns, 1 micron, 2 microns, 3 microns, as great as 5 microns, 8 microns, 10 microns, 12 microns, 15 microns, 20 microns, 25 microns, 50 microns, 100 microns, or within any range defined between any two of the foregoing values.

[0028] In one embodiment, the thermally conductive fillers have different particle sizes to increase the packing effect between filler particles. In some embodiments, the first and second thermally conductive fillers are two different types of thermally conductive fillers having different particle sizes. In some embodiments, the first and second thermally conductive fillers are the same thermally conductive filler, but have different particle sizes.

[0029] In one exemplary embodiment, each thermally conductive filler has a D50 value that differs from the D50 of the remaining thermally conductive fillers by at least a certain factor. Exemplary factors may be as little as 1, 2, 3, 5, as great as 10, 20, 50, or 100. Without wishing to be bound by any particular theory, it is believed that in some embodiments, particle size distribution is also important for packing density, in addition to average particle diameter.

1. First thermally conductive filler

[0030] In one exemplary embodiment, the thermally conductive filler includes a first thermally conductive filler. In one exemplary embodiment, the first thermally conductive filler is a metal, such as aluminum, copper, silver, zinc, nickel, tin, indium, or lead. In a more particular embodiment, the first thermally conductive filler is aluminum.

[0031] In one exemplary embodiment, the first thermally conductive filler comprises particles having a size as little as 1 micron 2 microns, 3 microns, 5 microns, 8 microns, as great as 10 microns, 12 microns, 15 microns, 20 microns, 25 microns, 50 microns, 100 microns, or within any range defined between any two of the foregoing values. In one more particular embodiment, the first thermally conductive filler has a particle size from about 1 to about 25 microns. In one more particular embodiment, the first thermally conductive filler has a particle size from about 3 to about 5 microns. In one more particular embodiment, the first thermally conductive filler has a particle size from about 3 to about 15 microns. In one more particular embodiment, the first thermally conductive filler has a particle size from about 8 to about 12 microns. In one more particular embodiment, the first thermally conductive filler has a particle size from about 3 to about 10 microns. In one more particular embodiment, the first thermally conductive filler has a particle size of about 3 microns. In one more particular embodiment, the first thermally conductive filler has a particle size of about 10 microns.

[0032] The TIM 22 may comprise the first thermally conductive filler in an amount as little as 10 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, 80 wt.%, 85 wt.%, as great as 90 wt.%, 92 wt.%, 95 wt.%, 97 wt.%, 98 wt.%, 99 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the

TIM 22.

2. Second thermally conductive filler

[0033] In one exemplary embodiment, the thermally conductive filler includes a first thermally conductive filler as described above and a second thermally conductive filler. In one exemplary embodiment, the first thermally conductive filler has a particle size larger than a particle size of the second thermally conductive filler. In one exemplary embodiment, the first and second thermally conductive material are different sized particles of the same material. In another exemplary embodiment, the first and second thermally conductive material are different sized particles of different materials.

[0034] In one exemplary embodiment, the second thermally conductive filler is a metal, such as aluminum, copper, silver, zinc, nickel, tin, indium, or lead. In a more particular embodiment, the second thermally conductive filler is aluminum.

[0035] In another exemplary embodiment, the second thermally conductive filler is metal oxide, such as alumina, aluminum nitride, boron nitride, zinc oxide, or tin oxide. In a more particular embodiment, the second thermally conductive filler is zinc oxide.

[0036] In one exemplary embodiment, the second thermally conductive filler comprises particles having a size as little as 10 nm, 20 nm, 50 nm, 0.1 microns, 0.2 microns, 0.5 microns, 0.6 microns, 0.7 microns, 0.8 microns, 0.9 microns, 1 micron, 2 microns, 3 microns, as great as 5 microns, 8 microns, 10 microns, 12 microns, 15 microns, 20 microns, 25 microns, 50 microns, 100 microns, or within any range defined between any two of the foregoing values. In one more particular embodiment, the second thermally conductive filler has a particle size from about 1 to about 5 microns. In a more particular embodiment, the second thermally conductive filler has a particle size of about 3 microns. In one more particular embodiment, the second thermally conductive material has a particle size from about 0.1 microns to about 1 micron. In a more particular embodiment, the second thermally conductive filler has a particle size of about 0.5 microns to 1 micron. In a more particular embodiment, the second thermally conductive filler has a particle size of about 0.2 microns.

[0037] The TIM 22 may comprise the second thermally conductive fillers in an amount as little as 10 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, 80 wt.%, 85 wt.%, as great as 90 wt.%, 92 wt.%, 95 wt.%, 97 wt.%, 98 wt.%, 99 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM 22.

[0038] The TIM 22 may comprise a ratio of the first thermally conductive filler to the second thermally conductive filler in an amount as little as 1:50, 1:10, 1:5, 1:3, 1:1, as great as 2:1, 3:1, 5:1, 10:1, 20:1, 50:1, or within any range defined between any of the foregoing values, such as from 1:50 to 50:1, from 1:10 to 10:1, or from 1:5 to 5:1.

3. Third thermally conductive filler

[0039] In one exemplary embodiment, the thermally conductive filler includes a first thermally conductive filler and a second thermally conductive filler as described above, and a third thermally conductive filler. In one exemplary embodiment, the first thermally conductive filler has a particle size larger than a particle size of the second thermally conductive filler, and the second thermally conductive filler has a particle size larger than a particle size of the third thermally conductive filler.

[0040] In one exemplary embodiment, the first, second, and third thermally conductive materials are different sized particles of the same material. In another exemplary embodiment, each of the first, second, and third thermally conductive materials are different sized particles of different materials. In still another exemplary embodiment, exactly two of the first, second, and third thermally conductive materials are different sized particles of the same material, and the remaining thermally conductive material is a different material.

[0041] In one exemplary embodiment, the third thermally conductive filler is a metal, such as aluminum, copper, silver, zinc, nickel, tin, indium, or lead. In a more particular embodiment, the third thermally conductive filler is aluminum.

[0042] In another exemplary embodiment, the third thermally conductive filler is metal oxide, such as alumina, aluminum nitride, boron nitride, zinc oxide, or tin

oxide. In a more particular embodiment, the second thermally conductive filler is zinc oxide.

[0043] In still another exemplary embodiment, the third thermally conductive filler is selected from the group consisting of graphene, graphite, and carbon nanotubes.

[0044] In one exemplary embodiment, the third thermally conductive filler comprises particles having a size as little as 10 nm, 20 nm, 50 nm, 0.1 microns, 0.2 microns, as great as 0.5 microns, 0.6 microns, 0.7 microns, 0.8 microns, 0.9 microns, 1 micron or within any range defined between any two of the foregoing values. In another more particular embodiment, the third thermally conductive filler has a particle size from about 0.1 microns to about 1 micron. In a more particular embodiment, the second thermally conductive filler has a particle size of about 0.5 microns to 1 micron. In a more particular embodiment, the second thermally conductive filler has a particle size of about 0.2 microns. In another more particular embodiment, the third thermally conductive filler has a particle size from about 10 nm to about 0.1 microns. In a more particular embodiment, the third thermally conductive filler has a particle size of about 10 nm to about 50 nm.

[0045] The TIM 22 may comprise the third thermally conductive fillers in an amount as little as 10 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, 80 wt.%, 85 wt.%, as great as 90 wt.%, 92 wt.%, 95 wt.%, 97 wt.%, 98 wt.%, 99 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM 22.

[0046] The TIM 22 may comprise a ratio of the first thermally conductive filler to the second thermally conductive filler in an amount as little as 1:50, 1:10, 1:5, 1:3, 1:1, as great as 2:1, 3:1, 5:1, 10:1, 20:1, 50:1, or within any range defined between any of the foregoing values, such as from 1:50 to 50:1, from 1:10 to 10:1, or from 1:5 to 5:1. The TIM 22 may further comprise a ratio of the total of the first and second fillers to the third filler in an amount as little as 1:50, 1:10, 1:5, 1:3, 1:1, as great as 2:1, 3:1, 5:1, 10:1, 20:1, 50:1, or within any range defined between any of the foregoing values, such as from 1:50 to 50:1, from 1:10 to 10:1, or from 1:5 to 5:1.

4. Pretreatment of thermally conductive fillers with a coupling agent

[0047] In some exemplary embodiments, at least one of the thermally conductive fillers is pretreated with a coupling agent. In some exemplary embodiments, the thermally conductive fillers are not pretreated with a coupling agent. Without wishing to be bound by any theory, it is believed that the coupling agent reacts with both the filler and the polymer matrix material to form or promote a strong bond at the interface, which helps to break the filler particle aggregates and disperse the filler particles in to polymer matrix. The coupling agent is also believed to reduce or prevent separation of the polymer matrix polymer from filler, improving the stability of filler-polymer composite. The coupling agent is further believed to reduce the viscosity of the system and improve the flowability of thermal conductive filler particles, which help to reduce the bond-line thickness (BLT) between the heat generating component and heat spreading component.

[0048] In some embodiments, such pretreatment with a coupling agent may be used with high loadings of filler particles may be used with high loadings of the thermally conductive filler, such as 80 wt.%, 85 wt.%, 90 wt.%, 95 wt.%, 99 wt.%, or higher. In some embodiments, such pretreatment with a coupling agent may be used with small particle sizes, such as sub-micron particle sizes, to avoid forming clumps during formulation.

[0049] The pretreated thermally conductive filler may comprise the coupling agent in an amount as little as 0.01 wt.%, 0.05 wt.%, 0.1 wt.%, 0.5 wt.%, as great as 1 wt.%, 2 wt.%, 5 wt.%, 10 wt.%, 20 wt.%, or greater, or within any range defined between any two of the foregoing values, based on the weight of the thermally conductive filler.

[0050] Exemplary coupling agents for use in pretreatment of the thermally conductive filler include silane coupling agents, titanate coupling agents, aluminate coupling agents, zirconate coupling agents, and stearate coupling agent. In some embodiments, the coupling agent for pre-treatment of the thermally conductive filler is selected from titanate coupling agents, aliphatic coupling agents, and silane coupling agents.

5. Illustrative mixtures of thermally conductive fillers

[0051] The following exemplary embodiments are intended to illustrate

mixtures of thermally conductive fillers, and are not to be construed as limiting the scope of the invention in any manner.

[0052] In one exemplary embodiment, the thermally conductive filler includes a first thermally conductive filler having a first average particle diameter (D50), a second average particle diameter, and a third average particle diameter. In one more particular embodiment, the first D50 is about 30 microns, the second D50 is about 3 microns, and the third D50 is about 0.3 microns. In another more particular embodiment, the first D50 is about 20 microns, the second D50 is about 3 microns, and the third D50 is about 0.6 microns. In still another more particular embodiment, the first D50 is about 5 microns, the second D50 is about 0.9 microns, and the third D50 is about 20 nm.

[0053] In one embodiment, the thermally conductive filler comprises a first thermally conductive filler having a first particle size and a second thermally conductive filler having a second particle size. In one more particular embodiment, the first particle size is from about 8 to about 12 microns and the second particle size is from about 2 to about 5 microns. In a more particular embodiment, the first particle size is about 10 microns and the second particle size is about 3 microns. In another more particular embodiment, the first and second thermally conductive fillers are each aluminum particles.

[0054] In a more particular embodiment of the above embodiments, the thermally conductive filler further comprises a third thermally conductive filler having a third particle size. In one more particular embodiment, the third thermally conductive filler has a particle size from about 0.1 microns to about 1 micron and even more particularly about 0.2 microns. In another more particular embodiment, the first thermally conductive filler and second thermally conductive filler are each aluminum and the third thermally conductive filler is zinc oxide.

[0055] In another embodiment, the thermally conductive filler comprises a first thermally conductive filler having a first particle size and a second thermally conductive filler having a second particle size. In one more particular embodiment, the first particle size is from about 3 to about 12 microns and the second thermally conductive filler has a particle size from about 0.1 microns to about 1 micron. In a

more particular embodiment, the first particle size is about 3 microns and the second particle size is about 0.1 – 1 micron, and more particularly about 0.2 microns. In another more particular embodiment, the first particle size is about 10 microns and the second particle size is about 0.1 – 1 micron, and more particularly about 0.2 microns. In another more particular embodiment, the first thermally conductive filler is aluminum and the second thermally conductive filler is zinc oxide.

[0056] In a more particular embodiment of the above embodiments, the thermally conductive filler further comprises a third thermally conductive filler having a third particle size. In one more particular embodiment, the third thermally conductive filler has a particle size from about 10 nm to about 0.1 microns and even more particularly about 10 nm to about 50 nm. In another more particular embodiment, the first thermally conductive filler is aluminum, the second thermally conductive filler is zinc oxide, and the third thermally conductive filler is graphene.

b. Polymer matrix material

[0057] In some exemplary embodiments, the TIM 22 comprises a polymer matrix material. In some exemplary embodiments, the polymer matrix material provides a matrix for incorporating the thermally conductive fillers, and provides flowability when pressed under heat and pressure.

[0058] In one exemplary embodiment, the polymer matrix material comprises a hydrocarbon rubber compound or a blend of rubber compounds. Exemplary materials include saturated and unsaturated rubber compounds. In some embodiments, saturated rubbers may be less sensitive to thermal oxidation degradation than unsaturated rubber compounds. Exemplary saturated rubber compounds include ethylene-propylene rubbers (EPR, EPDM), polyethylene/butylene, polyethylene-butylene-styrene, polyethylene-propylene-styrene, hydrogenated polyalkyldiene “mono-ols” (such as hydrogenated polybutadiene mono-ol, hydrogenated polypropadiene mono-ol, hydrogenated polypentadiene mono-ol), hydrogenated polyalkyldiene “diols” (such as hydrogenated polybutadiene diol, hydrogenated polypropadiene diol, hydrogenated polypentadiene diol) and hydrogenated polyisoprene, polyolefin elastomer, or any other suitable saturated rubber, or blends thereof. In one embodiment, the polymer

matrix material is a hydrogenated polybutadiene mono-ol, which may also be referred to as a hydroxyl-terminated ethylene butylene copolymer, specialty mono-ol.

[0059] In one exemplary embodiment, the polymeric matrix material comprises a silicone rubber, a siloxane rubber, a siloxane copolymer or any other suitable silicone-containing rubber.

[0060] In some exemplary embodiments, the TIM 22 may comprise the polymer matrix material in an amount as little as 1 wt.%, 3 wt.%, 5 wt.%, 10 wt.%, as great as 15 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM 22.

c. Phase change material

[0061] In some exemplary embodiments, the TIM 22 comprises one or more phase change materials. A phase change material is a material having a melting point or melting point range at or below the operating temperature of a portion of an electronic device in which the TIM 22 is to be used. An exemplary phase change material is a wax, such as paraffin wax. Paraffin waxes are a mixture of solid hydrocarbons having the general formula C_nH_{2n+2} and having melting points in the range of about 20° C to 100° C. Polymer waxes include polyethylene waxes and polypropylene waxes, and typically have a range of melting points from about 40° C. to 160° C. Other exemplary phase change materials include low melting alloys, such as Wood's metal, Field's metal, or a metal or alloy having a melting point between about 20°C and 90°C.

[0062] In some embodiments, the amount of phase change material can be used to can adjust the hardness of the TIM 22. For example, in some embodiments wherein the loading of the phase change material is low, the composition may be in the form of a soft gel, and in some embodiments wherein the loading of the phase change material is high, the composition may be a hard solid. The TIM 22 may comprise the one or more phase change materials in an amount as little as 1 wt.%, 3 wt.%, 5 wt.%, 10 wt.%, as great as 15 wt.%, 25 wt.%, 50 wt.%, 75 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM 22.

d. Coupling agent

[0063] In some exemplary embodiments, the TIM 22 comprises one or more coupling agents. In some exemplary embodiments, inclusion of a coupling agent may improve thermal properties, such as properties at relatively high temperatures. Exemplary coupling agents include titanate coupling agents, such as those disclosed in US Patent Application Publication 2011/0308782, the disclosure of which is hereby incorporated by reference in its entirety. Exemplary coupling agents include: titanium IV 2,2 (bis 2-propenolatomethyl)butanolato, tris(dioctyl)pyrophosphato-O; zirconium IV 2,2 (bis 2-propenolatomethyl)butanolato, tris(diisooctyl)pyrophosphato-O; titanium IV 2-propanolato, tris(dioctyl)-pyrophosphato-O) adduct with 1 mole of diisooctyl phosphite; titanium IV bis(dioctyl)pyrophosphato-O, oxoethylenediolato, (Adduct), bis(dioctyl) (hydrogen)phosphite-O; titanium IV bis(dioctyl)pyrophosphato-O, ethylenediolato (adduct), bis(dioctyl)hydrogen phosphite; and zirconium IV 2,2-bis(2-propenolatomethyl) butanolato, cyclo di[2,2-(bis 2-propenolatomethyl) butanolato], pyrophosphato-O,O. In one exemplary embodiment, the coupling agent is titanium IV 2, 2 (bis 2-propenolatomethyl) butanolato, tris(dioctyl)pyrophosphato-O.

[0064] In one embodiment, the coupling agent is the same as the coupling agent for the pre-treatment of the thermally conductive filler. In another embodiment, the coupling agent is a different coupling agent than the coupling agent for the pre-treatment of the thermally conductive filler.

[0065] In some exemplary embodiments, the TIM 22 may comprise the one or more coupling agents in an amount as little as 0.1 wt.%, 0.3 wt.%, 0.5 wt.%, as great as 1 wt.%, 2 wt.%, 3 wt.%, 5 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the central layer.

e. Additives

[0066] In some exemplary embodiments, the TIM 22 comprises one or more additives. Exemplary additives include antioxidants, ion scavengers, and crosslinkers.

[0067] Exemplary antioxidants include phenolic-type antioxidants, amine-type antioxidants, or any other suitable type of antioxidant or combinations thereof. In

some exemplary embodiments, the TIM 22 may comprise the one or more antioxidants in an amount as little as 0.1 wt.%, 0.5 wt.%, 1 wt.% as great as 1.5 wt.%, 2 wt.%, 5 wt.%, 10 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM.

[0068] Exemplary ion scavengers are disclosed in PCT application number PCT/CN2014/081724, the disclosure of which is hereby incorporated by reference in its entirety. In some exemplary embodiments, the TIM 22 may comprise the one or more ion scavengers in an amount as little as 0.1 wt.%, 0.5 wt.%, 1 wt.% as great as 1.5 wt.%, 2 wt.%, 5 wt.%, 10 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM.

[0069] Exemplary crosslinkers are disclosed in U.S. Patent No. 7,244,491, the disclosure of which is hereby incorporated by reference in its entirety. Exemplary crosslinkers include alkylated melamine resins. In some exemplary embodiments, the TIM 22 may comprise the one or more crosslinkers in an amount as little as 0.1 wt.%, 0.5 wt.%, 1 wt.% as great as 1.5 wt.%, 2 wt.%, 5 wt.%, 10 wt.%, or within any range defined between any two of the foregoing values, based on the total weight of the TIM.

B. Methods of forming a Thermal Interface Material

[0070] In some embodiments, the TIM 22 is formed from a dispensable formulation including one or more polymer matrix materials, one or more phase change materials, two or more thermally conductive fillers, one or more solvents, and, optionally, one or more additives.

[0071] Exemplary solvents are described in U.S. Patent Application Publication 2007/0517733, the disclosure of which is hereby incorporated by reference herein in its entirety. Suitable solvents include pure solvents or mixtures of organic or inorganic solvents that are volatilized at a desired temperature, such as the critical temperature, or that can facilitate any of the above-mentioned design goals or needs, and that are compatible with the phase change materials, in that they will interact with the phase change materials to achieve the previously-mentioned goals. In some embodiments, the solvent, solvent mixture or combination

thereof will solvate the phase change material such that it can be applied by printing techniques. In some exemplary embodiments, the solvent or mixture of two or more solvents are selected from the hydrocarbon family of solvents. Hydrocarbon solvents comprise carbon and hydrogen. A majority of hydrocarbon solvents are non-polar; however, there are a few hydrocarbon solvents that are considered polar.

[0072] Hydrocarbon solvents are generally classified into three classes: aliphatic, cyclic and aromatic. Aliphatic hydrocarbon solvents comprise both straight-chain compounds and compounds that are branched and possibly crosslinked, however, aliphatic hydrocarbon solvents are not typically considered cyclic. Cyclic hydrocarbon solvents are those solvents that comprise at least three carbon atoms oriented in a ring structure with properties similar to aliphatic hydrocarbon solvents. Aromatic hydrocarbon solvents are those solvents that comprise generally three or more unsaturated bonds with a single ring or multiple rings attached by a common bond and/or multiple rings fused together. In some exemplary embodiments, the solvent or mixture of two or more solvents are selected from solvents that are not considered part of the hydrocarbon solvent family of compounds, such as ketones, alcohols, esters, ethers and amines. In yet other contemplated embodiments, the solvent or solvent mixture may comprise a combination of any of the solvents mentioned herein.

[0073] Exemplary hydrocarbon solvents include toluene, xylene, p-xylene, m-xylene, mesitylene, solvent naphtha H, solvent naphtha A, Isopar H and other paraffin oils and isoparaffinic fluids, alkanes, such as pentane, hexane, isohexane, heptane, nonane, octane, dodecane, 2-methylbutane, hexadecane, tridecane, pentadecane, cyclopentane, 2,2,4-trimethylpentane, petroleum ethers, halogenated hydrocarbons, such as chlorinated hydrocarbons, nitrated hydrocarbons, benzene, 1,2-dimethylbenzene, 1,2,4-trimethylbenzene, mineral spirits, kerosene, isobutylbenzene, methylnaphthalene, ethyltoluene, ligroine. Exemplary ketone solvents include acetone, diethyl ketone, methyl ethyl ketone and the like.

[0074] In one exemplary embodiment, the solvent includes one or more solvents selected from: pentane, hexane, heptane, cyclohexane, paraffin oils, isoparaffinic fluids, benzene, toluene, xylene and mixtures or combinations thereof.

[0075] In some exemplary embodiments, the formulation may comprise the one or more solvents in an amount as little as 0.1 wt.%, 0.5 wt.%, 1 wt.% as great as 5 wt.%, 10 wt.%, 20 wt. %, or within any range defined between any two of the foregoing values, based on the total weight of the formulation.

[0076] In some exemplary embodiments, a method of forming a TIM 22 is provided. In some exemplary embodiments, forming the TIM 22 includes processes such as baking and drying the TIM 22.

[0077] In some exemplary embodiments, baking the TIM 22 include baking at a temperature as low as 25°C, 50°C, 75°C, 80°C, as high as 100°C, 125°C, 150°C, 170°C, or within any range defined between any two of the foregoing values. In some exemplary embodiments, the TIM 22 is baked for as little as 0.5 minutes, 1 minute, 30 minutes, 1 hour, 2 hours, as long as 8 hours, 12 hours, 24 hours, 36, hours, 48 hours, or within any range defined between any two of the foregoing values.

C. Thermal Interface Material Properties

[0078] In some exemplary embodiments, the TIM 22 has a thermal impedance as little as $0.05^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.06^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.07^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.75^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, as high as $0.08^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.09^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.1^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, $0.12^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$, or within any range defined between any two of the foregoing values.

[0079] In some exemplary embodiments, the TIM 22 has a thermal impedance following conditioning at a temperature of 130°C and a relative humidity of 85% for 96 hours that is no more than 20% greater, no more than 10% greater, no more than 5% greater, or no more than the thermal impedance of the TIM 22 prior to said conditioning.

[0080] In some exemplary embodiments, the TIM 22 has a thermal impedance following conditioning at a temperature of 150°C for 1000 hours that is no more than 20% greater, no more than 10% greater, no more than 5% greater, or no more than the thermal impedance of the TIM 22 prior to said conditioning.

[0081] The final thickness of the applied TIM, following application between the heat generating and heat dissipating components, is referred to as the bond line thickness (BLT). The value of the BLT is determined, in part, by the flowability of the

TIM when being heated by the heat generating component. Phase change materials (PCM) include a wax or other material to be increase the flowability of the TIM when heated by the heat generating component, which in turn reduced the BLT. BLT is related to thermal impedance (TI) and thermal conductivity (TC) by the formula $TI = BLT / TC$, such that lower BLT results in lower thermal impedance at the same thermal conductivity. Without wishing to be bound by any particular theory, it is believed that including multiple sizes of thermally conductive fillers allows smaller particle sizes to fill gaps present between larger particle sizes, increasing the flowability of the TIM and reducing the BLT. TIM formulations having low BLT tend to have low thermal impedance.

[0082] In some embodiments, when subjected to a pressure of 40 psi and heated to 80°C, the TIM 22 has a bond line thickness as great as 80 microns, 70 microns, 60 microns, 50 microns, 40 microns, as little as 30 microns, 25 microns, 20 microns, 15 microns, 10 microns, 5 microns, or less, or within any range defined between any two of the foregoing values, such as from 80 microns to 5 microns, from 60 microns to 10 microns, or from 30 to 20 microns.

EXAMPLES

[0083] Examples including a rubber elastomer, a first thermally conductive filler (aluminum particles between about 0.1 and about 25 microns), a second thermally conductive filler (zinc oxide particles between about 0.1 and 6 microns), a titanate coupling agent, an antioxidant, and a wax, were prepared as described below. Examples 1-5 generally contained about 65-75 wt.% of the aluminum filler and about 13-15 wt.% of the zinc oxide filler. Examples 6-13 generally contained about 50-80 wt.% of the aluminum filler and about 15-45 wt.% of the zinc oxide filler.

[0084] Example 1 and Comparative Example 1 were prepared according to the formulations (in weight percent) provided in Table 1.

Table 1: Formulations for Example 1 and Comparative Example 1

	Ex. 1	Comp. Ex. 1
Elastomer (wt.%)	8.6	8.6
Wax (wt.%)	3.1	3.1

Antioxidant (wt.%)	0.2	0.2
Titanate coupling agent (wt.%)	1.1	1.1
Aluminum(wt.%) (5 μm)	72.5	87
Zinc oxide (wt.%) (0.6 μm)	14.5	0
Thermal impedance ($^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$)	0.091	0.103

[0085] To prepare Example 1, a Kraton elastomer (a hydroxyl-terminated ethylene butylene copolymer, specialty mono-ol), a microcrystalline wax with a melting point of about 45°C , and an antioxidant were combined and blended in a heated mixer until the combination had melted and obtained a substantially homogeneous appearance. The titanium IV 2, 2 (bis 2-propenolatomethyl) butanolato, tris(dioctyl)pyrophosphato-O coupling agent was added, and the combination was again blended until the combination had a substantially homogeneous appearance. The aluminum powder and zinc oxide were added, followed by blending until the mixture had a substantially homogeneous appearance.

[0086] Comparative example 1 was prepared similarly to Example 1, except that the mixture of thermally conductive fillers in Example 1 was replaced with aluminum powder.

[0087] The thermal impedance of each TIM was determined using a cut bar test according to ASTM D5470-06. Each TIM was taped between two liner films at 90°C for 15 minutes. The liners were removed and a 25 mm diameter circle sample was cut from the TIM. The sample was placed between two nickel – coated copper bars, and placed under a pressure of 40 psi. The power was set to 125W, and the thermal properties were measured at 20 minutes, 25 minutes, and 30 minutes. The average of the three values was used to determine the thermal impedance value provided in Table 1.

[0088] As shown in Table 1, partially replacing some of the aluminum in comparative example 1 with an equivalent weight percent of zinc oxide led to a decrease in thermal impedance of $0.012^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$.

[0089] Examples 2-4 and Comparative Example 2 were prepared according to the formulations provided in Table 2.

Table 2: Formulations for Examples 2-4 and Comparative Example 2

	Ex. 2	Ex. 3	Ex. 4	Comp. Ex. 2
Elastomer (wt.%)	8.7	8.7	8.7	8.7
Wax (wt.%)	3.1	3.1	3.1	3.1
Antioxidant (wt.%)	0.1	0.1	0.1	0.1
Amino resin (wt.%)	0.6	0.6	0.6	0.6
Titanate coupling agent (wt.%)	1.5	1.5	1.5	1.5
Aluminum (wt.%) (3 μm)	71.67	71.67	71.67	71.67
Zinc oxide* (wt.%) (0.9 μm)	14.33	14.33	14.33	14.33
Thermal impedance ($^{\circ}\text{C}\cdot\text{cm}^2/\text{W}$)	0.106	0.079	0.115	0.098

*Note: in Ex. 2-4, Zinc Oxide was pre-treated with a coupling agent

[0090] To prepare Example 2, a Kraton elastomer (a hydroxyl-terminated ethylene butylene copolymer, specialty mono-ol), a microcrystalline wax with a melting point of about 45°C, an antioxidant, and an amino resin were combined and blended in a heated mixer until the combination had melted and obtained a substantially homogeneous appearance. The titanium IV 2-propanolato, tris isooctadecanoato – O coupling agent was added, and the combination was again blended until the combination had a substantially homogeneous appearance. The aluminum powder and zinc oxide pre-treated with a titanate coupling agent were added, followed by blending until the mixture had a substantially homogeneous appearance.

[0091] Example 3 was prepared similarly to Example 2, except that the zinc oxide was pre-treated with an aliphatic coupling agent rather than a titanate coupling agent. Example 4 was prepared similarly to Example 2, except that the zinc oxide was pre-treated with a silane coupling agent rather than a titanate coupling agent. Comparative Example 2 was prepared similarly to Example 2, except that the zinc oxide was not pre-treated.

[0092] The thermal impedance of each TIM was determined using a cut bar test according to ASTM D5470-06 as described above. The thermal impedance values are provided in Table 2. As shown in Table 2, pretreating the zinc oxide with

an aliphatic coupling agent led to a decrease in thermal impedance compared to pre-treatment with either the titanate coupling agent or the silane coupling agent.

[0093] Examples 5-10 were prepared according to the formulations provided in Table 3.

Table 3: Formulations for Examples 5-10 and Properties of Comparative

Example 3

	Ex. 5	Ex. 6	Ex. 7	Ex. 8	Ex. 9	Ex 10	Comp Ex. 3	Comp Ex. 4	Comp Ex. 5
Elastomer (wt.%)	6.2	5.27	4.6	4.6	3.94	3.94	4.6	5.42	-
Wax (wt.%)	1.4	1.5	1.31	1.31	1.12	1.12	1.31	1.50	-
Antioxidant (wt.%)	0.1	0.42	0.37	0.37	0.31	0.31	0.37	0.4	-
Titanate coupling agent (wt.%)	1.3	0.57	0.72	0.72	0.74	0.74	0.72	0.68	-
Aluminum (wt.%) (6.7 μm)	74	76.9	77.5	67.13	78.24	67.06	67.13	92	-
Zinc oxide (wt.%) (0.9 μm)	17	15.34	15.5	25.87	15.65	26.83	-	-	-
Alumina (0.8 μm) (wt.%)	-	-	-	-	-	-	25.87	-	-
Filler loading (wt.%)	91	92	93	93	94	94	93	92	-
Bond line thickness (μm)	-	-	-	25	-	28	28	30	-
Thermal impedance (°C·cm ² /W)	-	-	-	0.07	-	0.08	0.09	0.09	0.1

[0094] To prepare Examples 5-10, a Kraton elastomer (a hydroxyl-terminated ethylene butylene copolymer, specialty mono-ol), a microcrystalline wax with a melting point of about 45°C, and an antioxidant, were combined according to the amounts given in Table 3 and blended in a heated mixer until the combination had melted and obtained a substantially homogeneous appearance. The titanium IV 2, 2 (bis 2-propenolatomethyl) butanolato, tris(dioctyl)pyrophosphato-O coupling agent was added, and the combination was again blended until the combination had a substantially homogeneous appearance. The aluminum powder and zinc oxide were added, followed by blending until the mixture had a substantially homogeneous appearance.

[0095] Comparative Example 3 was prepared similarly to Examples 5-10, except that alumina was used in place of the zinc oxide.

[0096] Comparative Example 4 was prepared similarly to Examples 5-10, except that the mixture of thermally conductive fillers was replaced with aluminum powder.

[0097] Comparative Example 5 was a commercially available PTM 3180 material, available from Honeywell International, Inc.

[0098] Each TIM was taped between two liner films at 90°C for 15 minutes. The liners were removed and a 25 mm diameter circle sample was cut from the TIM. The sample was placed between a nickel-coated copper spreader and a silicone die, creating a test “sandwich” sample.

[0099] The sample was subjected to a 90°C baking oven under 40psi pressure, for 60 minutes using an Oven D2F-6050, supplied by Shanghai JINGHONG. The “sandwich” was measured with micrometer and the reading is the total thickness of silicone die – TIM – nickel-coated copper. The thickness of silicon die and nickel-coated copper was measured with micrometer in advance to obtain the bond-line thickness of the TIM (BLT). TIM formulations having good compressibility can be compressed to a very thin sample, measured as a very low BLT, and tend to have low thermal impedance.

[00100] The thermal impedance of each TIM was determined using a flash diffusivity of the test sandwich. Flash diffusivity was determined according to ASTM E1461 using a Netzsch LFA 447 equipment with a Xenon light source. The results are provided in Table 3.

[00101] As is shown in Table 3, the Examples including both aluminum particles and zinc oxide particles had lower thermal impedance than the Comparative Examples having only aluminum particles.

[00102] In addition, comparing the results of Example 8 with that of Comparative Example 4, Example 8 has lower BLT than Comparative Example 4, even though Example 8 has a higher filler loading (93%) than Comparative Example 4 (92%). This indicates that Example 8 has better compressibility than Comparative Example 4, despite the higher filler loading, which may lead to the lower thermal impedance.

[00103] Further, comparing the results of Example 8 with that of Comparative Example 3, the samples had similar filler loadings, but Example 8 used aluminum and zinc oxide particles, while comparative example 3 had aluminum and alumina particles. As shown in Table 3, Example 8 had lower BLT than Comparative Example 3, indicating better compressibility. Lower thickness as measure by BLT is related to thermal impedance by the formula $TI = BLT / TC$, where TI is thermal impedance, BLT is bond line thickness, and TC is thermal conductivity.

[00104] Example 8 was tested using a Highly Accelerated Stress Test (HAST test) in which the sample was conditioned at a temperature of 130°C and a relative humidity of 85% for 96 hours in an environmental chamber supplied by ESPEC. The thermal impedance of the sample was measured before or after the sample conditioning. An increase of less than 20% in thermal impedance indicated a passing HAST result, while an increase of 20% or more indicated a failing HAST result. As shown in Table 4, Example 8 passed the HAST test.

Table 4: HAST results

Materials	Sample No	Thermal Impedance (AC)	Thermal Impedance (HAST96hr)
Example 8	1	0.08	0.08
	2	0.08	0.08
	3	0.08	0.08
	4	0.08	0.08

[00105] Example 8 was also tested using a baking test in which the sample was conditioned at a temperature of 150°C for 1000 hours in an environmental chamber supplied by ESPEC. The thermal impedance of the sample was measured before or after the sample conditioning. An increase of less than 20% in thermal impedance indicated a passing baking test result, while an increase of 20% or more indicated a failing baking test result. As shown in Table 5, Example 8 passed the HAST test.

Table 5: HAST results

Materials	Sample No	Thermal Impedance (AC)	Thermal Impedance (150°Cbaking/1000hr)
Example 8	1	0.07	0.07
	2	0.08	0.07
	3	0.08	0.07
	4	0.07	0.07

[00106] While this invention has been described as having exemplary designs, the present invention can be further modified within the spirit and scope of this disclosure. This application is therefore intended to cover any variations, uses, or adaptations of the invention using its general principles. Further, this application is intended to cover such departures from the present disclosure as come within known or customary practice in the art to which this invention pertains and which fall within the limits of the appended claims.

Claims

1. A thermal interface material comprising:

at least one polymer including a hydrogenated polybutadiene mono-ol;

at least one phase change material including at least one wax;

a first thermally conductive filler in the form of aluminium particles having a first particle size between 1 and 15 microns;

a second thermally conductive filler in the form of aluminium particles having a second particle size between 1 and 5 microns wherein the first particle size is larger than the second particle size;

a third thermally conductive filler in the form of zinc oxide particles having a third particle size between 0.5 and 1 micron;

at least one titanate coupling agent; and

all thermally conductive fillers being present in a total amount of between 90 wt.% and 99 wt.% based on the total weight of the thermal interface material.

2. The thermal interface material of claim 1, wherein the thermal interface material has a bond line thickness (BLT) between 5 and 80 microns when subjected to a pressure of 40 psi and heated to 80°C.