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(54) **METHOD OF DEPOSITION OF A THERMAL INTERFACE MATERIAL ONTO A CIRCUIT ASSEMBLY AND AN INTEGRATED CIRCUIT FORMED THEREFROM**

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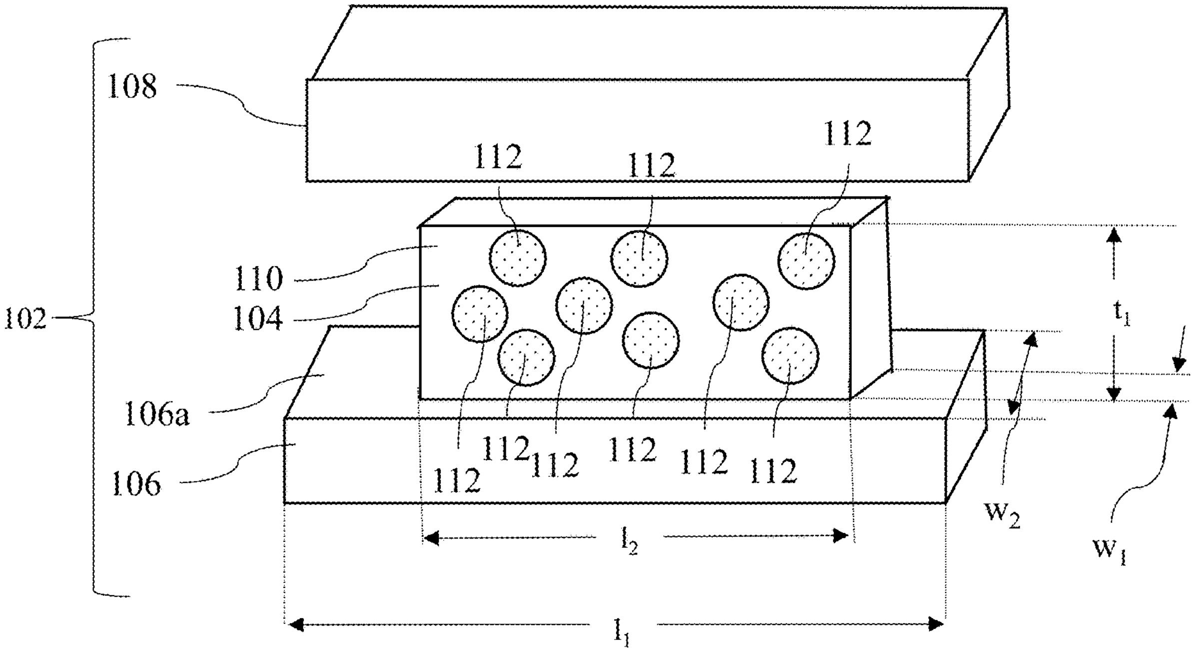
(57) **ABSTRACT**

A method of deposition of a thermal interface material onto a circuit assembly and an integrated circuit formed therefrom is provided. The method includes depositing a thermal interface material at a first layer thickness between a first layer of a circuit assembly and a second layer of the circuit assembly. The thermal interface material includes an emulsion of liquid metal droplets and polymer. The first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets prior to compressing the circuit assembly. The method includes compressing the circuit assembly to decrease the first layer thickness to a second layer thickness, thereby deforming the liquid metal droplets. The second layer thickness is no greater than a D_{90} of the liquid metal droplets in thermal interface material prior to compressing the circuit assembly.



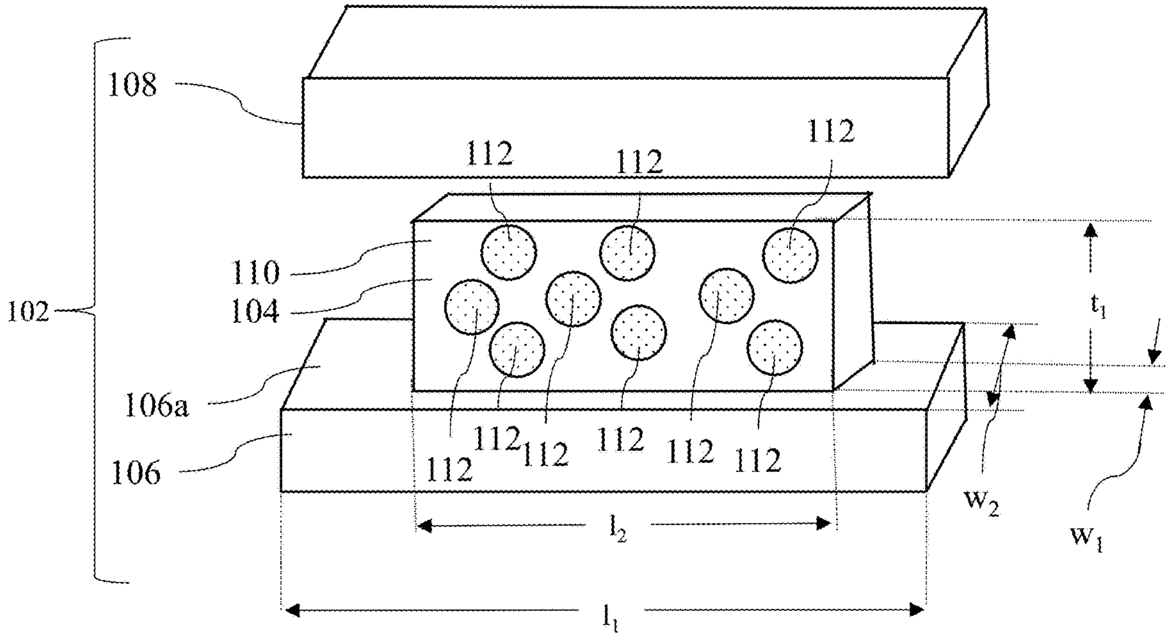
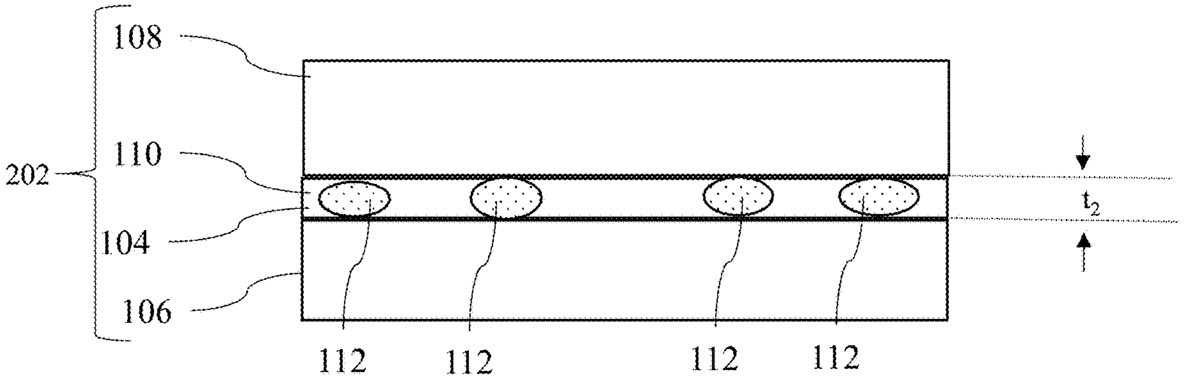

102
108
112
112
112
110
104
106a
106
112
112
112
112
112
112
t1
w2
w1
l2
l1

FIG. 1


202
108
110
104
106
t2
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112

FIG. 2

METHOD OF DEPOSITION OF A THERMAL INTERFACE MATERIAL ONTO A CIRCUIT ASSEMBLY AND AN INTEGRATED CIRCUIT FORMED THEREFROM

PRIORITY CLAIM

[0001] The subject application claims priority to U.S. provisional patent application Ser. No. 63/433,275, filed Dec. 16, 2022, having the same title and inventors as indicated above, and which is incorporated herein by reference it is entirety.

FIELD

[0002] The present disclosure relates to a method of deposition of a thermal interface material onto a circuit assembly and an integrated circuit formed therefrom.

BACKGROUND

[0003] A thermal interface material (TIM) can be used to thermally connect two or more layers together. For example, TIMs are often used in CPU packages to thermally connect the integrated heat spreader (IHS) of a CPU package to a heat sink. There are various types of methods to deposit TIMs that may be used. However, current methods of application of TIMs present challenges.

SUMMARY

[0004] In one general aspect, the present disclosure is directed towards a method of deposition of a thermal interface material (TIM) onto a circuit assembly. In various examples, the circuit assembly can be a processor, an ASIC, or a system-on-a-chip (SOC). The method comprises depositing the TIM at a first layer thickness between a first layer of a circuit assembly and a second layer of the circuit assembly. In various examples, the TIM can be applied directly to the first layer and, thereafter, the second layer can be applied directly to the TIM. In various other examples, the TIM can be applied directly to the second layer and, thereafter, the first layer can be applied directly to the TIM. In certain examples, the TIM can be applied to both the first layer and the second layer and then the first layer and the second layer can be applied together.

[0005] The thermal interface material comprises an emulsion of liquid metal droplets and polymer. In various examples, the liquid metal droplets comprise at least one of gallium, a gallium alloy, indium, an indium alloy, tin, a tin alloy, mercury, and a mercury alloy. In certain examples, the liquid metal droplets comprise a melting point no greater than 30 degrees Celsius. The first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets prior to compressing the circuit assembly, such as, for example, at least 2.5 times, at least 3 times, at least 4 times, at least 5 times, at least 6 times, at least 10 times, at least 20 times, at least 50 times, or at least 100 times all of a D_{90} of the liquid metal droplets prior to compressing the circuit assembly. The method comprises compressing the circuit assembly to decrease the first layer thickness to a second layer thickness, thereby deforming the liquid metal droplets. The second layer thickness is no greater than a D_{90} of the liquid metal droplets in thermal interface material prior to compressing the circuit assembly. The thermal interface material after compressing can comprise an effective thermal conductivity value of at least 5 W/m*K, such as, for example, at least 10 W/m*K, at least 12 W/m*K, at least 15 W/m*K, at least 17 W/m*K, or at least 20 W/m*K. In various examples, the liquid metal droplets are generally spherical prior to compressing, and the liquid metal droplets are generally ellipsoidal after compressing the circuit assembly.

[0006] The present invention can provide both a low contact resistance at the material interfaces and a low thermal resistance through the TIM. The low contact resistance can be enabled by the application of the polymer in a conformable state so that the polymer and liquid metal droplets can adapt to the surface of the layer to achieve a desired contact resistance. The low thermal resistance through the TIM can be enabled by liquid metal droplets, including the size and/or shape of the liquid metal droplets. Additionally, the methods described herein can achieve a desired distribution of the liquid metal droplets on the circuit assembly, a desired homogeneity of the liquid metal droplets within the TIM, and/or desired shape of the liquid metal droplets within the TIM, thereby enhancing the effective thermal conductivity of the TIM. These and other benefits realizable from various embodiments of the present invention will be apparent from the description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The features and advantages of various examples of the present invention, and the manner of attaining them, will become more apparent, and the examples will be better understood by reference to the following description of examples taken in conjunction with the accompanying drawing, wherein:

[0008] FIG. **1** is a perspective view of a circuit assembly according to the present disclosure after deposition of the thermal interface material; and

[0009] FIG. **2** is a side view of an integrated circuit formed by compressing the circuit assembly of FIG. **1**.

[0010] Corresponding reference characters indicate corresponding parts throughout the several views. The exemplifications set out herein illustrate certain examples, in one form, and such exemplifications are not to be construed as limiting the scope of the examples in any manner.

DETAILED DESCRIPTION

[0011] Certain exemplary aspects of the present invention will now be described to provide an overall understanding of the principles of the composition, function, manufacture, and use of the compositions and methods disclosed herein. An example or examples of these aspects are illustrated in the accompanying drawing. Those of ordinary skill in the art will understand that the compositions, articles, and methods specifically described herein and illustrated in the accompanying drawing are non-limiting exemplary aspects and that the scope of the various examples of the present invention is defined solely by the claims. The features illustrated or described in connection with one exemplary aspect may be combined with the features of other aspects. Such modifications and variations are intended to be included within the scope of the present invention.

[0012] Applying a thermal interface material (TIM) to a circuit assembly such that the TIM is between the a integrated heat spreader (IHS) and a heat sink can require balancing the thermal resistance through the TIM and the contact resistance at the material interfaces. For example, a polymeric material may have a low contact resistance at the material interfaces but a high thermal resistance through the material. A solid metal may have a low thermal resistance through the material but a high contact resistance at the material interfaces. Additionally, some solid materials (polymeric or metal) may require a large pressure during installation to achieve a desired contact resistance. Further, when utilizing a TIM with liquid metal droplets, the current inventors have determined there are challenges with achieving a desired distribution of the liquid metal droplets on the circuit assembly, a desired shape of the liquid metal droplets on the circuit assembly, and homogeneity of the liquid metal within the TIM, which can affect the effective thermal conductivity through the TIM.

[0013] For example, the present inventors observed that depositing the TIM at a thickness that is significantly less than 1.1 times a D_{90} of the liquid metal droplets can lead to inhomogeneities of the TIM and/or premature deformation of the liquid metal droplets. In an example application of stencil printing a TIM layer onto an integrated circuit, the present inventors observed that, when the blade was dragged across a mask for the integrated circuit, the blade would preferentially drag liquid metal droplets with it, while leaving behind a substantial amount of the polymer in the TIM. Additionally, the blade may have prematurely deformed the liquid metal droplets in the TIM. Therefore, an undesirably high concentration of polymer, undesirably distributed liquid metal droplets, and/or undesirably shaped liquid metal droplets may be present in the TIM leading to reduce the effective thermal conductivity of the TIM (e.g., increased thermal resistance).

[0014] Thus, the present inventors provide, in various examples, a method of deposition of a thermal interface material onto a circuit assembly and an integrated circuit formed therefrom that can provide enhanced homogeneity of the TIM after installation and/or desirably shaped liquid metal droplets, which can enhance the effective thermal conductivity of the TIM. The method comprises depositing a TIM at a first layer thickness between a first layer of a circuit assembly and a second layer of a circuit assembly. The TIM comprises an emulsion of liquid metal droplets and polymer. The first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets prior to compressing the circuit assembly. The method comprises compressing the circuit assembly to decrease the first layer thickness to a second layer thickness, thereby deforming the liquid metal droplets. The second layer thickness is no greater than a D_{90} of the liquid metal droplets in TIM prior to compressing the circuit assembly. In various examples, because the first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets during deposition, the liquid metal droplets may not be substantially separated from the polymer in the TIM during deposition and/or undesirably deformed.

[0015] As used in this specification, particularly in connection with layers, films, or materials, the terms “on,” “onto,” “over,” and variants thereof (e.g., “applied on,” “formed on,” “deposited on,” “provided on,” “located on,” and the like) mean applied, formed, deposited, provided, or otherwise located over a surface of a substrate but not necessarily in contact with the surface of the substrate. For example, a TIM “deposited on” a substrate does not preclude the presence of another layer or other layers of the same or different composition located between the applied TIM and the substrate. Likewise, a second layer “deposited on” a first layer does not preclude the presence of another layer or other layers of the same or different composition located between the deposited second layer and the deposited TIM.

[0016] As used in this specification, the terms “polymer” and “polymeric” means prepolymers, oligomers, and both homopolymers and copolymers. As used in this specification, “prepolymer” means a polymer precursor capable of further reactions or polymerization by a reactive group or reactive groups to form a higher molecular mass or cross-linked state.

[0017] The polymer can be at least one of a polymeric binder, a thermosetting polymer, and a thermoplastic polymer. As used herein, the term “thermosetting” refers to polymers that “set” irreversibly upon curing or cross-linking, where the polymer chains of the polymeric components are joined together by covalent bonds, which is often induced, for example, by heat or radiation.

[0018] In various examples, curing or a cross-linking reaction can be carried out under ambient conditions. Once cured or cross-linked, a thermosetting polymer may not flow upon the application of heat, may otherwise irreversibly increase in viscosity, and/or can be insoluble in conventional solvents. As used herein, the term “thermoplastic” refers to polymers that include polymeric components in which the constituent polymer chains are not joined (e.g., crosslinked) by covalent bonds and thereby can undergo liquid flow upon heating and are soluble in conventional solvents. In certain embodiments, the polymer can be elastomeric (e.g., rubbery, soft, stretchy) or rigid (e.g., glassy). For example, the polymer can be elastomeric.

[0019] Thermosetting polymers may include at least one of a cross-linking agent that may comprise, for example, aminoplasts, polyisocyanates (including blocked isocyanates), polyepoxides, beta-hydroxyalkylamides, polyacids, anhydrides, organometallic acid-functional materials, polyamines, polyvinyls, polysilicon hydrides, polyalcohols, polyacid chlorides, polyhalides, and polyamides. A polymer may have functional groups that are reactive with the cross-linking agent.

[0020] The polymer in the TIMs described herein may be selected from any of a variety of polymers well known in the art. For example, the thermosetting polymer may comprise at least one of an acrylic polymer, a polyester polymer, a polyurethane polymer, polybutadiene, a polyamide polymer, a polyether polymer, a polysiloxane polymer (e.g., poly (dimethylsiloxone)), a fluoropolymer, a polyisoprene polymer (e.g., rubber), and a copolymer thereof (e.g., styrene ethylene butylene styrene). The functional groups on a thermosetting polymer may be selected from any of a variety of reactive functional groups, including, for example, at least one of a carboxylic acid group, an amine group, an epoxide group, a hydroxyl group, a thiol group, a carbamate group, an amide group, a urea group, an isocyanate groups (including a blocked isocyanate group), a vinyl group, a silicon hydride group, an acid chloride group, an acrylate group, a halide group, and a mercaptan group.

[0021] The thermoplastic polymer can comprise at least one of propylene-ethylene co-polymer, styrene-butadiene-styrene, and styrene ethylene butylene styrene. The polymer can comprise a melting point of at least 100 degrees Celsius, such as, for example, at least 120 degrees Celsius, at least 150 degrees Celsius, or at least 200 degrees Celsius.

[0022] The polymeric binder can be a polyether binder.

[0023] The liquid metal droplets for the TIM can comprise at least one of gallium, a gallium alloy, indium, an indium alloy, tin, a tin alloy, mercury, and a mercury alloy. The liquid metal droplets can comprise a melting point of no greater than 30 degrees Celsius, such as, for example, no greater than 25 degrees Celsius, no greater than 20 degrees Celsius, no greater than 15 degrees Celsius, no greater than 10 degrees Celsius, no greater than 5 degrees Celsius, no greater than 0 degrees Celsius, or no greater than −10 degrees Celsius. The liquid metal droplets can comprise a melting point of at least −40 degrees Celsius, such as, for example, at least −20 degrees Celsius, at least −19 degrees Celsius, at least −10 degrees Celsius, at least 0 degrees Celsius, at least 5 degrees Celsius, at least 10 degrees Celsius, at least 15 degrees Celsius, at least 20 degrees Celsius, or at least 25 degrees Celsius. The liquid metal droplets can comprise a melting point in a range of −40 degrees Celsius to 30 degrees Celsius, such as, for example, −20 degrees Celsius to 30 degrees Celsius, −19 degrees Celsius to 30 degrees Celsius, or −19 degrees Celsius to 25 degrees Celsius. The determination of the melting point can be made at a pressure of 1 atmosphere absolute. In certain embodiments, the TIM can comprise Gallium Indium Tin (Galinstan) and a melting point of −19 degrees Celsius.

[0024] The TIM can be created by forming an emulsion of the polymer and the liquid metal droplets such that liquid metal droplets are substantially dispersed throughout the polymer. For example, the polymer and bulk liquid metal can be mixed together with at least one of a high shear mixer, a centrifugal mixer, by shaking in a container, a mortar and pestle, and sonication. More details about exemplary ways to form the emulsion and the liquid metal droplets are described in (1) published PCT WO/2019/136252, entitled "Method of Synthesizing a Thermally Conductive and Stretchable Polymer Composite", (2) published U.S. application US 2017/0218167, entitled "Polymer Composite with Liquid Phase Metal Inclusions," (3) U.S. Pat. No. 10,777,483, entitled "Method, apparatus, and assembly for thermally connecting layers", (4) U.S. Provisional Patent No. 63/268,134, entitled "Thermal interface material, an integrated circuit assembly, and a method for thermally connecting layers", and (5) published PCT WO 2022/204689 entitled "A method, apparatus, and assembly for thermally connecting layers with thermal interface materials comprising rigid particles", all of which are incorporated herein by reference in their entirety.

[0025] The composition and/or mixing techniques can be chosen such that the viscosity is less than 850,000 cP (centipoise), such as, for example, less than 750,000 cP, less than 500,000 cp, less than 250,000 cP, 200,000 cP, less than 150,000 cP, less than 100,000 cP, less than 50,000 cP, less than 15,000 cP, less than 14,000 cP, less than 13,000 cP, less than 12,000 cP, less than 11,000 cP, or less than 10,000 cP. For example, the composition and/or mixing techniques can be chosen such that the viscosity of the TIM is at least 1,000 cP, such as, for example, at least 2,000 cP, at least 5,000 cP, or at least 10,000 cP. The composition and/or mixing techniques can be chosen such that the viscosity of the TIM is in a range of 1,000 cP to 850,000 cP, such as, for example, 2,000 cP to 750,000 cP, or 2,000 cP to 500,000 cP. The viscosity of the TIM emulsion can be measured by a parallel plate (40 mm) rheometer at 25 degrees Celsius, a frequency of 10 radians per second, and a strain of 5%. Selecting the viscosity can require a balance of installation pressure, which may increase with a high viscosity and an ability to resist undesirably fast spreading during application of the TIM and pump out during operation.

[0026] The TIM can comprise at least 1% liquid metal droplets by total volume of the TIM, such as, for example, at least 5% liquid metal droplets, at least 10% liquid metal droplets, at least 20% liquid metal droplets, at least 30% liquid metal droplets, at least 40% liquid metal droplets, at least 50% liquid metal droplets, at least 60% liquid metal droplets, at least 70% liquid metal droplets, at least 80% liquid metal droplets, or at least 90% liquid metal droplets, all based on the total volume of the liquid metal droplets. The TIM can comprise no greater than 95% liquid metal droplets by total volume of the TIM, such as, for example, no greater than 93% liquid metal droplets, no greater than 90% liquid metal droplets, no greater than 80% liquid metal droplets, no greater than 70% liquid metal droplets, no greater than 60% liquid metal droplets, no greater than 50% liquid metal droplets, no greater than 40% liquid metal droplets, no greater than 30% liquid metal droplets, no greater than 20% liquid metal droplets, or no greater than 10% liquid metal droplets, all based on the total volume of the TIM. The TIM can comprise a range of 1% to 95% liquid metal droplets by total volume of the TIM, such as, for example, 5% to 93% liquid metal droplets, 50% to 93% liquid metal droplets, 60% to 93% liquid metal droplets, or 70% to 93% liquid metal droplets, all based on the total volume of the TIM. The amount of liquid metal droplets can be selected while balancing a desired elasticity and a desired effective thermal conductivity of the TIM.

[0027] The composition and/or mixing techniques can be selected to achieve a desired D_{50} and/or D_{90} of the liquid metal droplets in the TIM prior to compressing. The D_{50} of the liquid metal droplets can be at least 1 micron prior to compressing, such as, for example, at least 5 microns, at least 10 microns, at least 15 microns, at least 20 microns, at least 30 microns, at least 35 microns, at least 40 microns, at least 50 microns, at least 60 microns, at least 70 microns, at least 80 microns, at least 90 microns, at least 100 microns, at least 120 microns, or at least 150 microns, all prior to compressing. The D_{50} of the liquid metal droplets can be no greater than 200 micron, such as, for example, no greater than 150 microns, no greater than 120 microns, no greater than 100 microns, no greater than 90 microns, no greater than 80 microns, no greater than 70 microns, no greater than 60 microns, no greater than 50 microns, no greater than 40 microns, no greater than 35 microns, no greater than 30 microns, no greater than 20 microns, no greater than 10 microns, or no greater than 5 microns, all prior to compressing. For example, the D_{50} of the liquid metal droplets can be in a range of 1 microns to 200 microns, such as, for example, 5 microns to 150 microns, 15 to 150 microns, 35 microns to 150 microns, 35 microns to 70 microns, or 5 microns to 100 microns, all measured prior to compressing. In various embodiments, the composition and/or mixing techniques can be selected to achieve an average particle size of the liquid metal droplets that is larger than a D_{50} of rigid particles, if present, in the TIM, such as, for example, at least 1% larger, at least 2% larger, at least 5% larger, at least 10% larger, or at least 20% larger than the D_{50} of the rigid particles.

[0028] As used herein, D_{50} can be measured using microscopy (e.g., optical microscopy or electron microscopy). The size can be the diameter of spherical particles or the length along the largest dimension if ellipsoidal or otherwise irregularly shaped particle. As used herein, "D_X" of particles refers to the diameter at which X % of the volume of the particles have a smaller diameter.

[0029] The D_{90} of the liquid metal droplets can be at least 1 micron, such as, for example, at least 5 microns, at least 10 microns, at least 15 microns, at least 20 microns, at least 30 microns, at least 35 microns, at least 40 microns, at least 50 microns, at least 60 microns, at least 70 microns, at least 80 microns, at least 90 microns, at least 100 microns, at least 120 microns, or at least 150 microns, all prior to compressing. The D_{90} of the liquid metal droplets can be no greater than 300 micron, such as, for example, no greater than 200 microns, no greater than 150 microns, no greater than 120 microns, no greater than 100 microns, no greater than 90 microns, no greater than 80 microns, no greater than 70 microns, or no greater than 50 microns, all prior to compressing. For example, the D_{90} of the liquid metal droplets can be in a range of 1 microns to 300 microns, such as, for example, 10 microns to 200 microns, 15 to 150 microns, 35 microns to 150 microns, 35 microns to 120 microns, or 50 microns to 100 microns, all measured prior to compressing.

[0030] The TIM can optionally comprise other components such as, for example, rigid particles, a catalyst, and coupling agents. The rigid particles can comprise at least one of iron, an iron alloy (e.g., steel), vanadium, a vanadium alloy, niobium, a niobium alloy, titanium, a titanium alloy, copper, a copper alloy (e.g., bronze), a rigid polymer, a glass, and a ceramic. The rigid particles can be resistant to deformation and/or corrosion by the liquid metal droplets. For example, the rigid particles can comprise a Young's modulus of at least 100 MPa (megapascals), such as, for example, at least 110 MPa, at least 150 MPa, at least 200 MPa, at least 250 MPa, at least 500 MPa, at least 750 MPa, at least 1 GPa (gigapascals), or at least 2 GPa. Young's Modulus can be measured according to ASTM E 111-17. The TIM can comprise a range of 0.1% to 30% rigid particles by total volume of the TIM, such as, for example, 0.1% to 10% rigid particles, 0.1% to 5% rigid particles, 1% to 10% rigid particles, or 1% to 5% rigid particles, all based on the total volume of the TIM.

[0031] The D_{50} of the rigid particles in the TIM can be selected to achieve a desired bondline thickness in the assembly. The average particle size of the rigid particles can be at least 1 micron, such as, for example, at least 5 microns, at least 10 microns, at least 20 microns, at least 30 microns, at least 35 microns, at least 40 microns, at least 50 microns, at least 60 microns, at least 70 microns, at least 80 microns, at least 90 microns, at least 100 microns, at least 120 microns, or at least 125 microns. The D_{50} of the rigid particles can be no greater than 150 microns, such as, for example, no greater than 125 microns, no greater than 120 microns, no greater than 100 microns, no greater than 90 microns, no greater than 80 microns, no greater than 70 microns, no greater than 60 microns, no greater than 50 microns, no greater than 40 microns, no greater than 35 microns, no greater than 30 microns, no greater than 20 microns, no greater than 10 microns, or no greater than 5 microns. For example, the D_{50} of the rigid particles can be in a range of 1 microns to 150 microns, such as, for example, 15 to 150 microns, 5 microns to 125 microns, 35 microns to 125 microns, 35 microns to 70 microns, or 50 microns to 70 microns.

[0032] The TIM can be applied to various layers and devices and it is described below with reference to FIGS. **1-2** with reference to a circuit assembly but is not limited to only a circuit assembly and could be applied to other devices. Referring to FIG. **1**, the method according to the present disclosure comprises depositing a TIM **104** according to the present disclosure at a first layer thickness, t_1, between a first layer **106** of a circuit assembly **102** and a second layer **108** of the circuit assembly **102**. The first layer thickness, t_1, can be selected to enhance the effective thermal conductivity of the TIM **104** and/or the homogeneity of the TIM **104**.

[0033] As illustrated, the TIM **104** comprises an emulsion of liquid metal droplets **112** and polymer **110**. The first layer thickness, t_1, can be at least 1.1 times a D_{90} of the liquid metal droplets **112** prior to compression, such as, for example, at least 2.5 times, at least 3 times, at least 4 times, at least 5 times, at least 6 times, at least 10 times, at least 20 times, at least 50 times, or at least 100 times, all of a D_{90} of the liquid metal droplets **112** prior to compressing the circuit assembly **102**. The first layer thickness, t_1, can be no greater than 1,000 times a D_{90} of the liquid metal droplets **112**, such as, for example, no greater than 500 times, no greater than 250 times, no greater than 150 times, no greater than 100 times, no greater than 50 times, no greater than 15 times, no greater than 10 times, no greater than 6 times, or no greater than 5 times, all of a D_{90} of the liquid metal droplets **112** prior to compressing the circuit assembly **102**. The first layer thickness, t_1, can be in a range of 1.1 times to 1,000 times a D_{90} of the liquid metal droplets **112** prior to compressing the circuit assembly **102**, such as, for example, 2 times to 500 times, 2 times, to 150 times, 2 times to 100 times, 2 times to 50 times, 2 times to 10 times, 3 times to 10 times, or 3 times to 6 times, all of a D_{90} of the liquid metal droplets **112** prior to compressing the circuit assembly **102**. Because the first layer thickness, t_1, can be at least 1.1 times the D_{90} of the liquid metal droplets **112** prior to compression, a desired distribution of the liquid metal droplets on the circuit assembly **102** and homogeneity of the liquid metal droplets **112** within the TIM **104** can be achieved, thereby enhancing the effective thermal conductivity of the TIM **104**.

[0034] The first layer thickness, t_1, may be adjusted based on the wetting properties of the TIM **104**. For example, a TIM with a high contact angle with the first layer **106** and/or the second layer **108** may have poor wetting properties and may require an increased first layer thickness, t_1, compared to a TIM with a low contact angle with the first layer **106** and/or the second layer **108** that has better wetting properties.

[0035] The first layer thickness, t_1, can be at least 200 microns, such as, for example, at least 300 microns, at least 400 microns, at least 500 microns, or at least 600 microns. The first layer thickness, t_1, can be no greater than 2,000 microns, such as, for example, no greater than 1,500 microns, no greater than 1,000 microns, no greater than 750 microns, no greater than 600 microns, or no greater than 500 microns. The first layer thickness, t_1, can be in a range of 200 microns to 2,000 microns, such as, for example, 200 microns to 1,000 microns, 200 microns to 750 microns, or 300 microns to 600 microns.

[0036] Depositing the TIM **104** can comprise at least one of dispensing, extruding (e.g., through a nozzle, such as, a circular nozzle, a fan nozzle, or other nozzle shape), applying with a utensil (e.g., brush, spatula), stencil printing, 3D printing, and screen printing. The TIM **104** can be deposited in a conformable state such that the TIM **104** can adapt to the surfaces of the first layer **106** and the second layer **108** to achieve a desired level of surface contact therebetween. In various examples, the TIM **104** can be applied directly to the first layer **106** and, thereafter, the second layer **108** can be applied directly to the TIM **104**. In various other examples, the TIM **104** can be applied directly to the second layer **108** and, thereafter, the first layer **106** can be applied directly to the TIM **104**. In certain examples, the TIM **104** can be applied to both the first layer **106** and the second layer **108** and then the first layer **106** and the second layer **108** can be applied together. In various examples, after deposition of the TIM **104** and compression of the circuit assembly **102**, the TIM **104** can be in direct contact with the first layer **106** and the second layer **108**. In certain examples, the application of the TIM **104** may be limited to the surfaces of the first layer **106** such that the TIM **104** can be efficiently used.

[0037] The TIM can be dispensed from a container and applied to a layer in a conformable state. The TIM can be stored in a container prior to use. The TIM **104** can be in a conformable state in the container. The container can comprise at least one of a pillow pack, a syringe, a beaker, ajar, a bottle, and a drum. In various examples, the container can be a ready to use dispensing device, such as, for example, a pillow pack or a syringe. In certain examples, the TIM **104** may not be stored and can be used after creation of the emulsion without storage.

[0038] In various examples, the depositing of the TIM **104** can form a trace having a length, l_2, extending along at least 10% of a length, l_1, of the first layer **106**, such as, for example, at least 20% of the length, l_1, at least 30% of the length, l_1, at least 40%, of the length, l_1, at least 50% of the length, l_1, at least 60% of the length, l_1, at least 70% of the length, l_1, at least 80% of the length, l_1, at least 90% of the length, l_1, or at least 95% of the length, l_1. The length, l_2, can be no greater than 100% of the length, l_1, of the first layer **106**, such as, for example, no greater than 90% of the length l_1. For example, the length, l_2, can be in a range of 10% to 100% of the length, l_1, such as, for example, 20% to 100% of the length, l_1, 30% to 100% of the length, l_1, 50% to 100% of the length, l_1, 60% to 90% of the length, 11 or 70% to 90% of the length, l_1.

[0039] The depositing of the TIM **104** can form a trace having a width, w_2, extending along at least 1% of a width, w_1, of the first layer **106**, such as, for example, at least 5% of the width, w_1, at least 10% of the width, w_1, at least 20% of the width, w_1, at least 25% of the width, w_1, or at least 30% of the width, w_1. The width, w_2, can be no greater than 100% of the width, w_1, such as, for example, no greater than 50% of the width, w_1, no greater than 25% of the width, w_1, or no greater than 15% of the width, w_1. For example, the width, w_2, can be in a range of 1% to 100% of the width, w_1, such as, for example, 1% to 50% of the width, w_1, 5% to 50% of the width, w_1, or 5% to 25% of the width, w_1. In various examples, the trace may be linear.

[0040] The depositing of the TIM **104** can form another shape, such as, for example, a circle, a triangle, a rectangle, other polygon, a X shape, a hashed shape, two or more of the foregoing shapes, or other pattern. The TIM **104** can be applied to at least 1% of a surface area of an exposed side **106***a* of the first layer **106** prior to compressing the circuit assembly **102**, such as, for example, at least 2%, at least 5%, at least 10%, at least 20%, at least 30%, at least 40%, or at least 50%, all of the surface area of the exposed side **106***a* of the first layer **106**. For example, the TIM **104** can be applied to a range of 1% to 100% of the surface area of an exposed side **106***a* of the first layer **106** prior to compressing the circuit assembly **102**, such as, for example 2% to 100%, 5% to 90%, or 5% to 80%, all of the surface area of the exposed side **106***a* of the first layer **106**.

[0041] The first layer **106** can be a heat-generating electronic component (e.g., integrated circuit, such as, a processor, an ASIC, and/or a system-on-a-chip (SOC)) and/or thermally connected to the heat-generating electronic component. The second layer **108** can be an upper layer that can be thermally conductive. The first layer **106** and the second layer **108**, individually, can be at least one of a heat sink (e.g., fins, fan, liquid cooling), an integrated heat spreader, and packaging. For example, the first layer **106** can comprise an integrated heat spreader and the second layer **108** comprises a heat sink.

[0042] After deposition of the TIM **104**, the method comprises compressing the circuit assembly **102** to decrease the first layer thickness, t_1, to a second layer thickness, t_2, thereby deforming the liquid metal droplets **112** and forming an integrated circuit **202**. For example, referring to the detailed views in FIGS. **1-2**, the first layer **106** and the second layer **108** can be urged together.

[0043] For example, compressing the circuit assembly **102** can comprise applying a first pressure to the first layer **106** and the second layer **108** of at least 1 psi, such as, for example, at least 5 psi, at least 10 psi, at least 15 psi, or at least 20 psi. In various examples, compressing the circuit assembly **102** comprises a first compression process based on displacement where a first pressure is applied to the first layer **106** and the second layer **108** until the TIM **104** is compressed to a desired third layer thickness in a range of 5% to 30% greater than the second layer thickness, t_2. In various examples, the first pressure can be in a range of 1 psi to 10 psi.

[0044] Then, the compressing the circuit assembly **102** further comprises a second compression process based on pressure where the first layer **106** and the second layer **108** are compressed until predetermined pressure threshold is achieved, resulting in the second layer thickness, t_2, is achieved. In various examples, the predetermined pressure threshold can be in a range of 10 psi to 50 psi, such as, for example, 10 psi to 30 psi.

[0045] In various examples, the relative liquid metal surface area coverage between the TIM **104**, and the first layer **106** and the second layer **108** can be increased by compression. For example, the relative liquid metal surface area coverage after compression can be in a range of 1% to 100%, such as, for example, 1% to 5%, 5% to 10%, 10% to 30%, 30% to 50%, or increasing until the liquid metal surface area coverage achieves 100%. As used herein, "relative liquid metal area coverage" is the surface area covered by the liquid metal normalized by the total contact surface area between the TIM **104** and the first layer **106** and second layer **108**.

[0046] Relative liquid metal area coverage can be measured using cross-sectioning followed by optical imaging using a ZEISS Axio Zoom.V16 or confocal scanning acoustic microscopy using a Hitachi FineSAT III for CSAM.

[0047] The second layer thickness, t_2, can be the bondline thickness and the second layer thickness, t_2, can be no greater than 200 microns, such as, for example, no greater than 150 microns, no greater than 145 microns, no greater than 140 microns, no greater than 125 microns, no greater than 100 microns, no greater than 80 microns, no greater than 70 microns, no greater than 50 microns, no greater than 40 microns, no greater than 35 microns, or no greater than 30 microns. The second layer thickness, t_2, can be at least 1 microns, such as, for example, at least 15 microns, at least 30 microns, at least 35 microns, at least 40 microns, at least 50 microns, at least 70 microns, at least 75 microns, at least 80 microns, at least 100 microns, at least 120 microns, at least 140 microns, or at least 145 microns. The second layer thickness, t_2, can be in a range of 1 microns to 200 microns, such as, for example, 15 microns to 200 microns, 15 microns to 150 microns, 30 microns to 150 microns, 50 microns to 120 microns, 75 microns to 125 microns, or 15 microns to 100 microns.

[0048] The TIM can cover at least 90% of a surface area of an exposed side **106***a* of the first layer **106** after compressing the circuit assembly, such as, for example, at least 95% of the surface area of the exposed side **106***a*. As illustrated in FIG. **1**, the surface area of exposed surface can be the product of the length, l_1, times the width, w_1.

[0049] Compressing the circuit assembly **102** can apply a force to the TIM **104** and can deform the liquid metal droplets **112** dispersed within the polymer **110** of the TIM **104**. Because the polymer **110** is still conformable and moveable, the compressing force can deform the liquid metal droplets **112**. The liquid metal droplets **112** can be in the liquid phase during deformation such that a lower pressure is required for the compression and a desired deformation is achieved. For example, the liquid metal droplets **112** can be generally spherical as shown in FIG. **1** and thereafter can be generally ellipsoidal as shown in FIG. **2**. In various examples, the liquid metal droplets **112** prior to compressing can have a first average aspect ratio and after compressing the liquid metal droplets **112** can have a second average aspect ratio. The second average aspect ratio can be different that the first average aspect ratio. For example, the second average aspect ratio can be greater than the first average aspect ratio. The average aspect ratio can be a mean ratios of the width of the liquid metal droplets **112** to the height of the liquid metal droplets **112**. In various examples, the first aspect ratio can be 1 and the second aspect ratio can be greater than 1. In certain embodiments, the first aspect ratio can be in a range of 1 to 1.5. In certain embodiments, the second aspect ratio can be at least 0.5 greater than the first aspect ratio, such as, for example, at least 1 greater than the first aspect ratio, at least 2 greater than the first aspect ratio, or at least 5 greater than the first aspect ratio. In certain embodiments, the second aspect ratio can be at least 2 after compressing the circuit assembly **102**, such as, for example, at least 3, or at least 4 after compressing the circuit assembly **102**.

[0050] The width (e.g., longest dimension) of the liquid metal droplets **112** can be substantially aligned with the longitudinal plane of the TIM **104** in the circuit assembly **102** and the height of the liquid metal droplets **112** can be substantially aligned with the thickness of the TIM **104** (e.g., the distance, d_1). The width of the liquid metal droplets **112** can increase upon compression of the circuit assembly **102**. For example, in certain examples, the diameter of liquid metal droplets prior to compressing can be 200 m (with a first aspect ratio of 1) and after compression to a bondline thickness of 100 m, the liquid metal drop can be deformed to an ellipsoidal shape with a 400 μm width (e.g., second aspect ratio of 4).

[0051] In certain examples, the liquid metal droplets **112** can be aligned substantially in a monolayer as shown in FIG. **2** after compressing. The monolayer can be achieved by selecting the D_{50} and/or D_{90} of the liquid metal droplets **112**, the second thickness, t_2, and depositing with the first layer thickness, t_1. Configuring the liquid metal droplets **112** in a monolayer can reduce the thermal resistance of the TIM **104**.

[0052] The D_{50} and/or D_{90} of the liquid metal droplets **112**, deformation of the liquid metal droplets **112**, and the method of deposition of the liquid metal droplets **112** can improve the thermal resistance value of the TIM **104**. For example, the TIM **104** can comprise a thermal resistance value of at least 5 (° K*mm^2)/W, such as, for example, at least 1 (° K*mm^2)/W, at least 2 (° K*mm^2)/W, at least 3 (° K*mm^2)/W, at least 5 (° K*mm^2)/W, or at least 10 (° K*mm^2)/W. The TIM **104** can comprise a thermal resistance value of no greater than 30 (° K*mm^2)/W, such as, for example, no greater than 20 (° K*mm^2)/W, no greater than 15 (° K*mm^2)/W, no greater than 10 (° K*mm^2)/W, no greater than 9 (° K*mm^2)/W, no greater than 8 (° K*mm^2)/W, no greater than 7 (° K*mm^2)/W, or no greater than 5 (° K*mm^2)/W. The TIM **104** can comprise a thermal resistance value in a range of 0.5 (° K*mm^2)/W to 30 (° K*mm^2)/W, such as, for example, 0.5 (° K*mm^2)/W to 20 (° K*mm^2)/W, 0.5 (° K*mm^2)/W to 15 (° K*mm^2)/W, 1 (° K*mm^2)/W to 10 (° K*mm^2)/W, 2 (° K*mm^2)/W to 10 (° K*mm^2)/W, or 2 (° K*mm^2)/W to 8 (° K*mm^2)/W. The thermal resistance value can be measured using a TIMA 5 instrument from NanoTest (Germany).

[0053] The D_{50} and/or D_{90} of the liquid metal droplets **112**, deformation of the liquid metal droplets **112**, and the method of deposition of the liquid metal droplets **112** can improve the thermal conductivity value of the TIM **104**. For example, the TIM **104** can comprise an effective thermal conductivity value of at least 5 W/m*K, such as, for example, at least 10 W/m*K, at least 12 W/m*K, at least 15 W/m*K, at least 17 W/m*K, or at least 20 W/m*K. The TIM can comprise an effective thermal conductivity value in a range of 5 W/m*K to 50 W/m*K, such as, for example, 10 W/m*K to 40 W/m*K or 10 W/m*K to 30 W/m*K. As used herein, the effective thermal conductivity is a thickness of the TIM divided by a thermal resistance of the TIM.

[0054] The TIM **104** can be cured or may not be cured depending on the application. For example, the TIM **104** may be cured to solid or the TIM may be a paste. Curing the TIM **104** can increase the viscosity of the polymer **110** and can harden the polymer **110**. For example, the polymer **110** can become a solid. In various examples, the polymer **110** after curing is elastomeric. Curing the polymer **110** can inhibit pump out of the liquid metal droplets **112** during thermal cycling of the circuit assembly **102** and can provide a mechanical bond between the first layer **106** and the second layer **108**.

[0055] Curing the TIM **104** can comprise at least one of heating the TIM **104** (e.g., in examples with a thermosetting polymer), adding a catalyst to the TIM **104**, exposing the TIM **104** to air, cooling the TIM **104** (e.g., in examples with a thermoplastic polymer), applying electromagnetic radiation (e.g., photo-polymerization), and applying pressure to the TIM **104**. Curing the TIM **104** can increase the viscosity of the TIM emulsion to greater than 15,000 cP, such as, for example, greater than 20,000 cP, greater than 30,000 cP, greater than 50,000 cP, greater than 100,000 cP, greater than 150,000 cP, greater than 200,000 cP, greater than 250,000 cP, greater than 500,000 cP, greater than 750,000 cP, or greater than 850,000 cP. For example, the polymer in the TIM **104** can be cured. In various examples, the TIM **104** can be an adhesive. The polymer in the TIM **104** can be selected to reduce off-gasing of the TIM **104** during curing.

[0056] As used in this specification, the terms "cure" and "curing" refer to the chemical cross-linking of components in an emulsion or material applied over a substrate or the increase of viscosity of the components in the emulsion or material applied over the substrate. Accordingly, the terms "cure" and "curing" do not encompass solely physical drying of an emulsion or material through solvent or carrier evaporation. In this regard, the term "cured," as used in this specification in examples comprising a thermosetting polymer, refers to the condition of an emulsion or material in which a component of the emulsion or material has chemically reacted to form new covalent bonds in the emulsion or material (e.g., new covalent bonds formed between a binder resin and a curing agent). The term "cured", as used in this specification in examples comprising a thermoplastic polymer, refers to the condition of an emulsion or material in which the temperature of the thermoplastic polymer decreases below the melting point of the thermoplastic polymer such that the viscosity of the emulsion or material increases. In examples comprises both a thermosetting polymer and a thermoplastic polymer, the term "cured" refers to one of or both of the polymers curing as described herein.

[0057] In various other examples, the TIM according to the present disclosure can be used in a system on a package. For example, a single horizontal TIM layer can be in contact with multiple dies on one side (e.g., the integrated circuit can comprise multiple dies or multiple integrated circuits can be in contact with the same side of the TIM) and an upper layer or layers on a different side.

[0058] Those skilled in the art will recognize that the herein described compositions, articles, methods, and the discussion accompanying them are used as examples for the sake of conceptual clarity and that various configuration modifications are contemplated. Consequently, as used herein, the specific exemplars set forth and the accompanying discussion are intended to be representative of their more general classes. In general, use of any specific exemplar is intended to be representative of its class, and the non-inclusion of specific components (e.g., operations), devices, and objects should not be taken as limiting.

[0059] With respect to the appended claims, those skilled in the art will appreciate that recited operations therein may generally be performed in any order. Also, although various operational flows are presented in a sequence(s), it should be understood that the various operations may be performed in other orders than those that are illustrated or may be performed concurrently. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise. Furthermore, terms like "responsive to," "related to," or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

[0060] Although various examples have been described herein, many modifications, variations, substitutions, changes, and equivalents to those examples may be implemented and will occur to those skilled in the art. Also, where materials are disclosed for certain components, other materials may be used. It is therefore to be understood that the foregoing description and the appended claims are intended to cover all such modifications and variations as falling within the scope of the disclosed examples. The following claims are intended to cover all such modification and variations.

[0061] Various aspects of the invention according to the present disclosure include, but are not limited to, the aspects listed in the following numbered clauses.

[0062] Clause 1. A method comprising:

[0063] depositing a thermal interface material at a first layer thickness between a first layer of a circuit assembly and a second layer of the circuit assembly, wherein the thermal interface material comprises an emulsion of liquid metal droplets and polymer, wherein the first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets prior to compressing the circuit assembly; and

[0064] compressing the circuit assembly to decrease the first layer thickness to a second layer thickness, thereby deforming the liquid metal droplets, wherein the second layer thickness is no greater than a D_{90} of the liquid metal droplets in thermal interface material prior to compressing the circuit assembly.

[0065] Clause 2. The method of clause 1, wherein the first layer thickness is at least 2 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

[0066] Clause 3. The method of any of clauses 1-2, wherein the first layer thickness is at least 4 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

[0067] Clause 4. The method of any of clauses 1-3, wherein the first layer thickness is at least 5 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

[0068] Clause 5. The method of any of clauses 1-4, wherein the first layer thickness is at least 10 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

[0069] Clause 6. The method of any of clauses 1-5, wherein the first layer thickness is at least 200 microns.

[0070] Clause 7. The method of any of clauses 1-6, wherein the first layer thickness is at least 500 microns.

[0071] Clause 8. The method of any of clauses 1-7, wherein the second layer thickness is no greater than 150 microns.

[0072] Clause 9. The method of any of clauses 1-8, wherein the second layer thickness is no greater than 125 microns.

[0073] Clause 10. The method of any of clauses 1-9, wherein the second layer thickness is in a range of 15 microns to 150 microns.

[0074] Clause 11. The method of any of clauses 1-10, wherein the second layer thickness is in a range of 75 microns to 125 microns.

[0075] Clause 12. The method of any of clauses 1-11, wherein a D_{50} of the liquid metal droplets prior to compressing the circuit assembly is in a range of 1 microns to 200 microns.

[0076] Clause 13. The method of any of clauses 1-12, wherein a D_{50} of the liquid metal droplets prior to compressing the circuit assembly is in a range of 15 microns to 150 microns.

[0077] Clause 14. The method of any of clauses 1-13, wherein the depositing forms a linear trace extending along at least 10% of the length of the first layer and at least 1% of a width of the first layer.

[0078] Clause 15. The method of any of clauses 1-14, wherein the depositing forms a trace extending along a range of 60% to 90% of a length of the first layer and a range of 5% to 50% of a width of the first layer.

[0079] Clause 16. The method of any of clauses 1-15, wherein the thermal interface material covers at least 90% of a surface area of an exposed side of the first layer after compressing the circuit assembly.

[0080] Clause 17. The method of any of clauses 1-16, wherein the depositing comprises at least one of dispensing, extruding, applying with a utensil, stencil printing, 3D printing, and screen printing.

[0081] Clause 18. The method of any of clauses 1-17, wherein the compressing the circuit assembly comprises applying a first pressure to the first layer and the second layer of at least 1 psi.

[0082] Clause 19. The method of any of clauses 1-18, wherein the compressing the circuit assembly comprises;

[0083] compressing using a first compression process based on displacement; and

[0084] after the first compression process, compressing using a second compression process based on pressure.

[0085] Clause 20. The method of any of clauses 1-19, wherein the first layer and the second layer, individually, are at least one of a heat sink, an integrated heat spreader, and packaging.

[0086] Clause 21. The method of any of clauses 1-20, wherein the first layer comprises an integrated heat spreader and the second layer comprises a heat sink.

[0087] Clause 22. The method of any of clauses 1-21, wherein the liquid metal droplets comprise at least one of gallium, a gallium alloy, indium, an indium alloy, tin, a tin alloy, mercury, and a mercury alloy.

[0088] Clause 23. The method of any of clauses 1-22, wherein the liquid metal droplets comprise a melting point no greater than 30 degrees Celsius.

[0089] Clause 24. The method of any of clauses 1-23, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 5 W/m*K.

[0090] Clause 25. The method of any of clauses 1-24, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 10 W/m*K.

[0091] Clause 26. The method of any of clauses 1-25, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 15 W/m*K.

[0092] Clause 27. The method of any of clauses 1-26, wherein the polymer comprises a thermosetting polymer.

[0093] Clause 28. The method of any of clauses 1-27, wherein the polymer comprises a thermoplastic polymer.

[0094] Clause 29. The method of any of clauses 1-28, wherein the emulsion has a viscosity in a range of 1,000 cP to 850,000 cP prior to compressing measured at 25 degrees Celsius.

[0095] Clause 30. The method of any of clauses 1-29, wherein the liquid metal droplets are generally spherical prior to compressing and the liquid metal droplets are generally ellipsoidal after compressing the circuit assembly.

[0096] Clause 31. The method of any of clauses 1-30, wherein the liquid metal droplets comprise an aspect ratio of at least 2 after compressing the circuit assembly.

[0097] Clause 32. The method of any of clauses 1-31, wherein depositing comprises applying the thermal interface material direct to the first layer and, thereafter, directly applying the second layer to the thermal interface material.

[0098] Clause 33. The method of any of clauses 1-31, wherein depositing comprises applying the thermal interface material direct to the second layer and, thereafter, directly applying the first layer to the thermal interface material.

[0099] Clause 34. The method of any of clauses 1-31, wherein depositing comprises applying the thermal interface material to both the first layer and the second layer and then applying the first layer and the second layer together.

[0100] Clause 35. The method of any of clauses 1-34, further comprising curing the thermal interface material after compressing, thereby increasing the viscosity of the thermal interface material to maintain the second layer thickness.

[0101] Clause 36. The method of any of clauses 1-35, wherein the thermal interface material comprises a contact angle suitable to efficiently wet at least one of a surface of the first layer and a surface of the second layer.

[0102] Clause 37. An integrated circuit formed by the method of any of clauses 1-36.

[0103] Clause 38. The integrated circuit of clause 37, wherein the relative liquid metal surface area coverage between the thermal interface material, and the first layer and the second layer is in a range of 1% to 100%, such as, for example, 1% to 5%, 5% to 10%, 10% to 30%, 30% to 50%, or increasing until the liquid metal surface area coverage achieves 100%.

[0104] As used herein, “at least one of” a list of elements means one of the elements or any combination of two or more of the listed elements. As an example “at least of A, B, and C” means A only; B only; C only; A and B; A and C; B and C; or A, B, and C.

[0105] Various features and characteristics are described in this specification to provide an understanding of the composition, structure, production, function, and/or operation of the invention, which includes the disclosed compositions, coatings, and methods. It is understood that the various features and characteristics of the invention described in this specification can be combined in any suitable manner, regardless of whether such features and characteristics are expressly described in combination in this specification. The Inventors and the Applicant expressly intend such combinations of features and characteristics to be included within the scope of the invention described in this specification. As such, the claims can be amended to recite, in any combination, any features and characteristics expressly or inherently described in, or otherwise expressly or inherently supported by, this specification. Furthermore, the Applicant reserves the right to amend the claims to affirmatively disclaim features and characteristics that may be present in the prior art, even if those features and characteristics are not expressly described in this specification. Therefore, any such amendments will not add new matter to the specification or claims and will comply with the written description, sufficiency of description, and added matter requirements.

[0106] Any numerical range recited in this specification describes all sub-ranges of the same numerical precision (i.e., having the same number of specified digits) subsumed within the recited range. For example, a recited range of "1.0 to 10.0" describes all sub-ranges between (and including) the recited minimum value of 1.0 and the recited maximum value of 10.0, such as, for example, "2.4 to 7.6," even if the range of "2.4 to 7.6" is not expressly recited in the text of the specification. Accordingly, the Applicant reserves the right to amend this specification, including the claims, to expressly recite any sub-range of the same numerical precision subsumed within the ranges expressly recited in this specification. All such ranges are inherently described in this specification such that amending to expressly recite any such sub-ranges will comply with the written description, sufficiency of description, and added matter requirements.

[0107] Also, unless expressly specified or otherwise required by context, all numerical parameters described in this specification (such as those expressing values, ranges, amounts, percentages, and the like) may be read as if prefaced by the word "about," even if the word "about" does not expressly appear before a number. Additionally, numerical parameters described in this specification should be construed in light of the number of reported significant digits, numerical precision, and by applying ordinary rounding techniques. It is also understood that numerical parameters described in this specification will necessarily possess the inherent variability characteristic of the underlying measurement techniques used to determine the numerical value of the parameters.

[0108] Notwithstanding that numerical ranges and parameters setting forth the broad scope of the invention are approximations, numerical values set forth in the specific examples are reported precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard variation found in its respective testing measurements.

[0109] Reference throughout the specification to "various examples," "some examples," "one example," "an example," or the like means that a particular feature, structure, or characteristic described in connection with the example is included in an example. Thus, appearances of the phrases "in various examples," "in some examples," "in one example," "in an example," or the like, in places throughout the specification are not necessarily all referring to the same example. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in an example or examples. Thus, the particular features, structures, or characteristics illustrated or described in connection with one example may be combined, in whole or in part, with the features, structures, or characteristics of another example or other examples without limitation. Such modifications and variations are intended to be included within the scope of the present examples.

[0110] Any patent, publication, or other document identified in this specification is incorporated by reference into this specification in its entirety unless otherwise indicated but only to the extent that the incorporated material does not conflict with existing descriptions, definitions, statements, illustrations, or other disclosure material expressly set forth in this specification. As such, and to the extent necessary, the express disclosure as set forth in this specification supersedes any conflicting material incorporated by reference. Any material, or portion thereof, that is incorporated by reference into this specification, but which conflicts with existing definitions, statements, or other disclosure material set forth herein, is only incorporated to the extent that no conflict arises between that incorporated material and the existing disclosure material. Applicant reserves the right to amend this specification to expressly recite any subject matter, or portion thereof, incorporated by reference. The amendment of this specification to add such incorporated subject matter will comply with the written description, sufficiency of description, and added matter requirements.

[0111] Whereas particular examples of this invention have been described above for purposes of illustration, it will be evident to those skilled in the art that numerous variations of the details of the present invention may be made without departing from the invention as defined in the appended claims.

[0112] While the present disclosure provides descriptions of various specific aspects for the purpose of illustrating various aspects of the present disclosure and/or its potential applications, it is understood that variations and modifications will occur to those skilled in the art. Accordingly, the invention or inventions described herein should be understood to be at least as broad as they are claimed and not as more narrowly defined by particular illustrative aspects provided herein.

[0113] It is understood that the inventions described in this specification are not limited to the examples summarized in the Summary or Detailed Description. Various other aspects are described and exemplified herein.

What is claimed is:

1. A method comprising:

depositing a thermal interface material at a first layer thickness between a first layer of a circuit assembly and a second layer of the circuit assembly, wherein the thermal interface material comprises an emulsion of liquid metal droplets and polymer, wherein the first layer thickness is at least 1.1 times a D_{90} of the liquid metal droplets prior to compressing the circuit assembly; and

compressing the circuit assembly to decrease the first layer thickness to a second layer thickness, thereby deforming the liquid metal droplets, wherein the second layer thickness is no greater than a D_{90} of the liquid metal droplets in thermal interface material prior to compressing the circuit assembly.

2. The method of claim **1**, wherein the first layer thickness is at least 2 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

3. The method of claim **1**, wherein the first layer thickness is at least 4 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

4. The method of claim **1**, wherein the first layer thickness is at least 5 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

5. The method of claim **1**, wherein the first layer thickness is at least 10 times a D_{90} of the liquid metal droplets in the thermal interface material prior to compressing the circuit assembly.

6. The method of claim **1**, wherein the first layer thickness is at least 200 microns.

7. The method of claim **1**, wherein the first layer thickness is at least 500 microns.

8. The method of claim **1**, wherein the second layer thickness is no greater than 150 microns.

9. The method of claim **1**, wherein the second layer thickness is no greater than 125 microns.

10. The method of claim **1**, wherein the second layer thickness is in a range of 15 microns to 150 microns.

11. The method of claim **1**, wherein the second layer thickness is in a range of 75 microns to 125 microns.

12. The method of claim **1**, wherein a D_{50} of the liquid metal droplets prior to compressing the circuit assembly is in a range of 1 microns to 200 microns.

13. The method of claim **1**, wherein a D_{50} of the liquid metal droplets prior to compressing the circuit assembly is in a range of 15 microns to 150 microns.

14. The method of claim **1**, wherein the depositing forms a trace extending along at least 10% of a length of the first layer and at least 1% of a width of the first layer.

15. The method of claim **1**, wherein the depositing forms a linear trace extending along a range of 60% to 90% of a length of the first layer and a range of 5% to 50% of a width of the first layer.

16. The method of claim **1**, wherein the thermal interface material covers at least 90% of a surface area of an exposed side of the first layer after compressing the circuit assembly.

17. The method of claim **1**, wherein the depositing comprises at least one of dispensing, extruding, applying with a utensil, stencil printing, 3D printing, and screen printing.

18. The method of claim **1**, wherein the compressing the circuit assembly comprises applying a first pressure to the first layer and the second layer of at least 1 psi.

19. The method of claim **1**, wherein the compressing the circuit assembly comprises;

compressing using a first compression process based on displacement; and

after the first compression process, compressing using a second compression process based on pressure.

20. The method of claim **1**, wherein the first layer and the second layer, individually, are at least one of a heat sink, an integrated heat spreader, and packaging.

21. The method of claim **1**, wherein the first layer comprises an integrated heat spreader and the second layer comprises a heat sink.

22. The method of claim **1**, wherein the liquid metal droplets comprise at least one of gallium, a gallium alloy, indium, an indium alloy, tin, a tin alloy, mercury, and a mercury alloy.

23. The method of claim **1**, wherein the liquid metal droplets comprise a melting point no greater than 30 degrees Celsius.

24. The method of claim **1**, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 5 W/m*K.

25. The method of claim **1**, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 10 W/m*K.

26. The method of claim **1**, wherein the thermal interface material after compressing comprises an effective thermal conductivity value of at least 15 W/m*K.

27. The method of claim **1**, wherein the polymer comprises a thermosetting polymer.

28. The method of claim **1**, wherein the polymer comprises a thermoplastic polymer.

29. The method of claim **1**, wherein the emulsion has a viscosity in a range of 1,000 cP to 850,000 cP prior to compressing measured at 25 degrees Celsius.

30. The method of claim **1**, wherein the liquid metal droplets are generally spherical prior to compressing and the liquid metal droplets are generally ellipsoidal after compressing the circuit assembly.

31. The method of claim **1**, wherein the liquid metal droplets comprise an aspect ratio of at least 2 after compressing the circuit assembly.

32. The method of claim **1**, wherein depositing comprises applying the thermal interface material direct to the first layer and, thereafter, directly applying the second layer to the thermal interface material.

33. The method of claim **1**, wherein depositing comprises applying the thermal interface material direct to the second layer and, thereafter, directly applying the first layer to the thermal interface material.

34. The method of claim **1**, wherein depositing comprises applying the thermal interface material to both the first layer and the second layer and then applying the first layer and the second layer together.

35. The method of claim **1**, further comprising curing the thermal interface material after compressing, thereby increasing the viscosity of the thermal interface material to maintain the second layer thickness.

36. The method of claim **1**, wherein the thermal interface material comprises a contact angle suitable to efficiently wet at least one of a surface of the first layer and a surface of the second layer.

37. An integrated circuit formed by the method of claim **1**.

38. The integrated circuit of claim **37**, wherein the relative liquid metal surface area coverage between the thermal interface material, and the first layer and the second layer is in a range of 1% to 100%, such as, for example, 1% to 5%, 5% to 10%, 10% to 30%, 30% to 50%, or increasing until the liquid metal surface area coverage achieves 100%.

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