

LIQUID-INFUSED MICRO- OR NANO-STRUCTURED METAL COMPOSITE

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/545,849, filed October 26, 2023, and U.S. Provisional Patent Application No. 63/625,031, filed January 25, 2024, the contents of which are incorporated herein in their entireties.

GOVERNMENT RIGHTS

[0002] This invention was made with United States government support under 1916110 awarded by the National Science Foundation (NSF) and DE-AR0001761 awarded by the Department of Energy (DOE). The U.S. government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] The present application relates to a thermal management product, in particular thermal interface product for electronic devices, such as computer chips.

[0004] Efficient heat dissipation is essential for saving energy and preventing malfunction in all kinds of energy-dense devices and systems. Globally, in 2022, data centers consume about 240-340 terawatt hours of electricity annually (1-1.3% of total electricity used on Earth each year), which will continue to grow with the development of cloud computing and artificial intelligence. Cooling demands account for as much as 33-40 % of data center energy usage and consume billions of tons of water per year. Meanwhile, heat fluxes of high-power electronics, such as solid-state lasers, wide bandgap transistors, and phased array radars, have reached unprecedented ~ 1 kW/cm, which, without effective thermal solutions, will lead to rapid device performance and lifetime degradation. As heterogeneous integration becomes increasingly inevitable in future electrical devices and systems, thermal resistance at interfaces has emerged as a critical bottleneck for efficient thermal management. While thermal interface materials (TIMs), such as solders, greases, compounds, and pads, have been widely applied to alleviate thermal interface resistance, they must exhibit both a low bulk thermal resistance and a low

contact thermal resistance to ensure optimal thermal performance. Additionally, TIM should possess mechanical softness to effectively absorb the thermal stress resulting from the mismatch in the coefficient of thermal expansion (CTE) at the interface. Meeting these stringent requirements poses formidable challenges in the development of a high-performance multifunctional TIM.

[0005] Traditional solders and solderable nanostructured TIMs have high thermal conductivity and low contact resistance but rely on high-temperature soldering processes limited to specific material surfaces, which greatly hinder their applications as universal joints. Although polymer composite TIMs such as thermal greases and compounds have high compliance, they struggle with “pump-out” issues, which cause poor reliability and low thermal performance due to the scattered heat conduction among dispersed conductive fillers. Compared with liquid-form thermal greases/compounds, solid-state thermal pads are more programmable on the material alignment and, thereby, may potentially achieve a higher thermal conductivity. However, the substantial thickness (typically hundreds-of- μm) caused by the fabrication limitations and direct (“dry”) thermal contact with substrates results in high bulk and contact thermal resistances, compromising their overall thermal performance. To date, there is still a lack of universal high-performance TIM, that can meet the crucial demands of thermal management.

SUMMARY OF THE INVENTION

[0006] One aspect of the present application is a liquid-infused composite comprising a thermally conductive scaffold infused with an effective amount of thermal bridge liquid. The thermal bridge liquid may include any liquid that is hydrophilic with the scaffold, including, but not limited to, non-adhesive liquids, and/or adhesives, and/or liquid metals. The scaffold primarily comprises a first metal, has a self-supporting micro- or nano-structure, and is capable of retaining the thermal bridge liquid internally.

[0007] The scaffold may comprise 50%, preferably 70%, more preferably 80%, particularly 90% of the first metal based on the total weight of the scaffold (w/w).

[0008] The composite of the present application may be made by a method comprising the following steps:

preparing the scaffold; and

infusing an effective amount of the thermal bridge liquid into the scaffold.

[0009] The scaffold may be prepared by a process selected from the group consisting of 3D printing, templated manufacturing, lithography, self-assembly, chemical vapor depositions, physical vapor depositions, etching methods, electrodepositions, colloidal assembly, weaving and knitting, sol-gel processes, and combinations thereof.

[0010] The composite may be pre-packaged with at least one polymer layer, metal layer, cellulose layer, and/or composite layer to protect the composite from damage and contamination.

[0011] The effective amount of the thermal bridge liquid may comprise up to 95%, preferably up to 90%, and more preferably up to 80% of the total volume of LIMC (v/v). In some embodiment, an extremely small amount of thermal bridge liquid comprising less than 20% of the total volume of LIMC (v/v) may still provide a good thermal bridging effect as long as the liquid is gathering close to the top surface of LIMC.

[0012] The scaffold may also be made by additive manufacturing or 3D printing. And the composite may be formed by infusing the thermal bridge liquid into the 3D-printed scaffold.

[0013] The composite of the present application may be used in a component for dissipating heat. For example, the composite may be used as a universal thermal interface solution for cooling applications in data centers, GPU/CPU systems, solid-state lasers, thermoelectric modules, and LEDs.

[00014] Yet another aspect of the present application is a thermal component comprising:

a lower-temperature object;

a higher-temperature object; and

a composite of the present application serving as a thermal interface material and being positioned between the lower-temperature object and the higher-temperature object.

As examples, the higher-temperature object may be an electronic chip, battery, or laser module. The lower-temperature object may be a heat sink, such as an Al or Cu heat sink or a heat spreader.

BRIEF DESCRIPTION OF THE DRAWINGS

[00015] Figure 1 illustrates a liquid infused nanostructure composite based on an embodiment of the present application.

[00016] Figure 2 illustrates a liquid infused double-sided nanostructure composite based on another embodiment of the present application

[00017] Figure 3 illustrates a prepackaged LIMC based on one embodiment of the present application

[00018] Figure 4 illustrates LIMC infused with adhesive liquids mechanically bonding two objects based on yet another embodiment of the present application.

[00019] Figure 5 shows schematics of pure dry contact and liquid-bridged interface based on an embodiment of the present application.

[00020] Figure 6 shows temperature data of a 65W CPU tested at full load when using the same nanostructured film without and with different liquid bridges.

[00021] Figure 7 shows pressure dependent thermal resistance of LIMC without and with infused liquid of glycerol and liquid metal, tested under ASTM D5470 standard.

[00022] Figure 8 shows photos of bare metal nanostructure (left), glycerol-based LIMC (middle), and liquid-metal-based LIMC (right).

[00023] Figure 9 shows an example of glycerol-based LIMC prepackage in polyimide cover films.

[00024] Figure 10 shows temperature data of a 65W CPU tested at full load when using the same nanostructured film with glycerol as a liquid bridge before and after 20-time assembly and disassembly of the chip and cooler setup.

[00025] Figure 11 shows the thermal reliability of a LIMC based on an embodiment of the present application via an in-situ power cycling test.

[00026] Figure 12 shows the hydrophilicity and friction of the micro- or nano-structure holding the liquid from being pumped out.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[00027] As used herein, the term “about” when immediately preceding a numerical value means a range of plus or minus 10% of that value, for example, “about 50” means 45 to 55, “about 25,000” means 22,500 to 27,500, etc., unless the context of the disclosure indicates otherwise, or is inconsistent with such an interpretation.

[00028] As used herein, the singular forms “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. Nothing in this disclosure is to be construed as an admission that the embodiments described in this disclosure are not entitled to antedate such disclosure by virtue of prior invention. As used in this document, the term “comprising” means “including, but not limited to.”

[00029] While various compositions, methods, and devices are described in terms of "comprising" various components or steps (interpreted as meaning "including, but not limited to"), the compositions, methods, and devices may also "consist essentially of" or "consist of" the various components and steps, and such terminology should be interpreted as defining essentially closed-member groups.

[00030] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art may translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

[00031] It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (for example, bodies of the appended claims) are generally intended as "open" terms (for example, the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those skilled in the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to embodiments containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (for example, "a" and/or "an" should be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an

introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (for example, the bare recitation of "two recitations," without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (for example, "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (for example, "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

[00032] In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group.

[00033] As will be understood by one skilled in the art, for any and all purposes, such as in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof. Any listed range may be easily recognized as sufficiently describing and enabling the same range being broken down

into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each range discussed herein may be readily broken down into a lower third, middle third and upper third, etc. As will also be understood by one skilled in the art all language such as “up to,” “at least,” and the like include the number recited and refer to ranges which may be subsequently broken down into subranges as discussed above. Finally, as will be understood by one skilled in the art, a range includes each individual member. Thus, for example, a group having 1-3 cells refers to groups having 1, 2, or 3 cells. Similarly, a group having 1-5 cells refers to groups having 1, 2, 3, 4, or 5 cells, and so forth.

[00034] The micro- or nano-structured composite as used herein refers to a metal scaffold structure in the size of micro- or nano- scale that is infused with a thermal bridge liquid. Micro- or nano-structure refers to the architecture or arrangement of material components at the microscopic or nanoscopic scale, with features ranging from 1 nanometer to 1000 micrometers., preferably 10 nanometers to 100 micrometers, more preferably 100 nanometers to 10 micrometers.

[00035] The thermal bridge liquid used herein refers to the liquid infused in the scaffold, which thermally bridges the scaffold with the object surface. When directly applied at an interface, the mechanically soft micro- or nano- structure complies to the object surface and make thermal contact. However, there may exist air gaps between the scaffold and the object surface, leading to a large contact thermal resistance. By infusing a thermal bridge liquid into the scaffold and filling up the air gaps, the overall thermal resistance may be largely suppressed.

[00036] The liquid metal used herein refers to a metallic substance that is in its liquid state at 19 to 31°C.

[00037] This disclosure is not limited to the particular systems, devices, and methods described, as these may vary. The terminology used in the description is for the purpose of describing the particular versions or embodiments only and is not intended to limit the scope.

[00038] The material of the scaffold structure may be made of a metal or metal alloy that exists in solid form at relevant working environment where the composite will be used, e.g., -55~80°C. The material of the scaffold may be copper, silver, aluminum, tungsten, zinc, nickel, tin, or a combination thereof.

[00039] The structure of the metal scaffold is present in a form selected from the group consisting of aligned and/or distributed particles, crystals, wires, networks, tubes, rods, fibers, pillars, sheets, films, plates, islands, meshes, foams, pores, cages, composites, core-shells, heterostructures, and combinations thereof, preferably wires, tubes, meshes, and foams.

[00040] In some embodiments, the described herein includes a liquid-infused nanostructured Cu (LINC) as a universal high-performance TIM. As shown in **Figure 1**, LINC comprises a unique mechanically compliant and thermally conductive double-sided Cu nanowire (CuNW) array scaffold infused with a customized thermal-bridge liquid. Vertically aligned CuNWs with a typical diameter of 200 nm and height of ~25 μm were grown on both sides of a thin Cu foil (~10 μm thick) by scalable templated electrochemical deposition.

[00041] In some embodiments, the described herein includes a liquid thermal bridging technique where solvents and/or glue and/or liquid metals may be integrated with nanostructured thermal interface materials to turn point-to-point dry thermal contact into surface-to-surface composite contact. In some embodiments, solvents may be non-volatile. In some embodiments, solvents may be volatile. In some embodiments, solvents may include a combination of solvents.

[00042] The liquid thermal bridging techniques address the general challenge of dry thermal contact for all the emerging nanostructured thermal interface materials. Poor dry contact thermal performance may be significantly improved with the largely reduced contact resistance.

[00043] In some embodiments, the thermal bridge liquid may include any liquid that is hydrophilic with the micro- or nano-structure, including, but not limited to, non-adhesive liquids (including, but not limited to, water, organic solvents, ionic liquids, silicone, grease, oil, particle-liquid, and/or flake-liquid mixtures), and/or adhesives (including, but not limited to, glue, resin, and/or epoxy), and/or liquid metals (including, but not limited to, Hg, Cs, Ga, Rb, and/or alloys on their basis including but not limited to Ga-In, Ga-Sn, Ga-In-Sn, Ga-In-Sn-Zn). To facilitate the hydrophilicity between the micro- or nano-structured scaffold and the thermal bridge liquid, the scaffold surface may be treated to remove an oxide layer, or coated with another layer, or not treated, so that it is hydrophilic to the thermal bridge liquid.

[00044] In some embodiments, the composite of the present application has an effective thermal resistance $< 1 \text{ mm}^2 \cdot \text{K/W}$ under ASTM D5470 test standard, taking both bulk and contact thermal resistance into consideration.

[00045] In this application, we developed liquid-infused metal micro- or nano-structured composites (LIMC) as universal high-performance TIMs. As shown in **Figure 1**, LIMC is comprised of a mechanically compliant and thermally conductive micro- or nano-structure scaffold infused with a customized thermal-bridge liquid. The high-aspect-ratio micro- or nano-structures function as a conductive and compliant scaffold complying with the object surface morphology and acting like “micro-or nano-springs”, thereby serving as efficient heat flow channels across the interface when used as a TIM.

[00046] The scaffold has a self-supporting, reliable structure with integrity. The nano- or micro-structure may have a high aspect ratio (e.g., greater than 5) between their length and diameter. The structure may be formed of wires or rods or particles, where mechanical and electrical properties can be transferred through the structure. The nano or micro wires or rods or particles may be aligned or interconnected, forming a reliable structure with integrity. For instance, the scaffold may primarily comprise predominantly vertically aligned nanowires.

[00047] LIMC may be used in a single-side form, a double-side form, or a 3D composite structure form.

[00048] When used in single-side form, micro- or nano-structures are first formed on one side of an interface, followed by the infusing of thermal bridge liquids into the nanostructures, forming a single-sided composite, as shown in **Figure 1**. The opposite side of the interface is then pressed on top of the nanostructured composite layer to make contact.

[00049] When used in double-side form, nanostructures are first formed on both sides of a substrate, followed by the infusing of thermal bridge liquids into the nanostructures, forming a double-sided composite, as shown in **Figure 2**. The composite may then be applied at an interface, contacting both sides of the interface by the nanostructured composite layers. In some embodiment, a double-sided copper nanowires (CuNW) array, alongside a center Cu foil may function as a conductive and compliant scaffold due to the high thermal conductivity of Cu and the high aspect ratio (>100) of CuNWs. Based on low-cost roll-to-roll solution-processed manufacturing, one may achieve a scalable production (e.g., ~ 2 m long) of the CuNW scaffold.

[00050] In a 3D composite structure, a 3D free-standing metal scaffold permeable to liquid, e.g. in the form of mesh or foam, is infused with the thermal bridge liquid to form the LIMC. The 3D free-standing metal scaffold may function as a conductive and compliant scaffold to hold the thermal bridge liquid.

[00051] In some embodiments, the metal micro-/nano-structure is comprised of aligned and/or distributed particles, crystals, wires, networks, tubes, rods, fibers, pillars, sheets, films, plates, islands, meshes, foams, pores, cages, composites, core shells, heterostructures, and combinations thereof, preferably wires, tubes, meshes, and foams.

[00052] The infused liquid is multifunctional and highly customizable for a broad range of applications, divided into non-adhesive and adhesive liquids for without or with the function of adhesion.

[00053] When using non-adhesive liquids, LIMC allows for pre-packaging and provides high reworkability, facilitating convenient and repeated uses, as shown in **Figure 3**. The infused non-adhesive liquids may include, but are not limited to, solvents such as organic solvents (e.g., alcohols, ketones, esters), water, ionic liquids, and their mixtures. This category may also encompass organic and aqueous solutions, suspensions or dispersions containing particles, flakes, or nanomaterials, emulsions, and liquid metals (e.g., gallium-based alloys with melting points below 31 degrees Celsius). Additionally, non-adhesive liquids may include supercritical fluids, silicone oils, and low-viscosity polymers. When applied as an interface material, the hydrophilicity and friction with the metal nanostructure may effectively trap the infused liquid, preventing it from being pumped out.

[00054] When using adhesive liquids, LIMC enables mechanical bonding of an interface with excellent heat transfer at room temperature, as shown in **Figure 4**. Unlike the high-temperature soldering process with restricted material compatibility, adhesive liquid-based LIMC not only maintains excellent structural integrity at the interfaces akin to soldering but also expands its applicability to non-solderable materials such as polymers and ceramics.

[00055] By transforming the nanowire-surface point-to-point “dry” contact into nanowire/liquid-surface composite contact, the liquid infusion method based on the present application may effectively bridge the micro- or nano-structure tips thermally to a target surface and, therefore largely suppress the contact resistance of LIMC, considering that the thermal conductivity of liquids is usually more than one order of magnitude larger than that of air. The mechanism is schematically illustrated in **Figure 5**. Employing a high thermal conductivity infused liquid, such as liquid metal, also contributes to the substantial reduction of the bulk

thermal resistance of LIMC. Hence, in contrast with existing TIM studies that primarily focus on reducing the bulk resistance, LIMC simultaneously achieves a low bulk resistance and a low contact resistance, both of which are equally crucial aspects in practical applications.

[00056] Example 1 – liquid thermal bridge effect of the infused liquids on CPU cooling.

Figure 6 shows the temperature data of a 65W CPU tested at full load when using the same nanostructured film without and with different liquid bridges. Thermal conductivity (k) of air, IPA, glycerol, water, and GaInSn liquid metal are around 0.024, 0.140, 0.287, 0.600, and >30 W/m·K, respectively. The improved heat dissipation with increased k and the observed two-stage temperature behavior of the IPA bridged interface verify the thermal transport mechanism by liquid bridging.

[00057] Example 2 – liquid thermal bridge effect of the infused liquids on ASTM D5470 thermal measurements. **Figure 7** shows the pressure dependent thermal resistance of LIMC without and with infused liquid of glycerol and liquid metal, tested under ASTM D5470 standard. The overall thermal resistance is largely suppressed from dry thermal contact to Glycerol-LIMC, where the bulk thermal resistance barely changed, depicting the liquid thermal bridge effect remarkably reduces the contact thermal resistance. The further improvement from glycerol-LIMC to liquid-metal-LIMC discloses the benefit of using a thermal-bridge liquid with higher thermal conductivity, where both bulk thermal resistance and contact thermal resistance are simultaneously suppressed.

[00058] Example 3 – different liquid-infused LIMC. **Figure 8** shows the actual photo of bare metal nanostructure (left), glycerol-based LIMC (middle), and Liquid-Metal-based LIMC (right).

[00059] Example 4 – pre-packaged LIMC. **Figure 9** shows an example of glycerol-based LIMC prepackage in polyimide cover films.

[00060] Example 5 – highly reworkable LIMC when infused with non-adhesive liquid.

Figure 10 shows the temperature data of a 65W CPU tested at full load when using the same nanostructured film with glycerol as liquid bridge before and after 20-time assembly and disassembly of the chip and cooler setup. The thermal performance shows no degradation, demonstrating superior reworkability when using the liquid bridge.

[00061] Example 6 – Thermal reliability of LIMC via in-situ power cycling test. An in-situ power cycling setup (Figures 11a, b) equipped with a ceramic heater and an active air-cooler is established for reliability test of LIMC. In this test, the thermal expansion coefficient mismatch between the metal heat sink and the ceramic heater is ~ 4 times. With a constant cooling power, the heater is periodically turned on and off to cycle the TIMs from room temperature to an equilibrium temperature of $> 100\text{ }^{\circ}\text{C}$ (Figure 11c). A high heating power density of $\sim 46\text{ W/cm}^2$ is applied to magnify the temperature difference between the ambient and equilibrium (maximum) heater temperature, $\Delta T = T_{heater} - T_{ambient}$, which directly indicates the thermal performance of the TIMs. The degradation of the TIM performance can be observed in real-time through monitoring ΔT . As shown in Figure 11d for > 2600 cycles, our Liquid-Metal-LIMC shows no observable degradation during the entire test period.

[00062] Example 7 – Hydrophilicity and friction of micro- or nano-structure holding the liquid from being pumped out. The hydrophilicity and friction with micro- or nano-structure can effectively trap the infused liquid, preventing it from being pumped out. As shown in Figure 12, pure liquid metal tends to form droplets and leak from the interface, while our Liquid-Metal-LIMC retains the minor squeezed liquid metal and mitigates its movement, significantly benefiting the strong reliability of LIMC in real applications.

CLAIMS

We claim:

1. A liquid-infused composite comprising: a thermally conductive scaffold infused with an effective amount of thermal bridge liquid, wherein the scaffold primarily comprises a first metal, has a self-supporting micro- or nano-structure, and is capable of retaining the thermal bridge liquid internally.
2. The composite of claim 1 wherein the first metal is a metal or a metal alloy that exists in a solid form at a relevant working environment where the composite is to be used, preferably copper, silver, aluminum, tungsten, zinc, nickel, tin, or a combination thereof.
3. The composite of claim 1 wherein the composite is compliable so that it has a shape adjustable to a designated morphology.
4. The composite of claim 1 wherein the micro- or nano-structure is present in a form selected from the group consisting of aligned and/or distributed particles, crystals, wires, networks, tubes, rods, fibers, pillars, sheets, films, plates, islands, meshes, foams, pores, cages, composites, core-shells, heterostructures, and combinations thereof, preferably wires, tubes, meshes, and foams that form the self-supporting and reliable scaffold.
5. The composite of claim 1 wherein the micro- or nano-structure has such hydrophilicity and friction that retains the thermal bridge liquid internally from being pumped out and hence preventing leakage of the thermal bridge liquid.

6. The composite of claim 1 wherein the micro- or nano- structure is treated to remove an oxide layer or coated with another layer, or remains untreated, to be hydrophilic to the thermal bridge liquid.
7. The composite of claim 1 wherein the thermal-bridge liquid is a non-adhesive liquid selected from the group consisting of water, organic solvents, ionic liquids, silicone, grease, oil, particle-liquid, and/or flake-liquid mixtures, and combinations thereof.
8. The composite of claim 1 wherein the thermal-bridge liquid is an adhesive liquid selected from the group consisting of glue, resin, epoxy, liquid metals, and combinations thereof.
9. The composite of claim 1 wherein the thermal bridge liquid is a liquid metal selected from the group consisting of Ga, In, Tin, Hg, Cs, Rb, Zn, alloys thereof, and combinations thereof.
10. The composite of claim 7 wherein the alloys are selected from the group consisting of Ga-In, Ga-Sn, Ga-In-Sn, Ga-In-Sn-Zn, and combinations thereof.
11. The composite of claim 1 wherein the scaffold is self-standing or disposed or formed on a substrate or a thermal interface.
12. The composite of claim 10 wherein the scaffold is disposed or formed on two opposite sides of the substrate or thermal interface.
13. The composite of claim 10 wherein the scaffold is a free-standing metal mesh or foam.
14. The composite of claim 1 wherein the composite is prepackaged with a cover layer prior to use.
15. The composite of claim 1, wherein the scaffold is nano-structured and comprises nanowires.

16. The composite of claim 1 having an effective thermal resistance $< 1 \text{ mm}^2 \cdot \text{K/W}$ under ASTM D5470 test standard, taking both bulk and contact thermal resistance into consideration.
17. A method of making the composite of claim 1 comprising:
 - forming the thermally conductive scaffold; and
 - infusing the thermal bridge liquid into the scaffold.
18. Use of the composite of claim 1 at a thermal interface for transferring heat from one side of the thermal interface to the other side of the thermal interface.
19. A thermal component comprising:
 - a lower-temperature object;
 - a higher-temperature object ; and
 - a composite of claim 1 serving as a thermal interface material and being positioned between the lower-temperature object and the higher-temperature object.