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Hassani et al.

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- (54) **LOW THERMAL RESISTANCE POWER MODULE ASSEMBLY**
- (75) Inventors: **Vahab Hassani**, Denver, CO (US);
Andreas Vlahinos, Castle Rock, CO (US); **Desikan Bharathan**, Arvada, CO (US)

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Primary Examiner—Michael Datskovskiy
(74) Attorney, Agent, or Firm—Paul J. White

(57) **ABSTRACT**

A power module assembly with low thermal resistance and enhanced heat dissipation to a cooling medium. The assembly includes a heat sink or spreader plate with passageways or openings for coolant that extend through the plate from a lower surface to an upper surface. A circuit substrate is provided and positioned on the spreader plate to cover the coolant passageways. The circuit substrate includes a bonding layer configured to extend about the periphery of each of the coolant passageways and is made up of a substantially nonporous material. The bonding layer may be solder material which bonds to the upper surface of the plate to provide a continuous seal around the upper edge of each opening in the plate. The assembly includes power modules mounted on the circuit substrate on a surface opposite the bonding layer. The power modules are positioned over or proximal to the coolant passageways.

20 Claims, 11 Drawing Sheets

- (73) Assignee: **Midwest Research Institute**, Kansas City, MO (US)
- (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 86 days.

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H05K 7/20 (2006.01)

(52) **U.S. Cl.** **361/699**; 361/688; 361/698; 165/80.3; 165/80.4; 62/259.2

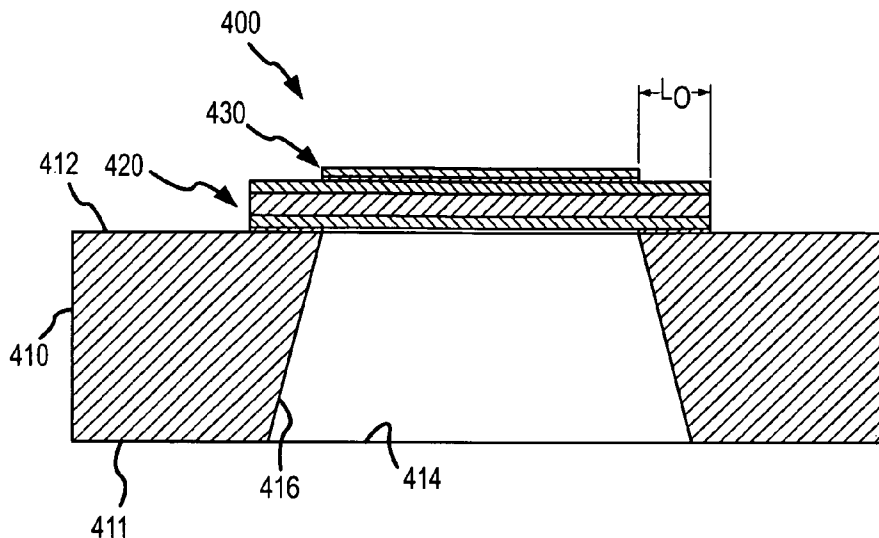
(58) **Field of Classification Search** 361/689, 361/698-699, 701-704, 707, 710, 714, 715, 361/717-722; 165/80.3, 80.4; 257/713-714, 257/723, 731, 789, 678, 796; 62/259.2; 174/16.3, 174/252; 29/521, 557, 505, 840, 890.03, 29/841

See application file for complete search history.

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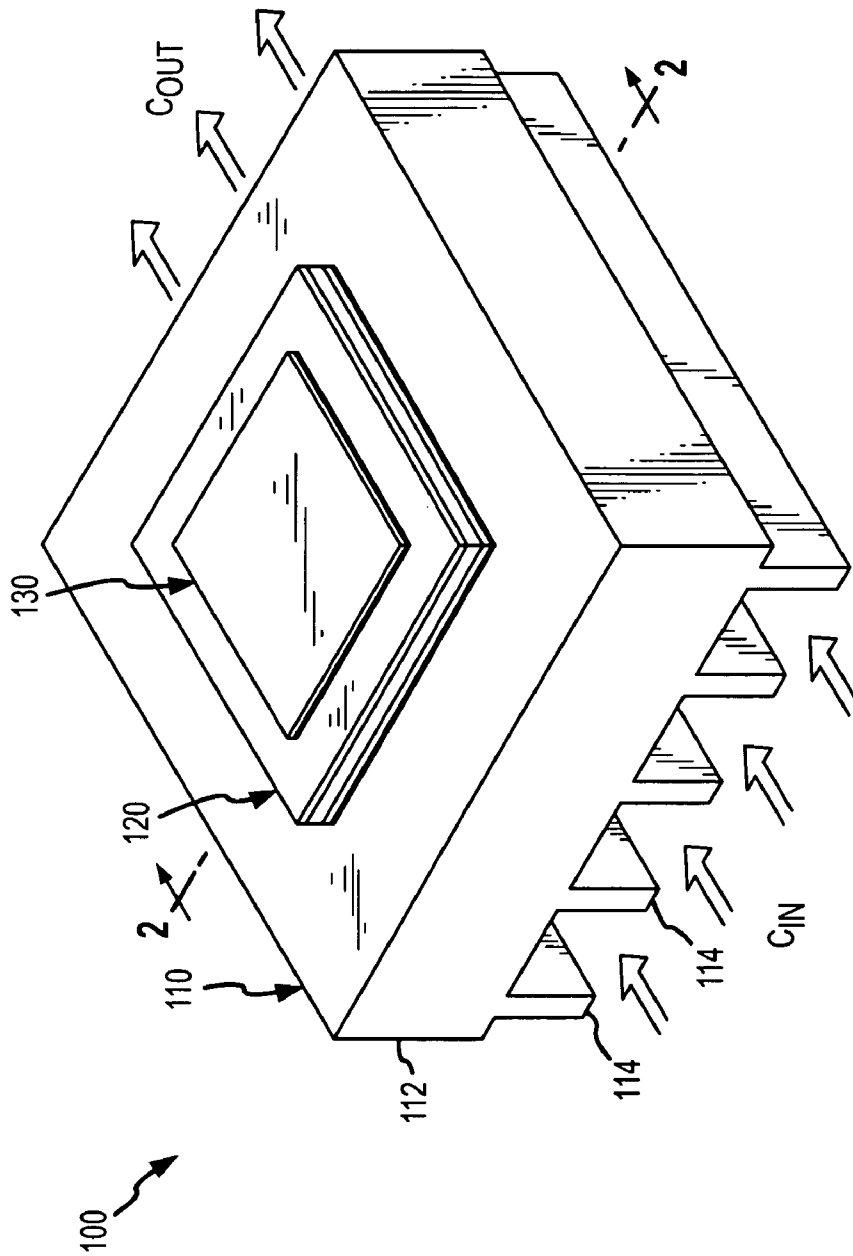


FIG. 1
PRIOR ART

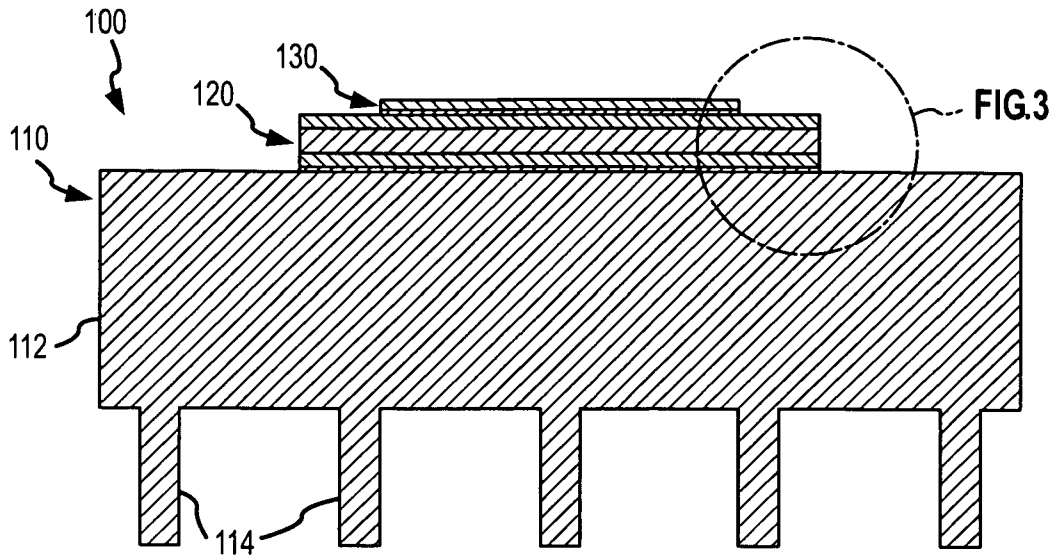


FIG. 2
PRIOR ART

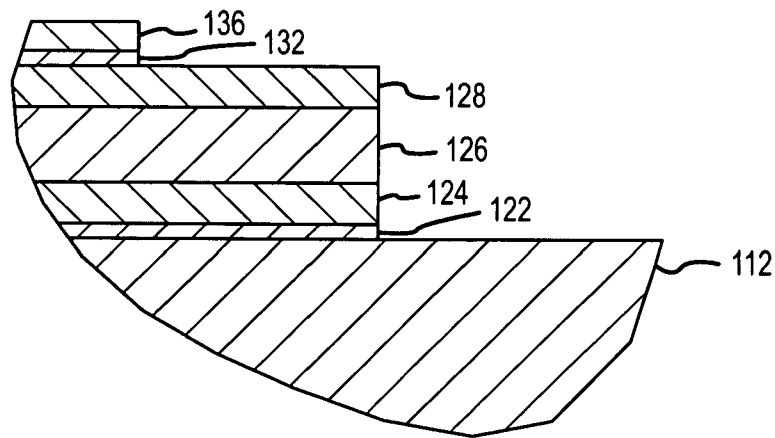


FIG. 3
PRIOR ART

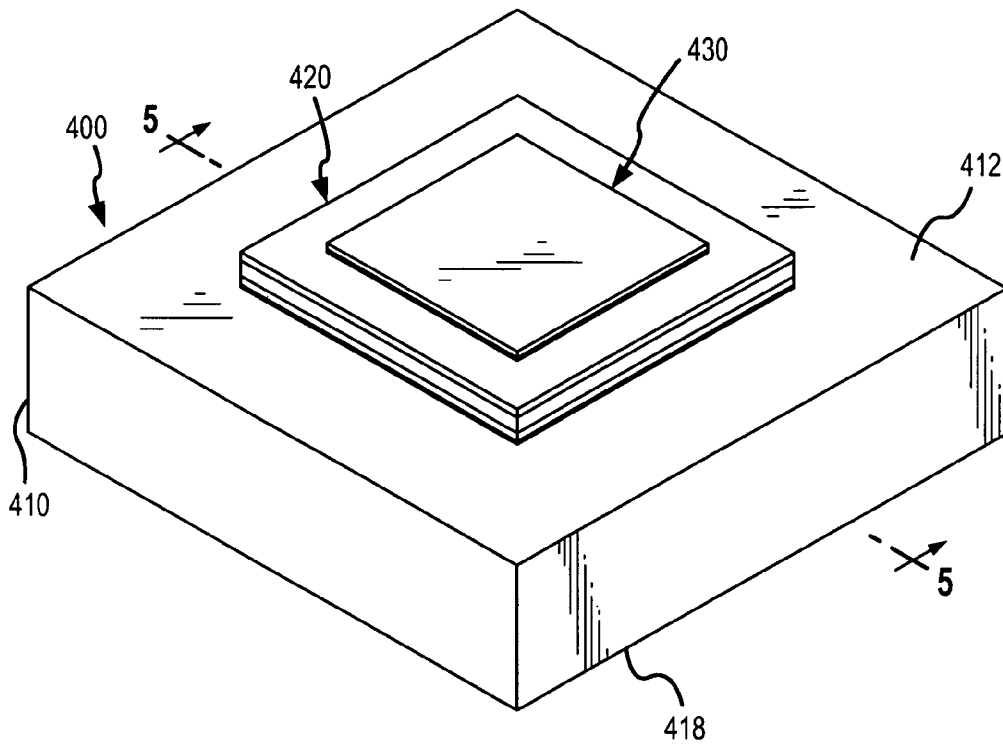


FIG. 4

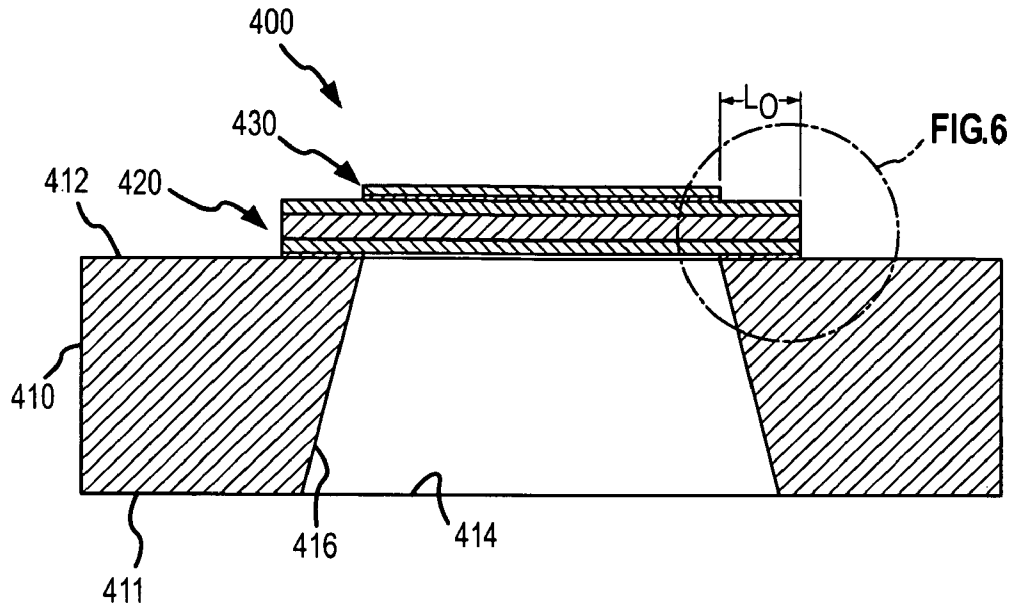


FIG. 5

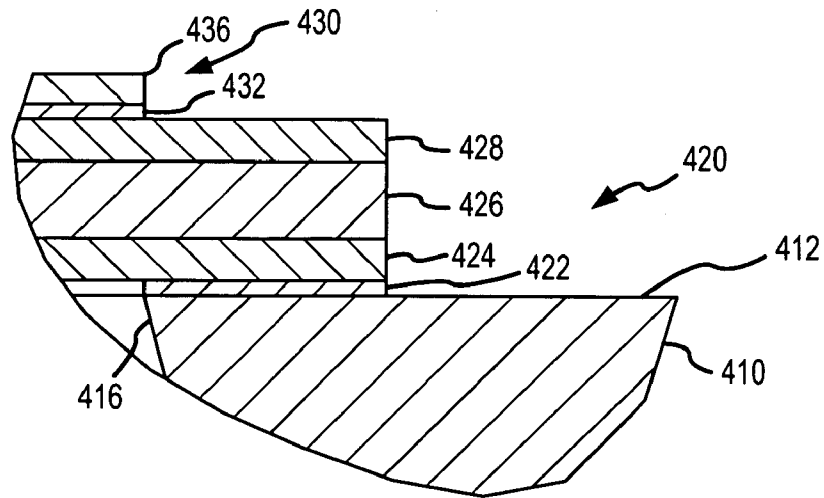


FIG. 6

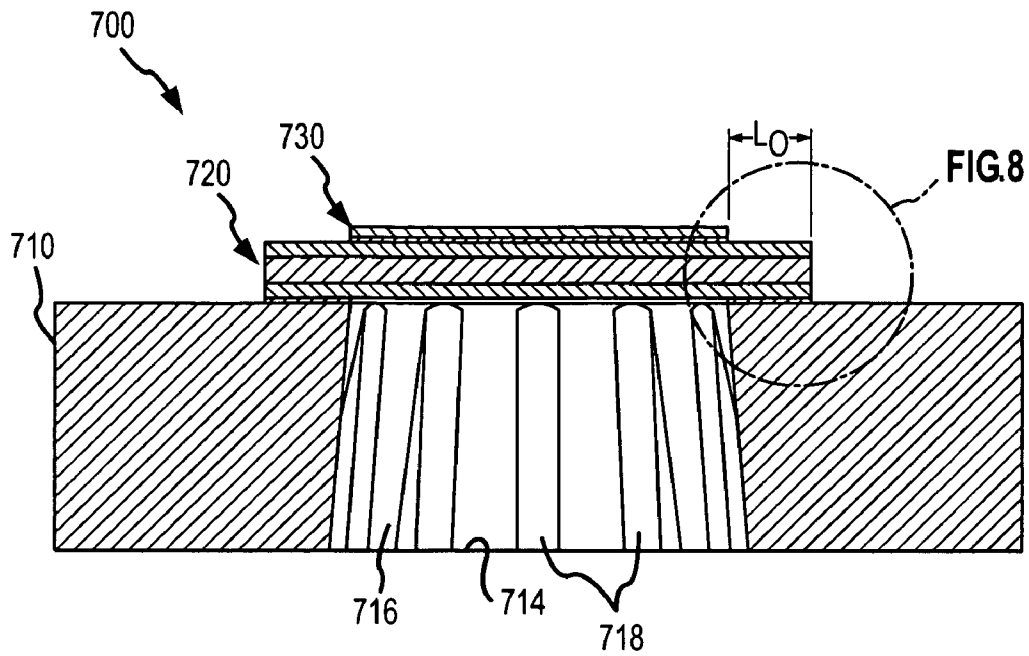


FIG. 7

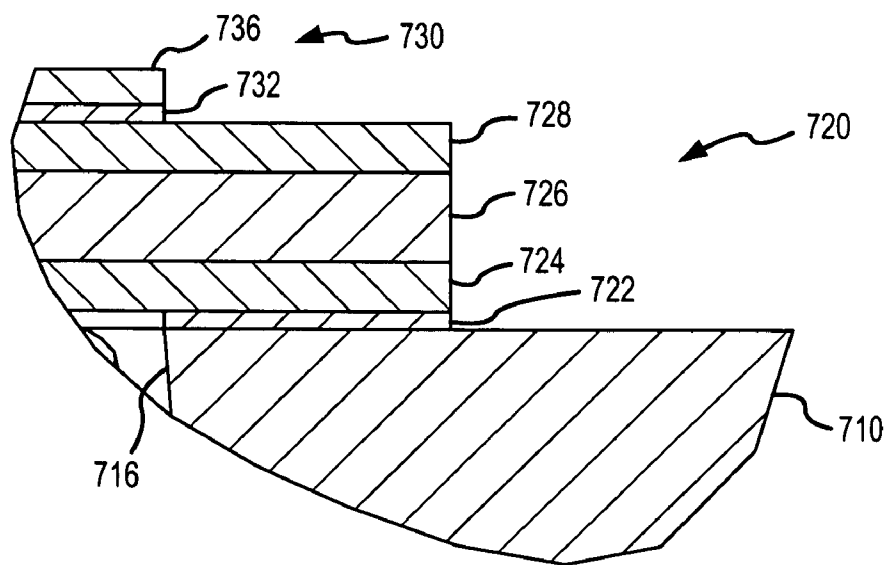


FIG. 8

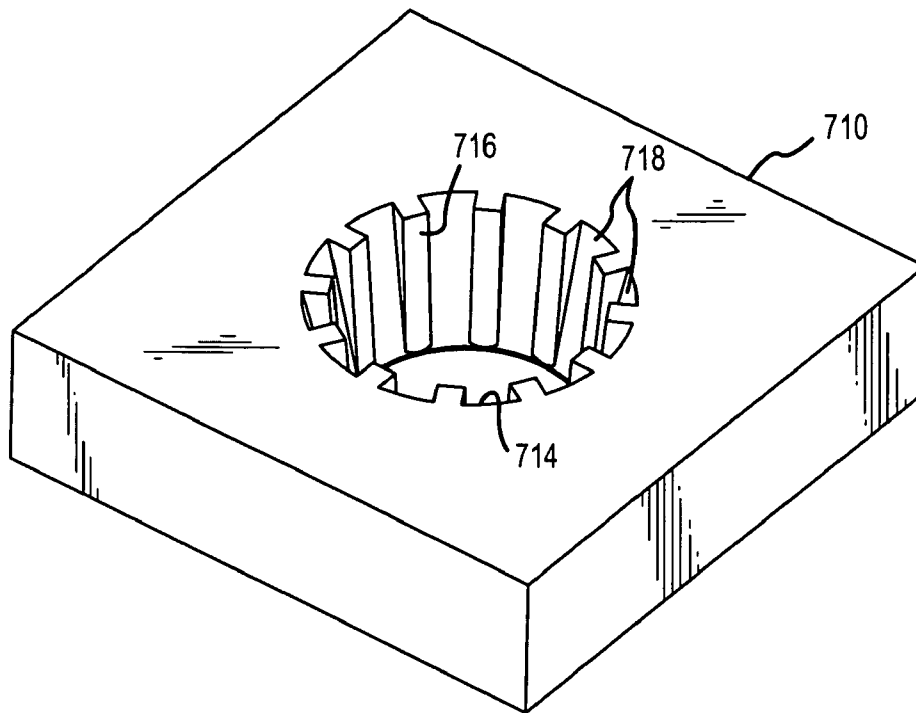


FIG. 9

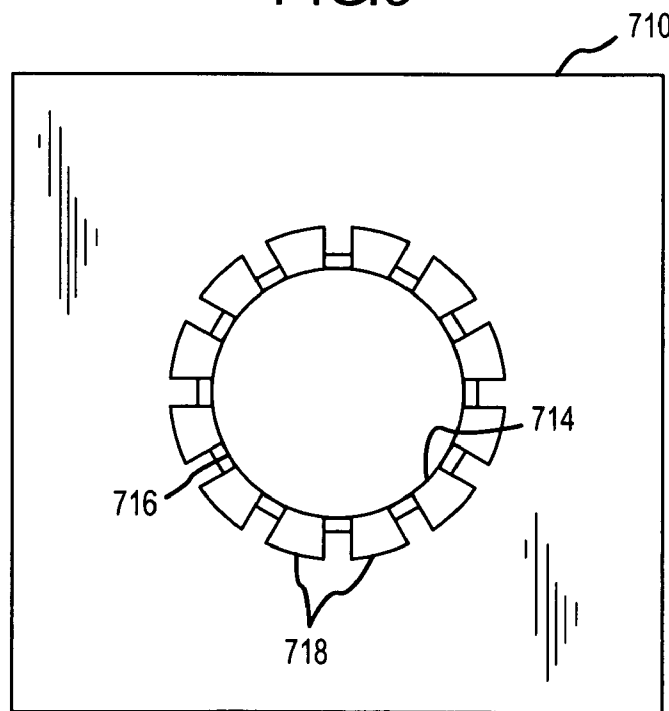


FIG. 10

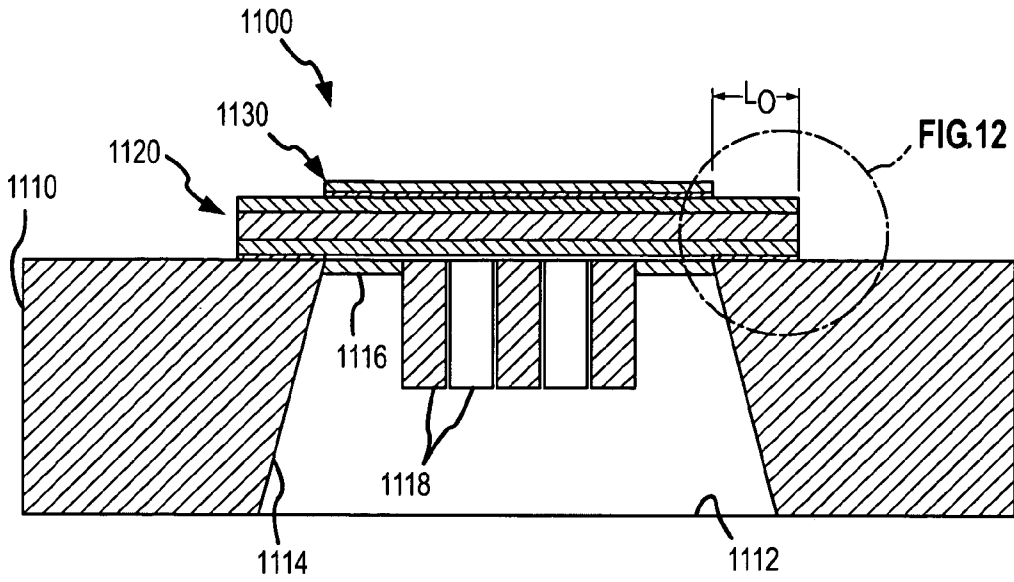


FIG. 11

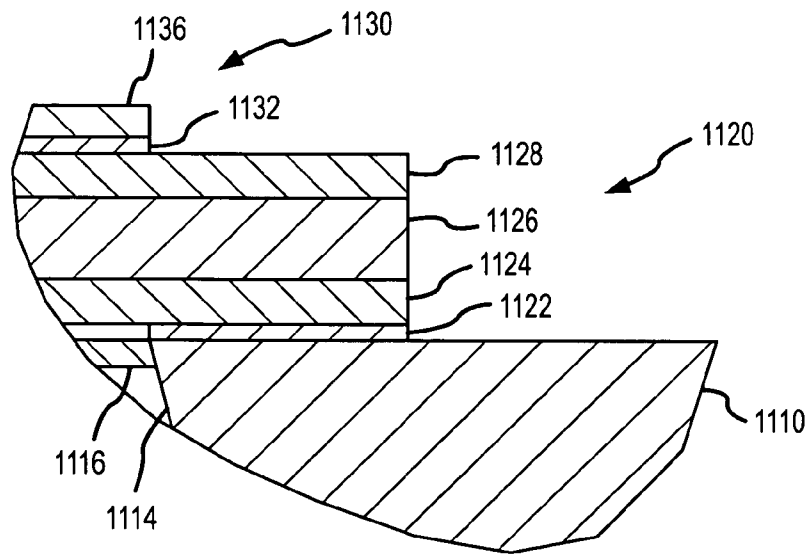


FIG. 12

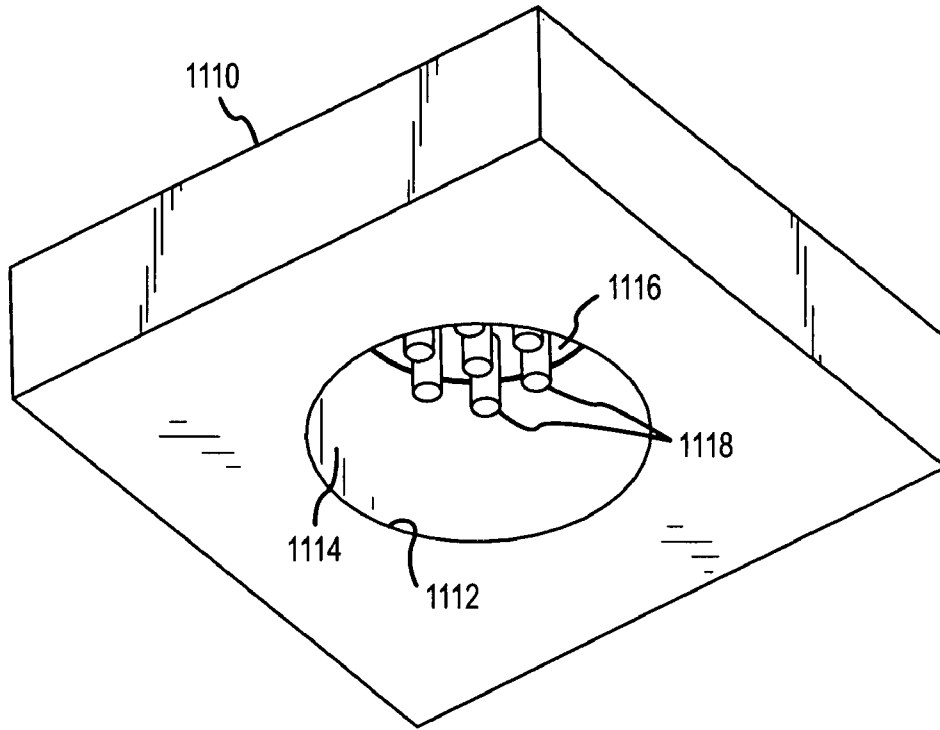


FIG. 13

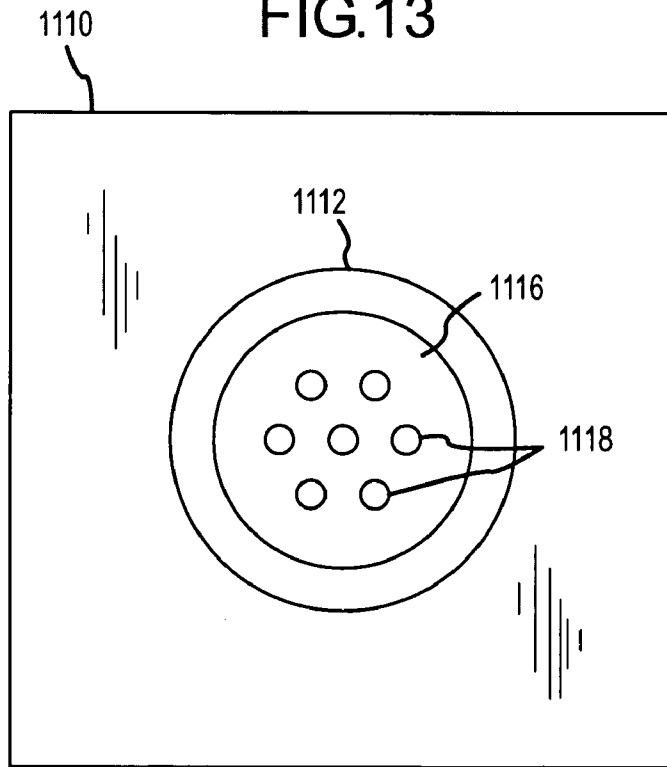


FIG. 14

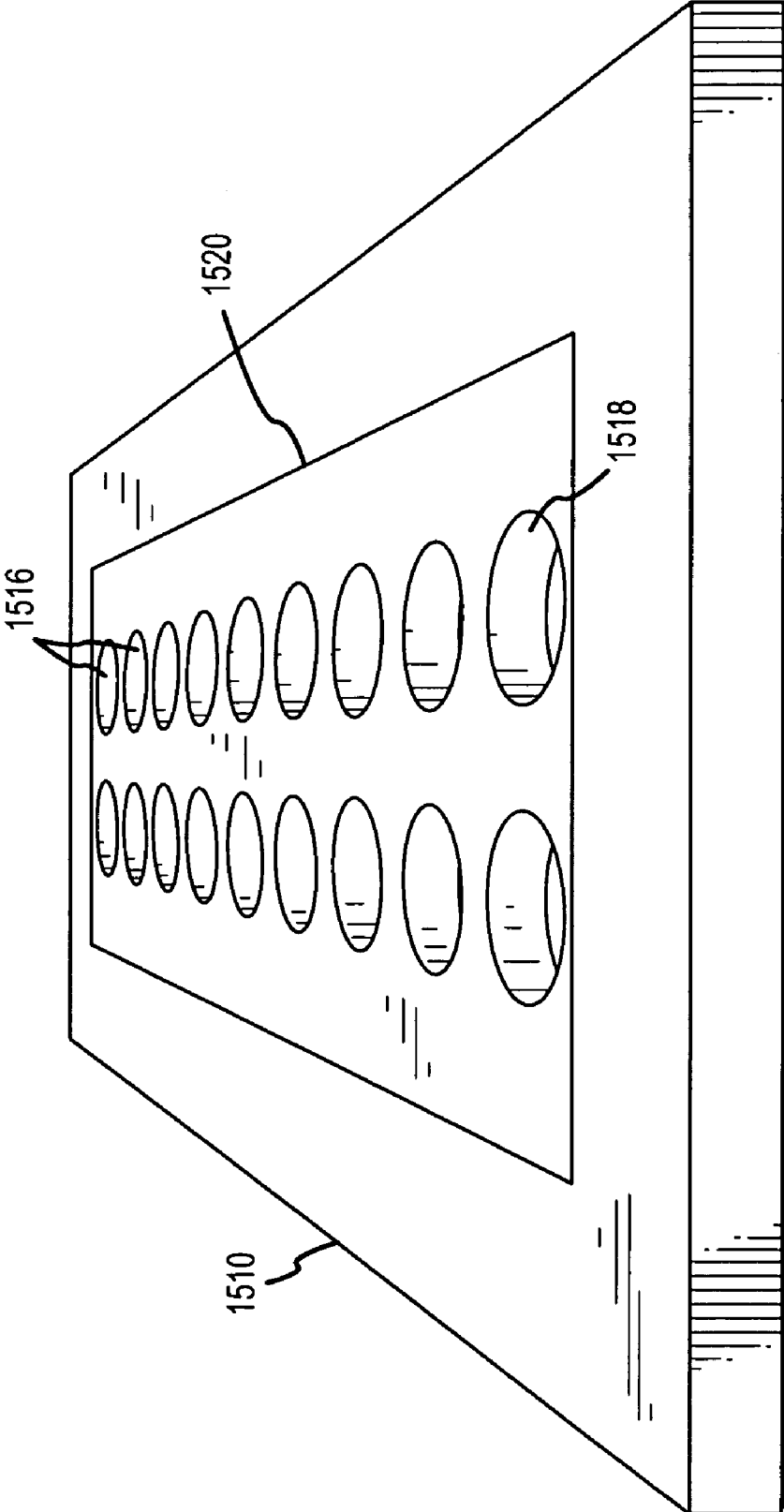


FIG.15

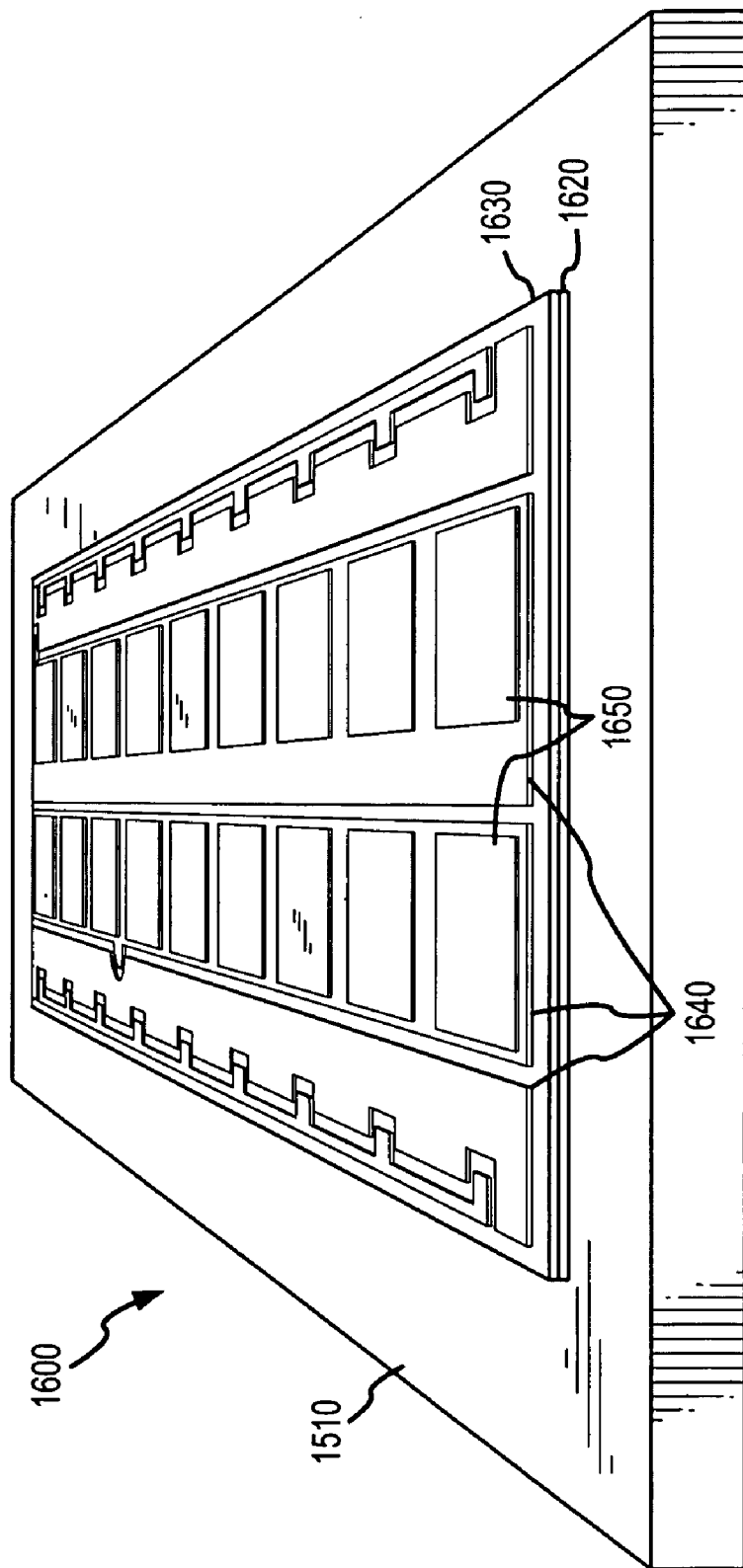


FIG.16

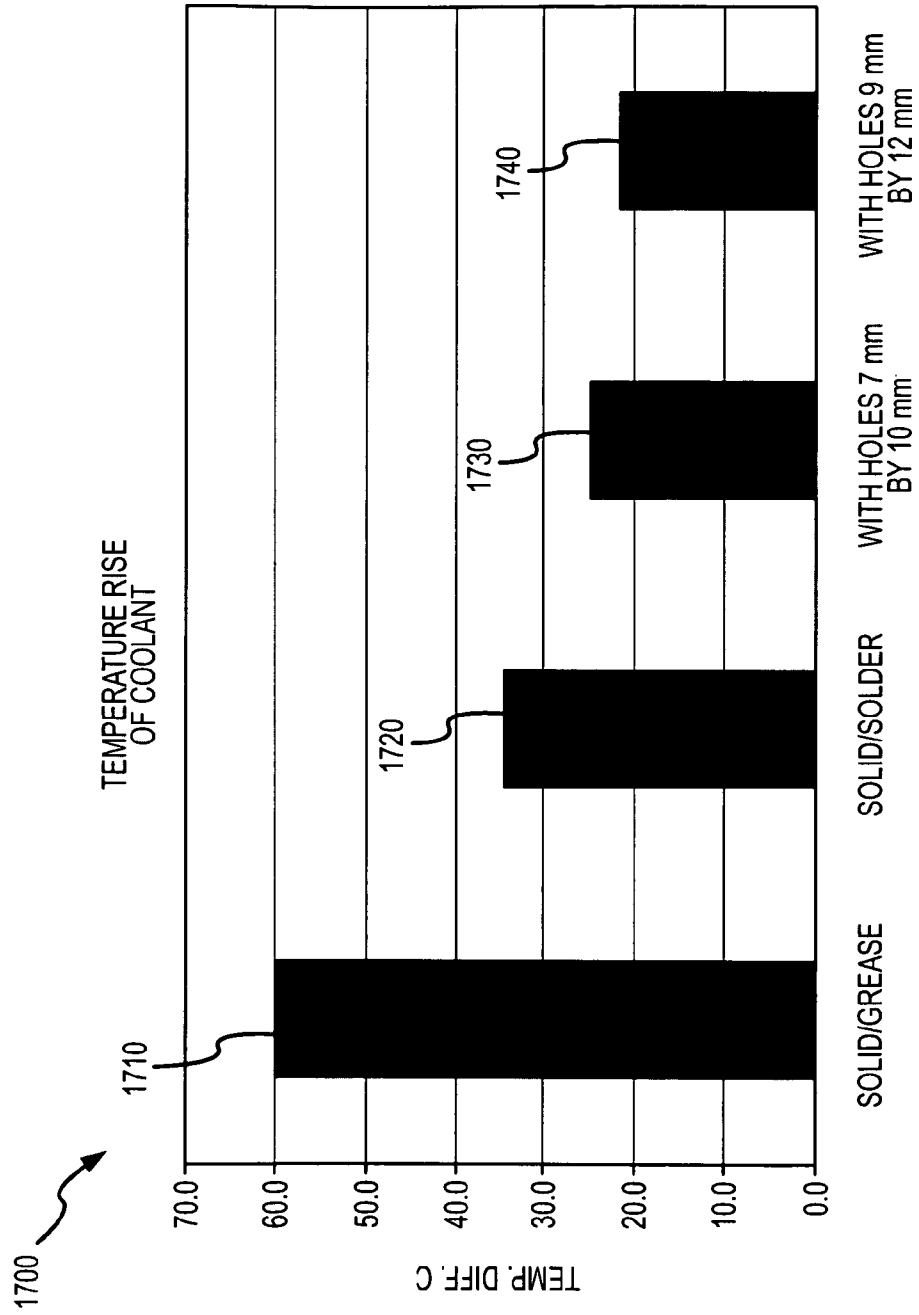


FIG.17

LOW THERMAL RESISTANCE POWER MODULE ASSEMBLY

CONTRACTUAL ORIGIN OF THE INVENTION

The United States Government has rights in this invention under Contract No. DE-AC36-99GO10337 between the United States Department of Energy and the National Renewable Energy Laboratory, a Division of the Midwest Research Institute.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates, in general, to cooling electric circuitry and to controlling the operating temperatures of electric modules such as power modules, and, more particularly, to power module assemblies configured to have low thermal resistances including a reduced number and thickness of thermal resistant or insulator layers, such as those in a semiconductor substrate, between a power module (or other electric component or element that generates heat) and a coolant and/or a heat sink.

2. Relevant Background

There continues to be a growing demand for power semiconductor or integrated circuit (IC) modules and other electric elements with higher power density, higher reliability, and improved cost effectiveness. Miniature power and electric modules are used extensively in a range of applications including automobiles, hard drives, data storage devices, and nearly any electronic product. These power and electric modules often operate at high voltage and current which causes them to generate a large amount of heat which causes the modules to become hot. For proper operation, the power and electric modules or elements need to be maintained below predefined operating temperatures to avoid performance degradation or failure, such as 125° C. for many power modules but the desired operating temperature may vary with the particular application. However, the goals of miniaturization and increased performance run are in conflict with effective thermal management because higher power demands result in greater heat generation while increased module density reduces the size of cooling surfaces. As a result, cooling problems plague all electronic systems and are particularly troubling in electronic systems utilizing IC power modules, such as Insulated-Gate Bipolar Transistors (IGBTs), power metal-oxide-semiconductor field-effect transistors (MOSFETs), and the like.

Electronic component designers have a number of options for attempting to dissipate or remove heat generated by an electronic circuit, such as power module, but none have adequately met the demands for higher performance with reduced size. Designers may use convection to remove heat by transferring heat away from the electric components with air flow. This is useful for small portable devices such as cell phones but is not as effective for power modules that are tightly spaced in enclosed spaces such as are present in automobiles and other products. In these cases, convection is supplemented or replaced by conduction in which heat is wicked or transferred away from the hot or higher temperature electronic circuit or power module to cool or lower temperature of components that contact or abut the electronic circuit or the substrate upon which the circuit is mounted. Typically, a coolant may be used to remove heat from the lower temperature components, e.g., water or another fluid may be pumped over a portion of components contacting the base of the electronic circuit to maintain a

lower temperature. In such conductive designs, increased heat transfer has typically been obtained by increasing the rate at which heat is transferred from the electronic circuit, as measured by the heat transfer coefficient of the electronic circuit or power module assembly. Unfortunately, such techniques of increasing the heat transfer coefficient have not been able to keep pace with the demand for increase module density and have caused many modules to be designed to operate at levels below performance capacity, e.g., at reduced power levels.

A specific example of an electronic system that must be designed for operating within an acceptable temperature range and therefore, for heat dissipation, is an IC power module assembly such as an IGBT device. FIGS. 1-3 illustrate a conventional design for a power module assembly 100. As shown, the power module assembly 100 includes a heat sink 110 made up of a spreader plate 112 and a number of channel walls (or heat transfer fins) 114. A cooling medium or coolant, such as water, is pumped through the walls 114 contacting the walls 114 and spreader plate 112 and removes heat from the heat sink 110 as the inlet coolant, C_{IN} , is at a lower temperature than the outlet coolant, C_{OUT} . The assembly 100 also includes a circuit substrate 120 that is mounted on the spreader plate 112 of the heat sink 110 and a power or circuit module 130 that is mounted on the circuit substrate 120. The power module 130 is shown in FIG. 3 to include a circuit layer, e.g., a silicon die with an IGBT, power MOSFET, or the like, 136 and a connection or joint layer 132, such as solder or other joining materials, for joining or mounting the circuit layer to the circuit substrate 120. Heat that is generated in the power module 130 is conducted through the circuit substrate 120 and heat sink 110 to the flowing coolant.

The thermal resistance of the power module assembly 100 depends mainly on the thermal resistance of the spreader plate 112 and circuit substrate 120. The circuit substrate 120 may take a number of forms, but in the case of an IGBT power module assembly 100, often take the form of a Direct Bonded Copper (DBC) substrate that is thermally bonded to the heat sink 110. In this example, as shown in FIG. 3, the circuit substrate 120 is thermally bonded to the spreader plate 112 with a thermal bonding layer 122 that typically would be thermal grease or paste. The circuit substrate 120 includes a ceramic isolation layer 126, such as layer of AlN or other ceramic material, sandwiched between two conductive layers, such as layers of copper or the like, 124, 128. As can be appreciated, maintaining the temperature of the power module 130 requires heat to be conducted through the bonding layer 132 of the power module 130, through the circuit substrate 120 including the thermal bonding layer 122, and through the spreader plate 112.

Attempts to improve the heat exchange characteristics of power module assemblies, such as assembly 100, have not been entirely effective requiring power (and corresponding heat) produced by the power module to be limited. Most conventional techniques have concentrated on increasing the heat transfer rate or coefficient on the fluid side on surface 114, such as by employing micro channels, by using extensions from the spreader plate (such as the channel walls or fins 114 in heat sink 110 of FIGS. 1 and 2), or by using other techniques to improve heat transfer effectiveness of the power module assembly.

Hence, there remains a need for improved designs for dissipating heat generated by electronic circuits, such as power modules. Preferably, such improved designs would be compatible with existing module designs and manufacturing

techniques and would significantly reduce the thermal resistance between the component generating the heat and the heat sink and/or coolant.

SUMMARY OF THE INVENTION

The present invention addresses the above problems by providing an electronic component assembly that is configured for low thermal resistance (e.g., reduced by more than 50 percent or more compared to convention devices) between a coolant or cooling medium and an electronic component or power module, such as a surface mounted device (SMD), an IGBT substrate, a MOSFET, an IC or printed circuit board or layer, or the like. The assembly generally achieves this reduction by providing a heat sink or spreader plate that includes a coolant passageway or opening for each module that is to be mounted on the heat sink or plate. The passageway or opening extends through the thickness of the heat sink or plate such that coolant can flow through the passageway or opening to more directly dissipate heat. A circuit substrate, such as a DBC substrate, is mounted to the plate with bonding material, such as solder or other nonporous material, providing a seal against flow of the coolant between the substrate and the plate. In this manner, coolant is able to directly contact the bottom layer of the circuit substrate rather than only contacting the plate, which required heat to be conducted through the plate and any bonding layer (such as thermal grease). The electronic component or power module is then mounted or bonded to the circuit substrate so as to be positioned generally opposite (or over) the passageway or opening, thereby providing a relatively direct path between the heat-generating module and portions of the circuit substrate contacting the coolant flowing in the passageway or plate opening. In this manner, thermal resistance can be reduced 50 percent or more when compared with more conventional, solid spreader plate designs.

More particularly, a power module assembly is provided with lower thermal resistance to enhance heat dissipation to a coolant. The assembly includes a heat sink plate with a lower surface and an upper surface. Significantly, the plate also includes a number of passageways for coolant that extend from the lower surface to the upper surface of the plate. A circuit substrate is included in the assembly and positioned on the heat sink plate so as to cover the coolant passageways. The circuit substrate includes a bonding layer that is configured to extend about the periphery of each of the coolant passageways and is made up of a substantially nonporous material. In one embodiment, the bonding layer is solder or a similar material which bonds to the upper surface of the plate to provide a continuous seal around the upper edge of each opening or passageway in the plate. The assembly also includes a set of power modules, such as IGBT modules, that are mounted on the circuit substrate on a surface opposite the bonding layer. Each of the power modules is preferably positioned on the substrate to be over or proximal to one of the coolant passageways. The passageways may have a variety of cross sectional shapes but in one embodiment, the passageways are circular in cross section and may be tapered with a smaller diameter at the upper surface of the plate than at the lower surface.

According to another aspect of the invention, a method is provided for manufacturing power module assemblies having reduced thermal resistance. The method includes providing a power module substrate that has a plurality of power modules distributed in a pattern on a circuit substrate. The circuit substrate is made up of a pair of electrical

conductor layers, e.g., copper layers, that sandwich a ceramic isolation layer (e.g., AlN or similar ceramic). To provide this power module substrate, the method may include providing silicon dies with IGBTs or other power circuits and a DBC substrate and then bonding (e.g., soldering) the modules to the substrate with the silicon dies arranged in the module pattern. The method also includes providing a plate made of other material that can be bonded to the circuit substrate. Then, based on the power module pattern, a hole is punched, cut, or otherwise formed or made through the thickness of the plate for each of the power modules. The method continues with applying a bonding material to an upper surface of the plate (or the layer can be applied prior to the hole formation step). The bonding material is applied in a continuous manner (i.e., without gaps) about the periphery of each hole in the plate. The plate is then bonded to the power module substrate with the bonding material. For example, if the bonding material is solder material, the bonding material is heated and then later cooled to affect bonding. During the bonding, the holes in the plate are aligned with the power modules to provide a relatively direct heat transfer path from the modules to coolant in the holes. For example, the central axis of the holes may be aligned with the center of each of the power modules. Preferably, in this method, the bonding material is selected to be substantially nonporous to liquids such as the coolant so as to form a liquid-tight seal between the upper surface of the plate and the mating electrical conductor layer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a prior art power module assembly utilizing a cooling medium or coolant to conduct heat away from a power module through a circuit substrate and spreader plate;

FIG. 2 is a cross sectional view of the power module assembly of FIG. 1 taken at line 2—2;

FIG. 3 illustrates in more detail a portion of the power module assembly of FIG. 2 illustrating layers of the power module assembly through which heat must flow to be dissipated from the electric circuit or power element, i.e., the portions of the power module assembly contributing to the thermal resistance of the prior art power module assembly;

FIG. 4 is a perspective view of a power module assembly configured according to the present invention with low thermal resistance;

FIG. 5 is a cross section of the power module assembly of FIG. 4 taken at line 5—5 illustrating modification of the spreader plate or heat sink to include an opening allowing coolant to contact the circuit substrate (e.g., DBC substrate);

FIG. 6 is a detailed view of a portion of the power module assembly of FIG. 5 showing the layers of the power module assembly and the sealed or water-tight connection of the circuit substrate to the spreader plate;

FIG. 7 is a cross sectional view similar to that of FIG. 5 of an alternative embodiment of a power module assembly according to the present invention;

FIG. 8 is a detailed view of a portion of the power module assembly of FIG. 7 similar to that of FIG. 6;

FIGS. 9 and 10 are a perspective and a top view, respectively, of the spreader plate or heat sink of the alternative power module assembly of FIGS. 7 and 8 showing in more detail the alternative configuration of a coolant opening or passageway in the plate or heat sink;

FIG. 11 is a cross sectional view similar to that of FIG. 5 of another alternative embodiment of a power module assembly according to the present invention;

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FIG. 12 is a detailed view of a portion of the power module assembly of FIG. 11 similar to that of FIG. 6;

FIGS. 13 and 14 are a perspective view and a top view, respectively, of the spreader plate or heat sink of the assembly of FIG. 11 showing in more detail the provision of a heat transfer base in the coolant opening or passageway and heat transfer extensions, e.g., columns in the illustrated example;

FIG. 15 illustrates a spreader plate or heat sink of a IGBT or power module assembly of the present invention configured for multiple power modules or circuit elements with multiple coolant passageways or openings and also showing an applied bonding and sealing layer, such as solder or other nonporous material;

FIG. 16 illustrates the spreader plate of FIG. 16 after a circuit substrate such as a DBC has been mounted and after a number of power modules or other electric circuit components have been bonded to the circuit substrate proximal to the coolant passageways; and

FIG. 17 is a bar graph illustrating temperature difference between coolant and IGBT in modeling of conventional power module assemblies and power module assemblies configured according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention is directed to electronic system design in which electric circuit elements or modules, such as IC power modules or other circuit elements that generate heat during use, are more effectively cooled by significantly reducing thermal resistance between the electric circuit element and a coolant or cooling medium. In exemplary embodiments of electric circuit assemblies of the invention, the electric circuit element or module is typically an IC that is provided in a die such as a silicon die and is mounted, e.g., soldered, to an electric circuit substrate, e.g., a DBC substrate. The electric circuit substrate is in turn mounted upon a heat sink such as a spreader plate and during operation, a cooling medium or coolant is forced to flow adjacent and in contact with the heat sink to remove heat from the electric circuit assembly.

According to one feature of the invention, a coolant passageway or heat dissipation opening is provided through (or nearly through) the heat sink to directly expose a surface of the electric circuit substrate to the coolant (such as a surface beneath at least a portion of the electric circuit element). As a result, the thermal resistance of electric circuit assemblies of the invention is significantly reduced when compared with prior assemblies, such as that shown in FIGS. 1–3, because the thermal resistance of the heat sink or spreader plate is removed (or at least significantly reduced) as is the heat resistance due to the thermal grease or paste typically used to mount a DBC substrate to a spreader plate. According to another feature of the invention, coolant is able to directly contact the electric circuit substrate, e.g., a DBC substrate, in part because a water-tight seal is provided between the heat sink or spreader plate and the electric circuit substrate. This is achieved by providing a bonding layer in the electric circuit substrate that not only bonds the substrate to the heat sink but also provides a seal that blocks the coolant from passing. Many non-porous materials and bonding techniques may be used, and in some embodiments of the invention, the bonding and sealing layer of the electric circuit substrate is solder material as the substrate is soldered

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to the heat sink in a continuous manner about the periphery of the coolant passageway or heat dissipation opening in the heat sink.

In the following discussion, the invention is explained in detail with reference to power module assemblies rather than more general electronic circuit assemblies. This is done for ease of explanation rather than as limiting the invention to power module applications. It will be understood by those skilled in the art that the concepts of the invention can readily be applied to nearly any electronic application in which an electric element such as an IC is generating excessive heat that needs to be effectively dissipated. A specific application of the invention is for providing effective heat dissipation from IGBTs which are used extensively in the electronics industry, but again, IGBTs are just one example of power modules that may be cooled with the features of the present invention. FIGS. 4–14 illustrate the invention with reference to a single power module but, as shown, in FIGS. 15–17, the concepts discussed with reference to the single power modules of FIGS. 4–14 are readily applicable to more conventional configurations or designs with multiple power modules or circuit elements (such as diodes and the like).

FIG. 4 illustrates an exemplary power module assembly 400 of the present invention. The power module assembly 400 includes a heat sink (which is in the following discussion used interchangeably with spreader plate) 410. A circuit substrate 420 is mounted upon an upper surface 412 of the spreader plate 410, and as shown, a power module 430 is mounted upon the circuit substrate 420. The power module assembly 400 would typically be implemented singly or with other assemblies 400 (not shown) which electrical and other connections (not shown) to the power module 430 and/or circuit substrate 420. As with the assembly 100 of FIG. 1, a coolant or cooling medium, such as water or other fluid, would be forced to flow adjacent the lower surface 411 (see FIG. 5) of the spreader plate 410 to dissipate heat generated by operation of the power module 430.

FIG. 5 illustrates a cross section of the power module assembly 400. As can be appreciated, heat that is generated in the power module 430 is conducted for dissipation through the abutting circuit substrate 420 to the spreader plate 410. As shown, the spreader plate 410 configuration differs from that of conventional spreader plates, such as plate 112 of FIG. 1, as it is configured to direct coolant flow to contact directly the circuit substrate. To this end, the spreader plate 410 includes a coolant passageway or heat dissipation opening 414 that allows coolant (not shown) to flow from the lower surface 411 of the plate 410 to the upper surface 412 of the plate 410 so as to contact the circuit assembly 420. In this manner, at least a portion of the heat generated by the power module 430 is dissipated from the electric substrate 420 directly to the flowing coolant rather than having to pass through the thickness of the spreader plate 410. As shown, the passageway or opening 414 is typically positioned within the power module assembly 400 to be beneath or adjacent the portion of the circuit substrate 420 on which the power module 430 is mounted. In other words, the passageway 414 is positioned such that there is a relatively direct path from the power module 430 through the substrate 420 to the coolant contacting the substrate 420.

The passageway or opening 414 may take many forms, shapes, and sizes to practice the invention. As shown, the opening 414 is generally circular at the lower and upper surfaces 411, 412 and includes a single wall 416 that slopes inward from the lower surface 411 to the upper surface 412 such that the opening 414 has a larger diameter at the lower

surface **411** than at the upper surface **412** (e.g., to better control coolant flow and allow smoother return flow from the electric substrate **420**). The size of the opening **414** at the upper surface **412** is, of course, selected to be smaller than the abutting or adjacent portion of the electric substrate **420** to provide an overlapping length, L_O , of the substrate **420** contacting the upper surface **412** about the periphery of the substrate **420** (this is shown as one dimension but may differ about the periphery in other embodiments). The size of the overlapping portion of the substrate **420** as measured by the length, L_O , may be selected to obtain a desired exposure of the substrate **420** to the coolant flowing in the opening **414** and also to provide a desired structural strength (e.g., to avoid cracking due to stresses occurring because of deflection and the like). For example, if the substrate **420** has dimensions of 10 mm by 10 mm adjacent the plate **410**, the diameter of the opening **414** at the upper surface **412** may be selected to be about 9 mm or less such that the length, L_O , of the overlapping or overhanging portion of the substrate **420** is at least about 0.5 mm. Additionally, in other embodiments, the opening **414** may be more cylindrical with a wall **416** that is generally perpendicular to the substrate **420** and/or may have differing cross sectional shapes such as oval or nearly a multi-sided or polygonal shape.

FIG. 6 illustrates a more detailed view of a portion of the power module assembly **400** including mating portions of the circuit substrate **420** and spreader plate **410** (i.e., the overlapping portion). The power module **430** is shown to include a circuit layer or die layer **436** that includes the circuit or electric component, such as an IGBT, and is often made up of an IC in a silicon die. The power module **430** further includes a bonding layer **432** for bonding the circuit layer **436** to the circuit substrate **420**, and the bonding layer **432** in one embodiment of the invention is made up a solder material, as the circuit layer **436** is soldered to the circuit substrate. Here and elsewhere in this description the term "solder" is used in the general sense in the electronics industry and includes a range of readily meltable metals and alloys used to solder or bond one metal or metal element to another.

As discussed above, an important feature of the invention is that the circuit substrate **420** is sealably bonded to or mated with the upper surface **412** of the spreader plate or heat sink **410** such that coolant flowing along plate wall **416** cannot leak or seep through and contact the power module **430**. In this regard, the circuit substrate **420** includes a bonding layer **422** made up of a nonporous material that rigidly bonds or mates the substrate **420** to the upper surface **412**. In one embodiment, the substrate **420** is soldered to the upper surface **412**, and in this case, the bonding layer **422** is made of solder or solder material that is mated to the upper surface **412** and to the adjacent layer of the substrate **420**. The bonding layer **422** extends about the entire periphery of the opening **414** typically adjacent the wall **416** at the upper surface **412** so as to provide a continuous seal or dam against coolant in the opening **414**. For example, as shown, the substrate **420** may be a DBC or similar substrate with two conductive layers **424**, **428** (such as copper or the like) and a ceramic isolation layer **426**, which may be made up of AlN or other ceramic materials. The upper copper or conductive layer **428** is in turn bonded to the power module **430** by the bonding layer **432** (e.g., layer of solder material). Note, FIGS. 5 and 6 are not drawn to scale to allow the bonding layers **422** and **432** to be more readily illustrated and these layers **422**, **432** are typically much thinner than the other layers of the module **430** and substrate **420**, with the specific

thicknesses of the various layers of the power module assembly **400** not being limiting of the invention.

As shown, some of the heat generated from the power module **430** may pass through the substrate **420** to the plate **410**. In this regard, the bonding layer **422** is preferably selected to have a relatively high thermal conductivity coefficient to enhance this heat transfer, e.g., is formed of a metal, metal alloy or the like such as a solder material. However, because a much larger amount of the generated heat is dissipated from the lower conductive or copper layer **424** directly to the coolant in the passageway **414**, the use of a metal or other low thermal resistance material for the bonding layer **422** is not a required feature of the invention.

FIGS. 7–10 illustrate another embodiment of a power module assembly **700**. As shown, the power module assembly **700** is similar to assembly **400** of FIGS. 4–6 in that it includes a spreader plate **710** that is sealably bonded to a circuit substrate **720** upon which a power module **730** is mounted. The power module **730** again includes a circuit or die layer **736** and a bonding layer **732**, such as a solder layer, for mating the power module to the circuit substrate **720**. The circuit substrate **720** includes a coolant-tight bonding layer **722** that sealably bonds the substrate **720** to the upper surface of the spreader plate **710**. As shown, the substrate **720** includes an isolation layer **726** (e.g., a layer of ceramic or other electric isolator material) sandwiched between a lower conductor layer **724** and an upper conductor layer **728**. The conductor layers **724**, **728** may include a thickness of copper or other electric conductors, with the upper layer **728** mating with the bonding layer **732** of the power module **730**. The lower conductor layer **724** mates with the bonding layer **722** and has a portion of its lower surface (i.e., a portion not mating with the bonding layer **722**) exposed or open to the passageway **714** and any coolant therein. In this manner, coolant in the passageway **714** can directly exchange heat with substrate **720** through the lower conductor layer **724**. Again, the size of the passageway **714** in the plate **710** is smaller at the upper surface of the plate **710** than the abutting substrate **720** to provide an overlapping or overhanging portion of the substrate **720** with a length, L_O , that provides adequate sealing surface and structural strength.

The power module assembly **700** differs from the power module assembly **400** in the configuration of its heat sink or spreader plate **710**. The spreader plate **710** includes a coolant passageway or heat dissipation opening **714** that extends through the thickness of the plate **710** as does the opening **414** of plate **410** but with a modified wall surface to provide an enhanced heat transfer rate. As shown, the opening **714** includes a wall **716** that extends from the lower surface to the upper surface of the plate **710** at an angle such that the opening **714** is smaller at the upper surface (i.e., the surface of the plate **710** that abuts the circuit substrate **720**) than at the lower surface. In the wall **716**, a plurality of recessed surfaces **718** are provided so as to increase the heat transfer surface area of the wall **716** that contacts coolant within the passageway **714** and/or to increase heat transfer rates by causing a desired coolant flow pattern. The cross section of the recessed surfaces **718** may vary to practice the invention and may take the trapezoidal form shown or take another shape, such as triangular, semicircular, or the like, with the shape often being selected to support efficient manufacturing techniques.

FIGS. 11–14 illustrate another power module assembly **1100** that provides low thermal resistance between a power module **1130** and coolant flowing adjacent a heat sink or spreader plate **1110**. As shown in FIG. 11, the power module assembly **1100** includes a power module **1130**, such as an

IGBT, mounted upon a circuit substrate **1120**, such as a DBC substrate, that is in turn mounted upon a spreader plate **1110**. As with the other assemblies **400**, **700**, a passageway or opening **1112** is provided in the spreader plate **1110** to reduce thermal resistance by bringing coolant or a cooling medium into closer proximity to the power module **1130**. In contrast to the other passageways, however, the passageway **1112** is shown to not extend completely through the thickness of the plate **1110** but instead extends substantially through the thickness of the plate **1110** to form a heat transfer plate or base **1116** that contacts the circuit substrate **1120**.

More specifically, the power module **1130** includes a circuit or element layer **1136**, such as a silicon die or IC chip, and a bonding layer **1132** to mate it with the circuit substrate **1120**. The circuit substrate **1120** includes a pair of conductor layers **1128**, **1124** sandwiching an electric isolation layer **1126**, such as a layer of ceramic or other insulation material. A bonding layer **1122** is provided to mate the substrate **1120** with an upper surface of the plate **1110**, and in some embodiments, the bonding layer **1122** is made up of solder material (but, of course, other materials may be used for the bonding layer **1122** to provide the desired bonding and sealing features) as the substrate **1120** is soldered to the upper surface of the plate **1110**, which as with the other plates typically is formed from a metal suited for bonding by soldering in this example (if other bonding materials are used, the material used for plate **1110** may be selected to be compatible with that bonding material and bonding technique).

As shown, in FIGS. **11–14**, the plate **1110** includes a passageway or opening **1112** with a wall **1114** configured similarly to wall **416** of assembly **400** in that it slopes inward from a lower to an upper surface of the plate **1110**, whereby the opening **1112** is larger at the lower surface of the plate than the upper surface. As illustrated, a heat transfer base or plate **1116** is formed at the upper end of the passageway **1112**. In other words, the passageway **1112** does not in this illustrated embodiment extend through the plate **1110** and coolant does not directly contact the substrate **1120**. Upon the base **1116**, a plurality of cooling rods or extensions **1118** are formed and extend outward from the base **1116** into the passageway **1112**. In this embodiment, heat generated by the power module **1130** is conducted through the layers of the circuit substrate **1120** for dissipation to coolant in the passageway **1112** via portions of the plate **1110** and mainly through the base **1116** and rods/extensions **1118**. The number, size, orientation, and spacing of the rods or extensions **1118** may vary to practice the invention with seven being shown for illustration purposes only.

In a variation of the assembly **1100** not shown, the base **1116** is removed or not provided with coolant being allowed to pass through the passageway or opening **1112** to contact the circuit substrate **1120** directly. In this variation, the bonding layer **1122** again acts as a seal between coolant in the passageway **1112** and the power module **1130** as coolant is allowed to directly contact the substrate **1120** (i.e., directly contact lower conductor layer **1124**). In this embodiment, the cooling rods or extensions **1118** protrude or extend directly from the lower conductor layer **1124**, and may be formed during the assembly of the substrate **1120** or formed separately and later bonded (e.g., soldered) to the layer **1124**.

The above description and corresponding figures describe power module assemblies having a single power module (or electric circuit or electric component) that is configured with low thermal resistance according to the invention. It may now be useful to describe fabrication of a low thermal resistance electric circuit assembly that includes a plurality

of electric circuit modules, which may include a variety of IC chips or the like such as power components, diodes, and the like. This manufacturing technique is suitable for producing chip set products such as power module assemblies with multiple IGBTs, diodes, and/or other IC chips or components, e.g., 2×9 (or other configuration) chip sets available from SEMIKRON or other electronics companies.

In this regard, FIGS. **15** and **16** illustrate the production of a 2×9 chip set assembly **1600** according to the present invention with low thermal resistance between electric modules (such as power modules, diodes, and the like) and a coolant (not shown). FIG. **15** illustrates a spreader plate (or heat sink) **1510**, which is typically made of materials with high thermal conductivity such as a metal or metal alloy. The number of modules to be cooled is determined, and then, fabrication continues with punching or otherwise providing holes, openings, or passageways **1516** for each module to be cooled by the spreader plate **1510**. As shown, eighteen holes or passageways **1516** with sidewalls **1518** are cut or punched through the entire thickness of the plate **1510**.

The sidewalls **1518** are shown to be perpendicular to the top surface of the plate **1510** but in other embodiments the sidewalls **1518** may be sloped as shown in FIGS. **4–14** and at this point in production, heat transfer enhancing elements may also be provided, such as those shown in FIGS. **7–14**. The positioning of the openings **1516** is selected to match the planned or mapped location of the electronic component modules or chips, e.g., with the center of each of the openings **1516** substantially aligning with a center of an overlying module or chip.

Because during use a coolant is allowed to flow through the passageways or openings **1516**, the manufacturing method includes mating a circuit substrate with the spreader plate **1510** in a manner that not only provides bonding but provides a seal about the periphery of the openings **1516** that blocks the flow of the coolant. With this in mind, FIG. **15** illustrates that a layer of bonding and sealing material **1520** is applied to the spreader plate **1510**. In one embodiment, the layer of bonding and sealing material **1520** is made up of a thin layer of soldering material that is applied to abut or be immediately adjacent the sidewalls **1518** of the openings **1516** (or to even cover a portion of the wall **1518**). In some cases, the bonding and sealing layer **1520** is applied to the plate **1510** and then, the holes **1516** are cut or punched to ensure adequate coverage of the bonding and sealing material, e.g., soldering material or the like.

With the bonding layer **1520** in place, the other components of the assembly **1600** may be positioned and bonded to the plate **1510**. In some embodiments, the other components/layers are produced as a single assembly and then, bonded (e.g., soldered) to the plate **1510**. In other embodiments, one or more layers is applied separately. As shown, these other components include a circuit substrate or stack that includes a lower conductive layer **1620**, an electric isolation layer **1630**, and an upper conductive layer **1640**. For example, the circuit substrate may be a DBC substrate and, in these embodiments, the lower conductive layer **1620** and the upper conductive layer **1640** are made up of a thickness of copper and the upper conductive layer **1640** is provided with a desired pattern to support circuit functionalities and mate with electric component modules or chips **1650**. In the DBC substrate embodiment, the isolation layer **1630** may be AlN or another useful ceramic material.

As shown, a plurality of electric component modules or chips **1650** are applied over the top layer of the circuit substrate **1640**. As discussed previously, the modules **1650** may include a silicon die or element layer that is soldered or

otherwise bound to the upper conductive layer 1640. The modules 1650 are positioned such that the openings 1516 are adjacent or directly beneath the modules 1650 such that during operation, heat generated by the modules 1650 is at least partially dissipated through the circuit substrate layers 1650, 1640, 1630 to a coolant in the opening 1516. In a typical manufacturing process, the spreader plate 1510 is prepared as shown in FIG. 15 and then, the circuit substrate with layers 1620, 1630, and 1640 and modules 1650 (which were assembled in a separate step(s)) are positioned on the plate 1510 with the lower conductive layer 1620 contacting the bonding and sealing layer 1520. If soldering is utilized, the layer 1520 is heated and allowed to cool to effect bonding between the upper surface of the plate 1510 and the lower conductive layer 1620 of the circuit substrate. In this bonding step, a seal is also created between the plate 1510 and the lower conductive layer 1620.

The assembly 1600 was modeled to determine the exemplary effectiveness of the low thermal resistance design. In the model, the modules 1650 were assumed to be IGBT's in a silicon die that were 10 mm by 10 mm, designed to operate below 125° C., and had a 90 W/cm² heat flux. Coolant or cooling medium that flowed over the lower surface of the heat sink or spreader plate 1510 (and into openings 1516) was assumed to have an inlet temperature of 90° C. The spreader plate 1510 was assumed to be a metal with a thickness of 3 to 6 mm. The electric substrate was a DBC substrate with an AlN layer sandwiched between two copper layers. The two bonding layers were assumed to be made up of a solder material, and specifically, 90Pb—10Sn solder. A uniform heat transfer coefficient of 50,000 W/m² K was used on the heat sink side. In addition to the inventive configuration, a conventional configuration with a solid spreader plate and a bonding material of thermal grease was modeled as was a configuration with a solid spreader plate and a bonding material of solder material.

A portion of the modeling results are illustrated in the bar graph 1700 of FIG. 17. The graph 1700 shows the temperature difference between the coolant and the power module during operation of the various configurations. As will be appreciated, it is highly desirable to reduce the temperature difference or rise in coolant required to maintain the power or other modules at desired operating temperatures. As shown by bar 1710, the modeled temperature difference for a conventional solid plate with thermal grease bonding material was 60° C. A large improvement was achieved in a configuration using solder material for the bonding material which is shown by bar 1720 to result in a temperature rise or difference of about 34° C.

An even larger or significant improvement is achieved when a spreader plate with heat coolant passageways are utilized. Bar 1730 shows the results of modeling a tapered passageway design with a lower diameter of 10 mm and an upper diameter of 7 mm (e.g., adjacent the circuit substrate). As can be seen, the temperature difference has been reduced to about 24° C. or less than 50 percent of the difference of a conventional configuration. If the opening dimensions are increased to a lower diameter of 12 mm and an upper diameter of 9 mm, the temperature difference is even further reduced to about 21° C. as shown by bar 1740.

The effectiveness of the low thermal resistance embodiments of the invention are verified with this modeling, and it should be readily apparent that power module assemblies can be produced with thermal resistance between the silicon die (or power module) and the heat sink being reduced by up to 50 percent or more. Stress distribution modeling was also performed, and it was determined that passageways or

openings through the spreader plate or heat sink can be utilized while maintaining the stress and deflection levels within acceptable ranges for power module assemblies such as standard operating requirements for IGBT stacks (although, of course, the maximum size of such passageways (or amount of overlap length, L_o) should be selected to suit the particular materials, layer thicknesses, and other design parameters). Additional details from the modeling are provided in the following table.

Cooling Plate	Solid	Solid	With openings of 7 mm upper diam and 9 mm lower diam Solder	With openings of 9 mm upper diam and 12 mm lower diam Solder
Substrate Bonding Material	Thermal Grease	Solder		
Max. Temp. of Power Module	149.9° C.	124.3° C.	114.5° C.	111.4° C.
Coolant Temperature	90° C.	90° C.	90° C.	90° C.

If a maximum operating temperature of the power module is assumed to be 125° C., it can be seen by the values of the model provided in the above table that the use of coolant passageways or openings is useful for maintaining the modules well below this temperature.

Although the invention has been described and illustrated with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the combination and arrangement of parts can be resorted to by those skilled in the art without departing from the spirit and scope of the invention, as hereinafter claimed. For example, the above examples show a planar heat sink provided in the form of a spreader plate, but a heat sink with fins, tabs, channels, and the like may be used in combination with the heat coolant passageways or openings of the invention. To further illustrate how the inventive concepts can be expanded, the plate 1510 of FIG. 15 may be modified to combine 2 or more of the coolant passageways. For example, the 18 passageways may be replaced with 2 passageways having an oval, elliptical, rectangular, or other shaped cross section, and these 2 passageways would extend substantially from one end to the other of the plate 1510 (e.g., the material between the illustrated passageways could be removed).

We claim:

1. A power module assembly with low thermal resistance, comprising:

- a heat sink plate with a lower surface and an upper surface, the heat sink plate comprising a plurality of passageways for coolant extending from the lower surface to the upper surface;
- a circuit substrate positioned on the heat sink plate covering the coolant passageways, wherein the circuit substrate comprises a bonding layer extending about the periphery of each of the coolant passageways and comprising a material nonporous to the coolant; and
- a set of power modules mounted on the circuit substrate opposite the bonding layer, each of the power modules being positioned on the circuit substrate over only one of the coolant passageways, wherein coolant flowing separately into each of the coolant passageways of the heat sink plate directly contacts the circuit substrate in an area opposite and proximate to each one of the power modules.

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2. The assembly of claim 1, wherein the bonding layer comprises a material with high thermal conductivity bonded to the upper surface of the heat sink plate.

3. The assembly of claim 2, wherein the bonding layer material comprises solder material.

4. The assembly of claim 1, wherein each of the coolant passageways has a circular cross section with a sidewall extending from the lower surface to the upper surface of the heat sink plate.

5. The assembly of claim 4, wherein the sidewalls slope inward from the lower surface such that each of the coolant passageways has a diameter at the lower surface that is greater than a diameter at the upper surface of the heat sink plate.

6. The assembly of claim 1, wherein the power modules each comprise an insulated gate bipolar transistor (IGBT) module and the circuit substrate further comprises a direct bonded copper (DBC) substrate bonded to the bonding layer and to the IGBT module, the DBC substrate comprising a pair of layers of copper sandwiching a ceramic isolation layer.

7. An electronic assembly with low thermal resistance, comprising:

a metallic spreader plate with a lower surface and an upper surface and a heat dissipation opening extending through the plate from the upper surface to the lower surface;

a circuit substrate;

a bonding and sealing layer disposed between the circuit substrate and the plate and bonding the circuit substrate to the upper surface of the plate; and

an electric component layer positioned on the circuit substrate distal to the plate comprising an integrated circuit (IC) generating heat during operation, the heat dissipating at least in part through the circuit substrate to a cooling medium in the heat dissipation opening, wherein the bonding and sealing layer blocks flow of the cooling medium between the circuit substrate and the plate;

wherein the heat dissipation opening has a circular cross section with a diameter at the upper surface that is lower than a diameter at the lower surface; and

wherein the heat dissipation opening comprises a side wall with a plurality of channels extending from the lower surface to the upper surface of the plate.

8. The assembly of claim 7, wherein the bonding and sealing layer is positioned about the periphery of the heat dissipation opening, whereby the cooling medium in the heat dissipation opening contacts the circuit substrate.

9. The assembly of claim 8, wherein the bonding and sealing layer comprises a nonporous solder material.

10. The assembly of claim 7, wherein the circuit substrate further comprises a plurality of cooling rods positioned within the heat dissipation opening and contacting and extending away from an electrical conductor layer of the circuit substrate.

11. The assembly of claim 7, wherein the IC comprises an insulated gate bipolar transistor (IGBT) and the electronic component layer further comprises a silicon die and wherein the circuit substrate comprises a ceramic isolation layer between an upper and a lower layer of electrically conductive material, the lower layer being sealably bonded to the bonding and sealing layer and being at least partially exposed to the cooling medium in the heat dissipation opening.

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12. A method of manufacturing a power module assembly with low thermal resistance, comprising:

providing a power module substrate comprising a plurality of power modules distributed in a pattern on a circuit substrate, the circuit substrate comprising a pair of electrical conductor layers with a ceramic isolation layer there between;

providing a metallic plate having a thickness;

based on the power module pattern, making a hole through the thickness of the plate for each of the power modules, wherein one of the holes is provided to extend through the plate to a particular one of the power modules to provide a path for coolant flowing on a first side of the plate flow to each of the power modules through the plate thickness;

applying a bonding material to an upper surface of the plate, wherein the bonding material is applied continuously about the periphery of each of the holes in the plate; and

bonding the plate to the power module substrate, wherein the holes in the plate are substantially aligned with the power modules with a central axis of the holes substantially aligned with a center of one of the power modules and wherein one of the electrical conductor layers mates with the bonding material.

13. The method of claim 12, wherein the bonding material comprises solder and the bonding comprises soldering the plate to the one of the electrical conductor layers with the solder.

14. The method of claim 12, wherein bonding material is substantially nonporous to liquids and after the bonding, the bonding material forms a liquid-tight seal between the upper surface of the plate and the mating one of the electrical conductor layers.

15. The method of claim 12, wherein the making comprises punching the holes in the plate.

16. The method of claim 12, wherein the holes are tapered with a diameter that increases with distance from the circuit substrate.

17. The method of claim 12, wherein the power modules each comprise an insulated gate bipolar transistor (IGBT) in a silicon die and wherein the circuit substrate comprises a direct bonded copper (DBC) substrate.

18. The method of claim 12, wherein the providing of the power module substrate comprises providing the silicon dies with the IGBTs and the DBC substrate and then, bonding the silicon dies to the second one of the electrical conductor layers in the power module pattern.

19. A method of manufacturing an electronic assembly with low thermal resistance, comprising:

providing a plurality of heat-generating electronic components distributed in a pattern on a circuit substrate, the circuit substrate comprising a pair of electrical conductor layers with an isolation layer there between;

providing a metallic plate having a thickness;

based on the power module pattern, making a hole through the thickness of the plate for each of the electronic components, wherein the holes are tapered to increase in size with distance from the circuit substrate; and

bonding the plate to the circuit substrate, wherein the holes in the plate are substantially aligned with the electronic components with a central axis of the holes substantially aligned with a center of one of the electronic components.

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20. A power module assembly with low thermal resistance, comprising:

- a heat sink plate with a lower surface and an upper surface, the heat sink plate comprising a plurality of passageways for coolant extending from the lower surface to the upper surface;
- a circuit substrate positioned on the heat sink plate covering the coolant passageways, wherein the circuit substrate comprises a bonding layer extending about the periphery of each of the coolant passageways and comprising a material nonporous to the coolant; and

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a set of power modules mounted on the circuit substrate opposite the bonding layer, each of the power modules being positioned on the circuit substrate proximal to one of the coolant passageways;

wherein each of the coolant passageways has a circular cross section with a sidewall extending from the lower surface to the upper surface of the heat sink plate and wherein the sidewalls slope inward from the lower surface such that each of the coolant passageways has a diameter at the lower surface that is greater than a diameter at the upper surface of the heat sink plate.

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