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(54) **SILICON-BASED COOLING PACKAGE WITH DIAMOND COATING FOR HEAT-GENERATING DEVICES**

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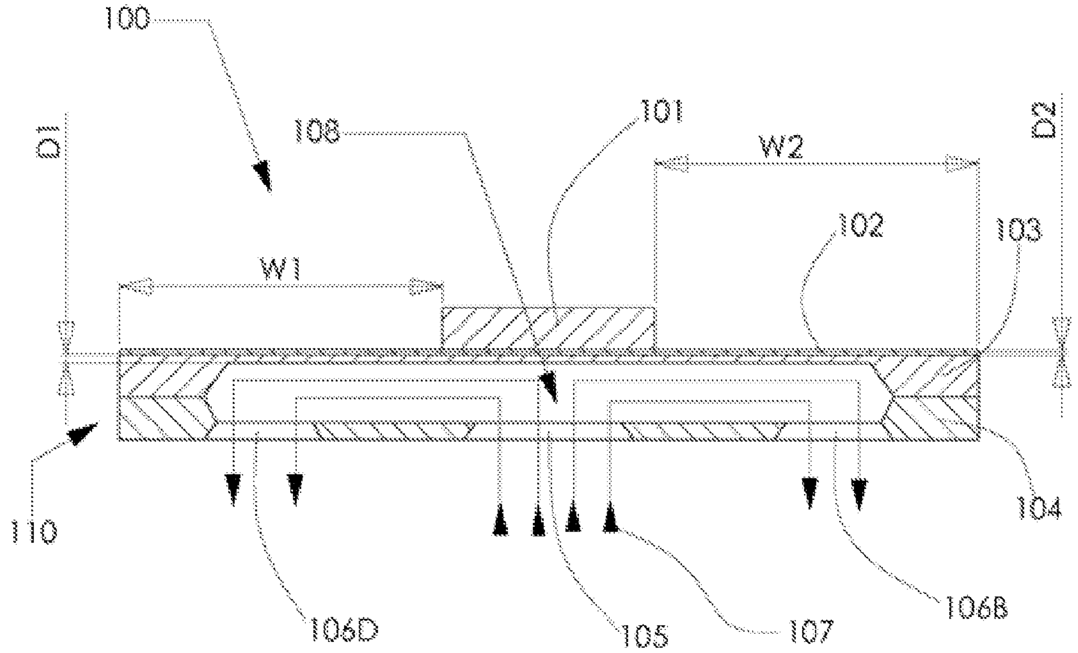
(57) **ABSTRACT**

Various embodiments of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device are described. In one aspect, a thermal energy transfer apparatus comprises a silicon-based manifold having an internal cavity, a first primary side, and a second primary side opposite the first primary side. The second primary side of the manifold has at least one coolant inlet port and at least one coolant outlet port that are connected to the internal cavity of the manifold, the at least one coolant inlet port being at a position directly opposite a position on the diamond layer where the heat-generating device is received. A diamond layer covers at least a portion of the first primary side of the manifold such that the heat-generating device is in direct contact with the diamond layer when the heat-generating device is received on the first primary side of the manifold.



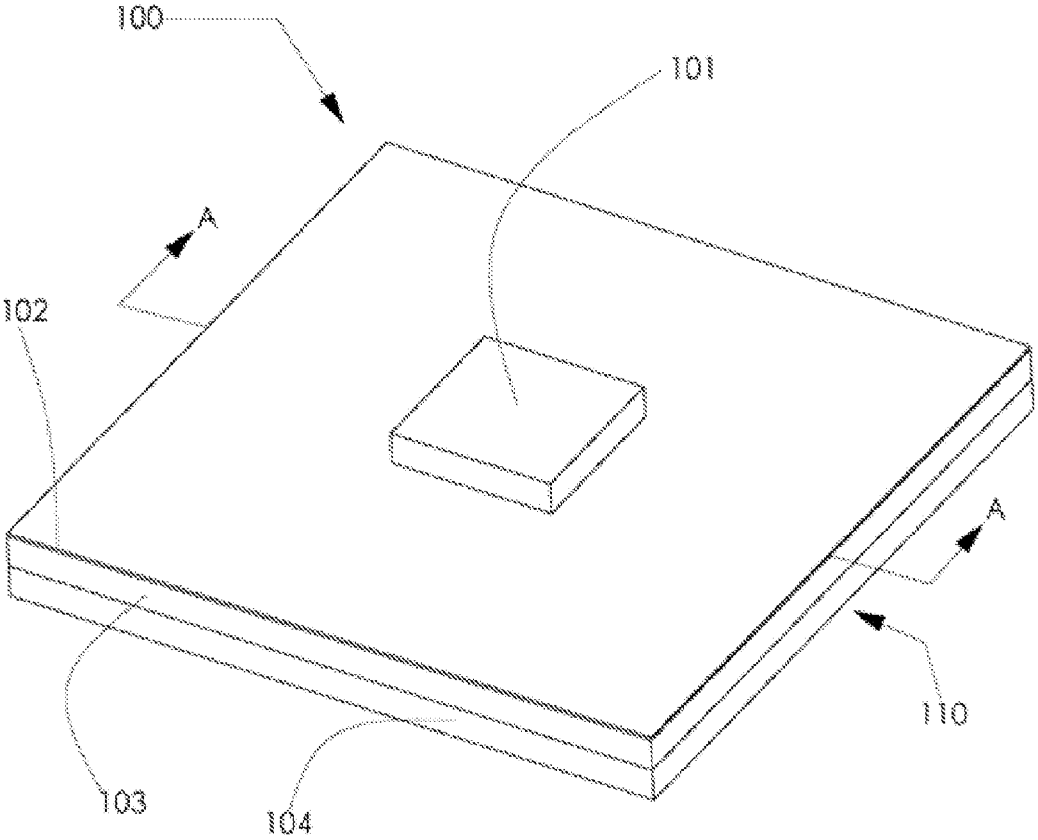


FIG. 1

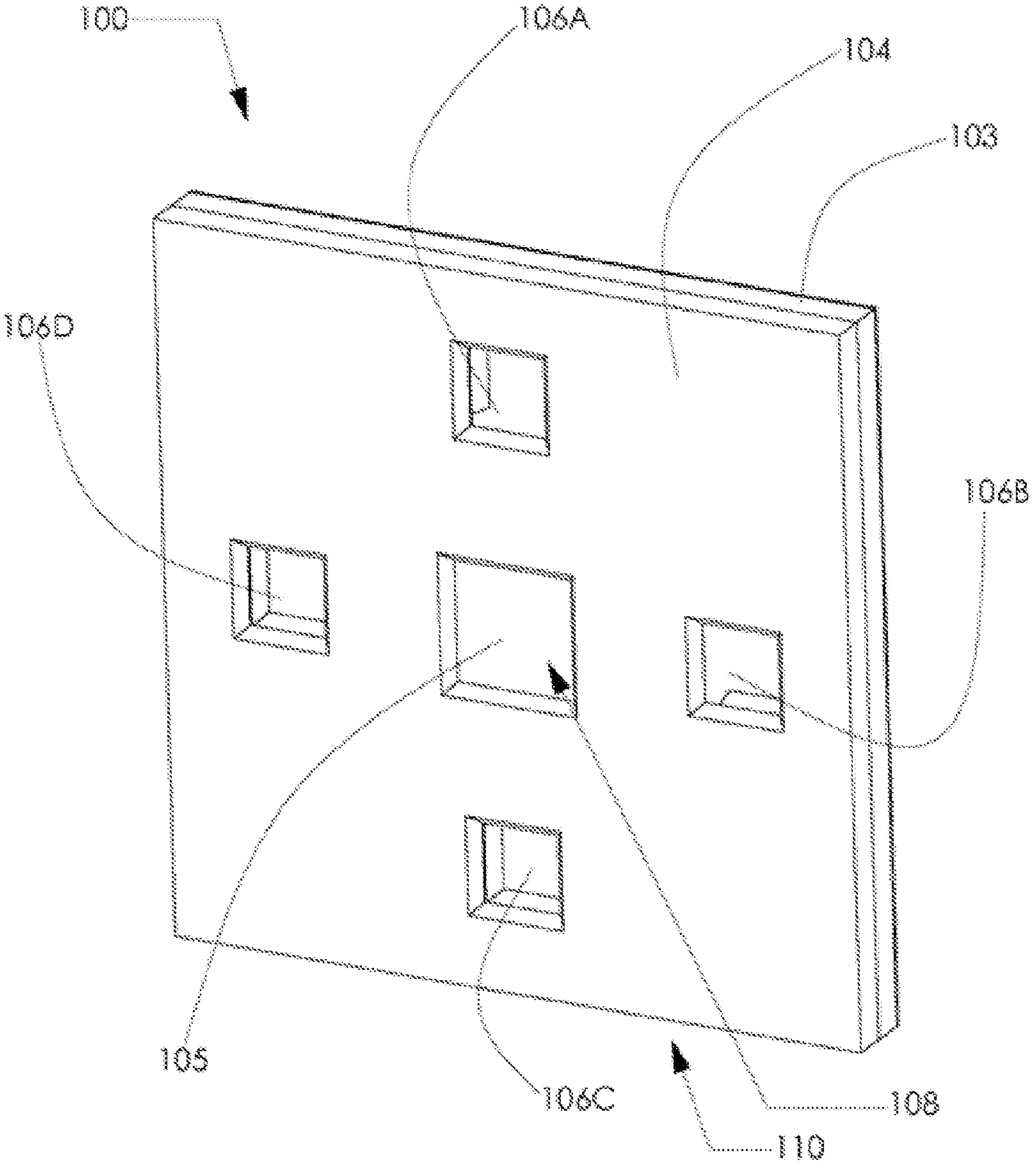


FIG. 2

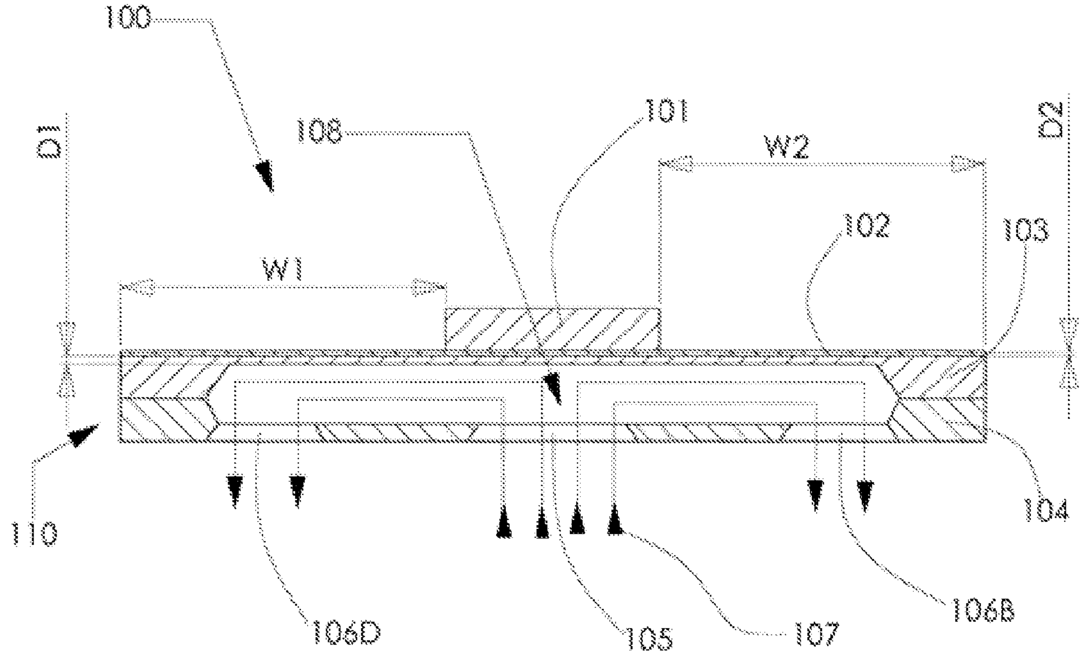


FIG. 3

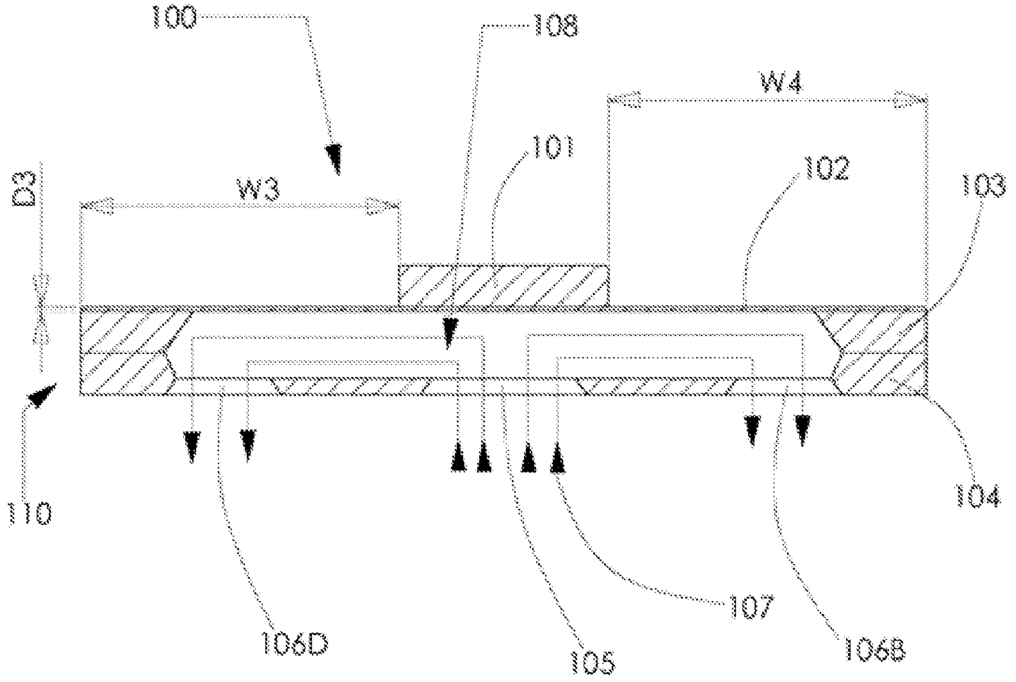


FIG. 4

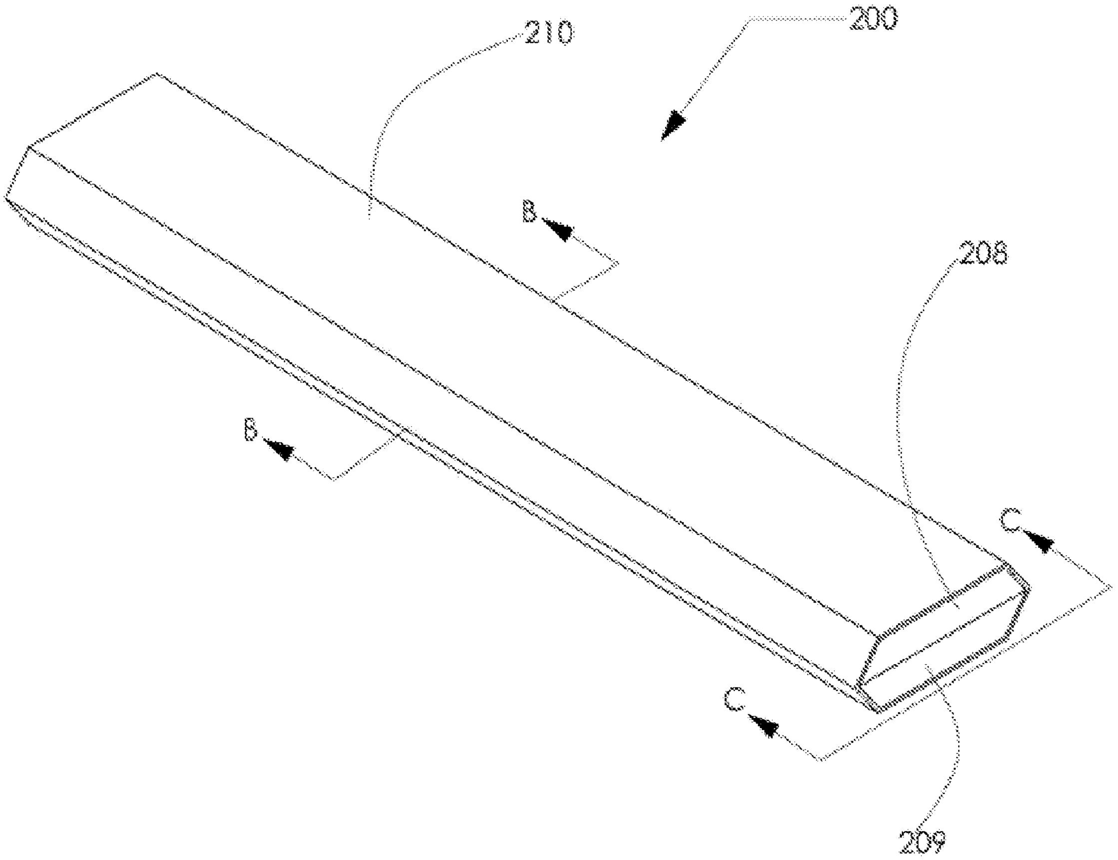


FIG. 5

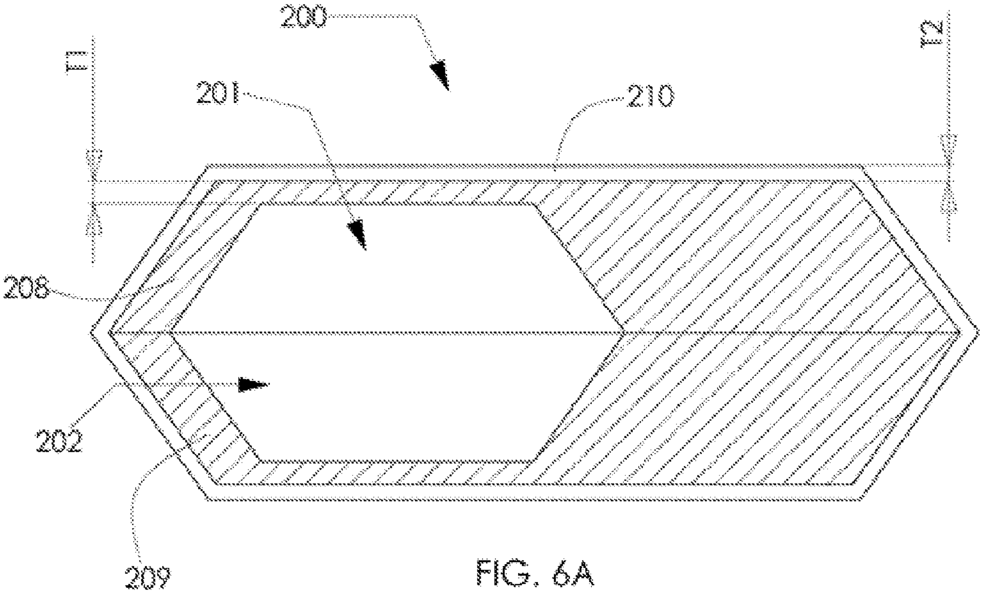


FIG. 6A

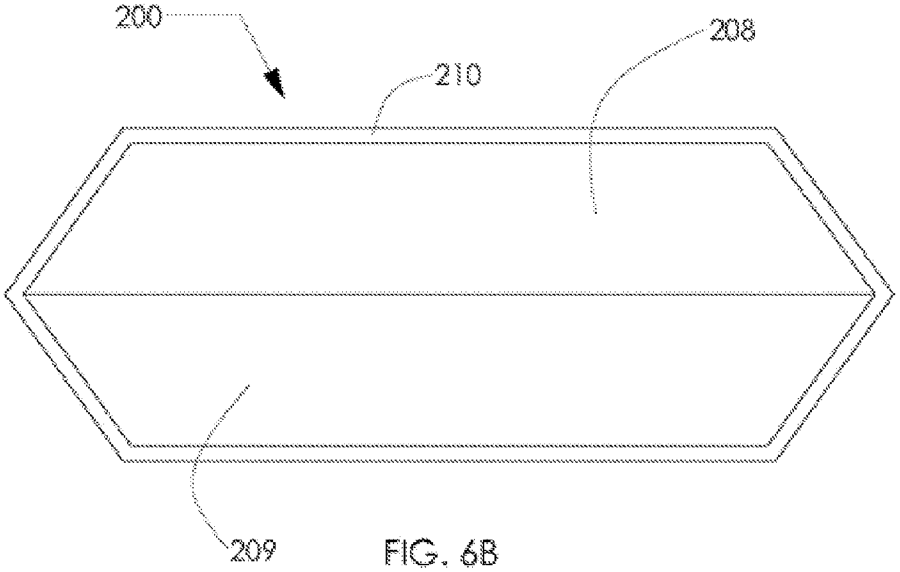


FIG. 6B

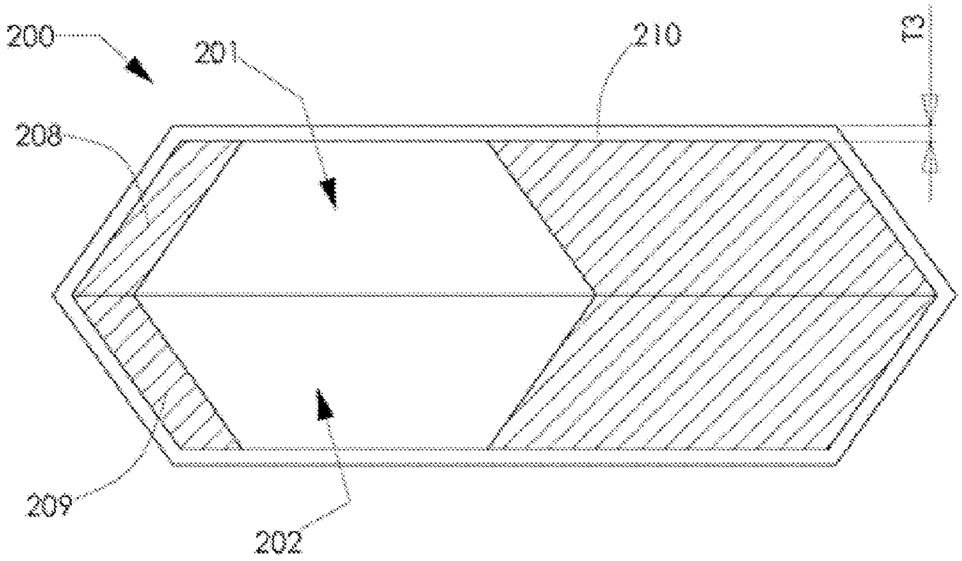


FIG. 7A

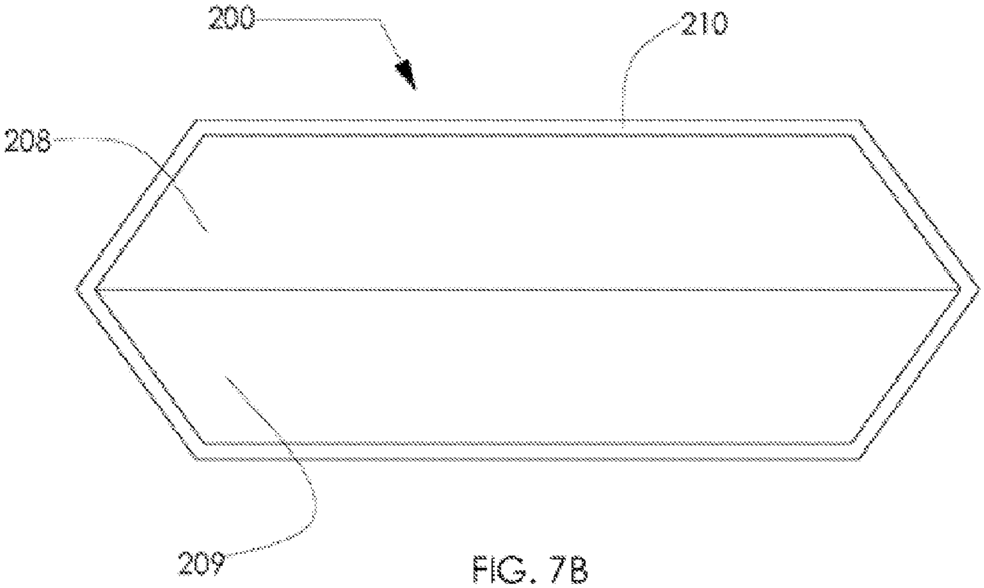


FIG. 7B

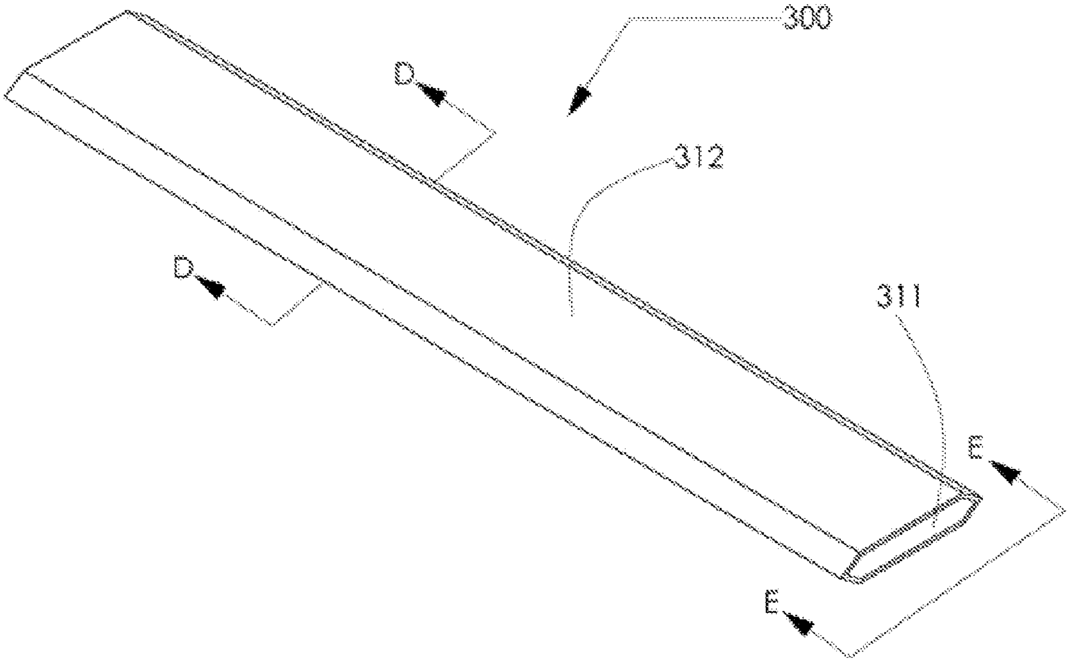


FIG. 8

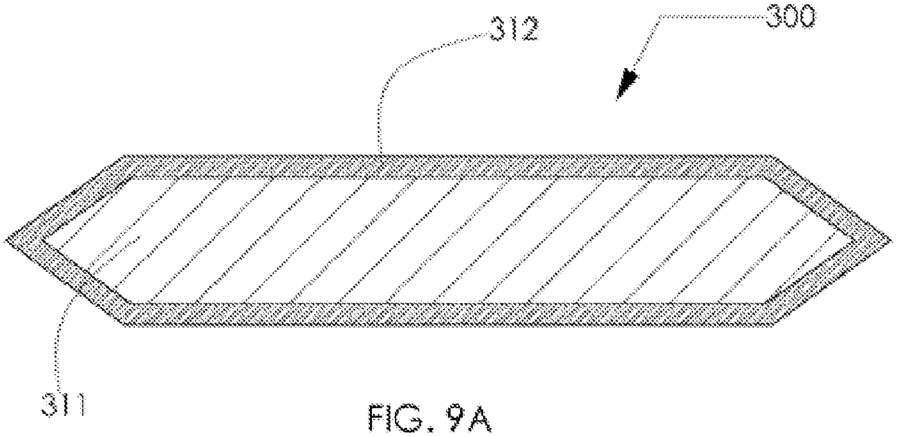


FIG. 9A

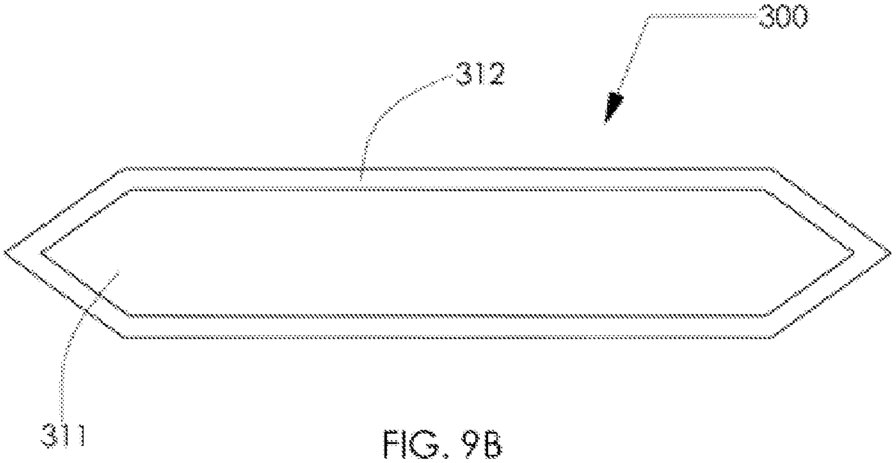


FIG. 9B

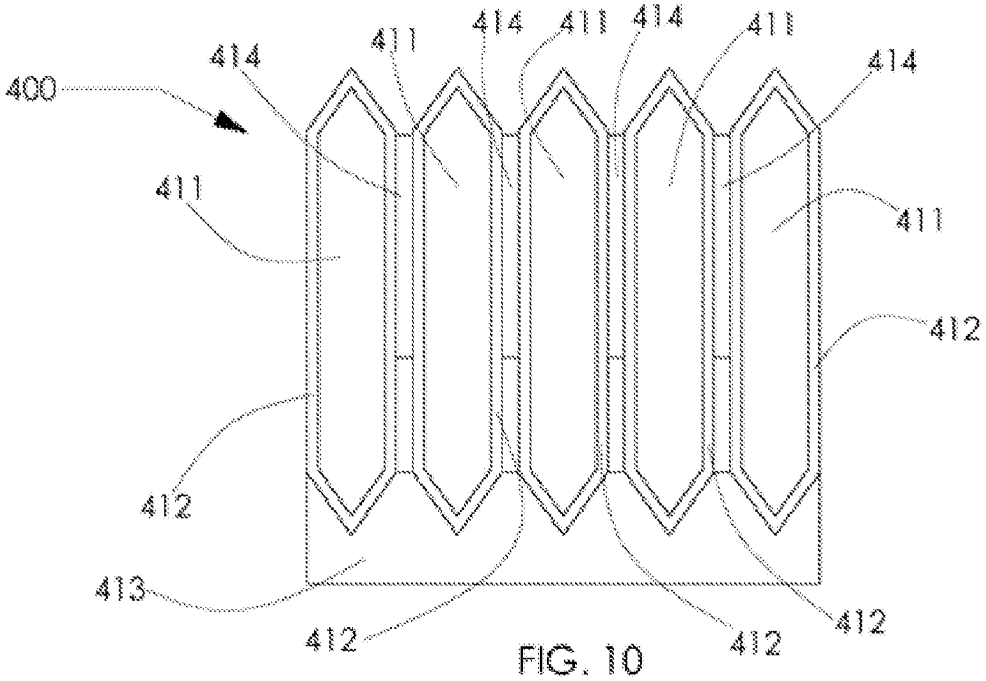

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FIG. 10

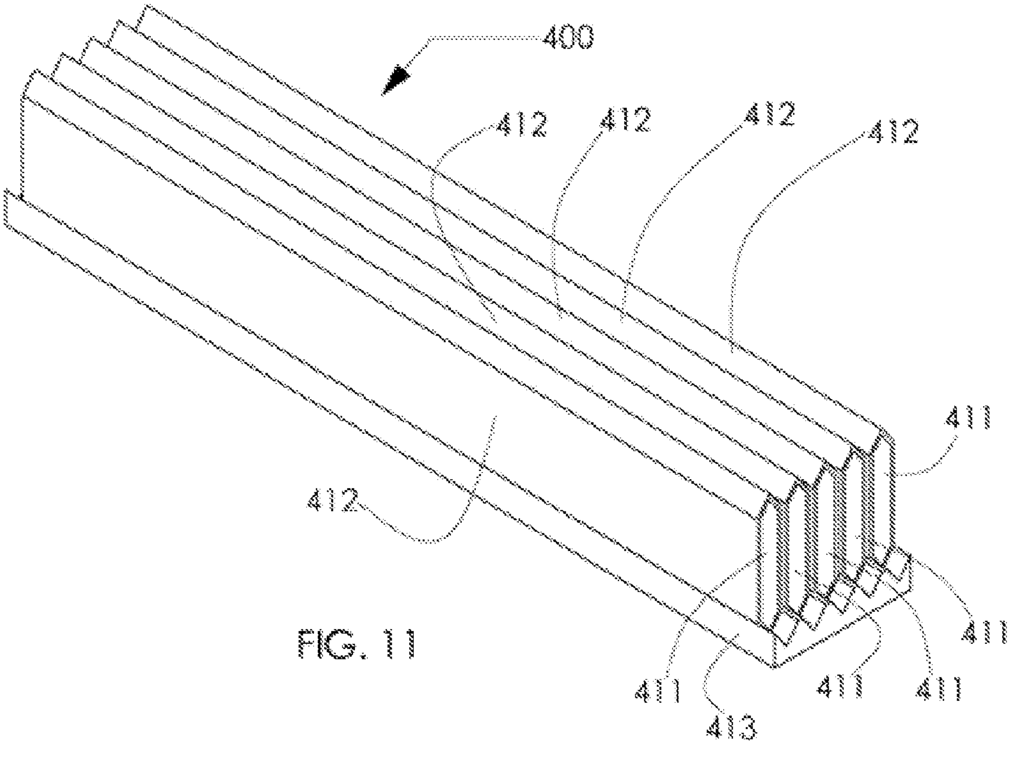
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FIG. 11

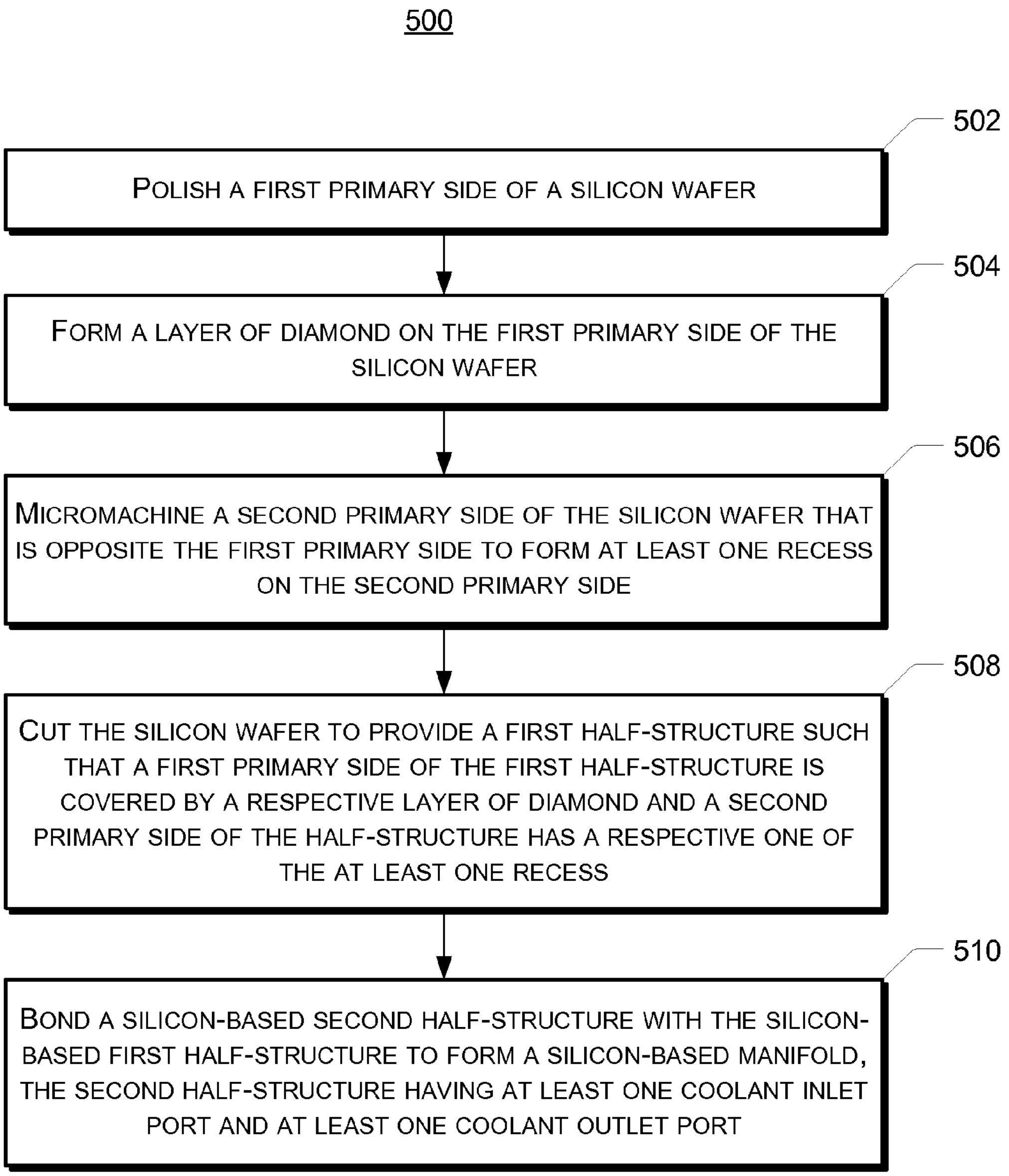
500
502
POLISH A FIRST PRIMARY SIDE OF A SILICON WAFER
504
FORM A LAYER OF DIAMOND ON THE FIRST PRIMARY SIDE OF THE SILICON WAFER
506
MICROMACHINE A SECOND PRIMARY SIDE OF THE SILICON WAFER THAT IS OPPOSITE THE FIRST PRIMARY SIDE TO FORM AT LEAST ONE RECESS ON THE SECOND PRIMARY SIDE
508
CUT THE SILICON WAFER TO PROVIDE A FIRST HALF-STRUCTURE SUCH THAT A FIRST PRIMARY SIDE OF THE FIRST HALF-STRUCTURE IS COVERED BY A RESPECTIVE LAYER OF DIAMOND AND A SECOND PRIMARY SIDE OF THE HALF-STRUCTURE HAS A RESPECTIVE ONE OF THE AT LEAST ONE RECESS
510
BOND A SILICON-BASED SECOND HALF-STRUCTURE WITH THE SILICON-BASED FIRST HALF-STRUCTURE TO FORM A SILICON-BASED MANIFOLD, THE SECOND HALF-STRUCTURE HAVING AT LEAST ONE COOLANT INLET PORT AND AT LEAST ONE COOLANT OUTLET PORT

FIG. 12

SILICON-BASED COOLING PACKAGE WITH DIAMOND COATING FOR HEAT-GENERATING DEVICES

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the priority benefit of U.S. Provisional Patent Application No. 61/445,171, filed on Feb. 22, 2011, the entirety of which is hereby incorporated by reference and made a part of this specification.

BACKGROUND

[0002] 1. Technical Field

[0003] The present disclosure generally relates to the field of transfer of thermal energy and, more particularly, to removal of thermal energy from a heat-generating device.

[0004] 2. Description of the Related Art

[0005] Heat-generating devices, such as vertical-cavity surface-emitting lasers (VCSELs), light-emitting diodes (LEDs), laser diodes, microprocessors and the like, generate thermal energy or heat when in operation. Regardless of which type of heat-generating device the case may be, heat generated by such a heat-generating device must be removed or dissipated from the heat-generating device in order to achieve optimum performance of the heat-generating device and keep the heat-generating device within its safe operating temperature. With the form factor of heat-generating devices and the applications they are implemented in becoming ever more compact, it is imperative to effectively dissipate the high-density heat generated in a small footprint area to ensure safe and optimum operation of heat-generating devices operating under such conditions.

[0006] Many metal-based water-cooled and air-cooled cooling packages have been developed for use in compact packages to dissipate heat generated by the various types of heat-generating devices mentioned above. For instance, heat exchangers and heat pipes made of a metallic material with high thermal conductivity, such as copper, silver, aluminum or iron, are commercially available. However, most metal-based heat exchangers and heat pipes experience oxidation, corrosion and/or crystallization after long periods of operation. Such fouling factors significantly reduce the heat transfer efficiency of metal-based heat exchangers and heat pipes. Other problems associated with the use of metal-based cooling packages include, for example, issues with overall compactness of the package, corrosion of the metallic material in water-cooled applications, difficulty in manufacturing, etc. Yet, increasing demand for higher power density in small form factor motivates the production of a compact cooling package with fewer or none of the aforementioned issues.

[0007] Heat-generating devices, such as vertical-cavity surface-emitting lasers (VCSELs), light-emitting diodes (LEDs), laser diodes, microprocessors and the like, generate thermal energy or heat when in operation. Regardless of which type of heat-generating device the case may be, heat generated by such a heat-generating device must be removed or dissipated from the heat-generating device in order to achieve optimum performance of the heat-generating device and keep the heat-generating device within its safe operating temperature. With the form factor of heat-generating devices and the applications they are implemented in becoming ever more compact, it is imperative to effectively dissipate the high-density heat generated in a small footprint area to ensure safe and optimum operation of heat-generating devices operating under such conditions.

[0008] Many metal-based water-cooled and air-cooled cooling packages have been developed for use in compact packages to dissipate heat generated by the various types of heat-generating devices mentioned above. For instance, heat exchangers and heat pipes made of a metallic material with high thermal conductivity, such as copper, silver, aluminum or iron, are commercially available. However, most metal-based heat exchangers and heat pipes experience oxidation, corrosion and/or crystallization after long periods of operation. Such fouling factors significantly reduce the heat transfer efficiency of metal-based heat exchangers and heat pipes. Other problems associated with the use of metal-based cooling packages include, for example, issues with overall compactness of the package, corrosion of the metallic material in water-cooled applications, difficulty in manufacturing, etc. Yet, increasing demand for higher power density in small form factor motivates the production of a compact cooling package with fewer or none of the aforementioned issues.

SUMMARY

[0009] Various embodiments of the present disclosure pertain to a silicon-based thermal energy transfer apparatus, or a cooling package, that remove thermal energy from a heat-generating device. The novel and non-obvious silicon-based thermal energy transfer apparatus eliminates problems with oxidation, corrosion and/or crystallization after long periods of operation as experienced by metal-based cooling packages. Other problems associated with the use of metal-based cooling packages such as issues with overall compactness of the package, corrosion of the metallic material in water-cooled applications, and difficulty in manufacturing may also be eliminated or minimized.

[0010] With a thermal conductivity of at least 900 W/(m·K), diamond serves as a much better thermal conductor than most commercially available metal and metal alloys. With a layer of diamond coating on the surface of the silicon-based thermal energy transfer apparatus, such that the heat-generating device is in direct contact with the layer of diamond when bonded, mounted, attached or otherwise fastened to the layer of diamond of the silicon-based thermal energy transfer apparatus, heat from the heat-generating device can quickly and widely spread across the layer of diamond to allow much higher efficiency in heat dissipation than existing technologies.

[0011] In one aspect, a thermal energy transfer apparatus that removes thermal energy from a heat-generating device may comprise: a silicon-based manifold having an internal cavity, a first primary side, and a second primary side opposite the first primary side. The second primary side may have at least one coolant inlet port and at least one coolant outlet port that are connected to the internal cavity of the manifold. The at least one coolant inlet port may be at a position directly opposite a position on the diamond layer where the heat-generating device is received. The apparatus further comprises a diamond layer covering at least a portion of the first primary side of the manifold such that the heat-generating device is in direct contact with the diamond layer when the heat-generating device is received on the first primary side of the manifold.

[0012] In one embodiment, the silicon-based manifold may comprise a silicon-based first plate and a silicon-based second plate. The first plate may have a first primary side and a second primary side opposite the first primary side. The first primary side of the first plate may be the first primary side of the manifold, the second primary side of the first plate may have a recess. The first plate may have an opening connecting the first primary side and the recess on the second primary side of the first plate such that a coolant flowing in the internal cavity of the manifold directly contacts the diamond layer. The second plate may have a first primary side as the second primary side of the manifold and a second primary side opposite the first primary side. The first primary side may have the at least one coolant inlet port and the at least one coolant outlet port. The second primary side may have a recess such that the opening in the first plate and the recess on the second primary side of the second plate form the internal cavity of the manifold when the first plate and the second plate are mated together with the second primary side of the first plate facing the second primary side of the second plate. At least the first primary side of the silicon-based first plate may have a surface roughness of a root mean squared (RMS) value of 2 microns or less.

[0013] In another embodiment, the silicon-based manifold may comprise a silicon-based first plate and a silicon-based second plate. The first plate may have a first primary side and a second primary side opposite the first primary side. The first primary side of the first plate may be the first primary side of the manifold on which the diamond layer is deposited. The second primary side of the first plate may have a recess. The second plate may have a first primary side as the second primary side of the manifold and a second primary side opposite the first primary side. The first primary side of the second plate may have the at least one coolant inlet port and the at least one coolant outlet port. The second primary side of the second plate may have a recess such that the recess on the second primary side of the first plate and the recess on the second primary side of the second plate form the internal cavity of the manifold when the first plate and the second plate are mated together with the second primary side of the first plate facing the second primary side of the second plate. At least the first primary side of the silicon-based first plate has a surface roughness of an RMS value of 2 microns or less.

[0014] In one embodiment, the diamond layer may have a thickness in a range between 10 μm and 500 μm.

[0015] In one embodiment, the diamond layer may cover a substantial portion of the first primary side of the manifold.

[0016] In another aspect, a thermal energy transfer apparatus that removes thermal energy from a heat-generating device may comprise: a silicon-based base plate, a silicon-based first fin structure and a silicon-based second fin structure. The silicon-based base plate may have a first primary side, a second primary side opposite the first primary side, a first groove on the first primary side, and a second groove on the first primary side parallel to the first groove. Each of the first and second fin structures respectively may have a first primary side and a second primary side opposite the first primary side. Each of the first and second fin structures respectively may further have, between the first primary side and the second primary side, a top edge, a bottom edge opposite the top edge, a front edge, and a back edge opposite the front edge.

[0017] The first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure may have a contiguous layer of diamond thereon. The first primary side, the top edge, the second primary side, and the bottom edge of the second fin structure may have a contiguous layer of diamond thereon. The bottom edge of the first fin structure may be received in the first groove, and the bottom edge of the second fin structure may be received in the second groove. The first groove and the second groove may be distanced from each other such that when the heat-generating device is received between the first fin structure and the second fin structure the heat-generating device is in direct contact with the layer of diamond on the first fin structure and with the layer of diamond on the second fin structure.

[0018] In one embodiment, the bottom edge of at least one of the first fin structure and the second fin structure may be V-shaped. At least one of the first groove and the second groove may be a V-shaped groove.

[0019] In one embodiment, at least one of the first and second fin structures may comprise at least one coolant inlet port on one of the respective edges, at least one coolant outlet port on one of the respective edges, and a coolant flow channel therein that connects the at least one coolant inlet port and the at least one coolant outlet port to allow a coolant to flow through the respective fin structure.

[0020] In one embodiment, the at least one of the first and second fin structures may comprise a silicon-based first half-fin structure and a silicon-based second half-fin structure that are configured in a fashion described below.

[0021] The first half-fin structure may have a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure. The second primary side of the first half-fin structure may have a recess. The first primary side of the first half-fin structure may have an opening connecting the first primary side of the first half-fin structure and the recess on the second primary side of the first half-fin structure such that the coolant flowing in the coolant flow channel of the respective fin structure is in direct contact with the layer of diamond.

[0022] The second half-fin structure may have a first primary side as the second primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure. The second primary side of the second half-fin structure may have a recess. The first primary side of the second half-fin structure may have an opening connecting the first primary side of the second half-fin structure and the recess on the second primary side of the second half-fin structure such that the coolant flowing in the coolant flow channel of the respective fin structure is in direct contact with the layer of diamond.

[0023] In one embodiment, at least the first primary side of the silicon-based first half-fin structure may have a surface roughness of an RMS value of 2 microns or less.

[0024] In another embodiment, at least one of the first and second fin structures may comprise a silicon-based first half-fin structure and a silicon-based second half-fin structure that are configured in a fashion described below.

[0025] The first half-fin structure may have a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure. The second primary side of the first half-fin structure may have a recess.

[0026] The second half-fin structure may have a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure. The second primary side of the second half-fin structure may have a recess such that the coolant flow channel of the respective fin structure is formed when the first half-fin structure and the second half-fin structure are mated together with the second primary side of the first half-fin structure facing the second primary side of the second half-fin structure.

[0027] In one embodiment, at least the first primary side of the silicon-based first half-fin structure has a surface roughness of an RMS value of 2 microns or less.

[0028] In one embodiment, the layer of diamond on at least one of the first fin structure and the second fin structure may have a thickness in a range between 10 μm and 500 μm.

[0029] In one aspect, a method may comprise: polishing a first primary side of a silicon wafer; forming a layer of diamond on the first primary side of the silicon wafer; micromachining a second primary side of the silicon wafer that is opposite the first primary side to form at least one recess on the second primary side; cutting the silicon wafer to provide a first half-structure such that a first primary side of the first half-structures is covered by a respective layer of diamond and a second primary side of the first half-structure has a respective one of the at least one recess; and bonding a silicon-based second half-structure with the first half-fin structure to form a silicon-based manifold, the second half-structure having at least one coolant inlet port and at least one coolant outlet port through which a coolant flows in and out of the manifold, respectively.

[0030] In one embodiment, polishing the first primary side of the silicon wafer may comprise polishing the first primary side of the silicon wafer such that the first primary side of the silicon wafer has a surface roughness of an RMS value of 2 microns or less.

[0031] In one embodiment, forming the layer of diamond on the first primary side of the silicon wafer may comprise forming, on the first primary side of the silicon wafer, a layer of diamond having a thickness in a range between 10 μm and 500 μm.

[0032] In one embodiment, micromachining the second primary side of the silicon wafer to form at least one recess on the second primary side may comprise micromachining the second primary side of the silicon wafer to form at least one recess on the second primary side such that at least a portion of the layer of diamond is exposed on the second primary side of the wafer. Furthermore, cutting the silicon wafer to provide the first half-structure such that a first primary side of the first half-structures is covered by a respective layer of diamond and a second primary side of the first half-structure has a respective one of the at least one recess may comprise cutting the silicon wafer to provide the first half-structure such that the first primary side of the first half-structures is covered by the respective layer of diamond and the second primary side of the first half-structure has a respective one of the at least one recess that exposes the respective layer of diamond on the second primary side of the first half-structure.

[0033] In one embodiment, the method may further comprise: attaching a heat-generating device to the manifold such that the heat-generating device is in direct contact with the layer of diamond on the first primary side of the first half-structure; and flowing the coolant into the manifold through the coolant inlet port and out of the manifold through the coolant outlet port to remove a portion of heat from the heat-generating device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] In the detailed description that follows, embodiments are described as illustrations since various changes and modifications will become apparent to those skilled in the art from the following detailed description. The use of the same reference numbers in different indicates similar or identical items. It is appreciable that the figures are not necessarily in scale as some components may be shown as out of proportion than the size in actual implementation in order to clearly illustrate the concept of the present disclosure.

[0035] FIG. **1** is a three-dimensional view of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with one embodiment of the present disclosure.

[0036] FIG. **2** is another three-dimensional view of the thermal energy transfer apparatus of FIG. **1** in accordance with one embodiment of the present disclosure.

[0037] FIG. **3** is a cross-sectional view of the thermal energy transfer apparatus of FIG. **1** in accordance with one embodiment of the present disclosure.

[0038] FIG. **4** is a cross-sectional view of the thermal energy transfer apparatus of FIG. **1** in accordance with another embodiment of the present disclosure.

[0039] FIG. **5** is a three-dimensional view of a fin structure of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with one embodiment of the present disclosure.

[0040] FIG. **6**A is a cross-sectional view of line BB of the fin structure of FIG. **5** in accordance with one embodiment of the present disclosure.

[0041] FIG. **6**B is a side view of line CC of the fin structure of FIG. **6**A in accordance with one embodiment of the present disclosure.

[0042] FIG. **7**A is a cross-sectional view of line BB of the fin structure of FIG. **5** in accordance with another embodiment of the present disclosure.

[0043] FIG. **7**B is a side view of line CC of the fin structure of FIG. **7**A in accordance with one embodiment of the present disclosure.

[0044] FIG. **8** is a three-dimensional view of a fin structure of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with another embodiment of the present disclosure.

[0045] FIG. **9**A is a cross-sectional view of line DD of the fin structure of FIG. **8** in accordance with one embodiment of the present disclosure.

[0046] FIG. **9**B is a side view of line EE of the fin structure of FIG. **9**A in accordance with one embodiment of the present disclosure.

[0047] FIG. **10** is a side view of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with another embodiment of the present disclosure.

[0048] FIG. **11** is a three-dimensional view of the thermal energy transfer apparatus of FIG. **10** in accordance with one embodiment of the present disclosure.

[0049] FIG. **12** is a flowchart of a process of fabricating a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with one embodiment of the present disclosure.

DETAILED DESCRIPTION

Overview

[0050] The present disclosure describes embodiments of a thermal energy transfer apparatus that removes thermal energy from a light-emitting device. While aspects of described techniques relating to a thermal energy transfer apparatus that removes thermal energy from a light-emitting device can be implemented in any number of different applications, the disclosed embodiments are described in context of the following exemplary configurations.

Illustrative First Thermal Energy Transfer Apparatus

[0051] FIG. **1** illustrates a three-dimensional view of a thermal energy transfer apparatus **100** that removes thermal energy from a heat-generating device **101** when the heat-generating device **101** is bonded, mounted, attached or otherwise fastened to the thermal energy transfer apparatus **100**. The heat-generating device **101** may be, for example, a VCSEL or a microprocessor chip.

[0052] The thermal energy transfer apparatus **100** comprises a silicon-based manifold **110**. The manifold **110** has an internal cavity **108** (not visible in FIG. **1** but partially visible in FIG. **2**), a first primary side (i.e., the top surface of the manifold **110** which faces the heat-generating device **101** in FIG. **1**), and a second primary side opposite the first primary side (i.e., the bottom surface of the manifold **110** which is not visible in FIG. **1**). In one embodiment, the silicon-based manifold **110** comprises a silicon-based first plate **103** and a silicon-based second plate **104**. Detailed description of the silicon-based first plate **103** and the silicon-based second plate **104** will be provided below with reference to FIGS. **3** and **4**.

[0053] The thermal energy transfer apparatus **100** further comprises a diamond layer **102**. The diamond layer **102** covers at least a portion of the first primary side of the manifold **110** such that the heat-generating device **101** is in direct contact with the diamond layer **102** when the heat-generating device **101** is received on the first primary side of the manifold **110**. For example, as shown in FIG. **1**, the diamond layer **102** may cover substantially the entire first primary side of the manifold **110**. When the heat-generating device **101** is bonded, mounted, attached or otherwise fastened to the diamond layer **102** of the thermal energy transfer apparatus **100**, heat from the heat-generating device **102** can quickly and widely spread across the layer of diamond since diamond has excellent thermal conductivity, i.e., 900-2,320 W/(m·K). As such, heat from the heat-generating device **102** can be better dissipated by the manifold **110** in addition to being radiated and convected to the ambience. This technique results in much higher efficiency in heat dissipation than existing cooling package technologies.

[0054] FIG. **2** illustrates another three-dimensional view of the thermal energy transfer apparatus **100** of FIG. **1** in accordance with one embodiment of the present disclosure.

[0055] The second primary side of the manifold **110** may have at least one coolant inlet port and at least one coolant outlet port that are connected to the internal cavity **108** of the manifold **110**. The number and location of each of the at least one coolant inlet port and the at least one coolant outlet port are designed so as to enhance heat transfer to a coolant flowing through the manifold **110**. In one embodiment, as shown in FIG. **2**, the second primary side of the manifold **110** has one coolant inlet port **105** and four coolant output ports **106**A, **106**B, **106**C and **106**D. To optimize the heat transfer efficiency, the at least one coolant inlet port, e.g., the coolant inlet port **105**, is at a position directly opposite a position on the diamond layer **102** where the heat-generating device **101** is received. Detailed description about the location of the coolant inlet port **105** will be provided below with reference to FIGS. **3** and **4**.

[0056] In other embodiments, there may be more coolant inlet port than shown in FIG. **2**. Even with more than one coolant inlet port, the at least one coolant inlet port may be designed to be positioned directly opposite a position on the diamond layer **102** where the heat-generating device **101** is bonded, mounted, attached or otherwise fastened to the diamond layer **102**.

[0057] The coolant output ports **106**A, **106**B, **106**C and **106**D surround the coolant inlet port **105** so that the coolant flowing into the manifold **110** has to spread out in four directions, thus absorbing the heat spread by the diamond layer **102** along the way, in order to flow out of the manifold **110** from the coolant output ports **106**A, **106**B, **106**C and **106**D. In other embodiments, there may be fewer or more coolant output ports than shown in FIG. **2**, and those coolant output ports may be at different positions on the second primary side of the manifold **110**.

[0058] FIG. **3** illustrates a cross-sectional view of the thermal energy transfer apparatus **100** of FIG. **1** in accordance with one embodiment of the present disclosure.

[0059] In one embodiment, as shown in FIG. **3**, the first plate **103** has a first primary side, i.e., the top side shown in FIG. **3**, and a second primary side opposite the first primary side, i.e., the bottom side shown in FIG. **3**. The first primary side of the first plate **103** is the first primary side of the manifold **110** on which the diamond layer **102** is deposited. The second primary side of the first plate **103** has a recess.

[0060] The second plate **104** has a first primary side, i.e., the bottom side shown in FIG. **3**, as the second primary side of the manifold **110** and a second primary side opposite the first primary side, i.e., the top side shown in FIG. **3**. The first primary side of the second plate **104** has the at least one coolant inlet port, e.g., the coolant inlet port **105**, and the at least one coolant outlet port, e.g., the coolant outlet ports **106**A, **106**B, **106**C and **106**D. The second primary side of the second plate **104** has a recess.

[0061] As shown in FIG. **3**, the coolant inlet port **105** is directly below the heat-generating device **101**. This allows a coolant **107** flowing into the manifold **110** through the coolant inlet port **105** to impinge on the second primary side of the first plate **103** which is directly below the heat-generating device **101**. This has been shown experimentally to result in optimal heat transfer from the heat-generating device **101** to the coolant **107**. Furthermore, with at least a portion of the heat from the heat-generating device **101** spread across the diamond layer **102**, this amount of heat can be more uniformly transferred from the diamond layer **102** to the first plate **103**, and subsequently to the coolant **107** as the coolant **107** flows through the manifold **110** before exiting the coolant outlet ports **106**A, **106**B, **106**C and **106**D.

[0062] The recess on the second primary side of the first plate **103** and the recess on the second primary side of the second plate **104** form the internal cavity **108** of the manifold **110** when the first plate **103** and the second plate **104** are mated together with the second primary side of the first plate **103** facing the second primary side of the second plate **104**.

[0063] In one embodiment, the first plate **103** and the second plate **104** are each micromachined from a single-crystal silicon wafer. In another embodiment, the first plate **103** and the second plate **104** are each micromachined from a polycrystal silicon wafer. The first plate **103** and the second plate **104** may be made from the same wafer or different wafers.

[0064] In one embodiment, at least the first primary side of the first plate **103** is polished to have a surface roughness of a root mean squared (RMS) value of 2 microns or less. In another embodiment, both the first primary side and the second primary side of the first plate **103** are polished to have a surface roughness of an RMS value of 2 microns or less.

[0065] As the diamond layer **102** is deposited or otherwise formed on the first primary side of the first plate **103**, a highly polished surface on the first primary side of the first plate **103**, i.e., having a low surface roughness RMS value, helps the formation of the diamond layer **102** having mirror-polished surfaces.

[0066] Having a highly polished surface on the second primary side of the first plate **103** supports a laminar flow of the coolant **107** in the internal cavity **108** of the manifold **110**. Laminar flow of the coolant **107** results in better heat transfer by convection compared to the case of turbulent flow. If the coolant **107** has a turbulent flow, e.g., at least partly due to the second primary side of the first plate **103** having rough surface finish, not only convective heat transfer is less than desirable with a turbulent flow but air pockets may likely form between the coolant **107** and the second primary side of the first plate **103** and further degrade heat transfer to the coolant **107**.

[0067] In one embodiment, the diamond layer **102** covers a substantial portion of the first primary side of the manifold. For example, as shown in FIGS. **1** and **3**, the diamond layer **102** covers substantially the entire first primary side of the manifold **110**, which is the first primary side of the first plate **103**. In other embodiments, the diamond layer **102** covers only a portion of the first primary side of the first plate **103** such that the heat-generating device **101** directly contacts the diamond layer **102**, not the first primary side of the first plate **103**. In other words, the dimensions W1 and W2 of the diamond layer **102**, as shown in FIG. **3**, may be different in different embodiments.

[0068] In one embodiment, the diamond layer **102** has a thickness, shown as the dimension D2 in FIG. **3**, in a range between 10 μm and 500 μm. The dimension D2 may be the same as or different from the thickness of the first plate **103**, shown as the dimension D1 in FIG. **3**.

[0069] FIG. **4** illustrates a cross-sectional view of the thermal energy transfer apparatus **100** of FIG. **1** in accordance with another embodiment of the present disclosure.

[0070] The embodiment of the thermal energy transfer apparatus **100** shown in FIG. **4** and the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **3** are similar. In the interest of brevity, features of the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **4** that are similar to those of the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **3** will not be repeated herein.

[0071] The main difference between the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **4** and the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **3** is that the first plate **103** has an opening connecting the first primary side and the recess on the second primary side of the first plate **103**. This way, the diamond layer **102** is exposed to the coolant **107** and, accordingly, the coolant **107** flowing in the internal cavity **108** of the manifold **110** directly contacts the diamond layer **102** to transfer heat away from the diamond layer **102**. Given that heat in the diamond layer **102** can be directly transferred to the coolant **107** without having to traverse through the thickness of the first plate **103**, as in the case shown in FIG. **3**, it is believed the embodiment of the thermal energy transfer apparatus **100** shown in FIG. **4** can better transfer heat away from the heat-generating device **101** than the embodiment shown in FIG. **3**.

[0072] In one embodiment, the first plate **103** and the second plate **104** are each micromachined from a single-crystal silicon wafer. In another embodiment, the first plate **103** and the second plate **104** are each micromachined from a polycrystal silicon wafer. The first plate **103** and the second plate **104** may be fabricated from the same wafer or different wafers. After the formation of the diamond layer **102** on the first primary side of the first plate **103**, the second primary side of the first plate **103** is etched to create an opening in the first plate **103** to expose the diamond layer **102** on the second primary side of the first plate **103**.

[0073] In one embodiment, at least the first primary side of the first plate **103** is polished to have a surface roughness of a root mean squared (RMS) value of 2 microns or less. As the diamond layer **102** is deposited or otherwise formed on the first primary side of the first plate **103**, a highly polished surface on the first primary side of the first plate **103**, i.e., having a low surface roughness RMS value, helps the formation of the diamond layer **102** having mirror-polished surfaces. Having a highly polished surface on the diamond layer **102** supports a laminar flow of the coolant **107** in the internal cavity **108** of the manifold **110**.

[0074] In one embodiment, the diamond layer **102** covers a substantial portion of the first primary side of the manifold. For example, as shown in FIGS. **1** and **4**, the diamond layer **102** covers substantially the entire first primary side of the manifold **110**, which is the first primary side of the first plate **103**. In other embodiments, the diamond layer **102** covers only a portion of the first primary side of the first plate **103** such that the heat-generating device **101** directly contacts the diamond layer **102**, not the first primary side of the first plate **103**. In other words, the dimensions W3 and W4 of the diamond layer **102**, as shown in FIG. **4**, may be different in different embodiments.

[0075] In one embodiment, the diamond layer **102** has a thickness, shown as the dimension D3 in FIG. **4**, in a range between 10 μm and 500 μm.

Illustrative Second Thermal Energy Transfer Apparatus

[0076] FIG. **5** illustrates a three-dimensional view of a fin structure **200** of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with one embodiment of the present disclosure.

[0077] The fin structure **200** has a first primary side and a second primary side opposite the first primary side. Between the first primary side and the second primary side, the fin structure **200** has a top edge, a bottom edge opposite the top edge, a front edge, and a back edge opposite the front edge.

[0078] As shown in FIG. **5**, the fin structure **200** comprises a silicon-based first half-fin structure **208** and a silicon-based second half-fin structure **209**. Detailed description of the silicon-based first half-fin structure **208** and the silicon-based second half-fin structure **209** will be provided below with reference to FIGS. **6**A, **6**B, **7**A and **7**B.

[0079] The first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **200** have a contiguous layer of diamond **210** coated thereon. That is, at least a portion of each of the first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **200** is covered by a portion of the layer of diamond **210**. In one embodiment, substantially the entire first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **200** are covered by the layer of diamond **210**.

[0080] In one embodiment, the bottom edge of the fin structure **200** and is V-shaped. In other embodiments, the bottom edge and at least one other edge of the fin structure **200** are V-shaped. For example, the top edge, bottom edge, front edge and back edge of the fin structure **200** may be V-shaped.

[0081] FIG. **6**A illustrates a cross-sectional view of the fin structure **200** of FIG. **5** in accordance with one embodiment of the present disclosure. FIG. **6**B illustrates a side view of the fin structure **200** of FIG. **6**A in accordance with one embodiment of the present disclosure.

[0082] In one embodiment, the fin structure **200** comprises at least one coolant inlet port on one of the respective edges, at least one coolant outlet port on one of the respective edges, and a coolant flow channel therein that connects the at least one coolant inlet port and the at least one coolant outlet port to allow a coolant to flow through the fin structure **200**.

[0083] The first half-fin structure **208** has a first primary side, i.e., the top side shown in FIG. **6**A, as the first primary side of the fin structure **200**, and a second primary side opposite the first primary side, i.e., the bottom side shown in FIG. **6**A. Between the first primary side and the second primary side, the first half-fin structure **208** has a top edge as half of the top edge of the fin structure **200**, a bottom edge as half of the bottom edge of the fin structure **200**, a front edge as half of the front edge of the fin structure **200**, and a back edge as half of the back edge of the fin structure **200**. The second primary side of the first half-fin structure **208** has a recess **201** that forms half of the coolant inlet port, the coolant flow channel, and the coolant outlet port.

[0084] The second half-fin structure **209** has a first primary side, i.e., the bottom side shown in FIG. **6**A, as the second primary side of the fin structure **200**, and a second primary side opposite the first primary side. Between the first primary side and the second primary side, the second half-fin structure **209** has a top edge as the other half of the top edge of the fin structure **200**, a bottom edge as the other half of the bottom edge of the fin structure **200**, a front edge as the other half of the front edge of the fin structure **200**, and a back edge as the other half of the back edge of the fin structure **200**. The second primary side of the second half-fin structure **209** has a recess **202** that forms the other half of the coolant inlet port, the coolant flow channel, and the coolant outlet port.

[0085] The coolant flow channel of the fin structure **200** is formed when the first half-fin structure **208** and the second half-fin structure **209** are mated together with the second primary side of the first half-fin structure facing the second primary side of the second half-fin structure.

[0086] In one embodiment, the first half-fin structure **208** and the second half-fin structure **209** are each micromachined from a single-crystal silicon wafer. In another embodiment, the first half-fin structure **208** and the second half-fin structure **209** are each micromachined from a poly-crystal silicon wafer. The first half-fin structure **208** and the second half-fin structure **209** may be made from the same wafer or different wafers.

[0087] In one embodiment, at least the first primary side of the first half-fin structure **208** is polished to have a surface roughness of an RMS value of 2 microns or less. In another embodiment, the first primary side and the second primary side of the first half-fin structure **208** are polished to have a surface roughness of an RMS value of 2 microns or less. Alternatively or additionally, at least the first primary side of the second half-fin structure **209** is polished to have a surface roughness of an RMS value of 2 microns or less. Alternatively or additionally, the first primary side and the second primary side of the second half-fin structure **209** are polished to have a surface roughness of an RMS value of 2 microns or less. Benefits of having a highly polished surface have been described above and thus, in the interest of brevity, will not be repeated herein.

[0088] In one embodiment, the layer of diamond **210** on the first fin structure **200** has a thickness T**2** in a range between 10 μm and 500 μm. The dimension T**2** may be the same as or different from the thickness T**1** of the first half-fin structure **208** and the second half-fin structure **209**.

[0089] FIG. **7**A illustrates a cross-sectional view of the fin structure **200** of FIG. **5** in accordance with another embodiment of the present disclosure. FIG. **7**B illustrates a side view of the fin structure **200** of FIG. **7**A in accordance with one embodiment of the present disclosure.

[0090] The embodiment of the fin structure **200** shown in FIGS. **7**A, **7**B and the embodiment of the fin structure **200** shown in FIGS. **6**A, **6**B are similar. In the interest of brevity, features of the embodiment of the fin structure **200** shown in FIGS. **7**A, **7**B that are similar to those of the embodiment of the sin structure **200** shown in FIGS. **6**A, **6**B will not be repeated herein.

[0091] The main difference between the embodiment of the fin structure **200** shown in FIGS. **7**A, **7**B and the embodiment of the fin structure **200** shown in FIGS. **6**A, **6**B is that either or both of the first half-fin structure **208** and the second half-fin structure **209** have an opening connecting its first primary side and the recess on its second primary side. This way, the layer of diamond **210** is exposed to the coolant and, accordingly, the coolant flowing in the coolant flow channel of the fin structure **200** directly contacts the layer of diamond **210** to transfer heat away from the layer of diamond **210**. Given that heat in the layer of diamond **102** can be directly transferred to the coolant without having to traverse through the thickness of the respective half-fin structure, it is believed the embodiment of the fin structure **200** shown in FIGS. **7**A, **7**B can better transfer heat away from a heat-generating device that is bonded, mounted, attached or otherwise fastened to the layer of diamond **210** than the embodiment shown in FIGS. **6**A, **6**B.

[0092] In one embodiment, the first half-fin structure **208** and the second half-fin structure **209** are each micromachined from a single-crystal silicon wafer. In another embodiment, the first half-fin structure **208** and the second half-fin structure **209** are each micromachined from a poly-crystal silicon wafer. The first half-fin structure **208** and the second half-fin structure **209** may be fabricated from the same wafer or different wafers. After the formation of the layer of diamond **210** on the first primary side of the first half-fin structure **208**, the second primary side of the first half-fin structure **208** is etched to create an opening in the first half-fin structure **208** to expose the layer of diamond **210** on the second primary side of the first half-fin structure **208**. A similar fabrication process may be carried out for the second half-fin structure **209**.

[0093] In one embodiment, at least the first primary side of the first half-fin structure **208** is polished to have a surface roughness of an RMS value of 2 microns or less. In another embodiment, the first primary side and the second primary side of the first half-fin structure **208** are polished to have a surface roughness of an RMS value of 2 microns or less. Alternatively or additionally, at least the first primary side of the second half-fin structure **209** is polished to have a surface roughness of an RMS value of 2 microns or less. Alternatively or additionally, the first primary side and the second primary side of the second half-fin structure **209** are polished to have a surface roughness of an RMS value of 2 microns or less. Benefits of having a highly polished surface have been described above and thus, in the interest of brevity, will not be repeated herein.

[0094] In one embodiment, the layer of diamond **210** has a thickness, shown as the dimension T**3** in FIGS. **7**A, **7**B, in a range between 10 μm and 500 μm.

[0095] FIG. **8** is a three-dimensional view of a fin structure **300** of a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with another embodiment of the present disclosure.

[0096] The fin structure **300** comprises a silicon-based fin structure **311**. The fin structure **311** has a first primary side and a second primary side opposite the first primary side. Between the first primary side and the second primary side, the fin structure **311** has a top edge, a bottom edge opposite the top edge, a front edge, and a back edge opposite the front edge.

[0097] The first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **311** have a contiguous layer of diamond **312** coated thereon. That is, at least a portion of each of the first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **311** is covered by a portion of the layer of diamond **312**. In one embodiment, substantially the entire first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure **311** are covered by the layer of diamond **312**.

[0098] In one embodiment, the bottom edge of the fin structure **311** and is V-shaped. In other embodiments, the bottom edge and at least one other edge of the fin structure **311** are V-shaped. For example, the top edge, bottom edge, front edge and back edge of the fin structure **311** may be V-shaped.

[0099] In one embodiment, the fin structure **311** is micromachined from a single-crystal silicon wafer. In another embodiment, the fin structure **311** is micromachined from a poly-crystal silicon wafer.

[0100] In one embodiment, at least the first primary side of the fin structure **311** is polished to have a surface roughness of an RMS value of 2 microns or less. In another embodiment, the first primary side and the second primary side of the fin structure **311** are polished to have a surface roughness of an RMS value of 2 microns or less. Alternatively, the first primary side, the second primary side, the top edge and the bottom edge of the fin structure **311** are polished to have a surface roughness of an RMS value of 2 microns or less. Benefits of having a highly polished surface have been described above and thus, in the interest of brevity, will not be repeated herein.

[0101] In one embodiment, the layer of diamond **312** on the fin structure **311** has a thickness in a range between 10 μm and 500 μm.

[0102] FIG. **9**A is a cross-sectional view of the fin structure **300** of FIG. **8** in accordance with one embodiment of the present disclosure. FIG. **9**B is a side view of the fin structure **300** of FIG. **9**A in accordance with one embodiment of the present disclosure.

[0103] FIG. **10** is a side view of a thermal energy transfer apparatus **400** that removes thermal energy from a heat-generating device in accordance with another embodiment of the present disclosure. FIG. **11** is a three-dimensional view of the thermal energy transfer apparatus **400** of FIG. **10** in accordance with one embodiment of the present disclosure.

[0104] The thermal energy transfer apparatus **400** removes thermal energy from one or more heat-generating device **414**. Although there are a fixed number of heat-generating devices **414** shown in FIGS. **10** and **11**, in various embodiments the number of the heat-generating devices **414** may be greater or smaller than that shown in FIGS. **10** and **11**.

[0105] The thermal energy transfer apparatus **400** comprises a silicon-based base plate **413** and a plurality of silicon-based fin structures including a silicon-based first fin structure and a silicon-based second fin structure. In one embodiment, least one of the plurality of silicon-based fin structures of the apparatus **400** may be the fin structure **200** shown in FIGS. **5**, **6**A, **6**B, **7**A and **7**B. In another embodiment, least one of the plurality of silicon-based fin structures of the apparatus **400** may be the fin structure **300** shown in FIGS. **8**, **9**A and **9**B. For illustrative purpose only, the fin structure **300** is shown as each of the plurality of fin structures of the apparatus **400** in FIGS. **10** and **11**.

[0106] The silicon-based base plate **413** has a first primary side, a second primary side opposite the first primary side, and a plurality of parallel grooves. For example, a first groove on the first primary side is parallel to a second groove on the first primary side of the base plate **413**.

[0107] The bottom edge of each of the plurality of fin structures is received in a respective one of the grooves. The groove are distanced from each other such that when a respective heat-generating device **414** is received between two neighboring fin structures the heat-generating device **414** is in direct contact with the layer of diamond **312** on each of the two fin structures **300**.

[0108] In one embodiment, the bottom edge of at least one of the fin structures is V-shaped. At least one of the grooves is a V-shaped groove to receive the V-shaped bottom edge of the fin structure.

Illustrative Fabrication Process

[0109] FIG. **12** illustrates a flowchart of a process **500** of fabricating a thermal energy transfer apparatus that removes thermal energy from a heat-generating device in accordance with one embodiment of the present disclosure.

[0110] At **502**, the process **500** polishes a first primary side of a silicon wafer. At **504**, the process **500** forms a layer of diamond on the first primary side of the silicon wafer. At **506**, the process **500** micromachines a second primary side of the silicon wafer that is opposite the first primary side to form at least one recess on the second primary side. At **508**, the process **500** cuts the silicon wafer to provide a first half-structure such that a first primary side of the first half-structures is covered by a respective layer of diamond and a second primary side of the first half-structure has a respective one of the at least one recess. At **510**, the process **500** bonds a silicon-based second half-structure with the first half-fin structure to form a silicon-based manifold, the second half-structure having at least one coolant inlet port and at least one coolant outlet port through which a coolant flows in and out of the manifold, respectively. Accordingly, the process **500** may be utilized to fabricate the components of the manifold **110** and the components of the fin structure **200** described above.

[0111] In one embodiment, the first primary side of the silicon wafer is polished such that the first primary side of the silicon wafer has a surface roughness of an RMS value of 2 microns or less.

[0112] In one embodiment, on the first primary side of the silicon wafer, a layer of diamond is formed and has a thickness in a range between 10 μm and 500 μm.

[0113] In one embodiment, the second primary side of the silicon wafer is micromachined to form at least one recess on the second primary side such that at least a portion of the layer of diamond is exposed on the second primary side of the wafer. Furthermore, the silicon wafer is cut to provide the first half-structure such that the first primary side of the first half-structures is covered by the respective layer of diamond and the second primary side of the first half-structure has a respective one of the at least one recess that exposes the respective layer of diamond on the second primary side of the first half-structure.

[0114] In one embodiment, the process **500** further comprises: attaching a heat-generating device to the manifold such that the heat-generating device is in direct contact with the layer of diamond on the first primary side of the first half-structure; and causing the coolant to flow into the manifold through the coolant inlet port and out of the manifold through the coolant outlet port to remove a portion of heat from the heat-generating device.

CONCLUSION

[0115] The above-described techniques pertain to silicon-based thermal energy transfer heat-generating devices. The novel and non-obvious silicon-based thermal energy transfer apparatus eliminates problems with oxidation, corrosion and/or crystallization after long periods of operation as experienced by metal-based cooling packages. Other problems associated with the use of metal-based cooling packages such as issues with overall compactness of the package, corrosion of the metallic material in water-cooled applications, and difficulty in manufacturing may also be eliminated or minimized.

[0116] Although the techniques have been described in language specific to structural features and/or methodological acts, it is to be understood that the appended claims are not necessarily limited to the specific features or acts described. Rather, the specific features and acts are disclosed as exemplary forms of implementing such techniques. Furthermore, although the techniques have been illustrated in the context of cooling package for a VCSEL and a microprocessor chip, the techniques may be applied in any other suitable context such as, for example, cooling package for laser diodes and LEDs.

What is claimed is:

1. A thermal energy transfer apparatus that removes thermal energy from a heat-generating device, the apparatus comprising:

a silicon-based manifold having an internal cavity, a first primary side, and a second primary side opposite the first primary side, the second primary side having at least one coolant inlet port and at least one coolant outlet port that are connected to the internal cavity of the manifold, the at least one coolant inlet port being at a position directly opposite a position on the diamond layer where the heat-generating device is received; and

a diamond layer covering at least a portion of the first primary side of the manifold such that the heat-generating device is in direct contact with the diamond layer when the heat-generating device is received on the first primary side of the manifold.

2. The apparatus of claim **1**, wherein the silicon-based manifold comprises:

a silicon-based first plate, the first plate having a first primary side and a second primary side opposite the first primary side, the first primary side of the first plate being the first primary side of the manifold, the second primary side of the first plate having a recess, the first plate having an opening connecting the first primary side and the recess on the second primary side of the first plate such that a coolant flowing in the internal cavity of the manifold directly contacts the diamond layer; and

a silicon-based second plate, the second plate having a first primary side as the second primary side of the manifold and a second primary side opposite the first primary side, the first primary side having the at least one coolant inlet port and the at least one coolant outlet port, the second primary side having a recess such that the opening in the first plate and the recess on the second primary side of the second plate form the internal cavity of the manifold when the first plate and the second plate are mated together with the second primary side of the first plate facing the second primary side of the second plate.

3. The apparatus of claim **2**, wherein at least the first primary side of the silicon-based first plate has a surface roughness of a root mean squared (RMS) value of 2 microns or less.

4. The apparatus of claim **1**, wherein the silicon-based manifold comprises:

a silicon-based first plate, the first plate having a first primary side and a second primary side opposite the first primary side, the first primary side of the first plate being the first primary side of the manifold on which the diamond layer is deposited, the second primary side of the first plate having a recess; and

a silicon-based second plate, the second plate having a first primary side as the second primary side of the manifold and a second primary side opposite the first primary side, the first primary side of the second plate having the at least one coolant inlet port and the at least one coolant outlet port, the second primary side of the second plate having a recess such that the recess on the second primary side of the first plate and the recess on the second primary side of the second plate form the internal cavity of the manifold when the first plate and the second plate are mated together with the second primary side of the first plate facing the second primary side of the second plate.

5. The apparatus of claim **4**, wherein at least the first primary side of the silicon-based first plate has a surface roughness of a root mean squared (RMS) value of 2 microns or less.

6. The apparatus of claim **1**, wherein the diamond layer has a thickness in a range between 10 μm and 500 μm.

7. The apparatus of claim **1**, wherein the diamond layer covers a substantial portion of the first primary side of the manifold.

8. A thermal energy transfer apparatus that removes thermal energy from a heat-generating device, the apparatus comprising:

a silicon-based base plate having a first primary side, a second primary side opposite the first primary side, a first groove on the first primary side, and a second groove on the first primary side parallel to the first groove; and

a silicon-based first fin structure and a silicon-based second fin structure, each of the first and second fin structures respectively having a first primary side and a second primary side opposite the first primary side, each of the first and second fin structures respectively further having, between the first primary side and the second primary side, a top edge, a bottom edge opposite the top edge, a front edge, and a back edge opposite the front edge,

the first primary side, the top edge, the second primary side, and the bottom edge of the first fin structure having a contiguous layer of diamond thereon,

the first primary side, the top edge, the second primary side, and the bottom edge of the second fin structure having a contiguous layer of diamond thereon,

the bottom edge of the first fin structure being received in the first groove, the bottom edge of the second fin structure being received in the second groove,

the first groove and the second groove being distanced from each other such that when the heat-generating device is received between the first fin structure and the second fin structure the heat-generating device is in direct contact with the layer of diamond on the first fin structure and with the layer of diamond on the second fin structure.

9. The apparatus of claim **8**, wherein the bottom edge of at least one of the first fin structure and the second fin structure is V-shaped, and wherein at least one of the first groove and the second groove is a V-shaped groove.

10. The apparatus of claim **8**, wherein at least one of the first and second fin structures comprises at least one coolant inlet port on one of the respective edges, at least one coolant outlet port on one of the respective edges, and a coolant flow channel therein that connects the at least one coolant inlet port and the at least one coolant outlet port to allow a coolant to flow through the respective fin structure.

11. The apparatus of claim **10**, wherein the at least one of the first and second fin structures comprises:

a silicon-based first half-fin structure, the first half-fin structure having a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure, the second primary side of the first half-fin structure having a recess, the first primary side of the first half-fin structure having an opening connecting the first primary side of the first half-fin structure and the recess on the second primary side of the first half-fin structure such that the coolant flowing in the coolant flow channel of the respective fin structure is in direct contact with the layer of diamond; and

a silicon-based second half-fin structure, the second half-fin structure having a first primary side as the second primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure, the second primary side of the second half-fin structure having a recess, the first primary side of the second half-fin structure having an opening connecting the first primary side of the second half-fin structure and the recess on the second primary side of the second half-fin structure such that the coolant flowing in the coolant flow channel of the respective fin structure is in direct contact with the layer of diamond.

12. The apparatus of claim **11**, wherein at least the first primary side of the silicon-based first half-fin structure has a surface roughness of a root mean squared (RMS) value of 2 microns or less.

13. The apparatus of claim **10**, wherein the at least one of the first and second fin structures comprises:

a silicon-based first half-fin structure, the first half-fin structure having a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure, the second primary side of the first half-fin structure having a recess; and

a silicon-based second half-fin structure, the second half-fin structure having a first primary side as the first primary side of the respective fin structure, a second primary side opposite the first primary side, a top edge as half of the top edge of the respective fin structure, a bottom edge as half of the bottom edge of the respective fin structure, a front edge as half of the front edge of the respective fin structure, and a back edge as half of the back edge of the respective fin structure, the second primary side of the second half-fin structure having a recess such that the coolant flow channel of the respective fin structure is formed when the first half-fin structure and the second half-fin structure are mated together with the second primary side of the first half-fin structure facing the second primary side of the second half-fin structure.

14. The apparatus of claim **13**, wherein at least the first primary side of the silicon-based first half-fin structure has a surface roughness of a root mean squared (RMS) value of 2 microns or less.

15. The apparatus of claim **8**, wherein the layer of diamond on at least one of the first fin structure and the second fin structure has a thickness in a range between 10 μm and 500 μm.

16. A method comprising:

polishing a first primary side of a silicon wafer;

forming a layer of diamond on the first primary side of the silicon wafer;

micromachining a second primary side of the silicon wafer that is opposite the first primary side to form at least one recess on the second primary side;

cutting the silicon wafer to provide a first half-structure such that a first primary side of the first half-structures is covered by a respective layer of diamond and a second primary side of the first half-structure that is opposite the first primary side of the half-structure has a respective one of the at least one recess; and

bonding a silicon-based second half-structure with the first half-fin structure to form a silicon-based manifold, the second half-structure having at least one coolant inlet port and at least one coolant outlet port.

17. The method of claim **16**, wherein polishing the first primary side of the silicon wafer comprises polishing the first primary side of the silicon wafer such that the first primary side of the silicon wafer has a surface roughness of a root mean squared (RMS) value of 2 microns or less.

18. The method of claim **16**, wherein forming the layer of diamond on the first primary side of the silicon wafer comprises forming, on the first primary side of the silicon wafer, a layer of diamond having a thickness in a range between 10 μm and 500 μm.

19. The method of claim **16**, wherein:

micromachining the second primary side of the silicon wafer to form at least one recess on the second primary side comprises micromachining the second primary side of the silicon wafer to form at least one recess on the second primary side such that at least a portion of the layer of diamond is exposed on the second primary side of the wafer; and

cutting the silicon wafer to provide the first half-structure such that a first primary side of the first half-structures is covered by a respective layer of diamond and a second primary side of the first half-structure has a respective one of the at least one recess comprises cutting the silicon wafer to provide the first half-structure such that the first primary side of the first half-structures is covered by the respective layer of diamond and the second primary side of the first half-structure has a respective one of the at least one recess that exposes the respective layer of diamond on the second primary side of the first half-structure.

20. The method of claim **16**, further comprising:

attaching a heat-generating device to the manifold such that the heat-generating device is in direct contact with the layer of diamond on the first primary side of the first half-structure; and

causing a coolant to flow into the manifold through the coolant inlet port and out of the manifold through the coolant outlet port to remove a portion of heat from the heat-generating device.

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