



(12) **United States Patent**
Koontz et al.

(10) **Patent No.:** **US 9,553,038 B2**
(45) **Date of Patent:** **Jan. 24, 2017**

(54) **SEMICONDUCTOR COOLING APPARATUS**

USPC 165/80.4, 46, 81, 83, 139, 144, 185;
361/698-702

(75) Inventors: **Christopher R. Koontz**, Manhattan Beach, CA (US); **Charles Chu**, Temple City, CA (US); **Rosalio S. Vidaurri**, Los Angeles, CA (US)

See application file for complete search history.

(73) Assignee: **Raytheon Company**, Waltham, MA (US)

(56) **References Cited**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 969 days.

U.S. PATENT DOCUMENTS

4,602,314 A * 7/1986 Broadbent 361/719
4,644,385 A 2/1987 Nakanishi et al.
4,747,450 A 5/1988 Ikegame et al.
4,759,403 A * 7/1988 Flint et al. 165/80.4

(Continued)

(21) Appl. No.: **13/558,759**

FOREIGN PATENT DOCUMENTS

(22) Filed: **Jul. 26, 2012**

EP 1739746 A2 1/2007
EP 2437293 A2 4/2012

(65) **Prior Publication Data**

US 2013/0255917 A1 Oct. 3, 2013

(Continued)

Related U.S. Application Data

Primary Examiner — Judy Swann

(60) Provisional application No. 61/619,153, filed on Apr. 2, 2012.

Assistant Examiner — Jose O Class-Quinones

(74) *Attorney, Agent, or Firm* — Burns & Levinson LLP; Joseph M. Maraia

(51) **Int. Cl.**

F28F 7/00 (2006.01)
H01L 23/433 (2006.01)
H01L 23/473 (2006.01)

(57) **ABSTRACT**

An apparatus for cooling semiconductor elements uses heat exchangers to transfer heat from the semiconductor elements to a coolant flowing through the heat exchangers. A central body, made from a flexible material, is positioned between the heat exchangers and a manifold from which the coolant is provided. The central body includes a plurality of flexible runners fluidly coupled to each heat exchanger and the manifold to provide the coolant to the heat exchanger. Heat is transferred away from the semiconductor elements by the coolant and heated coolant is returned from the heat exchanger to the manifold. Each flexible runner is configured to flex to conform to a height of a respective semiconductor element and thereby apply a force to the heat exchanger to maintain contact with the semiconductor element.

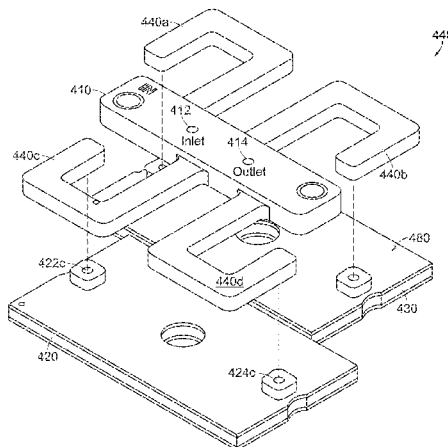
(52) **U.S. Cl.**

CPC **H01L 23/4332** (2013.01); **H01L 23/473** (2013.01); **H01L 2924/0002** (2013.01); **H01L 2924/15311** (2013.01)

(58) **Field of Classification Search**

CPC F28D 2021/0028; F28D 2021/0029; F28D 15/00; H01L 23/4332; H01L 23/34; H01L 23/36; H01L 23/367; H01L 23/3672; H01L 23/373; H01L 23/473; H01L 23/467; H01L 23/40; H01L 23/4006; H01L 23/46; H05K 7/20218; H05K 7/20336; H05K 7/20254; H05K 7/20263; H05K 7/20454; F28F 3/02; F28F 13/00

24 Claims, 11 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

4,977,444	A	12/1990	Nakajima et al.	
5,125,451	A	6/1992	Matthews	
5,150,274	A	9/1992	Okada et al.	
5,166,863	A	11/1992	Shmunis	
5,329,419	A	7/1994	Umezawa	
5,388,635	A *	2/1995	Gruber et al.	165/80.4
6,111,749	A	8/2000	Lamb et al.	
6,212,074	B1	4/2001	Gonsalves et al.	
6,587,345	B2 *	7/2003	Chu et al.	361/719
6,595,270	B2	7/2003	Machiroutu et al.	
6,778,393	B2	8/2004	Messina et al.	
6,867,973	B2	3/2005	Chang	
6,970,355	B2	11/2005	Ellsworth, Jr. et al.	
7,167,366	B2 *	1/2007	Cheon	361/699
7,515,418	B2	4/2009	Straznicky et al.	
7,624,791	B2	12/2009	Strobel et al.	
7,652,884	B2	1/2010	Suzuki et al.	
2005/0180107	A1 *	8/2005	Naganawa et al.	361/699
2006/0261469	A1	11/2006	Ni et al.	
2007/0000655	A1	1/2007	Uchida et al.	
2007/0091570	A1 *	4/2007	Campbell et al.	361/699
2009/0108429	A1	4/2009	Tsao et al.	
2012/0080785	A1	4/2012	Johnson et al.	

FOREIGN PATENT DOCUMENTS

JP	61226946	10/1986
JP	62118553	5/1987
WO	2010096355 A2	8/2010
WO	2011017385 A1	2/2011
WO	2011038184 A1	3/2011
WO	2011044445 A1	4/2011

* cited by examiner

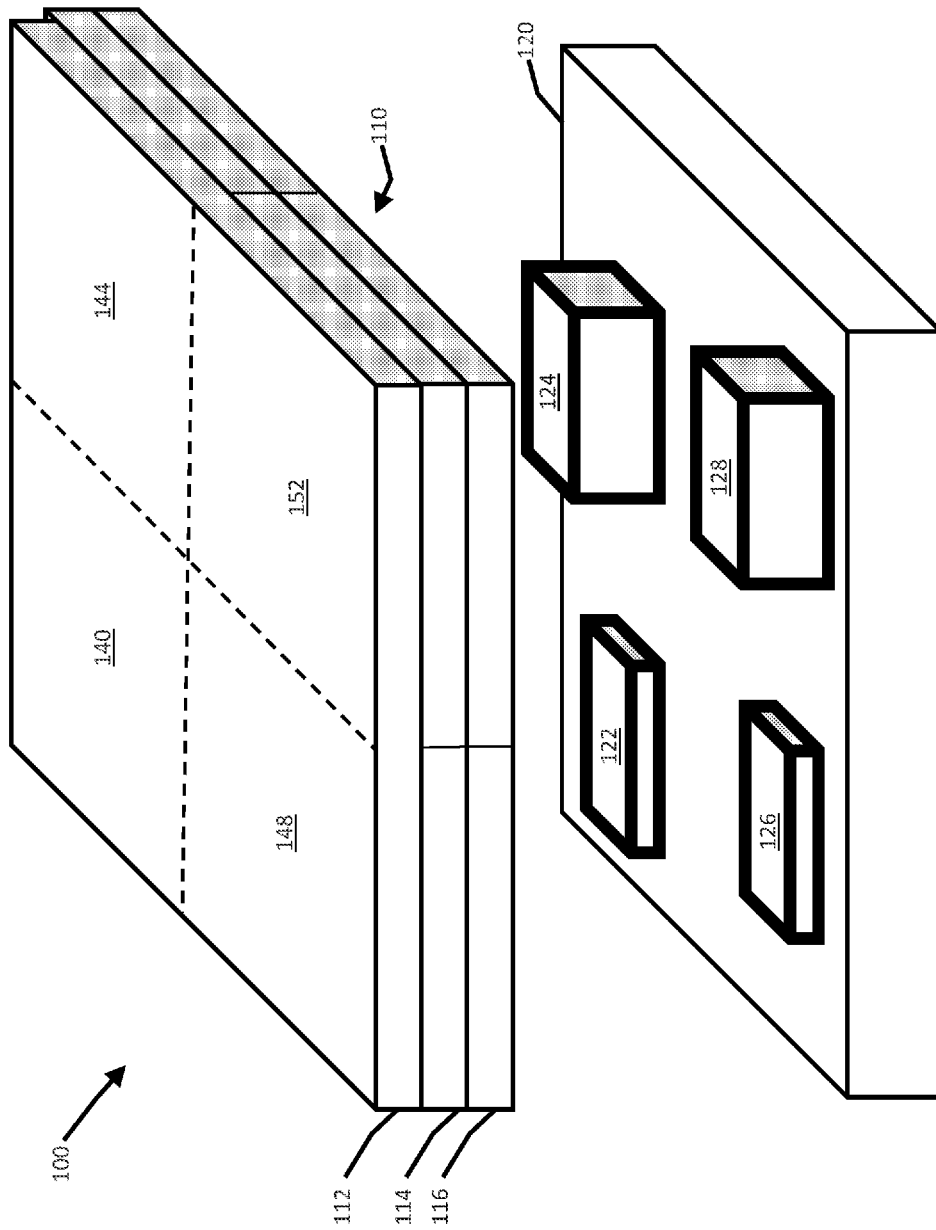


FIG. 1

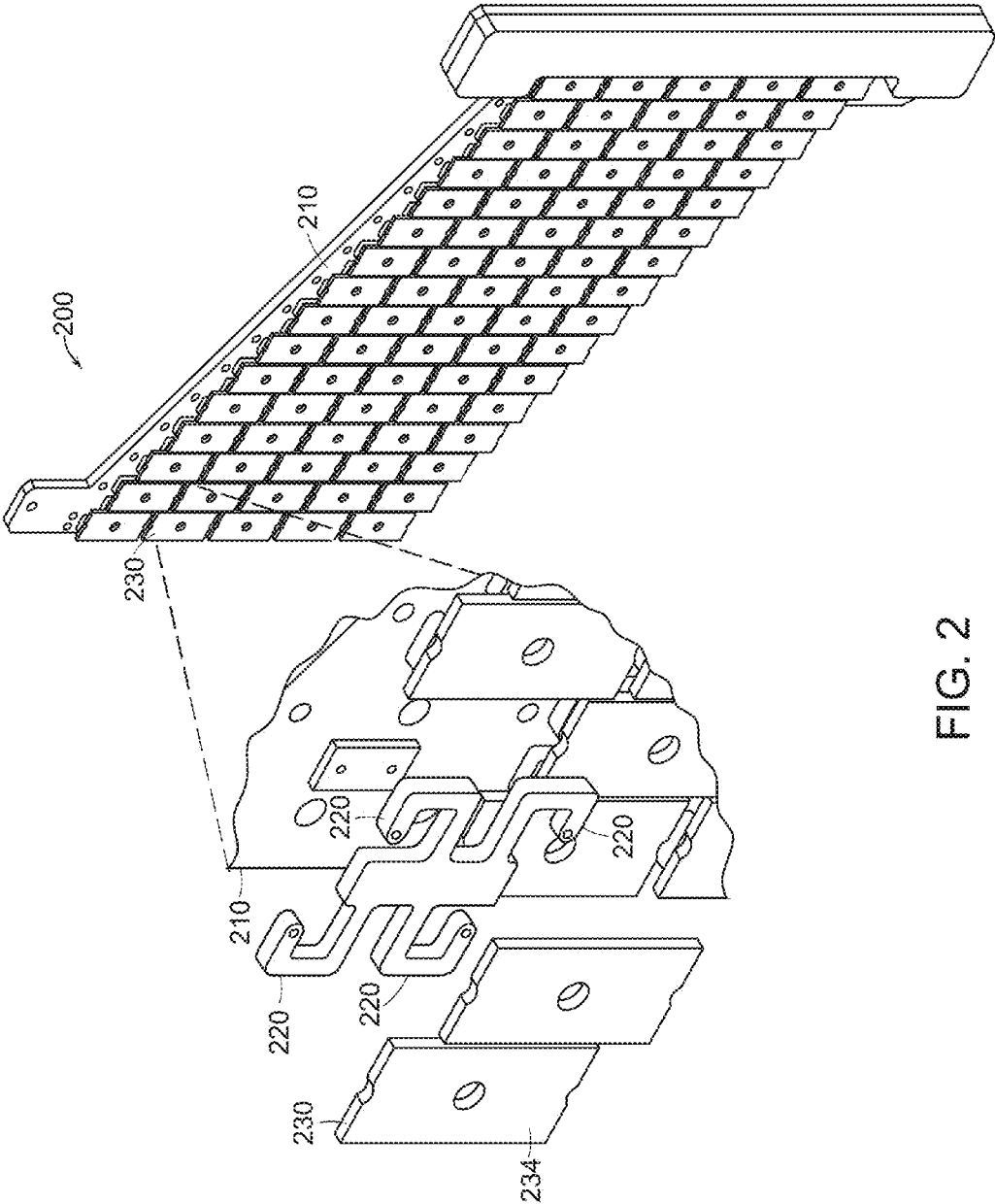


FIG. 2

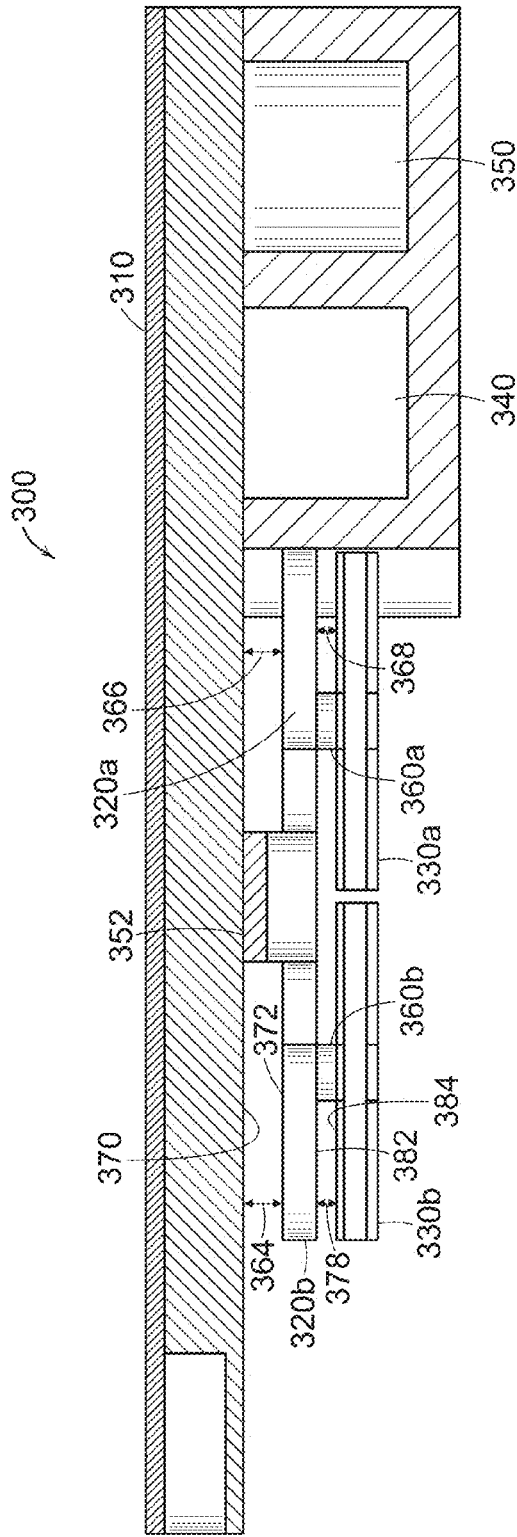


FIG. 3

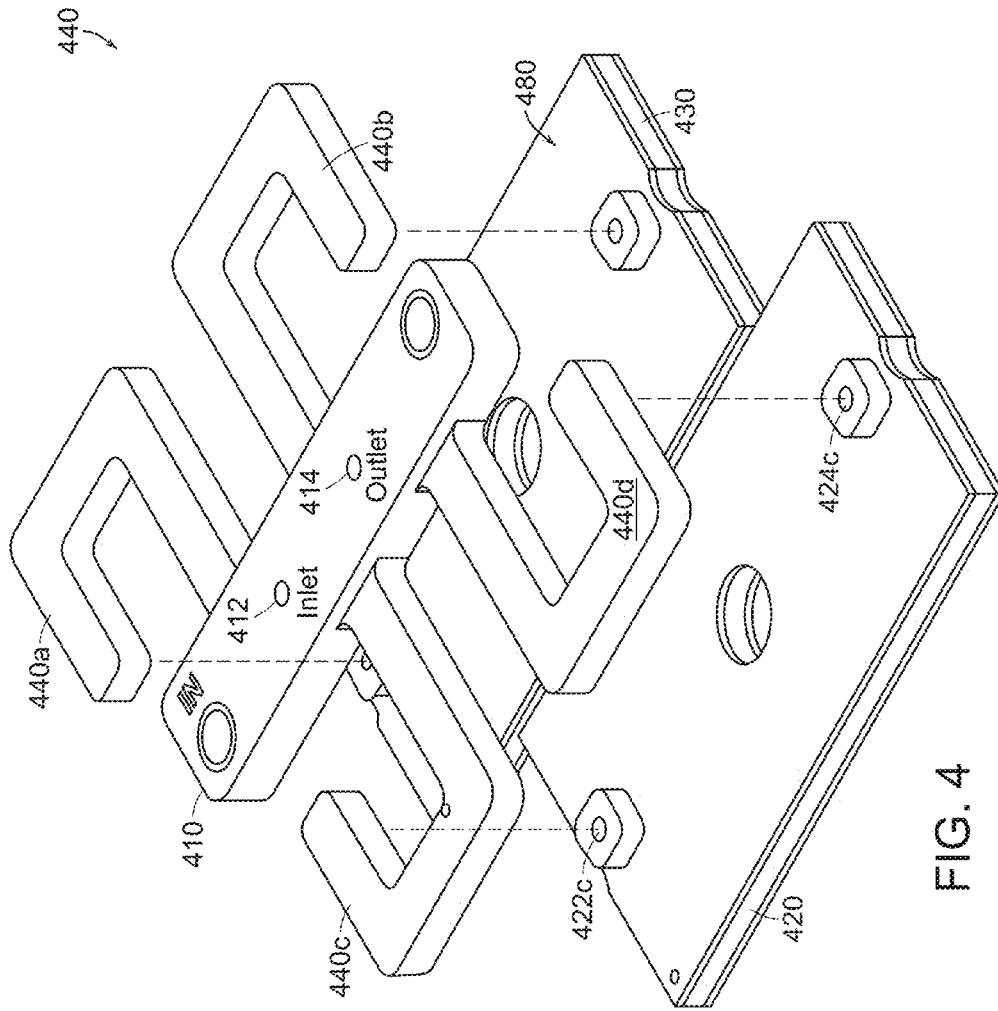


FIG. 4

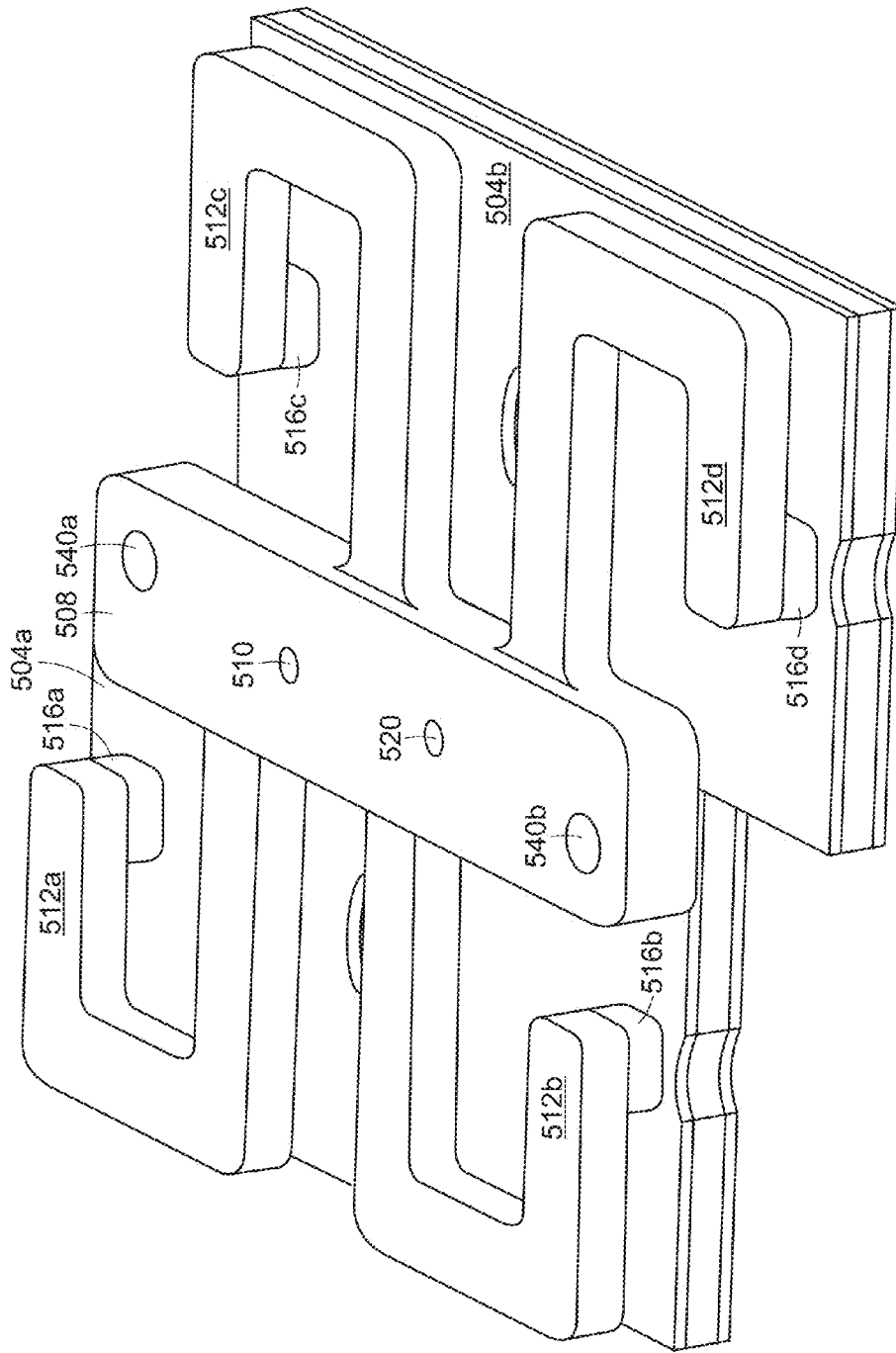


FIG. 5A

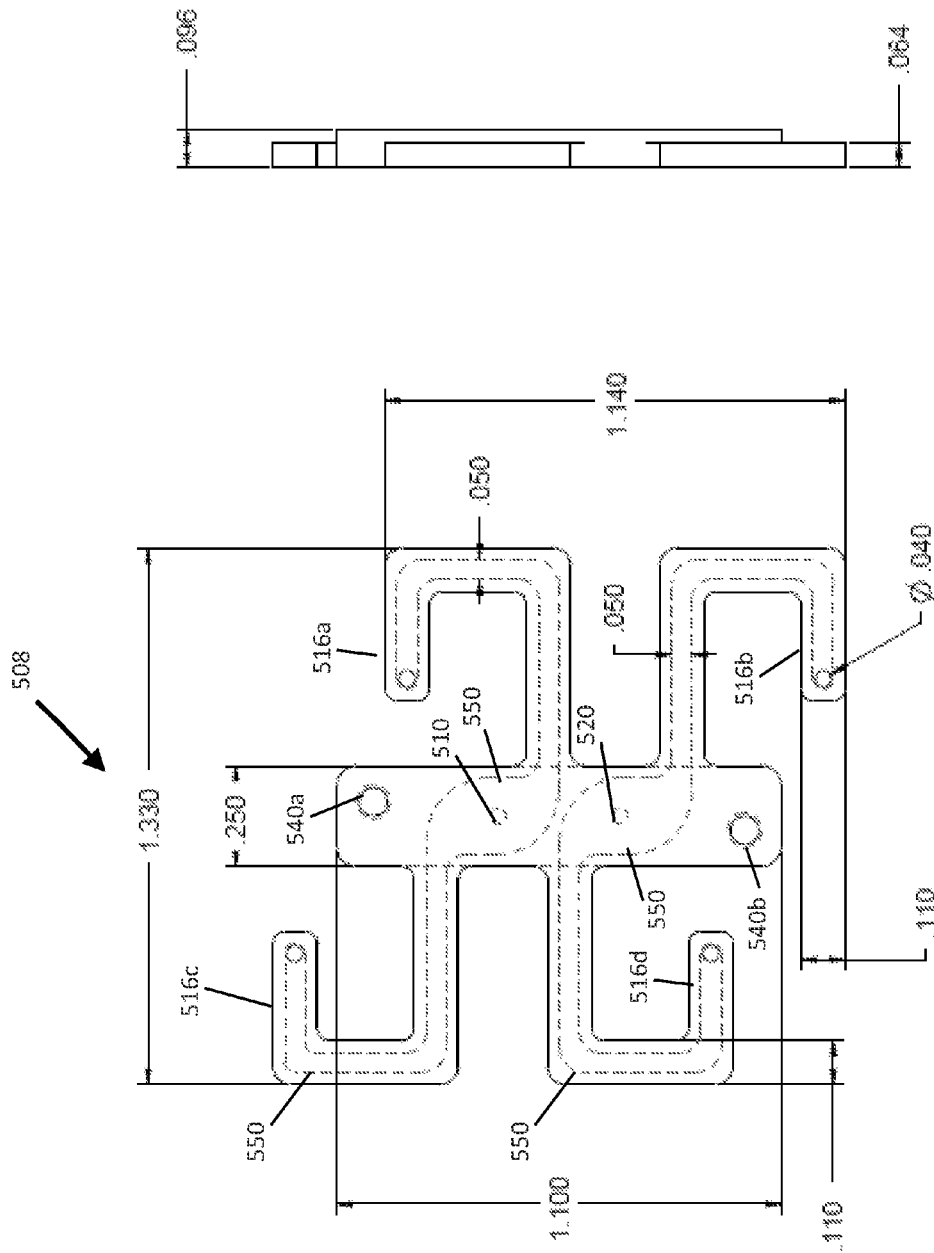


FIG. 5B

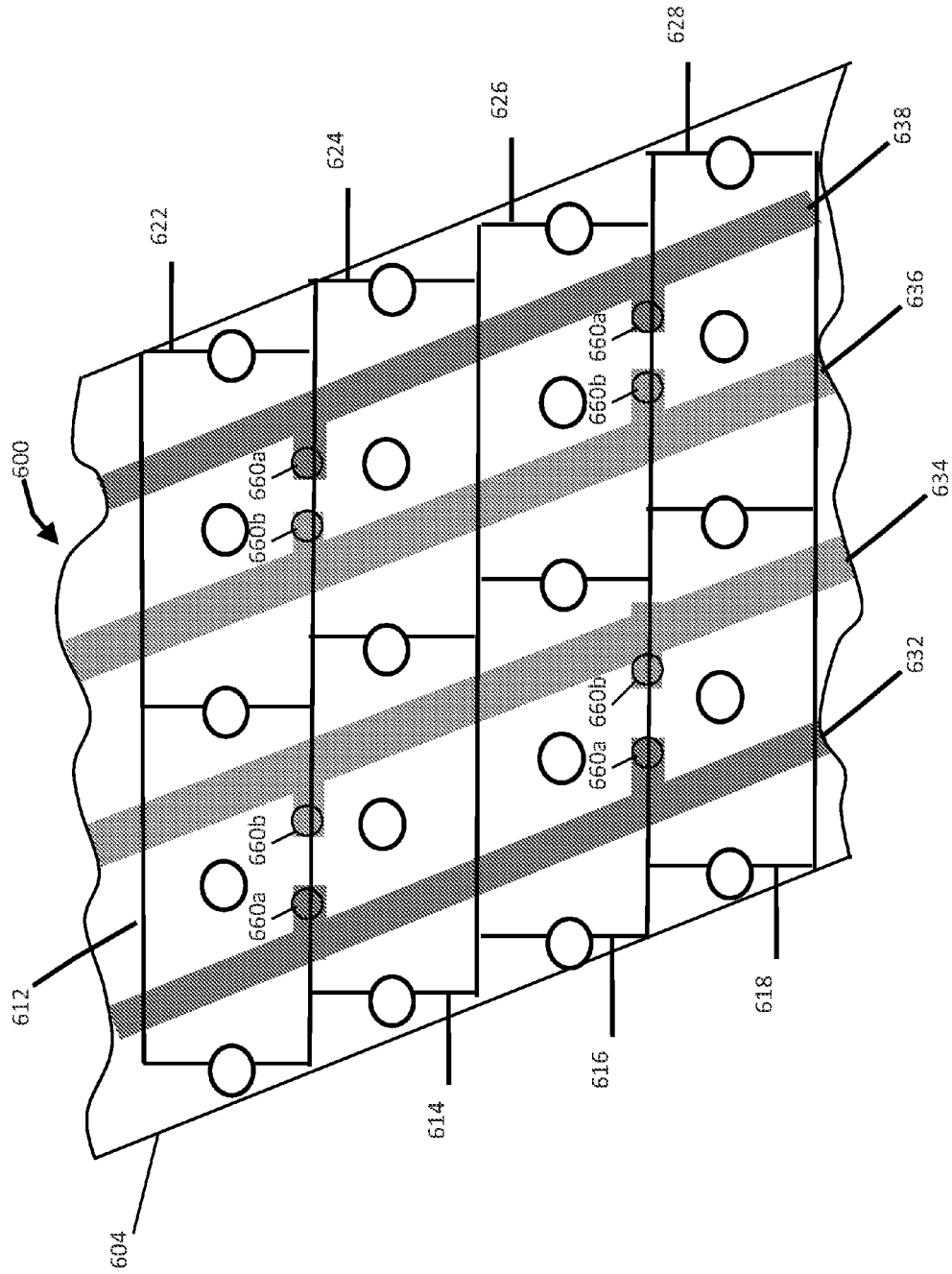


FIG. 6

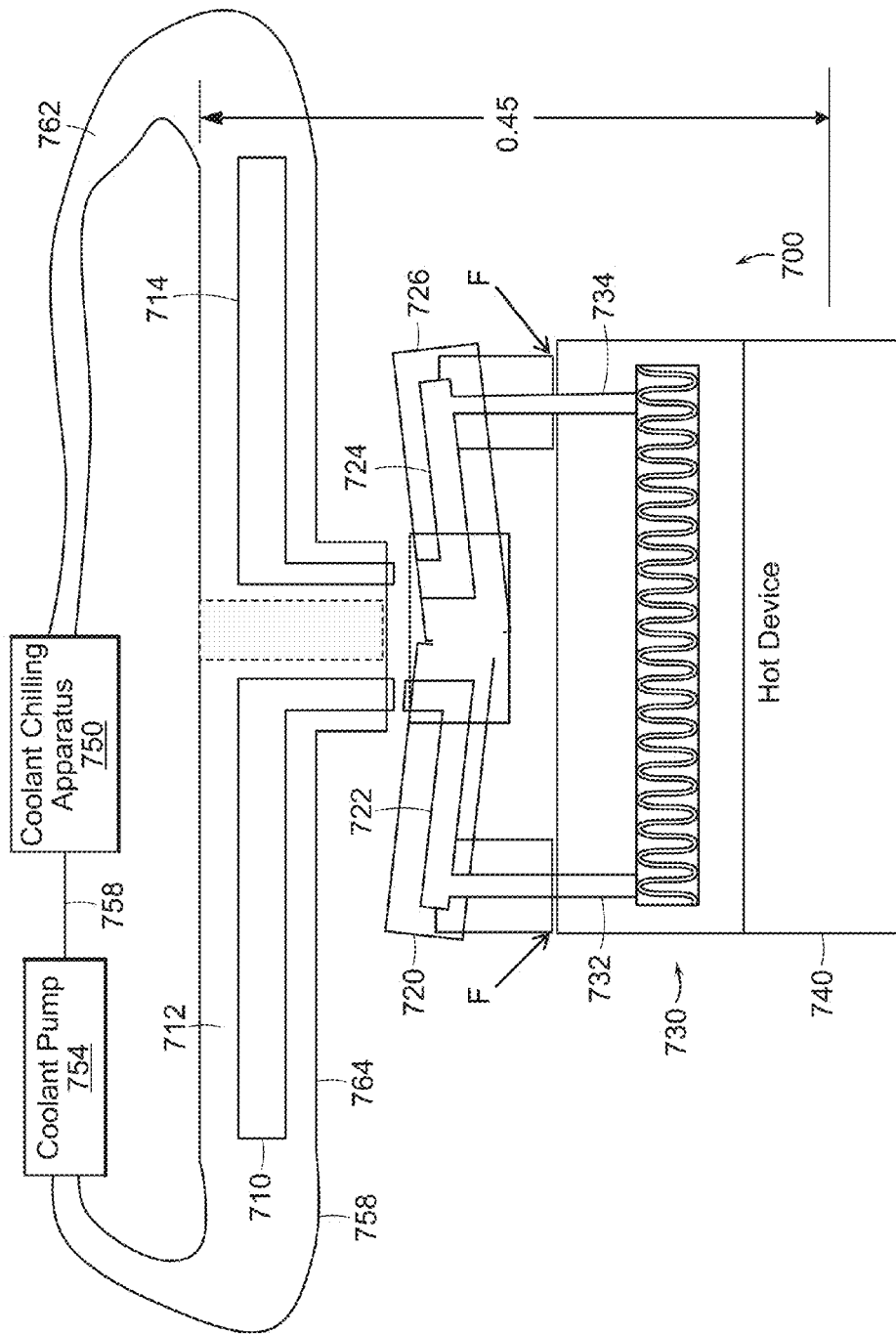


FIG. 7

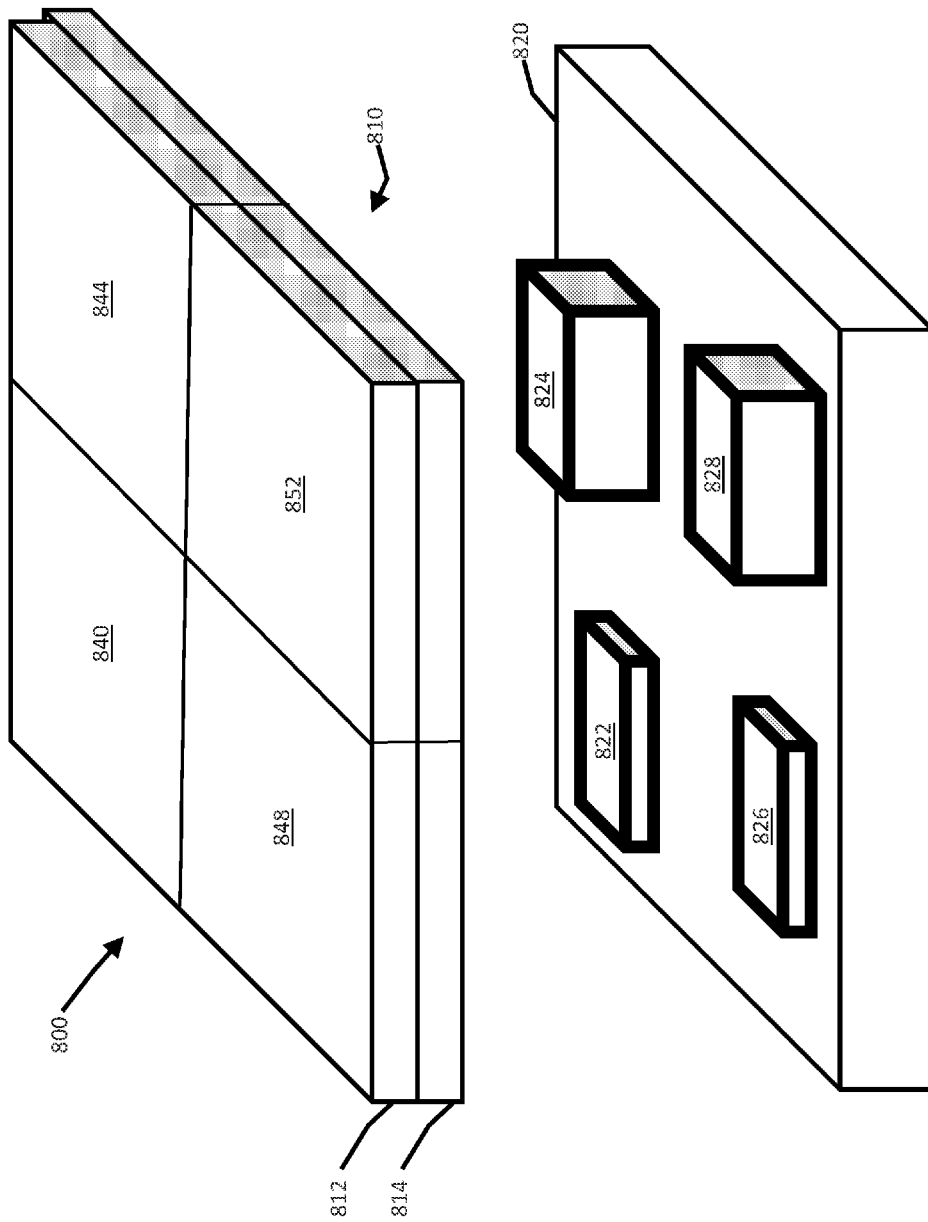


FIG. 8

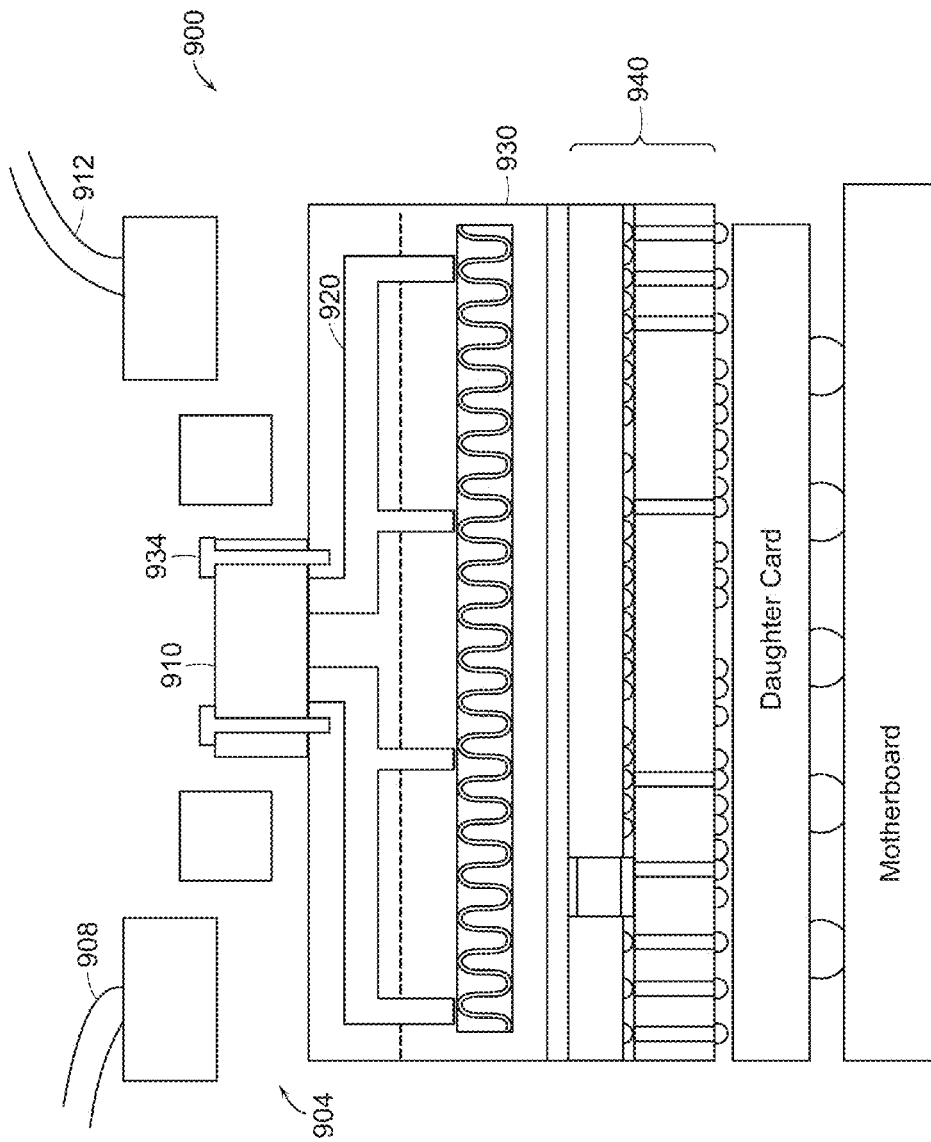


FIG. 9

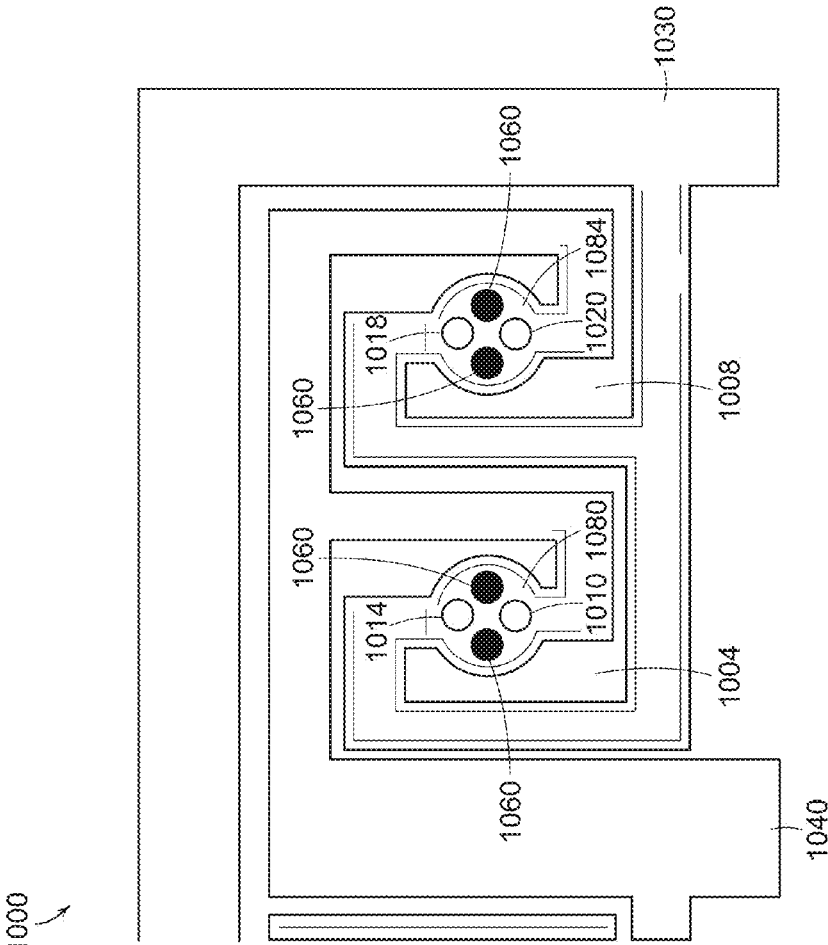


FIG. 10

SEMICONDUCTOR COOLING APPARATUS

RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Patent Application No. 61/619,153, filed Apr. 2, 2012, which is incorporated in its entirety herein by reference.

GOVERNMENT SUPPORT

The invention was supported, in whole or in part, by a grant, Contract No. FA8650-04-G-0002-0001 from the U.S. Air Force. The U.S. Government may have certain rights in the invention.

BACKGROUND

A flat aluminum brazed monolithic cooling apparatus can be used with highly conformal low thermal performance heat spreaders, such as a gap pad or gap filler material, to accommodate vertical height variations in semiconductors and individual variations in planarity with respect to the cooling apparatus surface. After the individual semiconductors are attached to an array, the semiconductor height variations can be mapped for the entire array in order to select custom heat spreaders for each semiconductor element. This solution, generally, is effective for planar arrays, but, generally, this solution is not effective for semiconductor arrays with various vertical height variations due to the inefficiency of the heat spreaders and the difficulties of accurately mapping and fitting the custom heat spreaders. Thus, a need exists in the art for a semiconductor cooling apparatus with the features as described herein.

SUMMARY

One approach to a semiconductor cooling apparatus includes a thermal assembly configured to thermally couple to an array of semiconductor elements. The assembly includes a plurality of heat exchangers configured to transfer heat from the semiconductor elements to coolant flowing through the heat exchangers. The assembly also includes a plurality of supply flexible runners and return flexible runners, a supply flexible runner coupled to each heat exchanger for providing coolant to the respective heat exchanger and a return flexible runner coupled to each heat exchanger for exhausting returned coolant from the respective heat exchanger, each flexible runner flexing to conform to a height of a respective semiconductor element and apply a force to the respective heat exchanger to maintain contact of the heat exchanger with the respective semiconductor element. The assembly also includes a manifold coupled to the plurality of supply flexible runners and the plurality of return flexible runners, the manifold for supplying coolant to the supply flexible runners and for exhausting returned coolant received from the return flexible runners.

Any of the approaches described herein can include one or more of the following examples. In some examples, the manifold has an input that is coupled to a coolant supply line and an output that is coupled to a coolant return line. In some examples, the assembly includes a coolant chilling apparatus coupled to the coolant supply line and the coolant return line and configured to chill coolant, and also includes a coolant pump configured to pump the coolant between the coolant chilling apparatus and the thermal assembly.

In some examples, the plurality of supply and return flexible runners are located over the heat exchangers. In

some examples, the manifold is located over the plurality of supply and return flexible runners. In some examples, a spring constant of each flexible runner is defined based on one or more of wall thickness of the respective flexible runner, material type of the respective flexible runner, or a geometric property of the respective flexible runner. In some examples, the apparatus includes aluminum, copper, stainless steel, titanium, alloys thereof, plastic, semiconductor fabrication materials, or any combination thereof.

In some examples, each heat exchanger is coupled to a respective semiconductor element as a packaging lid or packaging body for the respective semiconductor element.

Another approach to a semiconductor cooling apparatus includes a thermal assembly configured to thermally couple to a semiconductor element. The assembly includes a heat exchanger configured to transfer heat from the semiconductor element to coolant flowing through the heat exchanger. The assembly also includes at least one flexible runner coupled to the heat exchanger for providing coolant to the heat exchanger and for exhausting returned coolant from the heat exchanger, the at least one flexible runner flexes to conform to a height of the semiconductor element and apply a force to the heat exchanger to maintain contact of the heat exchanger with the semiconductor element. The assembly also includes a manifold coupled to the at least one flexible runner for supplying coolant to the at least one flexible runner and for exhausting returned coolant received from the at least one flexible runner.

In some examples, the at least one flexible runner includes a supply conduit and a return conduit within the at least one flexible runner, where the supply conduit provides coolant to the heat exchanger and the return conduit exhausts returned coolant from the heat exchanger. In some examples, the thermal assembly includes at least one supply flexible runner and at least one return flexible runner, where the at least one supply flexible runner provides coolant to the heat exchanger and the at least one return flexible runner exhausts returned coolant from the heat exchanger.

In some examples, the manifold has an input that is coupled to a coolant supply line and an output that is coupled to a coolant return line. In some examples, the apparatus includes a coolant chilling apparatus coupled to the coolant supply line and the coolant return line and configured to chill coolant, and a coolant pump configured to pump the coolant between the coolant chilling apparatus and the thermal assembly.

In some examples, the at least one flexible runner is located over the heat exchanger. In some examples, the manifold is located over the at least one flexible runner. In some examples, a spring constant of the flexible runner is defined based on one or more of wall thickness of the flexible runner, material type of the flexible runner, or a geometric property of the flexible runner. In some examples, the heat exchanger is coupled to the semiconductor element as a packaging lid for the semiconductor element.

Another approach to a semiconductor cooling apparatus includes a thermal assembly configured to thermally couple to an array of semiconductor elements. The assembly includes a plurality of heat exchangers configured to transfer heat from the semiconductor elements to coolant flowing through the heat exchangers. The assembly also includes a flexible manifold for supplying coolant to the heat exchangers and for exhausting returned coolant received from the heat exchangers, where the flexible manifold flexes to conform to a height of a stackup of each semiconductor element, and a respective heat exchanger, to apply a force to the stackup to maintain contact of the heat exchanger with the

3

respective semiconductor element. In some examples, the manifold is located over the heat exchangers.

Another approach to a semiconductor cooling apparatus includes a thermal assembly configured to thermally couple to a semiconductor element. The assembly includes a heat exchanger configured to transfer heat from the semiconductor element to coolant flowing through the heat exchanger. The assembly also includes a flexible manifold for supplying coolant to the heat exchanger and for exhausting returned coolant received from the heat exchanger, where the flexible manifold flexes to conform to a height of a stackup of the semiconductor element and the heat exchanger, to apply a force to the stackup to maintain contact of the heat exchanger with the semiconductor element.

Another approach to a cooling apparatus includes a thermal assembly configured to thermally couple to an array of objects. The assembly includes a plurality of heat exchangers configured to transfer heat from the objects to coolant flowing through the heat exchangers. The assembly also includes a plurality of supply flexible runners and return flexible runners, a supply flexible runner coupled to each heat exchanger for providing coolant to the respective heat exchanger and a return flexible runner coupled to each heat exchanger for exhausting returned coolant from the respective heat exchanger, each flexible runner flexing to conform to a height of a respective object and apply a force to the respective heat exchanger to maintain contact of the heat exchanger with the respective object. The assembly also include a manifold coupled to the plurality of supply flexible runners and the plurality of return flexible runners, the manifold for supplying coolant to the supply flexible runners and for exhausting returned coolant received from the return flexible runners.

The cooling methods and systems described herein (hereinafter “technology”) can provide one or more of the following advantages. One advantage of the technology is that the flexibility in the cooling apparatus advantageously increases the heat transfer between the semiconductor element and the cooling apparatus, thereby extending the life of the semiconductor element by promoting proper cooling of the semiconductor element. The flexibility of the cooling apparatus advantageously reduces the installation time and cost by removing any needed individual customizations due to, for example, differences in height of semiconductor elements or mechanical assembly tolerances, thereby decreasing the overall cost of the devices associated with the semiconductor element while increasing the heat transfer. The compact geometry of the cooling apparatus components advantageously allows for tighter spacing between semiconductor elements and/or other components of the devices associated with the semiconductor elements.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages will be apparent from the following more particular description of the embodiments, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the embodiments.

FIG. 1 is a block diagram of an exemplary semiconductor cooling apparatus and semiconductor array.

FIG. 2 is an illustration of another exemplary semiconductor cooling apparatus.

FIG. 3 is an illustration of another exemplary semiconductor cooling apparatus.

4

FIG. 4 is a view of exemplary heat exchangers and flexible runners of a cooling apparatus.

FIG. 5A is an illustration of heat exchangers and flexible runners of another exemplary semiconductor cooling apparatus.

FIG. 5B is an illustration of the flexible runners of FIG. 5A.

FIG. 6 is an illustration of an exemplary coolant flow path in a semiconductor cooling apparatus.

FIG. 7 is a cross-sectional view of an assembled semiconductor cooling apparatus, according to an illustrative embodiment.

FIG. 8 is a block diagram of an exemplary semiconductor cooling apparatus and semiconductor array.

FIG. 9 is a cross-sectional view of an assembled semiconductor cooling apparatus, according to an illustrative embodiment.

FIG. 10 is a top view of a flexible manifold of an exemplary cooling apparatus.

DETAILED DESCRIPTION

Semiconductor elements, such as a ball grid array (BGA), can be used as part of aerospace sensor architectures and/or other semiconductor architectures. In most instances, each of the semiconductor elements is soldered to a primary circuit board (e.g., motherboard, array, etc.) creating the semiconductor array. Due to the size, spacing, and thermal properties of the semiconductor elements on the array, a semiconductor cooling apparatus is needed to quickly and efficiently transfer heat from the array. However, each element in the semiconductor array can have different packaging and manufacturing tolerances, making it difficult to effectively transfer heat from each element.

Thus, the semiconductor cooling apparatus, as described herein, includes thermal assemblies, where each thermal assembly can be configured to thermally couple to semiconductor elements having different height stackups. Advantageously, each cooling element of a thermal assembly can independently flex to conform to the height of a respective semiconductor element (e.g., a math coprocessor is 0.02 inches high and a video processor is 0.04 inches high, an input/output processor is 0.023 inches high and an encryption processor is 0.034 inches high, etc.), thereby increasing the thermal transfer between the semiconductor elements and the thermal assemblies.

FIG. 1 is a block diagram **100** of an exemplary semiconductor cooling apparatus **110** and semiconductor array **120** (e.g., ball grid array (BGA), computer motherboard, etc.). The semiconductor cooling apparatus **110** includes a plurality of cooling elements **140**, **144**, **148**, and **152**. The semiconductor array **120** includes a thermal assembly that has semiconductor elements of various heights, widths, and lengths **122**, **124**, **126**, and **128**. Each cooling element **140**, **144**, **148**, and **152** of the semiconductor cooling apparatus **110** is configured to thermally couple (e.g., positioned near each other to enable thermal transfer, positioned near each other to maximize thermal transfer, etc.) to a respective semiconductor element **122**, **124**, **126**, and **128** of the array of semiconductor elements **120**. The cooling apparatus **110** includes a plurality of heat exchangers **116**, a plurality of flexible runners **114**, and a manifold **112**, described further in detail below.

As illustrated in FIG. 1, at least two of the semiconductor elements **122**, **124**, **126**, and **128** have a different height (e.g., with respect to the top of the semiconductor mounting surface, with respect to the bottom of the semiconductor

cooling apparatus **110**, with respect to each other, etc.). In operation, each cooling element **140**, **144**, **148**, and **152** independently flexes to conform to the height of the respective semiconductor element **122**, **124**, **126**, and **128**, respectively (e.g., the cooling elements flex from 0.001 to 0.009 inches, the cooling elements flex from 0.01 to 0.09 inches, etc.). For example, the cooling element **140** flexes independently from the other cooling elements **144**, **148**, and **152** to conform to the height of the semiconductor element **122**.

The independent flexibility of each cooling element advantageously increases the heat transfer between the semiconductor element and the cooling element, thereby extending the life of the semiconductor element by promoting proper cooling of the semiconductor element. The independent flexibility of each cooling element advantageously reduces the installation time and cost by removing any needed individual customizations, thereby decreasing the overall cost of the devices associated with the semiconductor element while increasing the heat transfer.

In some examples, the flexible properties of each cooling element **140**, **144**, **148**, and **152** reduces a thermal resistance interface between the cooling element **140**, **144**, **148**, and **152** and the respective semiconductor element **122**, **124**, **126**, and **128**. For example, the cooling element **140** flexes 0.030 inches to be in contact with the respective semiconductor element **122**, and the cooling element **144** flexes 0.002 inches to be in contact with the respective semiconductor element **124**. The independent flexibility of each cooling element **140**, **144**, **148**, and **152** advantageously enables the thermal resistance interface to be reduced (e.g., reduced thermal penalty from 20° C. to 10° C.; reduced thermal penalty from 8° C. to 3.2° C., etc.), thereby increasing the efficiency of the semiconductor cooling apparatus and increasing the life of the semiconductor elements.

In some examples, the semiconductor cooling apparatus can be produced using aluminum, copper, stainless steel, titanium, alloys thereof, and/or material with high heat transfer (e.g., Glidcop® available from SCM Metal Products, Inc., a copper alloy, etc.). In some examples, the semiconductor cooling apparatus can be produced using plastic material or semiconductor fabrication materials (e.g., silicon).

FIG. 2 is an illustration of another exemplary semiconductor cooling apparatus **200**. The cooling apparatus **200** includes a thermal assembly that has a plurality of heat exchangers **230**, a plurality of flexible runners **220**, and a manifold **210**. When installed, a surface **234** of each heat exchanger **230** is coupled to, or otherwise in contact with, a corresponding surface on a semiconductor element (e.g., element **122** of FIG. 1). The heat exchangers **230** are configured to transfer heat from the semiconductor elements to coolant flowing through the heat exchangers **230**.

The flexible runners **220** are coupled to a respective heat exchanger **230** for providing coolant to the respective heat exchanger **230**. The flexible runners **220** also exhaust returned coolant (e.g., heated coolant) from the heat exchangers **230**. The flexible runners **220** flex to conform to a height of a respective semiconductor element in contact with a respective heat exchanger **230** and apply a force to the heat exchanger **230** to maintain contact of the heat exchanger **230** with the semiconductor element.

The manifold **210** of the cooling apparatus **200** is coupled to the plurality of flexible runners **220**. The manifold **210** supplies coolant to the flexible runners **220** and exhausts returned coolant from the flexible runners **220**. In this embodiment, the manifold **210** is a unitary body that provides coolant to, and exhausts returned coolant from, each of

the plurality of flexible runners **220** and heat exchangers **230**. In some embodiments, the manifold **210** includes a plurality of manifolds, where a manifold provides coolant to a subset of the flexible runners and heat exchangers and also exhausts returned coolant from the subset of flexible runners.

Although FIG. 2 illustrates the heat exchangers **230** as having a generally rectangular shape and the flexible runners having a particular circuitous shape, alternate examples of these components of the semiconductor cooling apparatus **200** can have different shapes and/or relative dimensions. For example, the semiconductor cooling apparatus could include heat exchangers having square or circular shapes.

FIG. 3 is a cross-sectional view of another exemplary cooling apparatus **300**. The apparatus **300** includes a manifold **310** that has an input **340** and an output **350**. The input **340** is coupled to a coolant supply line (not shown) that provides coolant to the manifold **310**. The output **350** is coupled to a coolant return line (not shown) that exhausts returned coolant (e.g., coolant that has been heated in the heat exchanger).

Internal passages in the manifold **310** are used to transport the coolant to and from the flexible runners **320a** and **320b** (generally **320**). The flexible runners **320** are coupled to the heat exchangers **330a** and **330b** (generally **330**). The cooling apparatus **300** also includes several risers **352**, **360a**, and **360b** that maintain gaps between the different components of the cooling apparatus **300** so the flexible runners are able to conform to the different heights of the semiconductor elements (not shown) and apply force to heat exchangers in contact with the semiconductor elements. Riser **352** sets gaps **364** and **366** between a surface **370** of the manifold **310** and a surface **372** of the flexible runners **320a** and **320b**, respectively. The gaps **364** and **366** are shown as being the same size; however, the gaps will not necessarily be the same. The two gaps may have different sizes; depending on, for example, the relative heights of semiconductor elements contacting the heat exchangers abutting the flexible runners. Risers **360a** and **360b** set gaps **368** and **378** between a surface **382** of the flexible runners **320** and a surface **384** of the heat exchangers **330**. Again, the gaps **368** and **378** are shown as being the same size; however, the gaps will not necessarily be the same. The two gaps may have different sizes; depending on, for example, the relative heights of semiconductor elements contacting the heat exchangers abutting the flexible runners.

The risers **352**, **360a**, and **360b** also carry coolant through interior passages in the risers. The manifold **310** provides coolant to the flexible runners **320** via the interior passages of riser **352**. Returned fluid coming from the flexible runners **320** is also exhausted through an interior passage of riser **352** to the manifold **310** to be subsequently exhausted from the manifold via output **350**. Flexible runner **320a** provides coolant to heat exchanger **330a** via interior passages in the riser **360a**, and heat exchanger **330a** exhausts returned coolant to the flexible runner **320a** via a different interior passage of riser **360a**. Similarly, flexible runner **320b** provides coolant to heat exchanger **330b** via interior passages in the riser **360b**, and heat exchanger **330b** exhausts returned coolant to the flexible runner **320b** via a different interior passage of riser **360b**.

FIG. 4 is a view of exemplary heat exchangers **420** and **430** and flexible runners **440a**, **440b**, **440c**, and **440d** (generally **440**) of a cooling apparatus. The flexible runners **440** are united by a central body **410**; however, in some embodiments, no central body is required. As shown in FIG. 4 (and FIGS. 5A and 5B) each of the flexible runners **440** extends

from the central body in a J-shaped pattern. The flexible runner body **410** has an inlet **412** and an outlet **414**. The flexible runner body **410** includes markings that identify the inlet and outlet (marked, as “inlet” and “outlet”, respectively). The markings can be made using, for example, indelible ink or they can be etched. Additional markings can be used in this embodiment, and other embodiments, to identify the function, orientation, or how various components should be assembled for proper use. Coolant is supplied to the inlet **412** by a manifold (e.g., the manifold **210** of FIG. 2). Coolant flows through the interior of the flexible runners **440**. For example, in this embodiment, coolant enters inlet **412** and then flows through supply flexible runner **440c** and supply flexible runner **440a**. Supply flexible runner **440c** provides coolant to inlet **422c** of heat exchanger **420**. The heat exchangers **420** and **430** are shown with a face sheet **480** that seals the heat exchangers, therefore, the interior structure of the exemplary heat exchangers are not visible. The coolant flows through the interior passages of the heat exchanger **420** and exits the heat exchanger **420** at outlet **424c**. The returned coolant exiting outlet **424c** enters an inlet of return flexible runner **440d**. The coolant flows through the return flexible runner **440d** to the central body **410** where it then exits outlet **414**. The returned coolant exiting outlet **414** is provided to the manifold.

FIG. 5A is an illustration of another exemplary assembly **500** of flexible runners and heat exchangers for a semiconductor cooling apparatus. The assembly **500** includes two heat exchangers **504a** and **504b** (generally **504**). The assembly **500** also includes a flexible runner assembly **508** that includes four flexible runners **512a**, **512b**, **512c**, and **512d** (generally **512**). The assembly **500** also includes four risers **516a**, **516b**, **516c**, **516d** (generally **516**) that establish a gap between the heat exchangers **504** and the flexible runners **512**, similarly as described previously with respect to FIG. 3. The risers **516** are attached to the heat exchangers **504** and have holes through the body of the risers **516** that couple fluid passages in the flexible runners **512** to fluid passages within the heat exchangers **504**. In some embodiments, the risers are attached or otherwise installed on the heat exchangers, flexible runners and/or manifolds.

The assembly **500** also includes two thru-holes **540a** and **540b** in the flexible runner assembly **508**. Screws (not shown) are inserted through the thru-holes **540a** and **540b** and screwed into corresponding threaded holes in the manifold (not shown). The flexible runners **512** are coupled to the risers **516** by diffusion bonding or some other suitable bonding or attachment method (e.g., friction welding, brazing, adhesive bonding or by screws). By coupling the flexible runner assembly **508** to the heat exchangers **504**, a fluid seal is formed between the flexible runners **512**, the risers **516** and the heat exchangers **504**, thereby creating a sealed fluid path between the three components. In some embodiments, the interfaces between the three components include o-rings, adhesive, or any other suitable material to create fluid seals to contain the coolant within the components during use.

The assembly **500** also includes an inlet **510** and outlet **520** in the flexible runner assembly **508**. The inlet **510** receives coolant supplied by a manifold (not shown), for example, the manifold **310** of FIG. 3. Coolant flows into the inlet **510** and through the supply flexible runner **512a** where it is passed to the heat exchanger **504a**. The coolant flowing through the heat exchanger **504a** absorbs the heat of a semiconductor element in contact with the heat exchanger **504a**. The heated coolant is then returned by exhausting the returned coolant from the heat exchanger **504a** to the return

flexible runner **512b**. The return flexible runner **512b** then conveys the returned coolant to the outlet **520** where it is exhausted to the manifold. A similar process occurs with flexible runners **512c**, **512d**, and heat exchanger **504b**.

FIG. 5B is an illustration of the flexible runner assembly **508** of FIG. 5A. The figures depict the interior passages **550** within the flexible runners **512** that supply coolant to the heat exchangers **504** and exhaust returned coolant from the heat exchangers **504**. The force generated by a flexible runner to a heat exchanger **504** can be varied based on one or more of a variety of design parameters. If the deformation of a flexible runner is elastic, the force is a function of the spring constant of the flexible runner **512** and the displacement of the flexible runner **512** (e.g., in accordance with $F=kx$, where F is the force, k is the spring constant, and x is the displacement). The spring constant can be changed or specified based on, for example, the material type of the flexible runner **512**, the wall thickness of the flexible runner **512**, or another geometric property of the flexible runner **512** (e.g., length, width, thickness). In some embodiments, the runners **512** may be designed for plastic deformation instead of elastic deformation.

FIG. 6 is an illustration **600** of a portion of exemplary coolant flow paths in a manifold **604** of a semiconductor cooling apparatus (e.g., the manifold **210** of cooling apparatus **200**), where the flow paths are shown superimposed over the heat exchangers. The figure shows eight heat exchangers **612**, **614**, **616**, **618**, **622**, **624**, **626**, and **628**. Four fluid paths **632**, **634**, **636**, and **638** are depicted. The flexible runners (e.g., flexible runners **220**) of the cooling apparatus are omitted for clarity of illustration purposes. Fluid paths **632** and **638** are coolant supply paths, and fluid paths **634** and **636** are coolant return paths. Coolant from the manifold **604** would enter the inlet of the flexible runner assembly (e.g., flexible runner assembly **508** of FIGS. 5A and 5B) at location **660a**. Coolant returning from the heat exchangers would exit the flexible runner assembly at locations **660b**.

FIG. 7 is a cross-sectional, schematic illustration of an exemplary assembled semiconductor cooling apparatus **700** for cooling a semiconductor element **740**. The cooling apparatus **700** includes a coolant chilling apparatus **750** coupled to one or more coolant supply lines **758** and one or more coolant return lines **762**. The coolant chilling apparatus **750** is configured to chill coolant. The apparatus **700** also includes a coolant pump **754** that is configured to pump the coolant through the supply lines and various coolant passages in the cooling apparatus **700**. The pump **754** pumps chilled coolant through the coolant supply line **758** which is directed to an input **764** of the manifold **712**. The chilled coolant is pumped through coolant supply passages **710** in the manifold **712**. The chilled coolant is delivered to passages **722** in one or more supply flexible runners **720**. In some examples, the coolant includes single phase or two-phase coolants (e.g., where the liquid coolant evaporates in the heat exchanger). In some examples, the coolant includes single phase liquids (e.g., polyalphaolefin (PAO), Coolanol, water, glycol water mixtures (EGW, PGW), fuels (JP-5, JP-8)) and/or two-phase coolants (water, ammonia, methanol, Fluorinert, glycol water mixtures (EGW, PGW)).

The manifold **712**, flexible runners **720** and **726**, and heat exchanger **730** are shown in assembled form such that the flexible runners **720** and **726** are flexed to apply a force (F) to the heat exchanger **730** to maintain contact of the heat exchanger **730** with the semiconductor element **740**. The flexibility of the flexible runners **720** and **726** enables the runners to conform to height differentials in the stack up of components, including the semiconductor element **740**. In

this embodiment, the heat exchanger **730** also acts as a packaging lid for the semiconductor element **740**.

The chilled coolant is then delivered to passages **732** in one or more heat exchangers **730**. Heat from the semiconductor element **740** is transferred to the coolant flowing through the heat exchanger **730**. Heated coolant is then exhausted by the heat exchanger **730** through one or more passages **734** in the heat exchanger **730** to passages **724** in one or more return flexible runners **726**. The exhausted coolant is delivered to one or more coolant return passages **714** in the manifold **712**. The exhausted coolant is then pumped through one or more coolant return lines **762** to the coolant chilling apparatus where the coolant is chilled and reused in the apparatus **700**.

This embodiment includes two flexible runners **720** and **726**; however, in some embodiments, the cooling apparatus only includes one or more flexible runners. In embodiments with a single flexible runner, the flexible runner is still coupled to the manifold **712** and a single heat exchanger **730**. To both supply coolant to the heat exchanger as well as exhaust returned coolant from the heat exchanger, the single flexible runner includes both a supply conduit or passage as well as a return conduit or passage within the body of the flexible runner. The supply conduit of the single flexible runner receives coolant from the coolant supply passage **710** in the manifold **712**, and delivers the coolant to heat exchanger **730**. The return conduit of the single flexible runner receives returned coolant from the heat exchanger **730** and delivers the returned coolant to the coolant return passage **714** in the manifold **712**.

FIG. **8** is a block diagram **800** of an exemplary semiconductor cooling apparatus **810** and semiconductor array **820** (ball grid array (BGA), computer motherboard, etc.). The semiconductor cooling apparatus **810** includes a thermal assembly that has a plurality of cooling elements **840**, **844**, **848**, and **852**. The semiconductor array **820** includes semiconductor elements of various heights, widths, and lengths **822**, **824**, **826**, and **828**. Each cooling element **840**, **844**, **848**, and **852** of the semiconductor cooling apparatus **810** is configured to thermally couple (e.g., positioned near each other to enable thermal transfer, positioned near each other to maximize thermal transfer, etc.) to a respective semiconductor element **822**, **824**, **826**, and **828** of the array of semiconductor elements **820**. The cooling apparatus **810** includes a plurality of heat exchangers **814**, and a flexible manifold **812**, described further in detail below.

In operation, the flexible manifolds **812** flex to conform to the height of the respective heat exchangers **814** (e.g., the flexible manifolds flex from 0.001 to 0.009 inches, the flexible manifolds flex from 0.01 to 0.09 inches, etc.). For example, the flexible manifold **812** of cooling element **840** flexes independently from the flexible manifolds **812** of the other cooling elements **844**, **848**, and **852** to conform to the height of the heat exchangers **814**.

FIG. **9** is a cross-sectional, side view of an assembled semiconductor cooling apparatus **900** (e.g., cooling apparatus **810** of FIG. **8**) for cooling one or more semiconductor elements **940**. The apparatus **900** includes one or more heat exchangers **930** coupled to the semiconductor element **940**. The heat exchanger **930** also includes one or more internal passages **920**. The passages **920** receive coolant for cooling the semiconductor element **940** and exhaust heated coolant from the heat exchanger **930**.

This embodiment also provides flexibility in the thermal assembly of the cooling apparatus **900** to conform to differences in height of the semiconductor elements **940** and also to apply a force to the heat exchangers **930** coupled to

respective semiconductor elements **940**. However, in this embodiment, the flexibility is introduced by the manifold **904** rather than the flexible runners (as was illustrated in, for example, FIGS. **1-4**). The manifold is located over the heat exchanger **930**. A central portion **910** of the manifold **904** is connected to the heat exchanger **930** using a set of screws **934**. Alternative mechanisms (e.g., threaded rods with nuts) or connection methods (e.g., adhesive) can be used in alternative embodiments. The flexibility in the manifold **904** enables the manifold to conform to the height stackup of the semiconductor element and its respective heat exchanger **930** and also apply a force to the stackup to maintain contact between the heat exchanger and its respective semiconductor element **940**. Coolant is supplied to internal passages of the manifold **904** by a coolant supply line **908**. The chilled coolant is delivered by the manifold to the one or more internal passages **920** of the heat exchanger **930**. Heated coolant is then exhausted by the passages **920** of the heat exchanger **930** to one or more internal passages in the manifold **904**. The returned coolant is then exhausted to a coolant return line **912** by the manifold **904**.

The independent flexibility of the flexible manifold advantageously increases the heat transfer between the semiconductor element and the heat exchanger, thereby extending the life of the semiconductor element by promoting proper cooling of the semiconductor element. The independent flexibility of each manifold advantageously reduces the installation time and cost by removing any needed individual customizations, thereby decreasing the overall cost of the devices associated with the semiconductor element while increasing the heat transfer.

FIG. **10** is a top view of a manifold assembly **1000** of an exemplary cooling apparatus (e.g., flexible manifold **904** of FIG. **9**). The manifold assembly **1000** includes two flexible manifolds **1004** and **1008**. The central portions **1080** and **1084** of the manifolds **1004** and **1008**, respectively, are connected to two corresponding heat exchangers (not shown) by screws that pass through holes **1060**. The two manifolds **1004** and **1008** share a common coolant supply line **1040** and a common coolant return line **1030**. Chilled coolant travels through passages in the manifolds and is provided to heat exchangers via outlets **1010** and **1020**. Coolant exhausted by the heat exchangers is then received by inlets **1014** and **1018**. The returned coolant is then pumped to coolant return line **1030** and subsequently exhausted and chilled again for reuse.

Various methods and mechanisms can be used to couple, connect or otherwise join various components described herein. For example, fasteners, such as screws, nuts, threaded rods, hollow bolts, etc., can be used. In some examples, adhesives or epoxies can be used. In some examples, components are bonded together by diffusion bonding, adhesive bonding and/or brazing. In some embodiments, o-rings, polymers, films, etc. can be used between two components to improve or create fluid seals between the components.

Comprise, include, and/or plural forms of each are open ended and include the listed parts and can include additional parts that are not listed. And/or is open ended and includes one or more of the listed parts and combinations of the listed parts.

One skilled in the art will realize the invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting of the invention described herein. Scope of the invention is thus indicated by the

11

appended claims, rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein. In addition, the figures and foregoing descriptions identify a semiconductor to be thermally coupled to the heat exchanger, but the art described herein is not limited to semiconductors and can apply to any object which requires temperature control through heat rejection or addition.

What is claimed is:

1. A semiconductor cooling apparatus, comprising:
 - a thermal assembly configured to thermally couple to an array of semiconductor elements, the assembly comprising:
 - a plurality of heat exchangers, each heat exchanger configured to transfer heat from a respective semiconductor element to a coolant flowing through the respective heat exchanger;
 - a plurality of supply flexible runners and a plurality of return flexible runners, each supply flexible runner fluidly coupled to pass coolant to the respective heat exchanger and each return flexible runner fluidly coupled to exhaust coolant returned from the respective heat exchanger, each flexible runner configured to flex to conform to a height of a respective semiconductor element and to apply a force to the respective heat exchanger to maintain contact of the respective heat exchanger with the respective semiconductor element; and
 - a manifold fluidly coupled to the plurality of supply flexible runners and the plurality of return flexible runners, the manifold configured to supply coolant to the supply flexible runners and to exhaust returned coolant from the return flexible runners, the manifold comprising upper and lower planar surfaces and a sidewall,
 - wherein each of the supply flexible runners and the return flexible runners extends from the sidewall of the manifold,
 - wherein each of the supply flexible runners and the return flexible runners comprises respective upper and lower planar surfaces, and
 - wherein the respective lower planar surfaces of the supply flexible runners, the return flexible runners and the manifold are co-planar with one another.
 2. The apparatus of claim 1, wherein the manifold has an input that is configured to couple to a coolant supply line and an output that is configured to couple to a coolant return line.
 3. The apparatus of claim 2, further comprising:
 - a coolant chilling apparatus coupled to the coolant supply line and the coolant return line and configured to chill coolant; and
 - a coolant pump configured to pump the coolant between the coolant chilling apparatus and the thermal assembly.
 4. The apparatus of claim 1, wherein the plurality of supply and return flexible runners are located adjacent to the heat exchangers.
 5. The apparatus of claim 4, wherein the manifold is located adjacent to the plurality of supply and return flexible runners.
 6. The apparatus of claim 1, wherein a spring constant of each flexible runner is defined based on one or more of a wall thickness of the respective flexible runner, a material type of the respective flexible runner, or a geometric property of the respective flexible runner.

12

7. The apparatus of claim 1, wherein the semiconductor cooling apparatus comprises aluminum, aluminum alloys, copper, copper alloys, stainless steel, stainless steel alloys, titanium, titanium alloys, plastic, or any combination thereof.

8. The apparatus of claim 1, wherein each heat exchanger is configured to couple to a respective semiconductor element as a packaging lid for the respective semiconductor element.

9. A semiconductor cooling apparatus, comprising:

- a thermal assembly configured to thermally couple to a semiconductor element, the assembly comprising:
 - a heat exchanger configured to transfer heat from the semiconductor element to a coolant flowing through the heat exchanger;
 - at least one flexible runner fluidly coupled to the heat exchanger to provide coolant to the heat exchanger and to exhaust returned coolant from the heat exchanger, the at least one flexible runner configured to flex to conform to a height of the semiconductor element and to apply a force to the heat exchanger to maintain contact of the heat exchanger with the semiconductor element; and
 - a manifold fluidly coupled to the at least one flexible runner and configured to supply coolant to the at least one flexible runner and configured to exhaust returned coolant from the at least one flexible runner, the manifold comprising upper and lower planar surfaces and a sidewall,
 - wherein the at least one flexible runner extends from the sidewall of the manifold,
 - wherein the at least one flexible runner comprises respective upper and lower planar surfaces, and
 - wherein the respective lower planar surfaces of the at least one flexible runner and the manifold are co-planar with one another.

10. The apparatus of claim 9, wherein the at least one flexible runner includes a supply conduit and a return conduit within the at least one flexible runner, where the supply conduit is configured to provide coolant to the heat exchanger and the return conduit is configured to exhaust returned coolant from the heat exchanger.

11. The apparatus of claim 9, wherein the at least one flexible runner includes at least one supply flexible runner and at least one return flexible runner, where the at least one supply flexible runner is configured to provide coolant to the heat exchanger and the at least one return flexible runner is configured to exhaust returned coolant from the heat exchanger.

12. The apparatus of claim 9, wherein the manifold has an input that is configured to couple to a coolant supply line and an output that is configured to couple to a coolant return line.

13. The apparatus of claim 12, further comprising:

- a coolant chilling apparatus coupled to the coolant supply line and the coolant return line and configured to chill coolant; and
- a coolant pump configured to pump the coolant between the coolant chilling apparatus and the thermal assembly.

14. The apparatus of claim 9, wherein the at least one flexible runner is located adjacent the heat exchanger.

15. The apparatus of claim 14, wherein the manifold is located adjacent the at least one flexible runner.

16. The apparatus of claim 9, wherein a spring constant of the flexible runner is defined based on one or more of a wall

13

thickness of the flexible runner, a material type of the flexible runner, or a geometric property of the flexible runner.

17. The apparatus of claim 9, wherein the heat exchanger is configured to couple to the semiconductor element as a packaging lid for the semiconductor element.

18. A cooling apparatus, comprising:

a thermal assembly configured to thermally couple to an array of objects, the assembly comprising:

a plurality of heat exchangers, each heat exchanger configured to transfer heat from an object in the array of objects to a coolant flowing through the heat exchanger;

a plurality of supply flexible runners and a plurality of return flexible runners, each supply flexible runner fluidly coupled to pass coolant to a respective heat exchanger and each return flexible runner fluidly coupled to exhaust returned coolant from the respective heat exchanger, each flexible runner configured to flex to conform to a height of a respective object in the array of objects and to apply a force to the respective heat exchanger to maintain contact of the heat exchanger with the respective object in the array of objects; and

a manifold fluidly coupled to the plurality of supply flexible runners and the plurality of return flexible runners, the manifold configured to supply coolant to the supply flexible runners and to exhaust returned coolant from the return flexible runners, the manifold comprising upper and lower planar surfaces and a sidewall,

wherein each of the supply flexible runners and the return flexible runners extends from the sidewall of the manifold,

wherein each of the supply flexible runners and the return flexible runners comprises respective upper and lower planar surfaces, and

wherein the respective lower planar surfaces of the supply flexible runners, the return flexible runners and the manifold are co-planar with one another.

19. The apparatus of claim 1, further comprising:

a central body having a supply conduit fluidly coupled to at least one supply flexible runner and a return conduit fluidly coupled to at least one return flexible runner, wherein the supply and return conduits are not fluidly coupled to one another within the central body.

20. The apparatus of claim 19, wherein the central body, the fluidly coupled at least one supply flexible runner and the fluidly coupled at least one return flexible runner comprise a unitary structure.

21. The apparatus of claim 19, wherein at least one of the supply flexible runners and at least one of the return flexible runners extend from the central body in a J-shaped pattern.

22. A cooling apparatus, comprising:

a heat exchanger configured to transfer heat, from an element disposed adjacent to the heat exchanger, to a coolant conduit disposed within the heat exchanger;

a central body disposed adjacent the heat exchanger and having a supply conduit fluidly coupled to a supply runner and a return conduit fluidly coupled to a return runner, wherein the supply and return conduits are not fluidly coupled to one another within the central body, the central body comprising upper and lower planar surfaces and a sidewall;

the supply runner having a conduit fluidly coupled to the coolant conduit of the heat exchanger; and

14

the return runner having a conduit fluidly coupled to the coolant conduit of the heat exchanger,

wherein each of the supply and return runners is configured to flex and apply a force to the heat exchanger to maintain contact with the adjacent element,

wherein the central body, the supply runner and the return runner comprise a unitary structure,

wherein each of the supply and return runners extends from the sidewall of the central body,

wherein each of the supply flexible runners and the return flexible runners comprises respective upper and lower planar surfaces, and

wherein the respective lower planar surfaces of the supply runner, the return runner and the central body are co-planar with one another.

23. A cooling apparatus, comprising:

a heat exchanger configured to transfer heat, from an element disposed adjacent to the heat exchanger, to a coolant conduit disposed within the heat exchanger;

a central body disposed adjacent the heat exchanger and having a supply conduit fluidly coupled to a supply runner and a return conduit fluidly coupled to a return runner, wherein the supply and return conduits are not fluidly coupled to one another within the central body, the central body comprising upper and lower planar surfaces and a sidewall;

the supply runner having a conduit fluidly coupled to the coolant conduit of the heat exchanger; and

the return runner having a conduit fluidly coupled to the coolant conduit of the heat exchanger,

wherein each of the supply and return runners is configured to flex and apply a force to the heat exchanger to maintain contact with the adjacent element,

wherein the central body, the supply runner and the return runner comprise a unitary structure,

wherein each of the supply and return runners extends from the sidewall of the central body,

wherein each of the supply flexible runners and the return flexible runners comprises respective upper and lower planar surfaces,

wherein the respective lower planar surfaces of the supply runner, the return runner and the central body are co-planar with one another, and

wherein the supply and return runners extend from the central body in a J-shaped pattern.

24. A semiconductor cooling apparatus, comprising:

a thermal assembly configured to thermally couple to an array of semiconductor elements, the assembly comprising:

a plurality of heat exchangers, each heat exchanger configured to transfer heat from a respective semiconductor element to a coolant flowing through the respective heat exchanger;

a plurality of supply flexible runners and a plurality of return flexible runners, each supply flexible runner fluidly coupled to pass coolant to the respective heat exchanger and each return flexible runner fluidly coupled to exhaust coolant returned from the respective heat exchanger, each flexible runner configured to flex to conform to a height of a respective semiconductor element and to apply a force to the respective heat exchanger to maintain contact of the respective heat exchanger with the respective semiconductor element;

a manifold fluidly coupled to the plurality of supply flexible runners and the plurality of return flexible runners, the manifold configured to supply coolant to

the supply flexible runners and to exhaust returned coolant from the return flexible runners, the manifold comprising upper and lower planar surfaces and a sidewall; and
a central body having a supply conduit fluidly coupled 5
to at least one supply flexible runner and a return conduit fluidly coupled to at least one return flexible runner,
wherein each of the supply flexible runners and the return flexible runners extends from the sidewall of 10
the manifold,
wherein each of the supply flexible runners and the return flexible runners comprises respective upper and lower planar surfaces,
wherein the respective lower planar surfaces of the 15
supply flexible runners, the return flexible runners and the manifold are co-planar with one another,
wherein at least one of the supply flexible runners and at least one of the return flexible runners extend from the central body in a J-shaped pattern, and 20
wherein the supply and return conduits are not fluidly coupled to one another within the central body.

* * * * *