US 20250263292A1

(19) United States
(12) Patent Application Publication
Ganti et al.
(10) Pub. No.: US 2025/0263292 A1
(43) Pub. Date: Aug. 21, 2025

(54) TILES HAVING MULTIPLE COOLING CELLS FOR MEMS-BASED COOLING

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(21) Appl. No.: **19/042,492**

(22) Filed: **Jan. 31, 2025**

Related U.S. Application Data

(63) Continuation of application No. 17/474,815, filed on Sep. 14, 2021, now Pat. No. 12,240,750.

(60) Provisional application No. 63/220,862, filed on Jul. 12, 2021, provisional application No. 63/220,371, filed on Jul. 9, 2021, provisional application No. 63/079,450, filed on Sep. 16, 2020.

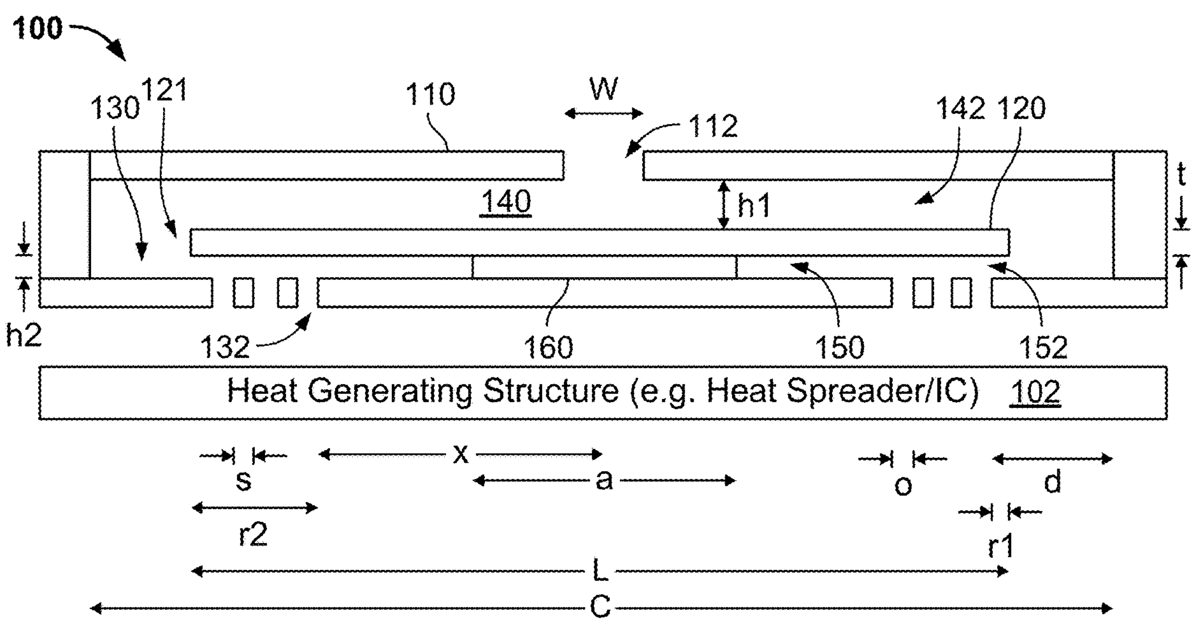
Publication Classification

(51) **Int. Cl.**
B81B 7/00 (2006.01)
H05K 7/20 (2006.01)

(52) **U.S. Cl.**
CPC ***B81B 7/0061*** (2013.01); ***B81B 7/0093*** (2013.01); ***H05K 7/20145*** (2013.01); ***H05K 7/20272*** (2013.01); *B81B 2203/0118* (2013.01)

(57) **ABSTRACT**

A system including a plurality of cooling cells is described. Each of the cooling cells includes a support structure and a cooling element. The cooling element has a central region having an axis and a perimeter. The cooling element IS supported by the support structure at the central region and along the axis. At least a portion of the perimeter being unpinned. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. A portion of the cooling cells aligned along the axis are physically connected such that the cooling cells form an integrated cooling cell tile.



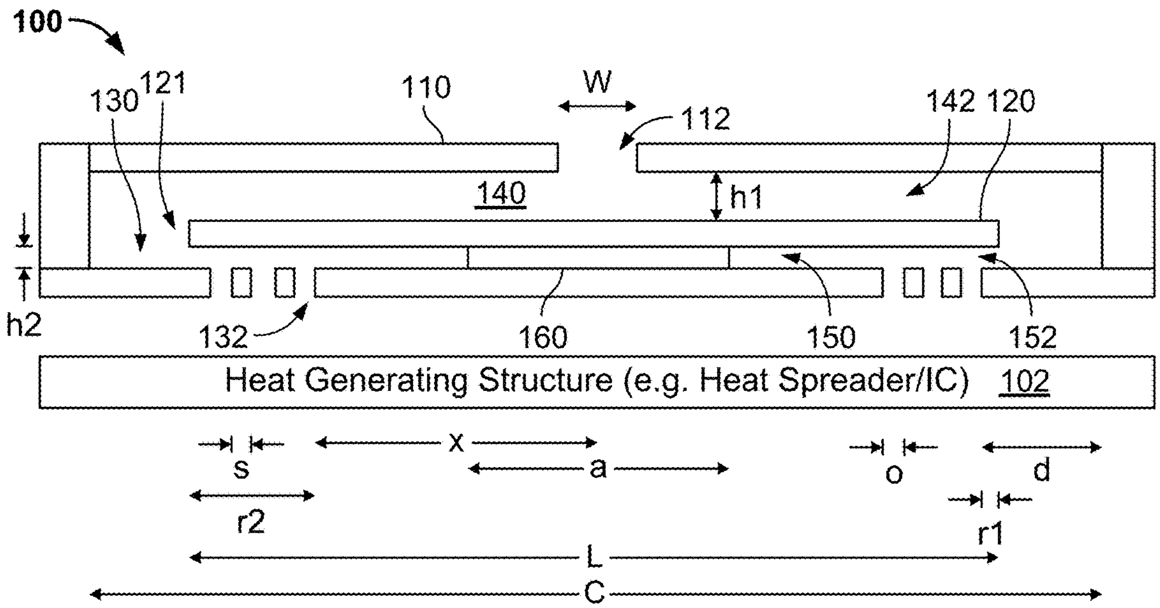


FIG. 1A

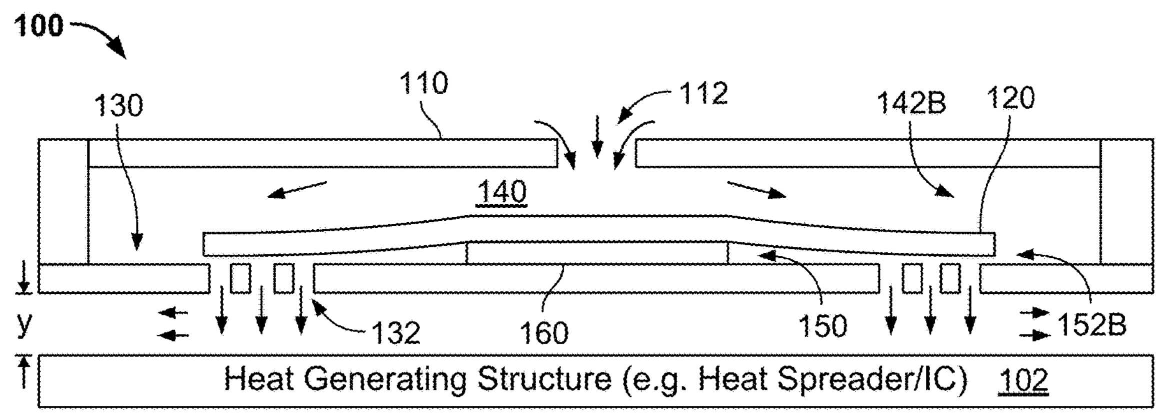


FIG. 1B

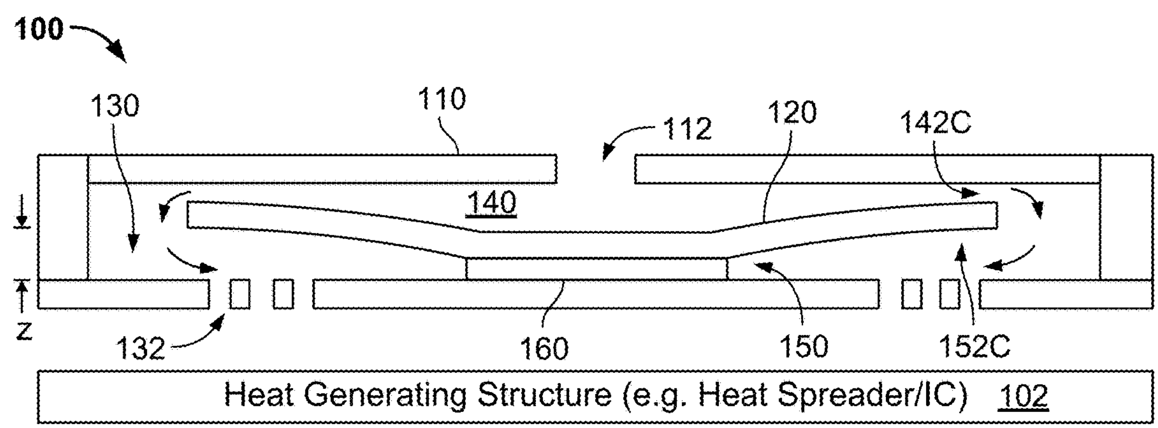


FIG. 1C

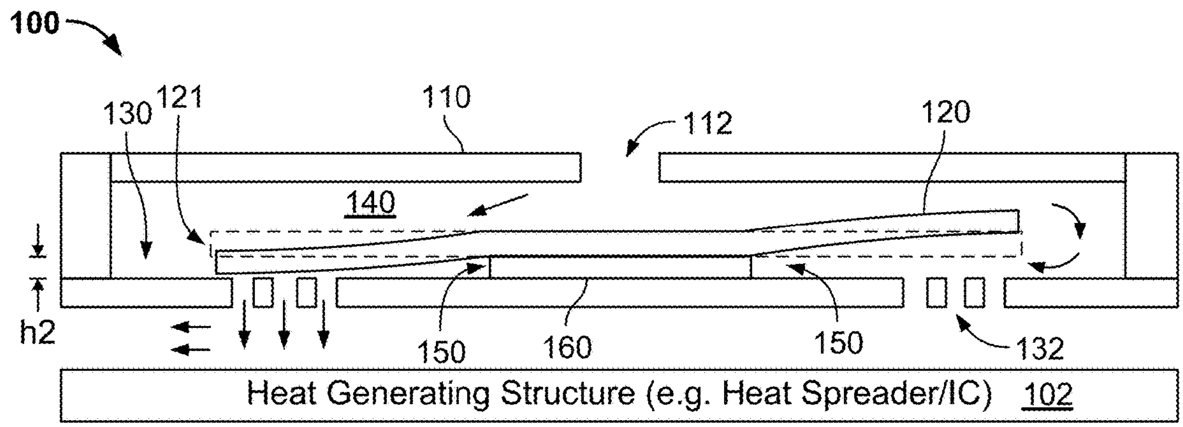


FIG. 1D

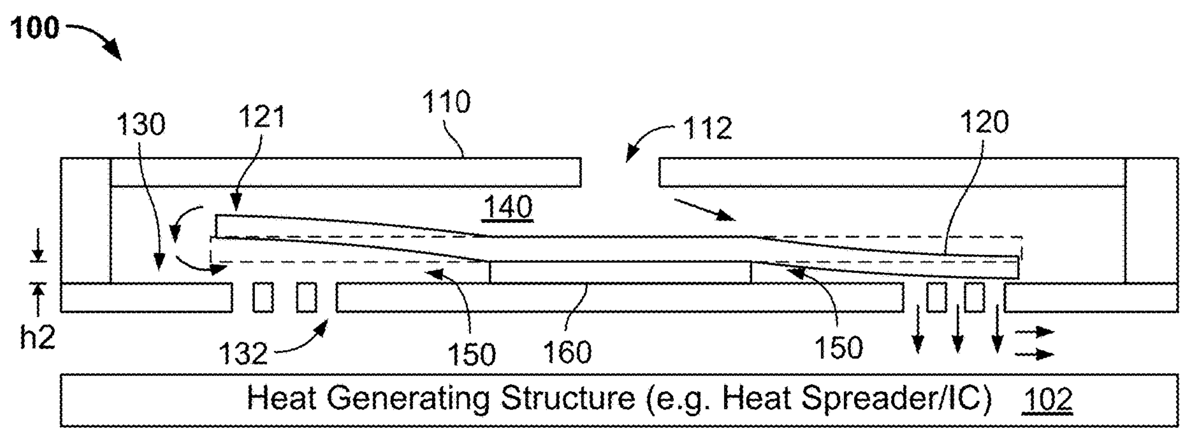


FIG. 1E

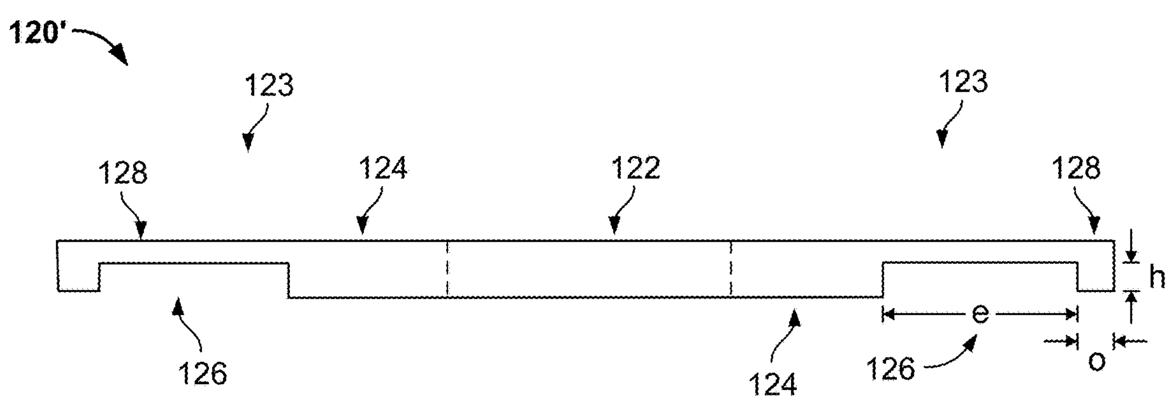


FIG. 1F

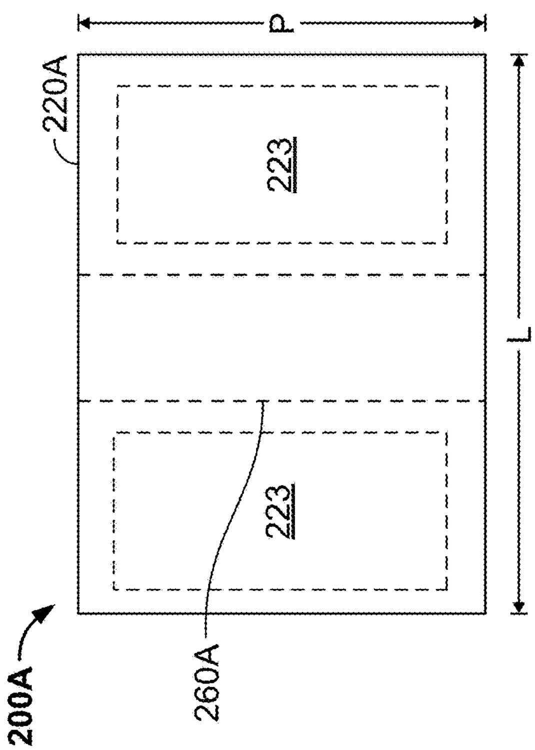


FIG. 2A

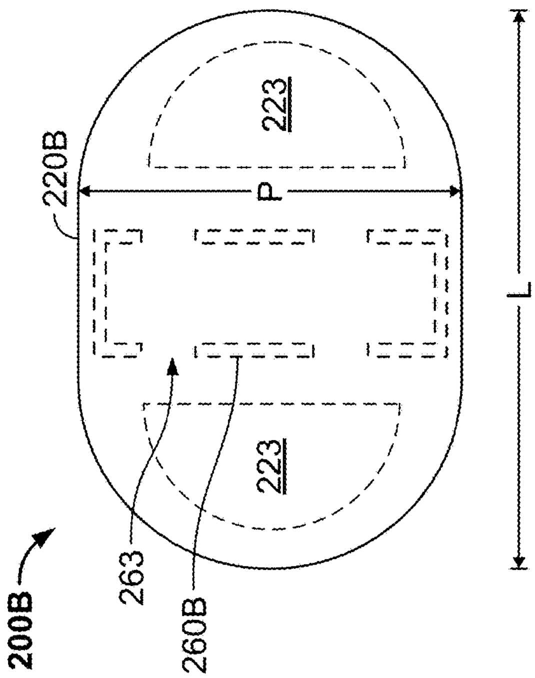


FIG. 2B

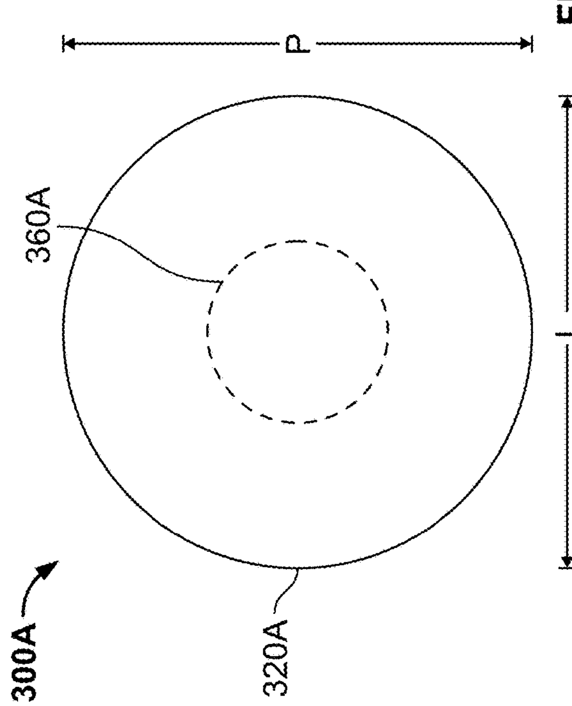


FIG. 3A

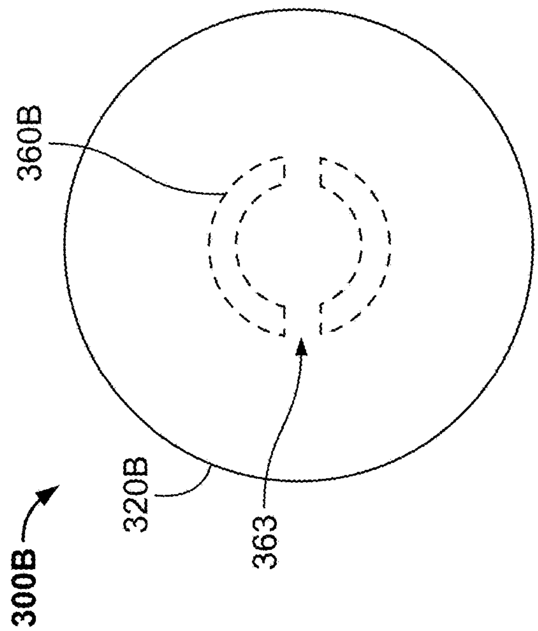


FIG. 3B

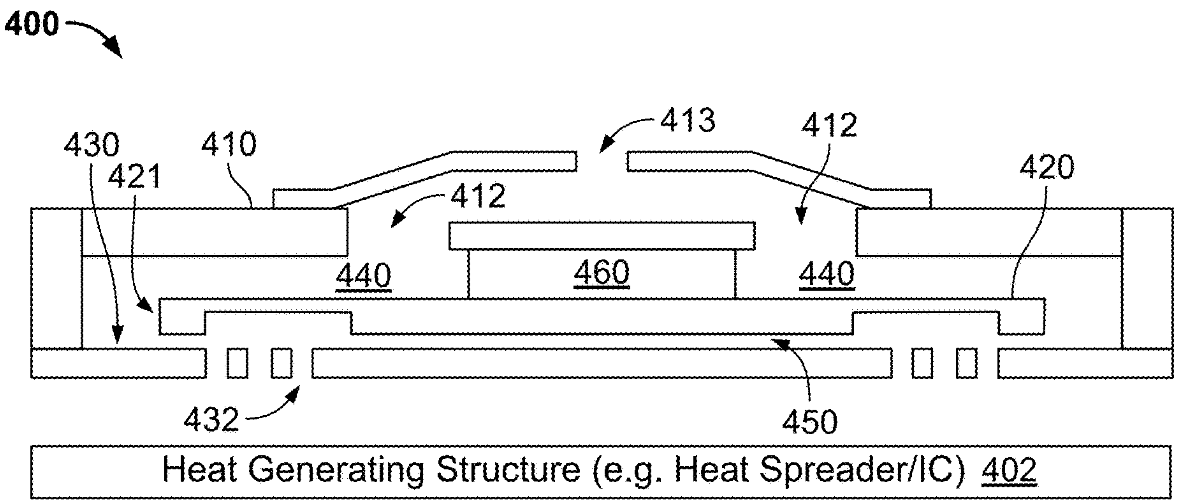

400
413
412
430
410
421
412
420
440
460
440
432
450
Heat Generating Structure (e.g. Heat Spreader/IC) 402

FIG. 4A

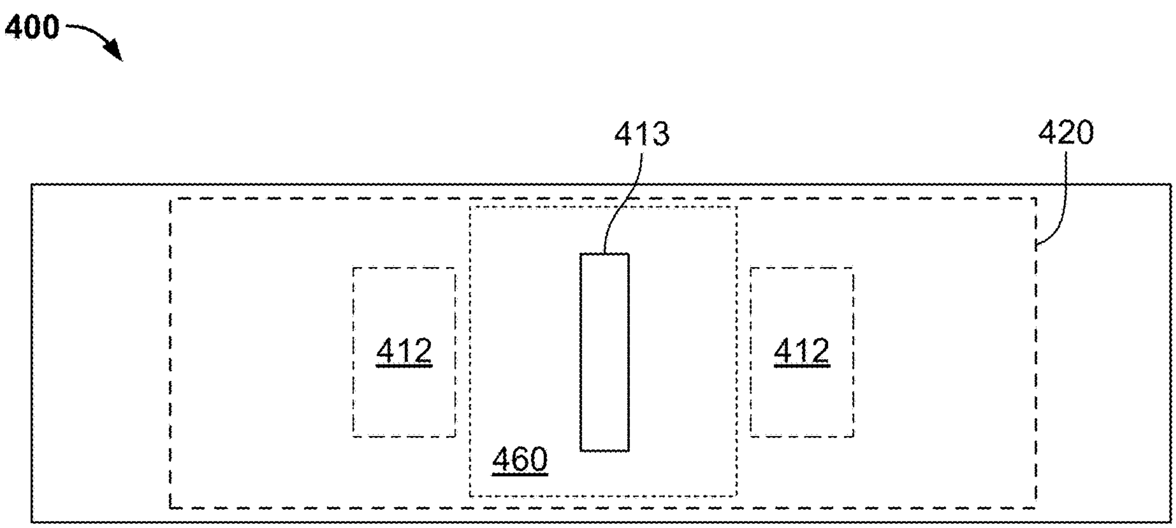

400
413
420
412
412
460

FIG. 4B

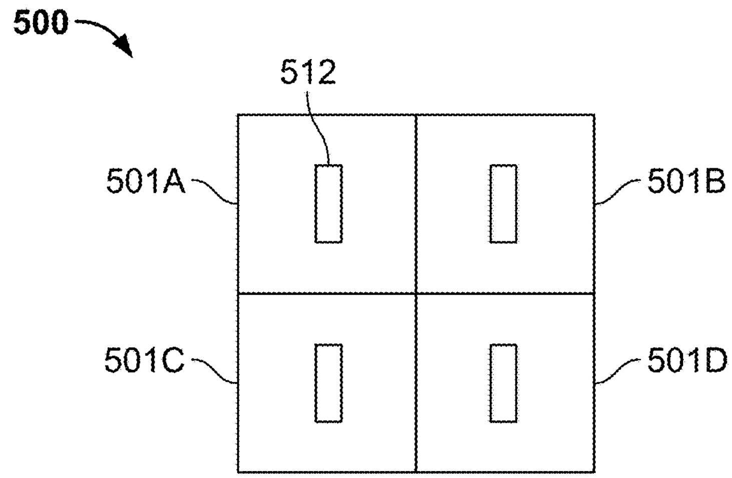


FIG. 5A

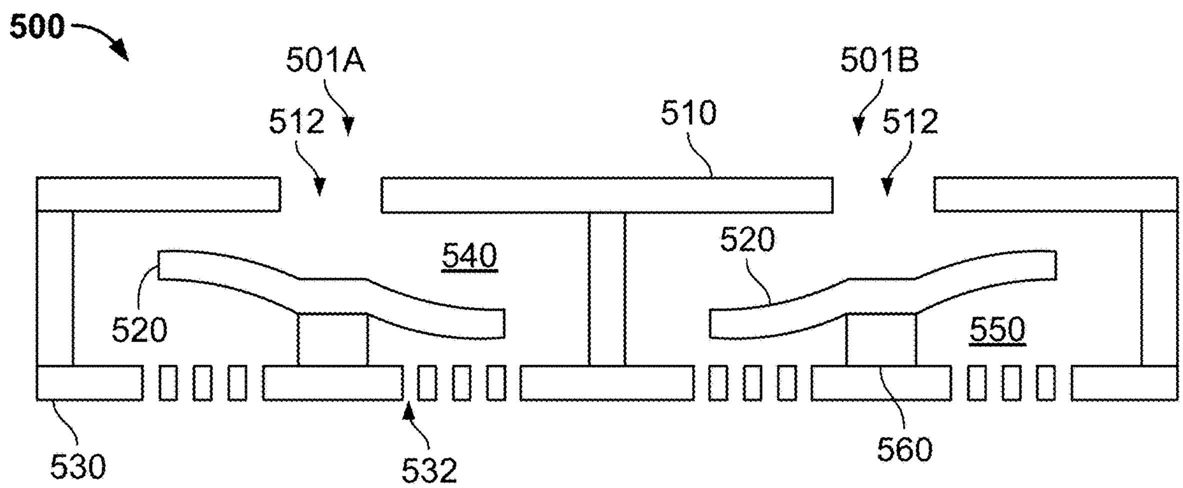


FIG. 5B

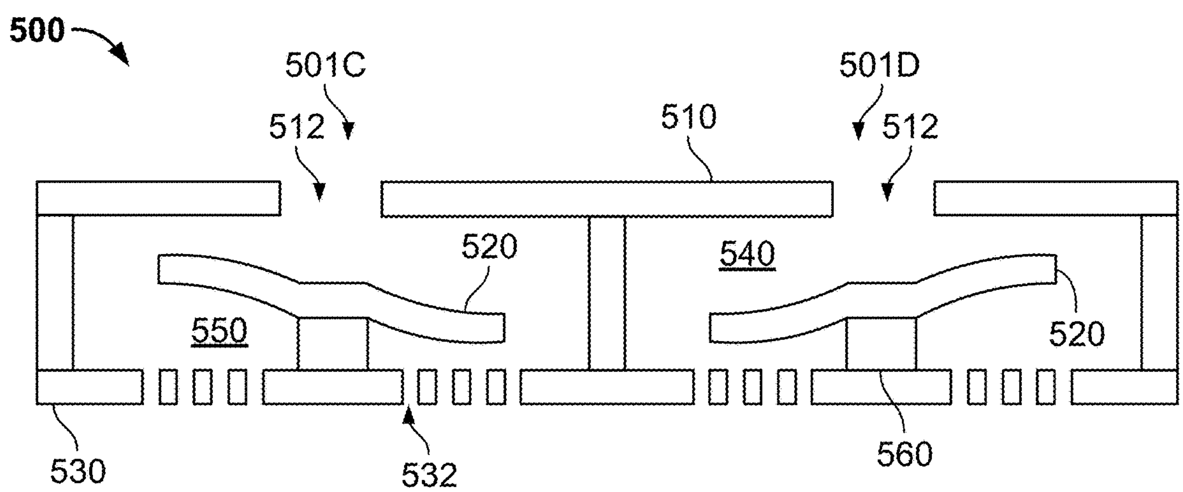


FIG. 5C

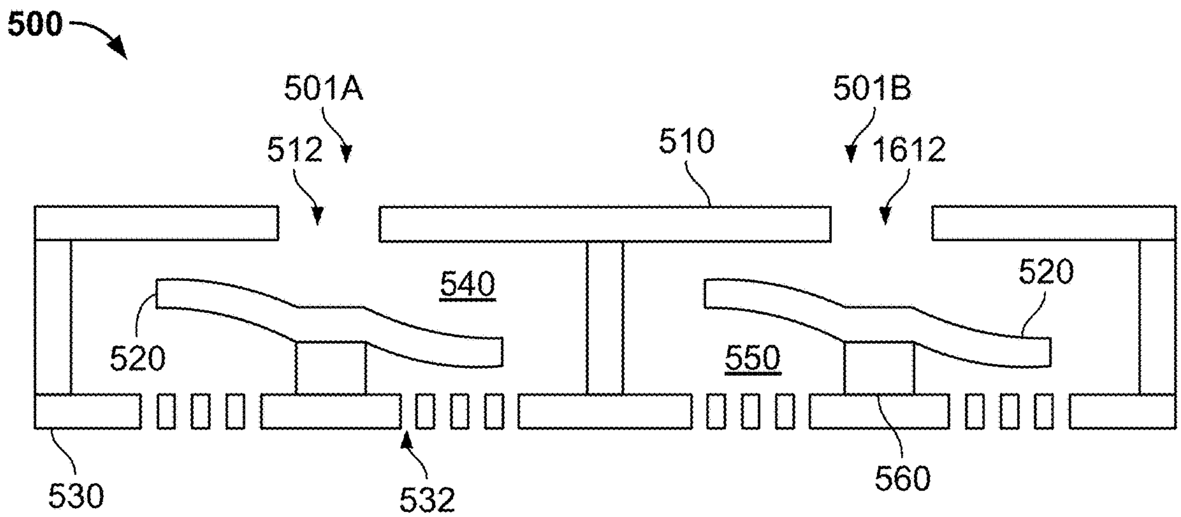
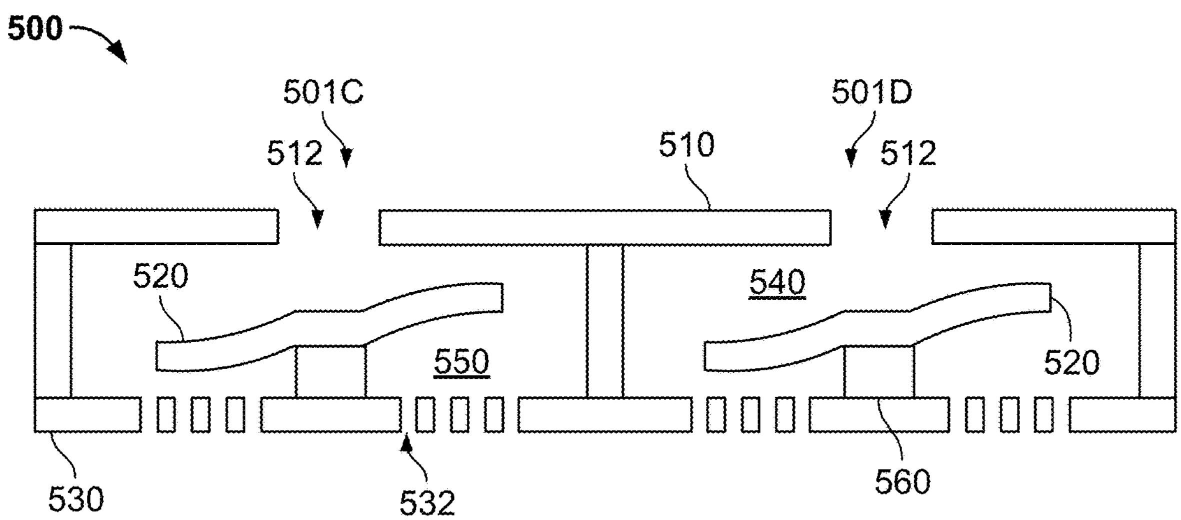

500
501A
501B
512
1612
510
540
520
520
550
530
532
560

FIG. 5D


500
501C
501D
512
512
510
520
540
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520
530
532
560

FIG. 5E

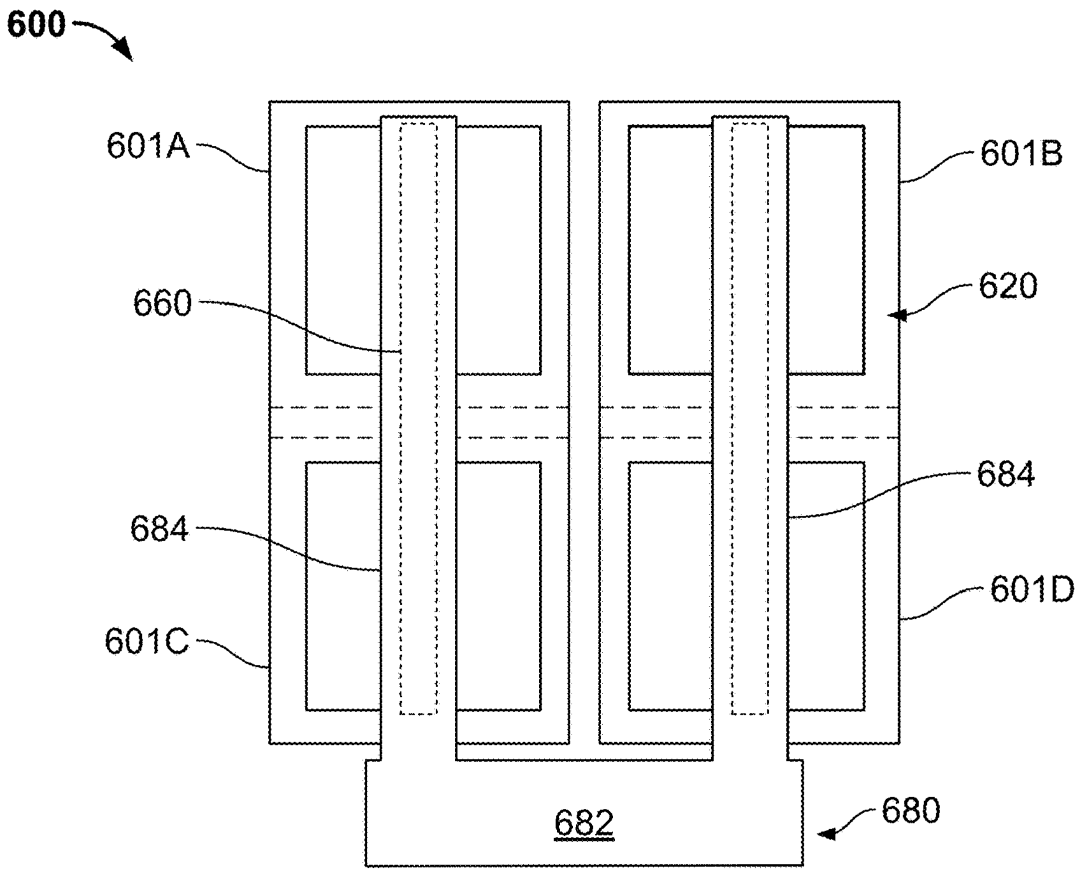

600
601A
601B
620
660
684
684
601D
601C
682
680

FIG. 6A

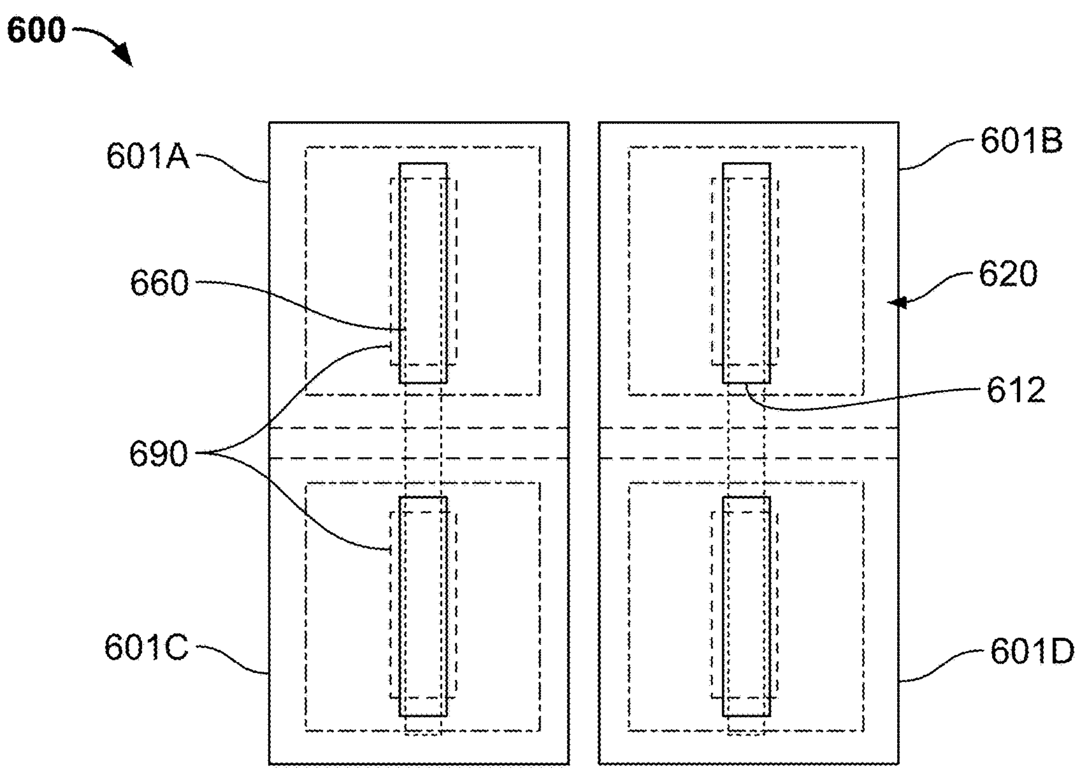
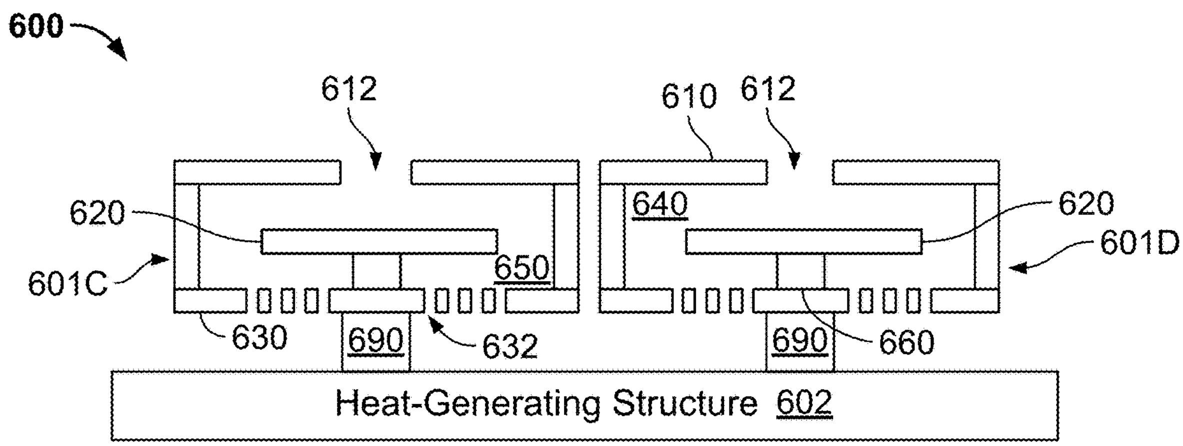

600
601A
601B
620
660
612
690
601C
601D

FIG. 6B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612
610
612
620
640
620
601D
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601C
630
690
632
690
660
Heat-Generating Structure 602

FIG. 6C

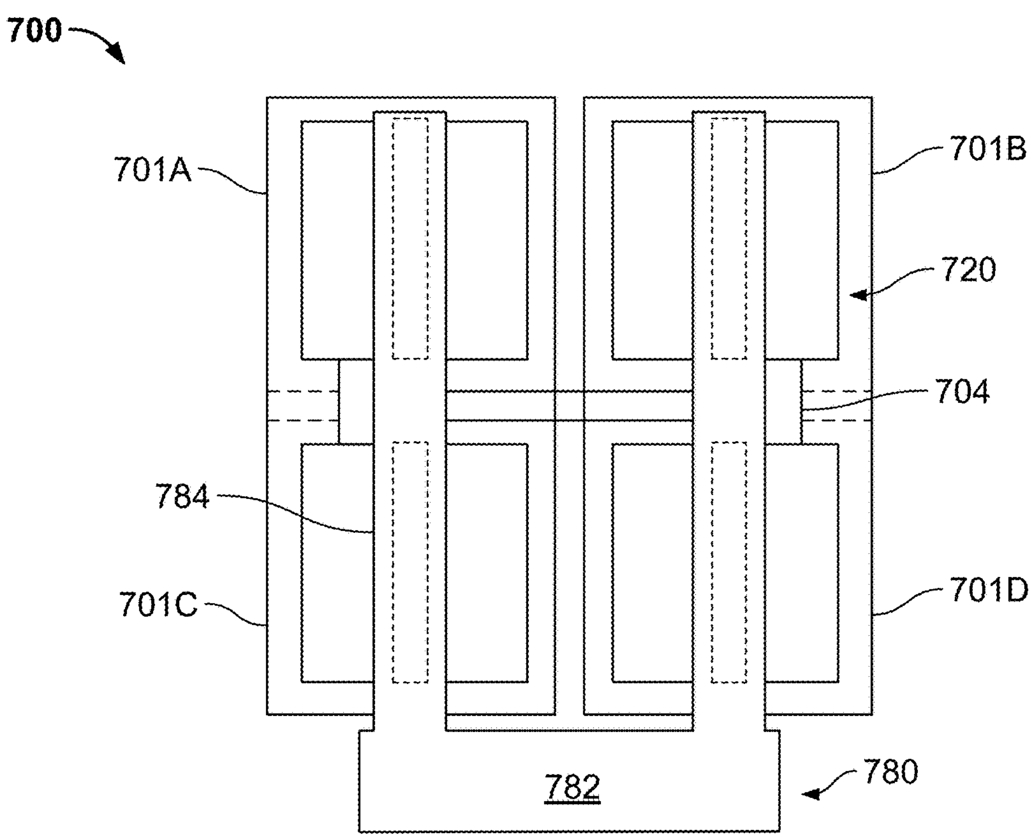
700
701A
701B
720
704
784
701C
701D
782
780

FIG. 7A

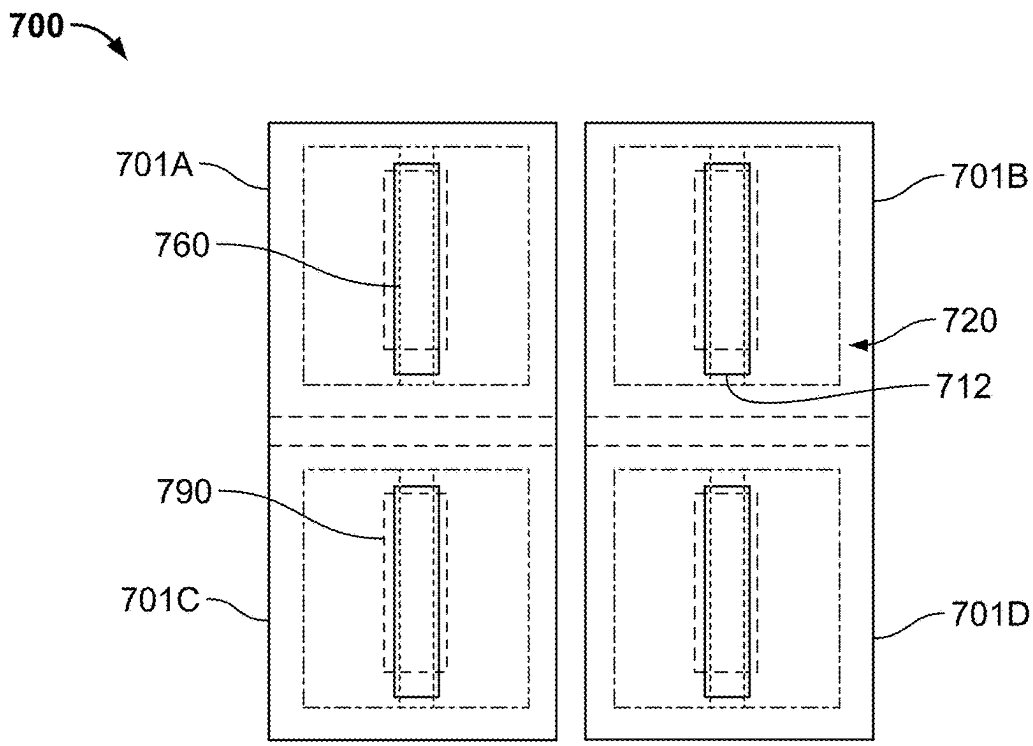
700
701A
760
790
701C
701B
720
712
701D

FIG. 7B

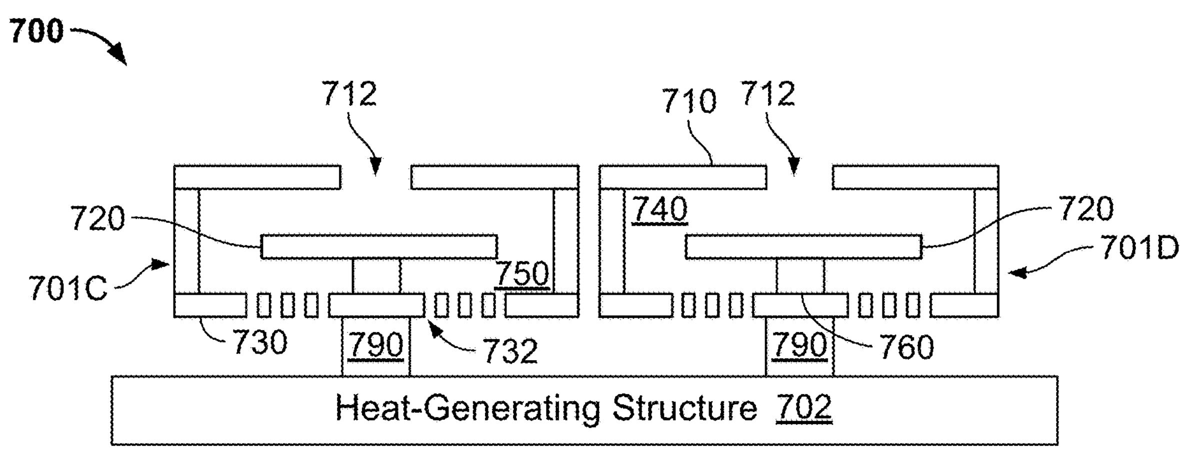
700
712
710
712
720
701C
750
740
720
701D
730
790
732
790
760
Heat-Generating Structure 702

FIG. 7C

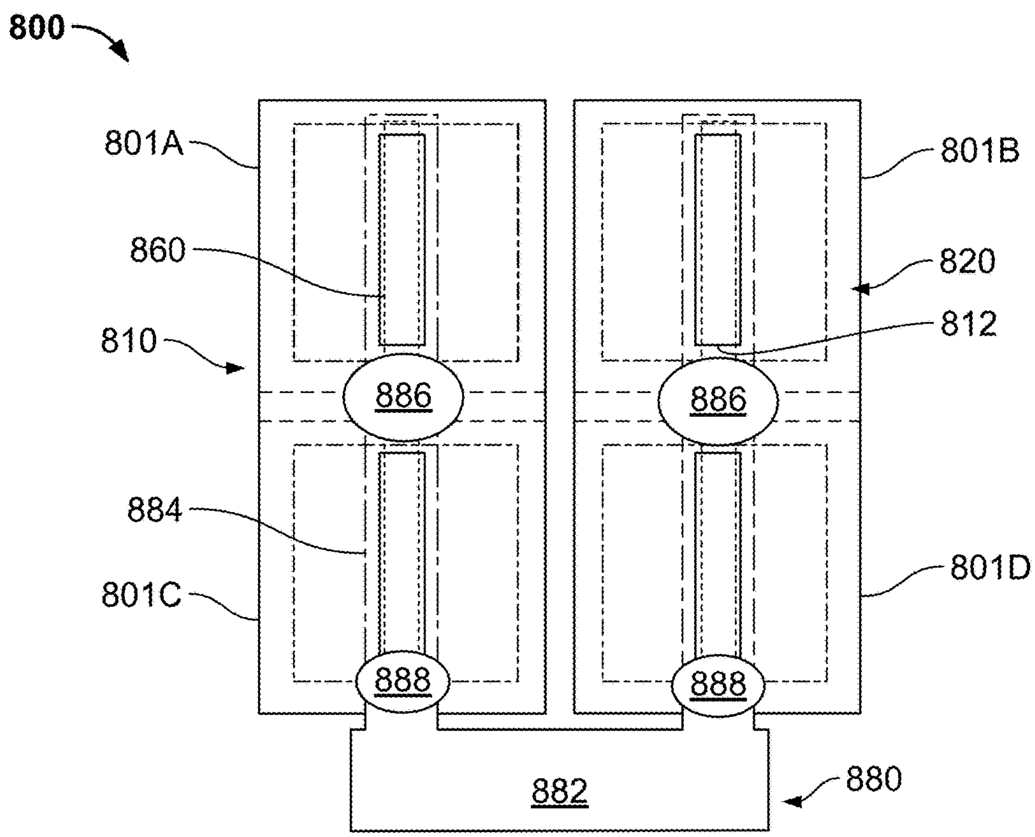
800
801A
860
810
884
801C
886
886
888
888
801B
820
812
801D
882
880

FIG. 8

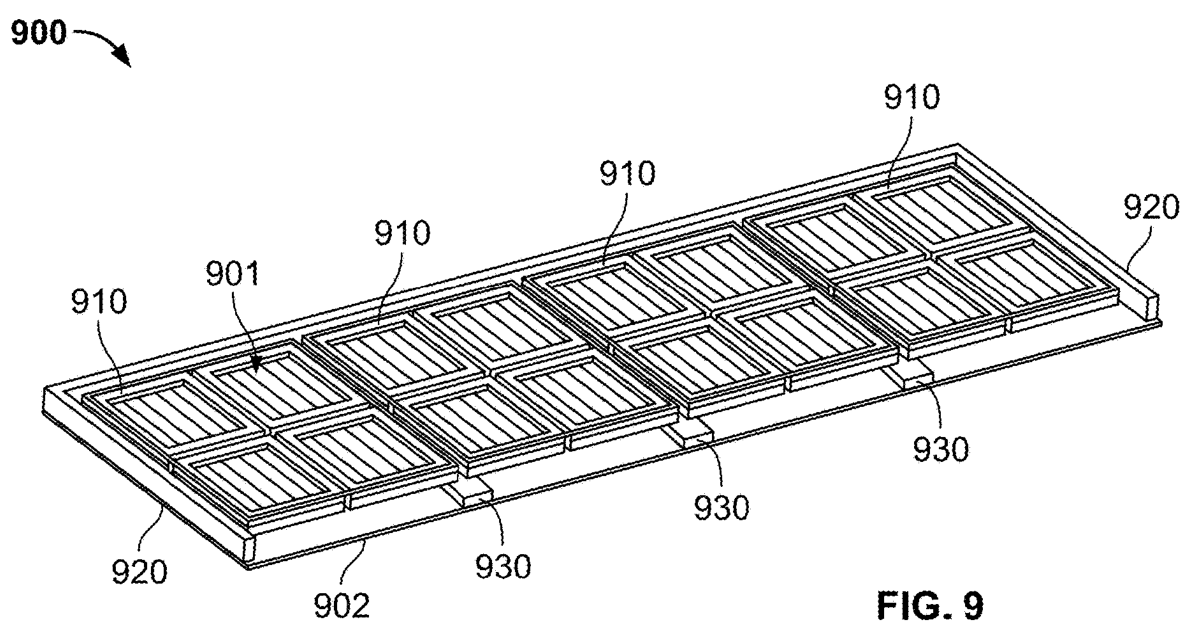
900
910
901
910
910
910
920
920
930
930
930
902

FIG. 9

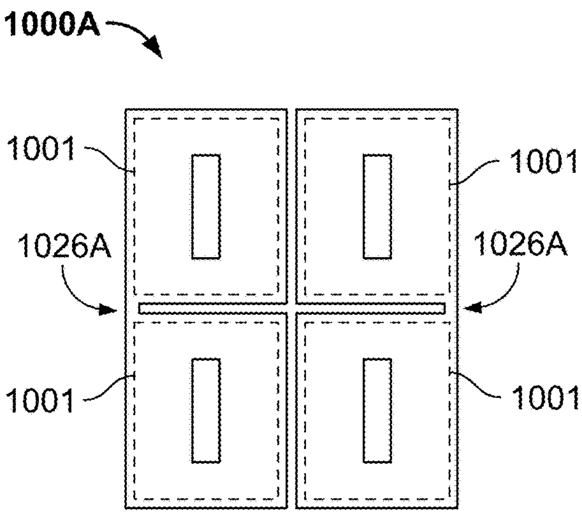

FIG. 10A

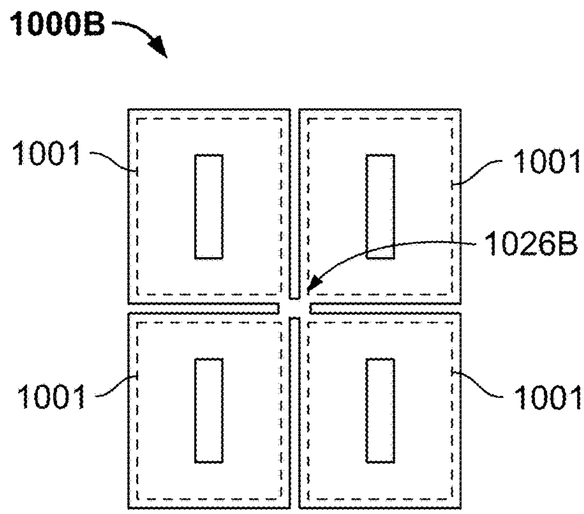

FIG. 10B

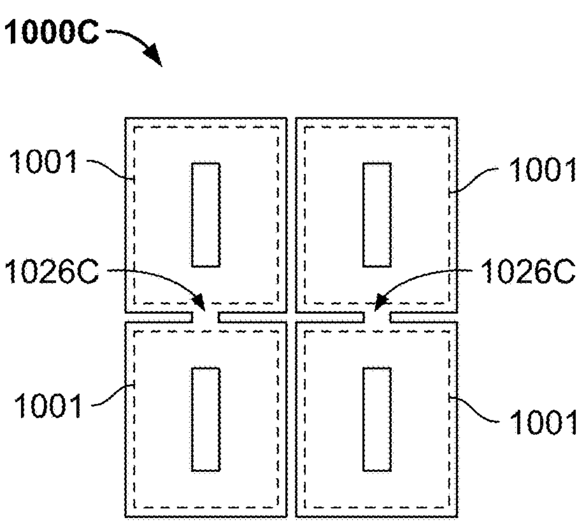

FIG. 10C

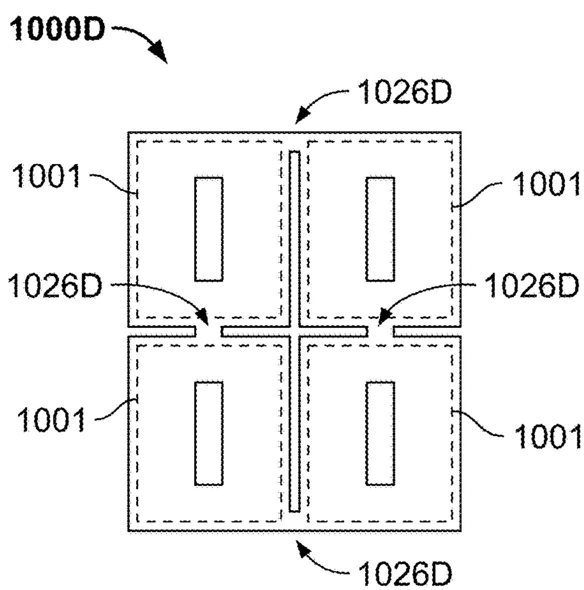

FIG. 10D

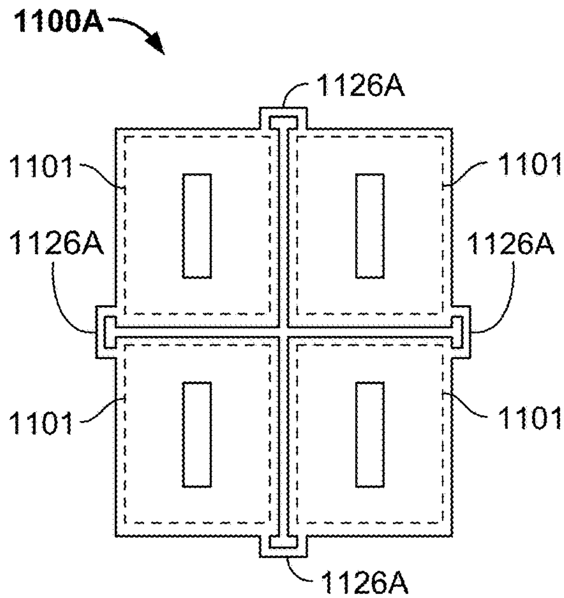

FIG. 11A

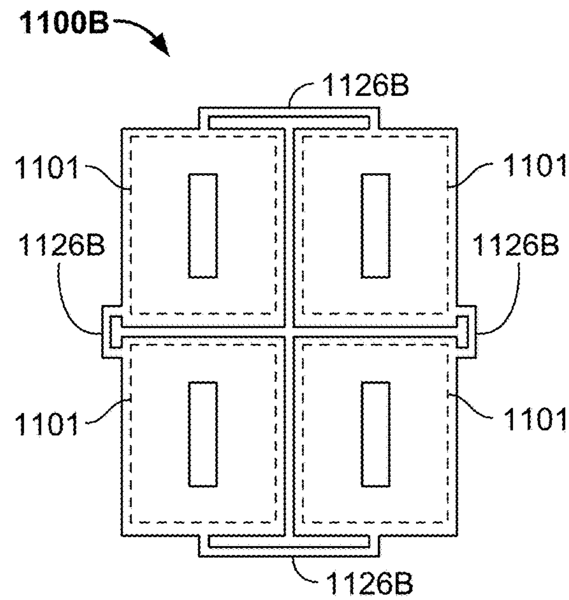

FIG. 11B

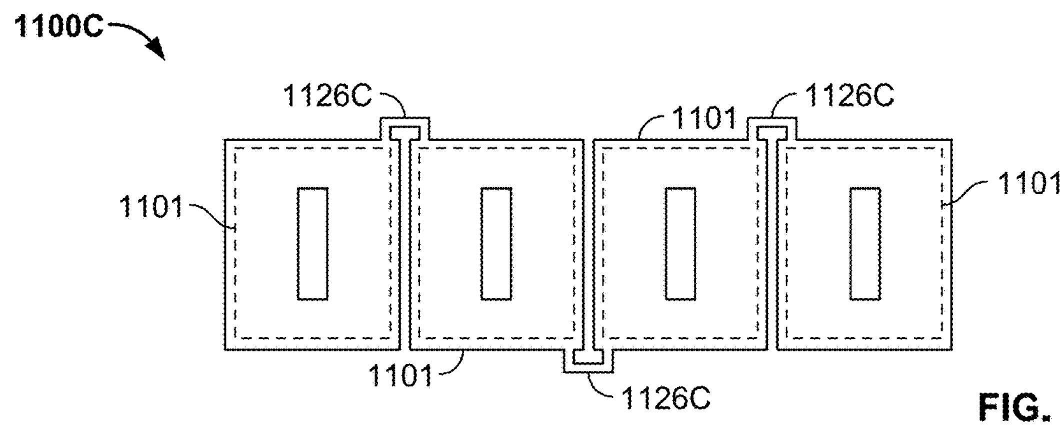

FIG. 11C

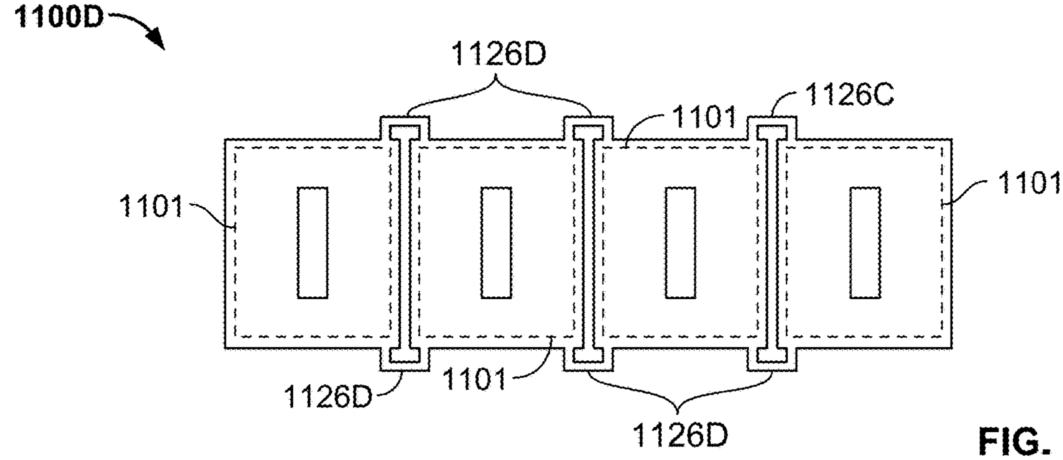

FIG. 11D

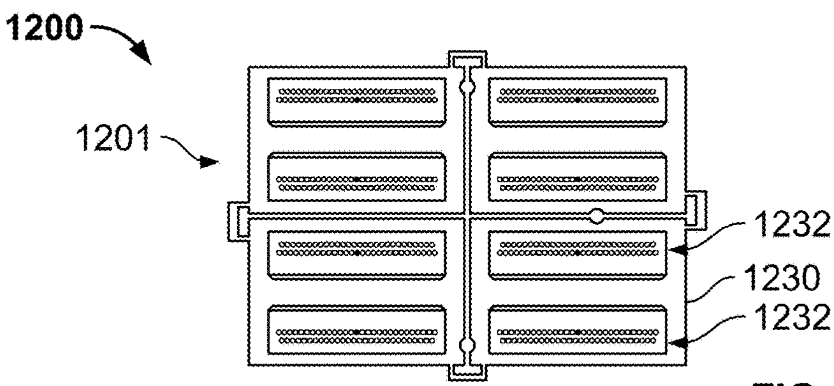

FIG. 12A

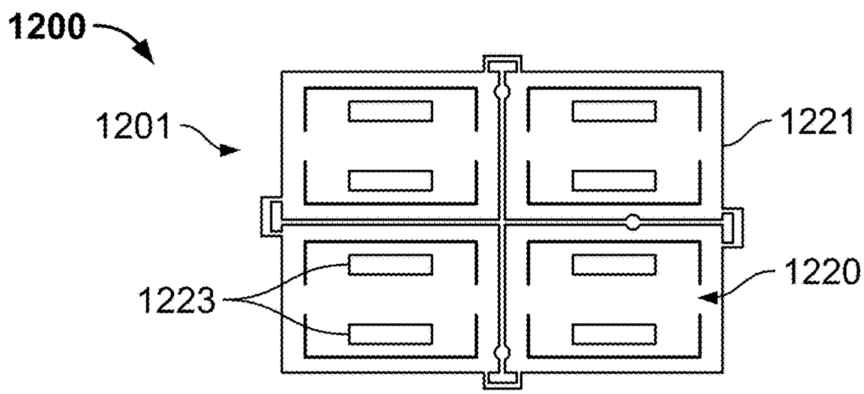

FIG. 12B

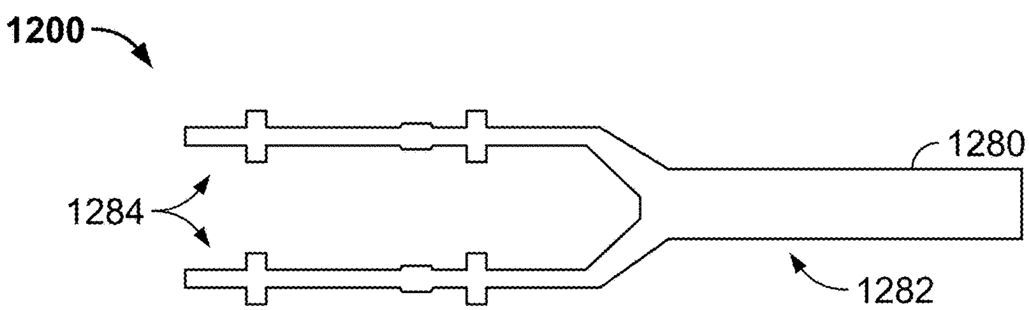

FIG. 12C

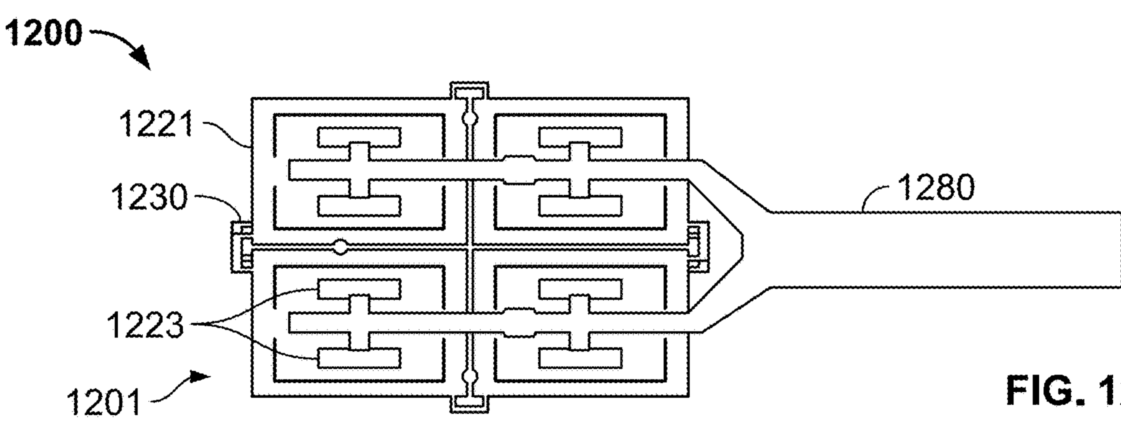

FIG. 12D

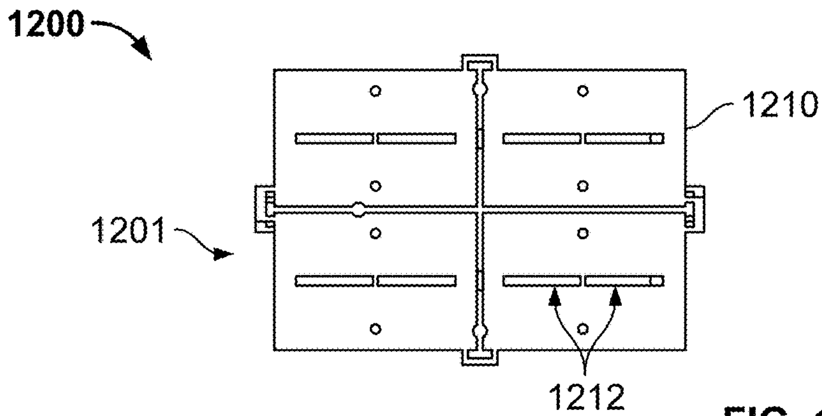

FIG. 12E

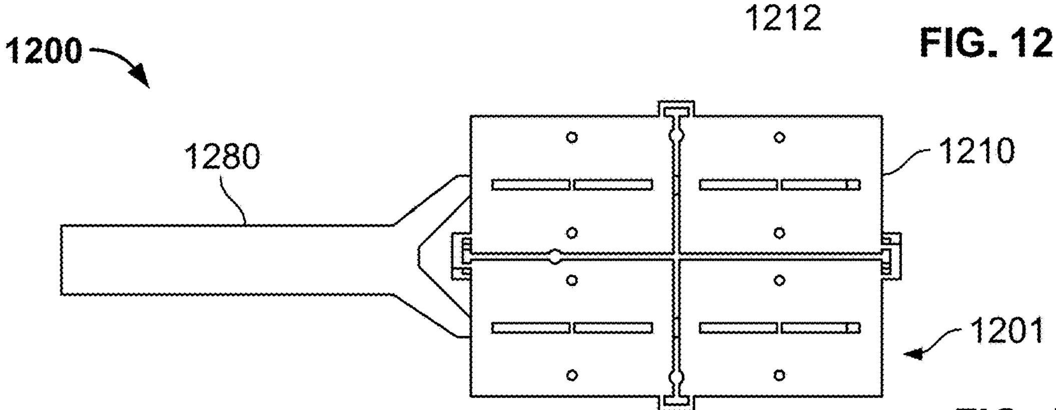

FIG. 12F

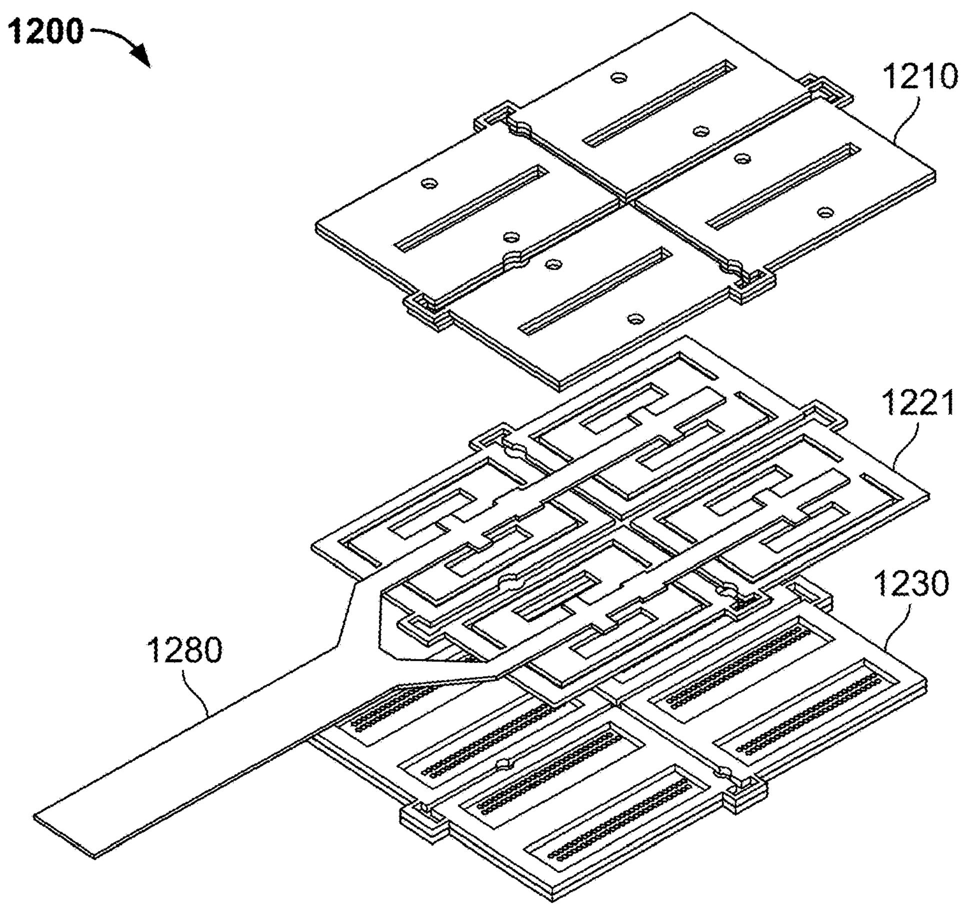

FIG. 12G

TILES HAVING MULTIPLE COOLING CELLS FOR MEMS-BASED COOLING

CROSS REFERENCE TO OTHER APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 17/474,815, entitled TILES HAVING MULTIPLE COOLING CELLS FOR MEMS-BASED COOLING filed Sep. 14, 2021 which is incorporated herein by reference for all purposes, which claims priority to U.S. Provisional Patent Application No. 63/079,450 entitled TILES HAVING MULTIPLE COOLING CELLS FOR MEMS-BASED COOLING filed Sep. 16, 2020, U.S. Provisional Patent Application No. 63/220,371 entitled MEMS-BASED ACTIVE COOLING SYSTEMS INCLUDING COOLING CELL ARRANGEMENT, TABS, ANCHOR BONDING, INTEGRATED SPREADER, ADHESIVE, AND POWER MANAGEMENT filed Jul. 9, 2021, and U.S. Provisional Patent Application No. 63/220,862 entitled PIEZOELECTRIC ACTIVE MEMS COOLING SYSTEMS INCLUDING ENGINEERED ACTUATORS, TAILORED ORIFICES, CONTROLLED GAPS, AND STRIP LEVEL MANUFACTURING filed Jul. 12, 2021, all of which are incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION

[0002] As computing devices grow in speed and computing power, the heat generated by the computing devices also increases. Various mechanisms have been proposed to address the generation of heat. Active devices, such as fans, may be used to drive air through large computing devices, such as laptop computers or desktop computers. Passive cooling devices, such as heat spreaders, may be used in smaller, mobile computing devices, such as smartphones, virtual reality devices and tablet computers. However, such active and passive devices may be unable to adequately cool both mobile devices such as smartphones and larger devices such as laptops and desktop computers. Consequently, additional cooling solutions for computing devices are desired.

BRIEF DESCRIPTION OF THE DRA WINGS

[0003] Various embodiments of the invention are disclosed in the following detailed description and the accompanying drawings.

[0004] FIGS. **1**A-**1**F depict an embodiment of an active cooling system including a centrally anchored cooling element.

[0005] FIGS. **2**A-**2**B depict embodiments of cooling elements usable in active cooling systems including centrally anchored cooling elements.

[0006] FIGS. **3**A-**3**B depict embodiments of cooling elements usable in active cooling systems including centrally anchored cooling elements.

[0007] FIGS. **4**A-**4**B depict an embodiment of an active cooling system including a centrally anchored cooling element.

[0008] FIGS. **5**A-**5**E depict an embodiment of an active cooling system formed in a tile.

[0009] FIGS. **6**A-**6**C depict an embodiment of an active cooling system formed in a tile.

[0010] FIGS. **7**A-**7**C depict an embodiment of an active cooling system formed in a tile.

[0011] FIG. **8** depicts an embodiment of an active cooling system formed in a tile.

[0012] FIG. **9** depicts an embodiment of multiple tiles configured to be used in a computing device.

[0013] FIGS. **10**A-**10**D depict embodiments of tiles having tabs that interconnect cells.

[0014] FIGS. **11**A-**11**D depict embodiments of tiles having tabs that interconnect cells.

[0015] FIGS. **12**A-**12**G depict an embodiment of a tile during fabrication.

DETAILED DESCRIPTION

[0016] The invention can be implemented in numerous ways, including as a process; an apparatus; a system; a composition of matter; a computer program product embodied on a computer readable storage medium; and/or a processor, such as a processor configured to execute instructions stored on and/or provided by a memory coupled to the processor. In this specification, these implementations, or any other form that the invention may take, may be referred to as techniques. In general, the order of the steps of disclosed processes may be altered within the scope of the invention. Unless stated otherwise, a component such as a processor or a memory described as being configured to perform a task may be implemented as a general component that is temporarily configured to perform the task at a given time or a specific component that is manufactured to perform the task. As used herein, the term 'processor' refers to one or more devices, circuits, and/or processing cores configured to process data, such as computer program instructions.

[0017] A detailed description of one or more embodiments of the invention is provided below along with accompanying figures that illustrate the principles of the invention. The invention is described in connection with such embodiments, but the invention is not limited to any embodiment. The scope of the invention is limited only by the claims and the invention encompasses numerous alternatives, modifications and equivalents. Numerous specific details are set forth in the following description in order to provide a thorough understanding of the invention. These details are provided for the purpose of example and the invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the invention is not unnecessarily obscured.

[0018] As semiconductor devices become increasingly powerful, the heat generated during operations also grows. For example, processors for mobile devices such as smartphones, tablet computers, notebooks, and virtual reality devices can operate at high clock speeds, but produce a significant amount of heat. Because of the quantity of heat produced, processors may run at full speed only for a relatively short period of time. After this time expires, throttling (e.g. slowing of the processor's clock speed) occurs. Although throttling can reduce heat generation, it also adversely affects processor speed and, therefore, the performance of devices using the processors. As technology moves to **5**G and beyond, this issue is expected to be exacerbated.

[0019] Larger devices, such as laptop or desktop computers include electric fans that have rotating blades. The fan that can be energized in response to an increase in temperature of internal components. The fans drive air through the larger devices to cool internal components. However, such fans are typically too large for mobile devices such as smartphones or for thinner devices such as tablet computers. Fans also may have limited efficacy because of the boundary layer of air existing at the surface of the components, provide a limited airspeed for air flow across the hot surface desired to be cooled and may generate an excessive amount of noise. Passive cooling solutions may include components such as a heat spreader and a heat pipe or vapor chamber to transfer heat to a heat exchanger. Although a heat spreader somewhat mitigates the temperature increase at hot spots, the amount of heat produced in current and future devices may not be adequately addressed. Similarly, a heat pipe or vapor chamber may provide an insufficient amount of heat transfer to remove excessive heat generated.

[0020] Varying configurations of computing devices further complicate heat management. For example, computing devices such as laptops are frequently open to the external environment while other computing devices, such as smartphones, are generally closed to the external environment. Thus, active heat management solutions for open devices, such as fans, may be inappropriate for closed devices. A fan driving heated fluid from the inside of the computing device to the outside environment may be too large for closed computing devices such as smartphones and may provide limited fluid flow. In addition, the closed computing device has no outlet for the heated fluid even if the fan can be incorporated into the closed computing device. Thus, the thermal management provided by such an open-device mechanism may have limited efficacy. Even for open computing devices, the location of the inlet and/or outlet may be configured differently for different devices. For example, an outlet for fan-driven fluid flow in a laptop may be desired to be located away from the user's hands or other structures that may lie within the outflow of heated fluid. Such a configuration not only prevents the user's discomfort but also allows the fan to provide the desired cooling. Another mobile device having a different configuration may require the inlets and/or outlets to be configured differently, may reduce the efficacy of such heat management systems and may prevent the use of such heat management systems. Thus, mechanisms for improving cooling in computing devices are desired.

[0021] A system including a plurality of cooling cells is described. Each of the cooling cells includes a support structure and a cooling element. The cooling element has a central region having an axis and a perimeter. The cooling element IS supported by the support structure at the central region and along the axis. At least a portion of the perimeter being unpinned. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. A portion of the cooling cells aligned along the axis are physically connected such that the cooling cells form an integrated cooling cell tile.

[0022] In some embodiments, the system also includes an electrical connection coupled to each of the portion of the plurality of cooling cells along the axis. A pedestal may couple each of the portion of the cooling cells to the heat-generating structure. The pedestal is aligned with the axis. The portion of the cooling cells along the axis may be physically connected by the pedestal. In some embodiments, the portion of the cooling cells along the axis are physically connected by a shared support structure. The shared support structure forms the support structure for each of the portion of the cooling cells. In some embodiments, the cooling cells are mechanically connected by tab(s) residing outside of a footprint of the plurality of cooling cells.

[0023] In some embodiments, the system includes an additional plurality of cooling cells, which are analogous to the plurality of cooling cells. The additional plurality of cooling cells form an additional integrated cooling cell tile. The integrated cooling cell tile and the additional integrated cooling cell tile are coupled to the heat-generating structure.

[0024] A system including an integrated cooling cell tile is also described. The cooling cell tile includes a plurality of cooling cells, a plurality of integrated tabs, and an electrical connector. Each of the cooling cells includes a support structure and a cooling element. The cooling element has a central region having an axis and a perimeter. The cooling element is supported by the support structure at the central region and along the axis. At least a portion of the perimeter is unpinned. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. A first portion of the cooling cells aligned along the axis are physically connected. The integrated tabs are mechanically connecting to a second portion of cooling cells. The electrical connector includes at least one longitudinal electrical connector extending along the axis and coupled to the portion of the plurality of cooling cells along the axis.

[0025] In some embodiments, the integrated cooling cell tile further includes pedestal(s) configured to couple each of the portion of the cooling cells to a heat generating-structure. The pedestal is aligned with the axis. The pedestal and/or the support structure physically connect the plurality of cooling cells.

[0026] A method is also described. The method includes providing cooling cells described herein. Aa portion of the plurality of cooling cells aligned along the axis are physically connected such that the plurality of cooling cells form an integrated cooling cell tile. Electrical connection is providing an electrical connection coupled to each of the portion of the plurality of cooling cells along the axis. The method may also provide a pedestal configured to couple each of the portion of the plurality of cooling cells to the heat-generating structure. The pedestal is aligned with the axis. In some embodiments, the portion of the cooling cells along the axis are physically connected by the pedestal. In some embodiments, the method includes providing the support structure as a shared support structure. The portion of the cooling cells along the axis being physically connected by the shared support structure. In some embodiments, providing the cooling cells includes mechanically connecting an additional portion of the cooling cells by at least one tab, the at least one tab residing outside of a footprint of the plurality of cooling cells.

[0027] FIG. **1**A depicts cooling system **100** in a neutral position. Thus, cooling element **120** is shown as substantially flat. For in-phase operation, cooling element **120** is driven to vibrate between positions shown in FIGS. **1**B and **1**C. This vibrational motion draws fluid (e.g. air) into vent **112**, through chambers **140** and **150** and out orifices **132** at high speed and/or flow rates. For example, the speed at which the fluid impinges on heat-generating structure **102** may be at least thirty meters per second. In some embodiments, the fluid is driven by cooling element **120** toward heat-generating structure **102** at a speed of at least forty-five meters per second. In some embodiments, the fluid is driven toward heat-generating structure **102** by cooling element **120** at speeds of at least sixty meters per second. Other speeds may be possible in some embodiments. Cooling system **100** is also configured so that little or no fluid is drawn back into chamber **140/150** through orifices **132** by the vibrational motion of cooling element **120**.

[0028] Heat-generating structure **102** is desired to be cooled by cooling system **100**. In some embodiments, heat-generating structure **102** generates heat. For example, heat-generating structure may be an integrated circuit. In some embodiments, heat-generating structure **102** is desired to be cooled but does not generate heat itself. Heat-generating structure **102** may conduct heat (e.g. from a nearby object that generates heat). For example, heat-generating structure **102** might be a heat spreader or a vapor chamber. Thus, heat-generating structure **102** may include semiconductor component(s) including individual integrated circuit components such as processors, other integrated circuit(s) and/or chip package(s); sensor(s); optical device(s); one or more batteries; other component(s) of an electronic device such as a computing device; heat spreaders; heat pipes; other electronic component(s) and/or other device(s) desired to be cooled. In some embodiments, heat-generating structure **102** may be a thermally conductive part of a module containing cooling system **100**. For example, cooling system **100** may be affixed to heat-generating structure **102**, which may be coupled to another heat sink, vapor chamber, integrated circuit, or other separate structure desired to be cooled.

[0029] The devices in which cooling system **100** is desired to be used may also have limited space in which to place a cooling system. For example, cooling system **100** may be used in computing devices. Such computing devices may include but are not limited to smartphones, tablet computers, laptop computers, tablets, two-in-one laptops, hand held gaming systems, digital cameras, virtual reality headsets, augmented reality headsets, mixed reality headsets and other devices that are thin. Cooling system **100** may be a micro-electro-mechanical system (MEMS) cooling system capable of residing within mobile computing devices and/or other devices having limited space in at least one dimension. For example, the total height of cooling system **100** (from the top of heat-generating structure **102** to the top of top plate **110**) may be less than 2 millimeters. In some embodiments, the total height of cooling system **100** is not more than 1.5 millimeters. In some embodiments, this total height is not more than 1.1 millimeters. In some embodiments, the total height does not exceed one millimeter. In some embodiments, the total height does not exceed two hundred and fifty micrometers. Similarly, the distance between the bottom of orifice plate **130** and the top of heat-generating structure **102**, y, may be small. In some embodiments, y is at least two hundred micrometers and not more than 1.2 millimeter. In some embodiments, y is at least five hundred micrometers and not more than one millimeter. In some embodiments, y is at least two hundred micrometers and not more than three hundred micrometers. Thus, cooling system **100** is usable in computing devices and/or other devices having limited space in at least one dimension. However, nothing prevents the use of cooling system **100** in devices having fewer limitations on space and/or for purposes other than cooling. Although one cooling system **100** is shown (e.g. one cooling cell), multiple cooling systems **100** might be used in connection with heat-generating structure **102**. For example, a one or two-dimensional array of cooling cells might be utilized.

[0030] Cooling system **100** is in communication with a fluid used to cool heat-generating structure **102**. The fluid may be a gas or a liquid. For example, the fluid may be air. In some embodiments, the fluid includes fluid from outside of the device in which cooling system **100** resides (e.g. provided through external vents in the device). In some embodiments, the fluid circulates within the device in which cooling system resides (e.g. in an enclosed device).

[0031] Cooling element **120** can be considered to divide the interior of active cooling system **100** into top chamber **140** and bottom chamber **150**. Top chamber **140** is formed by cooling element **120**, the sides, and top plate **110**. Bottom chamber **150** is formed by orifice plate **130**, the sides, cooling element **120** and anchor **160**. Top chamber **140** and bottom chamber **150** are connected at the periphery of cooling element **120** and together form chamber **140/150** (e.g. an interior chamber of cooling system **100**).

[0032] The size and configuration of top chamber **140** may be a function of the cell (cooling system **100**) dimensions, cooling element **120** motion, and the frequency of operation. Top chamber **140** has a height, h**1**. The height of top chamber **140** may be selected to provide sufficient pressure to drive the fluid to bottom chamber **150** and through orifices **132** at the desired flow rate and/or speed. Top chamber **140** is also sufficiently tall that cooling element **120** does not contact top plate **110** when actuated. In some embodiments, the height of top chamber **140** is at least fifty micrometers and not more than five hundred micrometers. In some embodiments, top chamber **140** has a height of at least two hundred and not more than three hundred micrometers.

[0033] Bottom chamber **150** has a height, h**2**. In some embodiments, the height of bottom chamber **150** is sufficient to accommodate the motion of cooling element **120**. Thus, no portion of cooling element **120** contacts orifice plate **130** during normal operation. Bottom chamber **150** is generally smaller than top chamber **140** and may aid in reducing the backflow of fluid into orifices **132**. In some embodiments, the height of bottom chamber **150** is the maximum deflection of cooling element **120** plus at least five micrometers and not more than ten micrometers. In some embodiments, the deflection of cooling element **120** (e.g. the deflection of tip **121**), z, has an amplitude of at least ten micrometers and not more than one hundred micrometers. In some such embodiments, the amplitude of deflection of cooling element **120** is at least ten micrometers and not more than sixty micrometers. However, the amplitude of deflection of cooling element **120** depends on factors such as the desired flow rate through cooling system **100** and the configuration of cooling system **100**. Thus, the height of bottom chamber **150** generally depends on the flow rate through and other components of cooling system **100**.

[0034] Top plate **110** includes vent **112** through which fluid may be drawn into cooling system **100**. Top vent **112** may have a size chosen based on the desired acoustic pressure in chamber **140**. For example, in some embodiments, the width, w, of vent **112** is at least five hundred micrometers and not more than one thousand micrometers. In some embodiments, the width of vent **112** is at least two hundred fifty micrometers and not more than two thousand micrometers. In the embodiment shown, vent **112** is a centrally located aperture in top plate **110**. In other embodiments, vent **112** may be located elsewhere. For example, vent **112** may be closer to one of the edges of top plate **110**. Vent **112** may have a circular, rectangular or other shaped footprint. Although a single vent **112** is shown, multiple vents might be used. For example, vents may be offset toward the edges of top chamber **140** or be located on the side(s) of top chamber **140**. Although top plate **110** is shown as substantially flat, in some embodiments trenches and/or other structures may be provided in top plate **110** to modify the configuration of top chamber **140** and/or the region above top plate **110**.

[0035] Anchor (support structure) **160** supports cooling element **120** at the central portion of cooling element **120**. Thus, at least part of the perimeter of cooling element **120** is unpinned and free to vibrate. In some embodiments, anchor **160** extends along a central axis of cooling element **120** (e.g. perpendicular to the page in FIGS. **1**A-**1**E). In such embodiments, portions of cooling element **120** that vibrate (e.g. including tip **121**) move in a cantilevered fashion. Thus, portions of cooling element **120** may move in a manner analogous to the wings of a butterfly (i.e. in phase) and/or analogous to a seesaw (i.e. out of phase). Thus, the portions of cooling element **120** that vibrate in a cantilevered fashion do so in phase in some embodiments and out of phase in other embodiments. In some embodiments, anchor **160** does not extend along an axis of cooling element **120**. In such embodiments, all portions of the perimeter of cooling element **120** are free to vibrate (e.g. analogous to a jellyfish). In the embodiment shown, anchor **160** supports cooling element **120** from the bottom of cooling element **120**. In other embodiments, anchor **160** may support cooling element **120** in another manner. For example, anchor **160** may support cooling element **120** from the top (e.g. cooling element **120** hangs from anchor **160**). In some embodiments, the width, a, of anchor **160** is at least 0.5 millimeters and not more than four millimeters. In some embodiments, the width of anchor **160** is at least two millimeters and not more than 2.5 millimeters. Anchor **160** may occupy at least ten percent and not more than fifty percent of cooling element **120**.

[0036] Cooling element **120** has a first side distal from heat-generating structure **102** and a second side proximate to heat-generating structure **102**. In the embodiment shown in FIGS. **1**A-**1**E, the first side of cooling element **120** is the top of cooling element **120** (closer to top plate **110**) and the second side is the bottom of cooling element **120** (closer to orifice plate **130**). Cooling element **120** is actuated to undergo vibrational motion as shown in FIGS. **1**A-**1**E. The vibrational motion of cooling element **120** drives fluid from the first side of cooling element **120** distal from heat-generating structure **102** (e.g. from top chamber **140**) to a second side of cooling element **120** proximate to heat-generating structure **102** (e.g. to bottom chamber **150**). The vibrational motion of cooling element **120** also draws fluid through vent **112** and into top chamber **140**; forces fluid from top chamber **140** to bottom chamber **150**; and drives fluid from bottom chamber **150** through orifices **132** of orifice plate **130**. Thus, cooling element **120** may be viewed as an actuator. Although described in the context of a single, continuous cooling element, in some embodiments, cooling element **120** may be formed by two (or more) cooling elements. Each of the cooling elements as one portion pinned (e.g. supported by support structure **160**) and an opposite portion unpinned. Thus, a single, centrally supported cooling element **120** may be formed by a combination of multiple cooling elements supported at an edge.

[0037] Cooling element **120** has a length, L, that depends upon the frequency at which cooling element **120** is desired to vibrate. In some embodiments, the length of cooling element **120** is at least four millimeters and not more than ten millimeters. In some such embodiments, cooling element **120** has a length of at least six millimeters and not more than eight millimeters. The depth of cooling element **120** (e.g. perpendicular to the plane shown in FIGS. **1**A-**1**E) may vary from one fourth of L through twice L. For example, cooling element **120** may have the same depth as length. The thickness, t, of cooling element **120** may vary based upon the configuration of cooling element **120** and/or the frequency at which cooling element **120** is desired to be actuated. In some embodiments, the cooling element thickness is at least two hundred micrometers and not more than three hundred and fifty micrometers for cooling element **120** having a length of eight millimeters and driven at a frequency of at least twenty kilohertz and not more than twenty-five kilohertz. The length, C of chamber **140/150** is close to the length, L, of cooling element **120**. For example, in some embodiments, the distance, d, between the edge of cooling element **120** and the wall of chamber **140/50** is at least one hundred micrometers and not more than five hundred micrometers. In some embodiments, d is at least two hundred micrometers and not more than three hundred micrometers.

[0038] Cooling element **120** may be driven at a frequency that is at or near both the resonant frequency for an acoustic resonance of a pressure wave of the fluid in top chamber **140** and the resonant frequency for a structural resonance of cooling element **120**. The portion of cooling element **120** undergoing vibrational motion is driven at or near resonance (the “structural resonance”) of cooling element **120**. This portion of cooling element **120** undergoing vibration may be a cantilevered section in some embodiments. The frequency of vibration for structural resonance is termed the structural resonant frequency. Use of the structural resonant frequency in driving cooling element **120** reduces the power consumption of cooling system **100**. Cooling element **120** and top chamber **140** may also be configured such that this structural resonant frequency corresponds to a resonance in a pressure wave in the fluid being driven through top chamber **140** (the acoustic resonance of top chamber **140**). The frequency of such a pressure wave is termed the acoustic resonant frequency. At acoustic resonance, a node in pressure occurs near vent **112** and an antinode in pressure occurs near the periphery of cooling system **100** (e.g. near tip **121** of cooling element **120** and near the connection between top chamber **140** and bottom chamber **150**). The distance between these two regions is C/2. Thus, $C/2=n\lambda/4$, where λ is the acoustic wavelength for the fluid and n is odd (e.g. n=1, 3, 5, etc.). For the lowest order mode, $C=\lambda/2$. Because the length of chamber **140** (e.g. C) is close to the length of cooling element **120**, in some embodiments, it is also approximately true that $L/2=n\lambda/4$, where λ is the acoustic wavelength for the fluid and n is odd. Thus, the frequency at which cooling element **120** is driven, ν, is at or near the structural resonant frequency for cooling element **120**. The frequency ν is also at or near the acoustic resonant frequency for at least top chamber **140**. The acoustic resonant frequency of top chamber **140** generally varies less dramatically with parameters such as temperature and size than the structural resonant frequency of cooling element **120**. Consequently, in some embodiments, cooling element **120** may be driven at (or closer to) a structural resonant frequency than to the acoustic resonant frequency.

[0039] Orifice plate **130** has orifices **132** therein. Although a particular number and distribution of orifices **132** are shown, another number and/or another distribution may be used. A single orifice plate **130** is used for a single cooling system **100**. In other embodiments, multiple cooling systems **100** may share an orifice plate. For example, multiple cells **100** may be provided together in a desired configuration. In such embodiments, the cells **100** may be the same size and configuration or different size(s) and/or configuration(s). Orifices **132** are shown as having an axis oriented normal to a surface of heat-generating structure **102**. In other embodiments, the axis of one or more orifices **132** may be at another angle. For example, the angle of the axis may be selected from substantially zero degrees and a nonzero acute angle. Orifices **132** also have sidewalls that are substantially parallel to the normal to the surface of orifice plate **130**. In some embodiments, orifices may have sidewalls at a nonzero angle to the normal to the surface of orifice plate **130**. For example, orifices **132** may be cone-shaped. Further, although orifice place **130** is shown as substantially flat, in some embodiments, trenches and/or other structures may be provided in orifice plate **130** to modify the configuration of bottom chamber **150** and/or the region between orifice plate **130** and heat-generating structure **102**.

[0040] The size, distribution and locations of orifices **132** are chosen to control the flow rate of fluid driven to the surface of heat-generating structure **102**. The locations and configurations of orifices **132** may be configured to increase/maximize the fluid flow from bottom chamber **150** through orifices **132** to the jet channel (the region between the bottom of orifice plate **130** and the top of heat-generating structure **102**). The locations and configurations of orifices **132** may also be selected to reduce/minimize the suction flow (e.g. back flow) from the jet channel through orifices **132**. For example, the locations of orifices are desired to be sufficiently far from tip **121** that suction in the upstroke of cooling element **120** (tip **121** moves away from orifice plate **13**) that would pull fluid into bottom chamber **150** through orifices **132** is reduced. The locations of orifices are also desired to be sufficiently close to tip **121** that suction in the upstroke of cooling element **120** also allows a higher pressure from top chamber **140** to push fluid from top chamber **140** into bottom chamber **150**. In some embodiments, the ratio of the flow rate from top chamber **140** into bottom chamber **150** to the flow rate from the jet channel through orifices **132** in the upstroke (the "net flow ratio") is greater than 2:1. In some embodiments, the net flow ratio is at least 85:15. In some embodiments, the net flow ratio is at least 90:10. In order to provide the desired pressure, flow rate, suction, and net flow ratio, orifices **132** are desired to be at least a distance, **r1**, from tip **121** and not more than a distance, **r2**, from tip **121** of cooling element **120**. In some embodiments **r1** is at least one hundred micrometers (e.g. $r1 \geq 100\ \mu m$) and **r2** is not more than one millimeter (e.g. $r2 \leq 1000\ \mu m$). In some embodiments, orifices **132** are at least two hundred micrometers from tip **121** of cooling element **120** (e.g. $r1 \geq 200\ \mu m$). In some such embodiments, orifices **132** are at least three hundred micrometers from tip **121** of cooling element **120** (e.g. $r1 \geq 300\ \mu m$). In some embodiments, orifices **132** have a width, o, of at least one hundred micrometers and not more than five hundred micrometers. In some embodiments, orifices **132** have a width of at least two hundred micrometers and not more than three hundred micrometers. In some embodiments, the orifice separation, s, is at least one hundred micrometers and not more than one millimeter. In some such embodiments, the orifice separation is at least four hundred micrometers and not more than six hundred micrometers. In some embodiments, orifices **132** are also desired to occupy a particular fraction of the area of orifice plate **130**. For example, orifices **132** may cover at least five percent and not more than fifteen percent of the footprint of orifice plate **130** in order to achieve a desired flow rate of fluid through orifices **132**. In some embodiments, orifices **132** cover at least eight percent and not more than twelve percent of the footprint of orifice plate **130**.

[0041] In some embodiments, cooling element **120** is actuated using a piezoelectric. Thus, cooling element **120** may be a piezoelectric cooling element. Cooling element **120** may be driven by a piezoelectric that is mounted on or integrated into cooling element **120**. In some embodiments, cooling element **120** is driven in another manner including but not limited to providing a piezoelectric on another structure in cooling system **100**. Cooling element **120** and analogous cooling elements are referred to hereinafter as piezoelectric cooling element though it is possible that a mechanism other than a piezoelectric might be used to drive the cooling element. In some embodiments, cooling element **120** includes a piezoelectric layer on substrate. The substrate may include or consist of stainless steel, a Ni alloy, Hastelloy, Al (e.g. an Al alloy), and/or a Ti (e.g. a Ti alloy such as Ti6Al-4V). In some embodiments, piezoelectric layer includes multiple sublayers formed as thin films on the substrate. In other embodiments, the piezoelectric layer may be a bulk layer affixed to the substrate. Such a piezoelectric cooling element **120** also includes electrodes used to activate the piezoelectric. The substrate functions as an electrode in some embodiments. In other embodiments, a bottom electrode may be provided between the substrate and the piezoelectric layer. Other layers including but not limited to seed, capping, passivation or other layers might be included in piezoelectric cooling element. Thus, cooling element **120** may be actuated using a piezoelectric.

[0042] In some embodiments, cooling system **100** includes chimneys (not shown) or other ducting. Such ducting provides a path for heated fluid to flow away from heat-generating structure **102**. In some embodiments, ducting returns fluid to the side of top plate **110** distal from heat-generating structure **102**. In some embodiments, ducting may instead direct fluid away from heat-generating structure **102** in a direction parallel to heat-generating structure **102** or perpendicular to heat-generating structure **102** but in the opposite direction (e.g. toward the bottom of the page). For a device in which fluid external to the device is used in cooling system **100**, the ducting may channel the heated fluid to a vent. In such embodiments, additional fluid may be provided from an inlet vent. In embodiments, in which the device is enclosed, the ducting may provide a circuitous path back to the region near vent **112** and distal from heat-generating structure **102**. Such a path allows for the fluid to dissipate heat before being reused to cool heat-generating structure **102**. In other embodiments, ducting may be omitted or configured in another manner. Thus, the fluid is allowed to carry away heat from heat-generating structure **102**.

[0043] Operation of cooling system **100** is described in the context of FIGS. **1**A-**1**E. Although described in the context of particular pressures, gap sizes, and timing of flow, operation of cooling system **100** is not dependent upon the explanation herein. FIGS. **1**B-**1**C depict in-phase operation of cooling system **100**. Referring to FIG. **1**B, cooling element **120** has been actuated so that its tip **121** moves away from top plate **110**. FIG. **1**B can thus be considered to depict the end of a down stroke of cooling element **120**. Because of the vibrational motion of cooling element **120**, gap **152** for bottom chamber **150** has decreased in size and is shown as gap **152**B. Conversely, gap **142** for top chamber **140** has increased in size and is shown as gap **142**B. During the down stroke, a lower (e.g. minimum) pressure is developed at the periphery when cooling element **120** is at the neutral position. As the down stroke continues, bottom chamber **150** decreases in size and top chamber **140** increases in size as shown in FIG. **1**B. Thus, fluid is driven out of orifices **132** in a direction that is at or near perpendicular to the surface of orifice plate **130** and/or the top surface of heat-generating structure **102**. The fluid is driven from orifices **132** toward heat-generating structure **102** at a high speed, for example in excess of thirty-five meters per second. In some embodiments, the fluid then travels along the surface of heat-generating structure **102** and toward the periphery of heat-generating structure **102**, where the pressure is lower than near orifices **132**. Also in the down stroke, top chamber **140** increases in size and a lower pressure is present in top chamber **140**. As a result, fluid is drawn into top chamber **140** through vent **112**. The motion of the fluid into vent **112**, through orifices **132**, and along the surface of heat-generating structure **102** is shown by unlabeled arrows in FIG. **1**B.

[0044] Cooling element **120** is also actuated so that tip **121** moves away from heat-generating structure **102** and toward top plate **110**. FIG. **1**C can thus be considered to depict the end of an up stroke of cooling element **120**. Because of the motion of cooling element **120**, gap **142** has decreased in size and is shown as gap **142**C. Gap **152** has increased in size and is shown as gap **152**C. During the upstroke, a higher (e.g. maximum) pressure is developed at the periphery when cooling element **120** is at the neutral position. As the upstroke continues, bottom chamber **150** increases in size and top chamber **140** decreases in size as shown in FIG. **1**C. Thus, the fluid is driven from top chamber **140** (e.g. the periphery of chamber **140**/**150**) to bottom chamber **150**. Thus, when tip **121** of cooling element **120** moves up, top chamber **140** serves as a nozzle for the entering fluid to speed up and be driven towards bottom chamber **150**. The motion of the fluid into bottom chamber **150** is shown by unlabeled arrows in FIG. **1**C. The location and configuration of cooling element **120** and orifices **132** are selected to reduce suction and, therefore, back flow of fluid from the jet channel (between heat-generating structure **102** and orifice plate **130**) into orifices **132** during the upstroke. Thus, cooling system **100** is able to drive fluid from top chamber **140** to bottom chamber **150** without an undue amount of backflow of heated fluid from the jet channel entering bottom chamber **140**. Moreover, cooling system **100** may operate such that fluid is drawn in through vent **112** and driven out through orifices **132** without cooling element **120** contacting top plate **110** or orifice plate **130**. Thus, pressures are developed within chambers **140** and **150** that effectively open and close vent **112** and orifices **132** such that fluid is driven through cooling system **100** as described herein.

[0045] The motion between the positions shown in FIGS. **1**B and **1**C is repeated. Thus, cooling element **120** undergoes vibrational motion indicated in FIGS. **1**A-**1**C, drawing fluid through vent **112** from the distal side of top plate **110** into top chamber **140**; transferring fluid from top chamber **140** to bottom chamber **150**; and pushing the fluid through orifices **132** and toward heat-generating structure **102**. As discussed above, cooling element **120** is driven to vibrate at or near the structural resonant frequency of cooling element **120**. Further, the structural resonant frequency of cooling element **120** is configured to align with the acoustic resonance of the chamber **140**/**150**. The structural and acoustic resonant frequencies are generally chosen to be in the ultrasonic range. For example, the vibrational motion of cooling element **120** may be at frequencies from 15 kHz through 30 kHz. In some embodiments, cooling element **120** vibrates at a frequency/frequencies of at least 20 kHz and not more than 30 kHz. The structural resonant frequency of cooling element **120** is within ten percent of the acoustic resonant frequency of cooling system **100**. In some embodiments, the structural resonant frequency of cooling element **120** is within five percent of the acoustic resonant frequency of cooling system **100**. In some embodiments, the structural resonant frequency of cooling element **120** is within three percent of the acoustic resonant frequency of cooling system **100**. Consequently, efficiency and flow rate may be enhanced. However, other frequencies may be used.

[0046] Fluid driven toward heat-generating structure **102** may move substantially normal (perpendicular) to the top surface of heat-generating structure **102**. In some embodiments, the fluid motion may have a nonzero acute angle with respect to the normal to the top surface of heat-generating structure **102**. In either case, the fluid may thin and/or form apertures in the boundary layer of fluid at heat-generating structure **102**. As a result, transfer of heat from heat-generating structure **102** may be improved. The fluid deflects off of heat-generating structure **102**, traveling along the surface of heat-generating structure **102**. In some embodiments, the fluid moves in a direction substantially parallel to the top of heat-generating structure **102**. Thus, heat from heat-generating structure **102** may be extracted by the fluid. The fluid may exit the region between orifice plate **130** and heat-generating structure **102** at the edges of cooling system **100**. Chimneys or other ducting (not shown) at the edges of cooling system **100** allow fluid to be carried away from heat-generating structure **102**. In other embodiments, heated fluid may be transferred further from heat-generating structure **102** in another manner. The fluid may exchange the heat transferred from heat-generating structure **102** to another structure or to the ambient environment. Thus, fluid at the distal side of top plate **110** may remain relatively cool, allowing for the additional extraction of heat. In some embodiments, fluid is circulated, returning to distal side of top plate **110** after cooling. In other embodiments, heated fluid is carried away and replaced by new fluid at the distal side of cooling element **120**. As a result, heat-generating structure **102** may be cooled.

[0047] FIGS. **1**D-**1**E depict an embodiment of active cooling system **100** including centrally anchored cooling element **120** in which the cooling element is driven out-of-phase. More specifically, sections of cooling element **120** on opposite sides of anchor **160** (and thus on opposite sides of the central region of cooling element **120** that is supported by anchor **160**) are driven to vibrate out-of-phase. In some embodiments, sections of cooling element **120** on opposite sides of anchor **160** are driven at or near one hundred and eighty degrees out-of-phase. Thus, one section of cooling element **120** vibrates toward top plate **110**, while the other section of cooling element **120** vibrates toward orifice plate **130**/heat-generating structure **102**. Movement of a section of cooling element **120** toward top plate **110** (an upstroke) drives fluid in top chamber **140** to bottom chamber **150** on that side of anchor **160**. Movement of a section of cooling element **120** toward orifice plate **130** drives fluid through orifices **132** and toward heat-generating structure **102**. Thus, fluid traveling at high speeds (e.g. speeds described with respect to in-phase operation) is alternately driven out of orifices **132** on opposing sides of anchor **160**. The movement of fluid is shown by unlabeled arrows in FIGS. **1**D and **1**E.

[0048] The motion between the positions shown in FIGS. **1**D and **1**E is repeated. Thus, cooling element **120** undergoes vibrational motion indicated in FIGS. **1**A, **1**D, and **1**E, alternately drawing fluid through vent **112** from the distal side of top plate **110** into top chamber **140** for each side of cooling element **120**; transferring fluid from each side of top chamber **140** to the corresponding side of bottom chamber **150**; and pushing the fluid through orifices **132** on each side of anchor **160** and toward heat-generating structure **102**. As discussed above, cooling element **120** is driven to vibrate at or near the structural resonant frequency of cooling element **120**. Further, the structural resonant frequency of cooling element **120** is configured to align with the acoustic resonance of the chamber **140**/**150**. The structural and acoustic resonant frequencies are generally chosen to be in the ultrasonic range. For example, the vibrational motion of cooling element **120** may be at the frequencies described for in-phase vibration. The structural resonant frequency of cooling element **120** is within ten percent of the acoustic resonant frequency of cooling system **100**. In some embodiments, the structural resonant frequency of cooling element **120** is within five percent of the acoustic resonant frequency of cooling system **100**. In some embodiments, the structural resonant frequency of cooling element **120** is within three percent of the acoustic resonant frequency of cooling system **100**. Consequently, efficiency and flow rate may be enhanced. However, other frequencies may be used.

[0049] Fluid driven toward heat-generating structure **102** for out-of-phase vibration may move substantially normal (perpendicular) to the top surface of heat-generating structure **102**, in a manner analogous to that described above for in-phase operation. Similarly, chimneys or other ducting (not shown) at the edges of cooling system **100** allow fluid to be carried away from heat-generating structure **102**. In other embodiments, heated fluid may be transferred further from heat-generating structure **102** in another manner. The fluid may exchange the heat transferred from heat-generating structure **102** to another structure or to the ambient environment. Thus, fluid at the distal side of top plate **110** may remain relatively cool, allowing for the additional extraction of heat. In some embodiments, fluid is circulated, returning to distal side of top plate **110** after cooling. In other embodiments, heated fluid is carried away and replaced by new fluid at the distal side of cooling element **120**. As a result, heat-generating structure **102** may be cooled.

[0050] Although shown in the context of a uniform cooling element in FIGS. **1A**-**1E**, cooling system **100** may utilize cooling elements having different shapes. FIG. **1**F depicts an embodiment of engineered cooling element **120'** having a tailored geometry and usable in a cooling system such as cooling system **100**. Cooling element **120'** includes an anchored region **122** and cantilevered arms **123**. Anchored region **122** is supported (e.g. held in place) in cooling system **100** by anchor **160**. Cantilevered arms **123** undergo vibrational motion in response to cooling element **120'** being actuated. Each cantilevered arm **123** includes step region **124**, extension region **126** and outer region **128**. In the embodiment shown in FIG. **1**F, anchored region **122** is centrally located. Step region **124** extends outward from anchored region **122**. Extension region **126** extends outward from step region **124**. Outer region **128** extends outward from extension region **126**. In other embodiments, anchored region **122** may be at one edge of the actuator and outer region **128** at the opposing edge. In such embodiments, the actuator is edge anchored.

[0051] Extension region **126** has a thickness (extension thickness) that is less than the thickness of step region **124** (step thickness) and less than the thickness of outer region **128** (outer thickness). Thus, extension region **126** may be viewed as recessed. Extension region **126** may also be seen as providing a larger bottom chamber **150**. In some embodiments, the outer thickness of outer region **128** is the same as the step thickness of step region **124**. In some embodiments, the outer thickness of outer region **128** is different from the step thickness of step region **124**. In some embodiments, outer region **128** and step region **124** each have a thickness of at least three hundred twenty micrometers and not more than three hundred and sixty micrometers. In some embodiments, the outer thickness is at least fifty micrometers and not more than two hundred micrometers thicker than the extension thickness. Stated differently, the step (difference in step thickness and extension thickness) is at least fifty micrometers and not more than two hundred micrometers. In some embodiments, the outer step (difference in outer thickness and extension thickness) is at least fifty micrometers and not more than two hundred micrometers. Outer region **128** may have a width, o, of at least one hundred micrometers and not more than three hundred micrometers. Extension region has a length, e, extending outward from the step region of at least 0.5 millimeter and not more than 1.5 millimeters in some embodiments. In some embodiments, outer region **128** has a higher mass per unit length in the direction from anchored region **122** than extension region **126**. This difference in mass may be due to the larger size of outer region **128**, a difference in density between portions of cooling element **120**, and/or another mechanism.

[0052] Use of engineered cooling element **120'** may further improve efficiency of cooling system **100**. Extension region **126** is thinner than step region **124** and outer region **128**. This results in a cavity in the bottom of cooling element **120'** corresponding to extension region **126**. The presence of this cavity aids in improving the efficiency of cooling system **100**. Each cantilevered arm **123** vibrates towards top plate **110** in an upstroke and away from top plate **110** in a downstroke. When a cantilevered arm **123** moves toward top plate **110**, higher pressure fluid in top chamber **140** resists the motion of cantilevered arm **123**. Furthermore, suction in bottom chamber **150** also resists the upward motion of cantilevered arm **123** during the upstroke. In the downstroke of cantilevered arm **123**, increased pressure in the bottom chamber **150** and suction in top chamber **140** resist the downward motion of cantilevered arm **123**. However, the presence of the cavity in cantilevered arm **123** corresponding to extension region **126** mitigates the suction in bottom chamber **150** during an upstroke. The cavity also reduces the increase in pressure in bottom chamber **150** during a downstroke. Because the suction and pressure increase are reduced in magnitude, cantilevered arms **123** may more readily move through the fluid. This may be achieved while substantially maintaining a higher pressure in top chamber **140**, which drives the fluid flow through cooling system **100**. Moreover, the presence of outer region **128** may improve the ability of cantilevered arm **123** to move through the fluid being driven through cooling system **100**. Outer region **128** has a higher mass per unit length and thus a higher momentum. Consequently, outer region **128** may improve the ability of cantilevered arms **123** to move through the fluid being driven through cooling system **100**. The magnitude of the deflection of cantilevered arm **123** may also be increased. These benefits may be achieved while maintaining the stiffness of cantilevered arms **123** through the use of thicker step region **124**. Further, the larger thickness of outer region **128** may aid in pinching off flow at the bottom of a downstroke. Thus, the ability of cooling element **120'** to provide a valve preventing backflow through orifices **132** may be improved. Thus, performance of cooling system **100** employing cooling element **120'** may be improved.

[0053] Using the cooling system **100** actuated for in-phase vibration or out-of-phase vibration of cooling element **120** and/or **120'**, fluid drawn in through vent **112** and driven through orifices **132** may efficiently dissipate heat from heat-generating structure **102**. Because fluid impinges upon the heat-generating structure with sufficient speed (e.g. at least thirty meters per second) and in some embodiments substantially normal to the heat-generating structure, the boundary layer of fluid at the heat-generating structure may be thinned and/or partially removed. Consequently, heat transfer between heat-generating structure **102** and the moving fluid is improved. Because the heat-generating structure is more efficiently cooled, the corresponding integrated circuit may be run at higher speed and/or power for longer times. For example, if the heat-generating structure corresponds to a high-speed processor, such a processor may be run for longer times before throttling. Thus, performance of a device utilizing cooling system **100** may be improved. Further, cooling system **100** may be a MEMS device. Consequently, cooling systems **100** may be suitable for use in smaller and/or mobile devices, such as smart phones, other mobile phones, virtual reality headsets, tablets, two-in-one computers, wearables and handheld games, in which limited space is available. Performance of such devices may thus be improved. Because cooling element **120/120'** may be vibrated at frequencies of 15 kHz or more, users may not hear any noise associated with actuation of cooling elements. If driven at or near structural and/or acoustic resonant frequencies, the power used in operating cooling systems may be significantly reduced. Cooling element **120/120'** does not physically contact top plate **110** or orifice plate **130** during vibration. Thus, resonance of cooling element **120/120'** may be more readily maintained. More specifically, physical contact between cooling element **120/120'** and other structures disturbs the resonance conditions for cooling element **120/120'**. Disturbing these conditions may drive cooling element **120/120'** out of resonance. Thus, additional power would need to be used to maintain actuation of cooling element **120/120'**. Further, the flow of fluid driven by cooling element **120/120'** may decrease. These issues are avoided through the use of pressure differentials and fluid flow as discussed above. The benefits of improved, quiet cooling may be achieved with limited additional power. Further, out-of-phase vibration of cooling element **120/120'** allows the position of the center of mass of cooling element **100** to remain more stable. Although a torque is exerted on cooling element **120/120'**, the force due to the motion of the center of mass is reduced or eliminated. As a result, vibrations due to the motion of cooling element **120/120'** may be reduced. Moreover, efficiency of cooling system **100** may be improved through the use of out-of-phase vibrational motion for the two sides of cooling element **120/120'**. Consequently, performance of devices incorporating the cooling system **100** may be improved. Further, cooling system **100** may be usable in other applications (e.g. with or without heat-generating structure **102**) in which high fluid flows and/or velocities are desired.

[0054] FIGS. **2**A-**2**B depict plan views of embodiments of cooling systems **200**A and **200**B analogous to active cooling systems such as cooling system **100**. FIGS. **2**A and **2**B are not to scale. For simplicity, only portions of cooling elements **220**A and **220**B and anchors **260**A and **260**B, respectively, are shown. Cooling elements **220**A and **220**B are analogous to cooling element **120/120'**. Thus, the sizes and/or materials used for cooling elements **220**A and/or **220**B may be analogous to those for cooling element **120/120'**. Anchors (support structures) **260**A and **260**B are analogous to anchor **160** and are indicated by dashed lines.

[0055] For cooling elements **220**A and **220**B, anchors **260**A and **260**B are centrally located and extend along a central axis of cooling elements **220**A and **220**B, respectively. Thus, the cantilevered portions that are actuated to vibrate are to the right and left of anchors **260**A and **260**B. In some embodiments, cooling element(s) **220**A and/or **220**B are continuous structures, two portions of which are actuated (e.g. the cantilevered portions outside of anchors **260**A and **260**B). In some embodiments, cooling element(s) **220**A and/or **220**B include separate cantilevered portions each of which is attached to the anchors **260**A and **260**B, respectively, and actuated. Cantilevered portions of cooling elements **220**A and **220**B may thus be configured to vibrate in a manner analogous to the wings of a butterfly (in-phase) or to a seesaw (out-of-phase). In FIGS. **2**A and **2**B, L is the length of the cooling element, analogous to that depicted in FIGS. **1**A-**1**E. Also in FIGS. **2**A and **2**B, the depth, P, of cooling elements **220**A and **220**B is indicated.

[0056] Also shown by dotted lines in FIGS. **2**A-**2**B are piezoelectric **223**. Piezoelectric **223** is used to actuate cooling elements **220**A and **220**B. In some embodiments, piezoelectric **223** may be located in another region and/or have a different configuration. Although described in the context of a piezoelectric, another mechanism for actuating cooling elements **220**A and **220**B can be utilized. Such other mechanisms may be at the locations of piezoelectric **223** or may be located elsewhere. In cooling element **220**A, piezoelectric **223** may be affixed to cantilevered portions or may be integrated into cooling element **220**A. Further, although piezoelectric **223** is shown as having particular shapes and sizes in FIGS. **2**A and **2**B, other configurations may be used.

[0057] In the embodiment shown in FIG. **2**A, anchor **260**A extends the entire depth of cooling element **220**A. Thus, a portion of the perimeter of cooling element **220**A is pinned.

The unpinned portions of the perimeter of cooling element **220**A are part of the cantilevered sections that undergo vibrational motion. In other embodiments, anchor need not extend the entire length of the central axis. In such embodiments, the entire perimeter of the cooling element is unpinned. However, such a cooling element still has cantilevered sections configured to vibrate in a manner described herein. For example, in FIG. **2**B, anchor **260**B does not extend to the perimeter of cooling element **220**B. Thus, the perimeter of cooling element **220**B is unpinned. However, anchor **260**B still extends along the central axis of cooling element **220**B. Cooling element **220**B is still actuated such that cantilevered portions vibrate (e.g. analogous to the wings of a butterfly).

[0058] Although cooling element **220** A is depicted as rectangular, cooling elements may have another shape. In some embodiments, corners of cooling element **220**A may be rounded. Cooling element **220**B of FIG. **2**B has rounded cantilevered sections. Other shapes are possible. In the embodiment shown in FIG. 2B, anchor **260**B is hollow and includes apertures **263**. In some embodiments, cooling element **220**B has aperture(s) in the region of anchor **260**B. In some embodiments, cooling element **220**B includes multiple portions such that aperture(s) exist in the region of anchor **260**B. As a result, fluid may be drawn through cooling element **220**B and through anchor **260**B. Thus, cooling element **220**B may be used in place of a top plate, such as top plate **110**. In such embodiments, apertures in cooling element **220**B and apertures **263** may function in an analogous manner to vent **112**. Further, although cooling elements **200**A and **200**B are depicted as being supported in a central region, in some embodiments, one cantilevered section of the cooling element **220**A and/or **220**B might be omitted. In such embodiments, cooling element **220**A and/or **220**B may be considered to be supported, or anchored, at or near one edge, while at least part of at least the opposing edge is free to undergo vibrational motion. In some such embodiments, the cooling element **220**A and/or **220**B may include a single cantilevered section that undergoes vibrational motion.

[0059] FIGS. **3**A-**3**B depict plan views of embodiments of cooling systems **300**A and **300**B analogous to active cooling systems such as cooling system **100**. FIGS. **3**A and **3**B are not to scale. For simplicity, only cooling elements **320**A and **320**B and anchors **360**A and **360**B, respectively, are shown. Cooling elements **320**A and **320**B are analogous to cooling element **120**/**120'**. Thus, the sizes and/or materials used for cooling elements **320**A and/or **320**B may be analogous to those for cooling element **120**/**120'**. Anchors **360**A and **360**B are analogous to anchor **160** and are indicated by dashed lines.

[0060] For cooling elements **320**A and **320**B, anchors **360**A and **360**B, respectively, are limited to a central region of cooling elements **320**A and **320**B, respectively. Thus, the regions surrounding anchors **360**A and **360**B undergo vibrational motion. Cooling elements **320**A and **320**B may thus be configured to vibrate in a manner analogous to a jellyfish or similar to the opening/closing of an umbrella. In some embodiments, the entire perimeter of cooling elements **320**A and **320**B vibrate in phase (e.g. all move up or down together). In other embodiments, portions of the perimeter of cooling elements **320**A and **320**B vibrate out of phase. In FIGS. **3**A and **3**B, L is the length (e.g. diameter) of the cooling element, analogous to that depicted in FIGS. **1**A-**1**E. Although cooling elements **320**A and **320**B are depicted as circular, cooling elements may have another shape. Further, a piezoelectric (not shown in FIGS. **3**A-**3**B) and/or other mechanism may be used to drive the vibrational motion of cooling elements **320**A and **320**B.

[0061] In the embodiment shown in FIG. **3**B, the anchor **360**B is hollow and has apertures **363**. In some embodiments, cooling element **320**B has aperture(s) in the region of anchor **360**B. In some embodiments, cooling element **320**B includes multiple portions such that aperture(s) exist in the region of anchor **360**B. As a result, fluid may be drawn through cooling element **320**B and through anchor **360**B. The fluid may exit through apertures **363**. Thus, cooling element **320**B may be used in place of a top plate, such as top plate **110**. In such embodiments, apertures in cooling element **320**B and apertures **363** may function in an analogous manner to vent **112**.

[0062] Cooling systems such as cooling system **100** can utilize cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements. Such cooling systems may also share the benefits of cooling system **100**. Cooling systems using cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements may more efficiently drive fluid toward heat-generating structures at high speeds. Consequently, heat transfer between the heat-generating structure and the moving fluid is improved. Because the heat-generating structure is more efficiently cooled, the corresponding device may exhibit improved operation, such as running at higher speed and/or power for longer times. Cooling systems employing cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements may be suitable for use in smaller and/or mobile devices in which limited space is available. Performance of such devices may thus be improved. Because cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements may be vibrated at frequencies of 15 kHz or more, users may not hear any noise associated with actuation of cooling elements. If driven at or near the acoustic and/or structural resonance frequencies for the cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements, the power used in operating cooling systems may be significantly reduced. Cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements may not physically contact the plates during use, allowing resonance to be more readily maintained. The benefits of improved, quiet cooling may be achieved with limited additional power. Consequently, performance of devices incorporating the cooling element(s) **220**A, **220**B, **320**A, **320**B and/or analogous cooling elements may be improved.

[0063] FIGS. **4**A-**4**B depict an embodiment of active cooling system **400** including a top centrally anchored cooling element. FIG. **4**A depicts a side view of cooling system **400** in a neutral position. FIG. **4**B depicts a top view of cooling system **400**. FIGS. **4**A-**4**B are not to scale. For simplicity, only portions of cooling system **400** are shown. Referring to FIGS. **4**A-**10**B, cooling system **400** is analogous to cooling system **100**. Consequently, analogous components have similar labels. For example, cooling system **400** is used in conjunction with heat-generating structure **402**, which is analogous to heat-generating structure **102**.

[0064] Cooling system **400** includes top plate **410** having vents **412**, cooling element **420**, orifice plate **430** including orifices **432**, top chamber **440** having a gap, bottom chamber **450** having a gap, flow chamber **440**/**450**, and anchor (i.e. support structure) **460** that are analogous to top plate **110**

having vent **112**, cooling element **220**, orifice plate **130** including orifices **132**, top chamber **140** having gap **142**, bottom chamber **150** having gap **152**, flow chamber **140**/**150**, and anchor (i.e. support structure) **160**, respectively. Thus, cooling element **420** is centrally supported by anchor **460** such that at least a portion of the perimeter of cooling element **420** is free to vibrate. In some embodiments, anchor **460** extends along the axis of cooling element **420** (e.g. in a manner analogous to anchor **260**A and/or **260**B). In other embodiments, anchor **460** is only near the center portion of cooling element **420** (e.g. analogous to anchor **460**C and/or **460**D). Although not explicitly labeled in FIGS. **4**A and **4**B, cooling element **420** includes an anchored region and cantilevered arms including step region, extension region and outer regions analogous to anchored region **122**, cantilevered arms **123**, step region **124**, extension region **126** and outer region **128** of cooling element **120'**. In some embodiments, cantilevered arms of cooling element **420** are driven in-phase. In some embodiments, cantilevered arms of cooling element **420** are driven out-of-phase. In some embodiments, a simple cooling element, such as cooling element **120**, may be used.

[0065] Anchor **460** supports cooling element **420** from above. Thus, cooling element **420** is suspended from anchor **460**. Anchor **460** is suspended from top plate **410**. Top plate **410** includes vent **413**. Vents **412** on the sides of anchor **460** provide a path for fluid to flow into sides of chamber **440**.

[0066] As discussed above with respect to cooling system **100**, cooling element **420** may be driven to vibrate at or near the structural resonant frequency of cooling element **420**. Further, the structural resonant frequency of cooling element **420** may be configured to align with the acoustic resonance of the chamber **440**/**1050**. The structural and acoustic resonant frequencies are generally chosen to be in the ultrasonic range. For example, the vibrational motion of cooling element **420** may be at the frequencies described with respect to cooling system **100**. Consequently, efficiency and flow rate may be enhanced. However, other frequencies may be used.

[0067] Cooling system **400** operates in an analogous manner to cooling system **100**. Cooling system **400** thus shares the benefits of cooling system **100**. Thus, performance of a device employing cooling system **400** may be improved. In addition, suspending cooling element **420** from anchor **460** may further enhance performance. In particular, vibrations in cooling system **400** that may affect other cooling cells (not shown), may be reduced. For example, less vibration may be induced in top plate **410** due to the motion of cooling element **420**. Consequently, cross talk between cooling system **400** and other cooling systems (e.g. other cells) or other portions of the device incorporating cooling system **400** may be reduced. Thus, performance may be further enhanced.

[0068] FIGS. **5**A-**5**E depict an embodiment of active cooling system **500** including multiple cooling cells configured as a tile, or array. FIG. **5**A depicts a top view, while FIGS. **5**B-**5**E depict side views. FIGS. **5**A-**5**E are not to scale. Cooling system **500** includes four cooling cells **501**A, **501**B, **501**C and **501**D (collectively or generically **501**), which are analogous to one or more of cooling systems described herein. More specifically, cooling cells **501** are analogous to cooling system **100** and/or **400**. Although four cooling cells **501** in a 2×2 configuration are shown, in some embodiments another number and/or another configuration of cooling cells **501** might be employed. In the embodiment shown, cooling cells **501** include shared top plate **510** having apertures **512**, cooling elements **520**, shared orifice plate **530** including orifices **532**, top chambers **540**, bottom chambers **550** and anchors (support structures) **560** that are analogous to top plate **110** having apertures **112**, cooling element **120**, orifice plate **130** having orifices **132**, top chamber **140**, bottom chamber **150** and anchor **160**. In some embodiments, cooling cells **501** may be fabricated together and separated, for example by cutting through top plate **510**, side walls between cooling cells **501**, and orifice plate **530**. Thus, although described in the context of a shared top plate **510** and shared orifice plate **530**, after fabrication cooling cells **501** may be separated. In some embodiments, tabs (not shown) and/or other structures such as anchors **560**, may connect cooling cells **501**. Further, tile **500** may be affixed to a heat-generating structure (e.g. a heat sink, integrated circuit, or other structure) that may be part of an integrated system including tile **500** or may be separate from tile **500**. In addition, a hood or other mechanism for directing fluid flow outside of cooling cells **501**, mechanical stability, or protection may also be included. Electrical connection to cooling cells **501** is also not shown in FIGS. **5**A-**5**E. Cooling elements **520** are driven out-of-phase (i.e. in a manner analogous to a seesaw). Further, as can be seen in FIGS. **5**B-**5**C and FIGS. **5**D-**5**E cooling element **520** in one cell is driven out-of-phase with cooling element(s) **520** in adjacent cell(s). In FIGS. **5**B-**5**C, cooling elements **520** in a row are driven out-of-phase. Thus, cooling element **520** in cell **501**A is out-of-phase with cooling element **520** in cell **501**B. Similarly, cooling element **520** in cell **501**C is out-of-phase with cooling element **520** in cell **501**D. In FIGS. **5**D-**5**E, cooling elements **520** in a column are driven out-of-phase. Thus, cooling element **520** in cell **501**A is out-of-phase with cooling element **520** in cell **501**C. Similarly, cooling element **520** in cell **501**B is out-of-phase with cooling element **520** in cell **501**D. By driving cooling elements **520** out-of-phase, vibrations in cooling system **500** may be reduced.

[0069] Cooling cells **501** of cooling system **500** functions in an analogous manner to cooling system(s) **100**, **400**, and/or an analogous cooling system. Consequently, the benefits described herein may be shared by cooling system **500**. Because cooling elements in nearby cells are driven out-of-phase, vibrations in cooling system **500** may be reduced. Because multiple cooling cells **501** are used, cooling system **500** may enjoy enhanced cooling capabilities. Further, multiples of individual cooling cells **501** and/or cooling system **500** may be combined in various fashions to obtain the desired footprint of cooling cells.

[0070] FIGS. **6**A-**6**C depict an embodiment of active cooling system **600** including multiple cooling cells configured as a tile, or array. FIG. **6**A depicts a top view with the top plate removed showing the electrical connections to cells **601**. FIG. **6**B depicts a top view of system **600**. FIG. **6**C depicts a side/cross-sectional view of system **600** as used to cool heat-generating structure **602**. FIGS. **6**A-**6**C are not to scale. Cooling system, or tile, **600** includes four cooling cells **601**A, **601**B, **601**C and **601**D (collectively or generically **601**), which are analogous to one or more of cooling systems described herein. More specifically, cooling cells **601** are analogous to cooling system **100**, **200**, **400**, **501** and/or another cooling system. Although four cooling cells **601** in a 2×2 configuration are shown, in some embodiments another number and/or another configuration of cooling cells

601 might be employed. In the embodiment shown, cooling cells **601** include top plate **610** having vents **612**, cooling elements **620**, orifice plate **630** including orifices **632**, top chambers **640**, bottom chambers **650** and anchors (support structures) **660** that are analogous to top plate **110** having apertures **112**, cooling element **120**, orifice plate **130** having orifices **132**, top chamber **140**, bottom chamber **150** and anchor **160**. Also shown are electrical connector **680** (shown in FIG. **6**A only) and pedestals **690** (shown in FIG. **6**C only). Cooling elements **620** may be driven out-of-phase (i.e. in a manner analogous to a seesaw) or in phase (i.e. in a manner analogous to a butterfly). In some embodiments, cooling elements **620** are driven in a manner analogous to that shown in FIGS. **5**B-**5**C or FIGS. **5**D-**5**E.

[0071] Referring back to FIGS. **6**A-**6**C, in some embodiments, cooling cells **601** may be fabricated together and separated, for example by cutting through top plate **610**, orifice plate **630**, and any layers, such as a layer of cooling elements **620**, between top plate **610** and orifice plate **630**. Cooling cells **601** have been separated by cutting through top plate **610** and orifice plate **630** in a direction parallel to the axis of anchor **660**. Thus, cells **601**A and **601**C are physically connected, cells **601**B and **601**D are connected, cell **601**A and **601**B are physically disconnected, and cells **601**C and **601**D are physically disconnected. In some embodiments, individual cells might be separated along dashed lines perpendicular to anchor **660**. In such embodiments, cells **601** along the axis of anchor **660** may still be coupled by anchor **660**. In some embodiments, pedestal **690** may extend along the axis. In such embodiments, therefore, pedestals **690** may connect cells **601** along the axis of anchor **660**. Because cells **601**A and **601**B and cells **601**C and **601**D are at least partially disconnected, cells **601** are better isolated against vibrations from the actuation of cooling elements **620** of other cells **601**. Although cells **601** are at least partially disconnected, cells **601** are physically connected through anchors **660**, pedestals **690**, and/or other features such as tabs (not shown in FIGS. **6**A-**6**C) such that cells **601** may be considered to be integrated into a single cooling system, or tile **600**.

[0072] Cooling cells **601** of tile **600** are driven via electrical connector **680**, which may be a flex connector. Electrical connector **680** includes tile portion **682** and cell portions **684**. Cell portions **684** provide electrical connection to cooling elements **620** in the connected cells **601** along the axis of anchor **660**. Because cell portions **684** of electrical connector **680** are aligned with anchor **660**, vibrations in cooling system **600** may be reduced. This is because cell portions **684** are aligned with the anchor region of cells **601**, which undergo less motion due to vibration of cooling elements **620**. Thus, fewer vibrations are introduced into cell portions **684** of electrical connector **680**. Further, because cell portions **684** are separated based on the alignment of the corresponding cells **601**, vibrations from one cell (e.g. **601**A or **601**C) are less likely to be communicated to another cell (e.g. cell **601**B and **601**D). Thus, cooling system **600** may be subject to less vibration. Although tile portion **682** is shown as terminating outside of the perimeter (or footprint) of cooling cells **601**, in some embodiments, tile portion **682** may extend into the footprint of cooling cells **601** (e.g. cells **601**C and **601**D).

[0073] Cooling system/tile **600** is coupled to heat-generating structure **602** by pedestals **690**. In some embodiments, heat-generating structure **602** is a heat spreader that may be coupled to another structure that generates heat, such as an integrated circuit, another heat spreader or another vapor chamber. Heat-generating structure **602** may thus be part of a module that integrates tile **600** and heat-generating structure/heat spreader **602**. Pedestals **690** are aligned with and extend in the direction of anchors **660**. Thus, each cooling cell **601** is coupled to heat-generating structure **602** at the region subject to less vibration (i.e. in proximity to anchor **660**). As a result, less vibration from cooling cells **601** is transmitted to heat-generating structure **602**. In some embodiments, pedestal **690** is thermally conductive. A high thermal conductivity (e.g. on the order of that of copper and/or other materials of a heat spreader) allows heat to be transferred from heat-generating structure **602** to cooling cells **601** via conduction. Operation of tile **600** cools not only heat-generating structure **602** via convection (e.g. fluid driven by cooling elements **620**), but also via conduction (e.g. heat conducted via pedestal **690** to cooling cells **601**) in combination with convection (e.g. fluid driven by cooling elements **620** that carries heat from the components of tile **600**). In some embodiments, pedestal **690** is a thermally conductive epoxy or other analogous adhesive. In some embodiments, pedestal **690** is a structure, such as a copper pedestal, which is affixed to heat-generating structure **602** and cooling cells **601**. In some embodiments, pedestals **690** are configured to reduce the transmission of vibrations between tile **600** and heat-generating structure **602**.

[0074] Cooling cells **601** of cooling system **600** function in an analogous manner to cooling system(s) **100**, **400**, **500** and/or an analogous cooling system. Consequently, the benefits described herein may be shared by cooling system **600**. Because cooling elements in nearby cells **601** can be driven out-of-phase, vibrations in cooling system **600** may be reduced. Further, the configuration of electrical connector **680**, the configuration and location of pedestal **690** and separation of cells **601** not aligned along the axis of anchor **660** further reduces the vibrations within cooling system **600** and the communication of vibrations to heat-generating structure **602**. Because multiple cooling cells **601** are used, cooling system **600** may enjoy enhanced cooling capabilities. Further, multiples of individual cooling cells **601** and/or cooling system **600** may be combined in various fashions to obtain the desired footprint of cooling cells. Thus, performance may be improved.

[0075] FIGS. **7**A-**7**C depict an embodiment of active cooling system **700** including multiple cooling cells configured as a tile, or array. FIG. **7**A depicts a top view of system **700** with the top plate removed. FIG. **7**B depicts a top view of system **700**. FIG. **7**C depicts a side view of system **700** as used to cool heat-generating structure **702**. FIGS. **7**A-**7**C are not to scale. Cooling system **700** includes four cooling cells **701**A, **701**B, **701**C and **701**D (collectively or generically **701**), which are analogous to one or more of cooling systems described herein. More specifically, cooling cells **701** are analogous to cooling system **100**, **400**, **501**, and/or another cooling system. Although four cooling cells **701** in a 2×2 configuration are shown, in some embodiments another number and/or another configuration of cooling cells **701** might be employed (for example 4×1 and/or m×n arrays). Cooling system **700** is also analogous to cooling system **600**. Consequently, analogous components have similar labels. In the embodiment shown, cooling cells **701**, top plate **710** having vents **712**, cooling elements **720**, orifice plate **730** including orifices **732**, top chambers **740**, bottom chambers

750, anchors (support structures) 760, electrical connector 780 (shown only in FIG. 7A) and pedestals 790 (shown only in FIG. 7C) are analogous to cooling cells 601, top plate 610 having vents 612, cooling elements 620, orifice plate 630 including orifices 632, top chambers 640, bottom chambers 650, anchors (support structures) 660, electrical connector 680 and pedestals 690. Cooling elements 720 may be driven out-of-phase (i.e. in a manner analogous to a seesaw) or in-phase (i.e. in a manner analogous to a butterfly). In some embodiments, cooling elements 720 are driven in a manner analogous to that shown in FIGS. 5B-5C or FIGS. 5D-5E.

[0076] Referring back to FIGS. 7A-7C, although anchors 760 are shown as separated to be limited to individual cells, the vibration isolation characteristics of cooling cells 701 are analogous to those of cells 601. Also shown in FIG. 7A is tab 704 in proximity to anchors 760. Tabs 704 are aligned along the anchor and hence may reduce the cross-talk between the cells during operation. In some embodiments, tabs 704 may be omitted. Similarly, although pedestals 790 are shown as separate, in some embodiments, pedestals 790 may extend over multiple cells 701 such that cells may be considered to share a pedestal. Although cells 701 are at least partially disconnected, cells 701 may be physically connected through anchors 760, pedestals 790, tabs 704 and/or other features such that cells 701 may be considered to be integrated into a single cooling system, or tile 700. Cooling cells 701 of tile 700 are driven via electrical connector 780 in a manner analogous to cooling cells 601 of tile 600.

[0077] Cooling cells 701 of cooling system 700 function in an analogous manner to cooling system(s) 100, 400, 500, 600 and/or an analogous cooling system. Consequently, the benefits described herein may be shared by cooling system 700. Because cooling elements 720 in nearby cells can be driven out-of-phase, vibrations in cooling system 700 may be reduced. Further, the configuration of electrical connector 780, the configuration and location of pedestal 790 and separation of cells 701 not aligned along the axis of anchor 760 further reduces the vibrations within cooling system 700 and the communication of vibrations to heat-generating structure 702. Because multiple cooling cells 701 are used, cooling system 700 may enjoy enhanced cooling capabilities. Further, multiples of individual cooling cells 701 and/or cooling system 700 may be combined in various fashions to obtain the desired footprint of cooling cells. Thus, performance may be improved.

[0078] FIG. 8 depicts a top view of an embodiment of active cooling system 800 including multiple cooling cells configured as a tile, or array. Consequently, the orifice plate and pedestals are not shown. Cooling system 800 is analogous to cooling system 600 and/or 700. FIG. 8 is not to scale. Cooling system 800 includes four cooling cells 801A, 801B, 801C and 801D (collectively or generically 801), which are analogous to one or more of cooling systems described herein. More specifically, cooling cells 801 are analogous to cooling system 100, 400, 501, and/or another cooling system. Although four cooling cells 801 in a 2×2 configuration are shown, in some embodiments another number and/or another configuration of cooling cells 801 might be employed. Cooling system 800 is also analogous to cooling system(s) 600 and/or 700. Consequently, analogous components have similar labels. In the embodiment shown, cooling cells 801, top plate 810 having vents 812, cooling elements 820, orifice plate (not shown) including orifices (not shown) therein, top chamber (not shown), bottom chamber (not shown), anchors (support structures) 860, electrical connector 880 and pedestals (not shown) are analogous to cooling cells 601/701, top plate 610/710 having vents 612/712, cooling elements 620/720, orifice plate 630/730 including orifices 632/732, top chambers 640/740, bottom chambers 650/70, anchors (support structures) 660/760, electrical connector 680/780 and pedestals 690/790. Cooling elements 820 may be driven out-of-phase (i.e. in a manner analogous to a seesaw) or in-phase (i.e. in a manner analogous to a butterfly). Cell portions 884 of connector 880, cooling elements 820, and anchor 860 under top plate 810 are shown as dashed/dotted lines. In some embodiments, cooling elements 820 are driven in a manner analogous to that shown in FIGS. 5B-5C or FIGS. 5D-5E. Also shown in FIG. 8 are epoxy or silicone sealant 886 and 888 that may be utilized if cells 801 are desired to be closed. In order to electrically connect to cooling elements 820, cell portions 884 of electrical connector 880 enter cells 801. Sealant/epoxy 886 and 888 may be used to seal the apertures through which cell portions 884 enter or leave cells 801. Thus, fluid may enter cells 801 only or primarily through vents 812. Although shown in particular locations in cooling system 800, in some embodiments, epoxy or silicone sealant 886 and/or 888 may be located elsewhere or replaced with other material(s).

[0079] Cooling cells 801 of cooling system 800 function in an analogous manner to cooling system(s) 100, 400, 500, 600, 700 and/or an analogous cooling system. Consequently, the benefits described herein may be shared by cooling system 800. Because cooling elements 820 in nearby cells can be driven out-of-phase, vibrations in cooling system 800 may be reduced. Further, the configuration of electrical connector 880, the configuration and location of pedestal 890 and separation of cells 801 not aligned along the axis of anchor 860 further reduces the vibrations within cooling system 800 and the communication of vibrations to heat-generating structure 802. Because multiple cooling cells 801 are used, cooling system 800 may enjoy enhanced cooling capabilities. Further, multiples of individual cooling cells 801 and/or cooling system 800 may be combined in various fashions to obtain the desired footprint of cooling cells. Thus, performance may be improved.

[0080] FIG. 9 depicts an embodiment of cooling system 900 including multiple tiles 910 configured to be used in cooling a computing device. For simplicity, only some features are shown or labeled. In addition to tiles 910, heat-generating structure 902, which is a heat spreader, is shown. Heat spreader 902 includes walls 930 between tiles 910. Also shown is fencing 920. In some embodiments, fencing 920 surrounds a portion of the perimeter of tiles 910. Fluid exiting cooling cells 901 thus travels along heat-generating structure 902, exiting at the region without fencing 920. In some embodiments, fencing 920 includes ducting that may be used to transfer fluid. Tiles 910 may, for example, be analogous to tiles 500, 600, 700 and/or 800. Cooling system 900 includes sixteen tiles cell 901, of which only one is labeled. Although shown in a 2×8 configuration, for other applications, tiles 910 may be arranged in another manner. Tiles 910 function in an analogous manner to tile(s) 500, 600, 700, 800 and/or an analogous cooling system. Consequently, the benefits described herein may be shared by cooling system 900. Because cooling elements in nearby cells within each tile 910 can be driven out-of-phase, and tiles 910 can be configured as described herein, vibrations in cooling system 900 may be reduced. Because multiple cooling tiles **910** are used, cooling system **900** may enjoy enhanced cooling capabilities. Further, multiples of individual tiles **910** may be combined in various fashions to obtain the desired footprint of cooling cells. Thus, performance may be improved.

[0081] FIGS. **10**A, **10**B, **10**C, and **10**D are diagrams depicting plan views of embodiments of cooling cells **1001** arranged in a tile **1000**A, **1000**B, **1000**C, and **1000**D (collectively or generically tiles **1000**), respectively, and connected via tabs **1026**A, **1026**B, **1026**C, and **1026**D (collectively or generically tabs **1026**), respectively. Only some portions of tiles **1000** are shown and FIGS. **10**A-**10**D are not to scale. In the embodiments shown, four cooling cells **1001** are shown as arranged in each tile **1000**. However, other numbers and/or other configurations may be used. The cooling cells **1001** may be considered at least partially separate. However, for mechanical stability during fabrication and for electrical connection during use, the cells **1001** may be desired to be connected. Tabs **1026** between cells **1001** may provide this stability. In some embodiments, tabs **1026** are in multiple layers of a tile **1000**. Tabs **1026** may be etched into the thickness of the structure(s) forming cooling cells **1001**. In some embodiments, tabs **1026** may be formed on a single layer, such as the top plate only. In some embodiments, tabs **1026** are separate structures that are coupled to tiles **1000** during fabrication. Tabs **1026** may thus be considered to be integrated into tile **1000**. In some embodiments, tabs **1026** may be removed after fabrication. However, this may complicate electrical connection individually to each cell **1001**.

[0082] FIGS. **11**A, **11**B, **11**C, and **11**D are diagrams depicting plan views of embodiments of cooling cells **1101** arranged in a tile **1100**A, **1100**B, **1100**C, and **1100**D (collectively or generically tiles **1100**), respectively, and connected via tabs **1126**A, **1126**B, **1126**C, and **1126**D (collectively or generically tabs **1126**), respectively. Only some portions of tiles **1100** are shown and FIGS. **11**A-**11**D are not to scale. For simplicity, only some tabs are labeled. In the embodiments shown, a four cooling cells **1101** are shown as arranged in tiles **1100**. A 2×2 configuration of cells **1101** is shown in tiles **1100**A and **1100**B. A 1×4 configuration of cells **1101** is shown in tiles **1100**C and **1100**D. Similarly, particular numbers and configurations of tabs **1126** are shown. However, other numbers and/or other configurations of tiles **1100** and/or tabs **1126** may be used.

[0083] Tabs **1126** extend outside of the footprint of cooling cells **1101** and tile **1100**. Stated differently, the tabs **1126** extend outside of the perimeter of tile **1100**. Tabs **1126** are also shown as u-shaped. In some embodiments, another shape (e.g. M-shaped) may be used. In Further, as indicated in FIG. **11**B, tabs **1126**B on a particular tile **1100**B need not be the same size. In some embodiments, tabs **1126** are 1-2 millimeters wide and 0.2-0.5 millimeters in width. In some embodiments, tabs **1126** are in multiple layers of a tile **1100**. Tabs **1126** may be etched into the thickness of the structure (s) forming cooling cells **1101**. For example, the tabs may be ⅓ to ½ of the thickness of sheets from which the orifice plate, cooling element, top plate and other structures are formed. These sheets may be laminated to form cooling cells **1101**. For the jet channel (the distance between the heat spreader and the bottom of the orifice plate), the tab may be less than the thickness of the spacers or pedestals, but have a different thickness than tabs formed at the top plate or orifice plate. In some embodiments, tabs **1126** may be formed on a single layer, such as the top plate only. In some embodiments, tabs **1126** are separate structure s that are coupled to tiles **1100** during fabrication. Tabs **1026** may thus be considered to be integrated into tile **1000**. In some embodiments, tabs **1126** have a maximum thickness of 300 microns. However other dimensions are possible. Tabs **1126** are compliant so that the communication of vibrations between cooling cells **1101** is reduced or eliminated. Electrical connection can be made through the tabs. Thus, the tabs may be designed to be used during operation. The tabs may be considered to act as low frequency springs, with a characteristic frequency of much less than the frequencies at which the actuators (not shown in FIGS. **11**A-**11**D) are vibrated (on the order of twenty kilohertz). Thus, tabs **1126** provide mechanical connection for assembly and manufacturing and electrical connection during operation. As such, performance of tiles **1100** may be improved.

[0084] FIGS. **12**A-**12**G depict an embodiment of tile **1200** during fabrication. Tile **1200** **800** is analogous to cooling system(s) **600**, **700**, **800**, and/or **900**. FIGS. **12**A-**12**G are not to scale. Tile **1200** includes four cooling cells **1201** of which one is labeled. Although four cooling cells **1201** in a 2×2 configuration are shown, in some embodiments another number and/or another configuration of cooling cells **1201** might be employed. Cells **1201** are analogous to one or more of cooling cells described herein (e.g. cooling cell(s) **100**, **400**, and/or **501**). Cooling system **1200** is also analogous to cooling system(s) **600**, **700**, and/or **200**. Consequently, analogous components have similar labels. FIG. **12**A depicts a plan view of orifice plate **1230** including orifices **1232** therein. In some embodiments, orifice plate **1230** is part of a sheet or other structure including multiple orifice plates **1230**. Although not labeled, orifice plate **1230** includes tabs at the sides, outside the footprint of the tile **1200** or cooling cells **1201**. FIG. **12**B depicts a plan view of cooling system **1200** after active element plate **1221** has been added to orifice plate **1230** (not shown in FIG. **12**B). In some embodiments, active element plate **1210** is part of a sheet or other structure including multiple active element plates **1210**. Thus, cooling elements **1220** are shown. Anchors (not shown in FIG. **12**B) may be formed on the opposing surface of active element plate **1221**, on the surface shown of orifice plate **1230**, or may be formed by an epoxy or other material used to attach orifice plate **1230** and active element plate **1221**. Tabs are also present but unlabeled on active element plate **1221**. Also depicted in FIG. **12**B are piezoelectric structures **1223**. Piezoelectric structures **1223** are used to drive vibrational motion of cooling elements **1220**. In some embodiments, another mechanism for driving cooling elements **1220** may be used.

[0085] FIG. **12**C depicts electrical connector **1280**, which may be a flex connector. Tile portion **1282** and cell portion **1284** are indicated. FIG. **12**D depicts tile **1200** after connector **1280** has been attached to active element plate **1221**. More specifically, connection has been made between electrical connector **1280** and piezoelectric structures **1223**. If multiple tiles are being fabricated, then electrical connector **1280** may be provided for each tile.

[0086] FIG. **12**E depicts top plate **1210** having vents **1212** therein. Although a particular number and placement of vents **1212** is shown, other configurations are possible. In some embodiments, top plate **1210** is part of a sheet or other structure including multiple top plates **1210**. FIGS. **12**F and **12**G depict top and exploded views of tile **1200** after top plate has been coupled to the remaining structures. If multiple tiles are formed from a sheet or other structure than individual tiles or desired configurations of tiles are separated from the sheet or other structure. For example, laser cutting may be performed. Subsequently, other structures, such as a heat spreader, may be attached to tile **1200** to form a cooling module. Thus, tiles **1200** may be more readily assembled. Consequently, some or all of the benefits of the active cooling structures described may be achieved.

[0087] Although various configurations are described herein, features of cooling systems **100**, **400**, **500**, **600**, **700**, **800**, **900**, **1000**, **1100** and/or **1200** may be combined in various manners not explicitly discussed herein. Consequently, devices incorporating cooling systems **100**, **400**, **500**, **600**, **700**, **800**, **900**, **1000**, **1100**, **1200**, and/or analogous cooling systems may be enhanced.

[0088] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, the invention is not limited to the details provided. There are many alternative ways of implementing the invention. The disclosed embodiments are illustrative and not restrictive.

1. A system, comprising:

an integrated cooling cell tile including

a plurality of cooling cells, each of the plurality of cooling cells including a support structure and a cooling element, the cooling element having a central region having an axis and a perimeter, the cooling element being supported by the support structure at the central region and along the axis, at least a portion of the perimeter being unpinned, the cooling element being configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure, a first portion of the plurality of cooling cells aligned along the axis being physically connected; and

an electrical connector including at least one longitudinal electrical connector extending along the axis and coupled to the portion of the plurality of cooling cells along the axis.

2. The system of claim **1**, wherein the integrated cooling cell tile further comprises:

at least one pedestal configured to couple each of the portion of the plurality of cooling cells to a heat generating-structure, the pedestal being aligned with the axis; and

wherein at least one of the pedestal and the support structure physically connect the plurality of cooling cells.

3. The system of claim **1**, wherein the integrated cooling cell tile further comprises:

a plurality of integrated tabs mechanically connecting a second portion of the plurality of cooling cells.

4. The system of claim **3**, wherein:

the integrated cooling cell tile further comprises:

at least one pedestal configured to couple each of the portion of the plurality of cooling cells to a heat generating-structure, the pedestal being aligned with the axis;

at least one of the pedestal and the support structure physically connect the plurality of cooling cells; and

a thickness of an integrated tab of the plurality of integrated tabs is less thick than a thickness of the least one pedestal.

5. The system of claim **1**, wherein:

a first number of cooling cells of the plurality of cooling cells in a first direction is different from a second number of cooling cells of the plurality of cooling cells in a second direction; and

the first direction is orthogonal to the second direction.

6. The system of claim **1**, wherein:

a first number of cooling cells of the plurality of cooling cells in a first direction is equal to a second number of cooling cells of the plurality of cooling cells in a second direction; and

the first direction is orthogonal to the second direction.

7. The system of claim **3**, wherein an integrated tab of the plurality of integrated tabs acts as a spring.

8. A method, comprising:

providing an integrated cooling cell tile including

a plurality of cooling cells, each of the plurality of cooling cells including a support structure and a cooling element, the cooling element having a central region having an axis and a perimeter, the cooling element being supported by the support structure at the central region and along the axis, at least a portion of the perimeter being unpinned, the cooling element being configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure, a first portion of the plurality of cooling cells aligned along the axis being physically connected; and

an electrical connector including at least one longitudinal electrical connector extending along the axis and coupled to the portion of the plurality of cooling cells along the axis.

9. The method of claim **8**, wherein the integrated cooling cell tile further comprises:

at least one pedestal configured to couple each of the portion of the plurality of cooling cells to a heat generating-structure, the pedestal being aligned with the axis; and

wherein at least one of the pedestal and the support structure physically connect the plurality of cooling cells.

10. The method of claim **8**, wherein the integrated cooling cell tile further comprises:

a plurality of integrated tabs mechanically connecting a second portion of the plurality of cooling cells.

11. The method of claim **10**, wherein the integrated cooling cell tile further comprises:

at least one pedestal configured to couple each of the portion of the plurality of cooling cells to a heat generating-structure, the pedestal being aligned with the axis; and

wherein:

at least one of the pedestal and the support structure physically connect the plurality of cooling cells; and

a thickness of at least one integrated tab of the plurality of integrated tabs is less thick than a thickness of the least one pedestal.

12. The method of claim **8**, wherein:

a first number of cooling cells of the plurality of cooling cells in a first direction is different from a second number of cooling cells of the plurality of cooling cells in a second direction; and

the first direction is orthogonal to the second direction.

13. The method of claim **8**, wherein:

a first number of cooling cells of the plurality of cooling cells in a first direction is equal to a second number of cooling cells of the plurality of cooling cells in a second direction; and

the first direction is orthogonal to the second direction.

14. The method of claim **10**, wherein an integrated tab of the plurality of integrated tabs acts as a spring.

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