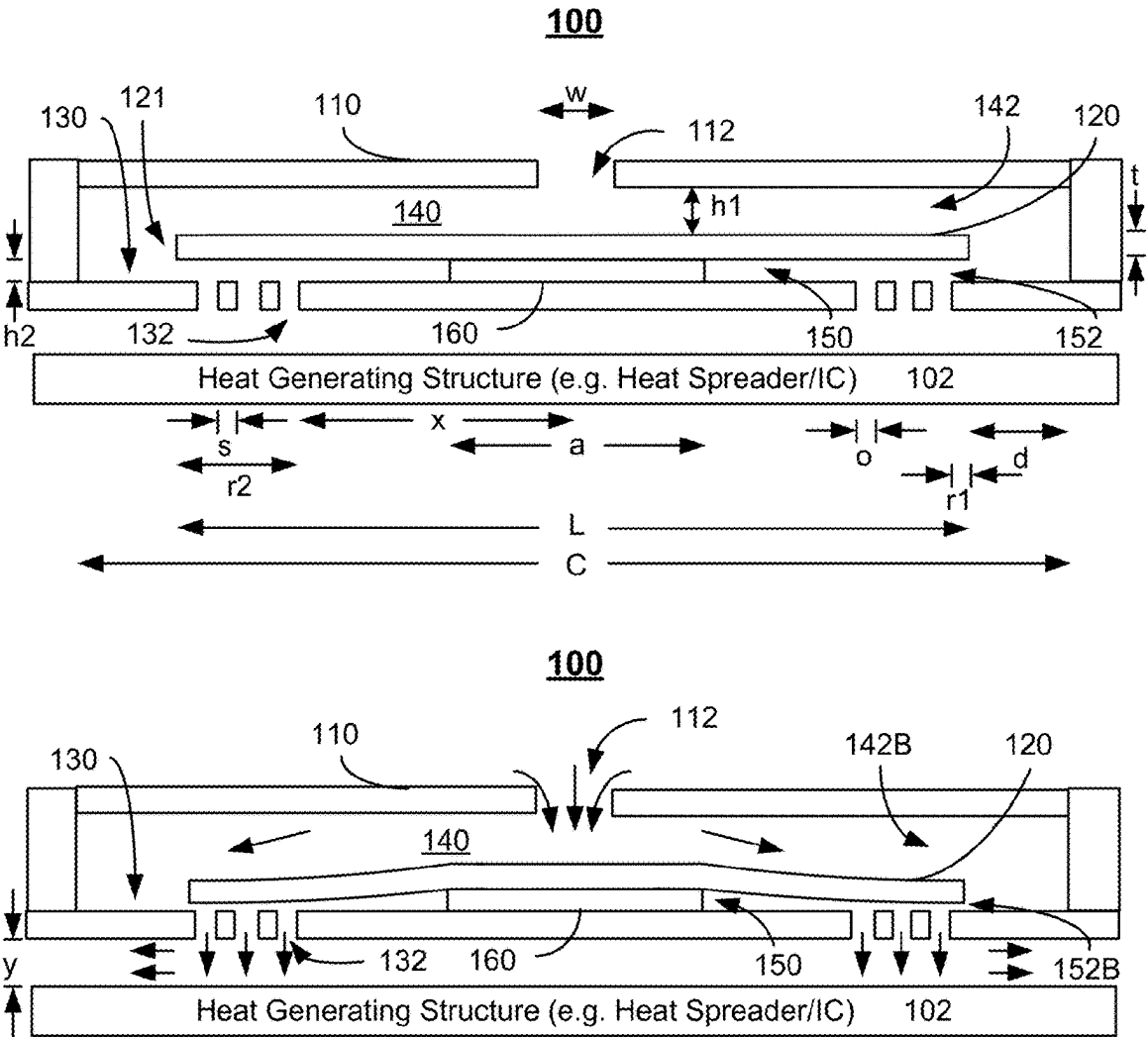


(54)	ACTUATOR DESIGNS FOR MEMS-BASED ACTIVE COOLING	Publication Classification
(71)	Applicant: Freore Systems Inc. , San Jose, CA (US)	(51) Int. Cl.
(72)	Inventors: Vikram Mukundan , San Ramon, CA (US); Suryaprakash Ganti , Los Altos, CA (US); Ananth Saran Yalamarthy , Stanford, CA (US); Prabhu Sathyamurthy , San Jose, CA (US); Seshagiri Rao Madhavapeddy , La Jolla, CA (US)	<i>H10N 30/20</i> (2023.01) <i>B81B 7/00</i> (2006.01)
(21)	Appl. No.: 19/191,886	(52) U.S. Cl.
(22)	Filed: Apr. 28, 2025	CPC <i>H10N 30/2041</i> (2023.02); <i>B81B 7/0061</i> (2013.01); <i>B81B 7/0093</i> (2013.01); <i>B81B 2201/05</i> (2013.01); <i>B81B 2203/0118</i> (2013.01)
	Related U.S. Application Data	(57) ABSTRACT
(63)	Continuation of application No. 17/473,818, filed on Sep. 13, 2021, now Pat. No. 12,317,749.	A cooling system is described. The cooling system includes a cooling element and a support structure. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. The cooling element includes a piezoelectric structure including a substrate having a first side and a second side opposite to the first side. A first piezoelectric layer is on the first side. A second piezoelectric layer is on the second side. The support structure is coupled to the cooling element and configured to support the cooling element.
(60)	Provisional application No. 63/079,445, filed on Sep. 16, 2020.	



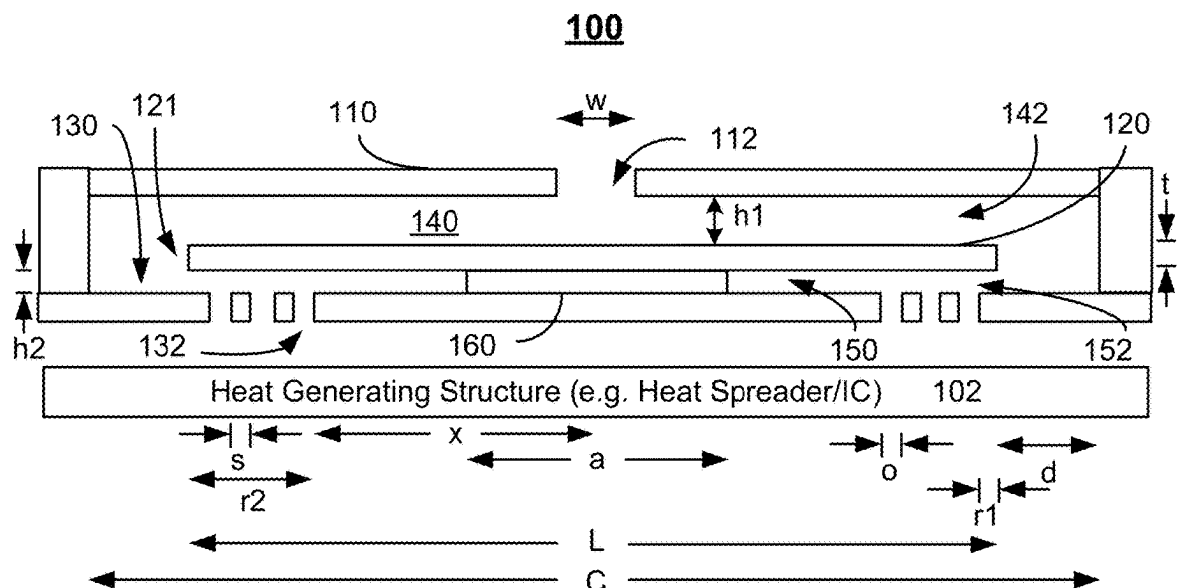


FIG. 1A
100

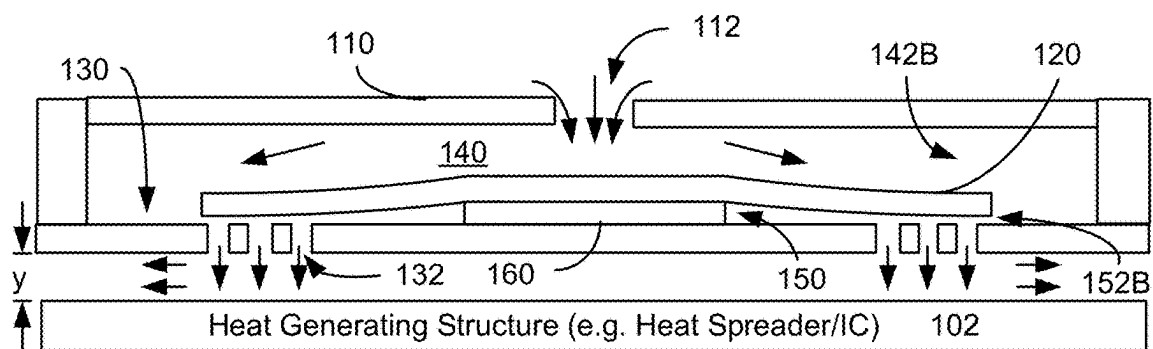


FIG. 1B

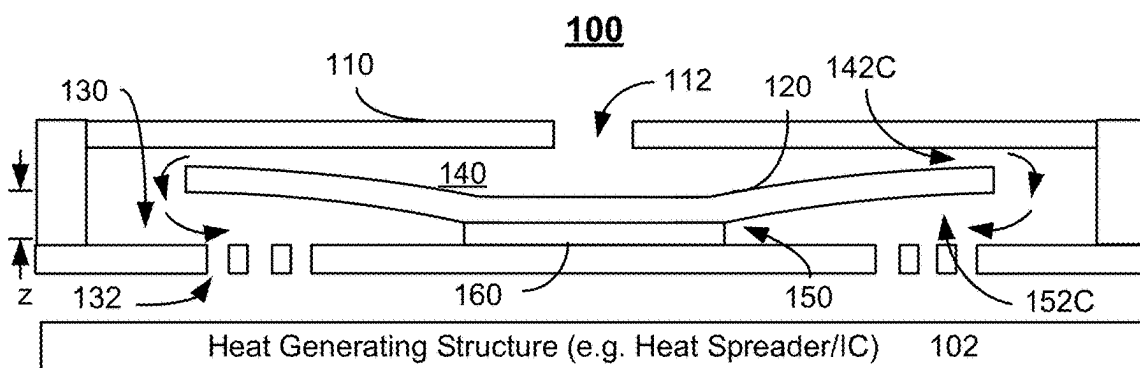


FIG. 1C

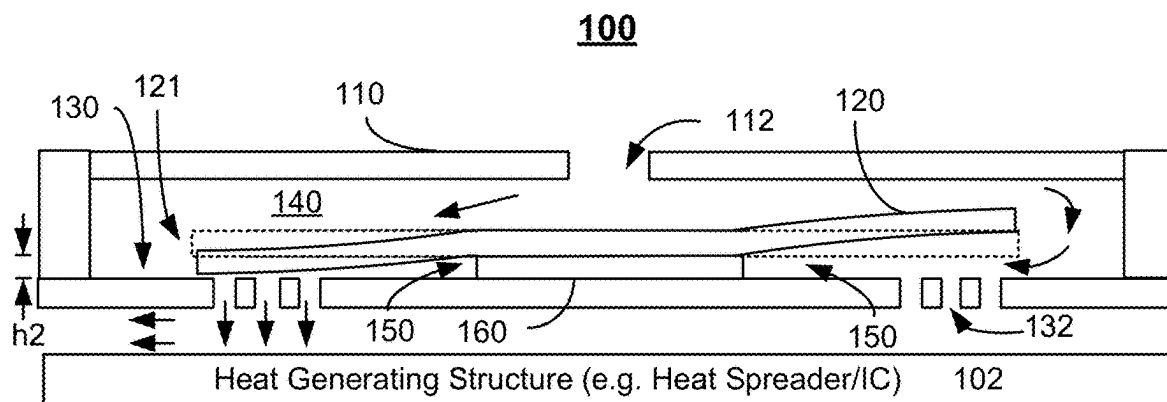


FIG. 1D

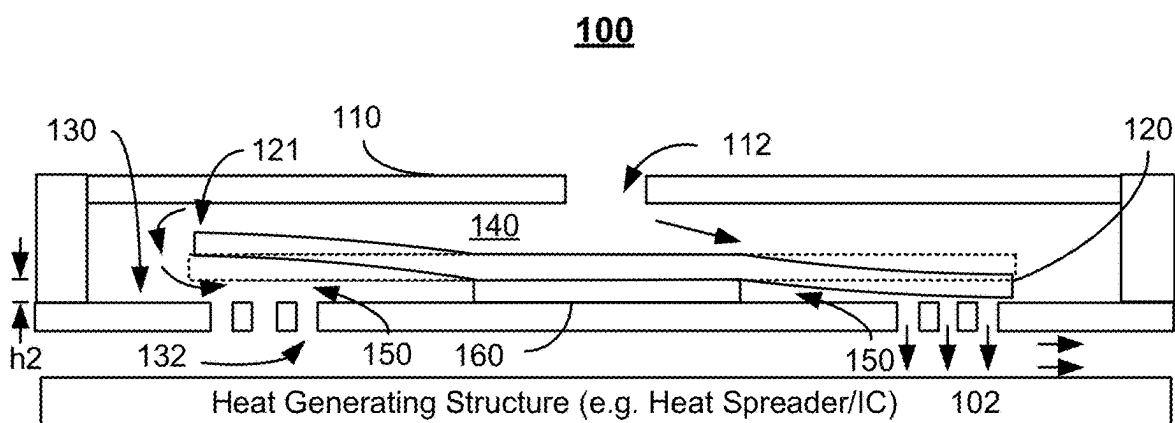


FIG. 1E

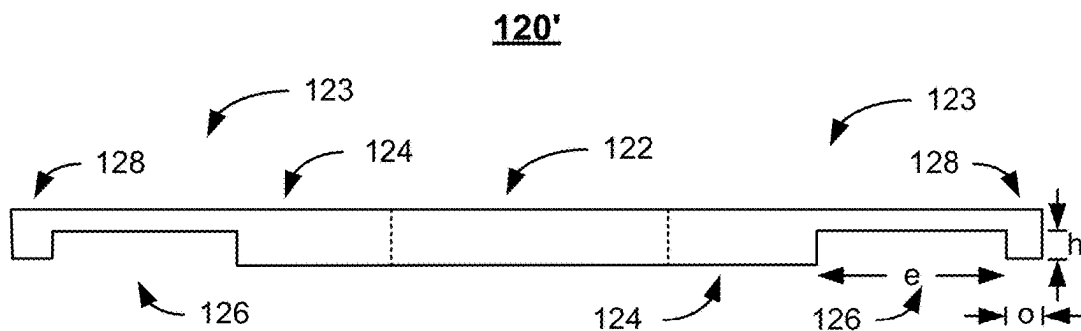


FIG. 1F

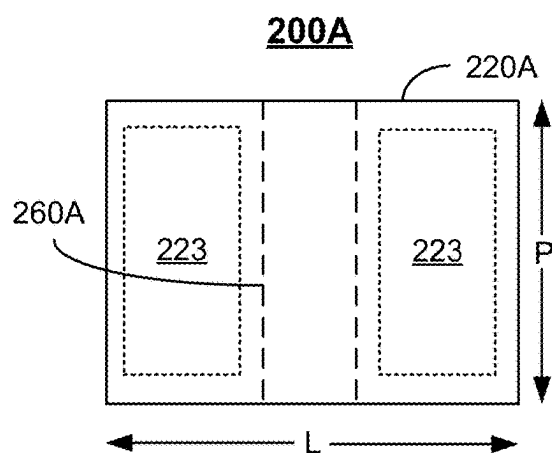


FIG. 2A

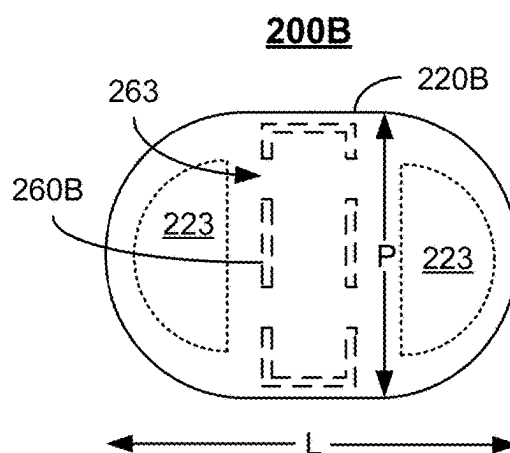


FIG. 2B

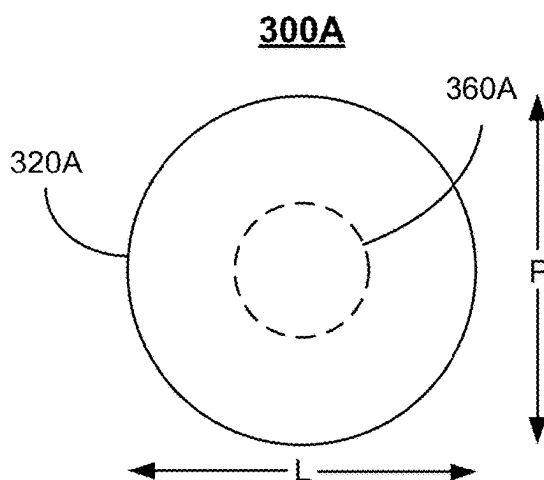


FIG. 3A

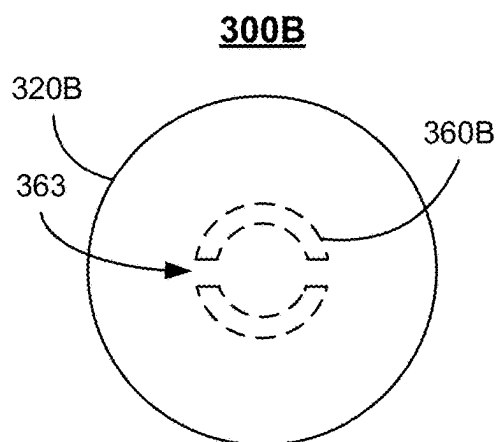
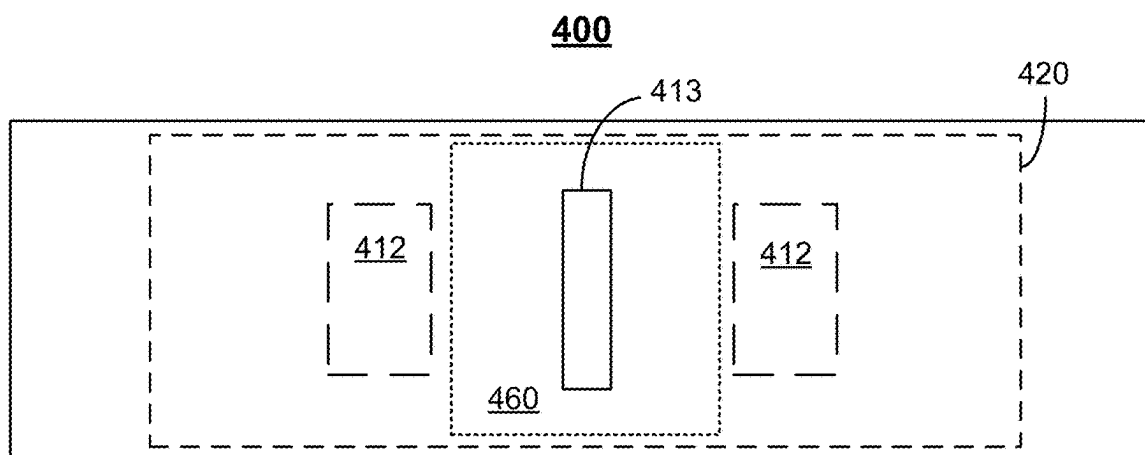
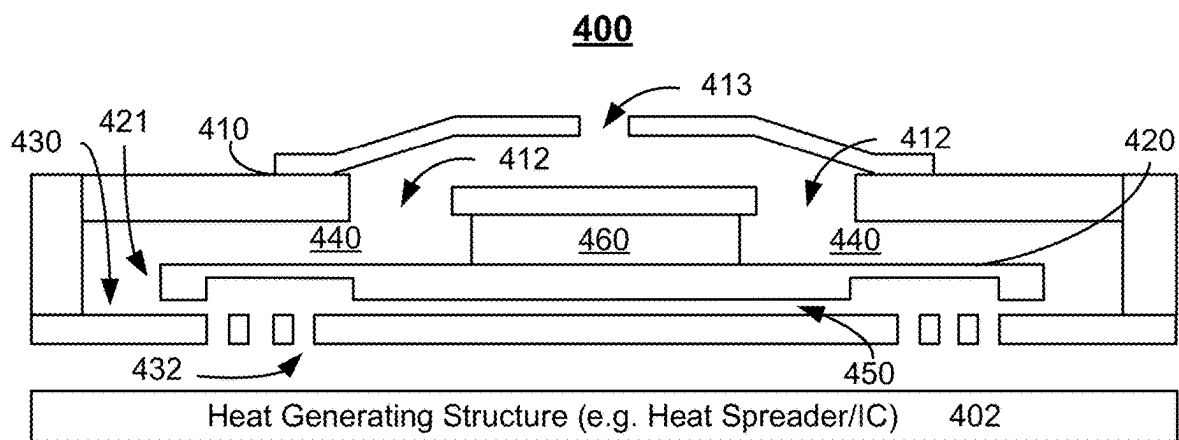


FIG. 3B



500

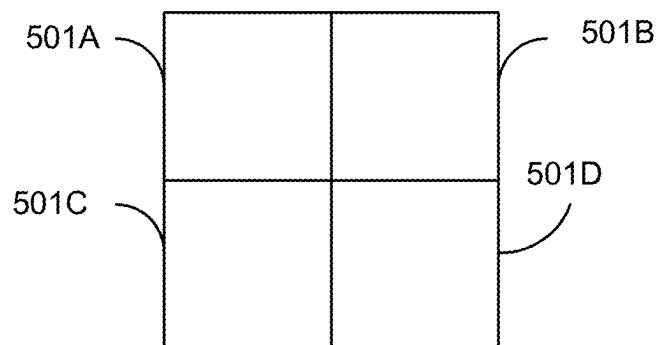


FIG. 5A

500

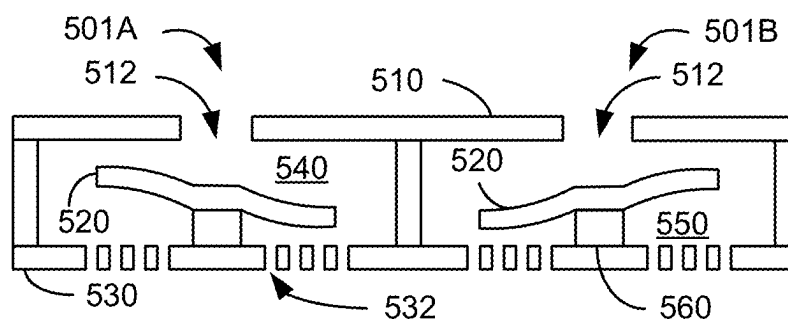


FIG. 5B

500

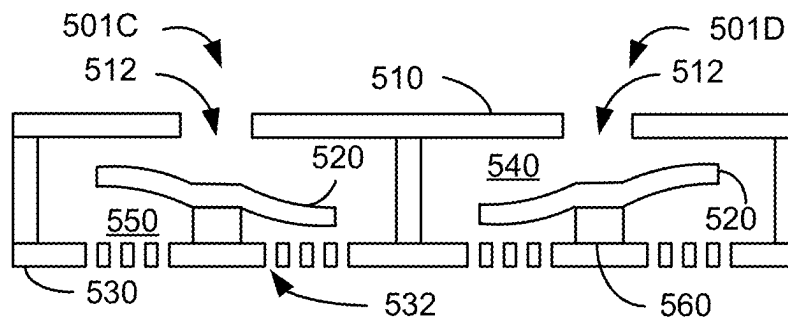


FIG. 5C

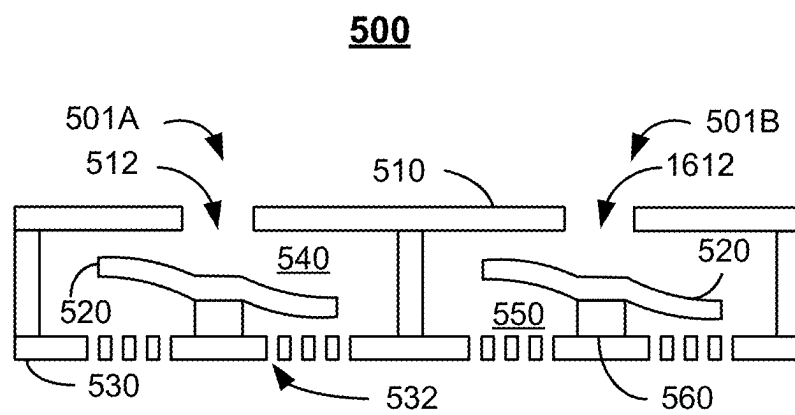


FIG. 5D

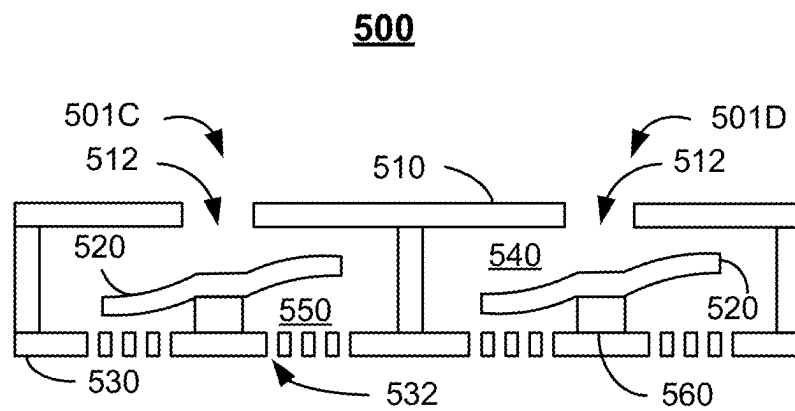


FIG. 5E

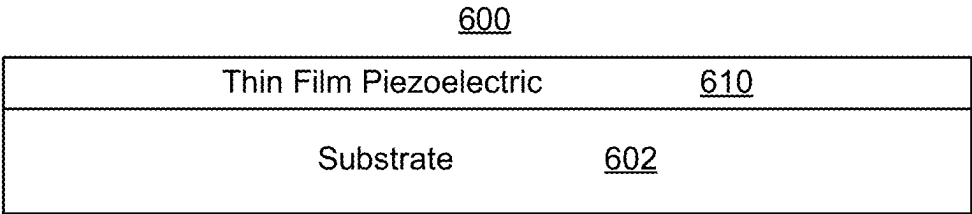


FIG. 6

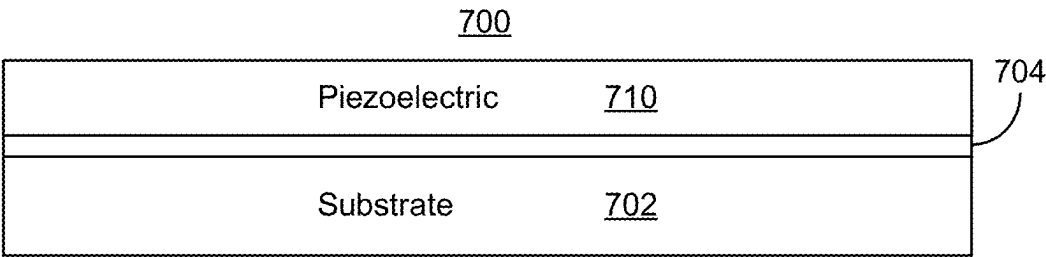


FIG. 7

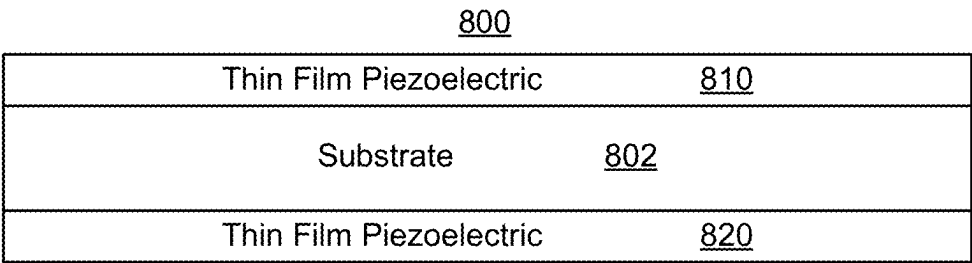


FIG. 8

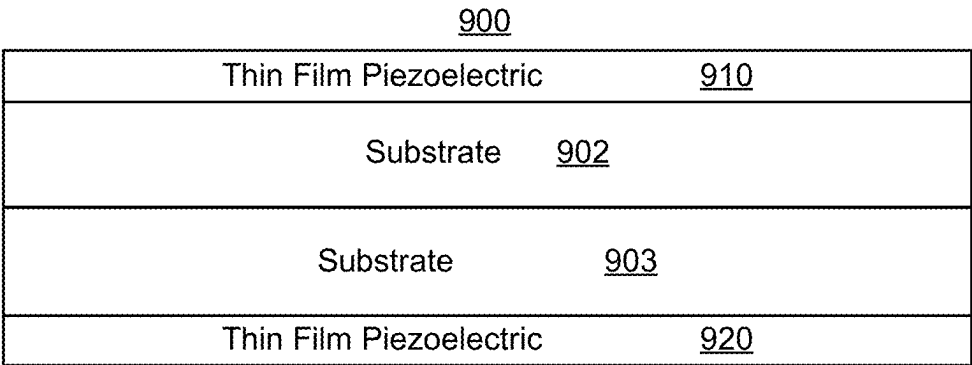


FIG. 9

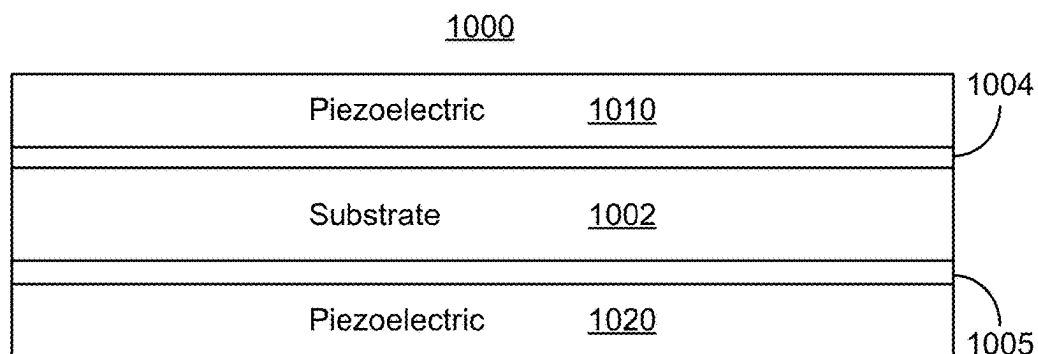


FIG. 10

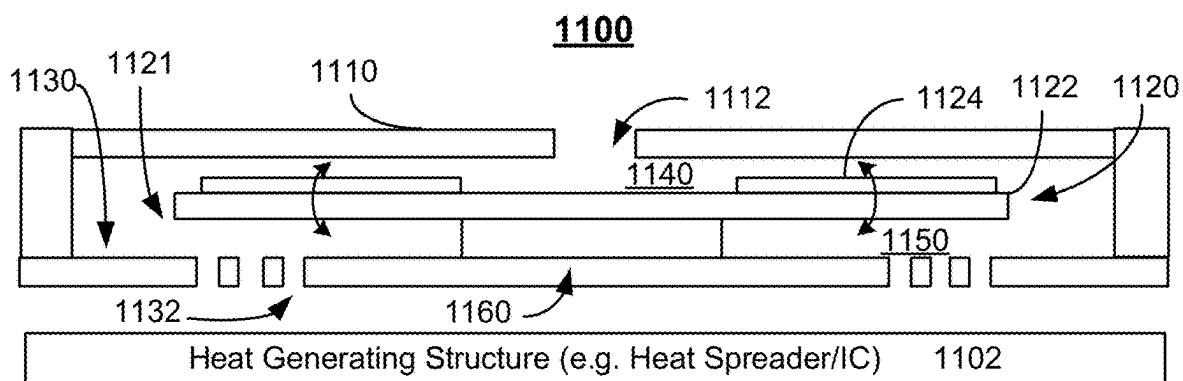


FIG. 11

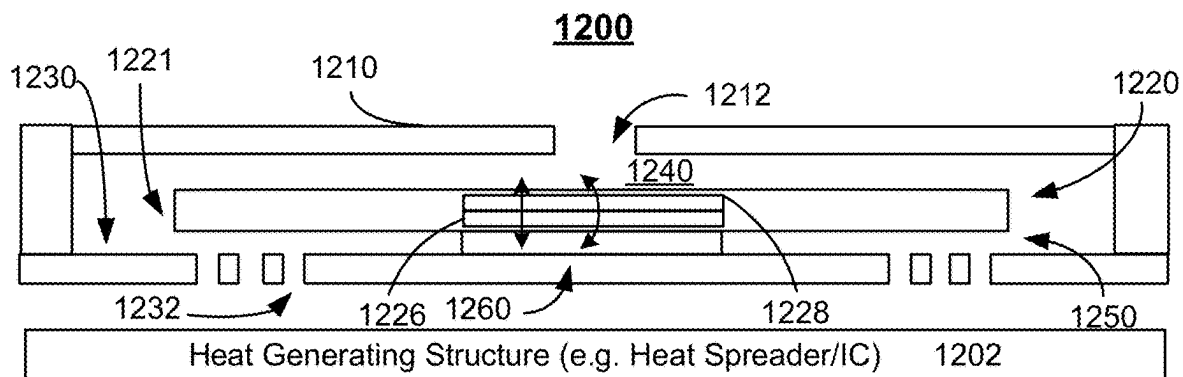


FIG. 12

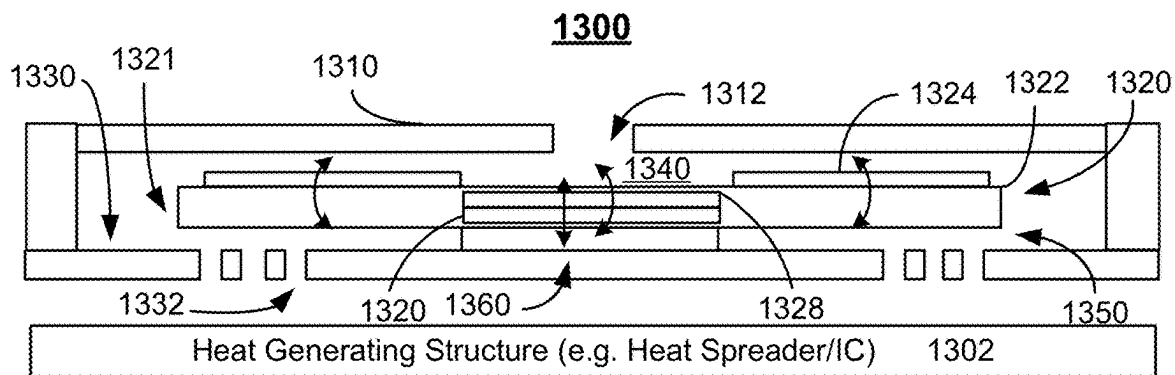


FIG. 13

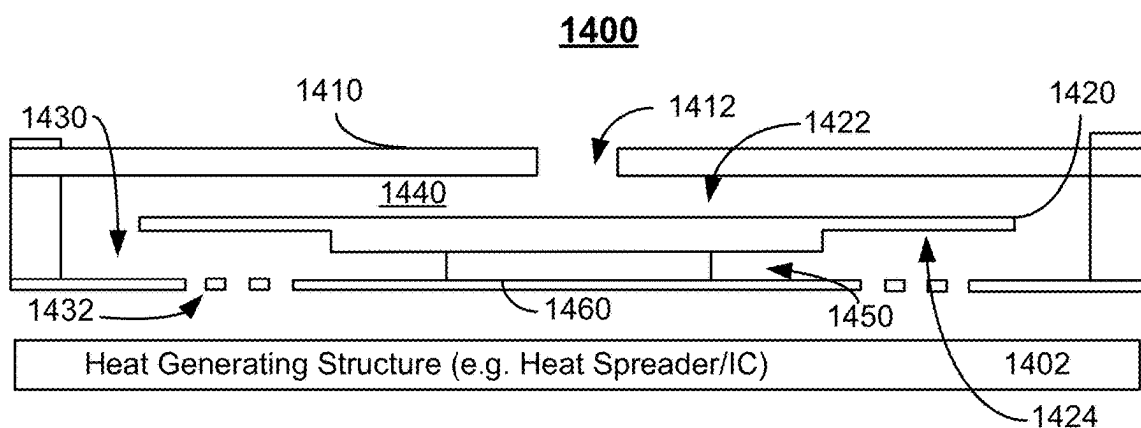


FIG. 14

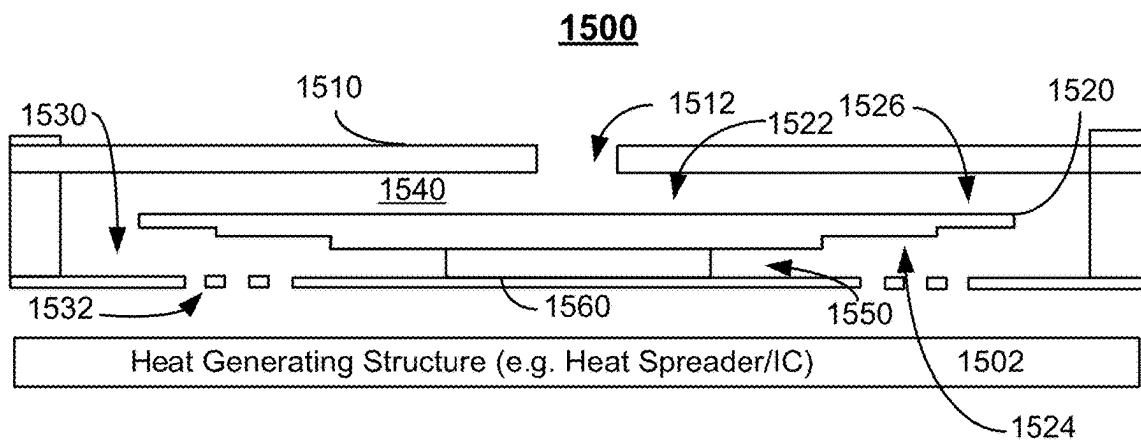


FIG. 15

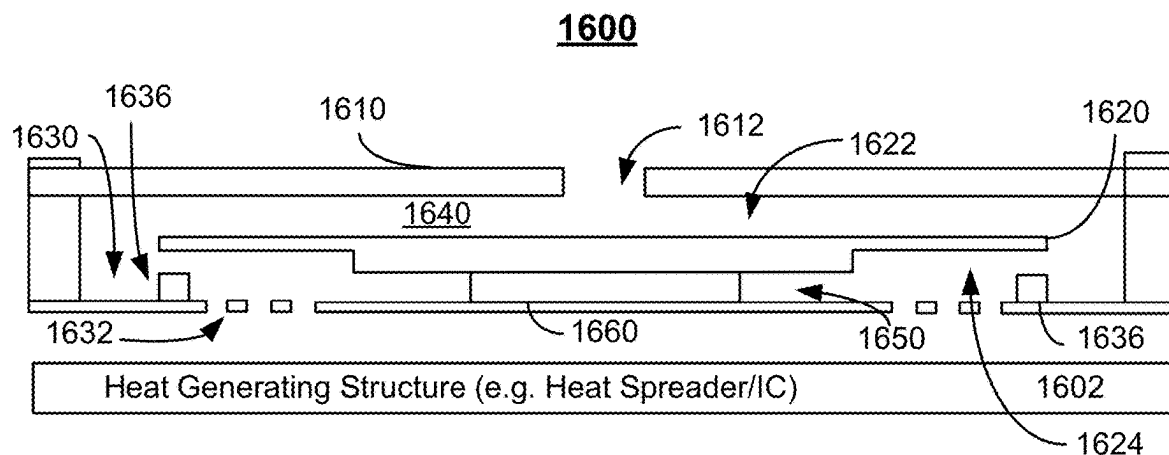


FIG. 16

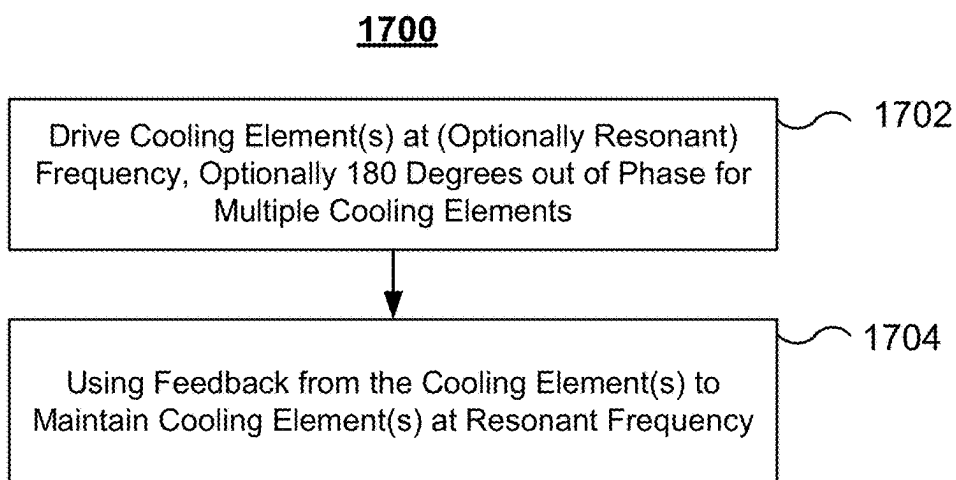


FIG. 17

ACTUATOR DESIGNS FOR MEMS-BASED ACTIVE COOLING

CROSS REFERENCE TO OTHER APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 17/473,818 entitled ACTUATOR DESIGNS FOR MEMS-BASED ACTIVE COOLING filed Sep. 13, 2021, which claims priority to U.S. Provisional Patent Application No. 63/079,445 entitled ACTUATOR DESIGNS FOR MEMS-BASED ACTIVE COOLING filed Sep. 16, 2020, both 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 DRAWINGS

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

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

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

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

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

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

[0009] FIGS. 6-10 depict embodiments of cooling elements usable in active cooling systems.

[0010] FIG. 11 depicts an embodiment of an active cooling system.

[0011] FIG. 12 depicts an embodiment of an active cooling system.

[0012] FIG. 13 depicts an embodiment of an active cooling system.

[0013] FIG. 14 depicts an embodiment of an active cooling system.

[0014] FIG. 15 depicts an embodiment of an active cooling system.

[0015] FIG. 16 depicts an embodiment of an active cooling system.

[0016] FIG. 17 is a flow chart depicting an embodiment of a method for driving a cooling element of an active cooling system.

DETAILED DESCRIPTION

[0017] 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.

[0018] 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.

[0019] 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 5G and beyond, this issue is expected to be exacerbated.

[0020] 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.

[0021] 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.

[0022] A cooling system is described. The cooling system includes a cooling element and a support structure. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. The cooling element includes a piezoelectric structure including a substrate having a first side and a second side opposite to the first side. A first piezoelectric layer is on the first side. A second piezoelectric layer is on the second side. The support structure is coupled to the cooling element and configured to support the cooling element. In some embodiments, the first piezoelectric layer is selected from a thin film piezoelectric layer and a bulk piezoelectric layer. The thin film piezoelectric layer has a first thickness of at least 0.1 micrometer and not more than fifty micrometers. In some embodiments, first thickness is not more than thirty micrometers. The bulk piezoelectric layer has a second thickness of at least thirty micrometers and not more than two hundred micrometers. In some embodiments, the second thickness is at least fifty micrometers. The cooling element may include an additional substrate between the substrate and the second piezoelectric layer. The second piezoelectric layer is coupled to the additional substrate. In some embodiments, the piezoelectric structure is embedded in the cooling element. The cooling element may include a central portion having a first thickness and an outer portion having a second thickness less than the first thickness. In some embodiments, the cooling system

includes an orifice plate having a plurality of orifices therein and a pedestal on the orifice plate. The cooling element may include a perimeter portion. The outer portion is between the central portion and the perimeter portion. The perimeter portion has a third thickness greater than the second thickness.

[0023] A cooling system including a cooling element and a support structure is described. The cooling element is configured to undergo vibrational motion when actuated to drive a fluid toward a heat-generating structure. The cooling element may include a central portion having a first thickness and an outer portion having a second thickness less than the first thickness. The support structure is coupled to the cooling element and configured to support the cooling element at the central portion. The cooling system may also include an orifice plate having a plurality of orifices therein and a pedestal on the orifice plate. The orifice plate may be between the cooling element and the heat-generating structure. The cooling element may include at least one of a thin film piezoelectric layer and a bulk piezoelectric layer. The thin film piezoelectric layer has a first thickness of at least 0.1 micrometer and not more than fifty micrometers. The bulk piezoelectric layer has a second thickness of at least thirty micrometers and not more than two hundred micrometers. In some embodiments, the cooling element includes a substrate and an additional piezoelectric layer. The piezoelectric layer is on a first side of the substrate. The additional piezoelectric layer is on a second side of the substrate opposite to the first side of the substrate. In some embodiments, the piezoelectric layer is embedded in the cooling element.

[0024] A method of cooling a heat-generating structure is described. The method includes driving a cooling element to induce a vibrational motion at a frequency. The cooling element includes a piezoelectric structure. The piezoelectric structure includes a substrate having a first side and a second side opposite to the first side. A first piezoelectric layer is on the first side and a second piezoelectric layer is on the second side. The piezoelectric structure may include an additional substrate between the second piezoelectric layer and the substrate. In some embodiments, the piezoelectric structure is embedded in the cooling element. The cooling element includes a central portion having a first thickness and an outer portion having a second thickness less than the first thickness. In some embodiments, an orifice plate is between the cooling element and a heat-generating structure. The orifice plate has a plurality of orifices therein and a pedestal on the orifice plate. In some such embodiments, the cooling element includes a perimeter portion, the outer portion being between the central portion and the perimeter portion, the perimeter portion having a third thickness greater than the second thickness.

[0025] FIGS. 1A-1F are diagrams depicting an exemplary embodiment of active cooling system 100 usable with heat-generating structure 102 and including a centrally anchored cooling element 120 or 120'. Cooling element 120 is shown in FIGS. 1A-1E and cooling element 120' is shown in FIG. 1F. For clarity, only certain components are shown. FIGS. 1A-1F are not to scale. Although shown as symmetric, cooling system 100 need not be.

[0026] Cooling system 100 includes top plate 110 having vent 112 therein, cooling element 120, orifice plate 130 having orifices 132 therein, support structure (or "anchor") 160 and chambers 140 and 150 (collectively chamber 140/

150) formed therein. Cooling element 120 is supported at its central region by anchor 160. Regions of cooling element 120 closer to and including portions of the cooling element's perimeter (e.g. tip 121) vibrate when actuated. In some embodiments, tip 121 of cooling element 120 includes a portion of the perimeter furthest from anchor 160 and undergoes the largest deflection during actuation of cooling element 120. For clarity, only one tip 121 of cooling element 120 is labeled in FIG. 1A.

[0027] FIG. 1A 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. 1B and 1C. 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. 1A-1E). 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. 1A-1E, 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. 1A-1E. 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. 1A-1E) 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 140/150 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, v , is at or near the structural resonant frequency for cooling element **120**. The frequency v 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 plate **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. $r1 \geq 100 \mu\text{m}$) and $r2$ is not more than one millimeter (e.g. $r2 \leq 1000 \mu\text{m}$). In some embodiments, orifices **132** are at least two hundred micrometers from tip **121** of cooling element **120** (e.g. $r1 \geq 200 \mu\text{m}$). In some such embodiments, orifices **132** are at least three hundred micrometers from tip **121** of cooling element **120** (e.g. $r1 \geq 300 \mu\text{m}$). 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 be a stainless steel, Ni alloy and/or Hastelloy substrate. 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. 1A-1E. 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. 1B-1C depict in-phase operation of cooling system 100. Referring to FIG. 1B, cooling element 120 has been actuated so that its tip 121 moves away from top plate 110. FIG. 1B 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 152B. Conversely, gap 142 for top chamber 140 has increased in size and is shown as gap 142B. 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. 1B. 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. 1B.

[0044] Cooling element 120 is also actuated so that tip 121 moves away from heat-generating structure 102 and toward top plate 110. FIG. 1C 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 142C. Gap 152 has increased in size and is shown as gap 152C. 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. 1C. 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. 1C. 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. 1B and 1C is repeated. Thus, cooling element 120 undergoes vibrational motion indicated in FIGS. 1A-1C, 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. 1D-1E 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. 1D and 1E.

[0048] The motion between the positions shown in FIGS. 1D and 1E is repeated. Thus, cooling element **120** undergoes vibrational motion indicated in FIGS. 1A, 1D, and 1E, 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. 1F 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. 1F, 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, *w*, of at least one hundred micrometers and not more than three hundred micrometers. Extension region has a length, *l*, 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. 2A-2B depict plan views of embodiments of cooling systems 200A and 200B analogous to active cooling systems such as cooling system 100. FIGS. 2A and 2B are not to scale. For simplicity, only portions of cooling elements 220A and 220B and anchors 260A and 260B, respectively, are shown. Cooling elements 220A and 220B are analogous to cooling element 120/120'. Thus, the sizes and/or materials used for cooling elements 220A and/or 220B may be analogous to those for cooling element 120/120'. Anchors (support structures) 260A and 260B are analogous to anchor 160 and are indicated by dashed lines.

[0055] For cooling elements 220A and 220B, anchors 260A and 260B are centrally located and extend along a central axis of cooling elements 220A and 220B, respectively. Thus, the cantilevered portions that are actuated to vibrate are to the right and left of anchors 260A and 260B. In some embodiments, cooling element(s) 220A and/or 220B are continuous structures, two portions of which are actuated (e.g. the cantilevered portions outside of anchors 260A and 260B). In some embodiments, cooling element(s) 220A and/or 220B include separate cantilevered portions each of which is attached to the anchors 260A and 260B, respectively, and actuated. Cantilevered portions of cooling elements 220A and 220B 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. 2A and 2B, L is the length of the cooling element, analogous to that depicted in

FIGS. 1A-1E. Also in FIGS. 2A and 2B, the depth, P, of cooling elements 220A and 220B is indicated.

[0056] Also shown by dotted lines in FIGS. 2A-2B are piezoelectric 223. Piezoelectric 223 is used to actuate cooling elements 220A and 220B. 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 220A and 220B can be utilized. Such other mechanisms may be at the locations of piezoelectric 223 or may be located elsewhere. In cooling element 220A, piezoelectric 223 may be affixed to cantilevered portions or may be integrated into cooling element 220A. Further, although piezoelectric 223 is shown as having particular shapes and sizes in FIG. 2A and 2B, other configurations may be used.

[0057] In the embodiment shown in FIG. 2A, anchor 260A extends the entire depth of cooling element 220A. Thus, a portion of the perimeter of cooling element 220A is pinned. The unpinned portions of the perimeter of cooling element 220A 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. 2B, anchor 260B does not extend to the perimeter of cooling element 220B. Thus, the perimeter of cooling element 220B is unpinned. However, anchor 260B still extends along the central axis of cooling element 220B. Cooling element 220B is still actuated such that cantilevered portions vibrate (e.g. analogous to the wings of a butterfly).

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

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

cooling elements 320A and/or 320B may be analogous to those for cooling element 120/120'. Anchors 360A and 360B are analogous to anchor 160 and are indicated by dashed lines.

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

[0061] In the embodiment shown in FIG. 3B, the anchor 360B is hollow and has apertures 363. In some embodiments, cooling element 320B has aperture(s) in the region of anchor 360B. In some embodiments, cooling element 320B includes multiple portions such that aperture(s) exist in the region of anchor 360B. As a result, fluid may be drawn through cooling element 320B and through anchor 360B. The fluid may exit through apertures 363. Thus, cooling element 320B may be used in place of a top plate, such as top plate 110. In such embodiments, apertures in cooling element 320B 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) 220A, 220B, 320A, 320B and/or analogous cooling elements. Such cooling systems may also share the benefits of cooling system 100. Cooling systems using cooling element(s) 220A, 220B, 320A, 320B 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) 220A, 220B, 320A, 320B 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) 220A, 220B, 320A, 320B 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) 220A, 220B, 320A, 320B and/or analogous cooling elements, the power used in operating cooling systems may be significantly reduced. Cooling element(s) 220A, 220B, 320A, 320B 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) 220A, 220B, 320A, 320B and/or analogous cooling elements may be improved.

[0063] FIGS. 4A-4B depict an embodiment of active cooling system 400 including a top centrally anchored cooling element. FIG. 4A depicts a side view of cooling system 400 in a neutral position. FIG. 4B depicts a top view of cooling system 400. FIGS. 4A-4B are not to scale. For simplicity, only portions of cooling system 400 are shown. Referring to FIGS. 4A-10B, 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 260A and/or 260B). In other embodiments, anchor 460 is only near the center portion of cooling element 420 (e.g. analogous to anchor 460C and/or 460D). Although not explicitly labeled in FIGS. 4A and 4B, 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. 5A-5E depict an embodiment of active cooling system 500 including multiple cooling cells configured as a tile, or array. FIG. 5A depicts a top view, while FIGS. 5B-5E depict side views. FIGS. 5A-5E are not to scale. Cooling system 500 includes four cooling cells 501A, 501B, 501C and 501D (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 2x2 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. 5A-5E. Cooling elements 520 are driven out-of-phase (i.e. in a manner analogous to a seesaw). Further, as can be seen in FIGS. 5B-5C and FIGS. 5D-5E cooling element 520 in one cell is driven out-of-phase with cooling element(s) 520 in adjacent cell(s). In FIGS. 5B-5C, cooling elements 520 in a row are driven out-of-phase. Thus, cooling element 520 in cell 501A is out-of-phase with cooling element 520 in cell 501B. Similarly, cooling element 520 in cell 501C is out-of-phase with cooling element 520 in cell 501D. In FIGS. 5D-5E, cooling elements 520 in a column are driven out-of-phase. Thus, cooling element 520 in cell 501A is out-of-phase with cooling element 520 in cell 501C. Similarly, cooling element 520 in cell 501B is out-of-phase with cooling element 520 in cell 501D. 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, cool-

ing 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] Cooling elements, such as cooling elements **120**, **120'**, **220A**, **220B**, **320A**, **320B**, **420**, and/or **520** may be configured in a variety of ways. Cooling elements may also be driven in a number of different manners. Various configurations of cooling elements and the piezoelectric structures are thus described herein. One or more features of such cooling elements and piezoelectric structures may be combined in manners not explicitly depicted.

[0071] FIG. 6 depicts cooling element **600** including substrate **602** and thin film piezoelectric layer **610**. FIG. 6 is not to scale. Although described as a cooling element, structure **600** is a piezoelectric structure that is a cooling element or forms part of a cooling element, such as cooling element **120**, **220**, **320**, **420**, or **520**. In some embodiments, a top electrode (not shown) is also formed on piezoelectric layer **610**. Substrate **602** may include or consist of one or more of a stainless steel (e.g. **304** stainless steel) substrate, a Hastelloy substrate, an Al-containing (e.g. an Al alloy) substrate, a Ti-containing (e.g. a Ti alloy such as Ti6Al-4V) substrate, and/or another substrate with thicknesses ranging from at least one hundred micrometers through not more than five hundred micrometers. Thus, substrate **602** may be conductive and may function as a bottom electrode. Cooling element **600** may include other layers (not shown). Such other layers may include but not be limited to seed, capping, passivation, an additional electrode layer, and/or other layers. Piezoelectric layer **610** is a thin film having a thickness of at least 0.1 micrometer and not more than fifty micrometers. In some embodiments, the thickness of the piezoelectric layer **610** is not more than thirty micrometers. In some embodiments, cooling element **600** has a total thickness of not more than two hundred micrometers. In some such embodiments, the thickness of cooling element(s) **600** is not more than one hundred micrometers (e.g. may be nominally one hundred micrometers). Other thicknesses are possible.

[0072] Piezoelectric layer **610** is also fabricated using thin film technology. Thus, piezoelectric layer **610** may be coated on substrate **602**. In some embodiments, thin piezoelectric layer **610** includes multiple sublayers formed using thin film techniques. Thus, piezoelectric layer **610** may be a multi-layer piezoelectric. For example, one or more piezoelectric sublayers may be coated onto a large substrate. Each sublayer may undergo additional processing. Once piezoelectric layer **610** is completed, the large substrate may be divided into individual cooling elements **600**. In some embodiments, cooling elements formed of or using piezoelectric structure **600** may be otherwise defined and manufacturing completed in another fashion. For example, substrate **602** may be a sheet that may be patterned to define multiple cooling elements **600**. Piezoelectric layer **610** (as well as other layers) may be selectively provided on regions of substrate **602** corresponding to cooling element **610**. Multiple cooling cells may be fabricated from the sheet. Individual cooling cells (and thus individual cooling elements **600**) or groups of cooling cells (and thus groups of cooling elements **600**) may then be separated.

[0073] FIG. 7 depicts cooling element **700** including substrate **702**, adhesive **704**, and bulk piezoelectric layer **710**. FIG. 7 is not to scale. Although described as a cooling element, structure **700** is a piezoelectric structure that is a

cooling element or forms part of a cooling element, such as cooling element **120**, **220**, **320**, **420**, or **520**. In some embodiments, a top electrode (not shown) is also formed on piezoelectric layer **710**. Substrate **702** may include or consist of a stainless steel (e.g. **304** stainless steel) substrate, a Hastelloy substrate, an Al-containing (e.g. an Al alloy) substrate, a Ti-containing (e.g. a Ti alloy such as Ti6Al-4V) substrate, and/or another substrate. Thus, substrate **702** may be conductive and may function as a bottom electrode. Additional electrode layer(s) may be provided on substrate **702** regardless of whether substrate **702** is conductive. Cooling element **700** may include other layers (not shown). Such other layers may include but not be limited to an additional electrode layer and/or other layers. In some embodiments, piezoelectric layer **710** has a thickness of at least thirty micrometers and not more than two hundred micrometers. In some embodiments, the thickness of piezoelectric layer **710** is at least fifty micrometers. In some embodiments, cooling element **700** has a total thickness of not more than three hundred micrometers. However, other thicknesses are possible.

[0074] Because piezoelectric layer **710** is a bulk layer, piezoelectric layer **710** may be fabricated separately and attached to substrate **702**. For example, one or more bulk piezoelectric layers may be attached to a large substrate using an adhesive. The adhesive may be electrically conductive or insulating depending on the configuration. Once attachment and other desired processing is completed, the large substrate may be divided into individual cooling elements **700**. In some embodiments, cooling elements formed of or using piezoelectric structure **700** may be otherwise defined and manufacturing completed in another fashion. For example, substrate **702** may be a sheet that may be patterned to define multiple cooling elements **700**. Piezoelectric layer **710** (as well as other layers) may be selectively provided on regions of substrate **702** corresponding to cooling element **700**. Multiple cooling cells may be fabricated from the sheet. Individual cooling cells (and thus individual cooling elements **700**) or groups of cooling cells (and thus groups of cooling elements **700**) may then be separated.

[0075] Cooling elements **600** and **700** include piezoelectric layers on a first side of the substrate. In some embodiments, piezoelectric layers may be on multiple (e.g. opposite) surfaces of the substrate. For example, FIG. 8 depicts cooling element **800** including substrate **802** and thin film piezoelectric layers **810** and **820**. FIG. 8 is not to scale. Although described as a cooling element, structure **800** is a piezoelectric structure that may form or be part of a cooling element, such as cooling element **120**, **220**, **320**, **420**, or **520**. In some embodiments, electrode(s) (not shown) are also formed on piezoelectric layer **810** and/or **820**. Substrate **802** may be a stainless steel (e.g. **304** stainless steel) substrate, a Hastelloy substrate, an Al-containing (e.g. an Al alloy) substrate, a Ti-containing (e.g. a Ti alloy such as Ti6Al-4V) substrate, and/or another substrate. Thus, substrate **802** may be conductive and may function as an electrode. Cooling element **800** may include other layers (not shown). Such other layers may include but not be limited to seed, capping, passivation, an additional electrode layer, and/or other layers. Thin film piezoelectric layers **810** and **820** each have a thickness of at least 0.1 micrometer and not more than fifty micrometers. In some embodiments, the thickness of each of piezoelectric layers **810** and **820** is not more than thirty

micrometers. In some embodiments, piezoelectric layers **810** and **820** have nominally the same thickness. In other embodiments, piezoelectric layers **810** and **820** have different thicknesses. Further, other thicknesses than described herein are possible.

[0076] Substrate **802** and piezoelectric layer **810** are analogous to substrate **602** and piezoelectric layer **610**. In addition, piezoelectric layer **820** has been fabricated on the opposite side of substrate **802**. Piezoelectric layer **820** is also fabricated using thin film technology. Thus, piezoelectric layer **820** may be coated on substrate **802**. In some embodiments, thin piezoelectric layer **820** includes multiple sublayers formed using thin film techniques. Thus, piezoelectric layer **820** may be a multilayer piezoelectric. For example, one or more piezoelectric sublayers may be coated onto a large substrate. Each sublayer may undergo additional processing. One or more additional piezoelectric layers may be coated onto the opposing surface of the large substrate and undergo additional processing. Once piezoelectric layers **810** and **820** are completed, the large substrate may be divided into individual cooling elements **800**. In some embodiments, cooling elements that are formed by or include piezoelectric structure **800** may be otherwise defined and manufacturing completed in another fashion. For example, substrate **802** may be a sheet that may be patterned to define multiple cooling elements **800**. Piezoelectric layer **810** (as well as other layers) may be selectively provided on regions of substrate **802** corresponding to cooling element **810**. Multiple cooling cells may be fabricated from the sheet. Individual cooling cells (and thus individual cooling elements **800**) or groups of cooling cells (and thus groups of cooling elements **800**) may then be separated.

[0077] Because two piezoelectric layers **810** and **820** are utilized, voltages of opposite polarities may be applied to piezoelectric layers **810** and **820** at substantially the same time. As a result, the deflection undergone by cooling element **800** may be increased for the same voltage applied. Stated differently, the same deflection of cooling element **800** may be obtained using lower magnitude opposite polarity voltages applied to piezoelectric layers **810** and **820**. In the embodiment shown in FIG. 8, voltages having magnitude V and opposite polarities applied to piezoelectric layers **810** and **820** result in the same deflection as a single voltage having magnitude $2V$ applied to only one piezoelectric layer **810** or **820**. Thus, lower voltages may be used in driving cooling element **800**.

[0078] FIG. 9 depicts cooling element **900** including substrates **902** and **902** as well as thin film piezoelectric layers **910** and **920**. FIG. 9 is not to scale. Although described as a cooling element, structure **900** is a piezoelectric structure that may form or be part of a cooling element, such as cooling element **120**, **220**, **320**, **420**, or **520**. In some embodiments, electrode(s) (not shown) are also formed on piezoelectric layer **910** and/or **920**. Substrate **902** and piezoelectric layer **910** are analogous to cooling element **600**. Similarly, substrate **903** and piezoelectric layer **920** are analogous to cooling element **600**. The back sides of substrates **902** and **903** have been attached, for example using an adhesive (not shown). Substrates **902** and **903** may include or consist of stainless steel (e.g. **340** stainless steel), Hastelloy, Al (e.g. an Al alloy), Ti (e.g. a Ti alloy such as Ti6Al-4V), and/or another material. Cooling element **900** may include other layers (not shown). Such other layers may include but not be limited to seed, capping, passivation, an

additional electrode layer, and/or other layers. Thin film piezoelectric layers **910** and **920** each have a thickness of at least **0.1** micrometer and not more than fifty micrometers. In some embodiments, the thickness of each of piezoelectric layers **910** and **920** is not more than thirty micrometers. In some embodiments, piezoelectric layers **910** and **920** have nominally the same thickness. In other embodiments, piezoelectric layers **910** and **920** have different thicknesses.

[0079] In some embodiments, thin piezoelectric layers **910** and **920** are formed on substrates **902** and **903**, respectively, using thin film techniques as described with respect to cooling elements **600** and **800**. For example, one or more piezoelectric sublayers may be coated onto a large substrate. Each sublayer may undergo additional processing. One or more additional piezoelectric layers may be coated onto the surface of another large substrate and undergo additional processing. The substrates **902** and **903** are affixed at their back sides. The large substrates may be divided into individual cooling elements **900** or may be processed as described above with respect to cooling elements **600**, **700**, and **800** such that multiple cooling cells (and thus multiple cooling elements/piezoelectric structures) are fabricated together. Because two piezoelectric layers **910** and **920** are present in cooling element **900**, lower voltages may be used to drive cooling element **900**.

[0080] FIG. 10 depicts cooling element **1000** including substrate **1002**, adhesives **1004** and **1005**, and bulk piezoelectric layers **1010** and **1020**. FIG. 10 is not to scale. Although described as a cooling element, structure **1000** is a piezoelectric structure that may form or be part of a cooling element, such as cooling element **120**, **220**, **320**, **420**, or **520**. In some embodiments, electrodes (not shown) are also formed on piezoelectric layers **1010** and **1020**. Substrate **1002** is analogous to substrate **702**. Piezoelectric layer **1010** and adhesive **1004** are analogous to piezoelectric layer **710** and adhesive **704**. Similarly, piezoelectric layer **1020** and adhesive **1005** analogous to piezoelectric layer **710** and adhesive **704**. Cooling element **1000** may include other layers (not shown). Such other layers may include but not be limited to an additional electrode layer and/or other layers. In some embodiments, each piezoelectric layer **1010** and **1020** has a thickness of at least thirty micrometers and not more than two hundred micrometers. In some embodiments, the thickness of each piezoelectric layer **1010** and **1020** is at least fifty micrometers. In some embodiments, piezoelectric layers **1010** and **1020** have nominally the same thickness. In other embodiments, piezoelectric layers **1010** and **1020** have different thicknesses. However, other thicknesses are possible.

[0081] Because piezoelectric layers **1010** and **1020** are bulk layers, piezoelectric layers **1010** and **1020** may be fabricated separately and attached to substrate **1002**. For example, one or more bulk piezoelectric layers may be attached to a first side of a large substrate using an adhesive. Other piezoelectric layer(s) may be attached to a second side of a large substrate using an adhesive. Once attachment and other desired processing is completed, the large substrate may be divided into individual cooling elements **1000** or may be processed as described above with respect to cooling elements **600** and **700** such that multiple cooling cells (and thus cooling elements) are fabricated together. In other embodiments, piezoelectric layer **1010** may be attached to a first substrate, piezoelectric layer **1020** may be attached to a second substrate, and the two substrates affixed in a manner

analogous to cooling element 900. Because two piezoelectric layers 1010 and 1020 are present in cooling element 1000, lower voltages may be used to drive cooling element 1000.

[0082] Although described in the context of cooling elements 600, 700, 800, 900 and 1000 that include either bulk piezoelectric layers or thin film piezoelectric layers, in some embodiments, bulk and thin film piezoelectric layers may be combined in other manners. For example, piezoelectric layers 820 may be replaced by a bulk piezoelectric layer affixed to substrate 802. Other combinations of piezoelectric layer(s) and substrates are also possible. Thus, the desired cooling element having one or more piezoelectric layers can be provided. In some embodiments, the piezoelectric layers may be separately controlled. Consequently, actuators may be used in MEMS-based active cooling systems to improve performance.

[0083] FIG. 11 depicts an embodiment of an active cooling system 1100 analogous to active cooling system 100. FIG. 11 is not to scale. For simplicity, only portions of cooling system 1100 are shown. Cooling system 1100 is analogous to cooling system 100. Consequently, analogous components have similar labels. Cooling system 1100 is shown as used in conjunction with heat-generating structure 1102, which is analogous to heat-generating structure 102. Cooling system 1100 includes top plate 1110 having vent 1112, cooling element 1120, orifice plate 1130 including orifices 1132, top chamber 1140 having a gap, bottom chamber 1150 having a gap and anchor (i.e. support structure) 1160 that are analogous to top plate 110 having vent 112, cooling element 120, orifice plate 130 including orifices 132, top chamber 140 having gap 142, bottom chamber 150 having gap 152 and anchor (i.e. support structure) 160, respectively. Thus, cooling element 1120 is centrally supported by anchor 1160 at its bottom such that at least a portion of the perimeter of cooling element 1120 is free to vibrate. In some embodiments, anchor 1160 extends along the axis of cooling element 1120 (e.g. in a manner analogous to anchor 260A and/or 260B). In other embodiments, anchor 1160 is only near the center portion of cooling element 1120 (e.g. analogous to anchor 360A and/or 360B). Although anchor 1160 is shown as supporting cooling element 1120 at its bottom, in some embodiments, anchor 1160 may be suspend cooling element 1120 from the top of cooling element 1120 (i.e. distal from heat-generating surface 1102) in a manner analogous to cooling element 420.

[0084] Cooling element 1120 includes piezoelectric layer(s) 1124. Although shown as residing on the top of cooling element 1120, piezoelectric layer 1124 may be embedded in or on the bottom of cooling element 1120. Further, multiple piezoelectric layers might be used in cooling element 1120. Although shown as a single substrate 1122 anchored at its center with multiple piezoelectric layers 1124, cooling element 1122 may be formed by multiple cooling elements supported at one region by anchor 1160 and free to vibrate at its opposing region (including tip 1121). Although shown as having piezoelectric layers 1124 on one side, in some embodiments, cooling element 1120 may have piezoelectric layers on both sides. For example, cooling element 900 and/or 1000 might be used. Thus, cooling element 1120 may be configured in a manner similar to one or more of cooling elements/piezoelectric structures 600, 700, 800, 900, and/or 1000. Piezoelectric layers 1124 may be driven to cause the free portions of cooling element 1120 to vibrate. For

example, the unpinned portions of cooling element 1100 may move in a manner analogous to the wings of a butterfly (in-phase) or in a manner analogous to a seesaw (out-of-phase). This motion is indicated by the unlabeled arrows in FIG. 11. Thus, cooling element 1120 can be driven to vibrate.

[0085] Cooling system 1100 functions in an analogous manner to cooling system 100. Consequently, the benefits described with respect to cooling system 100 may be achieved by cooling system 1100. Hence, performance of a device incorporating cooling system 1100 may be improved.

[0086] FIG. 12 depicts an embodiment of an active cooling system 1200 analogous to active cooling system 100. FIG. 12 is not to scale. For simplicity, only portions of cooling system 1200 are shown. Cooling system 1200 is analogous to cooling system 100. Consequently, analogous components have similar labels. Cooling system 1200 is shown as used in conjunction with heat-generating structure 1202, which is analogous to heat-generating structure 102. Cooling system 1200 includes top plate 1210 having vent 1212, cooling element 1220, orifice plate 1230 including orifices 1232, top chamber 1240 having a gap, bottom chamber 1250 having a gap and anchor (i.e. support structure) 1260 that are analogous to top plate 110 having vent 112, cooling element 120, orifice plate 130 including orifices 132, top chamber 140 having gap 142, bottom chamber 150 having gap 152 and anchor (i.e. support structure) 160, respectively. Thus, cooling element 1220 is centrally supported by anchor 1260 at its bottom such that at least a portion of the perimeter of cooling element 1220 is free to vibrate. In some embodiments, anchor 1260 extends along the axis of cooling element 1220 (e.g. in a manner analogous to anchor 260A and/or 260B). In other embodiments, anchor 1260 is only near the center portion of cooling element 1220 (e.g. analogous to anchor 360A and/or 360B). Although anchor 1260 is shown as supporting cooling element 1220 at its bottom, in some embodiments, anchor 1260 may be suspend cooling element 1220 from the top of cooling element 1220 (i.e. distal from heat-generating surface 1202) in a manner analogous to cooling element 420.

[0087] Cooling element 1220 includes piezoelectric layers 1226 and 1228. Piezoelectric layers 1226 and 1228 are embedded in cooling element 1220. In some embodiments, at least a portion of piezoelectric layers 1226 and 1228 may reside on and/or are aligned with anchor 1260. Piezoelectric layers 1226 and 1228 may be configured in a manner analogous to cooling element 900 and/or 1000. In some embodiments, piezoelectric layers 1226 and 1228 can be driven to induce a bending motion in central region of cooling element 1220 anchored to support structure 1260. This bending motion is indicated by the unlabeled curved arrow in FIG. 12. The bending of this portion of cooling element 1220 induces a vibrational motion, causing tip 1221 to deflect. For example, such a bending motion might be used to drive cooling element 1220 so that cantilevered arms on opposing sides of anchor 1260 vibrate out-of-phase (e.g. in a seesaw configuration). In some embodiments, piezoelectric layers 1226 and 1228 can be driven to induce a translational motion in central region of cooling element 1220 anchored to support structure 1260. This translation motion is indicated by the unlabeled straight arrow in FIG. 12. The translation of this portion of cooling element 1220 induces a vibrational motion, causing tip 1221 to deflect. For example, such a translational motion might be used to drive

cooling element **1220** so that cantilevered arms on opposite sides of anchor **1260** vibrate in-phase (e.g. in a butterfly configuration). Thus, cooling element **1220** can be driven to vibrate using bending and/or translation deflections.

[0088] Cooling system **1200** functions in an analogous manner to cooling system **100**. Consequently, the benefits described with respect to cooling system **100** may be achieved by cooling system **1200**. Hence, performance of a device incorporating cooling system **1200** may be improved.

[0089] FIG. **13** depicts an embodiment of an active cooling system **1300** analogous to active cooling systems **100**, **1000** and **1200**. FIG. **13** is not to scale. For simplicity, only portions of cooling system **1300** are shown. Cooling system **1300** is analogous to cooling system **100**. Consequently, analogous components have similar labels. Cooling system **1300** is shown as used in conjunction with heat-generating structure **1302**, which is analogous to heat-generating structure **102**. Cooling system **1300** includes top plate **1310** having vent **1312**, cooling element **1320**, orifice plate **1330** including orifices **1332**, top chamber **1340** having a gap, bottom chamber **1350** having a gap and anchor (i.e. support structure) **1360** that are analogous to top plate **110** having vent **112**, cooling element **120**, orifice plate **130** including orifices **132**, top chamber **140** having gap **142**, bottom chamber **150** having gap **152** and anchor (i.e. support structure) **160**, respectively. Thus, cooling element **1320** is centrally supported by anchor **1360** at its bottom such that at least a portion of the perimeter of cooling element **1320** is free to vibrate. In some embodiments, anchor **1360** extends along the axis of cooling element **1320** (e.g. in a manner analogous to anchor **260A** and/or **260B**). In other embodiments, anchor **1360** is only near the center portion of cooling element **1320** (e.g. analogous to anchor **360A** and/or **360B**). Although anchor **1360** is shown as supporting cooling element **1320** at its bottom, in some embodiments, anchor **1360** may be suspend cooling element **1320** from the top of cooling element **1320** (i.e. distal from heat-generating surface **1302**).

[0090] Cooling element **1320** includes piezoelectric layers **1324**, **1326** and **1328** that are analogous to piezoelectric layers **1124**, **1226** and **1228**, respectively. Piezoelectric layers **1326** and **1328** can be driven to induce a bending and/or translation motion in central region of cooling element **1320** anchored to support structure **1360**. Piezoelectric layers **1326** and **1328** may be configured in a manner analogous to cooling element **900** and/or **1000**. The bending and/or translation motion may cause the free portions of cooling element **1320** to vibrate. For example, a bending motion might be used to drive cooling element **1320** so that cantilevered arms on opposite sides of anchor **1360** vibrate out-of-phase (e.g. in a seesaw configuration). A translational motion might be used to drive cooling element **1320** so that cantilevered arms on opposite sides of anchor **1360** vibrate in-phase (e.g. in a butterfly configuration). Piezoelectric layer **1324** can directly induce vibrational motion in portions of cooling element **1320**. This motion is indicated by the unlabeled arrows in FIG. **13**. Cooling element **1320** can thus be driven to vibrate.

[0091] Cooling system **1300** functions in an analogous manner to cooling system **100**. Consequently, the benefits described with respect to cooling system **100** may be achieved by cooling system **1300**. Hence, performance of a device incorporating cooling system **1300** may be improved.

[0092] FIG. **14** depicts an embodiment of an active cooling system **1400** analogous to active cooling system **100**. FIG. **14** is not to scale. For simplicity, only portions of cooling system **1400** are shown. Cooling system **1400** is analogous to cooling system **100**. Consequently, analogous components have similar labels. Cooling system **1400** is shown as used in conjunction with heat-generating structure **1402**, which is analogous to heat-generating structure **102**. Cooling system **1400** includes top plate **1410** having vent **1412**, cooling element **1420**, orifice plate **1430** including orifices **1432**, top chamber **1440** having a gap, bottom chamber **1450** having a gap and anchor (i.e. support structure) **1460** that are analogous to top plate **110** having vent **112**, cooling element **120**, orifice plate **130** including orifices **132**, top chamber **140** having gap **142**, bottom chamber **150** having gap **152** and anchor (i.e. support structure) **160**, respectively. Thus, cooling element **1420** is centrally supported by anchor **1460** at its bottom such that at least a portion of the perimeter of cooling element **1420** is free to vibrate. In some embodiments, anchor **1460** extends along the axis of cooling element **1420** (e.g. in a manner analogous to anchor **260A** and/or **260B**). In other embodiments, anchor **1460** is only near the center portion of cooling element **1420** (e.g. analogous to anchor **360A** and/or **360B**). Although anchor **1460** is shown as supporting cooling element **1420** at its bottom, in some embodiments, anchor **1460** may be suspend cooling element **1420** from the top of cooling element **1420** (i.e. distal from heat-generating surface **1402**).

[0093] Cooling element **1420** includes a first (e.g. central) portion **1422** at least part of which is pinned by anchor **1460** and a second (e.g. perimeter) portion **1424** at least a portion of which is free to vibrate. The central portion **1422** of cooling element **1420** is thicker than perimeter portion **1424**. Stated differently, the thickness of cooling element **1420** may be considered to step down further from anchor **1460**. In some embodiments, the thickness of central portion **1422** is at least seventy five micrometers and not more than two hundred micrometers. The perimeter portion **1424** is at least fifty micrometers and not more than one hundred micrometers thinner than the central portion **1422**. For simplicity, piezoelectric layers are not shown for cooling element **1420**. Cooling element **1420** may be configured in a manner similar to one or more of cooling elements **600**, **700**, **800**, **900**, and/or **1000**. Thus, cooling element **1420** may be driven by one or more piezoelectric layers on one or multiple surface(s) of the substrate(s).

[0094] Cooling system **1400** functions in an analogous manner to cooling system **100**. Consequently, the benefits described with respect to cooling system **100** may be achieved by cooling system **1400**. In addition, because the thickness of perimeter portion **1424** of cooling element **1420** is less than the thickness of central portion **1422**, a larger static deflection may be achieved at the tips of cooling element **1420**. Further, cooling element **1420** may have a higher structural resonant frequency. Thus, cooling element **1420** may be driven at a higher frequency than a uniform cooling element having a constant thickness that is the same as the thickness of central portion **1422**. Because the thickness of central region **1422** is larger, the stiffness of cooling element **1420** is higher than that of a uniform cooling element having the (lower) thickness of perimeter region **1424**. Hence, an undue reduction of stiffness of cooling

element 1420 may be avoided. As a result, performance of a device incorporating cooling system 1400 may be improved.

[0095] FIG. 15 depicts an embodiment of an active cooling system 1500 analogous to active cooling systems 100 and 1400. FIG. 15 is not to scale. For simplicity, only portions of cooling system 1500 are shown. Cooling system 1500 is analogous to cooling system 100. Consequently, analogous components have similar labels. Cooling system 1500 is shown as used in conjunction with heat-generating structure 1502, which is analogous to heat-generating structure 102. Cooling system 1500 includes top plate 1510 having vent 1512, cooling element 1520, orifice plate 1530 including orifices 1532, top chamber 1540 having a gap, bottom chamber 1550 having a gap and anchor (i.e. support structure) 1560 that are analogous to top plate 110 having vent 112, cooling element 120, orifice plate 130 including orifices 132, top chamber 140 having gap 142, bottom chamber 150 having gap 152 and anchor (i.e. support structure) 160, respectively. Thus, cooling element 1520 is centrally supported by anchor 1560 at its bottom such that at least a portion of the perimeter of cooling element 1520 is free to vibrate. In some embodiments, anchor 1560 extends along the axis of cooling element 1520 (e.g. in a manner analogous to anchor 260A and/or 260B). In other embodiments, anchor 1560 is only near the center portion of cooling element 1520 (e.g. analogous to anchor 360A and/or 360B). Although anchor 1560 is shown as supporting cooling element 1520 at its bottom, in some embodiments, anchor 1560 may be suspend cooling element 1520 from the top of cooling element 1520 (i.e. distal from heat-generating surface 1502). For simplicity, piezoelectric layers are not shown for cooling element 1520. Cooling element 1520 may be configured in a manner similar to one or more of cooling elements 600, 700, 800, 900, and/or 1000. Thus, cooling element 1520 may be driven by one or more piezoelectric layers on one or multiple surface(s) of the substrate(s).

[0096] Cooling element 1520 is analogous to cooling element 1420. Thus, cooling element 1520 includes regions having stepped-down thicknesses. Cooling element 1520 includes first (e.g. central) portion 1522 at least part of which is pinned by anchor 1560, second (e.g. outer) region 1524, and third (e.g. perimeter) portion 1526 at least a portion of which is free to vibrate. The central portion 1522 of cooling element 1520 is thicker than outer portion 1524. Outer portion 1524 of cooling element 1520 is thicker than perimeter portion 1526. Stated differently, the thickness of cooling element 1520 may be considered to step down further from anchor 1560. In some embodiments, each step is at least fifty micrometers and not more than one hundred micrometers. For example, outer portion 1524 is at least fifty micrometers and not more than one hundred micrometers thinner than central portion 1522. Perimeter portion 1526 is at least fifty micrometers and not more than one hundred micrometers thinner than outer portion 1524. For example, central portion 1522 might be two hundred micrometers thick, outer portion 1524 may be one hundred and fifty micrometers thick, and perimeter portion 1526 may be seventy five micrometers thick. Other thicknesses are possible.

[0097] Cooling system 1500 functions in an analogous manner to cooling systems 100 and 1400. Consequently, the benefits described with respect to cooling systems 100 and

1400 may be achieved by cooling system 1500. As a result, performance of a device incorporating cooling system 1500 may be improved.

[0098] FIG. 16 depicts an embodiment of an active cooling system 1600 analogous to active cooling systems 100, 1400 and 1500. FIG. 16 is not to scale. For simplicity, only portions of cooling system 1600 are shown. Cooling system 1600 is analogous to cooling system 100. Consequently, analogous components have similar labels. Cooling system 1600 is shown as used in conjunction with heat-generating structure 1602, which is analogous to heat-generating structure 102. Cooling system 1600 includes top plate 1610 having vent 1612, cooling element 1620, orifice plate 1630 including orifices 1632, top chamber 1640 having a gap, bottom chamber 1650 having a gap and anchor (i.e. support structure) 1660 that are analogous to top plate 110 having vent 112, cooling element 120, orifice plate 130 including orifices 132, top chamber 140 having gap 142, bottom chamber 150 having gap 152 and anchor (i.e. support structure) 160, respectively. Thus, cooling element 1620 is centrally supported by anchor 1660 at its bottom such that at least a portion of the perimeter of cooling element 1620 is free to vibrate. In some embodiments, anchor 1660 extends along the axis of cooling element 1620 (e.g. in a manner analogous to anchor 260A and/or 260B). In other embodiments, anchor 1660 is only near the center portion of cooling element 1620 (e.g. analogous to anchor 360A and/or 360B). Although anchor 1660 is shown as supporting cooling element 1620 at its bottom, in some embodiments, anchor 1660 may be suspend cooling element 1620 from the top of cooling element 1620 (i.e. distal from heat-generating surface 1602).

[0099] Cooling element 1620 is analogous to cooling element 1420. Thus, cooling element 1620 includes regions having stepped-down thicknesses. Cooling element 1620 includes first (e.g. central) portion 1622 at least part of which is pinned by anchor 1660, second (e.g. outer) region 1624 that has a stepped down thickness. Additional thinned portion(s), such as a portion analogous to 1526 may be included in some embodiments. The central portion 1622 of cooling element 1620 is thicker than outer portion 1624. For simplicity, piezoelectric layers are not shown for cooling element 1620. Cooling element 1620 may be configured in a manner similar to one or more of cooling elements 600, 700, 800, 900, and/or 1000. Thus, cooling element 1620 may be driven by one or more piezoelectric layers on one or multiple surface(s) of the substrate(s).

[0100] In addition, pedestals 1636 from orifice plate 1630 are shown. Pedestals 1636 may be integrated into (e.g. formed from the same substrate as) orifice plate 1630 in some embodiments. In other embodiments, pedestals 1636 may be affixed to orifice plate 1630.

[0101] Cooling system 1600 functions in an analogous manner to cooling systems 100, 1400 and 1500. Consequently, the benefits described with respect to cooling systems 100, 1400 and 1500 may be achieved by cooling system 1600. In addition, pedestals 1636 may aid in controlling flow through orifices 1632. For example, pedestals 1636 may aid in cutting off flow (e.g. backflow) from orifices 1630 in a manner analogous to perimeter portion 128 of engineered cooling element 120'. Cooling element 1620 is thus able to be more efficiently driven to vibrate and control flow through cooling chambers 1640 and/or 1650.

As a result, performance of a device incorporating cooling system 1600 may be improved.

[0102] FIG. 17 is a flow chart depicting an exemplary embodiment of method 1700 for operating a cooling system. Method 1700 may include steps that are not depicted for simplicity. Method 1700 is described in the context of piezoelectric cooling system 100. However, method 1700 may be used with other cooling systems including but not limited to systems and cells described herein.

[0103] One or more of the cooling element(s) in a cooling system is actuated to vibrate, at 1702. At 1702, an electrical signal having the desired frequency is used to drive the cooling element(s). In some embodiments, the cooling elements are driven at or near structural and/or acoustic resonant frequencies at 1702. The driving frequency may be 15 kHz or higher. If multiple cooling elements are driven at 1702, the cooling elements may be driven out-of-phase. In some embodiments, the cooling elements are driven substantially at one hundred and eighty degrees out of phase. Further, in some embodiments, individual cooling elements are driven out-of-phase. For example, different portions of a cooling element may be driven to vibrate in opposite directions (i.e. analogous to a seesaw). In some embodiments, individual cooling elements may be driven in-phase (i.e. analogous to a butterfly). In addition, the drive signal may be provided to the cooling element(s) such that the cooling element is driven in the desired manner. For example, for cooling elements analogous to cooling element 1220 and/or 1320, the piezoelectric within the cooling element may be driven to translate or bend such that the desired frequency of vibration is achieved.

[0104] Feedback from the piezoelectric cooling element(s) is used to adjust the driving current, at 1704. In some embodiments, the adjustment is used to maintain the frequency at or near the acoustic and/or structural resonant frequency/frequencies of the cooling element(s) and/or cooling system. Resonant frequency of a particular cooling element may drift, for example due to changes in temperature. Adjustments made at 1704 allow the drift in resonant frequency to be accounted for.

[0105] For example, piezoelectric cooling element 120 may be driven at its structural resonant frequency/frequencies, at 1702. This resonant frequency may also be at or near the acoustic resonant frequency for top chamber 140. This may be achieved by driving piezoelectric layer(s) in anchor 160 (not shown in FIGS. 1A-1F) and/or piezoelectric layer(s) in cooling element 120. At 1704, feedback is used to maintain cooling element 120 at resonance and, in some embodiments in which multiple cooling elements are driven, one hundred and eighty degrees out of phase. Thus, the efficiency of cooling element 120 in driving fluid flow through cooling system 100 and onto heat-generating structure 102 may be maintained. In some embodiments, 1704 includes sampling the current through cooling element 120 and adjusting the current to maintain resonance and low input power.

[0106] Consequently, cooling elements may operate as described above. Method 1700 thus provides for use of piezoelectric cooling systems described herein. Thus, piezoelectric cooling systems may more efficiently and quietly cool semiconductor devices at lower power.

[0107] 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.

What is claimed is:

1. A cooling system, comprising:
 - a chamber;
 - a cooling element residing in the chamber and including a central portion and an outer portion, the cooling element being configured to undergo vibrational motion when actuated to drive a fluid through the chamber, the cooling element including a piezoelectric structure including a substrate having a first side and a second side opposite to the first side, a first piezoelectric layer on the first side, and a second piezoelectric layer on the second side; and
 - a support structure coupled to the cooling element and the chamber, the support structure being configured to support the cooling element at the central portion, the outer portion being unpinned from the support structure.
2. The cooling system of claim 1, wherein the first piezoelectric layer is selected from a thin film piezoelectric layer and a bulk piezoelectric layer, the thin film piezoelectric layer having a first thickness of at least 0.1 micrometer and not more than fifty micrometers and wherein the bulk piezoelectric layer has a second thickness of at least thirty micrometers and not more than two hundred micrometers.
3. The cooling system of claim 2, wherein the first thickness is not more than thirty micrometers and the second thickness is at least fifty micrometers.
4. The cooling system of claim 1, wherein the cooling element includes an additional substrate between the substrate and the second piezoelectric layer, the second piezoelectric layer being coupled to the additional substrate.
5. The cooling system of claim 1, wherein the piezoelectric structure is embedded in the cooling element.
6. The cooling system of claim 1, wherein the central portion of the cooling element has a first thickness and the outer portion has a second thickness less than the first thickness.
7. The cooling system of claim 6, further comprising:
 - an orifice plate having a plurality of orifices therein, the support structure being coupled to the orifice plate.
8. The cooling system of claim 6, wherein the cooling element includes a perimeter portion, the outer portion being between the central portion and the perimeter portion, the perimeter portion having a third thickness greater than the second thickness.
9. A cooling system, comprising:
 - a chamber;
 - a cooling element within the chamber and including a central portion and an outer portion, the cooling element configured to undergo vibrational motion when actuated to drive a fluid through the chamber, the cooling element including a central portion having a first thickness and an outer portion having a second thickness less than the first thickness; and
 - a support structure coupled to the cooling element and configured to support the cooling element at the central portion, the outer portion being unpinned from the support structure.
10. The cooling system of claim 9, wherein the chamber further includes:

an orifice plate having a plurality of orifices therein, the support structure being coupled with the orifice plate; and

a top plate having a least one vent therein.

11. The cooling system of claim **10**, wherein the cooling element includes at least one of a thin film piezoelectric layer and a bulk piezoelectric layer, the thin film piezoelectric layer having a first thickness of at least 0.1 micrometer and not more than fifty micrometers and wherein the bulk piezoelectric layer having a second thickness of at least thirty micrometers and not more than two hundred micrometers.

12. The cooling system of claim **11**, wherein the cooling element includes a substrate and an additional piezoelectric layer, the piezoelectric layer being on a first surface of the substrate, the additional piezoelectric layer being on a second surface of the substrate opposite to the first surface of the substrate.

13. The cooling system of claim **11**, wherein the piezoelectric layer is embedded in the cooling element.

14. A method of cooling a heat-generating structure, comprising:

driving a cooling element to induce a vibrational motion at a frequency, the cooling element residing in a chamber and having a central portion and an outer portion, the outer portion of the cooling element being configured to undergo the vibrational motion when actuated

to drive a fluid through the chamber, the central portion of the cooling element being coupled to the chamber by a support structure, the outer portion being unpinned from the support structure, the cooling element including a piezoelectric structure including a substrate having a first side and a second side opposite to the first side, a first piezoelectric layer on the first side, and a second piezoelectric layer on the second side.

15. The method of claim **14**, wherein the piezoelectric structure includes an additional substrate between the second piezoelectric layer and the substrate.

16. The method of claim **14**, wherein the piezoelectric structure is embedded in the cooling element.

17. The method of claim **14**, wherein the central portion has a first thickness and the outer portion having a second thickness less than the first thickness.

18. The method of claim **17**, wherein the cooling element includes a perimeter portion, the outer portion being between the central portion and the perimeter portion, the perimeter portion having a third thickness greater than the second thickness.

19. The method of claim **17**, wherein the chamber includes an orifice plate having a plurality of orifices therein and a projection on the orifice plate resides between the cooling element and a heat-generating structure.

* * * * *