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Li et al.

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(54) **PIEZOELECTRIC ACTIVE COOLING DEVICE**

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(51) **Int. Cl.**

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F04D 33/00	(2006.01)
G06F 1/20	(2006.01)
H01L 23/467	(2006.01)
H01L 41/04	(2006.01)

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

CPC ***F04D 33/00*** (2013.01); ***G06F 1/203*** (2013.01); ***G06F 1/206*** (2013.01); ***H01L 23/467*** (2013.01); ***H01L 41/042*** (2013.01); ***H01L 41/0933*** (2013.01); ***H01L 41/094*** (2013.01); *H01L 2924/0002* (2013.01); *Y02B 60/1275* (2013.01)

(58) **Field of Classification Search**

CPC H01L 41/08; H01H 97/00; G10K 11/004

USPC 310/311, 315, 316.01, 317, 318, 328, 310/330, 331, 341, 346

See application file for complete search history.

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Primary Examiner — Thomas Dougherty

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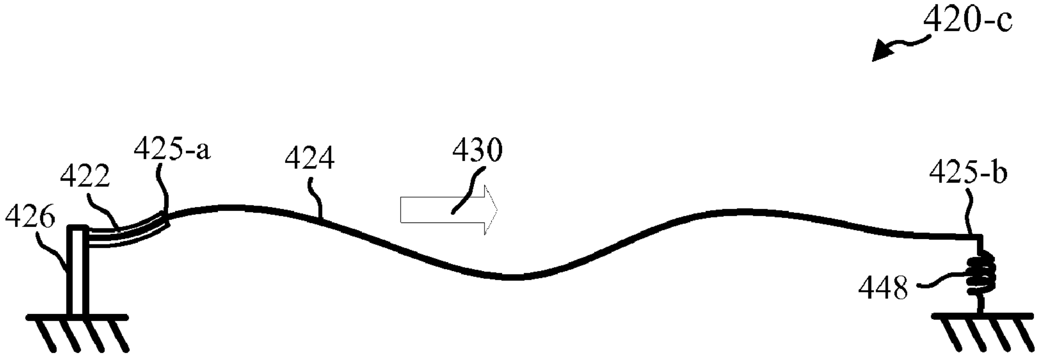
(57) **ABSTRACT**

Methods, systems, and devices for providing cooling for a mobile device using piezoelectric active cooling devices. Some embodiments utilize piezoelectric actuators that oscillate a planar element within an air channel to fan air within or at an outlet of the air channel. The air channel may be defined by at least one heat dissipation surface in thermal contact with components of the mobile device that generate excess waste heat. For example, the air channel may include a surface that is in thermal contact with a processor of the mobile computing device. In embodiments, the piezoelectric active cooling device may be used in an air gap between stacked packages in a package on package (PoP) processor package. The described embodiments provide active cooling using low power, can be controlled to provide variable cooling, use highly reliable elements, and can be implemented at low cost.

23 Claims, 13 Drawing Sheets



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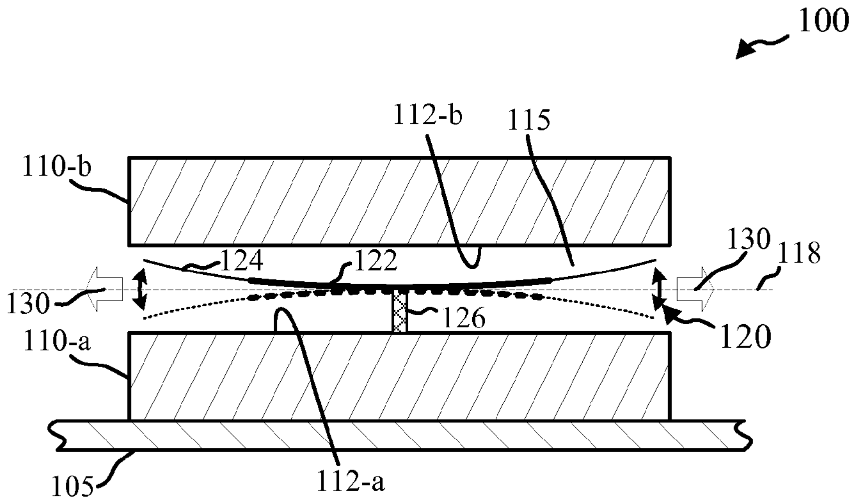
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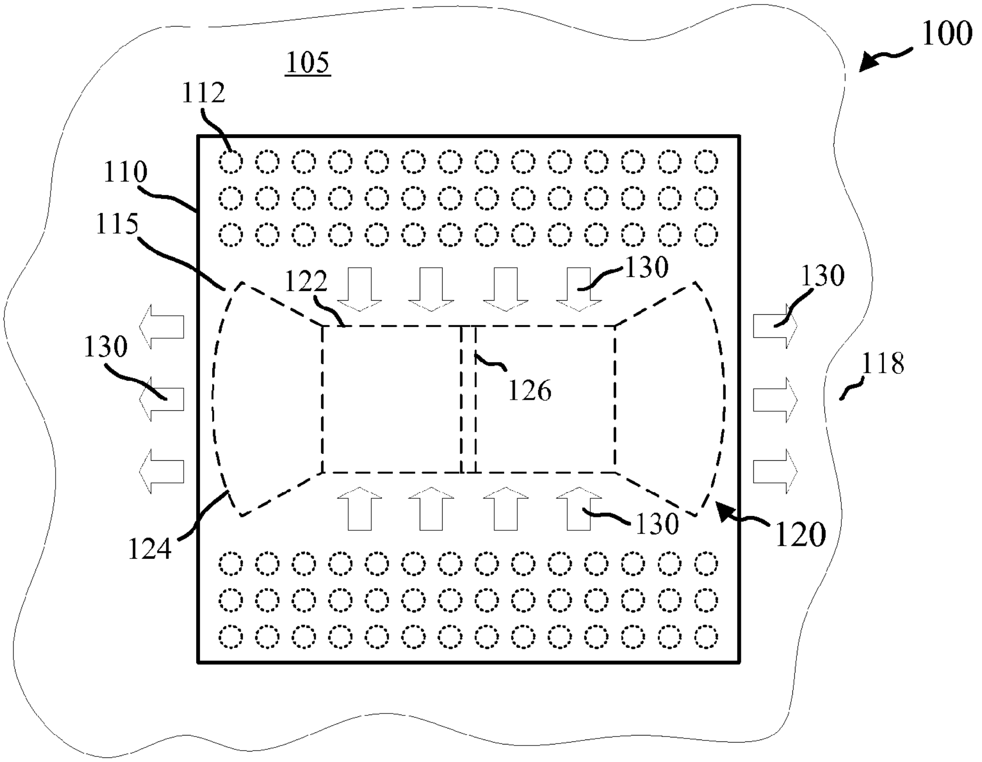
112-b
115
110-b
130
118
124
122
130
126
120
110-a
105
112-a

FIG. 1A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130
120

FIG. 1B

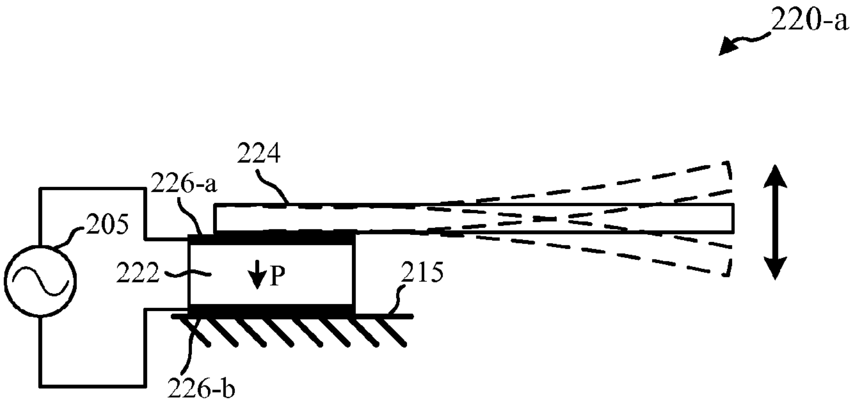


FIG. 2A

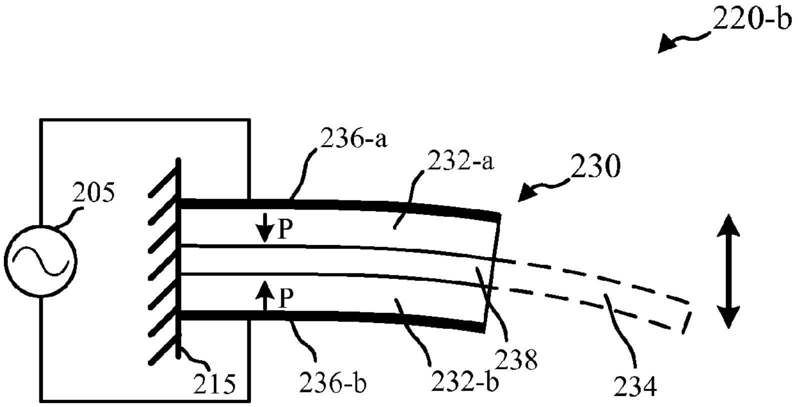


FIG. 2B

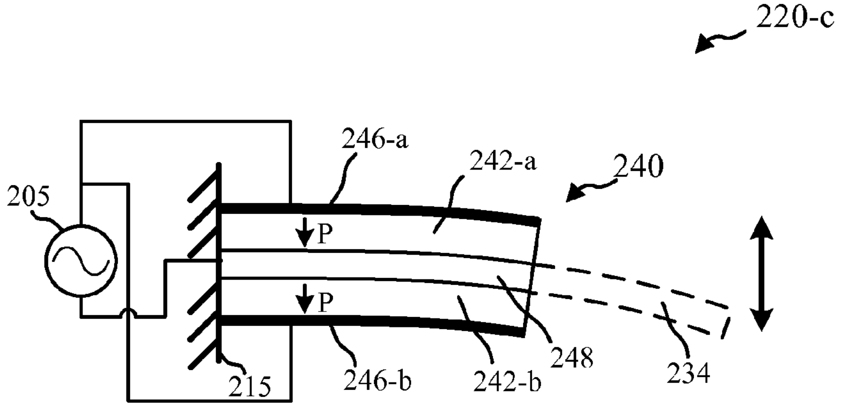
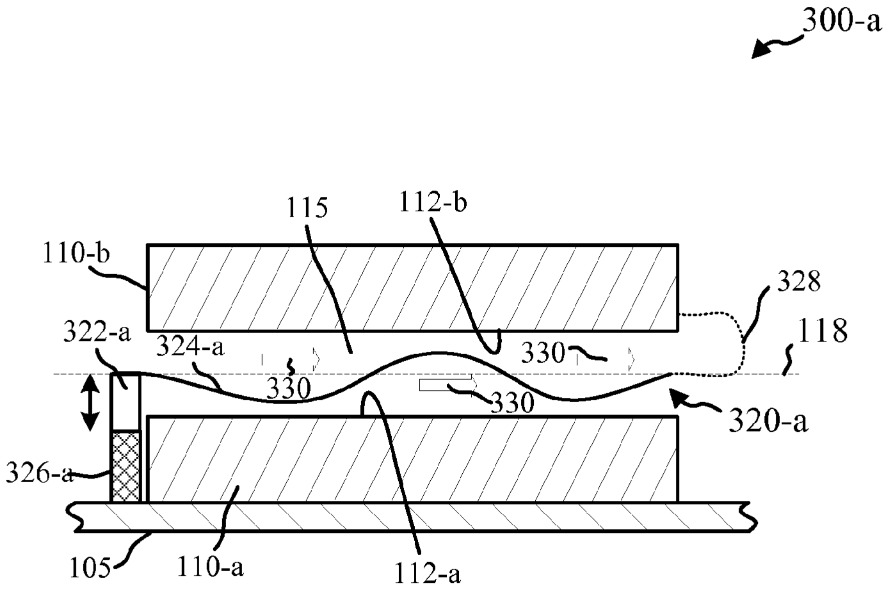


FIG. 2C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112-b
110-b
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326-a
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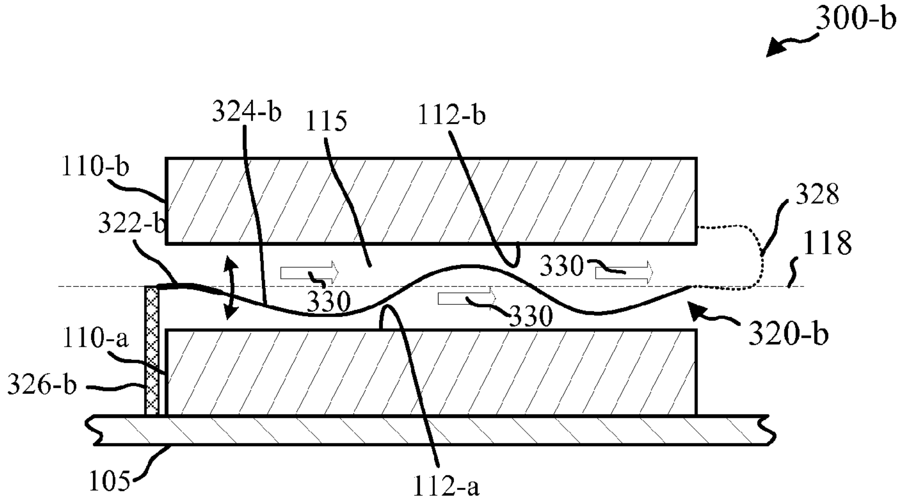
112-a

FIG. 3A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324-b
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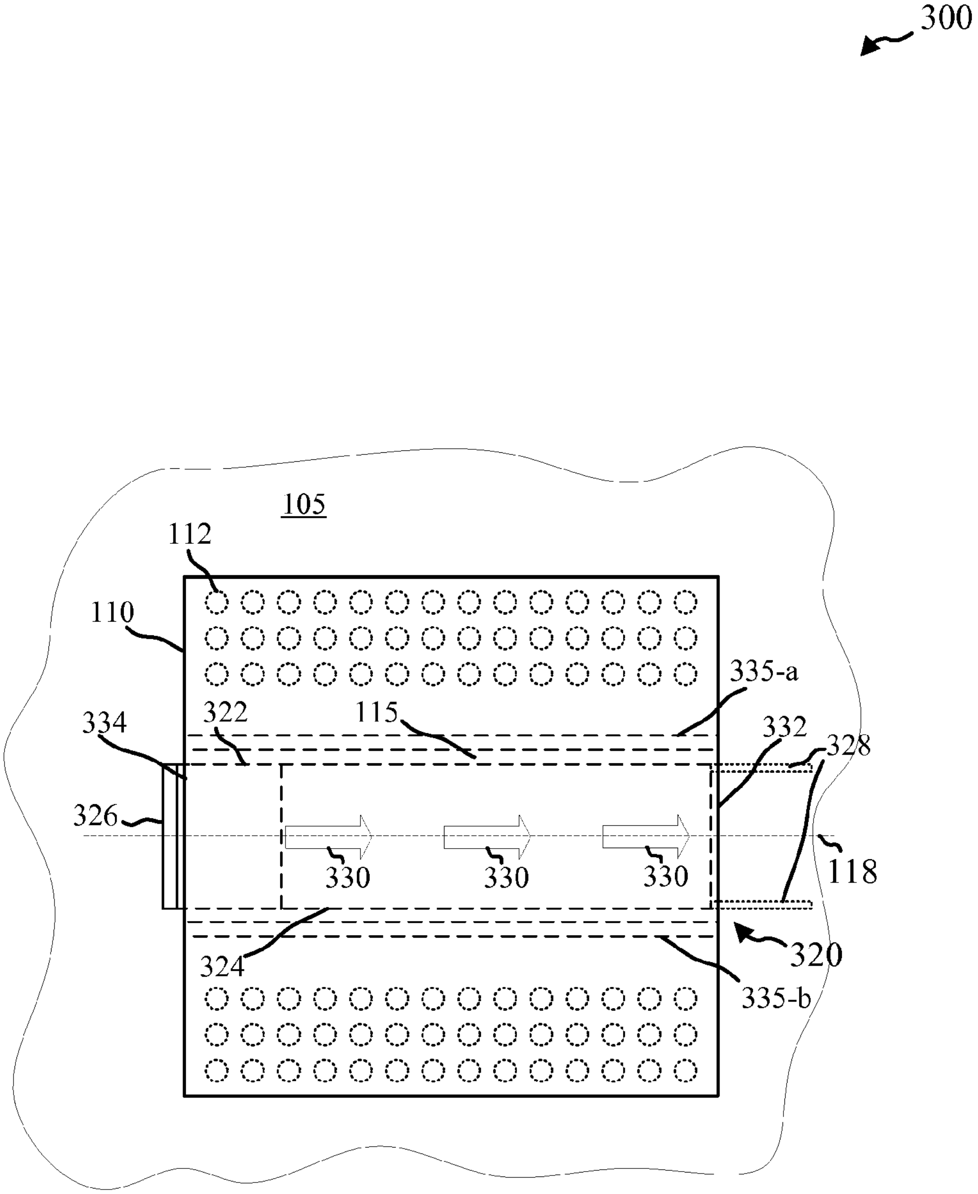
105
112-a

FIG. 3B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324
335-b

FIG. 3C

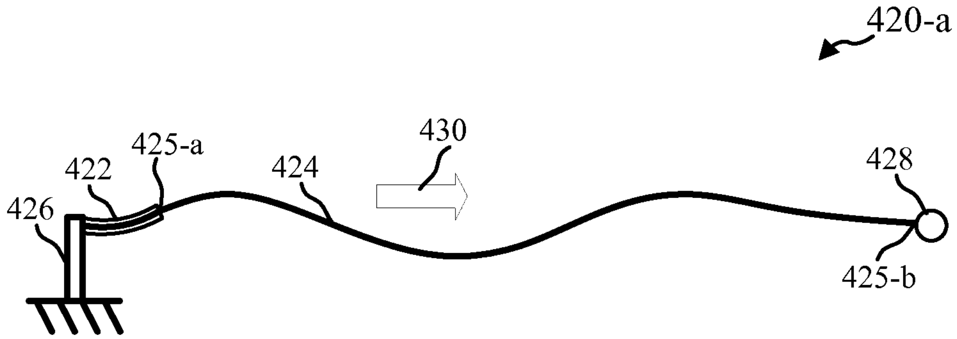


FIG. 4A

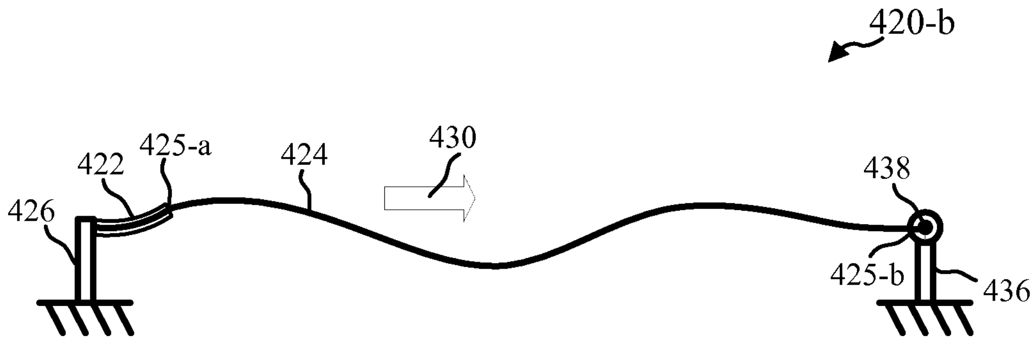


FIG. 4B

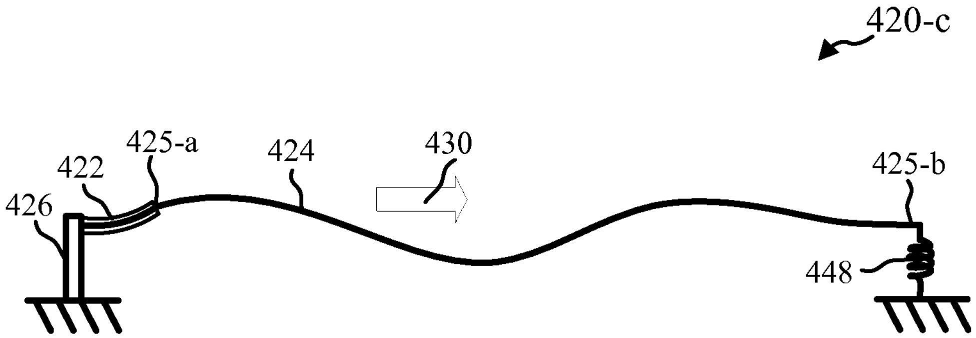


FIG. 4C

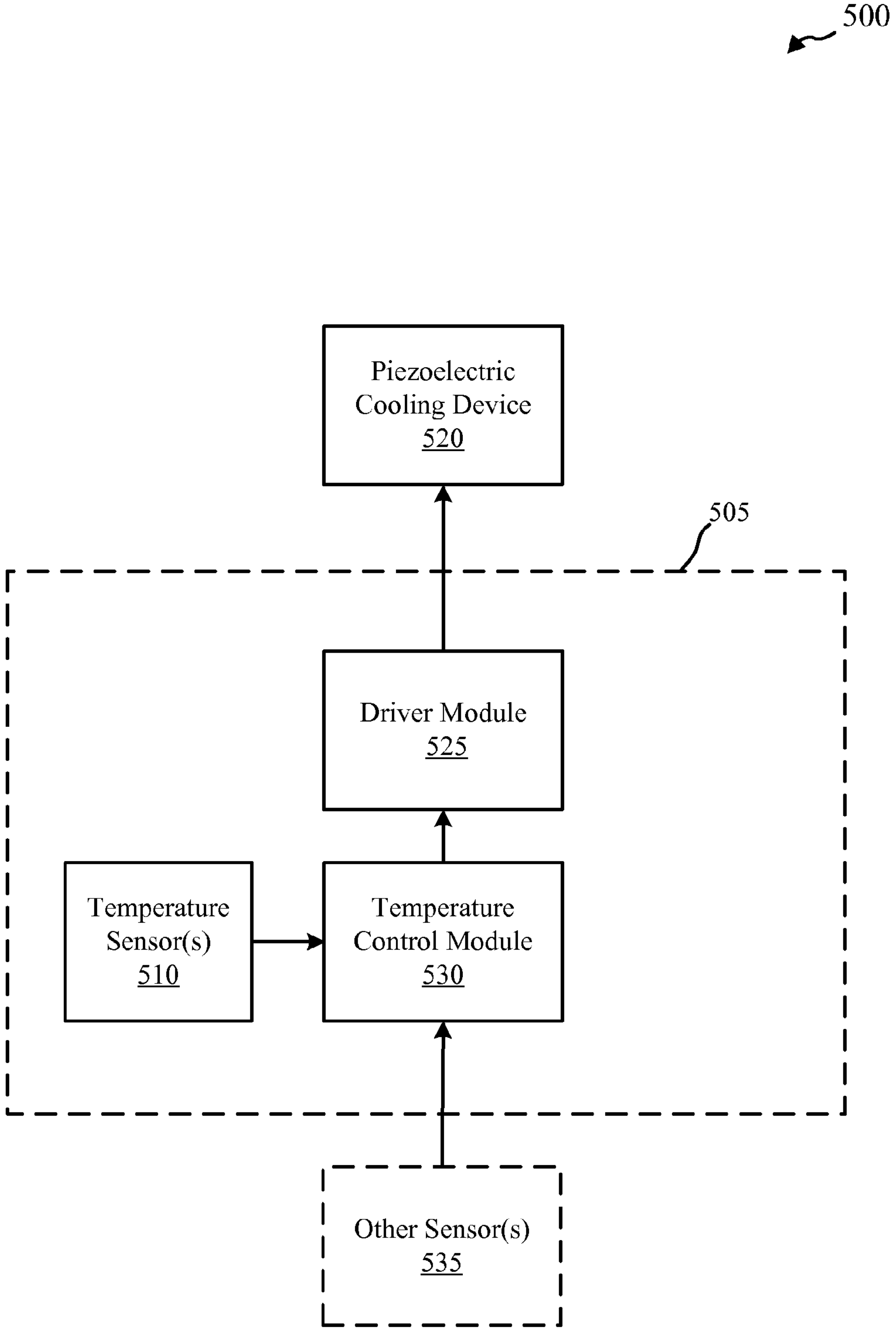
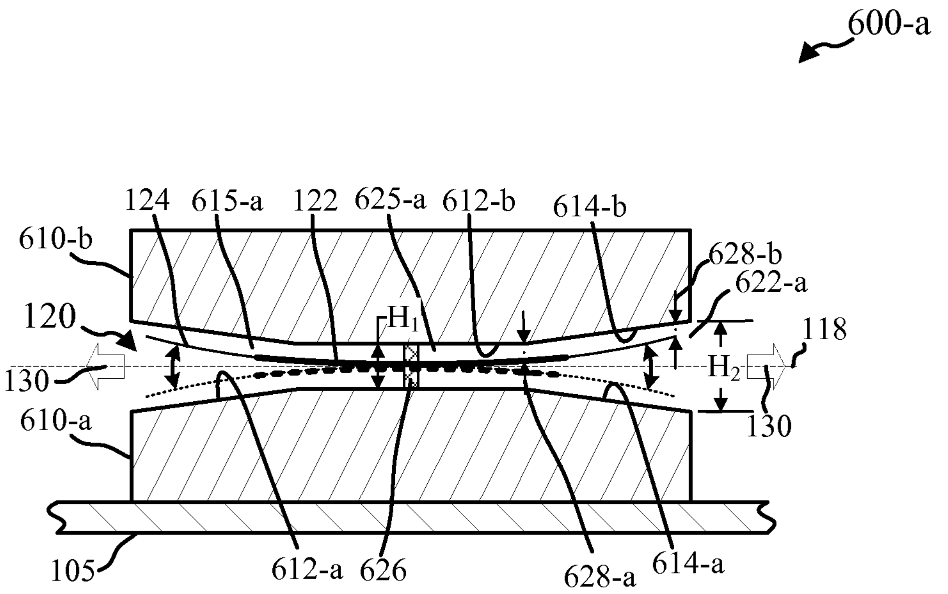

500
Piezoelectric Cooling Device 520
505
Driver Module 525
Temperature Sensor(s) 510
Temperature Control Module 530
Other Sensor(s) 535

FIG. 5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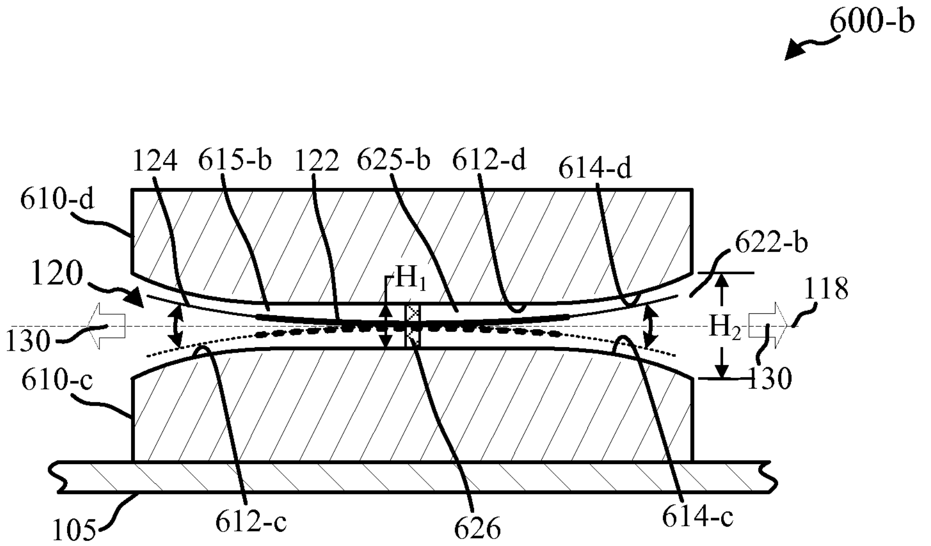
615-a
122
625-a
612-b
614-b
610-b
628-b
622-a
120
H_1
118
130
H_2
610-a
130
105
612-a
626
628-a
614-a

FIG. 6A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612-d
614-d
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120
H_1
118
130
H_2
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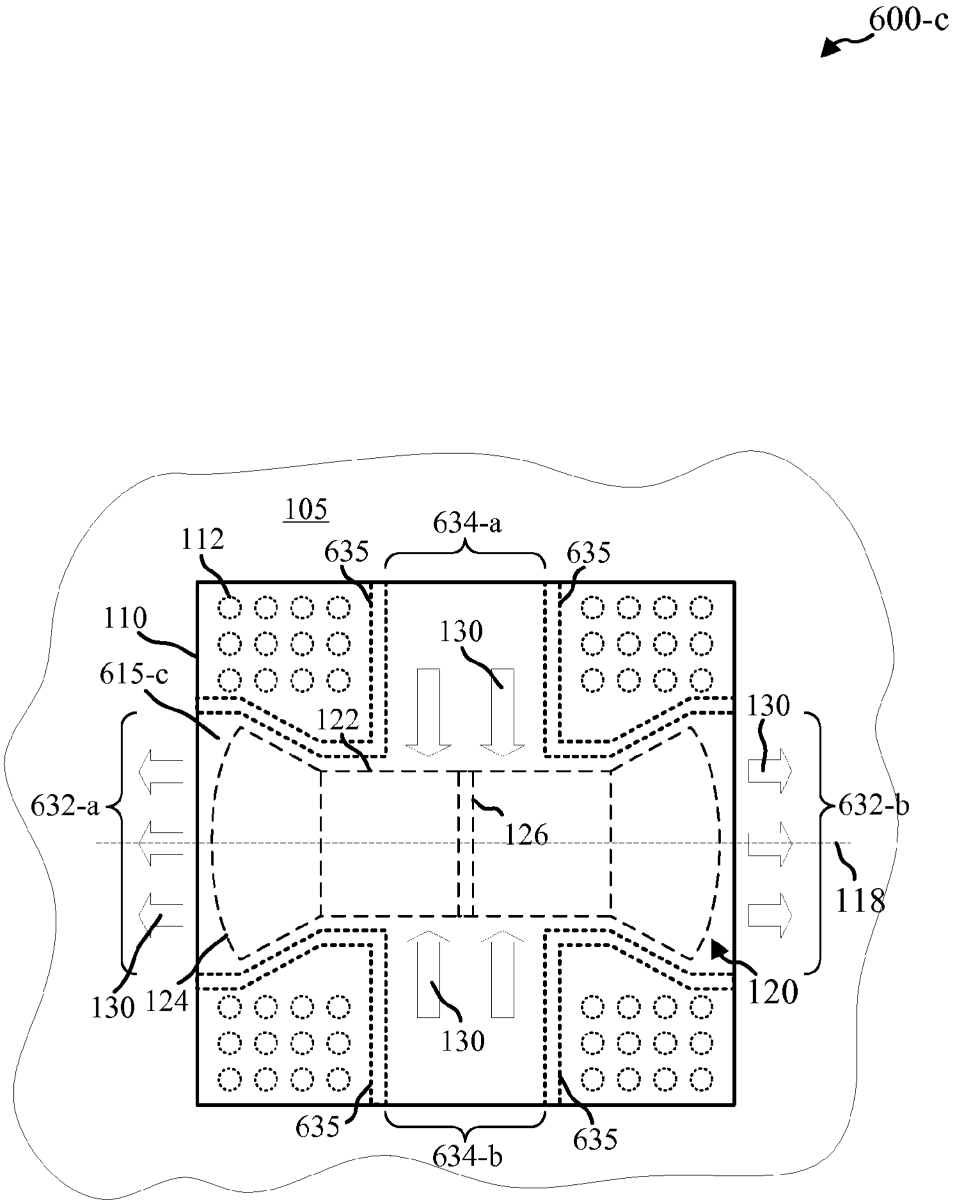
130
105
612-c
626
614-c

FIG. 6B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112
634-a
635
635
110
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615-c
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632-a
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632-b
118
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124
130
130
120
635
634-b
635

FIG. 6C

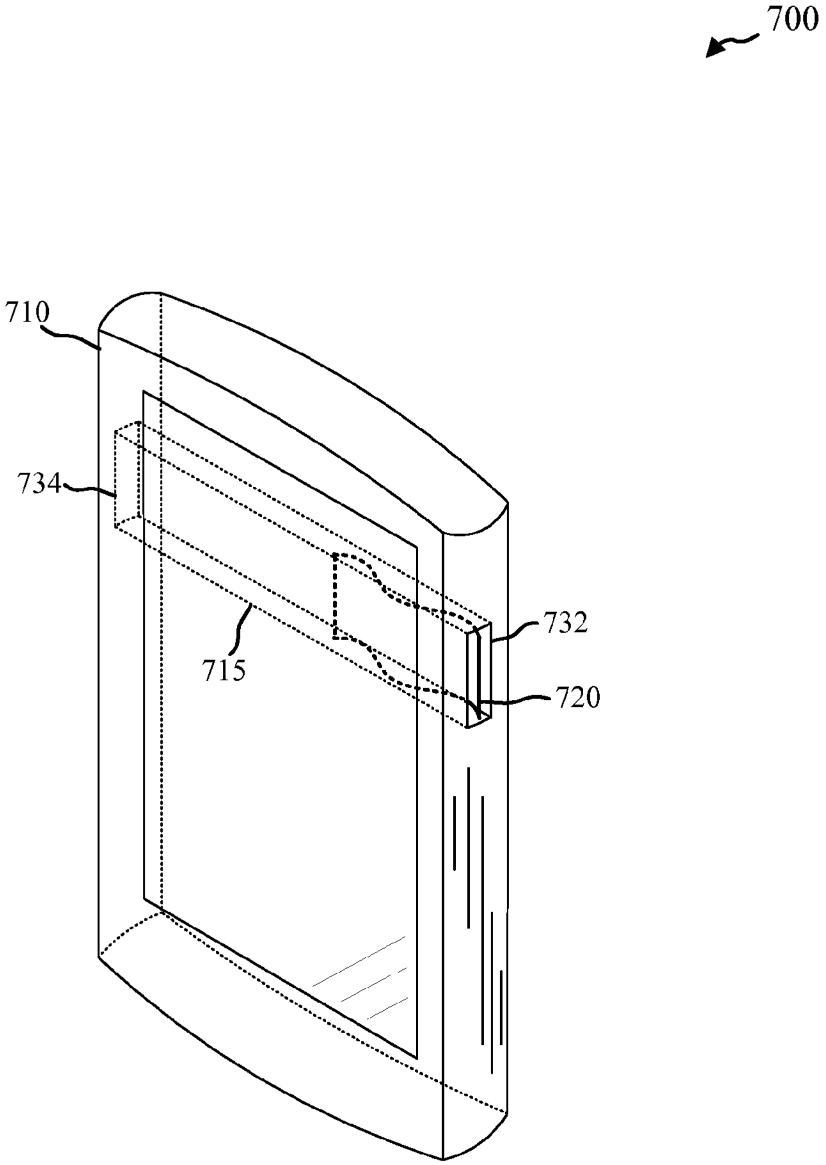

FIG. 7

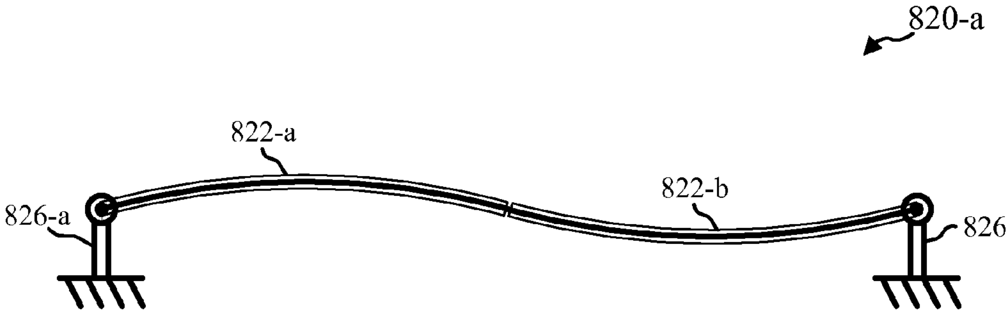

FIG. 8A

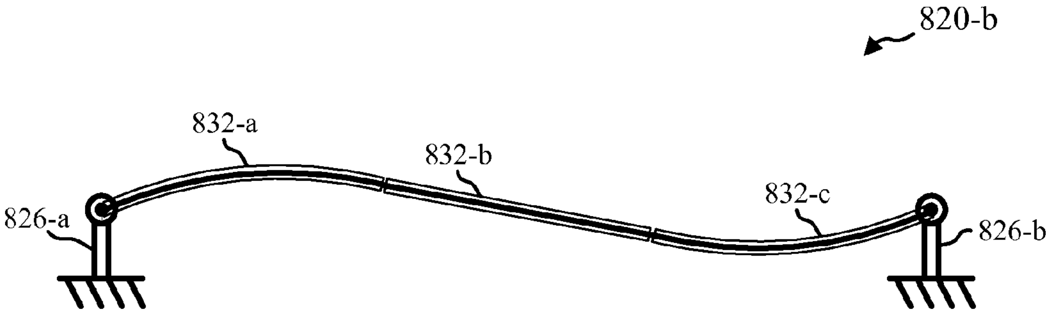

FIG. 8B

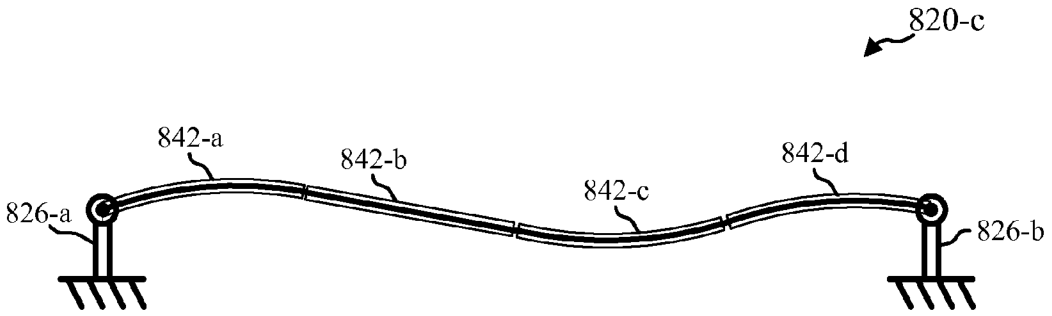

FIG. 8C

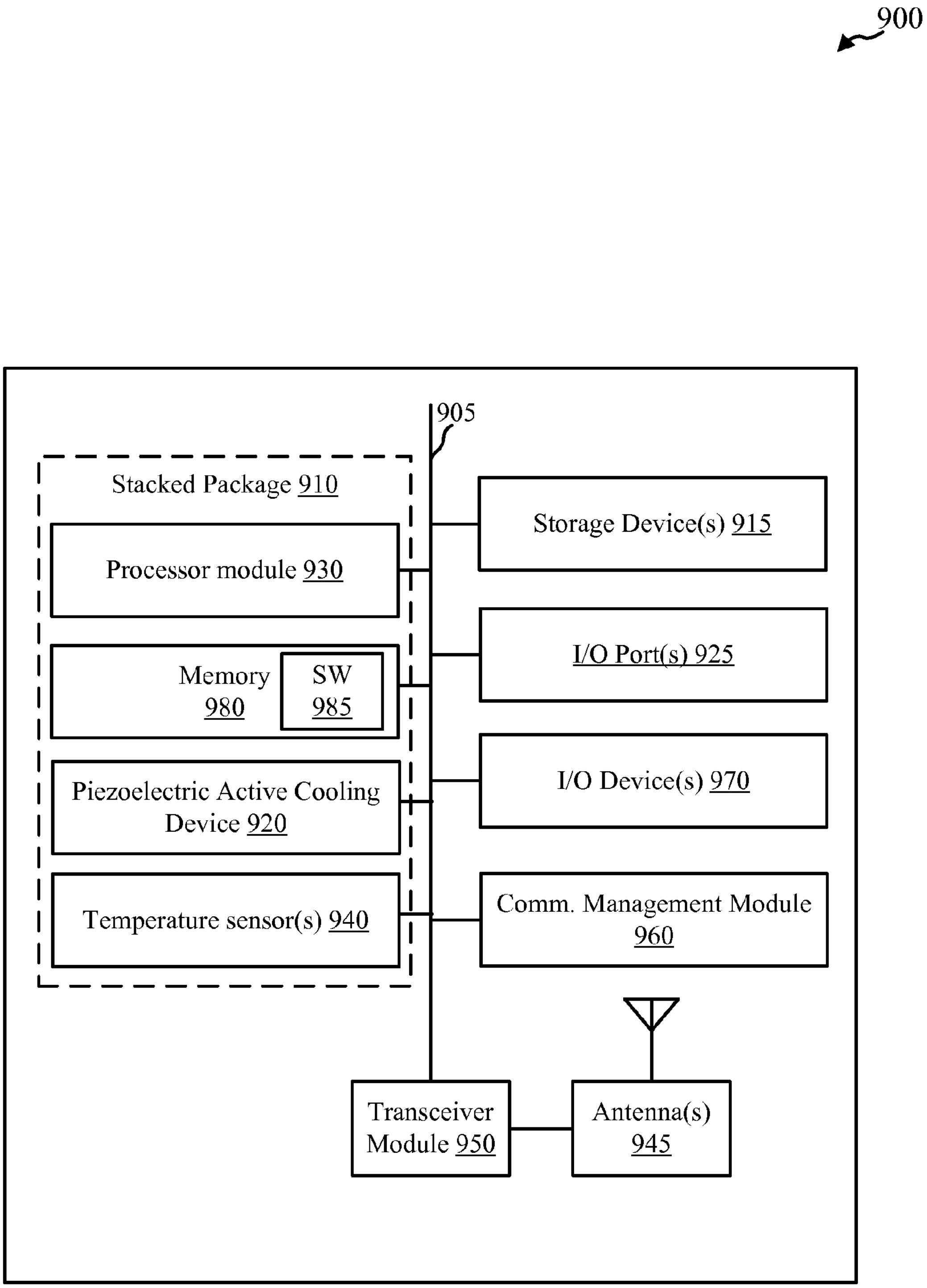
900
905
Stacked Package 910
Processor module 930
Memory 980
SW 985
Piezoelectric Active Cooling Device 920
Temperature sensor(s) 940
Storage Device(s) 915
I/O Port(s) 925
I/O Device(s) 970
Comm. Management Module 960
Transceiver Module 950
Antenna(s) 945

FIG. 9

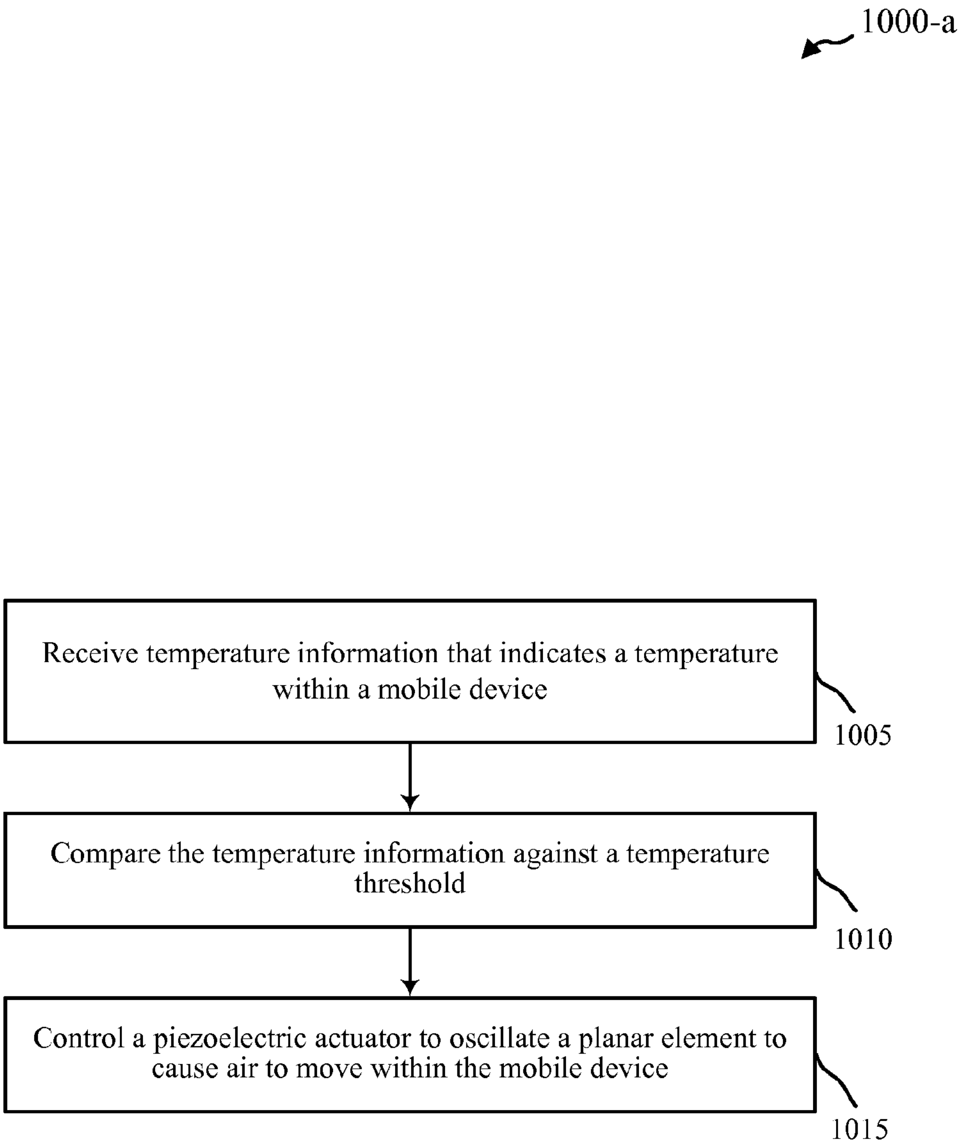
1000-a
Receive temperature information that indicates a temperature within a mobile device
1005
Compare the temperature information against a temperature threshold
1010
Control a piezoelectric actuator to oscillate a planar element to cause air to move within the mobile device
1015

FIG. 10A

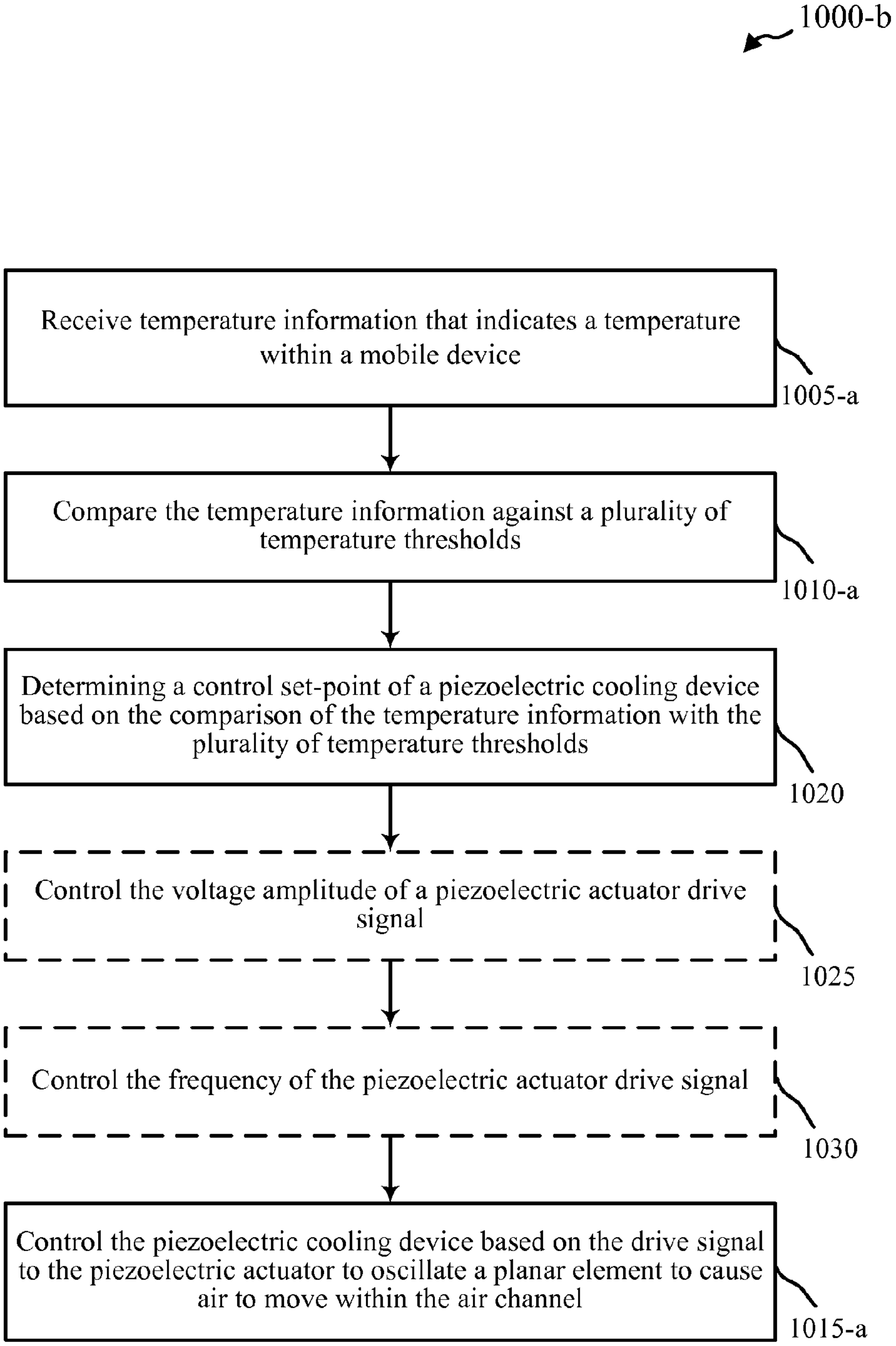
1000-b
Receive temperature information that indicates a temperature within a mobile device
1005-a
Compare the temperature information against a plurality of temperature thresholds
1010-a
Determining a control set-point of a piezoelectric cooling device based on the comparison of the temperature information with the plurality of temperature thresholds
1020
Control the voltage amplitude of a piezoelectric actuator drive signal
1025
Control the frequency of the piezoelectric actuator drive signal
1030
Control the piezoelectric cooling device based on the drive signal to the piezoelectric actuator to oscillate a planar element to cause air to move within the air channel
1015-a

FIG. 10B

PIEZOELECTRIC ACTIVE COOLING DEVICE

BACKGROUND

As mobile computing devices become more integrated and include more computing power, they may generate more heat. For example, a modern smartphone may include one or more highly integrated components known as a system on a chip ("SoC") or a system in package ("SiP"). Each SoC or SiP may have one or more integrated circuits ("ICs") with one or more processor cores, memory circuits, graphics processing circuits, radio frequency communication circuits, and other digital and analog circuits. Further, multiple SoCs or SiPs may be stacked in a package on package ("PoP") configuration. A common PoP configuration includes one SoC or SiP package that has processing and other circuits, with a second stacked package that includes volatile and/or non-volatile memory components.

These highly integrated processing components may generate a large amount of heat within a tightly integrated packaging structure. Additionally, many manufacturers desire to increase the number of processing cores and processor clock speeds, further increasing the amount of heat generated in the package. For mobile computing device processors especially, heat may become a limiting factor to computing performance.

Typically, mobile computing devices may include passive heat dissipation components (e.g., heat sinks, etc.) that transfer heat from the processor package and/or other components that require heat dissipation to an exterior surface of the mobile computing device. However, the overall ability to dissipate heat from the mobile computing device may be limited by the thermal conduction paths between the exterior surfaces of the mobile computing device and the environment (e.g., air or other medium in contact with the exterior surface). As power consumption of mobile processors continues to increase, passive heat dissipation techniques may no longer be able to keep up with the heat generated by the mobile computing device. While there are known techniques for active cooling such as cooling fans, these techniques may be difficult to integrate into the limited enclosure space of mobile computing devices.

SUMMARY

Methods, systems, and devices are described for providing active cooling for a mobile computing device using piezoelectric cooling devices. The described embodiments provide active cooling using low power, can be controlled to provide variable cooling, use highly reliable elements, and can be implemented at low cost. Some embodiments utilize piezoelectric actuators that oscillate a planar element within an air channel to fan air within or at an outlet of the air channel. The air channel may be defined by at least one heat dissipation surface in thermal contact with components of the mobile device that generate excess waste heat. For example, the air channel may include a surface that is in thermal contact with a processor of the mobile computing device. In embodiments, the piezoelectric active cooling device may be used in an air gap between stacked packages in a package on package (PoP) processor package. In embodiments, the piezoelectric actuator is actuated at a frequency lower than a user can typically hear.

In some embodiments, a piezoelectric actuator is a piezoelectric bimorph actuator. The piezoelectric bimorph actuator may be fixed at one end or in the middle, with at least one free end that oscillates on actuation of the piezoelectric bimorph actuator. The free end of the piezoelectric bimorph actuator may be attached to a planar element that may be oscillated by the piezoelectric bimorph actuator. The planar element may be fan shaped, with the free end having a semi-circular shape and/or having a greater width than the end that is attached to the piezoelectric bimorph actuator. The piezoelectric bimorph actuator may be driven in a series or parallel configuration with an AC drive signal such as a sine wave signal.

In some embodiments, the piezoelectric actuator is used to set up a traveling wave in a planar element. The traveling wave may push air through an air channel to set up an air flow generally between an inlet to the air channel and an outlet of the air channel. The planar element may be a resilient material such as spring steel, carbon fiber, plastic, and/or other material. The piezoelectric actuator may be piezoelectric bimorph that is fixed at one end and coupled to the planar element at a second end. The planar element may be free to vibrate at the other end, fixed, fixed in position but free to rotate, and/or coupled by a spring to the mobile computing device and/or air channel.

Some embodiments include a mobile device that includes an air channel defined by at least a first heat dissipation surface, a planar element disposed at least partially within the air channel, and a piezoelectric actuator configured to oscillate the planar element to cause air to move within the air channel. In some embodiments, the piezoelectric actuator and the planar element include a piezoelectric bimorph actuator. The mobile device may include a first semiconductor package having a top surface that comprises the first heat dissipation surface and a second semiconductor package having a bottom surface that comprises a second heat dissipation surface of the air channel, the second semiconductor package in a package on package (PoP) configuration with the first semiconductor package;

In some embodiments, the air channel includes an air inlet port on a housing of the mobile device and an air outlet port on the housing of the mobile device. Some embodiments include an air outlet of the air channel, where the planar element fans air away from the first heat dissipation surface at the air outlet of the air channel. Some embodiments include an air inlet having upper and lower surfaces that are substantially coplanar with the planar element and joined with the air channel at a side of the air channel adjacent to a lateral edge of the planar element. The planar element may include a first end coupled to the piezoelectric actuator and a second arcuately shaped free end.

In some embodiments, the planar element is coupled to the piezoelectric actuator at a first end and actuation of the piezoelectric actuator causes a transverse wave in the planar element that travels from the first end to a second distal end of the planar element. The piezoelectric actuator may include a piezoelectric bimorph where a first end of the piezoelectric bimorph is fixedly attached to the mobile device and a second end of the piezoelectric bimorph is coupled to the first end of the planar element. A spring element may be coupled to the second end of the planar element that springedly attaches the second end of the planar element to the mobile device. Alternatively, a weight may be coupled to the second end of the planar element and/or the second end of the planar element may be fixedly and/or rotationally attached to the mobile device.

In some embodiments, the piezoelectric actuator includes a piezoelectric bimorph actuator, where a center portion of the piezoelectric bimorph actuator is fixed to the mobile device and end portions of the piezoelectric bimorph actuator are free to move on actuation of the piezoelectric bimorph actuator. The piezoelectric bimorph actuator may include a plural-

ity of piezoelectric bimorph segments coupled end to end to form a strip, wherein a first end of the strip and a second distal end of the strip are coupled to the mobile device. The plurality of piezoelectric bimorph segments may be driven with a plurality of substantially sinusoidal drive waveforms.

In some embodiments, the mobile device includes a temperature sensor and a temperature controller coupled to the temperature sensor and the piezoelectric actuator, where the temperature controller controls the piezoelectric actuator to oscillate the planar element based on a measured temperature of the temperature sensor and a temperature threshold. The temperature controller may vary the amplitude of a drive signal to the piezoelectric actuator based on a measured temperature. The air channel may include a first portion having a first dimension and a second portion that tapers from the first dimension to a second larger dimension at an outlet port of the air channel. The air channel may include a first portion having a first dimension and a second portion that is arcuately shaped between the first dimension and a second larger dimension at an outlet port of the air channel. The second portion may be arcuately shaped to substantially match an extent of the planar element when oscillated.

Some embodiments include a method for cooling a mobile device. The method may include: disposing an air channel defined by at least a first heat dissipation surface within the mobile device; disposing a planar element at least partially within the air channel; coupling a piezoelectric actuator to the planar element; and/or controlling the piezoelectric actuator to oscillate the planar element to cause air to move within the air channel. The method may include measuring a temperature of the mobile device and controlling the piezoelectric actuator based on the measured temperature. The piezoelectric actuator may be coupled to a first end of the planar element and controlling the piezoelectric actuator may include setting up a transverse wave in the planar element that travels from the first end of the planar element to a second distal end of the planar element.

In some embodiments, a method for cooling a mobile device includes: receiving temperature information, the temperature information indicating temperature within the mobile device; comparing the temperature information against a temperature threshold; and/or controlling, responsive to the comparing, a piezoelectric actuator to oscillate a planar element to cause air to move within the mobile device. The piezoelectric actuator and/or the planar element may include a piezoelectric bimorph actuator. The temperature information may indicate a temperature of a processor of the mobile device. The temperature information may indicate a temperature of an air channel within the mobile device. The controlling may include controlling an amplitude of a drive voltage to the piezoelectric actuator based on the comparing of the temperature information against the temperature threshold. The temperature threshold may include a plurality of temperature thresholds and the comparing may include determining a control set-point of the piezoelectric actuator based on the plurality of temperature thresholds.

In some embodiments, the planar element is coupled to the piezoelectric actuator at a first end and controlling of the piezoelectric actuator includes generating a transverse wave in the planar element that travels from the first end to a second distal end of the planar element. The piezoelectric actuator may include a piezoelectric bimorph where a first end of the piezoelectric bimorph may be fixedly attached to the mobile device and a second end of the piezoelectric bimorph may be coupled to the first end of the planar element. The second end of the planar element may be coupled to a spring element that springedly attaches the second end of the planar element to the mobile device. The second end of the planar element may be coupled to a weight. The second end of the planar element may be fixedly or rotationally attached to the mobile device.

In some embodiments, the piezoelectric actuator includes a piezoelectric bimorph actuator, where a center portion of the piezoelectric bimorph actuator is fixed to the mobile device and end portions of the piezoelectric bimorph actuator are free to move on actuation of the piezoelectric bimorph actuator. In some embodiments, the piezoelectric actuator includes a plurality of piezoelectric bimorph segments coupled end to end to form a strip, where a first end of the strip and a second distal end of the strip are coupled to the mobile device. Controlling the piezoelectric actuator may include driving the plurality of piezoelectric bimorph segments with a plurality of drive waveforms, where each drive waveform includes an alternating voltage waveform having a phase offset from a drive waveform for an adjoining piezoelectric bimorph segment.

In some embodiments, a mobile device includes: means for receiving temperature information that indicates temperature within the mobile device; means for comparing the temperature information against a temperature threshold; and/or means for controlling, responsive to the comparing, a piezoelectric actuator to oscillate a planar element to move air within the mobile device. In some embodiments, a mobile device includes at least one processor. In embodiments, the processor is configured to: receive temperature information, the temperature information indicating temperature within the mobile device; compare the temperature information against a temperature threshold; and control, responsive to the comparison, a piezoelectric actuator to oscillate a planar element to move air within the mobile device.

The foregoing has outlined rather broadly the features and technical advantages of examples according to the disclosure in order that the detailed description that follows may be better understood. Additional features and advantages will be described hereinafter. The conception and specific examples disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present disclosure. Such equivalent constructions do not depart from the spirit and scope of the appended claims. Features which are believed to be characteristic of the concepts disclosed herein, both as to their organization and method of operation, together with associated advantages will be better understood from the following description when considered in connection with the accompanying figures. Each of the figures is provided for the purpose of illustration and description only, and not as a definition of the limits of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

A further understanding of the nature and advantages of the present invention may be realized by reference to the following drawings. In the appended figures, similar components or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

FIG. **1**A shows a side view of a stacked semiconductor package employing a piezoelectric active cooling device, according to various embodiments;

FIG. **1**B shows a top view of a stacked semiconductor package employing a piezoelectric active cooling device, according to various embodiments;

FIG. **2**A shows a piezoelectric active cooling device, according to various embodiments;

FIG. **2**B shows an active cooling device employing a piezoelectric actuator, according to various embodiments;

FIG. **2**C shows an active cooling device employing a piezoelectric bimorph actuator, according to various embodiments;

FIG. **3**A shows a side view of a stacked semiconductor package employing a traveling wave type piezoelectric active cooling device, according to various embodiments;

FIG. **3**B shows a side view of a stacked semiconductor package employing a traveling wave type piezoelectric active cooling device, according to various embodiments;

FIG. **3**C shows a top view of a stacked semiconductor package employing a traveling wave type piezoelectric active cooling device, according to various embodiments;

FIG. **4**A shows a traveling wave piezoelectric cooling device, according to various embodiments;

FIG. **4**B shows a traveling wave piezoelectric cooling device, according to various embodiments;

FIG. **4**C shows a traveling wave piezoelectric cooling device, according to various embodiments;

FIG. **5** shows a block diagram of a control system for a piezoelectric active cooling device in a mobile device, according to various embodiments;

FIG. **6**A shows a side view of a stacked semiconductor package employing a piezoelectric active cooling device within an air channel with tapered walls, according to various embodiments;

FIG. **6**B shows a side view of a stacked semiconductor package employing a piezoelectric active cooling device within an air channel with arcuately shaped walls, according to various embodiments;

FIG. **6**C shows a top view of a stacked semiconductor package employing a piezoelectric active cooling device, according to various embodiments;

FIG. **7** shows a mobile device employing a piezoelectric active cooling device, according to various embodiments;

FIG. **8**A shows a piezoelectric active cooling device employing multiple piezoelectric bimorph segments, according to various embodiments;

FIG. **8**B shows a piezoelectric active cooling device employing multiple piezoelectric bimorph segments, according to various embodiments;

FIG. **8**C shows a piezoelectric active cooling device employing multiple piezoelectric bimorph segments, according to various embodiments;

FIG. **9** shows a block diagram of a mobile device employing a piezoelectric active cooling device, according to various embodiments;

FIG. **10**A shows a block diagram of a method for providing active cooling for a mobile computing device, according to various embodiments; and

FIG. **10**B shows a block diagram of a method for providing active cooling for a mobile computing device, according to various embodiments.

DETAILED DESCRIPTION OF THE INVENTION

Described embodiments are directed to providing active cooling for a mobile computing device using piezoelectric cooling devices. Some embodiments utilize piezoelectric actuators that oscillate a planar element within an air channel to fan air within or at an outlet of the air channel. The air channel may be defined by at least one heat dissipation surface in thermal contact with components of the mobile device that generate excess waste heat. For example, the air channel may include a surface that is thermally coupled with a processor of the mobile computing device. In embodiments, the piezoelectric active cooling device may be used in an air gap between stacked packages in a package on package (PoP) processor package. In embodiments, the piezoelectric actuator is actuated at a frequency lower than a user can typically hear. The described embodiments provide active cooling using low power, can be controlled to provide variable cooling, use highly reliable elements, and can be implemented at low cost.

In some embodiments, the piezoelectric actuator of the active cooling device is a piezoelectric bimorph actuator. The piezoelectric bimorph actuator may be fixed at one end or in the middle, with at least one free end that oscillates on actuation of the piezoelectric bimorph actuator. The free end of the piezoelectric bimorph actuator may be attached to a planar element that may be oscillated by the piezoelectric bimorph actuator. The planar element may be fan shaped, with the free end having a semi-circular shape and/or having a greater width than the end that is attached to the piezoelectric bimorph actuator. The piezoelectric bimorph actuator may be driven in a series or parallel configuration with an AC drive signal such as a sine wave voltage signal.

In some embodiments, the piezoelectric actuator is used to set up a transverse traveling wave in a planar element. The traveling wave may push air through an air channel to set up an air flow generally within the air channel from an air inlet port to an outlet port of the air channel. The planar element may be a flexible and resilient material such as spring steel, carbon fiber, plastic, and/or other material. The piezoelectric actuator may be a piezoelectric bimorph that is fixed at one end and coupled to the planar element at a second end. The planar element may be free to vibrate at the other end, weighted, fixed, fixed in position but free to rotate, and/or coupled by a spring to the mobile computing device and/or air channel.

This description provides examples, and is not intended to limit the scope, applicability or configuration of the invention. Rather, the ensuing description will provide those skilled in the art with an enabling description for implementing embodiments of the invention. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the disclosure.

Various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, it should be appreciated that the methods may be performed in an order different than that described, and that various steps may be added, omitted or combined. Also, aspects and elements described with respect to certain embodiments may be combined in various other embodiments. It should also be appreciated that the following systems, methods, devices, and software may individually or collectively be components of a larger system, wherein other procedures may take precedence over or otherwise modify their application.

FIG. **1**A and FIG. **1**B show a stacked semiconductor package **100** (e.g., PoP, and the like) that employ a piezoelectric active cooling device **120**, according to various embodiments. FIG. **1**A illustrates a side view of the stacked package **100** mounted to a circuit board **105** with piezoelectric cooling device **120** employed within an air channel **115** defined by an upper surface **112**-*a* of a first package **110**-*a* and a lower surface **112**-*b* of a second package **110**-*b*. The upper surface **112**-*a* and/or lower surface **112**-*b* of the air channel **115** may be in thermal contact with processors or other components of the stacked package **100** that generate excess waste heat. For example, the stacked packages **110**-*a* and **110**-*b* may be made of a ceramic or other material that is thermally conductive to transfer waste heat from the integrated circuits in the packages to the heat dissipation surfaces **112**-*a* and **112**-*b* of the packages.

Active cooling of stacked semiconductor package **100** may provide several performance advantages including increasing processing capabilities and/or reducing power consumption of components of stacked semiconductor package **100**. For example, the performance of a processor component of stacked semiconductor package **100** may be thermally limited without active cooling. In this instance, the clock frequency and/or the number of processor operations may be controlled below the maximum capabilities of the processor to maintain thermal performance. Active cooling using piezoelectric active cooling device **120** may allow the frequency and/or number of processor operations to be increased without exceeding the thermal limit of the processor. Active cooling using piezoelectric active cooling device **120** may also be used to lower the operating temperature of the processor and/or other components (e.g., memory, etc.) of the stacked semiconductor package **100**. Lower operating temperature may reduce off-state leakage current of the components of stacked semiconductor package **100**, which may be a significant component of overall power consumption of stacked semiconductor package **100**. The power saved due to reduced off-state leakage current of components of stacked semiconductor package **100** may be greater than the power required to operate piezoelectric active cooling device **120**.

The piezoelectric active cooling device **120** illustrated in FIG. **1**A may be called a fan-type piezoelectric active cooling device because oscillation of the free ends of the piezoelectric cooling device **120** within the air channel **115** causes air movement **130** away from the oscillating ends of the piezoelectric cooling device **120**. The piezoelectric cooling device **120** may include a piezoelectric element **122**, where at least a portion of the piezoelectric element **122** is fixed relative to the package **100** and at least a portion of the piezoelectric element **122** is free to vibrate as the piezoelectric element **122** is actuated. In embodiments, piezoelectric element **122** is fixed within the air channel in a middle portion or an end portion, with at least one end freely vibrating. In the example shown in FIG. **1**A, piezoelectric element **122** is fixed in the middle by one or more supports **126**, with either end of the piezoelectric element **122** freely vibrating.

FIG. **1**B illustrates a top view of stacked package **100**. As can be seen in FIG. **1**B, the top and bottom packages **110** of stacked package **100** may be connected through an interconnect technology such as a ball grid array or pin grid array **112**. While not illustrated in FIGS. **1**A and **1**B, the bottom package **110**-*a* may be connected to circuit board **105** through a similar interconnect technology. FIG. **1**B illustrates that as air is forced away from the vibrating or oscillating ends of piezoelectric cooling device **120**, air may flow inwards from the sides of the piezoelectric cooling device **120**. This general air flow provides cooling to the stacked package **100** by exhausting heated air away from the air channel while cooler air flows into the air channel **115**. In embodiments, the ends of the piezoelectric cooling device **120** may be shaped to improve air movement. For example, the planar elements **124** may be fan-shaped or otherwise have an increased surface area to push more air away from the stacked package **100** as illustrated in FIG. **1**B.

Piezoelectric cooling device **120** may include one or more planar elements **124** made from a non-piezoelectric material such as plastic, metal, carbon, and/or other suitable material. Planar element(s) **124** may have a portion that is coupled to piezoelectric actuator **122** and have one or more free ends that vibrate when piezoelectric actuator **122** is vibrated. Planar element(s) **124** may cause amplification of the oscillation of piezoelectric actuator such that the free ends of planar element(s) **124** oscillate over a greater distance than piezoelectric actuator **122**. For example, oscillation of the free ends of planar element **124** may be amplified by actuation of piezoelectric actuator **122** at a resonant frequency of the piezoelectric actuator **122** and/or planar element **124**. As illustrated in FIG. **1**A, the piezoelectric actuator **122** and/or the planar element **124** may be disposed within the air channel **115** such that the piezoelectric actuator **122** and/or the planar element **124** are coplanar with a longitudinal axis **118** of the air channel **115**.

Planar element(s) **124** may be shaped such that the lateral edge furthest from the piezoelectric actuator **122** has a longer edge distance. For example, planar elements **124** may be trapezoidal in shape with the longer parallel edge of the trapezoid furthest from the piezoelectric actuator **122**. In embodiments, the lateral edge furthest from the piezoelectric actuator **122** may be arcuately shaped or semi-circular as illustrated in FIG. **1**B.

Piezoelectric actuator **122** may be a piezoelectric active material such as a piezoceramic material that has a polarization that causes a mechanical displacement when an electric field is applied. Piezoelectric element **122** may also be a piezoelectric unimorph, and/or piezoelectric bimorph material. A piezoelectric unimorph includes one active layer and one inactive layer bonded together. The active layer is a piezoelectric layer that deforms when an electric field is applied. The deformation of the active layer causes the piezoelectric unimorph to bend. A piezoelectric bimorph has two active layers separated by an inactive layer such as metal, carbon fiber, and/or other suitable material. Application of electric fields may be used to cause one piezoelectric layer to contract and the other to expand. Therefore, a piezoelectric bimorph is capable of bending in two directions according to the polarity of an applied field. If portion of a piezoelectric bimorph is fixed, application of an alternating electric field can cause a free end of the piezoelectric bimorph to vibrate back and forth.

Turning to FIG. **2**A, a piezoelectric cooling device **220**-*a* is illustrated in accordance with various embodiments. Piezoelectric cooling device **220**-*a* includes a piezoelectric actuator **222** fixed to a support **215** and operable to vibrate a planar element **224**. Piezoelectric actuator **222** may be polarized in a direction orthogonal to the plane of the planar element **224** and may include electrode layers **226**-*a* and **226**-*b* for application of an electric field using voltage driver **205**.

Turning to FIG. **2**B, a piezoelectric cooling device **220**-*b* is illustrated in accordance with various embodiments. Piezoelectric cooling device **220**-*b* includes a piezoelectric bimorph actuator **230** that includes a first piezoelectric layer **232**-*a*, a second piezoelectric layer **232**-*b*, and a center layer **238**. In the embodiment illustrated in FIG. **2**B, piezoelectric bimorph actuator **230** is illustrated in a serial connection configuration where piezoelectric layers **232**-*a* and **232**-*b* have opposite polarization directions and the electric field from voltage driver **205** is applied across both piezoelectric layers in series. Piezoelectric bimorph actuator **230** may include electrode layers **236**-*a* and **236**-*b* for application of the electric field using voltage source **205**. Center layer **238** may be a thin, conductive material such as spring steel or carbon fiber.

Turning to FIG. **2**C, a piezoelectric cooling device **220**-*c* is illustrated in accordance with various embodiments. Piezoelectric cooling device **220**-*c* includes a piezoelectric bimorph actuator **240** that includes a first piezoelectric layer **242**-*a*, a second piezoelectric layer **242**-*b*, and a center layer **248**. Piezoelectric bimorph actuator **240** may include electrode layers **246**-*a* and **246**-*b* for application of an electric field using voltage driver **205**. In the embodiment illustrated in FIG. **2**C, piezoelectric bimorph actuator **240** is illustrated in a parallel configuration connection configuration where piezoelectric layers **242**-*a* and **242**-*b* have the same polarization directions and the electric field from voltage driver **205** is applied in parallel between an electrode of each piezoelectric layer (e.g., **246**-*a*, **246**-*b*) and a common electrode. The common electrode may be, for example, center layer **248**. Center layer **248** may be a thin, conductive material such as spring steel or carbon fiber.

In embodiments, piezoelectric cooling devices **220**-*b* and/or **220**-*c* may include a planar extension **234** that is attached to the free end of piezoelectric bimorph actuators **230** and/or **240**. The planar extension may be made of a rigid material, or it may be made of a flexible material to provide further amplification to the oscillation of the end of the piezoelectric bimorph actuator **230** and/or **240**. In embodiments, the planar extension **234** may be an extension of center layer **238** and/or **248**. For example, piezoelectric cooling device **120** as illustrated in FIG. **1**A and/or FIG. **1**B may be constructed according to FIG. **2**B and/or FIG. **2**C with planar extensions **124** corresponding to planar extensions **234** of piezoelectric actuators **230** and/or **240**. In embodiments, planar extensions **234** may be constructed from spring steel, carbon fiber, and/or plastic.

FIG. **3**A illustrates another embodiment of a stacked package architecture **300**-*a* that employs a piezoelectric active cooling device **320**-*a*, according to various embodiments. In stacked package architecture **300**-*a*, piezoelectric cooling device **320**-*a* includes a piezoelectric element **322**-*a* that vibrates one end of a planar element **324**-*a* to set up a transverse wave in the planar element that travels from the end vibrated by the piezoelectric element **322**-*a* towards the opposite end. In the embodiment of piezoelectric active cooling device **320**-*a* illustrated in FIG. **3**A, piezoelectric actuator **322**-*a* vibrates orthogonally to the longitudinal axis **118** of the air channel **115**, generally moving the end of the planar element **324**-*a* fixed to the piezoelectric actuator **322**-*a* orthogonally to the longitudinal axis **118**.

As the traveling wave on the planar element **324**-*a* moves through air channel **115**, it pushes air along with the traveling wave, establishing air flow **330** generally from one side of the stacked package **300**-*a* to the other side through the air channel **115**. For example, the transverse wave in the planar element **324**-*a* may deform the planar element **324**-*a* such that the wave height takes up substantially the height of the air channel **115**. As the wave travels away from the piezoelectric actuator **322**-*a*, air is pushed along with the wave to the opposite end of the planar element **324**-*a*. Air flowing through the air channel **115** dissipates heat from surfaces **112**-*a* and/or **112**-*b* of the packages **110**-*a* and/or **110**-*b*, and the warmer heated air flows out of the air channel **115** at an air outlet of the air channel, exhausting waste heat from the stacked package **300**-*a*. The planar element **324**-*a* may optionally be coupled to the package **300**-*a* at the outlet end of the air channel **115**. For example, planar element **324**-*a* may be coupled to the stacked package **300**-*a* using spring(s) **328** to assist in setting up the transverse traveling wave in the planar element **324**-*a*. The planar element **324**-*a* may be made of a suitably flexible but resilient material such as spring steel, carbon, and/or plastic.

FIG. **3**B illustrates another embodiment of a stacked package architecture **300**-*b* that employs a piezoelectric active cooling device **320**-*b*, according to various embodiments. Similarly to piezoelectric cooling device **320**-*a*, piezoelectric cooling device **320**-*b* includes a piezoelectric element **322**-*b* that vibrates one end of a planar element **324**-*b* to set up a transverse wave in the planar element that travels from the end vibrated by the piezoelectric element **322**-*b* towards the opposite end. Piezoelectric cooling device **320**-*b* may use a piezoelectric bimorph actuator **322**-*b* to generate the traveling wave in the planar element **324**-*b*. For example, one end of the piezoelectric bimorph **322**-*b* may be fixed to a support **326**-*b* relative to the air channel **115**, while the other end is coupled to the planar element **324**-*b*. As an electric field is applied to the piezoelectric bimorph **324**-*b*, the bending of the piezoelectric bimorph **324**-*b* vibrates the end of the planar element **324**-*b*, setting up the transverse traveling wave in the planar element **324**-*b*.

FIG. **3**C illustrates a top view of stacked package architecture **300**, according to various embodiments. For example, FIG. **3**C may illustrate a top view of stacked packages **300**-*a* and/or **300**-*b* as illustrated in FIG. **3**A and/or FIG. **3**B. FIG. **3**C illustrates generally the flow of air **330** generated by piezoelectric cooling device **320** through stacked package **300**. In embodiments, channel walls **335**-*a* and **335**-*b* may be used to define sides to the air channel **115** to maintain an air flow from an inlet **334** to an outlet **332** of the air channel **115**. Thus, air channel **115** may have a cross-section orthogonal to the longitudinal axis **118** where the width of the cross-section is greater than the height of the cross-section.

FIGS. **4**A-**4**C illustrate various embodiments of piezoelectric cooling devices **420** that move air by setting up a transverse traveling wave in a planar element. In one embodiment illustrated in FIG. **4**A, a traveling wave piezoelectric cooling device **420**-*a* employs a weighted end to help in generating the traveling wave in the planar element. Piezoelectric cooling device **420**-*a* may be used to cause air to move within a mobile device or air channel within a mobile device. In piezoelectric cooling device **420**-*a*, piezoelectric bimorph actuator **422** is attached at one end to a mobile device or air channel of a mobile device at support **426**. An opposing end of the piezoelectric bimorph actuator **422** is attached to one end **425**-*a* of a planar element **424** and vibrates upon actuation of the piezoelectric bimorph actuator **422**. Actuation of piezoelectric bimorph actuator **422** causes a traveling wave in planar element **424** that generally travels from end **425**-*a* towards end **425**-*b* of the planar element **424**. When piezoelectric cooling device **420**-*a* is employed within an air channel, the traveling wave pushes air generally in direction **430** from the end of the planar element **425**-*a* attached to the piezoelectric bimorph actuator **422** to the opposite end **425**-*b*. In piezoelectric cooling device **420**, the opposite end **425**-*b* of the planar element **424** is attached to weight **428** that dampens movement of the end **425**-*b* to help in generating the traveling wave.

In the embodiment of a piezoelectric cooling device **420**-*b* illustrated in FIG. **4**B, end **425**-*b* of planar element **424** is rotationally attached to support **436** through rotational coupling **438**. For example, rotational coupling **438** may support sides of end **425**-*b* of planar element **424** using a pin inserted into a sleeve that allows planar element **424** to rotate relative to support **436**. Rotational coupling **438** may assist in generating the traveling wave on planar element **424** using oscillation of piezoelectric actuator **422**.

In the embodiment of a piezoelectric cooling device **420**-*c* illustrated in FIG. **4**C, planar element **424** is attached at the opposite end from the piezoelectric actuator using a spring **448**. Spring **448** may be a leaf-type spring, coil-type spring, and/or any other type of spring that allows some vertical movement and/or rotational movement at the end **425**-*b* of planar element **424** but provides a feedback force that helps to set up the traveling wave in planar element **424**.

The amount of cooling provided by piezoelectric active cooling devices **120**, **220**, **320**, and/or **420** illustrated in FIG. **1**A, FIG. **1**B, FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **3**A, FIG. **3**B, FIG. **4**A, FIG. **4**B, and/or FIG. **4**C may be controlled by controlling the amplitude and frequency of oscillation of the piezoelectric actuator. For example, the amplitude of deflection of a piezoelectric bimorph may be proportional to the amplitude of an applied voltage. Therefore, varying the amplitude of an applied alternating voltage may be used to vary the amount of air movement. Varying the frequency of the piezoelectric actuator will also vary the amount of air movement. For example, higher actuation frequencies may push more air in fan-type and traveling wave type piezoelectric cooling devices. However, relatively low frequency actuation may provide sufficient cooling without creating audible sound waves that may be objectionable to a user. In embodiments, the piezoelectric actuator is driven at frequencies below an audible frequency level, for example, at a frequency lower than about 20 Hz. Alternatively, the piezoelectric actuator may be driven at higher frequencies, including frequencies within the auditory range or even above the auditory frequency range (e.g., greater than about 20 KHz). Different types of drive signals may also be used with piezoelectric active cooling devices **120**, **220**, **320**, and/or **420**. For example, sine wave, square wave, triangular wave, and/or other types of drive signals may be used depending on the desired actuation of the piezoelectric actuator.

The mobile computing device may include one or more temperature sensors and a control block that measures the temperature of the mobile computing device and controls the actuation of the piezoelectric actuator according to the measured temperature. The alternating voltage applied to the piezoelectric actuator may be generated by a switching circuit or other circuit that generates an alternating voltage or be generated by a self-resonant circuit that oscillates at the resonant frequency of the piezoelectric actuator.

FIG. **5** is a block diagram of an active cooling system **500** for a mobile device in accordance with various embodiments. System **500** may include one or more temperature sensors **510**, piezoelectric active cooling device **520**, a temperature control module **530**, and/or a driver module **525**. In system **500**, piezoelectric active cooling device **520** may be one of the fan-type or traveling wave type piezoelectric active cooling devices **120**, **220**, **320**, and/or **420** illustrated in FIG. **1**A, FIG. **1**B, FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **3**A, FIG. **3**B, FIG. **4**A, FIG. **4**B, and/or FIG. **4**C.

Temperature sensor(s) **510**, temperature control module **530**, and/or driver module **525** may be implemented as components housed within a semiconductor package such as the stacked packages **100** and/or **300** illustrated in FIG. **1**A, FIG. **1**B, FIG. **3**A, and/or FIG. **3**B. For example, temperature sensor(s) **510**, temperature control module **530**, and/or driver module **525** may be implemented on a processor **505** housed within a semiconductor package such as semiconductor packages **100** and/or **300**. The temperature sensor(s) may be on-chip temperature sensors on processor **505**, positioned at other locations within the semiconductor package, and/or may be external to the semiconductor package. For example, one or more of temperature sensor(s) **510** may be located in the air channel to measure the temperature of a heat dissipation surface of the air channel, or the air temperature of the air channel (e.g., inlet air temperature, outlet air temperature, etc.). Driver module **525** may include one or more components (e.g., digital to analog converters (DACs), op-amps, transistors, capacitors, inductor, resistors, etc.) that generate an analog drive voltage or use the resonance of the piezoelectric actuator to create a self-resonant circuit that may be controlled via a control voltage or other control input.

System **500** may be configured to control piezoelectric active cooling device **520** to maintain a certain temperature of components within the semiconductor package and/or mobile device. For example, temperature control module **530** may be configured to monitor temperature sensor(s) **510** and control piezoelectric active cooling device **520** via driver module **525** based on the monitored temperature. In an embodiment, temperature control module **530** is configured to drive piezoelectric active cooling device **520** to cause air to move within the mobile device when the measured temperature exceeds a temperature threshold.

Control of piezoelectric active cooling device **520** may include control of drive voltage and/or drive frequency of a piezoelectric actuator of piezoelectric active cooling device **520**. For example, in an amplitude control configuration, the amplitude of the drive voltage for a piezoelectric actuator of piezoelectric active cooling device **520** may be controlled based on temperature. In some embodiments, temperature control module **530** is configured to control a drive voltage amplitude of piezoelectric active cooling device **520** via driver module **525** based on the monitored temperature according to a predetermined temperature vs. voltage relationship using multiple temperature set-points or thresholds (e.g., look-up-table, predefined equation, linear interpolation, etc.). In a frequency control configuration, drive frequency of the piezoelectric actuator of piezoelectric active cooling device **520** is controlled based on temperature. In some embodiments, amplitude and frequency of the drive voltage for a piezoelectric actuator of piezoelectric active cooling device **520** are controlled simultaneously. For example, in traveling wave configurations such as those illustrated in FIGS. **3**A, **3**B, **3**C, **4**A, **4**B, and/or **4**C, frequency and amplitude of the drive voltage to piezoelectric actuator may be controlled using a linear or non-linear relationship to vary air movement while maintaining a traveling wave on the planar element.

System **500** may also include other sensor(s) **535** such as ambient air sensors, orientation sensors, air flow sensors, etc. For example, other sensor(s) **535** may include one or more air flow sensors and temperature control module **530** may control piezoelectric active cooling device **520** to provide a predetermined air flow through the mobile device based on a temperature reading of temperature sensor(s) **510**. In one embodiment, temperature control module **530** varies drive voltage and/or frequency of a piezoelectric actuator of piezoelectric active cooling device **520** based on measured air flow from air flow sensor(s) **535** and temperature readings of temperature sensor(s) **510**. Air flow may be controlled in a predetermined relationship to measured temperature of the temperature sensor(s) **510** of the mobile device. In embodiments, an air flow sensor **535** may detect when air flow in an air channel of a mobile device is impeded and prevent operation of the piezoelectric active cooling device **520** when air flow is impeded in the air channel. For example, when a mobile device is placed in a protective sleeve, pocket, or other environment that impedes air flow, the piezoelectric cooling device may be deactivated.

The components of system **500** may, individually or collectively, be implemented with one or more Application Specific Integrated Circuits (ASICs) adapted to perform some or all of the applicable functions in hardware. Alternatively, the functions may be performed by one or more other processing units (or cores), on one or more integrated circuits. In other embodiments, other types of circuit components may be used (e.g., Structured/Platform ASICs, Field Programmable Gate Arrays (FPGAs), other Semi-Custom ICs, other digital or analog ICs, and/or other discrete components), which may be programmed in any manner known in the art. The functions of each unit may also be implemented, in whole or in part, with instructions embodied in a memory, formatted to be executed by one or more general or application-specific processors. It will be apparent to those skilled in the art that substantial variations may be used in accordance with specific requirements. For example, customized hardware might also be used, or particular elements might be implemented in hardware, software (including portable software, such as applets), or both.

Some embodiments include an air channel of the mobile device that employs channel wall structures that improve the air flow within the channel and/or away from the mobile device. In some embodiments, the air channel may include channel walls that define air inlet ports and/or air outlet ports, and/or direct air flow within the mobile device. In some embodiments, the air channel walls are tapered or arcuately shaped at an outlet port of the air channel to improve the air flow generated by a piezoelectric active cooling device that is configured with a freely vibrating end at or near the outlet port. The air channel may be tapered or arcuately shaped to substantially match the extent of vibration of the freely vibrating end of the piezoelectric active cooling device. For example, a piezoelectric active cooling device may be fixed towards the middle or interior of the air channel and one or more ends of the piezoelectric active cooling device may be free to vibrate towards an outlet port of the air channel. The air channel may have a smaller height towards the middle or interior of the air channel where the extent of vibration of the piezoelectric active cooling device is smaller and a larger height towards the outlet port where the freely vibrating end of the piezoelectric active cooling device vibrates over a larger extent. The air channel walls may be tapered between the smaller height and the larger height to substantially match the extent of vibration of the piezoelectric active cooling device along the length of the device. For example, the air channel walls may be linearly tapered between the smaller height and the larger height or may be arcuately shaped to substantially match the curved shape of the piezoelectric active cooling device at an extent of travel when vibrated.

FIG. **6**A shows a side view of a stacked semiconductor package **600**-*a* employing a piezoelectric active cooling device **120** within an air channel **615**-*a* with tapered walls, according to various embodiments. The stacked semiconductor package **600**-*a* includes a first package **610**-*a* and a second package **610**-*b*. The top surface **612**-*a* of the first package **610**-*a* and the bottom surface **612**-*b* of the second package **610**-*b* define surfaces or channel walls of the air channel **615**-*a*. The piezoelectric active cooling device **120** may be coupled to the stacked semiconductor package **600**-*a* within the air channel using support **626**. An end of the piezoelectric active cooling device **120** may be freely vibrating. The freely vibrating end may be located at or near an outlet port **622**-*a* of the air channel **615**-*a*.

The air channel **615**-*a* may include a portion **625**-*a* having a smaller dimension perpendicular to a planar element of the piezoelectric active cooling device **120** towards the interior or middle of the air channel **615**-*a*. For example, the portion **625**-*a* may be adjacent to the middle or an end of the piezoelectric active cooling device **120** that is coupled to the stacked semiconductor package **600**-*a*. The air channel walls **612**-*a* and/or **612**-*b* may have tapered portions **614**-*a* and/or **614**-*b* such that the air channel **615**-*a* has a larger dimension at the outlet port **622**-*a*. The tapered portions **614**-*a* and/or **614**-*b* may be linearly tapered between the smaller dimension and the larger dimension. The tapered portions **614**-*a* and **614**-*b* may be tapered such that a distance between the extent of the vibration of the piezoelectric active cooling device **120** and the channel wall is approximately constant at the beginning and end of the taper. For example, a distance **628**-*a* between the activated piezoelectric active cooling device **120** and the tapered portion **614**-*b* at the point where the taper starts may be approximately equal to a distance **628**-*b* between the end of the activated piezoelectric active cooling device **120** and the tapered portion **614**-*b*.

FIG. **6**B shows a side view of a stacked semiconductor package **600**-*b* employing a piezoelectric active cooling device **120** within an air channel **615**-*b* with arcuately shaped walls, according to various embodiments. The stacked semiconductor package **600**-*b* includes a first package **610**-*c* and a second package **610**-*d*. The top surface **612**-*c* of the first package **610**-*c* and the bottom surface **612**-*d* of the second package **610**-*d* define surfaces or channel walls of the air channel **615**-*b*. The piezoelectric active cooling device **120** may be coupled to the stacked semiconductor package **600**-*b* within the air channel using support **626**. An end of the piezoelectric active cooling device **120** may be freely vibrating. The freely vibrating end may be located at or near an outlet port **622**-*b* of the air channel **615**-*b*.

The air channel **615**-*b* may include a portion **625**-*b* having a smaller dimension perpendicular to a planar element of the piezoelectric active cooling device **120** towards the interior or middle of the air channel **615**-*b*. For example, the portion **625**-*b* may be adjacent to the middle or an end of the piezoelectric active cooling device **120** that is coupled to the stacked semiconductor package **600**-*b*. The air channel walls **612**-*c* and **612**-*d* may include arcuately shaped portions **614**-*c* and/or **614**-*d* such that the air channel **615**-*b* has a larger dimension at the outlet port **622**-*b*. The arcuately shaped portions **614**-*c* and **614**-*d* may have a shape that substantially matches the curved shape of the extent of the piezoelectric active cooling device **120** when it is vibrated.

FIG. **6**C illustrates a semiconductor package **600**-*c* that uses a piezoelectric cooling device **120** in accordance with various embodiments. In semiconductor package **600**-*c*, air channel walls **635** generally define air channel **615**-*c* to have two air inlet ports **634**-*a* and **634**-*b*, and two air outlet ports **632**-*a* and **632**-*b*. Air channel walls **635** may generally follow the shape of the sides of the piezoelectric active cooling device **120** for a portion of the length of the piezoelectric active cooling device **120**. Piezoelectric active cooling device **120** fans air away from air outlet ports **632**-*a* and **632**-*b*, generally establishing an air flow that flows in air inlet ports **634**-*a* and **634**-*b* on opposing sides of the package and out air outlet ports **632**-*a* and **632**-*b* on the other opposing sides of the package. The air inlet ports **634**-*a* and **634**-*b* may have upper and lower surfaces that are substantially coplanar with the top and bottom surfaces of the air channel **615**-*c* and are joined with the air channel **615**-*c* at a side of the air channel adjacent to a lateral edge of the piezoelectric active cooling device **120**. The air inlet ports may be joined with the air channel **615**-*c* at a portion of the side of air channel **615**-*c* while the channel walls **635** block air flow from the inlet ports **634**-*a* and **634**-*b* to other portions of the air channel **615**-*c*.

While FIG. **1**A, FIG. **1**B, FIG. **3**A, FIG. **3**B, FIG. **3**C, and FIG. **6** illustrate piezoelectric active cooling devices **120** and **320** employed within air channels **115**, **615**-*a*, **615**-*b*, and/or **615**-*c* of a stacked package, these devices may be employed in other suitable air channels of a mobile device. For example, an air channel may be designed into the case of a mobile computing device, and a piezoelectric cooling device according to disclosed embodiments may be used to develop air flow through the air channel of the mobile computing device. Air channels in the mobile device may have air inlet and outlet ports on the housing of the mobile device, with portions of the air channel defined by an air gap in a stacked package of the mobile device. For example, semiconductor package **600**-*c* may be integrated within a mobile device such that inlet ports **634**-*a* and **634**-*b* correspond to inlet ports on the mobile device and outlet ports **632**-*a* and **632**-*b* correspond to outlet ports on the mobile device. In this way, ambient air may be caused to move within the mobile device and directly cool a semiconductor package **600**-*c* where much of the waste heat of the mobile device may be generated.

FIG. **7** illustrates a mobile device **700** that employs a piezoelectric active cooling device to move air within an air channel **715** of the mobile device in accordance with various embodiments. As illustrated in FIG. **7**, mobile device **700** includes air channel **715** with an air inlet **734** and air outlet **732**. Piezoelectric active cooling device **720** is illustrated positioned in air channel **715** to move air generally from air inlet port **734** to air outlet or exhaust port **732**. Piezoelectric active cooling device **720** is illustrated in FIG. **7** as a traveling wave type piezoelectric cooling device. However, fan-type piezoelectric cooling devices as described with reference to FIG. **1**A, FIG. **1**B, and FIG. **6** may also be employed within air channel **715** to cause air to move within the mobile device.

Surfaces of air channel **715** may be in thermal communication with components of the mobile device **700** that generate waste heat. For example, surfaces of air channel **715** may be surfaces of heat-sink elements for components such as processing components of the mobile device **700**. In an embodiment, a portion of air channel **715** includes an air gap in a stacked package that houses processing and/or other computing components of the mobile device such as the stacked packages **100**, **300**, **600**-*a*, **600**-*b*, and/or **600**-*c* described with reference to FIG. **1**A, FIG. **1**B, FIG. **3**A, FIG. **3**B, FIG. **3**C, FIG. **6**A, FIG. **6**B, and/or FIG. **6**C. Additionally, air channel **715** may include more than one air inlet port **734** and/or air outlet port **732**. For example, air channel **715** may include two air inlet ports **734** generally corresponding to air inlet ports **634**-*a* and **634**-*b* of stacked package **600**-*c* and two air outlet ports **732** generally corresponding to air outlet ports **632**-*a* and **632**-*b* of stacked package **600**-*c*. In embodiments, air channel **715** may include tapered and/or arcuately shaped air channel wall portions such as air channel **615**-*a* and/or **615**-*b* as illustrated in FIG. **6**A and/or FIG. **6**B.

In embodiments, a piezoelectric active cooling device may include multiple planar piezoelectric bimorph segments that are coupled together to form a piezoelectric active cooling device. FIG. **8**A illustrates a piezoelectric active cooling device **820**-*a* that includes two piezoelectric bimorph segments **822**-*a* and **822**-*b*. The piezoelectric bimorph segments **822**-*a* and **822**-*b* may be coupled at supports **826**-*a* and **826**-*b* to a mobile device or air channel within the mobile device, and coupled together mechanically at the middle of the piezoelectric active cooling device **820**-*a*. Actuation of the piezoelectric bimorphs **822**-*a* and **822**-*b* of piezoelectric cooling device **820**-*a* using out of phase alternating voltage waveforms will cause each segment to bend in alternate directions, generally approximating a standing wave in piezoelectric cooling device **820**-*a*.

In some embodiments, an approximation of a transverse traveling wave may be generated using more than two piezoelectric bimorph segments that are joined end-to-end in a piezoelectric active cooling device. For example, FIG. **8**B illustrates an embodiment of a planar active cooling device **820**-*b* with three piezoelectric bimorph segments joined end-to-end. One end of the first piezoelectric bimorph segment **832**-*a* may be coupled to support **826**-*a*, with the other end coupled to one end of piezoelectric bimorph segment **832**-*b*, which is coupled at the other end to one end of piezoelectric bimorph segment **832**-*c*. The other end of piezoelectric bimorph segment **832**-*c* may be coupled to support **826**-*b*. Piezoelectric bimorph segments **832**-*a*, **832**-*b*, and **832**-*c* may be driven with alternating voltage waveforms having different respective phases, causing an approximation of a transverse traveling wave in planar piezoelectric active cooling device **820**-*b*.

It may be appreciated that more piezoelectric bimorph segments may allow a closer approximation of a transverse traveling wave in the planar piezoelectric active cooling device. For example, FIG. **8**C illustrates an embodiment of a planar piezoelectric active cooling device **820**-*c* with four piezoelectric bimorph segments (**842**-*a*, **842**-*b*, **842**-*c*, and **842**-*d*) joined end-to-end and coupled to a mobile device and/or air channel at supports **826**-*a* and/or **826**-*b*. As with planar piezoelectric active cooling device **820**-*b*, piezoelectric bimorph segments **842**-*a*, **842**-*b*, **842**-*c*, and **842**-*d* may be driven with alternating voltage waveforms having different respective phases, causing an approximation of a transverse traveling wave in planar piezoelectric active cooling device **820**-*c*. While more segments may allow a closer approximation of a transverse travelling wave, a planar piezoelectric active cooling device having as few as three segments as illustrated in FIG. **8**B may provide air movement within an air channel that is generally in one direction.

While FIGS. **8**A, **8**B, and **8**C illustrate piezoelectric active cooling devices **820**-*a*, **820**-*b*, and/or **820**-*c* rotationally coupled to supports **826**-*a* and/or **826**-*b*, other coupling methods may be used for multi-segment piezoelectric bimorph active cooling devices. For example, piezoelectric active cooling devices **820**-*a*, **820**-*b*, and/or **820**-*c* may be coupled to supports **826**-*a* and/or **826**-*b* using coupling methods including those illustrated for end **425**-*b* of planar element **424** of FIGS. **4**A, **4**B, and/or **4**C, and/or other coupling methods.

FIG. **9** shows a block diagram of a mobile device **900** that employs a piezoelectric active cooling device in accordance with various embodiments. Mobile device **900** may include processor module **930**, temperature sensor(s) **940**, memory **980**, piezoelectric active cooling device **920**, storage device(s) **915** (e.g., SSD, disk drive, etc.), I/O port(s) **925** (e.g., USB, power supply, video, audio, etc.), I/O device(s) **970** (e.g., touch-screen, QWERTY keyboard, scroll-wheel, click-wheel, buttons, etc.), communications management module **960**, transceiver module **950**, and/or antenna(s) **945**. These components may be communicatively coupled through one or more electrical interfaces such as bus **905**. Processor module **930**, temperature sensor(s) **940**, memory **980**, and/or piezoelectric active cooling device **920** may be configured in a stacked package semiconductor package **910** such as stacked packages **100**, **300**, **600**-*a*, **600**-*b*, and/or **600**-*c* as described above with reference to FIG. **1**A, FIG. **1**B, FIG. **3**A, FIG. **3**B, FIG. **3**C, FIG. **6**A, FIG. **6**B, and/or FIG. **6**C. Piezoelectric active cooling device **920** may be one of the fan-type or traveling wave type piezoelectric cooling devices **120**, **220**, **320**, **420**, and/or **820** as described above with reference to FIG. **1**A, FIG. **1**B, FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **3**A, FIG. **3**B, FIG. **3**C, FIG. **4**A, FIG. **4**B, FIG. **4**C, FIG. **8**A, FIG. **8**B, and/or FIG. **8**C.

The memory **980** may store computer-readable, computer-executable software code **985** containing instructions that are configured to, when executed, cause the processor module **930** to perform various functions described herein (e.g., monitor temperature sensors and/or other sensors, control drive attributes of piezoelectric active cooling device **920**, etc.). Alternatively, the software code **985** may not be directly executable by the processor module **930** but be configured to cause the processor module **930** (e.g., when compiled and executed) to perform functions described herein. Processor module **930** may include one or more processing cores that perform the functions described herein. For example, the instructions may cause the processor module to receive a measured temperature from a temperature sensor, compare the measured temperature against a temperature threshold, and control the piezoelectric active cooling device **920** to move air to cool the mobile device.

FIG. **10**A shows a flow diagram of a method **1000**-*a* for active cooling of a mobile device in accordance with various embodiments. Method **1000**-*a* may be implemented utilizing various mobile devices such as mobile devices **500** and/or **700** as seen in FIG. **5** and/or FIG. **7**, employing piezoelectric active cooling devices including, but not limited to, piezoelectric active cooling devices **120**, **220**, **320**, **420** and/or **820** as seen in FIG. **1**A, FIG. **1**B, FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **3**A, FIG. **3**B, FIG. **3**C, FIG. **4**A, FIG. **4**B, FIG. **4**C, FIG. **8**A, FIG. **8**B, and/or FIG. **8**C.

At block **1005** of method **1000**-*a*, temperature information that indicates a temperature within a mobile device is received. The temperature information may indicate the temperature of a processor of the mobile device or other internal temperature of the mobile device such as the temperature of a heat dissipation surface of an air channel within the mobile device. For example, temperature information may be received in a processor of a mobile device such as processor module **930** of mobile device **900** from temperature sensor(s) **940**.

At block **1010** of method **1000**-*a*, the temperature information is compared with a temperature threshold. For example, the temperature threshold may be set by a desired operational temperature of the mobile device or a component of the mobile device. For example, the temperature threshold may be set according to a maximum desired operational temperature of a processor of the mobile device. At block **1015**, a piezoelectric actuator may be controlled to oscillate a planar element to cause air to move within the mobile device.

FIG. **10**B shows a flow diagram of a method **1000**-*b* for active cooling of a mobile device in accordance with various embodiments. Method **1000**-*b* may be implemented utilizing various mobile devices such as mobile devices **500** and/or **700** as seen in FIG. **5** and/or FIG. **7**, employing piezoelectric active cooling devices including, but not limited to, piezoelectric active cooling devices **120**, **220**, **320**, **420**, and/or **820** as seen in FIG. **1**A, FIG. **1**B, FIG. **2**A, FIG. **2**B, FIG. **2**C, FIG. **3**A, FIG. **3**B, FIG. **3**C, FIG. **4**A, FIG. **4**B, FIG. **4**C, FIG. **8**A, FIG. **8**B, and/or FIG. **8**C.

At block **1005** of method **1000**-*b*, temperature information that indicates a temperature within a mobile device is received. The temperature information may indicate the temperature of a processor of the mobile device or other internal temperature of the mobile device such as the temperature of a heat dissipation surface of an air channel within the mobile device. For example, temperature information may be received in a processor of a mobile device such as processor module **930** of mobile device **900** from temperature sensor(s) **940**.

At block **1010**-*a* of method **1000**-*b*, the temperature information is compared with a plurality of temperature thresholds. For example, the temperature information may be compared against a look-up-table of temperature thresholds At block **1020**, a control set-point of a piezoelectric cooling device is determined based on the comparison of the temperature information with the plurality of temperature thresholds. For example, the control set-point of the piezoelectric cooling device may be determined from the look-up-table. The control set-point of the piezoelectric cooling device may represent an amount of desired cooling from the piezoelectric cooling device.

At block **1025**, a voltage amplitude for a drive signal for a piezoelectric actuator of the piezoelectric cooling device may be determined from the control set-point of the piezoelectric cooling device. At block **1030** a frequency for the drive signal for the piezoelectric actuator of the piezoelectric cooling device may be determined from the control set-point of the piezoelectric cooling device. At block **1015**-*a*, the piezoelectric actuator of the piezoelectric cooling device may be controlled according to the drive signal to oscillate a planar element to cause air to move within the mobile device.

It should be noted that the methods, systems and devices discussed above are intended merely to be examples. It must be stressed that various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, it should be appreciated that, in alternative embodiments, the methods may be performed in an order different from that described, and that various steps may be added, omitted or combined. Also, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. Also, it should be emphasized that technology evolves and, thus, many of the elements are exemplary in nature and should not be interpreted to limit the scope of the invention.

Specific details are given in the description to provide a thorough understanding of the embodiments. However, it will be understood by one of ordinary skill in the art that the embodiments may be practiced without these specific details. For example, well-known circuits, processes, algorithms, structures, and techniques have been shown without unnecessary detail in order to avoid obscuring the embodiments.

Also, it is noted that the embodiments may be described as a process which is depicted as a flow diagram or block diagram. Although each may describe the operations as a sequential process, many of the operations can be performed in parallel or concurrently. In addition, the order of the operations may be rearranged. A process may have additional steps not included in the figure.

Moreover, as disclosed herein, the term “memory” or “memory unit” may represent one or more devices for storing data, including read-only memory (ROM), random access memory (RAM), magnetic RAM, core memory, magnetic disk storage mediums, optical storage mediums, flash memory devices or other computer-readable mediums for storing information. The term “computer-readable medium” includes, but is not limited to, portable or fixed storage devices, optical storage devices, wireless channels, a sim card, other smart cards, and various other mediums capable of storing, containing or carrying instructions or data.

Furthermore, embodiments may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware or microcode, the program code or code segments to perform the necessary tasks may be stored in a computer-readable medium such as a storage medium. Processors may perform the necessary tasks.

Having described several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the invention. For example, the above elements may merely be a component of a larger system, wherein other rules may take precedence over or otherwise modify the application of the invention. Also, a number of steps may be undertaken before, during, or after the above elements are considered. Accordingly, the above description should not be taken as limiting the scope of the invention.

What is claimed is:

1. A mobile device, comprising:

an air channel defined by at least a first heat dissipation surface; and

a piezoelectric cooling device comprising:

a planar element disposed at least partially within the air channel;

a piezoelectric actuator coupled to the planar element at a first end of the planar element and configured to oscillate the first end of the planar element to cause a transverse wave in the planar element that travels from the first end to a second, distal end of the planar element; and

a spring element coupled to the second end of the planar element, the spring element springedly attaching the second end of the planar element to the mobile device.

2. The mobile device of claim **1**, wherein the piezoelectric actuator and the planar element comprise a piezoelectric bimorph actuator.

3. The mobile device of claim **1**, wherein the mobile device further comprises:

a first semiconductor package having a top surface that comprises the first heat dissipation surface; and

a second semiconductor package having a bottom surface that comprises a second heat dissipation surface of the air channel, the second semiconductor package in a package on package (PoP) configuration with the first semiconductor package.

4. The mobile device of claim **3**, wherein the air channel further comprises:

an air inlet port on a housing of the mobile device; and

an air outlet port on the housing of the mobile device.

5. The mobile device of claim **1**, further comprising:

an air outlet of the air channel, wherein the planar element is configured to fan air away from the first heat dissipation surface at the air outlet of the air channel.

6. The mobile device of claim **5**, further comprising:

an air inlet having upper and lower surfaces substantially parallel with the planar element and joined with the air channel at a side of the air channel adjacent to a lateral edge of the planar element.

7. The mobile device of claim **1**, wherein the second end is arcuately shaped.

8. The mobile device of claim **1**, wherein the piezoelectric actuator comprises a piezoelectric bimorph, a first end of the piezoelectric bimorph fixedly attached to the mobile device and a second end of the piezoelectric bimorph coupled to the first end of the planar element.

9. The mobile device of claim **1**, further comprising:

a temperature sensor; and

a temperature controller coupled to the temperature sensor and the piezoelectric actuator, wherein the temperature controller controls the piezoelectric actuator to oscillate the first end of the planar element based on a measured temperature of the temperature sensor and a temperature threshold.

10. The mobile device of claim **9**, wherein the temperature controller varies the amplitude of a drive signal to the piezoelectric actuator based on a measured temperature.

11. The mobile device of claim **1**, wherein the air channel comprises:

a first portion having a first dimension; and

a second portion that tapers from the first dimension to a second larger dimension at an outlet port of the air channel.

12. The mobile device of claim **1**, wherein the air channel comprises:

a first portion having a first dimension; and

a second portion that is arcuately shaped between the first dimension and a second larger dimension at an outlet port of the air channel, the second portion shaped to substantially match an extent of the planar element when oscillated.

13. A method for cooling a mobile device, the method comprising:

disposing an air channel defined by at least a first heat dissipation surface within the mobile device;

disposing a piezoelectric cooling device comprising a piezoelectric actuator and a planar element at least partially within the air channel;

coupling the piezoelectric actuator to the planar element at a first end of the planar element; and

controlling the piezoelectric actuator to oscillate the first end of the planar element to cause a transverse wave in the planar element that travels from the first end to a second, distal end of the planar element,

wherein a spring element is coupled to the second end of the planar element, the spring element springedly attaching the second end of the planar element to the mobile device.

14. The method of claim **13**, further comprising:

measuring a temperature of the mobile device; and

controlling the piezoelectric actuator based on the measured temperature.

15. A method for cooling a mobile device, the method comprising:

receiving temperature information, the temperature information indicating temperature within the mobile device;

comparing the temperature information against a temperature threshold;

controlling, responsive to the comparing, a piezoelectric cooling device comprising a piezoelectric actuator coupled to a planar element to oscillate a first end of the planar element to cause a transverse wave in the planar element that travels from the first end to a second, distal end of the planar element; and

wherein a spring element is coupled to the second end of the planar element, the spring element springedly attaching the second end of the planar element to the mobile device.

16. The method of claim **15**, the piezoelectric actuator comprising a piezoelectric bimorph actuator.

17. The method of claim **15**, the piezoelectric actuator and the planar element comprising a piezoelectric bimorph actuator.

18. The method of claim **15**, wherein the temperature information indicates a temperature of a processor of the mobile device.

19. The method of claim **15**, wherein the temperature information indicates a temperature of an air channel within the mobile device.

20. The method of claim **15**, wherein the controlling comprises controlling an amplitude of a drive voltage to the piezoelectric actuator based on the comparing of the temperature information against the temperature threshold.

21. The method of claim **20**, wherein the temperature threshold comprises a plurality of temperature thresholds and the comparing comprises determining a control set-point of the piezoelectric actuator based on the plurality of temperature thresholds.

22. A mobile device, comprising:

means for receiving temperature information, the temperature information indicating temperature within the mobile device;

means for comparing the temperature information against a temperature threshold; and

means for controlling, responsive to the comparing, a piezoelectric cooling device comprising a piezoelectric actuator coupled to a planar element to oscillate a first end of the planar element to cause a transverse wave in the planar element that travels from the first end to a second, distal end of the planar element,

wherein a spring element is coupled to the second end of the planar element, the spring element springedly attaching the second end of the planar element to the mobile device.

23. A mobile device comprising:

at least one processor configured to:

receive temperature information, the temperature information indicating temperature within the mobile device;

compare the temperature information against a temperature threshold; and

control, responsive to the comparison, a piezoelectric cooling device comprising a piezoelectric actuator coupled to a planar element to oscillate a first end of the planar element to cause a transverse wave in the planar element that travels from the first end to a second, distal end of the planar element,

wherein a spring element is coupled to the second end of the planar element, the spring element springedly attaching the second end of the planar element to the mobile device.

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