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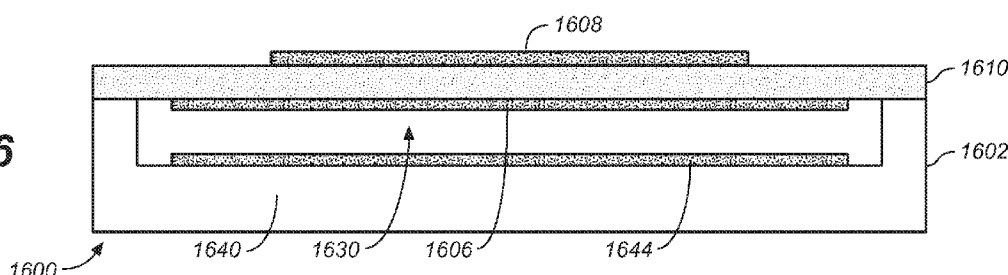
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FIG. 16

(57) **Abstract:** A Piezoelectric Micromachined Ultrasonic Transducer (PMUT) device is provided. The PMUT includes a substrate and an edge support structure connected to the substrate. A membrane is connected to the edge support structure such that a cavity is defined between the membrane and the substrate, where the membrane is configured to allow movement at ultrasonic frequencies. The membrane comprises a piezoelectric layer and first and second electrodes coupled to opposing sides of the piezoelectric layer. For operation in a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode, a third electrode is disposed on the substrate and separated by an air gap in the cavity from the second electrode. Also provided are an integrated MEMS array, a method for operating an array of PMUT / CMUT dual-mode devices, and a PMUT / CMUT dual-mode device.



SUPPLEMENTAL SENSOR MODES AND SYSTEMS FOR ULTRASONIC TRANSDUCERS

RELATED APPLICATIONS

[0001] This application claims priority to and the benefit of co-pending U.S. Patent Provisional Patent Application 62/334,413, filed on May 10, 2016, entitled "SUPPLEMENTAL SENSOR MODES AND SYSTEMS FOR ULTRASONIC TRANSDUCERS," by Mike Daneman, having Attorney Docket No. IVS-689.PR, and assigned to the assignee of the present application, which is incorporated herein by reference in its entirety.

[0002] This application is also a continuation of, and claims priority to, co-pending U.S. Patent Application No. 15/419,835, filed on January 30, 2017, entitled "SUPPLEMENTAL SENSOR MODES AND SYSTEMS FOR ULTRASONIC TRANSDUCERS" by Apte et al., having Attorney Docket No. IVS-718, and assigned to the assignee of the present application, which is incorporated herein by reference in its entirety.

BACKGROUND

[0003] Piezoelectric materials facilitate conversion between mechanical energy and electrical energy. Moreover, a piezoelectric material can generate an electrical signal when subjected to mechanical stress, and can vibrate when subjected to an electrical voltage. Piezoelectric materials are widely utilized in piezoelectric ultrasonic transducers to generate acoustic waves based on an actuation voltage applied to electrodes of the piezoelectric ultrasonic transducer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The accompanying drawings, which are incorporated in and form a part of the Description of Embodiments, illustrate various embodiments of the subject matter and, together with the Description of Embodiments, serve to explain principles of the subject matter discussed below. Unless specifically noted, the drawings referred to in this Brief Description of Drawings should be understood as not being drawn to scale. Herein, like items are labeled with like item numbers.

[0005] FIG. 1A is a diagram illustrating a piezoelectric micromachined ultrasonic transducer (PMUT) device having a center pinned membrane, according to some embodiments.

[0006] FIG. 1B is a diagram illustrating a PMUT device having an unpinned membrane, according to some embodiments.

[0007] FIG. 2 is a diagram illustrating an example of membrane movement during activation of a PMUT device having a center pinned membrane, according to some embodiments.

[0008] FIG. 3 is a top view of the PMUT device of FIG. 1A, according to some embodiments.

[0009] FIG. 4 is a simulated map illustrating maximum vertical displacement of the membrane of the PMUT device shown in FIGs. 1A-3, according to some embodiments.

[0010] FIG. 5 is a top view of an example PMUT device having a circular shape, according to some embodiments.

[0011] FIG. 6 is a top view of an example PMUT device having a hexagonal shape, according to some embodiments.

[0012] FIG. 7 illustrates an example array of circular-shaped PMUT devices, according to some embodiments.

[0013] FIG. 8 illustrates an example array of square-shaped PMUT devices, according to some embodiments.

[0014] FIG. 9 illustrates an example array of hexagonal-shaped PMUT devices, according to some embodiments.

[0015] FIG. 10 illustrates an example pair of PMUT devices in a PMUT array, with each PMUT having differing electrode patterning, according to some embodiments.

[0016] FIGs. 11A, 11B, 11C, and 11D illustrate alternative examples of interior support structures, according to various embodiments.

[0017] FIG. 12 is a block diagram of a PMUT array that includes temperature measurement.

[0018] FIGs. 13A-C illustrate an embodiment of a device operating in a Surface Acoustic Wave (SAW) mode.

[0019] FIGs. 14A-14B illustrate, in top plan view (FIG. 14A) and a side cross-sectional view (FIG. 14B), an embodiment of a dual-mode device structure for operating in switchable PMUT / SAW modes.

[0020] FIG. 15A illustrates an embodiment of a device operable in a PMUT mode.

[0021] FIG. 15B illustrates an embodiment of a device operable in a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode.

[0022] FIG. 15C illustrates an embodiment of a device operable in a PMUT mode or a CMUT mode.

[0023] FIG. 16 illustrates, in a side cross-sectional view, an embodiment of a device structure for operating in switchable PMUT / CMUT modes.

[0024] FIG. 17 is a flow chart, illustrating an embodiment of a method for operating an array of PMUT / CMUT dual-mode devices in an active operational mode.

[0025] FIG. 18 illustrates several exemplary array configurations.

[0026] FIG. 19 illustrates in partial cross-section one embodiment of an integrated sensor of the present invention formed by wafer bonding.

DESCRIPTION OF EMBODIMENTS

[0027] The following Description of Embodiments is merely provided by way of example and not of limitation. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding background or in the following Description of Embodiments.

[0028] Reference will now be made in detail to various embodiments of the subject matter, examples of which are illustrated in the accompanying drawings. While various embodiments are discussed herein, it will be understood that they are not intended to limit to these embodiments. On the contrary, the presented embodiments are intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope the various embodiments as defined by the appended claims. Furthermore, in this Description of Embodiments, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present subject matter. However, embodiments may be practiced without these specific details. In other instances, well known methods, procedures, components, and circuits have not been described in detail as not to unnecessarily obscure aspects of the described embodiments.

Notation and Nomenclature

[0029] Some portions of the detailed descriptions which follow are presented in terms of procedures, logic blocks, processing and other symbolic representations of operations on data within an electrical device. These descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. In the present application, a procedure, logic block, process, or the like, is conceived to be one or more self-consistent procedures or instructions leading to a desired result. The procedures are those requiring physical manipulations of physical quantities. Usually, although not necessarily, these quantities take the form of acoustic (e.g., ultrasonic) signals capable of being transmitted and received by an electronic device and/or electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated in an electrical device.

[0030] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussions, it is appreciated that throughout the description of embodiments, discussions utilizing terms such as “transmitting,” “receiving,” “sensing,” “generating,” “imaging,” or the like, refer to the actions and processes of an electronic device such as an electrical device.

[0031] Embodiments described herein may be discussed in the general context of processor-executable instructions residing on some form of non-transitory processor-readable medium, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc., that perform particular tasks or implement particular abstract data types. The functionality of the program modules may be combined or distributed as desired in various embodiments.

[0032] In the figures, a single block may be described as performing a function or functions; however, in actual practice, the function or functions performed by that block may be performed in a single component or across multiple components, and/or may be performed using hardware, using software, or using a combination of hardware and software. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, logic, circuits, and steps have been described generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure. Also, the example systems described herein may include components other than those shown, including well-known components.

[0033] Various techniques described herein may be implemented in hardware, software, firmware, or any combination thereof, unless specifically described as being implemented in a specific manner. Any features described as modules or components may also be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a non-transitory processor-readable storage medium comprising instructions that, when executed, perform one or more of the methods described herein. The non-transitory processor-readable data storage medium may form part of a computer program product, which may include packaging materials.

[0034] The non-transitory processor-readable storage medium may comprise random access memory (RAM) such as synchronous dynamic random access memory (SDRAM), read only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), FLASH memory, other known storage media, and the like. The techniques additionally, or alternatively, may be realized at least in part by a processor-readable communication medium that carries or communicates code in the form of instructions or data structures and that can be accessed, read, and/or executed by a computer or other processor.

[0035] Various embodiments described herein may be executed by one or more processors, such as one or more motion processing units (MPUs), sensor processing units (SPUs), host processor(s) or core(s) thereof, digital signal processors (DSPs), general purpose microprocessors, application specific integrated circuits (ASICs), application specific instruction set processors (ASIPs), field programmable gate arrays (FPGAs), a programmable logic controller (PLC), a complex programmable logic device (CPLD), a discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein, or other equivalent integrated or discrete logic circuitry. The term “processor,” as used herein may refer to any of the foregoing structures or any other structure suitable for implementation of the techniques described herein. As is employed in the subject specification, the term “processor” can refer to substantially any computing processing unit or device comprising, but not limited to comprising, single-core processors; single-processors with software multithread execution capability; multi-core processors; multi-core processors with software multithread execution capability; multi-core processors with hardware multithread technology; parallel platforms; and parallel platforms with distributed shared memory. Moreover, processors can exploit nano-scale architectures such as, but not limited to, molecular and quantum-dot based transistors, switches and gates, in order to optimize space usage or enhance performance of user equipment. A processor may also be implemented as a combination of computing processing units.

[0036] In addition, in some aspects, the functionality described herein may be provided within dedicated software modules or hardware modules configured as described herein. Also, the techniques could be fully implemented in one or more circuits or logic elements. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of an SPU/MPU and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with an SPU core, MPU core, or any other such configuration.

Overview of Discussion

[0037] Discussion begins with a description of an example Piezoelectric Micromachined Ultrasonic Transducer (PMUT), in accordance with various embodiments. Example arrays including PMUT devices are then described. Example operations of the example arrays of PMUT devices are then further described. Further, dual-mode PMUT / Surface Acoustic Wave (SAW) and PMUT / Capacitive Micromachined Ultrasonic Transducer (CMUT) devices and arrays of such devices are also described.

[0038] A conventional piezoelectric ultrasonic transducer able to generate and detect pressure waves can include a membrane with the piezoelectric material, a supporting layer, and electrodes combined with a cavity beneath the electrodes. Miniaturized versions are referred to as PMUTs. Typical PMUTs use an edge anchored membrane or diaphragm that maximally oscillates at or near the center of the membrane at a resonant frequency (f) proportional to h/a^2 , where h is the thickness, and a is the radius of the membrane. Higher frequency membrane oscillations can be created by increasing the membrane thickness, decreasing the membrane radius, or both. Increasing the membrane thickness has its limits, as the increased thickness limits the displacement of the membrane. Reducing the PMUT membrane radius also has limits, because a larger percentage of PMUT membrane area is used for edge anchoring.

[0039] Embodiments described herein relate to a PMUT device for ultrasonic wave generation and sensing. In accordance with various embodiments, an array of such PMUT devices is described. The PMUT includes a substrate and an edge support structure connected to the substrate. A membrane is connected to the edge support structure such that a cavity is defined between the membrane and the substrate, where the membrane is configured to allow movement at ultrasonic frequencies. The membrane includes a piezoelectric layer and first and second electrodes coupled to opposing sides of the piezoelectric layer. An interior support structure is disposed within the cavity and connected to the substrate and the membrane.

[0040] The described PMUT device and array of PMUT devices can be used for generation of acoustic signals or measurement of acoustically sensed data in various applications, such as, but not limited to, medical applications, security systems, biometric systems (e.g., fingerprint sensors and/or motion/gesture recognition sensors), mobile communication systems, industrial automation systems, consumer electronic devices, robotics, etc. In one embodiment, the PMUT device can facilitate ultrasonic signal generation and sensing (transducer). Moreover, embodiments described herein provide a sensing component including a silicon wafer having a two-dimensional (or one-dimensional) array of ultrasonic transducers.

[0041] Embodiments described herein provide a PMUT that operates at a high frequency for reduced acoustic diffraction through high acoustic velocity materials (e.g., glass, metal), and for shorter pulses so that spurious reflections can be time-gated out. Embodiments described herein also provide a PMUT that has a low quality factor providing a shorter ring-up and ring-down time to allow better rejection of spurious reflections by time-gating. Embodiments described herein also provide a PMUT that has a high fill-factor providing for large transmit and receive signals.

Piezoelectric Micromachined Ultrasonic Transducer (PMUT)

[0042] Systems and methods disclosed herein, in one or more aspects provide efficient structures for an acoustic transducer (e.g., a piezoelectric actuated transducer or PMUT). One or more embodiments are now described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the various embodiments. It may be evident, however, that the various embodiments can be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to facilitate describing the embodiments in additional detail.

[0043] As used in this application, the term “or” is intended to mean an inclusive “or” rather than an exclusive “or”. That is, unless specified otherwise, or clear from context, “X employs A or B” is intended to mean any of the natural inclusive permutations. That is, if X employs A; X employs B; or X employs both A and B, then “X employs A or B” is satisfied under any of the foregoing instances. In addition, the articles “a” and “an” as used in this application and the appended claims should generally be construed to mean “one or more” unless specified otherwise or clear from context to be directed to a singular form. In addition, the word “coupled” is used herein to mean direct or indirect electrical or mechanical coupling. In addition, the word “example” is used herein to mean serving as an example, instance, or illustration.

[0044] FIG. 1A is a diagram illustrating a PMUT device 100 having a center pinned membrane, according to some embodiments. PMUT device 100 includes an interior pinned membrane 120 positioned over a substrate 140 to define a cavity 130. In one embodiment, membrane 120 is attached both to a surrounding edge support 102 and interior support 104. In one embodiment, edge support 102 is connected to an electric potential. Edge support 102 and interior support 104 may be made of electrically conducting materials, such as and without limitation, aluminum, molybdenum, or titanium. Edge support 102 and interior support 104 may also be made of dielectric materials, such as silicon dioxide, silicon nitride or aluminum oxide that have electrical connections the sides or in vias through edge support 102 or interior support 104, electrically coupling lower electrode 106 to electrical wiring in substrate 140.

[0045] In one embodiment, both edge support 102 and interior support 104 are attached to a substrate 140. In various embodiments, substrate 140 may include at least one of, and without limitation, silicon or silicon nitride. It should be appreciated that substrate 140 may include electrical wirings and connection, such as aluminum or copper. In one embodiment, substrate 140 includes a CMOS logic wafer bonded to edge support 102 and interior support 104. In one embodiment, the membrane 120 comprises multiple layers. In an example embodiment, the

membrane 120 includes lower electrode 106, piezoelectric layer 110, and upper electrode 108, where lower electrode 106 and upper electrode 108 are coupled to opposing sides of piezoelectric layer 110. As shown, lower electrode 106 is coupled to a lower surface of piezoelectric layer 110 and upper electrode 108 is coupled to an upper surface of piezoelectric layer 110. It should be appreciated that, in various embodiments, PMUT device 100 is a microelectromechanical (MEMS) device.

[0046] In one embodiment, membrane 120 also includes a mechanical support layer 112 (e.g., stiffening layer) to mechanically stiffen the layers. In various embodiments, mechanical support layer 140 may include at least one of, and without limitation, silicon, silicon oxide, silicon nitride, aluminum, molybdenum, titanium, etc. In one embodiment, PMUT device 100 also includes an acoustic coupling layer 114 above membrane 120 for supporting transmission of acoustic signals. It should be appreciated that acoustic coupling layer can include air, liquid, gel-like materials, or other materials for supporting transmission of acoustic signals. In one embodiment, PMUT device 100 also includes platen layer 116 above acoustic coupling layer 114 for containing acoustic coupling layer 114 and providing a contact surface for a finger or other sensed object with PMUT device 100. It should be appreciated that, in various embodiments, acoustic coupling layer 114 provides a contact surface, such that platen layer 116 is optional. Moreover, it should be appreciated that acoustic coupling layer 114 and/or platen layer 116 may be included with or used in conjunction with multiple PMUT devices. For example, an array of PMUT devices may be coupled with a single acoustic coupling layer 114 and/or platen layer 116.

[0047] FIG. 1B is identical to FIG. 1A in every way, except that the PMUT device 100' of FIG. 1B omits the interior support 104 and thus membrane 120 is not pinned (e.g., is "unpinned"). There may be instances in which an unpinned membrane 120 is desired. However, in other instances, a pinned membrane 120 may be employed.

[0048] FIG. 2 is a diagram illustrating an example of membrane movement during activation of pinned PMUT device 100, according to some embodiments. As illustrated with respect to FIG. 2, in operation, responsive to an object proximate platen layer 116, the electrodes 106 and 108 deliver a high frequency electric charge to the piezoelectric layer 110, causing those portions of the membrane 120 not pinned to the surrounding edge support 102 or interior support 104 to be displaced upward into the acoustic coupling layer 114. This generates a pressure wave that can be used for signal probing of the object. Return echoes can be detected as pressure waves causing movement of the membrane, with compression of the piezoelectric material in the membrane causing an electrical signal proportional to amplitude of the pressure wave.

[0049] The described PMUT device 100 can be used with almost any electrical device that converts a pressure wave into mechanical vibrations and/or electrical signals. In one aspect, the PMUT device 100 can comprise an acoustic sensing element (e.g., a piezoelectric element) that generates and senses ultrasonic sound waves. An object in a path of the generated sound waves can create a disturbance (e.g., changes in frequency or phase, reflection signal, echoes, etc.) that can then be sensed. The interference can be analyzed to determine physical parameters such as (but not limited to) distance, density and/or speed of the object. As an example, the PMUT device 100 can be utilized in various applications, such as, but not limited to, fingerprint or physiologic sensors suitable for wireless devices, industrial systems, automotive systems, robotics, telecommunications, security, medical devices, etc. For example, the PMUT device 100 can be part of a sensor array comprising a plurality of ultrasonic transducers deposited on a wafer, along with various logic, control and communication electronics. A sensor array may comprise homogenous or identical PMUT devices 100, or a number of different or heterogenous device structures.

[0050] In various embodiments, the PMUT device 100 employs a piezoelectric layer 110, comprised of materials such as, but not limited to, aluminum nitride (AlN), lead zirconate titanate (PZT), quartz, polyvinylidene fluoride (PVDF), and/or zinc oxide, to facilitate both acoustic signal production and sensing. The piezoelectric layer 110 can generate electric charges under mechanical stress and conversely experience a mechanical strain in the presence of an electric field. For example, the piezoelectric layer 110 can sense mechanical vibrations caused by an ultrasonic signal and produce an electrical charge at the frequency (e.g., ultrasonic frequency) of the vibrations. Additionally, the piezoelectric layer 110 can generate an ultrasonic wave by vibrating in an oscillatory fashion that might be at the same frequency (e.g., ultrasonic frequency) as an input current generated by an alternating current (AC) voltage applied across the piezoelectric layer 110. It should be appreciated that the piezoelectric layer 110 can include almost any material (or combination of materials) that exhibits piezoelectric properties, such that the structure of the material does not have a center of symmetry and a tensile or compressive stress applied to the material alters the separation between positive and negative charge sites in a cell causing a polarization at the surface of the material. The polarization is directly proportional to the applied stress and is direction dependent so that compressive and tensile stresses results in electric fields of opposite polarizations.

[0051] Further, the PMUT device 100 comprises electrodes 106 and 108 that supply and/or collect the electrical charge to/from the piezoelectric layer 110. It should be appreciated that electrodes 106 and 108 can be continuous and/or patterned electrodes (e.g., in a continuous layer and/or a patterned layer). For example, as illustrated, electrode 106 is a patterned electrode and electrode 108 is a continuous electrode. As an example, electrodes 106 and 108

can be comprised of almost any metal layers, such as, but not limited to, aluminum (Al)/titanium (Ti), molybdenum (Mo), etc., which are coupled with an on opposing sides of the piezoelectric layer 110. In one embodiment, PMUT device also includes a third electrode, as illustrated in FIG. 10 and described below.

[0052] According to an embodiment, the acoustic impedance of acoustic coupling layer 114 is selected to be similar to the acoustic impedance of the platen layer 116, such that the acoustic wave is efficiently propagated to/from the membrane 120 through acoustic coupling layer 114 and platen layer 116. As an example, the platen layer 116 can comprise various materials having an acoustic impedance in the range between 0.8 to 4 Mega Rayleigh (MRayl), such as, but not limited to, plastic, resin, rubber, Teflon, epoxy, etc. In another example, the platen layer 116 can comprise various materials having a high acoustic impedance (e.g., an acoustic impedance greater than 10 MRayl), such as, but not limited to, glass, aluminum-based alloys, sapphire, etc. Typically, the platen layer 116 can be selected based on an application of the sensor. For instance, in fingerprinting applications, platen layer 116 can have an acoustic impedance that matches (e.g., exactly or approximately) the acoustic impedance of human skin (e.g., 1.6×10^6 Rayl). Further, in one aspect, the platen layer 116 can further include a thin layer of anti-scratch material. In various embodiments, the anti-scratch layer of the platen layer 116 is less than the wavelength of the acoustic wave that is to be generated and/or sensed to provide minimum interference during propagation of the acoustic wave. As an example, the anti-scratch layer can comprise various hard and scratch-resistant materials (e.g., having a Mohs hardness of over 7 on the Mohs scale), such as, but not limited to sapphire, glass, titanium nitride (TiN), silicon carbide (SiC), diamond, etc. As an example, PMUT device 100 can operate at 20 MHz and accordingly, the wavelength of the acoustic wave propagating through the acoustic coupling layer 114 and platen layer 116 can be 70-150 microns. In this example scenario, insertion loss can be reduced and acoustic wave propagation efficiency can be improved by utilizing an anti-scratch layer having a thickness of 1 micron and the platen layer 116 as a whole having a thickness of 1-2 millimeters. It is noted that the term “anti-scratch material” as used herein relates to a material that is resistant to scratches and/or scratch-proof and provides substantial protection against scratch marks.

[0053] In accordance with various embodiments, the PMUT device 100 can include metal layers (e.g., aluminum (Al)/titanium (Ti), molybdenum (Mo), etc.) patterned to form electrode 106 in particular shapes (e.g., ring, circle, square, octagon, hexagon, etc.) that are defined in-plane with the membrane 120. Electrodes can be placed at a maximum strain area of the membrane 120 or placed at close to either or both the surrounding edge support 102 and interior support 104. Furthermore, in one example, electrode 108 can be formed as a continuous layer providing a ground plane in contact with mechanical support layer 112, which

can be formed from silicon or other suitable mechanical stiffening material. In still other embodiments, the electrode 106 can be routed along the interior support 104, advantageously reducing parasitic capacitance as compared to routing along the edge support 102.

[0054] For example, when actuation voltage is applied to the electrodes, the membrane 120 will deform and move out of plane. The motion then pushes the acoustic coupling layer 114 it is in contact with and an acoustic (ultrasonic) wave is generated. Oftentimes, vacuum is present inside the cavity 130 and therefore damping contributed from the media within the cavity 130 can be ignored. However, the acoustic coupling layer 114 on the other side of the membrane 120 can substantially change the damping of the PMUT device 100. For example, a quality factor greater than 20 can be observed when the PMUT device 100 is operating in air with atmosphere pressure (e.g., acoustic coupling layer 114 is air) and can decrease lower than 2 if the PMUT device 100 is operating in water (e.g., acoustic coupling layer 114 is water).

[0055] FIG. 3 is a top view of the PMUT device 100 of FIG. 1A having a substantially square shape, which corresponds in part to a cross section along dotted line 101 in FIG. 3. Layout of surrounding edge support 102, interior support 104, and lower electrode 106 are illustrated, with other continuous layers not shown. It should be appreciated that the term “substantially” in “substantially square shape” is intended to convey that a PMUT device 100 is generally square-shaped, with allowances for variations due to manufacturing processes and tolerances, and that slight deviation from a square shape (e.g., rounded corners, slightly wavering lines, deviations from perfectly orthogonal corners or intersections, etc.) may be present in a manufactured device. While a generally square arrangement PMUT device is shown, alternative embodiments including rectangular, hexagon, octagonal, circular, or elliptical are contemplated. In other embodiments, more complex electrode or PMUT device shapes can be used, including irregular and non-symmetric layouts such as chevrons or pentagons for edge support and electrodes.

[0056] FIG. 4 is a simulated topographic map 400 illustrating maximum vertical displacement of the membrane 120 of the PMUT device 100 shown in FIGs. 1A-3. As indicated, maximum displacement generally occurs along a center axis of the lower electrode, with corner regions having the greatest displacement. As with the other figures, FIG. 4 is not drawn to scale with the vertical displacement exaggerated for illustrative purposes, and the maximum vertical displacement is a fraction of the horizontal surface area comprising the PMUT device 100. In an example PMUT device 100, maximum vertical displacement may be measured in nanometers, while surface area of an individual PMUT device 100 may be measured in square microns.

[0057] FIG. 5 is a top view of another example of the PMUT device 100 of FIG. 1A having a substantially circular shape, which corresponds in part to a cross section along dotted line 101 in FIG. 5. Layout of surrounding edge support 102, interior support 104, and lower electrode 106 are illustrated, with other continuous layers not shown. It should be appreciated that the term “substantially” in “substantially circular shape” is intended to convey that a PMUT device 100 is generally circle-shaped, with allowances for variations due to manufacturing processes and tolerances, and that slight deviation from a circle shape (e.g., slight deviations on radial distance from center, etc.) may be present in a manufactured device.

[0058] FIG. 6 is a top view of another example of the PMUT device 100 of FIG. 1A having a substantially hexagonal shape, which corresponds in part to a cross section along dotted line 101 in FIG. 6. Layout of surrounding edge support 102, interior support 104, and lower electrode 106 are illustrated, with other continuous layers not shown. It should be appreciated that the term “substantially” in “substantially hexagonal shape” is intended to convey that a PMUT device 100 is generally hexagon-shaped, with allowances for variations due to manufacturing processes and tolerances, and that slight deviation from a hexagon shape (e.g., rounded corners, slightly wavering lines, deviations from perfectly orthogonal corners or intersections, etc.) may be present in a manufactured device.

[0059] FIG. 7 illustrates an example two-dimensional array 700 of circular-shaped PMUT devices 701 formed from PMUT devices having a substantially circular shape similar to that discussed in conjunction with FIGs. 1A, 2 and 5. Layout of circular surrounding edge support 702, interior support 704, and annular or ring shaped lower electrode 706 surrounding the interior support 704 are illustrated, while other continuous layers are not shown for clarity. As illustrated, array 700 includes columns of circular-shaped PMUT devices 701 that are offset. It should be appreciated that the circular-shaped PMUT devices 701 may be closer together, such that edges of the columns of circular-shaped PMUT devices 701 overlap. Moreover, it should be appreciated that circular-shaped PMUT devices 701 may contact each other. In various embodiments, adjacent circular-shaped PMUT devices 701 are electrically isolated. In other embodiments, groups of adjacent circular-shaped PMUT devices 701 are electrically connected, where the groups of adjacent circular-shaped PMUT devices 701 are electrically isolated.

[0060] FIG. 8 illustrates an example two-dimensional array 800 of square-shaped PMUT devices 801 formed from PMUT devices having a substantially square shape similar to that discussed in conjunction with FIGs. 1A, 2 and 3. Layout of square surrounding edge support 802, interior support 804, and square-shaped lower electrode 806 surrounding the interior support 804 are illustrated, while other continuous layers are not shown for clarity. As illustrated, array 800 includes columns of square-shaped PMUT devices 801 that are in rows

and columns. It should be appreciated that rows or columns of the square-shaped PMUT devices 801 may be offset. Moreover, it should be appreciated that square-shaped PMUT devices 801 may contact each other or be spaced apart. In various embodiments, adjacent square-shaped PMUT devices 801 are electrically isolated. In other embodiments, groups of adjacent square-shaped PMUT devices 801 are electrically connected, where the groups of adjacent square-shaped PMUT devices 801 are electrically isolated.

[0061] FIG. 9 illustrates an example two-dimensional array 900 of hexagon-shaped PMUT devices 901 formed from PMUT devices having a substantially hexagon shape similar to that discussed in conjunction with FIGs. 1A, 2 and 6. Layout of hexagon-shaped surrounding edge support 902, interior support 904, and hexagon-shaped lower electrode 906 surrounding the interior support 904 are illustrated, while other continuous layers are not shown for clarity. It should be appreciated that rows or columns of the hexagon-shaped PMUT devices 901 may be offset. Moreover, it should be appreciated that hexagon-shaped PMUT devices 901 may contact each other or be spaced apart. In various embodiments, adjacent hexagon-shaped PMUT devices 901 are electrically isolated. In other embodiments, groups of adjacent hexagon-shaped PMUT devices 901 are electrically connected, where the groups of adjacent hexagon-shaped PMUT devices 901 are electrically isolated. While FIGs. 7, 8 and 9 illustrate example layouts of PMUT devices having different shapes, it should be appreciated that many different layouts are available. Moreover, in accordance with various embodiments, arrays of PMUT devices are included within a MEMS layer.

[0062] In operation, during transmission, selected sets of PMUT devices in the two-dimensional array can transmit an acoustic signal (e.g., a short ultrasonic pulse) and during sensing, the set of active PMUT devices in the two-dimensional array can detect an interference of the acoustic signal with an object (in the path of the acoustic wave). The received interference signal (e.g., generated based on reflections, echoes, etc. Of the acoustic signal from the object) can then be analyzed. As an example, an image of the object, a distance of the object from the sensing component, a density of the object, a motion of the object, etc., can all be determined based on comparing a frequency and/or phase of the interference signal with a frequency and/or phase of the acoustic signal. Moreover, results generated can be further analyzed or presented to a user via a display device (not shown).

[0063] FIG. 10 illustrates a pair of example PMUT devices 1000 in a PMUT array, with each PMUT sharing at least one common edge support 1002. As illustrated, the PMUT devices have two sets of independent lower electrode labeled as 1006 and 1026. These differing electrode patterns enable antiphase operation of the PMUT devices 1000, and increase flexibility of device operation. In one embodiment, the pair of PMUTs may be identical, but the two

electrodes could drive different parts of the same PMUT antiphase (one contracting, and one extending), such that the PMUT displacement becomes larger. While other continuous layers are not shown for clarity, each PMUT also includes an upper electrode (e.g., upper electrode 108 of FIG. 1A). Accordingly, in various embodiments, a PMUT device may include at least three electrodes.

[0064] FIGs. 11A, 11B, 11C, and 11D illustrate alternative examples of interior support structures, in accordance with various embodiments. Interior supports structures may also be referred to as “pinning structures,” as they operate to pin the membrane to the substrate. It should be appreciated that interior support structures may be positioned anywhere within a cavity of a PMUT device, and may have any type of shape (or variety of shapes), and that there may be more than one interior support structure within a PMUT device. While FIGs. 11A, 11B, 11C, and 11D illustrate alternative examples of interior support structures, it should be appreciated that these examples are for illustrative purposes, and are not intended to limit the number, position, or type of interior support structures of PMUT devices.

[0065] For example, interior supports structures do not have to be centrally located with a PMUT device area, but can be non-centrally positioned within the cavity. As illustrated in FIG. 11A, interior support 1104a is positioned in a non-central, off-axis position with respect to edge support 1102. In other embodiments such as seen in FIG. 11B, multiple interior supports 1104b can be used. In this embodiment, one interior support is centrally located with respect to edge support 1102, while the multiple, differently shaped and sized interior supports surround the centrally located support. In still other embodiments, such as seen with respect to Figs. 11C and 11D, the interior supports (respectively 1104c and 1104d) can contact a common edge support 1102. In the embodiment illustrated in FIG. 11D, the interior supports 1104d can effectively divide the PMUT device into subpixels. This would allow, for example, activation of smaller areas to generate high frequency ultrasonic waves, and sensing a returning ultrasonic echo with larger areas of the PMUT device. It will be appreciated that the individual pinning structures can be combined into arrays.

[0066] FIG. 12 is a block diagram of a PMUT device 1200 that includes temperature measurement. PMUT array 1210 is a two-dimensional array of PMUT devices similar to array 700, including variations that may be introduced in such an array. Temperature sensor 1220 includes circuitry for temperature measurement. Timing module 1230 receives temperature sensor information 1225 from temperature sensor 1220 and creates timing signals 1235. Among other things, timing module 1230 may adjust for changes in expected ultrasonic signal travel time based on the measured temperature. Timing signals 1235 are used to drive PMUT array 1210.

[0067] There are a number of ways known in the art to provide temperature sensor 1220. In an embodiment, temperature sensor 1220 is an integrated silicon thermistor that can be incorporated in the MEMS manufacturing process with PMUT array 1210. In another embodiment, temperature sensor 1220 is a MEMS structure different from PMUT array 1210 but compatible with the MEMS manufacturing process for PMUT array 1210. In another embodiment, temperature sensor 1220 is circuitry that determines temperature by associating a known temperature dependency with the quality factor (Q) of some or all of the resonators that comprise the PMUT array 1210. In another embodiment, temperature sensor 1220 and a portion of timing module 1230 together comprise a MEMS oscillator manufactured with a process compatible with PMUT array 1210 from which a frequency stable clock may be directly derived over a broad operating temperature range.

[0068] By providing temperature sensor information 1225, the PMUT device can generate dependable frequencies for timing signals 1235. In this way, the PMUT device can be clockless, not requiring a separate input from an external clock. This simplifies the design process for an engineer incorporating the PMUT device 1200 into a design. An external oscillator or clock signal is not needed, eliminating a part and associated routing. In the case of a typical quartz oscillator used for an external clock-generation circuit, there may also be an efficiency gain as quartz devices typically consume more power than MEMS-based clocks. Having the timing signals 1235 generated on chip further enables improved signal compensation and conditioning.

[0069] The temperature or reference clock may optionally be shared outside of device 1200. Optional interface 1240 in communication with temperature sensor 1220 or timing module 1230 provides signals 1245 to an external device 1250. Signals 1245 may represent measured temperature or a reference clock frequency from the PMUT device 1200. Optional external device 1250 may include another integrated circuit device, or a data or system bus. Other blocks and signals may be introduced into PMUT device 1200, provided that an external clock signal is not used to generate timing signals 1235.

[0070] Surface Acoustic Wave (SAW) devices are commonly used as resonators and filters. In a SAW device, an acoustic wave is launched along the surface of a piezoelectric material. A surface acoustic wave is typically launched using a set of interdigitated electrodes, although other electrode configurations may also be employed.

[0071] This is different than BAW (Bulk Acoustic Wave) or BAR (Bulk Acoustic Resonator) devices where a wave is launched inside the bulk of the piezo material. It is also different from PMUT devices, where a flexural motion is induced in the piezo membrane.

[0072] FIGs. 13A-C illustrate an embodiment of a device operating in a SAW mode. FIG. 13A shows in operation a MEMS device 1300 similar to PMUT device 100'. In PMUT mode, reflected energy is measured from signals orthogonal to a reflected surface, such as an echo in an acoustic frequency range. By contrast, in SAW mode, energy propagated through and along the surface of a piezoelectric material is measured in MEMS device 1300. Such a signal may be an ambient wave in a radio frequency range. FIG. 13B illustrates a cross section of MEMS device 1300 showing displacement in a SAW mode. FIG. 13C illustrates another frequency and its resulting displacement in SAW mode. Similar to FIG. 4, the illustrations in Fig. 13B and 13C are exaggerated in scale to show resulting movement of membrane 1320. It should be appreciated that the embodiments described in FIGs. 13A-C may also include a PMUT device having an interior support (e.g., PMUT device 100).

[0073] Like a PMUT device, a SAW device relies upon the conversion of mechanical energy causing a deformation in membrane 1320 and its piezoelectric layer 1310 into an electrical signal characteristic of the energy input. Similar manufacturing techniques may be used to fabricate a MEMS PMUT device and a MEMS SAW device. The piezoelectric material in either instance may be tuned by design for sensitivity to particular frequencies and for particular applications. For SAW mode, applications are likely to include a number of tasks, including fingerprint recognition through ultrasonic frequencies. SAW devices are used with radio frequencies as filters. It is also known in the art to adapt a SAW device to detect temperature, pressure, the existence of chemicals or other desired parameters.

[0074] In some embodiments, MEMS devices 1300 in an array may be identical for operation in PMUT mode and SAW mode. Further, selective switching between one mode and the other may be provided. In other embodiments, the array may include heterogeneous array elements that are compatible with the same manufacturing process. Some elements may be designed and tuned for performance in PMUT mode, while other elements may be designed and tuned for performance in SAW mode. The array elements may also include variation within each mode. As an example, there may be elements designed and tuned for performance in SAW mode that target different radio frequencies of interest for filtering. As understood in the art, there are multiple ways to design and tune the elements for particular performance, including size of array element, composition and thickness of material stack, elasticity of the piezoelectric layer, and size and structure of the supports.

[0075] FIGs. 14A-14B depict an embodiment of a dual-mode device 1400 that can be selectively operated both in SAW and PMUT modes, by switching between the two modes. FIG. 14A is a top plan view, while FIG. 14B is a side cross-sectional view. The dual-mode

device 1400 includes a piezoelectric layer 1410 positioned over a substrate 1440 to define a cavity 1430. In one embodiment, piezoelectric layer 1410 is attached to a surrounding edge support 1402. Edge support 1402 and substrate 1440 may be unitary (as shown) or separate components, in either case made of dielectric materials, such as silicon dioxide, silicon nitride or aluminum oxide that have electrical connections in the sides or in vias through edge support 1402. It should be appreciated that dual-mode device 1400 may also include an interior support (e.g., interior support 104 of PMUT device 100).

[0076] The dual-mode device 1400 further includes a lower electrode 1406, disposed on a bottom surface of the piezoelectric layer 1410; the lower electrode 1406 may be considered to be equivalent to the lower electrode 106 depicted in FIGs. 1A-1B. The dual-mode device 1400 also includes a first pair of interdigitated electrodes 1408a and a second pair of interdigitated electrodes 1408b, both disposed on a top surface of the piezoelectric layer 1410. The two pairs of interdigitated electrodes 1408a, 1408b may be considered to be equivalent to the upper electrode 108 depicted in FIGs. 1A-1B. The first pair of interdigitated electrodes 1408a comprises electrodes 1408a1 and 1408a2, disposed in an interdigitated pattern. The second pair of interdigitated electrodes 1408b comprises electrodes 1408b1 and 1408b2, disposed in an interdigitated pattern. The two pairs of interdigitated electrodes 1408a and 1408b are separated by a distance d .

[0077] In the SAW mode, electrodes 1408a1 and 1408a2 are used to inject an AC signal from an AC source 1450 and generate a surface acoustic wave in the surface of the piezoelectric layer 1410 across the distance d , while electrodes 1408b1 and 1408b2 are used to receive the propagated wave and convert the acoustic wave to a voltage output 1452. In this SAW mode, the dual-mode device 1400 can be used as a sensor, filter or resonator, for example. In this configuration, lower electrode 1406 can be either ground or floating.

[0078] In the PMUT mode, electrodes 1408a1, 1408a2, 1408b1, and 1408b2 are all driven at the same potential, with electrode 1406 at another potential. In the PMUT mode, the dual-mode device 1400 produces a flexural mode of motion in the piezoelectric layer 1410. In the PMUT mode, the dual-mode device 1400 can be used as a sensor, such as a fingerprint sensor or temperature sensor, for example.

[0079] In another embodiment, the PMUT device includes a Capacitive Micromachined Ultrasonic Transducer (CMUT) portion or is operated in part in a CMUT mode. Like a PMUT device, a CMUT device relies upon the deflection of a membrane through an electrical effect – whether electromechanical in the case of the PMUT, or electrostatic in the case of the CMUT. Similar manufacturing techniques may be used to fabricate a MEMS PMUT device and a MEMS

CMUT device. In operation, a PMUT device uses electrodes proximate a piezoelectric layer in the membrane to generate or to measure a deformation of the membrane. By contrast, at least one electrode in a CMUT device is positioned on the other side of a cavity to create a capacitive effect. The design and tuning of the layers in the material stack may target particular applications and use in a PMUT mode or a CMUT mode. In CMUT mode, a device may be used for fingerprint recognition as well as other applications.

[0080] FIG. 15A illustrates an embodiment of a MEMS device operable in a PMUT mode. The essential elements of PMUT device 100' are captured in device 1500A to show operation in a PMUT mode. Membrane 1520 is deformed out of plane based on the piezoelectric effect. Membrane 1520 includes top electrode 1508, bottom electrode 1506, and piezoelectric layer 1510. The membrane 1520 is attached to a substrate 1540 through supports 1502 along the periphery of the device, forming cavity 1530. For operation in PMUT mode, the piezoelectric layer 1510 is proximate the top electrode 1508 and the bottom electrode 1506. An AC voltage is either transmitted across electrodes 1506 and 1508 to force a deformation, or such a signal is read across electrodes 1506 and 1508 to measure a deformation. The signal may be an ultrasonic signal. A DC bias voltage is not typically required for operation of device 1500A in PMUT mode. It should be appreciated that device 1500A may also include an interior support (e.g., interior support 104 of PMUT device 100).

[0081] FIG. 15B illustrates an embodiment of a device operable in a CMUT mode. Device 1500B is similar to device 1500A, but includes electrode 1544 and removes bottom electrode 1506. Device 1500B is a simplified device to illustrate operation in CMUT mode. Device 1500B forms a capacitor between membrane 1520 and substrate 1540. It should be appreciated that device 1500B may also include an interior support (e.g., interior support 104 of PMUT device 100). Top electrode 1508 and electrode 1544 are the electrode layers of the capacitor, while the combination of membrane dielectric 1520, cavity 1530, and dielectric on substrate 1540 form the dielectric layer of the capacitor. In operation, a DC bias voltage is typically applied between the electrodes 1508 and 1544, and membrane 1520 is deflected towards substrate 1540 by electrostatic forces. The mechanical restoring forces caused by stiffness of membrane 1520 resist the electrostatic force. Signals can then be transmitted on, or received from, oscillations in membrane 1520 as an AC voltage.

[0082] FIG. 15C illustrates an embodiment of a device 1500C operable in a PMUT mode or a CMUT mode. Device 1500C is an integration of device 1500A and device 1500B. It is suitable for operation in either a PMUT mode or a CMUT mode. The PMUT mode arises with an AC voltage across electrodes 1506 and 1508. The CMUT mode arises with DC bias voltage and

AC signal voltage across electrodes 1508 and 1544. There may be other layers, over layers, and intermediate layers to membrane 1520 and the devices illustrated in FIG. 15C, such as stiffening layers, coupling layers, etc. The piezoelectric layer 1510 in device 1500B may comprise a non-piezoelectric material in certain embodiments. The design and tuning of the layers in the material stack may target particular applications and use in a PMUT mode or a CMUT mode. In CMUT mode, a device may be used as a sensitive pressure sensor, such as for fingerprint recognition, either to transmit or to receive ultrasonic signals. Other sensor capabilities are possible. It should be appreciated that device 1500C may also include an interior support (e.g., interior support 104 of PMUT device 100).

[0083] Some embodiments may comprise elements similar to device 1500C, which may be operated in either a PMUT mode or a CMUT mode, including being switchable between the two modes. In other embodiments, an array may include heterogeneous PMUT and CMUT elements similar to devices 1500A and 1500B that are compatible with the same manufacturing process. Some elements may be designed and tuned for performance in PMUT mode, while other elements may be designed and tuned for performance in CMUT mode. There may be embodiments for a fingerprint recognition application where it is preferable to transmit an ultrasonic signal in one mode and to detect its reflection or echo in a different mode. As understood in the art, there are multiple ways to design and tune the elements for particular performance, including size of array element, composition and thickness of material stack, elasticity of the diaphragm, and size and structure of the supports.

[0084] FIG. 16, which is a side cross-sectional view, depicts an embodiment of a dual-mode device 1600 that can be selectively operated both in CMUT and PMUT modes. The dual-mode device 1600 includes a piezoelectric layer 1610 positioned over a substrate 1640 to define a cavity 1630. In one embodiment, piezoelectric layer 1610 is attached to a surrounding edge support 1602. Edge support 1602 and substrate 1640 may be unitary (as shown) or separate components, in either case made of dielectric materials, such as silicon dioxide, silicon nitride or aluminum oxide that have electrical connections in the sides or in vias through edge support 1602. It should be appreciated that device 1600 may also include an interior support (e.g., interior support 104 of PMUT device 100).

[0085] The dual-mode device 1600 further includes a lower electrode 1606, disposed on a bottom surface of the piezoelectric layer 1610; the lower electrode 1606 may be considered to be equivalent to the lower electrode 106 depicted in FIGs. 1A-1B. The dual-mode device 1600 also includes an upper electrode 1608 disposed on a top surface of the piezoelectric layer 1610. The upper electrode 1608 may be considered to be equivalent to the upper electrode 108 depicted in FIGs. 1A-1B. In addition to the lower electrode 1606 and upper electrode 1608, the

dual-mode device also includes a third electrode 1644, disposed on an upper surface of the substrate 1640 and spaced apart from the first, or lower, electrode 1606. The dual-mode device 1600 is seen to be essentially the same as device 1500C in FIG. 15C.

[0086] In the CMUT mode, the piezoelectric layer 1610 is actuated electrostatically by placing a potential difference across the air gap under the piezoelectric layer 1610, between electrodes 1608 and 1644. In this mode, electrode 1606 may be either at the same potential as electrode 1608 or floating. In an alternate embodiment, the CMUT mode is actuated electrostatically by placing a potential difference between electrodes 1606 and 1644. In this mode, electrode 1608 may be either at the same potential as electrode 1606 or floating.

[0087] In the PMUT mode, the piezoelectric layer 1610 is actuated piezoelectrically by placing a potential difference across the piezoelectric layer 1610, between electrodes 1606 and 1608. In this mode, electrode 1644 may be either at the same potential as electrode 1606 or floating.

[0088] An embodiment of a method for operating an array of PMUT / CMUT dual-mode devices 1600 in an active operational mode is shown in FIG. 17. In the method 1700, a CMUT mode is selected 1705 by placing an AC voltage between the first and third electrodes 1606, 1644, where the second electrode 1608 is either the same potential as the first electrode 1606 or floating. Or, a PMUT mode is selected 1710 by placing an AC voltage between the first and second electrodes 1606, 1608, where the third electrode 1644 is either the same potential as the second electrode 1608 or floating, causing the device to produce a flexural mode of motion in the membrane. Devices in the array are selectively switched 1715 between the PMUT mode and the CMUT mode, wherein sensing can occur in either of the two modes.

[0089] FIG. 18 illustrates several example array configurations. The size of an array element is one of the design parameters to tune. In an embodiment, array 1800 is substantially comprised of PMUT devices, such as the element 1810 at row 1, column C. In this illustration, only the diaphragm shape is illustrated for clarity. Instead of a generally square PMUT device as shown in FIGs. 1A-1B or the circular PMUT device as shown in the array of FIG. 5, PMUT device 1810 is generally hexagonal. Other shapes and sizes could be used.

[0090] Embedded within array 1800 are alternative devices. Alternative devices 1820, 1830, 1840 and 1850 may be selected from differently configured PMUT devices, SAW devices, and CMUT devices, provided the material stack is compatible with the manufacture of PMUT device 1710. In this connection, various combinations of PMUT, SAW, and CMUT devices may be formed and operated.

[0091] The four shapes illustrated in alternative devices 1820, 1830, 1840 and 1850 permit tuning based on diaphragm size. It is also possible that the shape of alternative devices match PMUT device 1810. The shape of alternative devices may be pertinent to other effects, such as frequency selectivity for a SAW device. In control electronics (not shown), it would be possible to drive the alternative devices without disruption of the grid format. Device 1820 could be driven with control electronics for row 6, column B. Device 1850, which is a small triangle, could have its control electronics associated with row 3, column I, while device 1840 could have its control electronics associated with row 5, column I.

[0092] FIG. 19 illustrates in partial cross section one embodiment of an integrated sensor 1800 formed by wafer bonding a substrate 1940 of a CMOS logic wafer 1960 and a MEMS wafer 1970 defining PMUT devices having a common edge support 1902. PMUT device 1900 has a membrane 1920 formed over a substrate 1940 to define cavity 1930. The membrane 1920, primarily composed of silicon etched along its periphery to form a relatively compliant section, is attached both to a surrounding edge support 1902. The membrane 1920 is formed from multiple layers, including a piezoelectric layer 1910. The sensor includes an interior pinning support 1904.

[0093] As short summaries, this writing has disclosed at least the following broad concepts:

Concept 1. A Piezoelectric Micromachined Ultrasonic Transducer (PMUT) device comprising:

- a substrate;
- an edge support structure connected to the substrate;
- a membrane connected to the edge support structure such that a cavity is defined between the membrane and the substrate, the membrane configured to allow movement at ultrasonic frequencies, the membrane comprising:
 - a piezoelectric layer,
 - a first electrode coupled to one side of the piezoelectric layer, and
 - a second electrode coupled to an opposing side of the piezoelectric layer; and
- a third electrode disposed on the substrate and separated by an air gap in the cavity from the second electrode;

wherein the PMUT is configured to operate in a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode.

Concept 2. The PMUT device of Concept 1, further comprising an interior support structure disposed within the cavity and connected to the substrate and the membrane.

Concept 3. The PMUT device of Concept 2, wherein the second electrode extends into the cavity and defines an area between the edge support structure and the interior support structure.

Concept 4. The PMUT device of Concept 2, wherein at least one of the first electrode and the second electrode is electrically coupled through the interior support structure.

Concept 5. The PMUT device of Concept 1, the membrane further comprising: a mechanical support layer connected to the first electrode.

Concept 6. The PMUT device of Concept 1, wherein the piezoelectric layer defines a continuous layer.

Concept 7. The PMUT device of Concept 1, wherein the piezoelectric layer is a patterned layer.

Concept 8. The PMUT device of Concept 1, wherein the PMUT device is substantially circular such that the edge support structure and the membrane are substantially circular.

Concept 9. The PMUT device of Concept 1, wherein the PMUT device is substantially square-shaped such that the edge support structure and the membrane are substantially square-shaped.

Concept 10. The PMUT device of Concept 1, wherein the edge support structure is connected to an electric potential.

Concept 11. The PMUT device of Concept 1, wherein the substrate comprises a CMOS logic wafer.

Concept 12. The PMUT device of Concept 1, which is selectively switchable between the CMUT mode and an ultrasonic mode.

Concept 13. The PMUT device of Concept 12, wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and

wherein in the ultrasonic mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

Concept 14. An integrated MEMS array comprising: a plurality of MEMS Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) for transmitting ultrasonic beams and receiving ultrasonic signals;

wherein at least a portion of the PMUTs are operable in two modes, a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode and an ultrasonic mode.

Concept 15. The integrated MEMS array of Concept 14, wherein the plurality of MEMS PMUT elements and the MEMS CMUT elements comprise a piezoelectric layer of a same material.

Concept 16. The integrated MEMS array of Concept 15, wherein the piezoelectric layer comprises aluminum nitride.

Concept 17. The integrated MEMS array of Concept 16, wherein each of the plurality of MEMS PMUT elements is defined by an active membrane having first shape and a first size, and at least one other element is defined by an active membrane having a second shape and a second size, the first shape and the second shape being different but related by proportionality of the first size and the second size so that the integrated MEMS array is contiguous.

Concept 18. The integrated MEMS array of Concept 17, wherein the first shape is selected from a circle, an oval, a square, a rectangle, a hexagon, an octagon, or a chevron.

Concept 19. The integrated MEMS array of Concept 14 wherein each PMUT includes a first electrode disposed on one side of the piezoelectric layer, a second electrode disposed on an opposing side of the piezoelectric layer, and a third electrode disposed on a substrate opposite the second electrode and separated by an air space therefrom;

wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and

wherein in the ultrasonic mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

Concept 20. A method for operating an array of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode devices, each dual-mode device including a piezoelectric layer, a first electrode disposed on one side of the piezoelectric layer, a second electrode disposed on an opposing side of the piezoelectric layer, and a third electrode disposed on a substrate opposite the second electrode and separated by an air space therefrom, the method comprising:

selecting a CMUT mode by placing an AC voltage between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; or

selecting a PMUT mode by placing an AC voltage between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane; and

selectively switching between the PMUT mode and the CMUT mode, wherein sensing can occur in either of the two modes.

Concept 21. The method of Concept 20, wherein the array includes heterogeneous elements, in which some elements are configured for performance in the PMUT mode and other elements are configured for performance in the CMUT mode.

Concept 22. A Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode device, comprising:

a substrate;

an edge support structure connected to the substrate; and

a membrane connected to the edge support structure such that a cavity is defined between the membrane and the substrate, the membrane configured to allow movement at ultrasonic frequencies, the membrane comprising:

- a piezoelectric layer,
- a first electrode coupled to one side of the piezoelectric layer, and
- a second electrode coupled to an opposing side of the piezoelectric layer; and
- a third electrode disposed on the substrate opposite the second electrode in the cavity;

wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and

wherein in the PMUT mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

Concept 23. An array of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode devices, the array comprising a plurality of the PMUT / CMUT dual-mode devices of Concept 22.

[0094] What has been described above includes examples of the subject disclosure. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the subject matter, but it is to be appreciated that many further combinations and permutations of the subject disclosure are possible. Accordingly, the claimed subject matter is intended to embrace all such alterations, modifications, and variations that fall within the spirit and scope of the appended claims.

[0095] In particular and in regard to the various functions performed by the above described components, devices, circuits, systems and the like, the terms (including a reference to a “means”) used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (e.g., a functional equivalent), even though not structurally equivalent to the disclosed structure, which performs the function in the herein illustrated exemplary aspects of the claimed subject matter.

[0096] The aforementioned systems and components have been described with respect to interaction between several components. It can be appreciated that such systems and components can include those components or specified sub-components, some of the specified components or sub-components, and/or additional components, and according to various permutations and combinations of the foregoing. Sub-components can also be implemented as components communicatively coupled to other components rather than included within parent

components (hierarchical). Additionally, it should be noted that one or more components may be combined into a single component providing aggregate functionality or divided into several separate sub-components. Any components described herein may also interact with one or more other components not specifically described herein.

[0097] In addition, while a particular feature of the subject innovation may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. Furthermore, to the extent that the terms “includes,” “including,” “has,” “contains,” variants thereof, and other similar words are used in either the detailed description or the claims, these terms are intended to be inclusive in a manner similar to the term “comprising” as an open transition word without precluding any additional or other elements.

[0098] Thus, the embodiments and examples set forth herein were presented in order to best explain various selected embodiments of the present invention and its particular application and to thereby enable those skilled in the art to make and use embodiments of the invention. However, those skilled in the art will recognize that the foregoing description and examples have been presented for the purposes of illustration and example only. The description as set forth is not intended to be exhaustive or to limit the embodiments of the invention to the precise form disclosed.

CLAIMS

What is claimed is:

1. A Piezoelectric Micromachined Ultrasonic Transducer (PMUT) device comprising:
 - a substrate;
 - an edge support structure connected to the substrate;
 - a membrane connected to the edge support structure such that a cavity is defined between the membrane and the substrate, the membrane configured to allow movement at ultrasonic frequencies, the membrane comprising:
 - a piezoelectric layer,
 - a first electrode coupled to one side of the piezoelectric layer, and
 - a second electrode coupled to an opposing side of the piezoelectric layer; and
 - a third electrode disposed on the substrate and separated by an air gap in the cavity from the second electrode;wherein the PMUT is configured to operate in a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode.
2. The PMUT device of claim 1, further comprising an interior support structure disposed within the cavity and connected to the substrate and the membrane.
3. The PMUT device of claim 2, wherein the second electrode extends into the cavity and defines an area between the edge support structure and the interior support structure.
4. The PMUT device of claim 2, wherein at least one of the first electrode and the second electrode is electrically coupled through the interior support structure.
5. The PMUT device of claim 1, the membrane further comprising:
 - a mechanical support layer connected to the first electrode.
6. The PMUT device of claim 1, wherein the piezoelectric layer defines a continuous layer.
7. The PMUT device of claim 1, wherein the piezoelectric layer is a patterned layer.
8. The PMUT device of claim 1, wherein the PMUT device is substantially circular such that the edge support structure and the membrane are substantially circular.

9. The PMUT device of claim 1, wherein the PMUT device is substantially square-shaped such that the edge support structure and the membrane are substantially square-shaped.

10. The PMUT device of claim 1, wherein the edge support structure is connected to an electric potential.

11. The PMUT device of claim 1, wherein the substrate comprises a CMOS logic wafer.

12. The PMUT device of claim 1, which is selectively switchable between the CMUT mode and an ultrasonic mode.

13. The PMUT device of claim 12,
wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and

wherein in the ultrasonic mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

14. An integrated MEMS array comprising:
a plurality of MEMS Piezoelectric Micromachined Ultrasonic Transducers (PMUTs) for transmitting ultrasonic beams and receiving ultrasonic signals;
wherein at least a portion of the PMUTs are operable in two modes, a Capacitive Micromachined Ultrasonic Transducer (CMUT) mode and an ultrasonic mode.

15. The integrated MEMS array of claim 14, wherein the plurality of MEMS PMUT elements and the MEMS CMUT elements comprise a piezoelectric layer of a same material.

16. The integrated MEMS array of claim 15, wherein the piezoelectric layer comprises aluminum nitride.

17. The integrated MEMS array of claim 16, wherein each of the plurality of MEMS PMUT elements is defined by an active membrane having first shape and a first size, and at least one other element is defined by an active membrane having a second shape and a

second size, the first shape and the second shape being different but related by proportionality of the first size and the second size so that the integrated MEMS array is contiguous.

18. The integrated MEMS array of claim 17, wherein the first shape is selected from a circle, an oval, a square, a rectangle, a hexagon, an octagon, or a chevron.

19. The integrated MEMS array of claim 14 wherein each PMUT includes a first electrode disposed on one side of the piezoelectric layer, a second electrode disposed on an opposing side of the piezoelectric layer, and a third electrode disposed on a substrate opposite the second electrode and separated by an air space therefrom;

wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and

wherein in the ultrasonic mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

20. A method for operating an array of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode devices, each dual-mode device including a piezoelectric layer, a first electrode disposed on one side of the piezoelectric layer, a second electrode disposed on an opposing side of the piezoelectric layer, and a third electrode disposed on a substrate opposite the second electrode and separated by an air space therefrom, the method comprising:

selecting a CMUT mode by placing an AC voltage between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; or

selecting a PMUT mode by placing an AC voltage between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane; and

selectively switching between the PMUT mode and the CMUT mode, wherein sensing can occur in either of the two modes.

21. The method of claim 20, wherein the array includes heterogeneous elements, in which some elements are configured for performance in the PMUT mode and other elements are configured for performance in the CMUT mode.

22. A Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode device, comprising:

a substrate;

an edge support structure connected to the substrate; and
a membrane connected to the edge support structure such that a cavity is defined between the membrane and the substrate, the membrane configured to allow movement at ultrasonic frequencies, the membrane comprising:
a piezoelectric layer,
a first electrode coupled to one side of the piezoelectric layer, and
a second electrode coupled to an opposing side of the piezoelectric layer; and
a third electrode disposed on the substrate opposite the second electrode in the cavity;
wherein in the CMUT mode, an AC voltage is placed between the first and third electrodes, where the second electrode is either the same potential as the first electrode or floating; and
wherein in the PMUT mode, an AC voltage is placed between the first and second electrodes, where the third electrode is either the same potential as the second electrode or floating, causing the device to produce a flexural mode of motion in the membrane.

23. An array of Piezoelectric Micromachined Ultrasonic Transducer (PMUT) / Capacitive Micromachined Ultrasonic Transducer (CMUT) dual-mode devices, the array comprising a plurality of the PMUT / CMUT dual-mode devices of claim 22.

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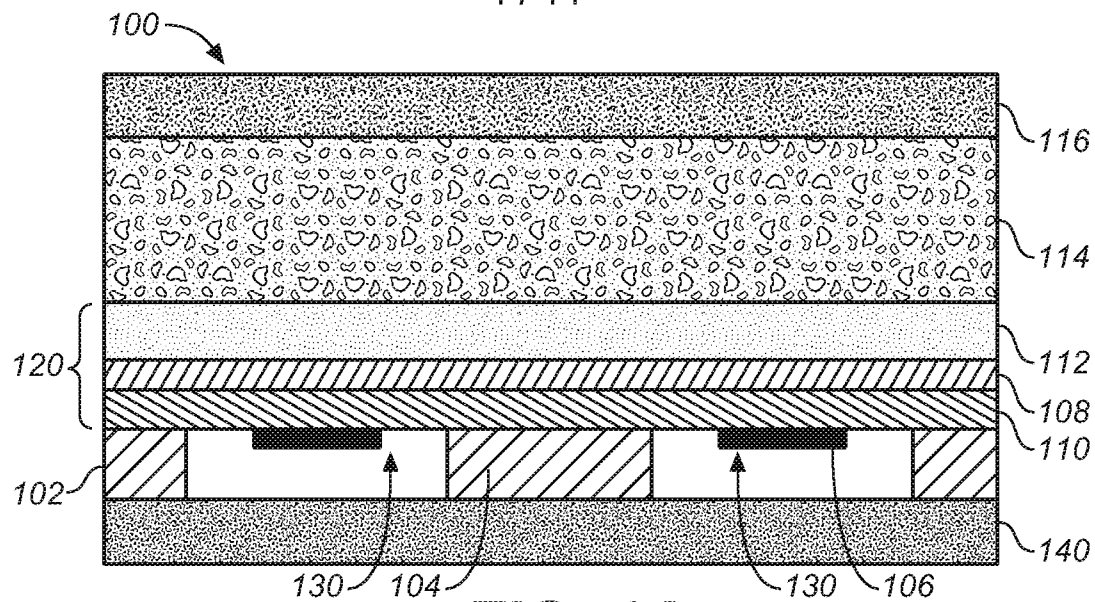


FIG. 1A

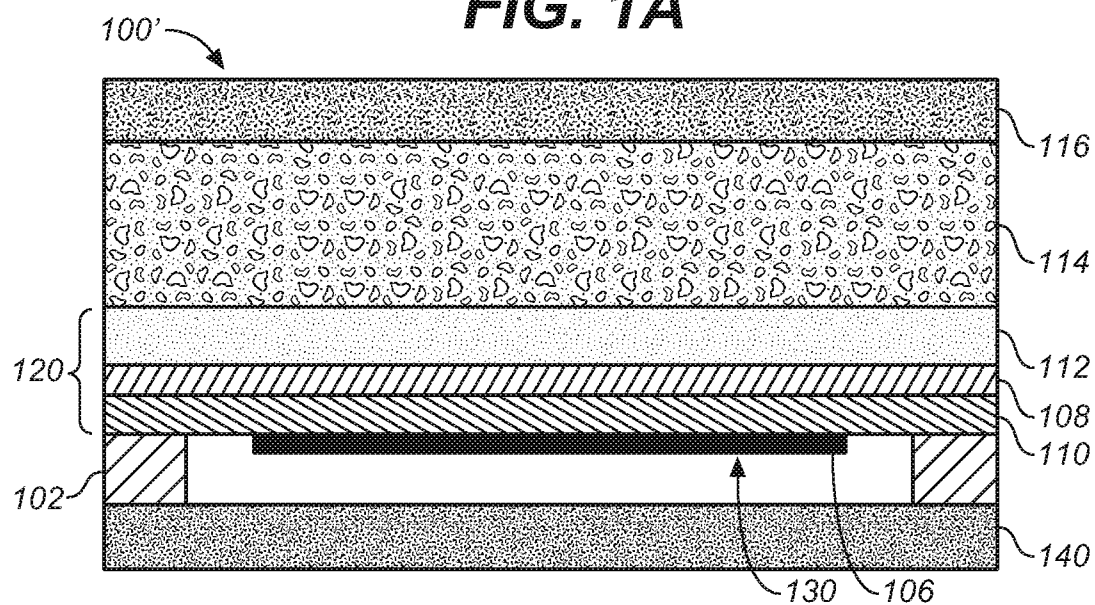


FIG. 1B

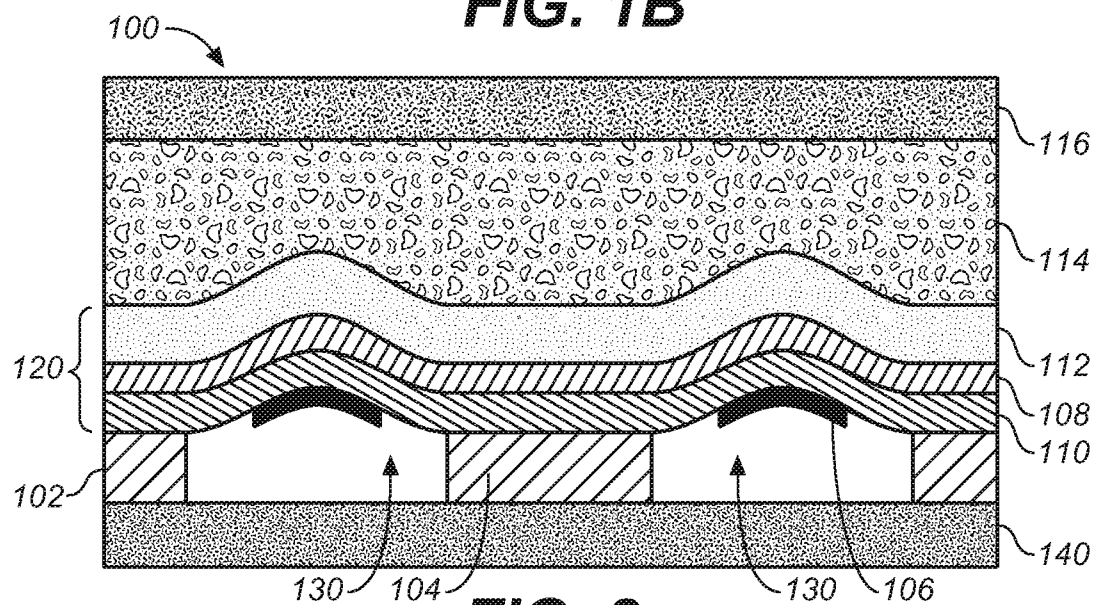
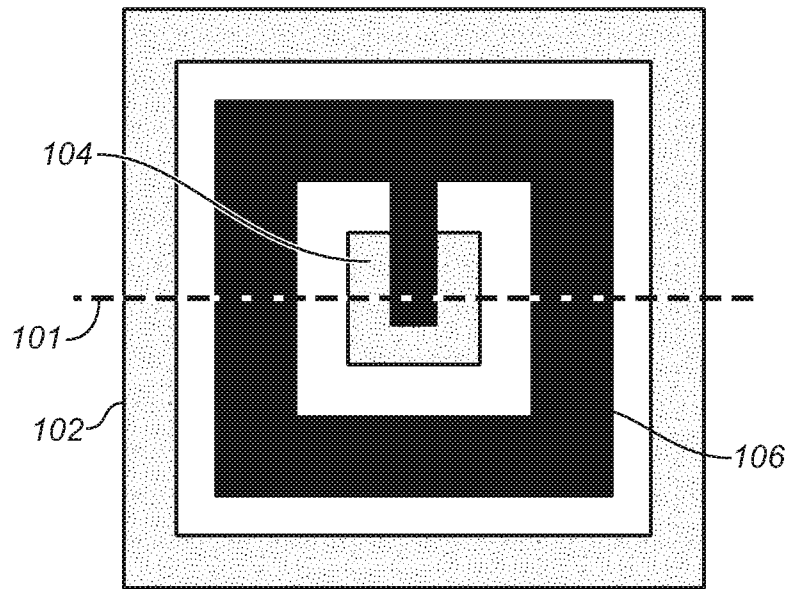
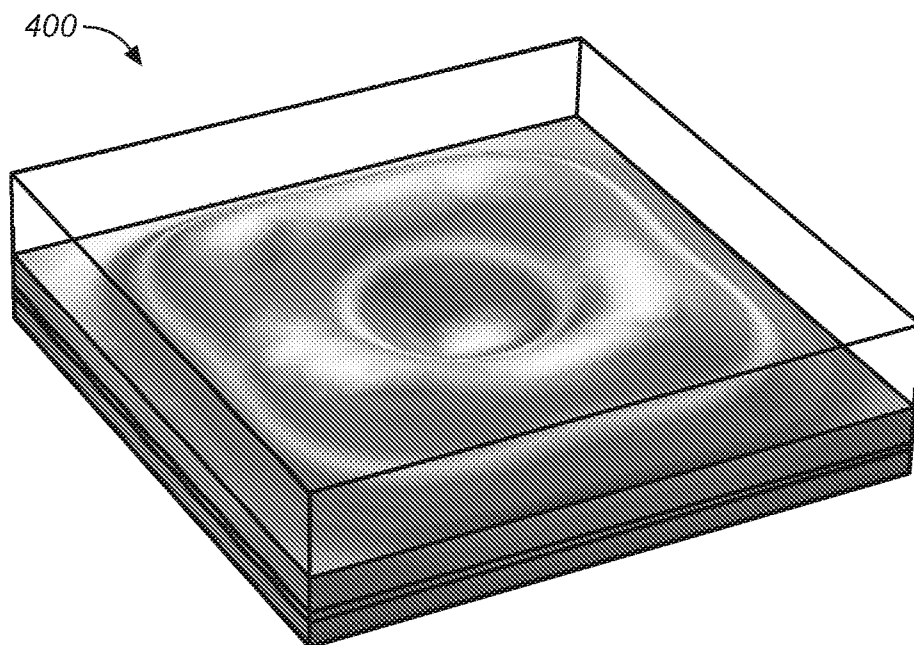


FIG. 2

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**FIG. 3****FIG. 4**

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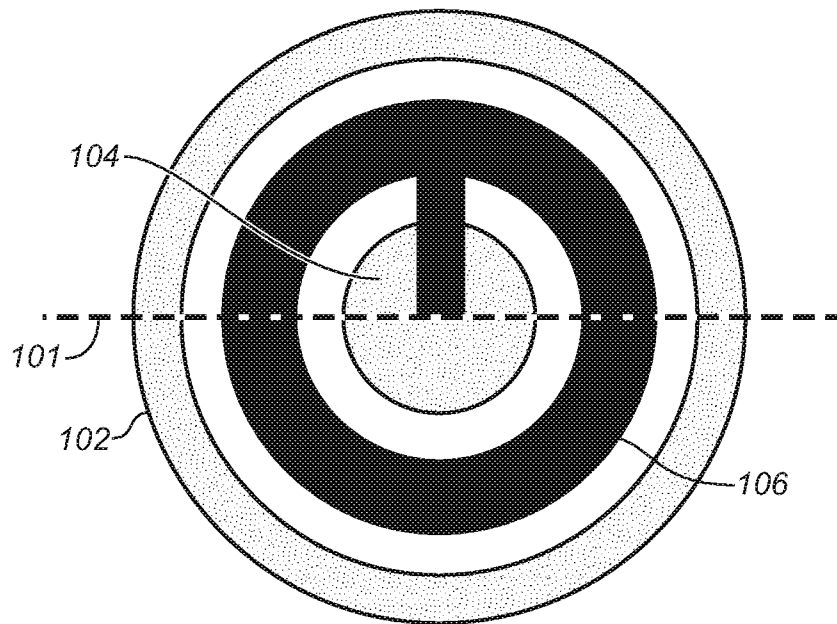


FIG. 5

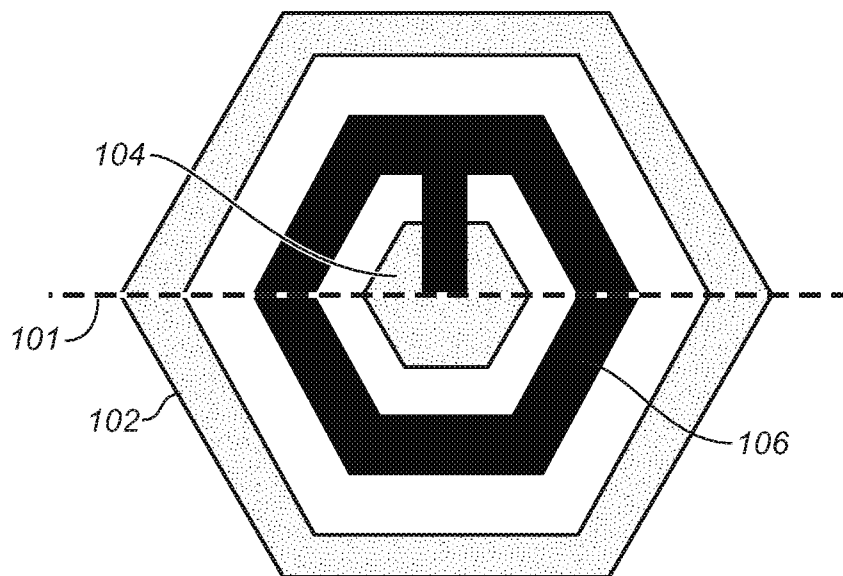
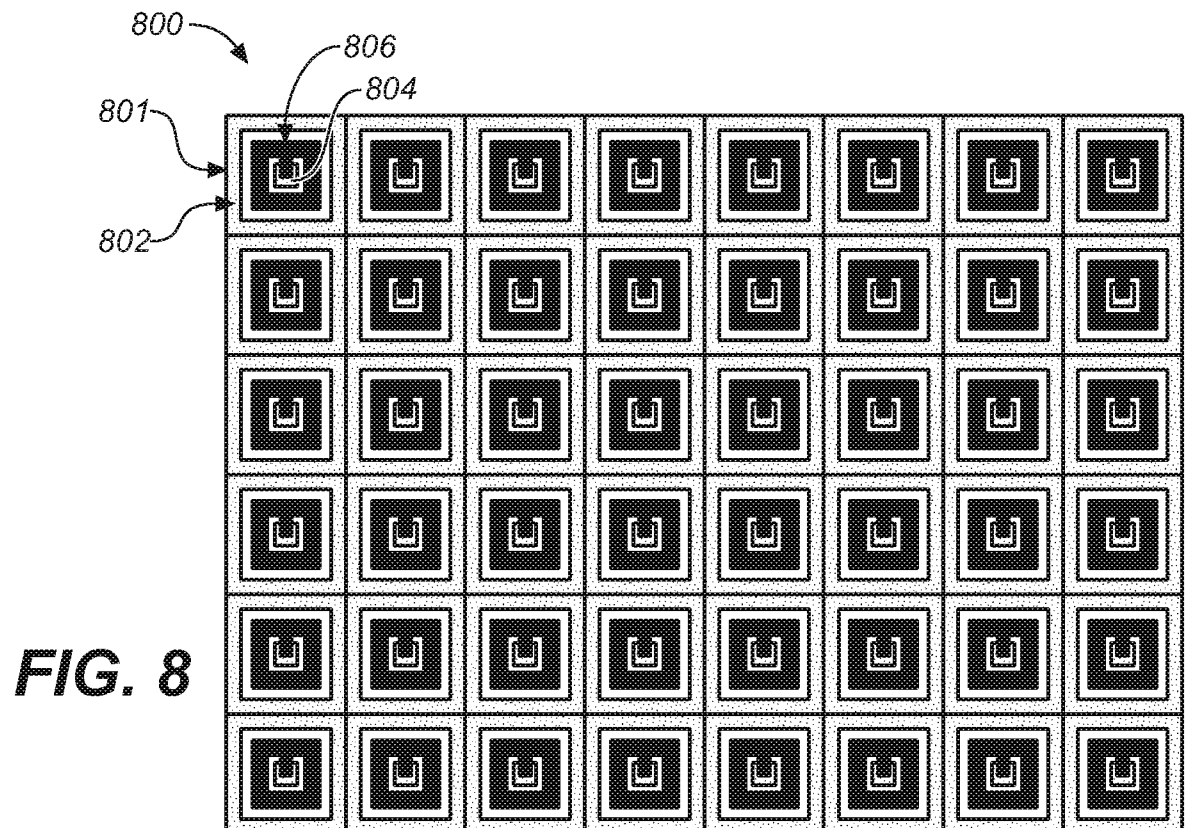
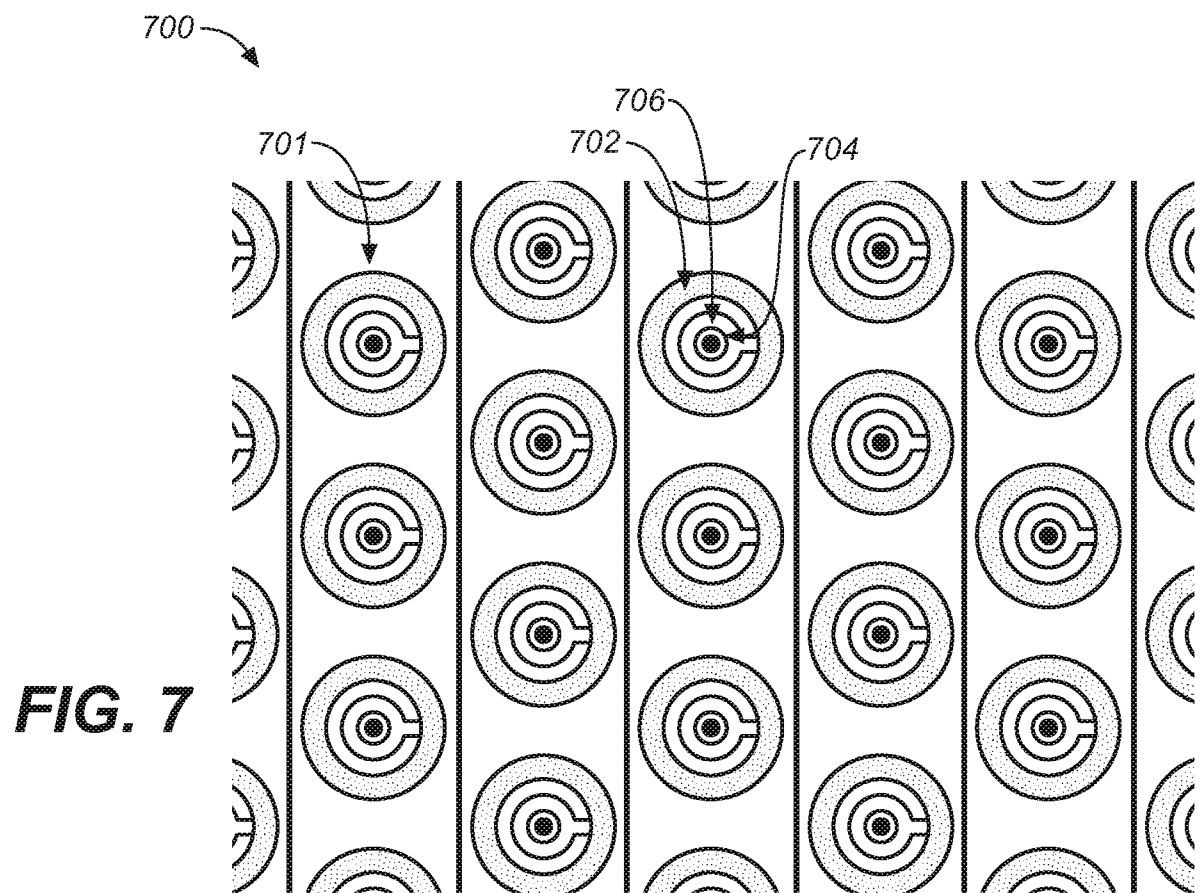
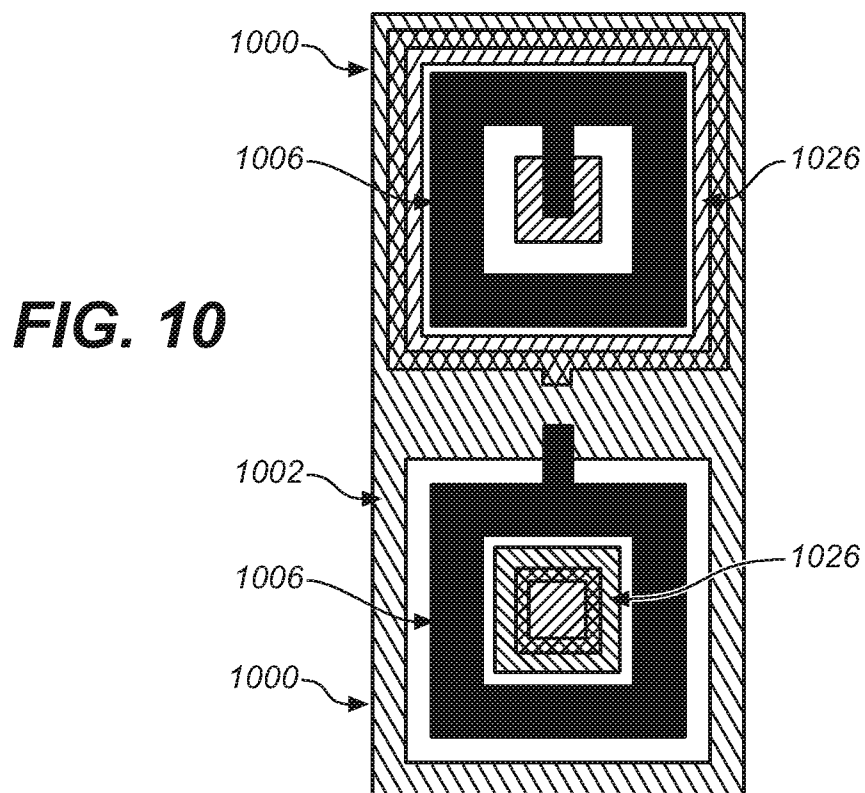
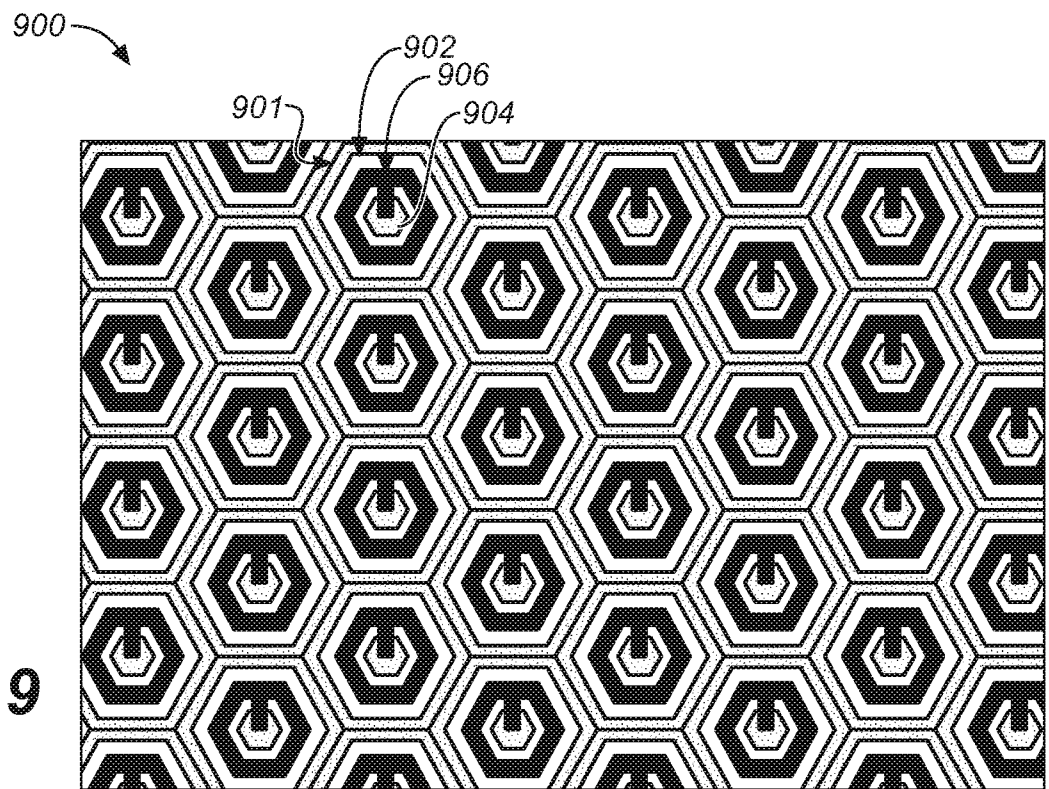
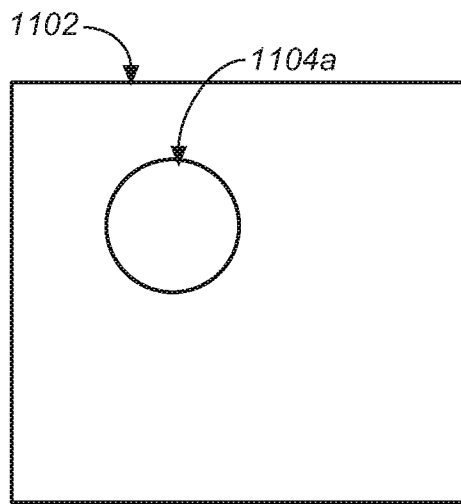
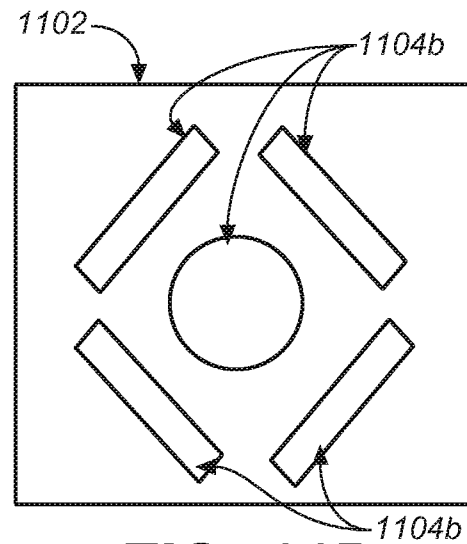
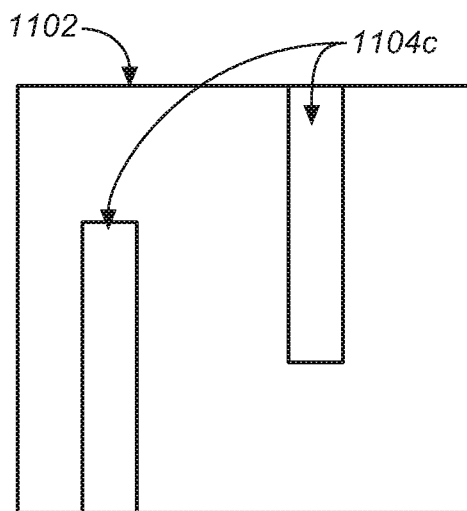
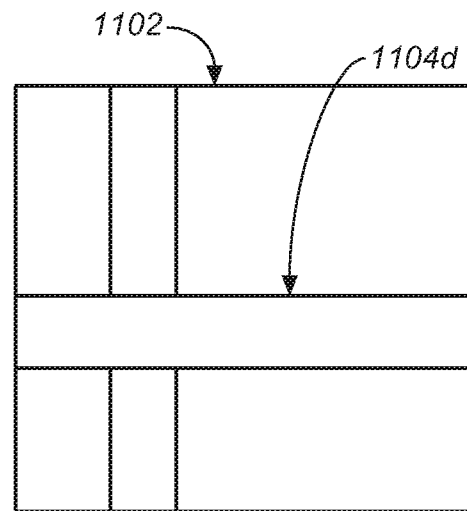


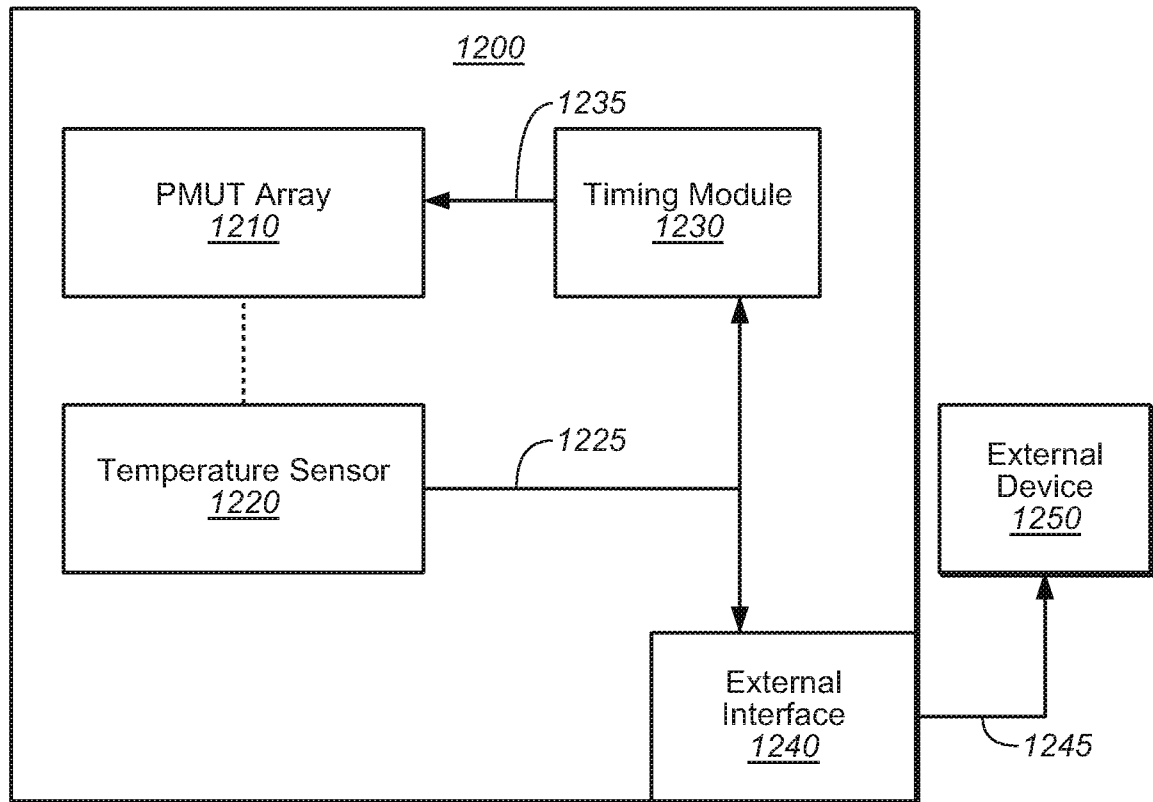
FIG. 6





**FIG. 11A****FIG. 11B****FIG. 11C****FIG. 11D**

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**FIG. 12**

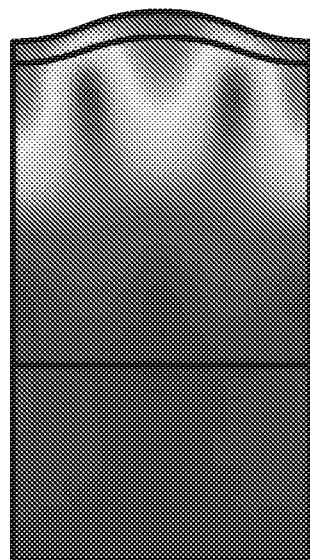
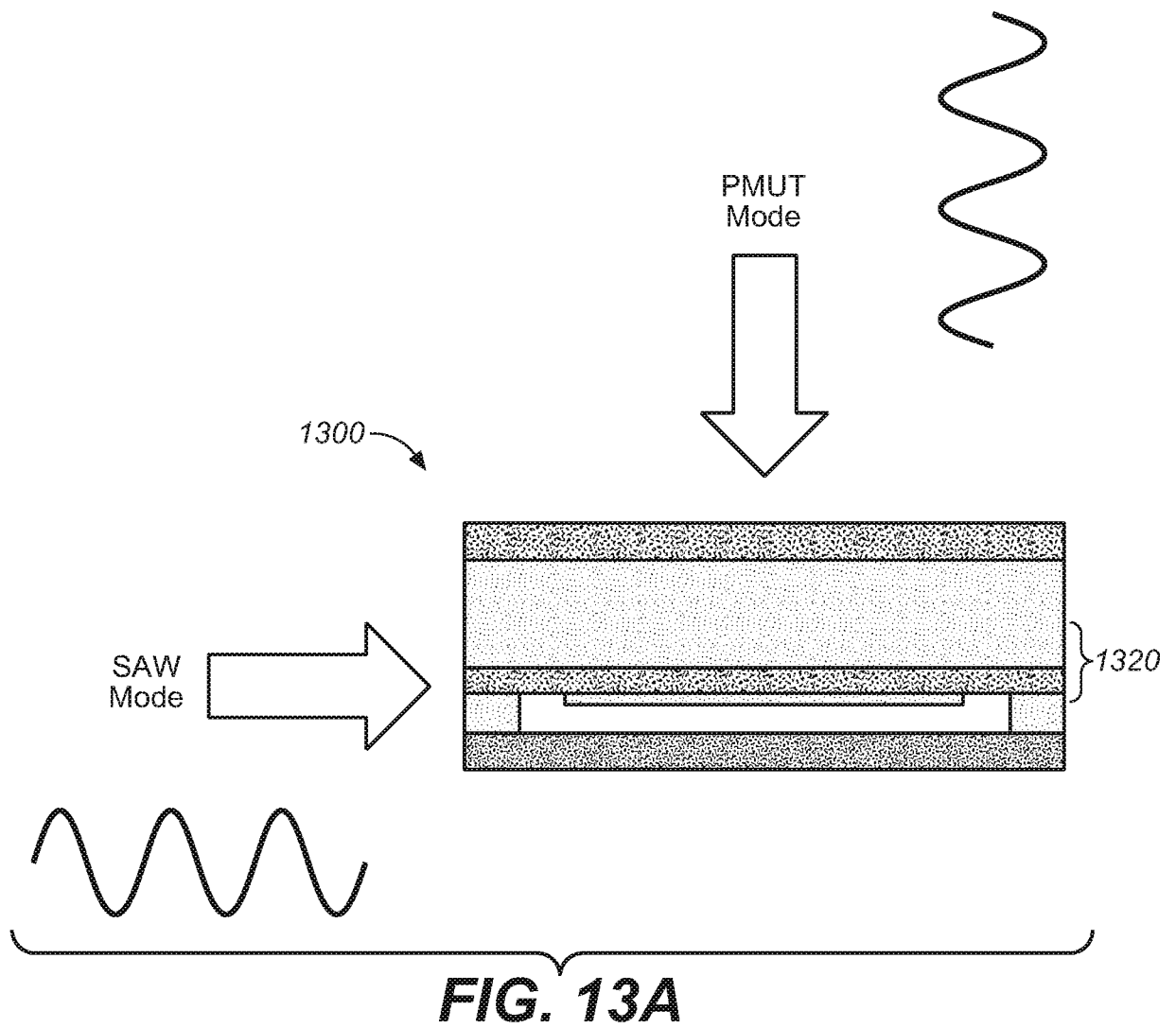


FIG. 13B

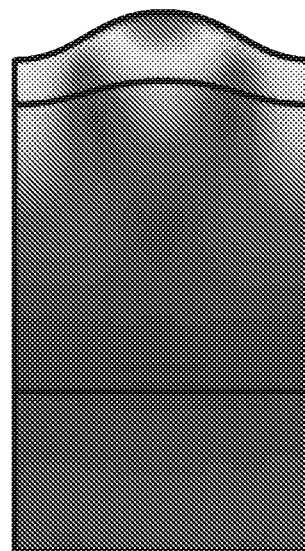


FIG. 13C

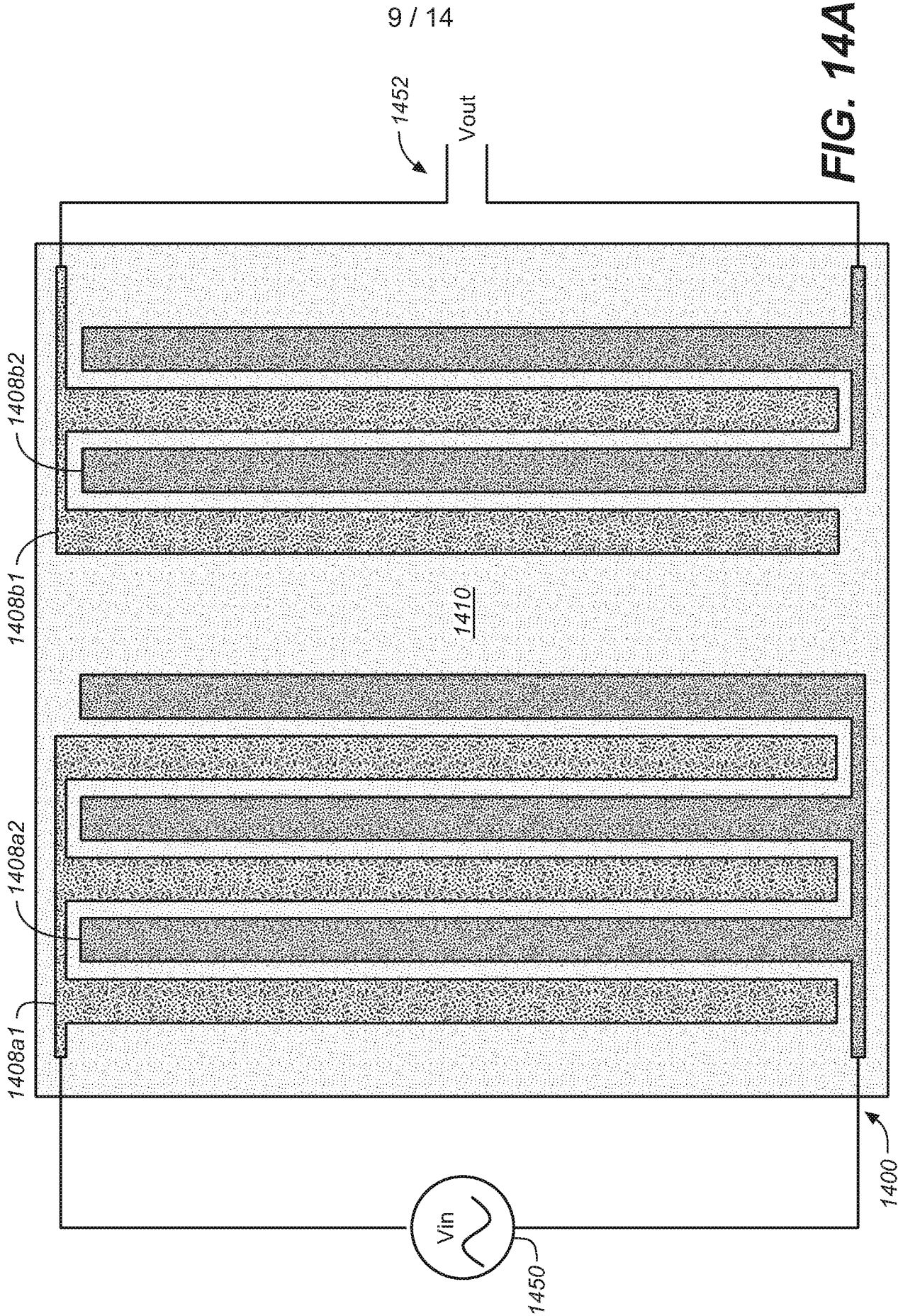


FIG. 14A

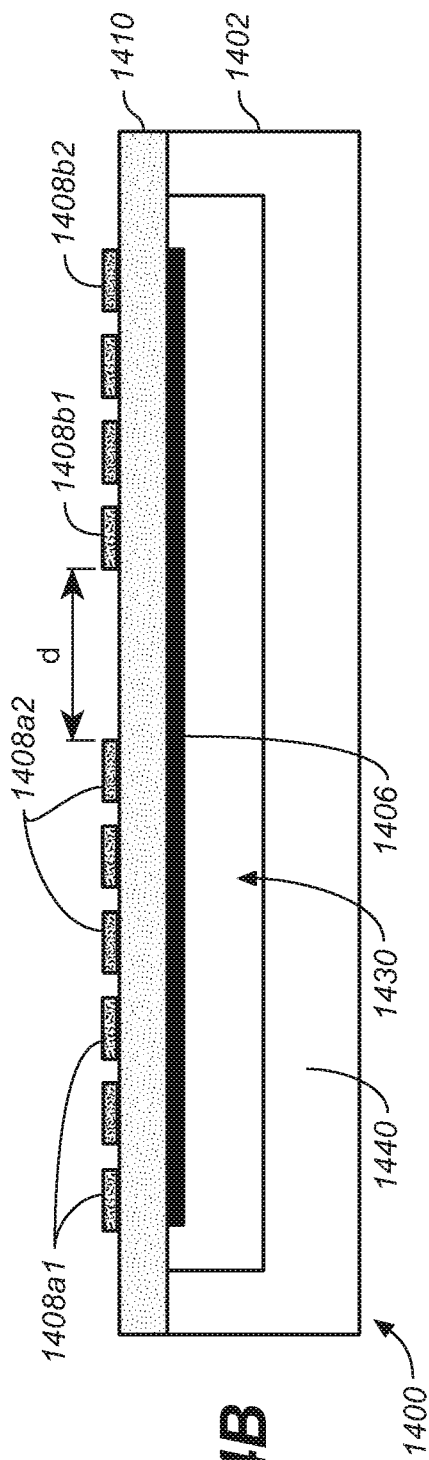


FIG. 14B

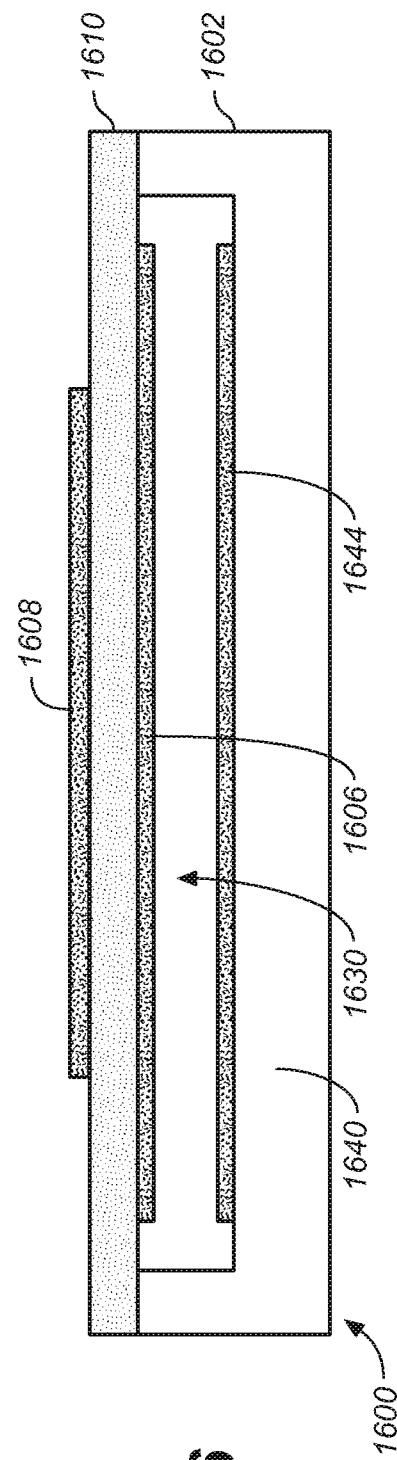


FIG. 16

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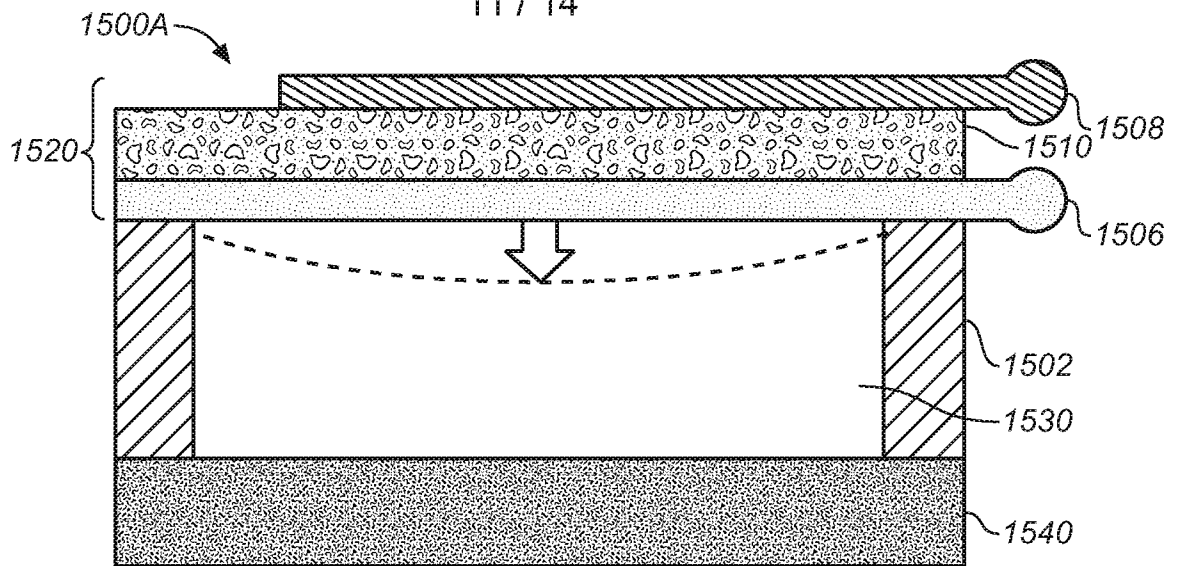


FIG. 15A

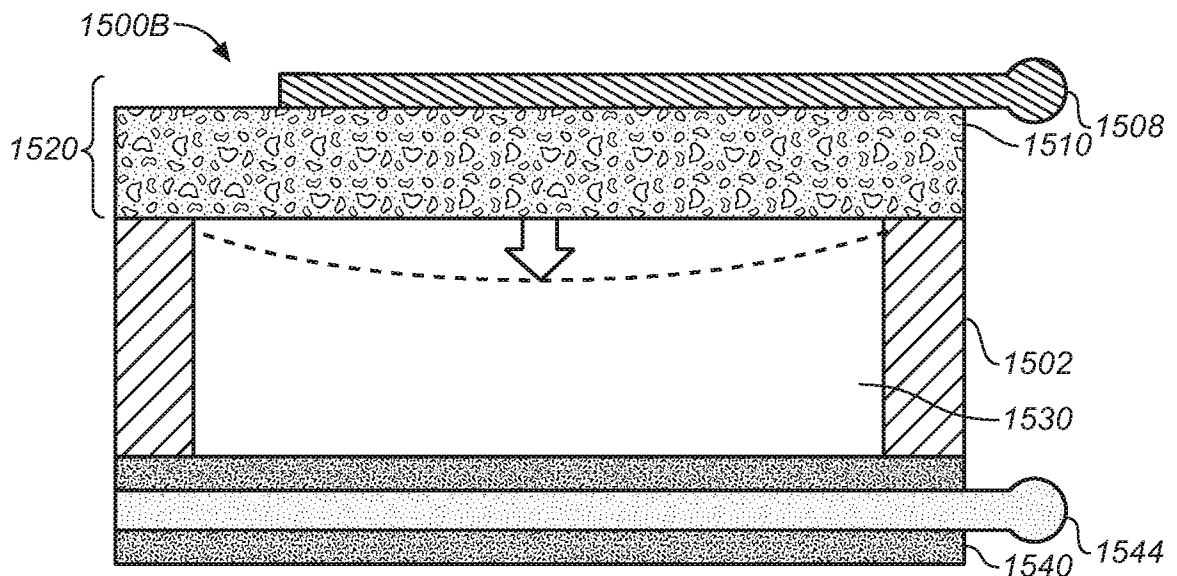


FIG. 15B

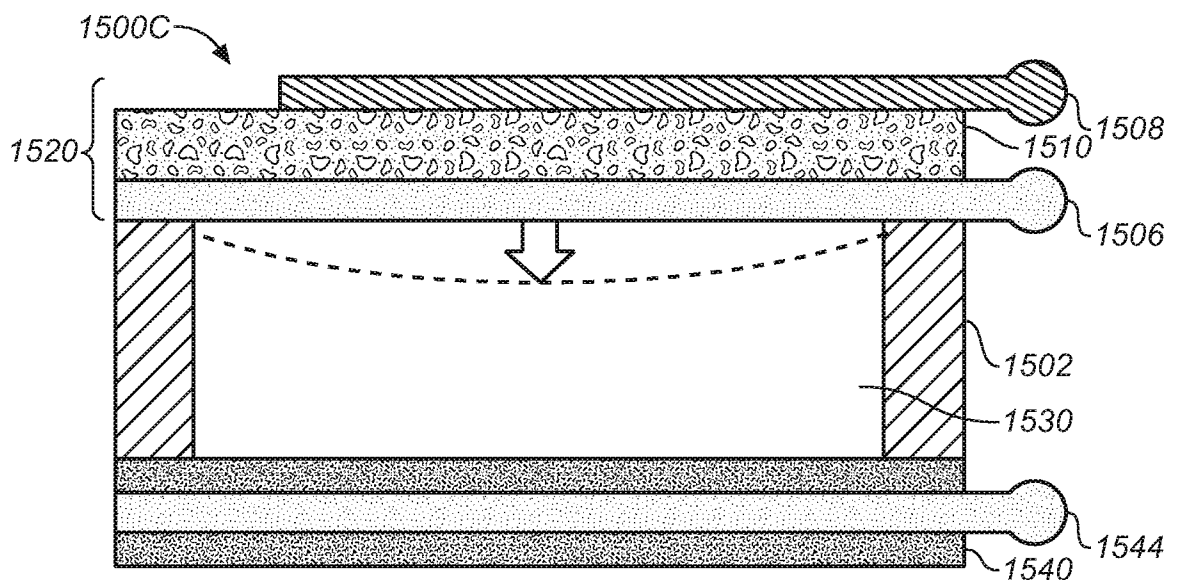
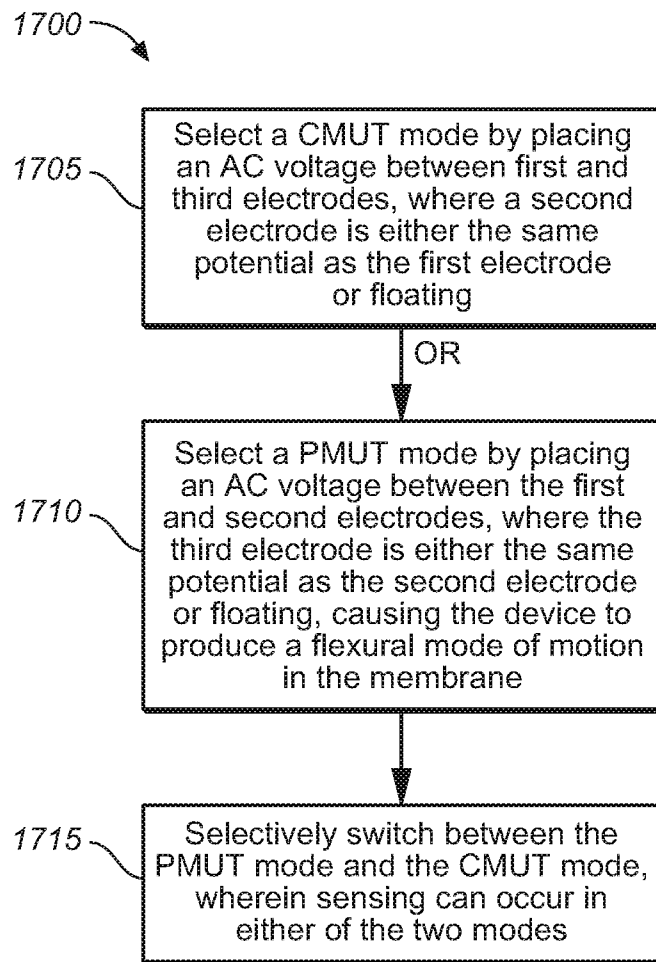


FIG. 15C

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**FIG. 17**

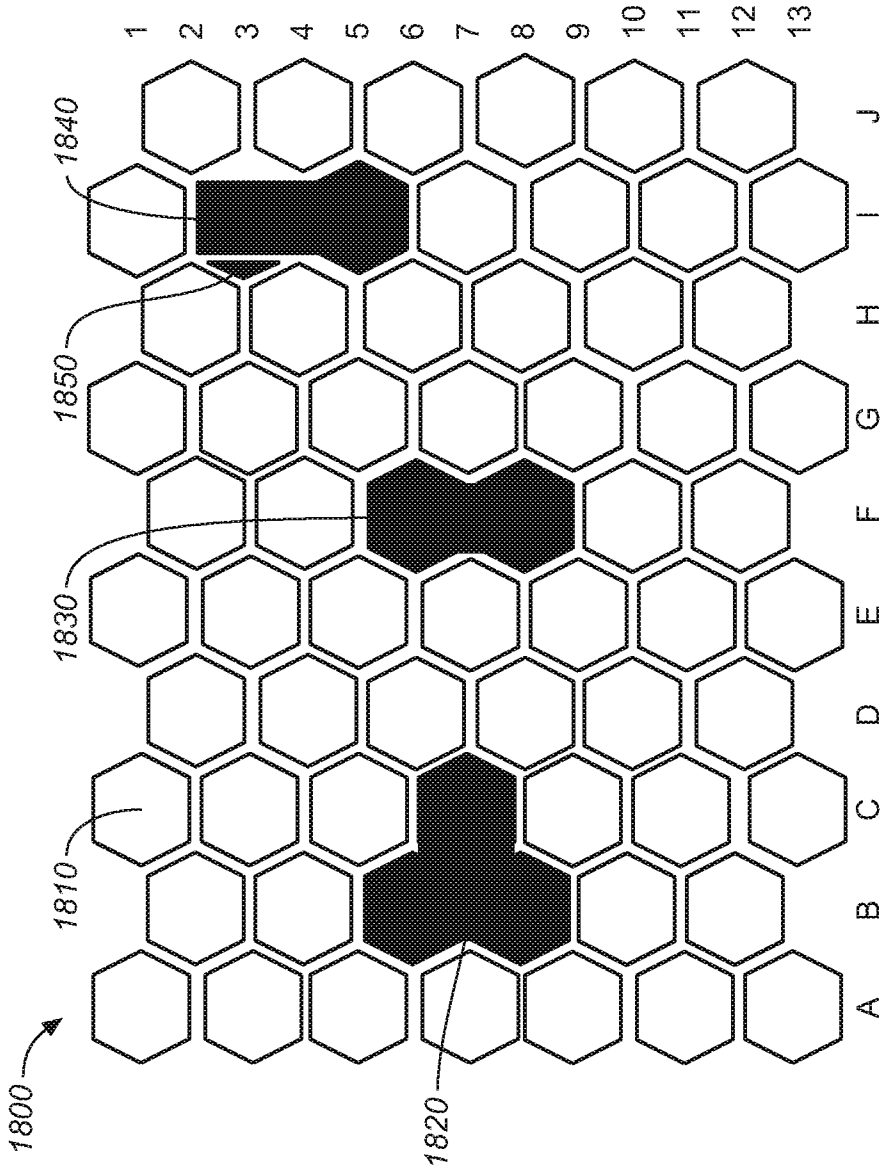


FIG. 18

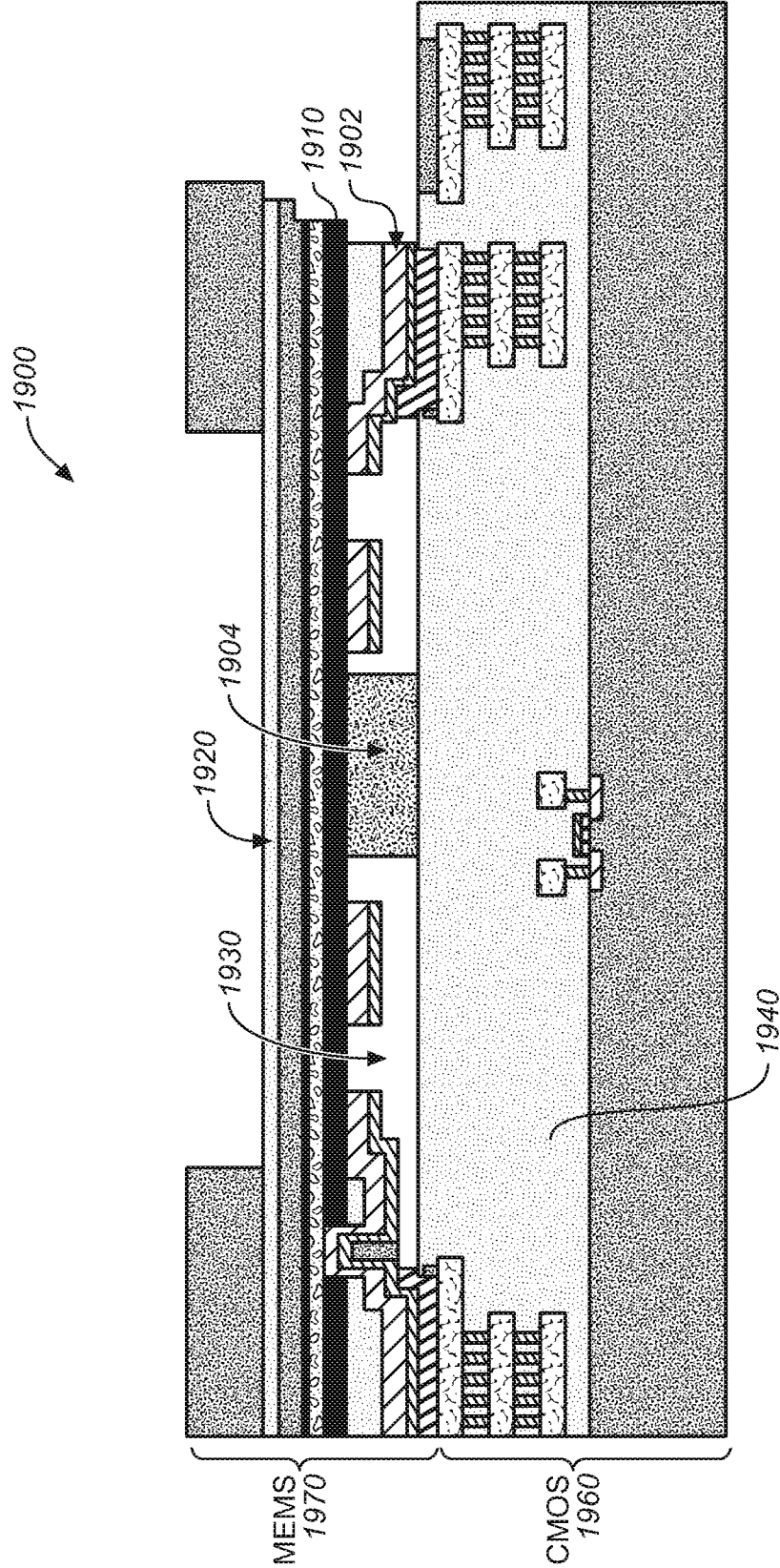


FIG. 19

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2017/031421

A. CLASSIFICATION OF SUBJECT MATTER
 INV. B06B1/02 B06B1/06
 ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 B06B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/201222 A1 (ADACHI HIDEO [JP] ET AL) 12 August 2010 (2010-08-12)	1,2,4-8, 10-12, 14-16
Y	paragraphs [0004], [0008], [0081] -	9
A	[0089], [0091], [0095] - [0097], [0102] - [0120], [0127], [0134], [0135], [0161], [0181] - [0190]; figures 1,3,5,6,7,8,12	3,13, 17-23
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A	US 2005/162040 A1 (ROBERT PHILIPPE [FR]) 28 July 2005 (2005-07-28) paragraphs [0041] - [0045], [0065] - [0069]; figure 1	1-23
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Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

12 June 2017

Date of mailing of the international search report

21/06/2017

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INTERNATIONAL SEARCH REPORT

International application No

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	paragraphs [0045], [0047], [0054], [0056], [0057], [0059], [0061]; figures 1-2D, 6A, 8A-8H	17
A	----- US 2013/294202 A1 (HAJATI ARMAN [US]) 7 November 2013 (2013-11-07) paragraphs [0002], [0025] - [0027], [0029], [0031]; figure 1A -----	17

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International application No

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