

PIEZOELECTRIC DEVICE AND METHOD OF FORMING THE SAME**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the benefit of priority of Singapore application No. 10202302726Q filed September 26, 2023, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of this disclosure may relate to a piezoelectric device. Various embodiments of this disclosure may relate to a method of forming a piezoelectric device.

BACKGROUND

[0003] Conventional micro-electromechanical systems (MEMS) piezoelectric acoustic devices, such as piezoelectric micromachined ultrasonic transducers (PMUTs), microphones and micro-speakers are based on the bending motion of a piezoelectric film coupled with an elastic layer (also known as unimorph structure), which is necessary to cause different amounts of strains against the active piezoelectric layer during the operation. In the piezoelectric unimorph structure, the elastic layer is mechanically passive and works as an effective load for both actuation and sensing, as shown in FIG. 1A. FIG. 1A shows a cross-sectional schematic of a conventional unimorph piezoelectric device. Bimorph structures made up of two piezoelectric layers with anti-phase operation were also reported. However, such bimorph structures necessarily increase the complexity of integration (multi-stack deposition and etch) and typically have more interconnections to address or read electrical signals to the different electrode layers in the stack, as shown in FIG. 1B. FIG. 1B shows a cross-sectional schematic of a conventional bimorph piezoelectric device. In piezoelectric bimorph structures, the

positioning of the neutral axis may be of critical importance for achieving the desired bending motion. If the neutral axis falls within the piezoelectric layer, the lower and upper portions of the lead zirconate titanate (PZT) work in opposite to each other, leading to a drastic decline in performance. Attaining an appropriate neutral axis for the bimorph structure may prove to be an exceedingly challenging task, particularly when employing thin film processes.

[0004] Piezoelectric thin films (including materials such as PZT, scandium aluminum nitride (ScAlN)) may also be particularly challenging to etch using reactive ion etching (RIE) as they are chemically inert and mechanically hard. In addition, dedicated materials (e.g., platinum (Pt), molybdenum (Mo) or lithium nickel oxide (LNO)) may be required for electrodes of piezoelectric stacks. These dedicated materials typically form very stubborn etch by-products, and require a longer etch time with poor uniformity and selectivity compared to other thin film materials. FIG. 2A shows scanning electron microscopy (SEM) images of an etch by-product of lead zirconate titanate (PZT) etching. FIG. 2B shows scanning electron microscopy (SEM) images illustrating the irregular edge patterns formed from lead zirconate titanate (PZT) etching. In addition, a pullback etch may be required to minimize the etch by-product, which leads to poor pattern definition. FIG. 2C shows a scanning electron microscopy (SEM) image illustrating the sloped side wall of lead zirconate titanate (PZT) stack due to the pullback etch to minimize the etch by-product. Further, the dedicated materials may require dry and wet removal processes after etching. In addition, frequent process tool maintenance may be required to clean the process kits and process chambers.

SUMMARY

[0005] Various embodiments may relate to a piezoelectric device. The piezoelectric device may include a substrate at least partially defining a cavity. The piezoelectric device may also include a piezoelectric stacked arrangement with a step portion over the cavity and an outer

portion adjoining the step portion. The piezoelectric stacked arrangement may include a continuous piezoelectric layer. The piezoelectric stacked arrangement may also include a continuous first electrode layer in contact with a first surface of the piezoelectric layer. The first electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement. The piezoelectric stacked arrangement may further include a continuous second electrode layer in contact with a second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer. The second electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement.

[0006] Various embodiments may relate to a method of forming a piezoelectric device. The method may include forming a cavity in a substrate such that the substrate at least partially defines the cavity. The method may also include forming a piezoelectric stacked arrangement with a step portion over the cavity and an outer portion adjoining the step portion. The piezoelectric stacked arrangement may also include a continuous first electrode layer in contact with a first surface of the piezoelectric layer. The first electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement. The piezoelectric stacked arrangement may further include a continuous second electrode layer in contact with a second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer. The second electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1A shows a cross-sectional schematic of a conventional unimorph piezoelectric device.

FIG. 1B shows a cross-sectional schematic of a conventional bimorph piezoelectric device.

FIG. 2A shows scanning electron microscopy (SEM) images of an etch by-product of lead zirconate titanate (PZT) etching.

FIG. 2B shows scanning electron microscopy (SEM) images illustrating the irregular edge patterns formed from lead zirconate titanate (PZT) etching.

FIG. 2C shows a scanning electron microscopy (SEM) image illustrating the sloped side wall of lead zirconate titanate (PZT) stack due to the pullback etch to minimize the etch by-product.

FIG. 3A shows a cross-sectional schematic of a first piezoelectric device according to various embodiments.

FIG. 3B shows a cross-sectional schematic of a second piezoelectric device according to various other embodiments.

FIG. 3C shows a cross-sectional schematic of a third piezoelectric device according to yet various other embodiments.

FIG. 3D shows a cross-sectional schematic of a fourth piezoelectric device according to further various other embodiments.

FIG. 3E shows a cross-sectional schematic of a fifth piezoelectric device according to additional various other embodiments.

FIG. 3F shows a cross-sectional schematic of a sixth piezoelectric device according to various other embodiments.

FIG. 3G shows a cross-sectional schematic of a seventh piezoelectric device according to yet various other embodiments.

FIG. 3H shows a cross-sectional schematic of an eighth piezoelectric device according to further various other embodiments.

FIG. 3I shows a cross-sectional schematic of a ninth piezoelectric device according to additional various other embodiments.

FIG. 3J shows a cross-sectional schematic of a tenth piezoelectric device according to various other embodiments.

FIG. 3K shows a cross-sectional schematic of an eleventh piezoelectric device according to yet various other embodiments.

FIG. 4A shows a general illustration of a method of forming a piezoelectric device according to various embodiments.

FIG. 4B shows a process flow of forming a piezoelectric device according to various embodiments.

FIG. 5 shows cross-sectional schematics of piezoelectric devices according to various embodiments.

FIG. 6 shows (a) a cross-sectional schematic of a transmitter based on the piezoelectric device according to various embodiments; and (b) a cross-sectional schematic of a receiver based on the piezoelectric device according to various embodiments.

FIG. 7A shows the first four vibration mode-shapes of a circular quasi-bimorph piezoelectric device according to various embodiments. The different shadings represent the relative amplitude of motion.

FIG. 7B illustrates the operation of a quasi-bimorph piezoelectric device in different phases when applying alternating current (AC) driving voltage according to various embodiments.

FIG. 7C illustrates the operation of a conventional bimorph structure.

FIG. 8A shows a plot of peak-peak displacement magnitude (in micrometers or μm) as a function of step height (in micrometers or μm) illustrating the variation of the peak-to-peak displacements of the stacked arrangements having piezoelectric layers with different thicknesses (i.e., 2 μm and 4 μm) according to various embodiments with step height at resonance when a unit alternating current (AC) is applied, with the inset showing a cross-sectional schematic of a portion of a stacked arrangement to illustrate the step height.

FIG. 8B shows a table illustrating the peak-to-peak displacements of the stacked arrangements having piezoelectric layers with different thicknesses (i.e., 2 μm and 4 μm) according to various embodiments at different step heights.

FIG. 9A shows a plot of peak-to-peak (PkPk) displacement (in micrometers or μm) as a function of frequency (in Mega-Hertz or MHz) illustrating the displacement frequency response function of the piezoelectric device according to various embodiments with a step height of zero.

FIG. 9B is a three-dimensional (3D) plot of z (in micrometers or μm) as a function of x (in micrometers or μm) and y (in micrometers or μm) illustrating the contour of the membrane portion of the piezoelectric device according to various embodiments at the resonance frequency of 1.07 MHz.

FIG. 9C illustrates the Butterworth-Van Dyke (BVD) model for lumped parameter extraction according to various embodiments.

FIG. 9D shows a plot of admittance (in siemens or S) as a function of frequency (in kilo-Hertz or kHz) illustrating the lumped parameter extraction using the Butterworth-Van Dyke (BVD) model curve fitting for a piezoelectric device according to various embodiments with zero step height.

FIG. 10A shows a plot of piezoelectric coupling coefficient k_t^2 (in percent or %) as a function of step height (in micrometers or μm) illustrating the variation of k_t^2 with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments.

FIG. 10B shows a plot of resonance frequency f_r (in kilo-Hertz or kHz) as a function of step height (in micrometers or μm) illustrating the variation of f_r with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments.

FIG. 10C shows a plot of static capacitance C_o (in farad or F) as a function of step height (in micrometers or μm) illustrating the variation of C_o with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments.

FIG. 10D shows a plot of motional capacitance C_m (in farad or F) as a function of step height (in micrometers or μm) illustrating the variation of C_m with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments.

FIG. 10E shows a table illustrating the extracted lumped parameters for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments at different step heights.

FIG. 11 shows a table comparing the piezoelectric coupling coefficients k_t^2 of (a) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an unetched piezoelectric layer; (b) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an etched piezoelectric layer; (c) a conventional two-port piezoelectric micromachined ultrasonic transducer (pMUT); and (d) the quasi-bimorph piezoelectric device according to various embodiments.

FIG. 12A shows a table illustrating the extracted piezoelectric coupling coefficient (k_t^2) at different elastic layer thicknesses for the conventional one-port and two-port unimorph structures.

FIG. 12B shows a plot of static displacement (in micrometers or μm) as a function of elastic layer thickness/step height (in micrometers or μm) illustrating the static deflection magnitude of the conventional structures as well as the quasi-bimorph piezoelectric device according to various embodiments at different elastic layer thicknesses/step heights when subjected to 1V excitation.

FIG. 13A shows a plot of output voltage (in volts or V) as a function of frequency (in Mega-Hertz or MHz) illustrating the voltage frequency response function of the piezoelectric devices with different step heights (in micrometers or μm) according to various embodiments.

FIG. 13B shows a plot of the peak-to-peak (PkPk) output (o/p) voltage at resonance (in volts or V) as a function of step height (in micrometers or μm) illustrating the variation of peak-to-peak voltage of the piezoelectric devices with different step heights according to various embodiments subjected to a pressure input of 1 kPa.

FIG. 13C shows a table illustrating the different resonance frequencies f_n and peak-to-peak output voltages (PkPk V_{out}), under 1 kPa of pressure input, of piezoelectric devices having different step heights according to various embodiments.

FIG. 14 shows a table comparing the receive (Rx) sensitivity of (a) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an unetched piezoelectric layer; (b) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an etched piezoelectric layer; and (c) the quasi-bimorph piezoelectric device according to various embodiments.

FIG. 15A shows a circular membrane portion of a piezoelectric device according to various embodiments. A circular membrane may be most effective from a single-element design perspective.

FIG. 15B shows a rectangular membrane portion of a piezoelectric device according to various embodiments to maximize the areal efficiency in array arrangement.

FIG. 15C shows a hexagonal membrane portion of a piezoelectric device according to various embodiments to make the most of the surface area and also to exploit the efficiency of near circular design.

FIG. 15D shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion includes perforations.

FIG. 15E shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion is anchored at two opposing portions of the substrate.

FIG. 15F shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion is anchored at two opposing portions of the substrate and a third portion of the substrate joining the two opposing portions of the substrate.

FIG. 16A shows a three-dimensional (3D) schematic of a piezoelectric (lead zirconate titanate (PZT)) disc under uniform mechanical loading according to various embodiments.

FIG. 16B shows a corresponding cross-sectional two-dimensional (2D) schematic of the piezoelectric disc under uniform mechanical loading according to various embodiments.

FIG. 16C shows a model of the piezoelectric disc formed using a finite element mesh of three dimensional (3D) triangular elements according to various embodiments.

FIG. 16D shows a plot of stress components σ_{11} (in Pascals or Pa) as a function of diameter (in micrometers or μm) illustrating the variation of the stress components along the top surface and the bottom surface of the piezoelectric disc according to various embodiments; and (inset) the stress probe line along which the stress components are determined according to various embodiments.

FIG. 16E shows (left) the simulated stress components on the top surface of the piezoelectric disc according to various embodiments; and (right) the simulated stress components on the bottom surface of the piezoelectric disc according to various embodiments.

FIG. 17A shows the cross-sectional schematic of piezoelectric devices with different step heights according to various embodiments. The following electrical boundaries conditions may be set – (a) grounding of bottom electrode, and (b) application of an alternating current (AC) voltage to the top electrode ($V = 1V$).

FIG. 17B shows a plot of resonance frequency f_n (in kilo-Hertz or kHz) as a function of anchor length (in micrometers or μm) illustrating the variation of resonance frequency with the anchor length for piezoelectric devices with different step heights according to various embodiments.

FIG. 17C shows a plot of piezoelectric coupling coefficient (k_t^2) as a function of anchor length (in micrometers or μm) illustrating the variation of k_t^2 with the anchor length for piezoelectric devices with different step heights according to various embodiments.

DESCRIPTION

[0008] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0009] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0010] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0011] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance, e.g. within 10% of the specified value.

[0012] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0013] By “comprising” it is meant including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0014] By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of”. Thus, the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0015] Embodiments described in the context of one of the piezoelectric devices are analogously valid for the other piezoelectric devices, embodiments described in the context of a method are analogously valid for a piezoelectric device, and vice versa.

[0016] Various embodiments may address one or more issues faced by conventional approaches. Various embodiments may make use of push-pull operation to achieve bimorph-like behavior from a single piezoelectric stack. The quasi-piezoelectric design may enable improved driving and sensing performance compared to conventional unimorph structures. Various embodiments may allow for a simpler piezoelectric stack design compared to a conventional bimorph structure, but with comparable performance. Various embodiments may enable less complex integration processes by reducing the number of process steps and time. Various embodiments may reduce the maintenance frequency required.

[0017] FIG. 3A shows a cross-sectional schematic of a first piezoelectric device according to various embodiments. FIG. 3B shows a cross-sectional schematic of a second piezoelectric device according to various other embodiments. FIG. 3C shows a cross-sectional schematic of a third piezoelectric device according to yet various other embodiments. FIG. 3D shows a cross-sectional schematic of a fourth piezoelectric device according to further various other embodiments. FIG. 3E shows a cross-sectional schematic of a fifth piezoelectric device according to additional various other embodiments. FIG. 3F shows a cross-sectional schematic of a sixth piezoelectric device according to various other embodiments. FIG. 3G shows a cross-sectional schematic of a seventh piezoelectric device according to yet various other embodiments. FIG. 3H shows a cross-sectional schematic of an eighth piezoelectric device according to further various other embodiments. FIG. 3I shows a cross-sectional schematic of a ninth piezoelectric device according to additional various other embodiments. FIG. 3J shows a cross-sectional schematic of a tenth piezoelectric device according to various other embodiments. FIG. 3K shows a cross-sectional schematic of an eleventh piezoelectric device according to yet various other embodiments.

[0018] Generally speaking, the piezoelectric device may include a substrate 302a-k at least partially defining a cavity. The piezoelectric device may also include a piezoelectric stacked arrangement 304a-k with a step portion (alternatively referred to as “step structure”) over the cavity and an outer portion adjoining the step portion. The piezoelectric stacked arrangement 304a-k may include a continuous piezoelectric layer 306a-k. The piezoelectric stacked arrangement 304a-k may also include a continuous first electrode layer 308a-k in contact with a first surface of the piezoelectric layer 306a-k. The first electrode layer 308a-k may extend between at least a part of the outer portion of the piezoelectric stacked arrangement 304a-k and at least a part of the step portion of the piezoelectric stacked arrangement 304a-k. The piezoelectric stacked arrangement 304a-k may further include a continuous second electrode

layer 310a-k in contact with an entire second surface of the piezoelectric layer 306a-k opposite the first surface of the piezoelectric layer 306a-k. The second electrode layer 310a-k may extend between at least a part of the outer portion of the piezoelectric stacked arrangement 304a-k and at least a part of the step portion of the piezoelectric stacked arrangement 304a-k.

[0019] For avoidance of doubt, FIGS. 3A – 3K seek to illustrate some features of piezoelectric devices according to various embodiments, and are not intended to limit, for instance, the dimensions (e.g., thicknesses), orientation, shapes etc. of the various features. For instance, the layers in the stacked arrangements 304a-k may be of any suitable thickness. In addition to the piezoelectric devices shown in FIGS. 3A – 3K, various embodiments may include other piezoelectric devices, including but not limited to a piezoelectric device with three or more piezoelectric layers, or a piezoelectric device with “U” shaped design and multiple piezoelectric layers.

[0020] In various embodiments, a width of the step portion may be smaller than a width of the cavity. The step portion may be directly over the cavity. The step portion may be aligned to the cavity along a vertical axis which is substantially perpendicular to a top surface of the substrate 302a-e. The outer portion may surround a perimeter or circumference of the step portion. In other words, the step portion and the outer portion may form a concentric arrangement in which the center of the piezoelectric stacked arrangement 304a-k is included in the step portion (e.g., is at the center of the step portion), and the outer portion is around the step portion. In various embodiments, a surface area of the stacked arrangement 304a-k may be larger or may be of a same size as a traverse cross-section area of the cavity.

[0021] FIG. 3A shows an inverted “U” -shaped piezoelectric stacked arrangement 304a. As shown in FIG. 3A, a height of the step portion of the piezoelectric stacked arrangement 304a may be greater than a height of the outer portion of the piezoelectric stacked arrangement 304a. In other words, a distance between the step portion of the piezoelectric stacked arrangement

304a and a bottom surface of the substrate 302a may be greater than a distance between the outer portion of the piezoelectric stacked arrangement 304a and a bottom surface of the substrate 302a.

[0022] As indicated in FIG. 3A, the piezoelectric device or the piezoelectric stacked arrangement 304a may have a “step height”, which may be defined as a distance between the first surface of the piezoelectric layer 306a in the step portion and the second surface of the piezoelectric layer 306a in the outer portion for an inverted “U”-shaped piezoelectric stacked arrangement 304c. When the step height of the piezoelectric device, is zero, the second surface of the piezoelectric layer 306a in the step portion and the first surface of the piezoelectric layer 306a in the outer portion may be in the same plane, which is parallel to a top surface of the substrate. An “anchor length” of the piezoelectric device may be defined as a length between an anchor point of the piezoelectric stacked arrangement 304a (i.e., a point of the piezoelectric stacked arrangement 304a at an interface between the cavity and the substrate 302a) and a point (along the radius from the outer circumference/perimeter to the center point of the membrane portion) in which all layers of the piezoelectric stacked arrangement 304a starts to bend away from the plane of the top surface of the substrate 302a. FIG. 3B shows another inverted “U” - shaped piezoelectric stacked arrangement 304b. Unlike the piezoelectric arrangement 304a as shown in FIG. 3A which covers an entire surface area of a top surface of the substrate 302a, the piezoelectric stacked arrangement 304b may cover only a part of the surface area of a top surface of the substrate 302b.

[0023] On the other hand, FIG. 3C shows an “U”-shaped piezoelectric stacked arrangement 304c. As shown in FIG. 3C, a height of an outer portion of the piezoelectric stacked arrangement 304c may be greater than a height of the step portion of the piezoelectric stacked arrangement 304c. In other words, a distance between the outer portion of the piezoelectric stacked arrangement 304b and a bottom surface of the substrate 302c may be greater than a distance

between the step portion of the piezoelectric stacked arrangement 304c and a bottom surface of the substrate 302c.

[0024] As indicated in FIG. 3C, the piezoelectric device or the piezoelectric stacked arrangement 304c may have a “step height”, which may be defined as a distance between the second surface of the piezoelectric layer 306c in the step portion and the first surface of the piezoelectric layer 306c in the outer portion for a “U”-shaped piezoelectric stacked arrangement 304c. An “anchor length” of the piezoelectric device may be defined as a length between an anchor point of the piezoelectric stacked arrangement 304c (i.e., a point of the piezoelectric stacked arrangement 304c at an interface between the cavity and the substrate 302c) and a point (along the radius from the outer circumference/perimeter to the center point of the membrane portion) in which all layers of the piezoelectric stacked arrangement 304c starts to bend away from the plane of the top surface of the substrate 302c. FIG. 3D shows another “U” -shaped piezoelectric stacked arrangement 304d. Unlike the piezoelectric arrangement 304c as shown in FIG. 3C which covers an entire surface area of a top surface of the substrate 302c, the piezoelectric stacked arrangement 304d may cover only a part of the surface area of a top surface of the substrate 302d.

[0025] FIG. 3E shows an inverted “U” -shaped piezoelectric stacked arrangement 304e with a further step portion. The further step portion may extend from an inner portion of the step portion. The step portion and the further step portion may form a nested arrangement or concentric arrangement (when viewed from the top or bottom). FIG. 3F shows another inverted “U” -shaped piezoelectric stacked arrangement 304f with a further step portion. Unlike the piezoelectric arrangement 304e as shown in FIG. 3E which covers an entire surface area of a top surface of the substrate 302e, the piezoelectric stacked arrangement 304f may cover only a part of the surface area of a top surface of the substrate 302f.

[0026] FIG. 3G shows an “U”-shaped piezoelectric stacked arrangement 304g with a further step portion. The further step portion may extend from an inner portion of the step portion. The step portion and the further step portion may form a nested arrangement or concentric arrangement (when viewed from the top or bottom). FIG. 3H shows another “U” -shaped piezoelectric stacked arrangement 304g with a further step portion. Unlike the piezoelectric arrangement 304g as shown in FIG. 3G which covers an entire surface area of a top surface of the substrate 302g, the piezoelectric stacked arrangement 304h may cover only a part of the surface area of a top surface of the substrate 302h.

[0027] As shown in FIG. 3I, the piezoelectric device may include a further piezoelectric stacked arrangement 304i'. While FIG. 3I shows the further piezoelectric stacked arrangement 304i' over the piezoelectric stacked arrangement 304i, it may be envisioned that in various other embodiments, the further piezoelectric stacked arrangement 304i' may be below the piezoelectric stacked arrangement 304i. The further piezoelectric stacked arrangement 304i' may have a step portion over the cavity. As shown in FIG. 3I, the further piezoelectric stacked arrangement 304i' may include a continuous further piezoelectric layer 312i and a continuous further electrode layer 314i. The continuous second electrode layer 310i of the further piezoelectric stacked arrangement 304e may be in contact with an entire first surface of the further piezoelectric layer 312i, while the continuous further electrode layer 314i may be in contact with an entire second surface of the further piezoelectric layer 312i opposite the first surface. The further piezoelectric layer 312i may be in phase with the piezoelectric layer 306i (i.e., during operation). FIG. 3J shows a piezoelectric device with a further piezoelectric stacked arrangement 304j' including a further piezoelectric layer 312j and a continuous further electrode layer 314j. Unlike the piezoelectric arrangements 304i, 304i' as shown in FIG. 3I which overlap with an entire surface area of a top surface of the substrate 302i, the piezoelectric

stacked arrangements 304j, 304j' may overlap with only a part of a top surface of the surface area of the substrate 302j.

[0028] Generally speaking, the piezoelectric device may include one or more further piezoelectric stacked arrangements, each of the one or more further piezoelectric stacked arrangements having a step portion over the cavity. Each of the one or more further piezoelectric stacked arrangements may include a continuous piezoelectric layer in phase with the piezoelectric layer of the piezoelectric stacked arrangement (i.e., during operation). Each of the one or more further piezoelectric stacked arrangements may include a continuous further electrode layer.

[0029] FIG. 3K shows a piezoelectric stacked arrangement 304k with a continuous piezoelectric layer 306k, a continuous first electrode layer 308k and a continuous second electrode layer 310k. Unlike the piezoelectric devices shown in FIGS. 3A – 3J in which the second electrode layer 310a-j is in contact with an entire second surface area of the piezoelectric layer 306a-j, the second electrode layer 310k may extend between only a part of the step portion and only a part of the outer portion. While FIG. 3K shows the first electrode 308k in contact with an entire first surface area of the piezoelectric layer 306k, it may be envisioned that in various embodiments, the first electrode layer 308k may extend between only a part of the step portion and only a part of the outer portion. Generally speaking, the first electrode may be in contact with an entire first surface of the piezoelectric layer or may extend between at least a part of the step portion (i.e., an entire step portion or only a part of the step portion) and at least a part of the outer portion (i.e., an entire outer portion or only a part of the outer portion). Further, the second electrode may be in contact with an entire second surface of the piezoelectric layer or may extend between at least a part of the step portion (i.e., an entire step portion or only a part of the step portion) and at least a part of the outer portion (i.e., an entire outer portion or only a part of the outer portion).

[0030] In various embodiments, the piezoelectric layer 306a-k may be of substantially uniform thickness. In various embodiments, the first electrode layer 308a-k may be of substantially uniform thickness. In various embodiments, the second electrode layer 310a-k may be of substantially uniform thickness. In various embodiments, the further piezoelectric layer 312i-j shown in FIGS. 3I – 3J or the respective continuous piezoelectric layer included in each of the one or more further piezoelectric stacked arrangements as described above may be of substantially uniform thickness. Likewise, in various embodiments, the further electrode layer 314i-j shown in FIGS. 3I – 3J or the respective further electrode layer included in each of the one or more further piezoelectric stacked arrangements as described above may be of substantially uniform thickness. In various other embodiments, the piezoelectric layer, the first electrode layer, the second electrode layer, the further piezoelectric layer, the respective piezoelectric layer, the further electrode and/or the respective further electrode may be of non-uniform thickness.

[0031] In the current context, a layer of “substantially uniform thickness” may mean that the layer has a 1σ variance of 10% throughout the layer. In various embodiments, a layer of substantially uniform thickness may have a 1σ thickness variance of 10% throughout the layer.

[0032] In various embodiments, the step portion or the further step portion may be part of a membrane portion suspended over the cavity. The membrane portion, i.e., the part of the piezoelectric stacked arrangement(s) that is suspended over the cavity, is illustrated in FIGS. 3A – 3B. For sake of clarity and to avoid clutter, the membrane portion is not labelled in FIGS. 3C – 3K. In various embodiments, the membrane portion may be fully anchored to the substrate 302a-k, while in various other embodiments, the membrane portion may be partially anchored to the substrate 302a-k. The membrane portion may be of any suitable shape. In various embodiments, the membrane portion may have any one shape selected from a group consisting of a circle, a rectangular, and a hexagon (when viewed from the top or bottom). In various

embodiments, the membrane portion may have one or more perforations extending from a first surface of the piezoelectric stacked arrangement to a second surface of the piezoelectric stacked arrangement opposite the first surface. In various embodiments, the membrane portion may be anchored at two opposing portions of the substrate 302a-k. In various embodiments, the membrane portion may be anchored at two opposing portions of the substrate and a third portion of the substrate joining the two opposing portions of the substrate 302a-k.

[0033] In various embodiments, the piezoelectric device may further include an alternating current (AC) source. The AC source may have a first contact coupled to the first electrode layer 308a-h, k and a second contact coupled to the second electrode layer 310a-h, k. In various other embodiments, either the first electrode layer 308a-h, k or the second electrode layer 310a-h, k may be grounded, while the remaining electrode layer is coupled to an AC source. In various other embodiments, the piezoelectric device may include a direct current (DC) source, or a combination of an DC and an AC source. The DC source, or the combination of the DC source and the AC source may be coupled to one electrode layer or both electrode layers.

[0034] For the piezoelectric device shown in FIGS. 3I – 3J, voltages may be applied to electrode layers 308i-j, 310i-j and 314i-j such that the piezoelectric layers 306i-j, 312i-j operate in-phase with each other. For instance, the first electrode layer 308i-j may be applied with a first AC or DC voltage, the second electrode layer 310i-j may be applied with a second AC or DC voltage higher and in phase with first AC or DC voltage, and the third electrode layer 314i-j may be applied with a third AC or DC voltage higher and in phase with the second AC or DC voltage.

[0035] FIG. 4A shows a general illustration of a method of forming a piezoelectric device according to various embodiments. The method may include, in S1, forming a cavity in a substrate such that the substrate at least partially defines the cavity. The method may also include, in S2, forming a piezoelectric stacked arrangement with a step portion over the cavity

and an outer portion adjoining the step portion. The piezoelectric stacked arrangement may include a continuous piezoelectric layer, and a continuous first electrode layer in contact with a first surface of the piezoelectric layer. The first electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement. The piezoelectric stacked arrangement may also include a continuous second electrode layer in contact with a second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer. The second electrode layer may extend between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement.

[0036] For avoidance of doubt, FIG. 4A seeks to illustrate certain steps to form the piezoelectric device, and is not intended to limit the sequence of the various steps. For instance, S2 may occur before S1. FIG. 4B shows a process flow of forming a piezoelectric device according to various embodiments. As shown in FIG. 4B, the method may include, in T1, patterning or etching a substrate. The method may also include, in T2, forming a piezoelectric stacked arrangement with a step portion on or over the substrate after patterning or etching the substrate in T1. The piezoelectric stacked arrangement (i.e. the first electrode layer, followed by the piezoelectric layer and the second electrode layer) may be formed on or over the patterned substrate. In other words, a front surface or side of the substrate may be patterned or etched, and materials may be deposited over the patterned or etched front surface or side of the substrate so that the step portion is formed using the patterned or etched front surface of the substrate as a template. The method may also include, in T3, forming a cavity in the substrate by etching the substrate after forming the piezoelectric stacked arrangement with the step portion in T2. The cavity of the substrate may be formed by etching through a back side or surface of the substrate, the back side or surface opposite the front side or surface. The cavity formed may extend from the back surface or side of the substrate to the front surface or side of

the substrate opposite the back surface or side of the substrate. In various embodiments, a portion of the substrate below the membrane portion of the piezoelectric stacked arrangement may also be etched away. Various embodiments may not involve etching of the piezoelectric layer, the first electrode layer and the second electrode layer, and may not generate etch by-products. In various other embodiments, one or more perforations may be formed in the piezoelectric stacked arrangement, i.e., in a membrane portion of the piezoelectric stacked arrangement, for frontside release. The one or more perforations may extend from a first surface of the piezoelectric stacked arrangement to a second surface of the piezoelectric stacked arrangement opposite the first surface, and may carry etchants for etching an underlying portion of the substrate to form the cavity.

[0037] In various embodiments, the piezoelectric layer may be of substantially uniform thickness. The first electrode layer may be of substantially uniform thickness. The second electrode layer may be of substantially uniform thickness.

[0038] In various embodiments, the piezoelectric stacked arrangement may further include a further step portion.

[0039] In various embodiments, the method may also include forming one or more further piezoelectric stacked arrangements, each of the one or more further piezoelectric stacked arrangements having a step portion over the cavity.

[0040] In various embodiments, each of the one or more further piezoelectric stacked arrangements may include a continuous piezoelectric layer in phase with the piezoelectric layer of the piezoelectric stacked arrangement.

[0041] Various embodiments may relate to a “quasi-bimorph” piezoelectric device. FIG. 5 shows cross-sectional schematics of piezoelectric devices according to various embodiments. Each of the piezoelectric devices may include a substrate 502a-b with a cavity, and a piezoelectric stacked arrangement 504a-b with a step structure (or step portion) over the cavity

to leverage mechanical amplification. The left schematic shows a device with an inverted “U”-shaped piezoelectric stacked arrangement, while the right schematic shows a device with an “U” shaped piezoelectric stacked arrangement. Various embodiments may also relate to a piezoelectric device with multiple piezoelectric stacked arrangements.

[0042] The piezoelectric device may utilize push-pull driving to achieve actuation by amplifying displacement (instead of bending moment used by conventional acoustic transducers) to achieve bimorph-like behavior from a single piezoelectric stacked arrangement. In push-pull actuation, the step portion of the membrane may push, while the outer portion (i.e., the portion anchored to the substrate) pulls. The sensing may be achieved by compressive-tensile stressing to the piezoelectric layer through force application. The piezoelectric membrane may be operated by in-phase operation with a simple electrode configuration compared to the complex electrode configuration in a conventional bimorph structure. During operation, the membrane may be addressed using a signal applied to either the top electrode or the bottom electrode, with the remaining electrode being grounded.

[0043] When a PMUT is used as a transmitter, electrical energy may be converted into mechanical vibrations through piezoelectric material of the piezoelectric layer, thereby generating acoustic waves via the inverse piezoelectric effect. Conversely, when the PMUT is used as a receiver, the applied external load/pressure may lead to out-of-plane bending of piezoelectric layer, thereby generating an electric potential via the direct piezoelectric effect, which can then be measured.

[0044] The piezoelectric coupling coefficient (k_t^2) may describe the efficiency with which electrical energy is converted to mechanical energy and vice versa. A higher k_t^2 value may mean that the transducer can generate a stronger acoustic wave for a given electrical input, which is desirable for many applications such as medical imaging, industrial inspection, and non-

destructive testing. Therefore, the k_t^2 constant may be an important parameter to consider when designing and optimizing PMUT transmitters/receivers.

[0045] To analyze the transmission and receive sensitivities of a PZT “quasi-bimorph” PMUT, a two-dimensional (2D) axis-symmetric structure may first be modelled using COMSOL Multiphysics version 6.1 finite element software. As per earlier studies, the Quality-factor (Q-factor) of the PMUTs when operated in air may range between 100 and 300. A Q-factor of 200 is assumed for the current simulation. The mechanical damping factor (ζ) may be inversely proportional to the Q-factor. FIG. 6 shows (a) a cross-sectional schematic of a transmitter based on the piezoelectric device according to various embodiments; and (b) a cross-sectional schematic of a receiver based on the piezoelectric device according to various embodiments. Each piezoelectric device may include a silicon (Si) substrate, a 2 μm or 4 μm thick piezoelectric layer, a 200 nm thick platinum first electrode (or bottom electrode) as well as a 200 nm thick platinum second electrode (or top electrode).

[0046] For the transmission analysis, a sinusoidal alternating current (AC) voltage of 1V amplitude is applied between the transmitter electrode (top electrode) and the ground electrode (bottom electrode), which induces a transverse stress in the piezoelectric layer between the top electrode and the bottom electrode. Similarly, for the reception simulation, a uniform mechanical external load of 1kPa is applied onto the top surface of the PMUT structure (stacked arrangement), thereby generating a stress gradient in the piezoelectric layer, which produces an electric charge on the top electrode and on the bottom electrode as shown in FIG. 6(b). As mentioned above, the PZT ($e_{31,f} = -15.64 \text{ C/m}^2$, $\epsilon_{33} = 1100$, $s_{11} = 1.43 \times 10^{-11} \text{ Pa}^{-1}$) piezoelectric layer may be 2 μm or 4 μm thick, while the platinum electrodes ($E = 180 \text{ GPa}$) may each have a thickness of 200 nm. The PMUT element has a 150 μm diameter. The height of the step may be optimized to improve the performance parameters of the device. A fine triangular finite element mesh is employed for accurate simulation.

[0047] FIG. 7A shows the first four vibration mode-shapes of a circular quasi-bimorph piezoelectric device according to various embodiments. The different shadings represent the relative amplitude of motion. The 00 mode, which shows the largest average surface displacement, may be the preferred vibration mode for most acoustic devices because it generates the highest acoustic pressure, making it especially suitable for designing and developing high-performance acoustic devices for various applications, such as microspeakers, microphones, and ultrasound transducers. In a push-pull quasi-bimorph structure, the stepped portion and the outer portion may vibrate out of phase with each other in 00 mode. This may create a push-pull effect, where one portion of the membrane pushes while the other portion pulls, resulting in a 00 mode with an overall increase in displacement and transmission efficiency.

[0048] FIG. 7B illustrates the operation of a quasi-bimorph piezoelectric device in different phases when applying alternating current (AC) driving voltage according to various embodiments. FIG. 7C illustrates the operation of a conventional bimorph structure.

[0049] The step height may play a crucial role in fully using the push-pull operation to achieve bimorph-like behavior from a single piezoelectric stacked arrangement in the quasi-bimorph piezoelectric device. To evaluate the effect of the step height on transmitter performance parameters, including peak-to-peak displacement at resonance and k_t^2 , a comprehensive parametric analysis has been performed.

[0050] FIG. 8A shows a plot of peak-peak displacement magnitude (in micrometers or μm) as a function of step height (in micrometers or μm) illustrating the variation of the peak-to-peak displacements of the stacked arrangements having piezoelectric layers with different thicknesses (i.e., 2 μm and 4 μm) according to various embodiments with step height at resonance when a unit alternating current (AC) is applied, with the inset showing a cross-sectional schematic of a portion of a stacked arrangement to illustrate the step height. The solid

line in FIG. 8A represents a piezoelectric layer thickness (i.e., PZT thickness or tPZT) of 2 μm , while the dashed line represents a piezoelectric layer thickness (i.e., PZT thickness or tPZT) of 4 μm . The inset shows that the step height may be defined as a distance between the second surface of the piezoelectric layer in the step portion and the first surface of the piezoelectric layer in the outer portion.

[0051] FIG. 8B shows a table illustrating the peak-to-peak displacements of the stacked arrangements having piezoelectric layers with different thicknesses (i.e., 2 μm and 4 μm) according to various embodiments at different step heights.

[0052] A greater peak-to-peak displacement may be achieved when the step height is lower. A smaller step height can result in a stronger push-pull effect and a more efficient transfer of electrical energy into mechanical motion due to the bimorph-like behavior of the PMUT.

[0053] The optimal step height may balance the push-pull effect with other design considerations such as resonance frequency and ease of fabrication. The optimal step height achieved through computational simulations may be a value selected from a range from 0 μm to 0.5 μm . Within this range, the average peak-to-peak displacement may be determined to be 9.21 μm for a PZT layer thickness of 2 μm , and 2.94 μm for a PZT layer thickness of 4 μm . The higher displacement output of the 2 μm thick PZT may be attributed to its lower compliance compared to the 4 μm thick PZT layer.

[0054] FIG. 9A shows a plot of peak-to-peak (PkPk) displacement (in micrometers or μm) as a function of frequency (in Mega-Hertz or MHz) illustrating the displacement frequency response function of the piezoelectric device according to various embodiments with a step height of zero. The maximum peak-to-peak displacement magnitude of 9.34 μm may be obtained at the resonance frequency of 1.07 MHz.

[0055] FIG. 9B is a three-dimensional (3D) plot of z (in micrometers or μm) as a function of x (in micrometers or μm) and y (in micrometers or μm) illustrating the contour of the

membrane portion of the piezoelectric device according to various embodiments at the resonance frequency of 1.07 MHz.

[0056] The impedance curves may be fitted to a Butterworth-Van Dyke (BVD) model. FIG. 9C illustrates the Butterworth-Van Dyke (BVD) model for lumped parameter extraction according to various embodiments. The BVD equivalent electrical circuit on the left of FIG. 9C shows the resistance R_m , inductance L_m , motional Capacitance C_m connected in series and a C_0 connected again in parallel. Y_m is the admittance of the motional branch and Y_{C_0} is the admittance of the feedthrough branch. ω is the frequency in radians.

[0057] The key parameters of the PMUT including resonance frequency f_r , motional capacitance C_m , static capacitance C_0 , and k_t^2 , were subsequently extracted and presented in FIG. 9D (for zero step height), for a device with PZT thickness of 2 μm . FIG. 9D shows a plot of admittance (in siemens or S) as a function of frequency (in kilo-Hertz or kHz) illustrating the lumped parameter extraction using the Butterworth-Van Dyke (BVD) model curve fitting for a piezoelectric device according to various embodiments with zero step height. The figure of merit (FOM) for the transmitter, k_t^2 may be defined as:

$$k_t^2 = \frac{\pi^2 C_m}{8 C_0} \quad (1)$$

[0058] Next, the k_t^2 , f_r , C_m , and C_0 may be extracted at various step heights. FIG. 10A shows a plot of piezoelectric coupling coefficient k_t^2 (in percent or %) as a function of step height (in micrometers or μm) illustrating the variation of k_t^2 with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments. FIG. 10B shows a plot of resonance frequency f_r (in kilo-Hertz or kHz) as a function of step height (in micrometers or μm) illustrating the variation of f_r with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments. FIG. 10C shows a plot of static capacitance C_0 (in farad or F) as a function of step height (in micrometers or μm) illustrating the variation of C_0 with step height for piezoelectric devices having different

piezoelectric layer thicknesses according to various embodiments. FIG. 10D shows a plot of motional capacitance C_m (in farad or F) as a function of step height (in micrometers or μm) illustrating the variation of C_m with step height for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments. FIG. 10E shows a table illustrating the extracted lumped parameters for piezoelectric devices having different piezoelectric layer thicknesses according to various embodiments at different step heights.

[0059] The results show that at lower step heights (less than $0.5\ \mu\text{m}$), the k_t^2 value may be higher (approximately 15% for PZT layer thickness of $2\ \mu\text{m}$ and approximately 18% for PZT layer thickness of $4\ \mu\text{m}$). This finding shows that maximum transduction may be achieved at these step heights. Conversely, as the step height increases, the k_t^2 value may decrease. The k_t^2 of the quasi-bimorph PMUT according to various embodiments at the optimum step height is compared with the conventional one-port and two-port unimorph PMUT structures in FIG. 11. FIG. 11 shows a table comparing the piezoelectric coupling coefficients k_t^2 of (a) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an unetched piezoelectric layer; (b) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an etched piezoelectric layer; (c) a conventional two-port piezoelectric micromachined ultrasonic transducer (pMUT); and (d) the quasi-bimorph piezoelectric device according to various embodiments. As illustrated in FIG. 11, the quasi-bimorph piezo design according to various embodiments may enable improved driving performance compared to conventional one-port pMUT structures, and may have comparable performance compared to the conventional two-port pMUT structure. In all these test cases, the pMUT membrane diameter is fixed at $150\ \mu\text{m}$. For the conventional structures, the silicon (Si) device layer serves as the elastic layer. The optimal thickness of the elastic layer of the conventional structures in FIG. 11(a) – (c) is $3\ \mu\text{m}$, which was determined through systematic parametric analysis aimed at achieving maximum k_t^2 , as presented in FIG. 12A. FIG. 12A shows a table illustrating the

extracted piezoelectric coupling coefficient (k_r^2) at different elastic layer thicknesses for the conventional one-port and two-port unimorph structures. The neutral plane of the PMUTs in FIG. 11(a) – (c) falls within the elastic layer at an elastic layer thickness of 3 μm . If the neutral axis falls within the piezoelectric layer, the lower portion and upper portion of the PZT may work in opposite to each other, leading to a drastic decline in PMUT performance and a substantial reduction in k_r^2 . FIG. 12B shows a plot of static displacement (in micrometers or μm) as a function of elastic layer thickness/step height (in micrometers or μm) illustrating the static deflection magnitude of the conventional structures as well as the quasi-bimorph piezoelectric device according to various embodiments at different elastic layer thicknesses/step heights when subjected to 1V excitation. Compared to the conventional structures, the quasi-bimorph piezoelectric device may show greater deflection when the step height of the quasi-bimorph piezoelectric device is within the range from 0 μm to 0.5 μm . The quasi-bimorph piezoelectric device may be advantageous over the conventional unimorph PMUT structures, since the quasi-bimorph piezoelectric device can generate pure bending deformation without requiring a supporting elastic layer, resulting in a reduced effective load for both actuation and sensing operations.

[0060] Simulation for the receiver mode is also carried out. The voltage frequency response function is shown in FIG. 13A, while the peak-to-peak output voltages at resonance frequency for different step heights are shown in FIG. 13B. FIG. 13A shows a plot of output voltage (in volts or V) as a function of frequency (in Mega-Hertz or MHz) illustrating the voltage frequency response function of the piezoelectric devices with different step heights (in micrometers or μm) according to various embodiments. FIG. 13B shows a plot of the peak-to-peak (PkPk) output (o/p) voltage at resonance (in volts or V) as a function of step height (in micrometers or μm) illustrating the variation of peak-to-peak voltage of the piezoelectric devices with different step heights according to various embodiments subjected to a pressure input of 1 kPa. The

maximum receive output voltage may be achieved at a step height selected from a range from $-0.5\text{ }\mu\text{m}$ to $0\text{ }\mu\text{m}$. FIG. 13C shows a table illustrating the different resonance frequencies f_n and peak-to-peak output voltages (PkPk V_{out}), under 1 kPa pressure input, of piezoelectric devices having different step heights according to various embodiments.

[0061] FIG. 14 shows a table comparing the receive (Rx) sensitivity of (a) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an unetched piezoelectric layer; (b) a conventional one-port piezoelectric micromachined ultrasonic transducer (pMUT) with an etched piezoelectric layer; and (c) the quasi-bimorph piezoelectric device according to various embodiments. The quasi-bimorph piezoelectric device according to various embodiments may exhibit $\sim 2.9\times$ higher Rx sensitivity compared to the conventional unimorph PMUT (with an unetched piezoelectric layer) and $\sim 1.4\times$ higher Rx sensitivity compared to the unimorph PMUT with the piezoelectric layer trimmed down to 70% of the membrane.

[0062] Various embodiments may be formed using MEMS processing techniques. The piezoelectric device may have membrane portions (alternatively referred to as membranes) of different shapes. FIG. 15A shows a circular membrane portion of a piezoelectric device according to various embodiments. A circular membrane may be most effective from a single-element design perspective. FIG. 15B shows a rectangular membrane portion of a piezoelectric device according to various embodiments to maximize the areal efficiency in array arrangement. A rectangular membrane may have a wider bandwidth compared to a circular membrane. In addition, a rectangular membrane may be more easily packed, i.e., a rectangular membrane may have a higher areal density compared to a circular design for array applications. The rectangular membrane portion may be suitable for applications such as piezoelectric microphones and micro-speakers. FIG. 15C shows a hexagonal membrane portion of a piezoelectric device according to various embodiments to make the most of the surface area

and also to exploit the efficiency of near circular design. A hexagonal membrane may have increased areal density without significant compromise on the performance of individual elements. FIG. 15D shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion includes perforations. Various embodiments may have a membrane portion, in which the membrane portion has one or more perforations extending from a first surface of the piezoelectric stacked arrangement to a second surface of the piezoelectric stacked arrangement opposite the first surface. The perforation(s) may be etch holes for frontside release without penetrating the wafer backside. While FIG. 15D shows a circular membrane portion with perforations, various embodiments may include a membrane portion of any suitable shape and having one or more perforations.

[0063] FIG. 15E shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion is anchored at two opposing portions of the substrate. The design shown in FIG. 15E may be referred to as a “double-end fixed plate” design. FIG. 15F shows a membrane portion of a piezoelectric device according to various embodiments, in which the membrane portion is anchored at two opposing portions of the substrate and a third portion of the substrate joining the two opposing portions of the substrate. The design shown in FIG. 15F may be referred to as a “partially open membrane” design. The structures shown in FIGS. 15E-F may be potential replacements of balanced armature drivers to generate higher output pressures with a smaller form-factor.

[0064] Tests may be carried out to determine the optimum anchor lengths. FIG. 16A shows a three-dimensional (3D) schematic of a piezoelectric (lead zirconate titanate (PZT)) disc under uniform mechanical loading according to various embodiments. FIG. 16B shows a corresponding two-dimensional (2D) cross-sectional schematic of the piezoelectric disc under uniform mechanical loading according to various embodiments. FIG. 16C shows a model of

the piezoelectric disc formed using a finite element mesh of three dimensional (3D) triangular elements according to various embodiments.

[0065] FIG. 16D shows a plot of stress components σ_{11} (in Pascals or Pa) as a function of diameter (in micrometers or μm) illustrating the variation of the stress components along the top surface and the bottom surface of the piezoelectric disc according to various embodiments; and (inset) the stress probe line along which the stress components are determined according to various embodiments. The dashed line shown in the plot of FIG. 16D denotes the points in which the stress distribution is zero. It can also be seen from FIG. 16D that the stress distribution at the edge portion of the disc is opposite that at the middle portion of the disc, and that the stress distribution at the top surface of the disc is opposite that at the bottom surface of the disc. FIG. 16E shows (left) the simulated stress components on the top surface of the piezoelectric disc according to various embodiments; and (right) the simulated stress components on the bottom surface of the piezoelectric disc according to various embodiments. The dashed circles in FIG. 16E denote points in which the stress distribution is zero. From FIGS. 16D-E, it can be seen that the area in which the stress value is zero is approximately distributed at 70% from the center of the disc. The step should be placed at 20 μm to 25 μm from the fixed end of the clamped-clamped piezoelectric circular disc.

[0066] Next, the anchor beam length may be varied for piezoelectric devices with step heights of 0 μm , 1 μm and 5 μm . FIG. 17A shows the cross-sectional schematic of piezoelectric devices with different step heights according to various embodiments. The following electrical boundaries conditions may be set – (a) grounding of bottom electrode, and (b) application of an alternating current (AC) voltage to the top electrode ($V = 1\text{ V}$). The mechanical damping factor (ζ) may be equal to $1/Q$, in which Q is the Quality-factor and may be set at 200.

[0067] FIG. 17B shows a plot of resonance frequency f_n (in kilo-Hertz or kHz) as a function of anchor length (in micrometers or μm) illustrating the variation of resonance frequency with

the anchor length for piezoelectric devices with different step heights according to various embodiments. FIG. 17C shows a plot of piezoelectric coupling coefficient (k_t^2) as a function of anchor length (in micrometers or μm) illustrating the variation of k_t^2 with the anchor length for piezoelectric devices with different step heights according to various embodiments. As shown in FIG. 17C, the optimum anchor length may be of a value selected from a range from 20 μm to 30 μm (for a quasi-bimorph piezoelectric device with a step portion having a length or diameter of 100 μm) at step heights of 0 μm , 1 μm and 5 μm . The curves for devices with step heights of 0 μm and 1 μm may be almost the same. Generally speaking, the shorter the step height, the better the performance in terms of k_t^2 .

[0068] Various embodiments may relate to a quasi-bimorph piezoelectric device, which may make use of push-pull operation to achieve bimorph-like behaviour from a single piezoelectric stack. The effect of the step height on the performance of the PMUT has been evaluated through a systematic parametric analysis. It has been found that the optimal step height for the quasi-bimorph structure may be in the range of -0.5 μm to 0.5 μm , which may offer a balance between the push-pull effect and other design considerations such as resonance frequency and ease of fabrication with high driving and receiving performance. The quasi-bimorph structure may exhibit higher k_t^2 and Rx values compared to the conventional unimorph PMUT structure. Various embodiments may have a simpler piezoelectric stack structure compared to conventional bimorph structures with comparable performance. Various embodiments may be formed via simpler integration processes by reducing process steps and time, which may also reduce the maintenance frequency. Additionally, the quasi-bimorph structure may generate pure bending deformation without requiring a supporting elastic layer, resulting in a reduced effective load for both driving and receiving operations. Various embodiments may be suitable for various applications, including medical imaging, microspeakers, microphones, and acoustic devices.

Claims

1. A piezoelectric device comprising:
 - a substrate at least partially defining a cavity; and
 - a piezoelectric stacked arrangement with a step portion over the cavity and an outer portion adjoining the step portion;wherein the piezoelectric stacked arrangement comprises:
 - a continuous piezoelectric layer;
 - a continuous first electrode layer in contact with a first surface of the piezoelectric layer, the first electrode layer extending between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement;
 - and
 - a continuous second electrode layer in contact with a second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer, the second electrode layer extending between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement.
2. The piezoelectric device according to claim 1,
 - wherein the piezoelectric layer is of substantially uniform thickness;
 - wherein the first electrode layer is of substantially uniform thickness; and
 - wherein the second electrode layer is of substantially uniform thickness.
3. The piezoelectric device according to claim 1,

wherein a height of the step portion of the piezoelectric stacked arrangement is greater than a height of the outer portion of the piezoelectric stacked arrangement.

4. The piezoelectric device according to claim 1,
wherein a height of the outer portion of the piezoelectric stacked arrangement is greater than a height of the step portion of the piezoelectric stacked arrangement.
5. The piezoelectric device according to claim 1,
wherein a width of the step portion is smaller than a width of the cavity.
6. The piezoelectric device according to claim 1,
wherein the piezoelectric stacked arrangement further comprises a further step portion.
7. The piezoelectric device according to claim 1,
wherein the further step portion extends from an inner portion of the step portion.
8. The piezoelectric device according to claim 1, further comprising:
one or more further piezoelectric stacked arrangements, each of the one or more further piezoelectric stacked arrangements having a step portion over the cavity.
9. The piezoelectric device according to claim 8,
wherein each of the one or more further piezoelectric stacked arrangements comprises a continuous piezoelectric layer in phase with the piezoelectric layer of the piezoelectric stacked arrangement.

10. The piezoelectric device according to claim 1,
wherein the step portion is part of a membrane portion suspended over the cavity.
11. The piezoelectric device according to claim 10,
wherein the membrane portion has any one shape selected from a group consisting of a circle, a rectangular, and a hexagon.
12. The piezoelectric device according to claim 10,
wherein the membrane portion has one or more perforations extending from a first surface of the piezoelectric stacked arrangement to a second surface of the piezoelectric stacked arrangement opposite the first surface.
13. The piezoelectric device according to claim 10,
wherein the membrane portion is fully anchored to the substrate.
14. The piezoelectric device according to claim 10,
wherein the membrane portion is partially anchored to the substrate.
15. The piezoelectric device according to claim 1,
wherein a surface area of the stacked arrangement is larger or may be of a same size as a traverse cross-section area of the cavity.
16. A method of forming a piezoelectric device, the method comprising:
forming a cavity in a substrate such that the substrate at least partially defines the cavity; and

forming a piezoelectric stacked arrangement with a step portion over the cavity and an outer portion adjoining the step portion;

wherein the piezoelectric stacked arrangement comprises:

a continuous piezoelectric layer;

a continuous first electrode layer in contact with an entire first surface of the piezoelectric layer, the first electrode layer extending between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement; and

a continuous second electrode layer in contact with an entire second surface of the piezoelectric layer opposite the first surface of the piezoelectric layer, the second electrode layer extending between at least a part of the outer portion of the piezoelectric stacked arrangement and at least a part of the step portion of the piezoelectric stacked arrangement.

17. The method according to claim 16,

wherein the piezoelectric stacked arrangement further comprises a further step portion.

18. The method according to claim 16, further comprising:

forming one or more further piezoelectric stacked arrangements, each of the one or more further piezoelectric stacked arrangements having a step portion over the cavity.

19. The method according to claim 18,

wherein each of the one or more further piezoelectric stacked arrangements comprises a continuous piezoelectric layer in phase with the piezoelectric layer of the piezoelectric stacked arrangement.

20. The method according to claim 16,

wherein the piezoelectric layer is of substantially uniform thickness;
wherein the first electrode layer is of substantially uniform thickness; and
wherein the second electrode layer is of substantially uniform thickness.