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Piezoelectric device and acoustic transducer

Abstract

A piezoelectric device includes a substrate including a first main surface and a second main surface. A piezoelectric element is on the first main surface. A cover on the first main surface. The cover covers the piezoelectric element and is spaced apart from piezoelectric element on the first main surface side. The piezoelectric element includes a base portion and a membrane portion. The base portion is on the first main surface and has an annular external shape when viewed from the first main surface side. The membrane portion is inside the annular base portion when viewed from the first main surface side. The cover includes a first through hole. The substrate includes a second through hole facing the membrane portion and extends between the first main surface and the second main surface.

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5955821	12/1998	Yamamoto	310/326	G10K 9/122
9521499	12/2015	Theuss	N/A	H04R 19/005
2006/0158064	12/2005	Asakawa	310/328	H04R 1/2842
2007/0047744	12/2006	Harney et al.	N/A	N/A
2007/0058826	12/2006	Sawamoto et al.	N/A	N/A
2010/0202649	12/2009	Inoda et al.	N/A	N/A
2010/0284553	12/2009	Conti	381/174	B81B 7/0061
2012/0300969	12/2011	Tanaka et al.	N/A	N/A
2015/0264488	12/2014	Onishi	N/A	N/A
2017/0184718	12/2016	Horsley et al.	N/A	N/A
2018/0317033	12/2017	Zhang	N/A	B81B 3/007
2023/0283963	12/2022	Chen	381/114	H04R 1/04

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
59-69591	12/1983	JP	N/A
2007081614	12/2006	JP	N/A
2008-236556	12/2007	JP	N/A
2008283312	12/2007	JP	N/A
2009506658	12/2008	JP	N/A
2010187076	12/2009	JP	N/A
2018098546	12/2017	JP	N/A
2011/093157	12/2010	WO	N/A
2014/061584	12/2013	WO	N/A

OTHER PUBLICATIONS

Official Communication issued in International Patent Application No. PCT/JP2019/051194, mailed on Feb. 18, 2020. cited by applicant

First Office Action in JP2021-519305, mailed Oct. 4, 2022, 3 pages. cited by applicant

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS (1) This application claims the benefit of priority to Japanese Patent Application No. 2019-092681 filed on May 16, 2019 and is a Continuation Application of PCT Application No. PCT/JP2019/051194 filed on Dec. 26, 2019. The entire contents of each application are hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION
1. Field of the Invention
(1) The present invention relates to a piezoelectric device and an acoustic transducer.
2. Description of the Related Art
(2) One of the documents of the related art that disclose configurations of piezoelectric devices is U.S. Patent Application Publication No. 2017/0184718. The piezoelectric device described in U.S. Patent Application Publication No. 2017/0184718 includes a substrate, a cover that is attached to the substrate, an ultrasonic transducer that includes a membrane portion and that is disposed on the substrate, and an integrated circuit that is disposed on the substrate and that is operatively coupled to the ultrasonic transducer. The cover surrounds the ultrasonic transducer and the integrated circuit. An acoustic cavity is formed in the substrate. The ultrasonic transducer is fixed to the substrate so as to substantially cover the acoustic cavity.
(3) In a piezoelectric device of the related art, a through hole is formed only in a portion of a substrate that faces a membrane portion. In this piezoelectric device, acoustic waves that are generated by vibration of the membrane portion are emitted through the through hole. Alternatively, acoustic waves that reach the membrane portion through the through hole cause the membrane portion to vibrate. These acoustic waves resonate in a region extending from an open end of the through hole that is located on the side opposite to the membrane portion side to the membrane portion. This resonance can improve device characteristics of the piezoelectric device such as the sound pressure, the sensitivity, and the band of the piezoelectric device.
(4) However, in the case of causing acoustic waves at lower frequencies to resonate in the above-described region so as to improve the device characteristics, it is necessary to further increase the distance from the open end of the substrate, the open end being located on the side opposite to the membrane portion side, to the membrane portion. When the above-described distance is increased, the thickness of the entire piezoelectric device increases.
SUMMARY OF THE INVENTION
(5) Preferred embodiments of the present invention provide piezoelectric devices and acoustic transducers that are each able to improve device characteristics without increasing the thickness of the piezoelectric devices.
(6) A piezoelectric device according to a preferred embodiment of the present invention includes a substrate, a piezoelectric element, and a cover. The substrate includes a first main surface and a second main surface opposite to the first main surface. The piezoelectric element is on the first main surface. The cover is on the first main surface. The cover covers the piezoelectric element and is spaced apart from the piezoelectric element on the first main surface side. The piezoelectric element includes a base portion and a membrane portion. The base portion is on the first main surface and has an annular external shape when viewed from the first main surface side. The

membrane portion is located inside the annular base portion when viewed from the first main surface side. The cover includes a first through hole. The substrate includes a second through hole at a position facing the membrane portion and extending between the first main surface and the second main surface.
(7) An acoustic transducer according to a preferred embodiment of the present invention includes a piezoelectric device, a mounting substrate, and a housing. The piezoelectric device includes a substrate, a piezoelectric element, and a cover. The substrate includes a first main surface and a second main surface opposite to the first main surface. The piezoelectric element is on the first main surface. The piezoelectric element includes a base portion and a membrane portion. The base portion is on the first main surface and has an annular external shape when viewed from the first main surface side. The membrane portion is located inside the annular base portion when viewed from the first main surface side. The cover covers the piezoelectric element and is spaced apart from the piezoelectric element on the first main surface side. The piezoelectric device is mounted on the mounting substrate such that the mounting substrate faces the second main surface. The housing accommodates the piezoelectric device and the mounting substrate. The housing includes a first wall and a second wall. The first wall is on a side opposite to the mounting substrate side with respect to the piezoelectric device. The second wall is on a side opposite to the piezoelectric device side with respect to the mounting substrate. The cover includes a first through hole. The substrate includes a second through hole at a position facing the membrane portion and extending between the first main surface and the second main surface. The mounting substrate includes a third through hole at a position facing the second through hole. The first wall includes a fourth through hole at a position facing the first through hole. The second wall includes a fifth through hole at a position facing the third through hole.
(8) According to preferred embodiments of the present invention, device characteristics are able to be improved without increasing the thicknesses of piezoelectric devices.
(9) The above and other elements, features, steps, characteristics and advantages of the present invention will become more apparent from the following detailed description of the preferred embodiments with reference to the attached drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a plan view illustrating a piezoelectric device according to a first preferred embodiment of the present invention.
(2) FIG. **2** is a sectional view of the piezoelectric device illustrated in FIG. **1** taken along line II-II of FIG. **1**.
(3) FIG. **3** is a sectional view of the piezoelectric device illustrated in FIG. **2** taken along line of FIG. **2**.
(4) FIG. **4** is a sectional view illustrating an acoustic transducer according to the first preferred embodiment of the present invention.
(5) FIG. **5** is a sectional view illustrating a piezoelectric device according to a second preferred embodiment of the present invention.
(6) FIG. **6** is a sectional view illustrating a portion of a piezoelectric device according to a third preferred embodiment of the present invention and a portion of an acoustic transducer according to the third preferred embodiment of the present invention.
(7) FIG. **7** is a diagram illustrating the piezoelectric device illustrated in FIG. **6** when viewed in the direction of arrow VII.
(8) FIG. **8** is a diagram illustrating the portion of the piezoelectric device and the portion of the acoustic transducer, which are illustrated in FIG. **6**, when viewed in the direction of arrow VIII.

(9) FIG. **9** is a sectional view illustrating a portion of a piezoelectric device according to a fourth preferred embodiment of the present invention and a portion of an acoustic transducer according to the fourth preferred embodiment of the present invention.

(10) FIG. **10** is a diagram illustrating the piezoelectric device illustrated in FIG. **9** when viewed in the direction of arrow X.

(11) FIG. **11** is a diagram illustrating the piezoelectric device and the acoustic transducer, which are illustrated in FIG. **9**, when viewed in the direction of arrow XI.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

(12) Piezoelectric devices and acoustic transducers according to preferred embodiments of the present invention will be described below with reference to the drawings. In the following descriptions of the preferred embodiments, portions that are the same as each other or that correspond to each other in the drawings are denoted by the same reference characters, and the descriptions thereof will not be repeated. In the present specification, the term “acoustic wave” includes “ultrasonic wave”, and the term “acoustic transducer” includes “ultrasonic transducer”.

First Preferred Embodiment

(13) A piezoelectric device according to the first preferred embodiment of the present invention will be described. FIG. **1** is a plan view illustrating a piezoelectric device according to a first preferred embodiment of the present invention. FIG. **2** is a sectional view of the piezoelectric device illustrated in FIG. **1** taken along line II-II of FIG. **1**. FIG. **3** is a sectional view of the piezoelectric device illustrated in FIG. **2** taken along line III-III of FIG. **2**.

(14) As illustrated in FIG. **1** to FIG. **3**, a piezoelectric device **100** includes a substrate **110**, a piezoelectric element **120**, and a cover **130**.

(15) As illustrated in FIG. **2**, the substrate **110** includes a first main surface **111** and a second main surface **112** opposite to the first main surface **111**. The substrate **110** includes a peripheral side surface **113** that connects the first main surface **111** and the second main surface **112** to each other.

(16) A second through hole **117** that is different from a first through hole, which will be described later, is provided in the substrate **110**. Details of the second through hole **117** will be described later.

(17) As illustrated in FIG. **2** and FIG. **3**, in the present preferred embodiment, the substrate **110** has a rectangular or substantially rectangular external shape when viewed from a direction normal to the first main surface **111**. When viewed from the direction normal to the first main surface **111**, the length of one side of the substrate **110** is, for example, about 1 mm or more and about 3 mm or less. The thickness of the substrate **110** in the direction normal to the first main surface **111** is, for example, about 0.1 mm or more and about 0.3 mm or less.

(18) Examples of a substrate that is used as the substrate **110** include a substrate such as a glass-epoxy substrate made of a material that is a combination of a resin and glass fiber, a multilayer substrate made of a low-temperature co-fired ceramic (LTCC), and a substrate made of a ceramic material containing, for example, alumina.

(19) A plurality of first electrodes **114** are provided on the first main surface **111** so as to be spaced apart from each other. Each of the plurality of first electrodes **114** is electrically connected to one of a plurality of electrodes (described later) of the piezoelectric element **120**.

(20) A plurality of second electrodes **115** are provided on the second main surface **112** so as to be spaced apart from one another. When the piezoelectric device **100** is mounted onto a mounting substrate, the plurality of second electrodes **115** are electrically connected to the mounting substrate. When the plurality of second electrodes **115** are connected to the mounting substrate, flow paths through which air can pass are provided between adjacent ones of the plurality of the second electrodes **115**. In other words, when the piezoelectric device **100** is mounted onto the mounting substrate, the air on the second main surface **112** can flow into the space outside the peripheral side surface **113** of the substrate **110** by passing through the gaps between the adjacent second electrodes **115**.

(21) In the present preferred embodiment, the plurality of first electrodes **114** are electrically connected to some of the plurality of second electrodes **115** by via electrodes **116**. The via electrodes **116** extend through the substrate **110** from the first main surface **111** to the second main surface **112**.
(22) As illustrated in FIG. **2** and FIG. **3**, the piezoelectric element **120** is disposed on the first main surface **111**. The piezoelectric element **120** includes a base portion **121** and a membrane portion **122**.
(23) As illustrated in FIG. **3**, the base portion **121** is located on the first main surface **111**, and the external shape of the base portion **121** is an annular shape when viewed from the first main surface **111**. In the present preferred embodiment, when viewed from the first main surface **111**, a peripheral side surface of the base portion **121** has a rectangular or substantially rectangular shape. When viewed from the first main surface **111**, the peripheral side surface of the base portion **121** may have a circular or substantially circular shape or a polygonal or substantially polygonal shape, for example.
(24) When viewed from the first main surface **111**, the membrane portion **122** is located inside the annular base portion **121**. The membrane portion **122** is supported by the base portion **121**. Thus, as illustrated in FIG. **2**, the piezoelectric element **120** includes a recess **123** that is surrounded by the base portion **121** and the membrane portion **122** on the side on which the substrate **110** is provided.
(25) The membrane portion **122** may include a slit that extends through the membrane portion **122** in the direction normal to the first main surface **111**. By providing such a slit, the membrane portion **122** may include a plurality of beam portions, at least one end of each beam portion being supported by the base portion **121**.
(26) As illustrated in FIG. **3**, in the present preferred embodiment, the membrane portion **122** has a circular or substantially circular external shape when viewed in the direction normal to the first main surface **111**. The diameter of the membrane portion **122** is, for example, about 0.5 mm or more and about 1.3 mm or less. When viewed in the direction normal to the first main surface **111**, the membrane portion **122** may have a rectangular or substantially rectangular external shape. The thickness of the membrane portion **122** in the direction normal to the first main surface **111** is, for example, about 0.5 μm or more and about 6.0 μm or less. When viewed in the direction normal to the first main surface **111**, the external shape of the membrane portion **122** may be a polygonal or substantially polygonal shape or a rectangular or substantially rectangular shape, for example.
(27) As illustrated in FIG. **2** and FIG. **3**, in the present preferred embodiment, the membrane portion **122** includes at least an upper electrode layer **124**, a lower electrode layer **125**, and a piezoelectric layer **126**. In the direction normal to the first main surface **111**, when the side on which the substrate **110** is provided with respect to the membrane portion **122** and the side opposite to the side on which the substrate **110** is provided with respect to the membrane portion **122** are respectively referred to as a lower side and an upper side, the upper electrode layer **124** is located on the upper side of the piezoelectric layer **126**. The lower electrode layer **125** faces at least a portion of the upper electrode layer **124** with the piezoelectric layer **126** interposed therebetween.
(28) As illustrated in FIG. **3**, the upper electrode layer **124** and the lower electrode layer **125** are arranged so as to extend from the membrane portion **122** toward the base portion **121**. The upper electrode layer **124** and the lower electrode layer **125** are electrically connected to the plurality of first electrodes **114** by wire bonding using a plurality of bonding wires **127**.
(29) In the present preferred embodiment, the membrane portion **122** is configured as described above, so that the membrane portion **122** can vibrate in the direction normal to the first main surface **111**. More specifically, in ultrasonic waves in a low-frequency region of about 20 kHz or higher and about 60 kHz or lower, for example, the membrane portion **122** is configured to vibrate in the direction normal to the first main surface **111** at a mechanical resonant frequency.
(30) As illustrated in FIG. **2**, in the present preferred embodiment, the piezoelectric element **120** is bonded to the substrate **110** with a die bonding material **128** that is provided between the base

portion **121** and the first main surface **111**. As illustrated in FIG. **2** and FIG. **3**, in the present preferred embodiment, by using the die bonding material **128**, the base portion **121** is bonded to the first main surface **111** of the substrate **110** without any gap therebetween along the entire or substantially the entire periphery of the base portion **121** when viewed in the direction normal to the first main surface **111**. As a result, the space on the side on which the recess **123** is provided with respect to the membrane portion **122** and the space on the side opposite to the side on which the recess **123** is provided with respect to the membrane portion **122** can be acoustically isolated from each other. In the case where a portion of the base portion **121** is bonded to the first main surface **111** of the substrate **110** with the die bonding material **128**, the above-described spaces may be acoustically isolated from each other by additionally injecting the die bonding material **128** or another material into the gap between the base portion **121** and the first main surface **111** of the substrate **110**.

(31) As illustrated in FIG. **3**, in the present preferred embodiment, the piezoelectric element **120** has a rectangular or substantially rectangular external shape when viewed in the direction normal to the first main surface **111**. When viewed in the direction normal to the first main surface **111**, the length of one side of the piezoelectric element **120** is, for example, about 0.5 mm or more and about 1.5 mm or less. The thickness of the piezoelectric element **120** in the direction normal to the first main surface **111** is, for example, about 0.2 mm or more and about 0.5 mm or less.

(32) In the present preferred embodiment, the piezoelectric element **120** is a micro-electromechanical systems (MEMS) element. In the present preferred embodiment, the piezoelectric element **120** can emit or receive ultrasonic waves by causing the membrane portion **122** to vibrate at a relatively low resonant frequency. In the present preferred embodiment, the frequency of these ultrasonic waves is specifically about 20 kHz or higher and about 60 kHz or lower, for example.

(33) As illustrated in FIG. **1** and FIG. **3**, the cover **130** is disposed on the first main surface **111**. In the present preferred embodiment, the cover **130** has an external shape that is the same or substantially the same as the external shape of the substrate **110** when viewed in the direction normal to the first main surface **111**.

(34) The cover **130** covers the piezoelectric element **120** and is spaced apart from the piezoelectric element **120** on the side on which the first main surface **111** is provided. The cover **130** is provided so as not to be in contact with the plurality of bonding wires **127**.

(35) The thickness of the cover **130** is adjusted so as to be smaller than a quarter of the wavelength of the vibration frequency of the piezoelectric element **120**. The thickness of the cover **130** is, for example, about 0.1 mm or more and about 0.3 mm or less.

(36) The cover **130** includes a first through hole **131**. In the present preferred embodiment, the first through hole **131** is provided so as to enable acoustic waves to enter and exit from a resonance space (described later) through the through hole **131** and to resonate in the resonance space. As a result of the resonance of acoustic waves in the resonance space, the device characteristics of the piezoelectric device **100**, such as the sound pressure, the sensitivity, and the band of the piezoelectric device **100**, are improved. In the present preferred embodiment, the first through hole **131** is provided at a position facing the membrane portion **122**. When viewed in the direction normal to the first main surface **111**, the center of the first through hole **131** may deviate from the center of the membrane portion **122**. When viewed in the direction normal to the first main surface **111**, the first through hole **131** may be positioned so as not to overlap the membrane portion **122**.

(37) In the present preferred embodiment, when viewed in a direction in which the first through hole **131** extends through the cover **130** (hereinafter referred to as “extending direction”), the first through hole **131** has a circular or substantially circular external shape. When viewed in the extending direction of the first through hole **131**, the external shape of the first through hole **131** may have a rectangular or substantially rectangular shape or a polygonal or substantially polygonal shape, for example.

(38) In the present preferred embodiment, the cover **130** is made of a metal material or a resin material. The cover **130** may be formed by cutting or press-working a member made of one of the above materials or may be formed by molding, for example.
(39) In the present preferred embodiment, the cover **130** is connected to the substrate **110** with a cover-portion adhesive **132** that is provided between the cover **130** and the first main surface **111**. In the present preferred embodiment, by using the cover-portion adhesive **132**, the cover **130** is bonded to the first main surface **111** without any gap therebetween along the whole outer periphery of the cover **130** when viewed in the direction normal to the first main surface **111**. As a result, a resonance space **134**, which is the space surrounded by the cover **130** and the piezoelectric element **120**, and the space outside the piezoelectric device **100** acoustically communicate with each other substantially only through the first through hole **131**.
(40) In the present preferred embodiment, the first through hole **131** faces the membrane portion **122**. Note that the position of the first through hole **131** is not particularly limited as long as the resonance space **134** and the space outside the piezoelectric device **100** acoustically communicate with each other.
(41) In the present preferred embodiment, a length L of the first through hole **131** in the extending direction, an area S of the first through hole **131** when viewed in the extending direction, and a volume V of the resonance space **134** are set such that acoustic waves that are transmitted from and received by the piezoelectric element **120** cause Helmholtz resonance in the resonance space **134**. More specifically, the length L, the area S, and the volume V are adjusted such that the value of a resonance frequency f expressed by the following formula (1) becomes close to the frequency of the acoustic waves transmitted from and received by the piezoelectric element **120**. Note that c in the following formula (1) stands for acoustic velocity.
(42) $f=\frac{c}{2}\sqrt{\frac{S}{VL}}$ (1)
(43) As described above, the length L of the first through hole **131** in the extending direction, the area S of the first through hole **131** when viewed in the extending direction, and the volume V of the resonance space **134** are set so as to cause Helmholtz resonance in the resonance space **134**, such that the device characteristics of the piezoelectric device **100**, such as the sound pressure, the sensitivity, and the band, can be improved. Note that, by taking into consideration the shape of the first through hole **131**, the length with end correction is used as the length L.
(44) In the piezoelectric device **100** according to the first preferred embodiment of the present invention, a voltage is applied to the plurality of second electrodes **115**, so that the voltage is applied between the upper electrode layer **124** and the lower electrode layer **125**, each of which is electrically connected to one of the plurality of second electrodes **115**. As a result, the piezoelectric layer **126** between the upper electrode layer **124** and the lower electrode layer **125** vibrates. Vibration of the piezoelectric layer **126** causes the membrane portion **122** to vibrate, and an ultrasonic wave is generated as an acoustic wave. This ultrasonic wave resonates in the resonance space **134** such that its sound pressure is amplified and then is emitted to the external space through the first through hole **131**.
(45) In the case where the piezoelectric device **100** receives acoustic waves such as ultrasonic waves, the acoustic waves that have entered the resonance space **134** through the first through hole **131** resonate in the resonance space **134**, and in a state where the sound pressure of the acoustic waves is amplified, the acoustic waves cause the membrane portion **122** to vibrate. As a result, a potential difference is generated between the upper electrode layer **124** and the lower electrode layer **125**, which sandwich the driven piezoelectric layer **126** from both sides of the piezoelectric layer **126**. This potential difference can be detected by the plurality of second electrodes **115**, which are electrically connected to the upper electrode layer **124** and the lower electrode layer **125**. In this manner, the piezoelectric device **100** according to the present preferred embodiment can receive acoustic waves.

(46) Here, details of the second through hole **117** provided in the substrate **110** will now be described. As illustrated in FIG. **2**, the second through hole **117** extends between the first main surface **111** and the second main surface **112**. The second through hole **117** is provided at a position facing the membrane portion **122**. As a result, the space in the recess **123** communicates with the space on the side on which the second main surface **112** of the substrate **110** is present via the second through hole **117**.
(47) If the second through hole **117** is not provided, the recess **123** is covered with the substrate **110**. In the case where the recess **123** is covered with the substrate **110**, when the membrane portion **122** vibrates, the air in the recess **123** acts on the membrane portion **122** as an air spring. As a result, the amount of displacement of the membrane portion **122** decreases, the resonant frequency of the membrane portion **122** becomes higher, or the frequency band of the resonant frequency becomes narrower. In the present preferred embodiment, since the second through hole **117** is provided, the probability that the air in the recess **123** will act on the membrane portion **122** as an air spring can be reduced.
(48) Note that, in the first preferred embodiment of the present invention, the second through hole **117** has a circular or substantially circular external shape when viewed in the direction normal to the first main surface **111**. The inner diameter of the second through hole **117** is, for example, about 0.1 mm or more and about 1.3 mm or less. Note that the second through hole **117** may have a rectangular or substantially rectangular external shape when viewed in the direction normal to the first main surface **111**. In addition, when viewed in the direction normal to the first main surface **111**, the second through hole **117** is located inside the base portion **121**.
(49) As described above, in the piezoelectric device **100** according to the first preferred embodiment of the present invention, the cover **130** includes the first through hole **131**. The substrate **110** includes the second through hole **117** at a position facing the membrane portion **122** and that extends between the first main surface **111** and the second main surface **112**.
(50) With the above-described configuration, acoustic waves can resonate in the resonance space **134**, and the probability that the air in the recess **123** of the piezoelectric element **120** will act on the membrane portion **122** as an air spring can be reduced. As a result, the device characteristics of the piezoelectric device **100** can be improved without increasing the thickness of the piezoelectric device **100**.
(51) Next, an acoustic transducer according to the first preferred embodiment of the present invention will be described. FIG. **4** is a sectional view illustrating the configuration of the acoustic transducer according to the first preferred embodiment of the present invention.
(52) As illustrated in FIG. **4**, an acoustic transducer **10** includes the piezoelectric device **100**, a mounting substrate **11**, and a housing **12**.
(53) The piezoelectric device **100** is mounted on the mounting substrate **11** such that the mounting substrate **11** faces the second main surface **112**. More specifically, the plurality of second electrodes **115** on the second main surface **112** are joined to the mounting substrate **11**. The plurality of second electrodes **115** are electrically connected to wiring lines (not illustrated) of the mounting substrate **11**.
(54) The mounting substrate **11** includes a third through hole **11***h* at a position facing the second through hole **117**.
(55) The piezoelectric device **100** and the mounting substrate **11** are accommodated in the housing **12**. The housing **12** includes a first wall **13** and a second wall **14**. The first wall **13** and the second wall **14** are connected to each other by a third wall **15**.
(56) The first wall **13** is located on the side opposite to the side on which the mounting substrate **11** is provided with respect to the piezoelectric device **100**. The first wall **13** includes a fourth through hole **13***h* at a position facing the first through hole **131**.
(57) The second wall **14** is located on the side opposite to the side on which the piezoelectric device **100** is provided with respect to the mounting substrate **11**. The second wall **14** includes a

fifth through hole **14***h* at a position facing the third through hole **11***h*.
(58) A first gasket **16** is disposed between the cover **130** and the first wall **13**. The first gasket **16** fixes the position of the first wall **13** relative to the cover **130**. The first gasket **16** is disposed such that no substantial gap is provided between a portion of the first gasket **16** that is in contact with the cover **130** and the cover **130** and such that no substantial gap is provided between a portion of the first gasket **16** that is in contact with the first wall **13** and the first wall **13**. The first gasket **16** includes a sixth through hole **16***h*. The sixth through hole **16***h* is located between the first through hole **131** and the fourth through hole **13***h*. In other words, the first gasket **16** surrounds the first through hole **131** and the fourth through hole **13***h* when viewed in the direction normal to the first main surface **111**.
(59) A second gasket **17** is disposed between the mounting substrate **11** and the second wall **14**. The second gasket **17** fixes the position of the second wall **14** relative to the mounting substrate **11**. The second gasket **17** is disposed such that no substantial gap is provided between a portion of the second gasket that is in contact with the mounting substrate **11** and the mounting substrate **11** and such that no substantial gap is provided between a portion of the second gasket **17** that is in contact with the second wall **14** and the second wall **14**. The second gasket **17** includes a seventh through hole **17***h*. The second gasket **17** is located between the third through hole **11***h* and the fifth through hole **14***h*. In other words, the second gasket **17** surrounds the third through hole **11***h* and the fifth through hole **14***h* when viewed in the direction normal to the first main surface **111**.
(60) As described above, in the acoustic transducer **10** according to the first preferred embodiment of the present invention, the mounting substrate **11** includes the third through hole **11***h* at the position facing the second through hole **117**. The first wall **13** includes the fourth through hole **13***h* at the position facing the first through hole **131**. The second wall **14** includes the fifth through hole **14***h* at the position facing the third through hole **11***h*.
(61) As a result, the piezoelectric device **100** can transmit and receive an acoustic wave **1** on both the side on which the first through hole **131** is provided and the side on which the second through hole **117** is provided. Consequently, compared with an acoustic transducer that performs transmission and reception of acoustic waves on only one side, the angle at which the acoustic transducer **10** according to the present preferred embodiment is capable of transmitting and receiving acoustic waves can be widened.
Second Preferred Embodiment
(62) A piezoelectric device according to a second preferred embodiment of the present invention will be described below. A main difference between the piezoelectric device according to the second preferred embodiment of the present invention and the piezoelectric device according to the first preferred embodiment of the present invention is the design of a second through hole. Thus, the descriptions of components that are the same as or similar to those of the piezoelectric device **100** according to the first preferred embodiment of the present invention will not be repeated.
(63) FIG. **5** is a sectional view illustrating the piezoelectric device according to the second preferred embodiment of the present invention. FIG. **5** illustrates the same cross section as in FIG. **2**.
(64) As illustrated in FIG. **5**, in a piezoelectric device **200** according to the second preferred embodiment of the present invention, a second through hole **217** is provided such that its hole diameter decreases from the side on which the first main surface **111** is provided toward the side on which the second main surface **112** is provided. As a result, as in the first preferred embodiment of the present invention, deterioration of device characteristics can be reduced or prevented by the second through hole **217**, and in the case of transmitting acoustic waves only from the side on which the first through hole **131** is provided, the probability that an unnecessary acoustic wave will be emitted to the outside the piezoelectric device **200** through the second through hole **217** can be reduced. Accordingly, the probability that an acoustic wave that is emitted from the side on which the second through hole **217** is provided will interfere with an acoustic wave that is transmitted

from the side on which the first through hole **131** is provided can be reduced.
(65) In the piezoelectric device **200** according to the second preferred embodiment of the present invention, a porous material **240** is injected into at least a portion of the first through hole **131** or at least a portion of the second through hole **217**. As a result, in the case of performing transmission and reception of acoustic waves on only one of the side on which the first through hole **131** is provided and the side on which the second through hole **217** is provided, an unnecessary acoustic wave can be absorbed on the side on which the transmission and reception of acoustic waves are not performed. Accordingly, the probability that the above-described unnecessary acoustic wave will pass through the second through hole **217** and will interfere with acoustic waves that are transmitted from and received by the piezoelectric device **200** can be reduced.
(66) In the present preferred embodiment, the porous material **240** is injected into the second through hole **217**. In addition, in the present preferred embodiment, the second through hole **217** is filled with the porous material **240**. In the case where the second through hole **217** is filled with the porous material **240**, it is preferable that the porous material **240** include open cells.
Third Preferred Embodiment
(67) A piezoelectric device according to a third preferred embodiment of the present invention and an acoustic transducer according to the third preferred embodiment of the present invention will be described below. A main difference between the piezoelectric device according to the third preferred embodiment of the present invention and the piezoelectric device **100** according to the first preferred embodiment of the present invention is the design of a second through hole. A main difference between the acoustic transducer according to the third preferred embodiment of the present invention and the acoustic transducer **10** according to the first preferred embodiment of the present invention is the structure of a mounting substrate. Thus, the descriptions of components that are the same as or similar to those of the piezoelectric device **100** and the acoustic transducer **10** according to the first preferred embodiment of the present invention will not be repeated.
(68) FIG. **6** is a sectional view illustrating a portion of the piezoelectric device according to the third preferred embodiment of the present invention and a portion of the acoustic transducer according to the third preferred embodiment of the present invention. FIG. **7** is a diagram illustrating the piezoelectric device illustrated in FIG. **6** when viewed in the direction of arrow VII. FIG. **8** is a diagram illustrating the portion of the piezoelectric device and the portion of the acoustic transducer, which are illustrated in FIG. **6**, when viewed in the direction of arrow VIII. FIG. **6** illustrates the same cross section as in FIG. **2**.
(69) As illustrated in FIG. **6**, in the acoustic transducer according to the third preferred embodiment of the present invention, a mounting substrate **31** includes no through hole. Thus, a piezoelectric device **300** according to the third preferred embodiment of the present invention is configured such that the probability that the air in the recess **123** will act on the membrane portion **122** as an air spring can be further reduced by the shape of a second through hole **317**.
(70) More specifically, in the piezoelectric device **300** according to the third preferred embodiment of the present invention, the hole diameter of the second through hole **317** on the side on which the second main surface **112** is provided is larger than the hole diameter of the second through hole **317** on the side on which the first main surface **111** is provided. This makes it difficult for the recess **123** to act as an air spring together with the second through hole **317**, which is in communication with the recess **123**, and thus, deterioration of the device characteristics of the piezoelectric device **300** can be further reduced or prevented.
(71) As illustrated in FIG. **6** to FIG. **8**, in the acoustic transducer according to the third preferred embodiment of the present invention, the second main surface **112** and the mounting substrate **31** are not in direct contact with each other, and the plurality of second electrodes **115** on the second main surface **112** are spaced apart from one another. Thus, a space that is defined by the recess **123** and the second through hole **317** communicates with the space on the side on which peripheral side surface **113** of the piezoelectric device **300** is provided via the gaps between the plurality of second

electrodes **115**. Each of the plurality of second electrodes **115** has a relatively small thickness. As a result, in the acoustic transducer according to the third preferred embodiment of the present invention, air flow paths **2** are provided between the plurality of second electrodes **115** on the side on which the second through hole **317** is provided, and emission of unnecessary ultrasonic waves is reduced or prevented.

Fourth Preferred Embodiment

(72) A piezoelectric device according to a fourth preferred embodiment of the present invention will be described below. A difference between the piezoelectric device according to the fourth preferred embodiment of the present invention and the piezoelectric device according to the third preferred embodiment of the present invention is the structure of a substrate. Thus, the descriptions of components that are the same as or similar to those of the piezoelectric device **300** according to the third preferred embodiment of the present invention will not be repeated.

(73) FIG. **9** is a sectional view illustrating a portion of the piezoelectric device according to the fourth preferred embodiment of the present invention and a portion of an acoustic transducer according to the fourth preferred embodiment of the present invention. FIG. **10** is a diagram illustrating the piezoelectric device illustrated in FIG. **9** when viewed in the direction of arrow X. FIG. **11** is a diagram illustrating the piezoelectric device and the acoustic transducer, which are illustrated in FIG. **9**, when viewed in the direction of arrow XI. FIG. **9** illustrates the same cross section as in FIG. **6**.

(74) As illustrated in FIG. **9** to FIG. **11**, in the fourth preferred embodiment of the present invention, the substrate **110** includes communication portions **418** that extend from the peripheral side surface **113** so as to communicate with a second through hole **417**. In other words, the second through hole **417** and the communication portions **418** allow communication between the space inside the recess **123** and the space outside a piezoelectric device **400**, so that the air flow paths **2** are provided. As a result, the probability that the air in the recess **123** of the piezoelectric element **120** will act on the membrane portion **122** as an air spring can be further reduced. Accordingly, deterioration of the device characteristics of the piezoelectric device **400** can be further reduced or prevented.

(75) In the fourth preferred embodiment of the present invention, the substrate **110** includes the plurality of communication portions **418**. When the substrate **110** is viewed from the second main surface **112**, the plurality of communication portions **418** are positioned between adjacent ones of the plurality of second electrodes **115** at the four corners.

(76) In the above-described preferred embodiments, the configurations that can be combined may be combined with each other.

(77) While preferred embodiments of the present invention have been described above, it is to be understood that variations and modifications will be apparent to those skilled in the art without departing from the scope and spirit of the present invention. The scope of the present invention, therefore, is to be determined solely by the following claims.

Claims

1. A piezoelectric device comprising: a substrate including a first main surface and a second main surface opposite to the first main surface; a piezoelectric element on the first main surface; and a cover on the first main surface, covering the piezoelectric element, and being spaced apart from the piezoelectric element on the first main surface side; wherein the piezoelectric element includes a base portion on the first main surface and having an annular external shape when viewed from the first main surface side and a membrane portion inside the annular base portion when viewed from the first main surface side; the cover includes a first through hole; the substrate includes a second through hole facing the membrane portion and extending between the first main surface and the second main surface; a hole diameter of the second through hole on the second main surface side is

larger than a hole diameter of the second through hole on the first main surface side; and a porous material is provided at least at a portion of the first through hole or at a portion of the second through hole.

2. The piezoelectric device according to claim 1, wherein a thickness of the substrate is about 0.1 mm or more and about 0.3 mm or less.

3. The piezoelectric device according to claim 1, wherein a plurality of first electrodes are provided on the first main surface so as to be spaced apart from each other; and a plurality of second electrodes are provided on the second main surface so as to be spaced apart from each other.

4. The piezoelectric device according to claim 3, wherein at least one of the plurality of first electrodes is electrically connected to a corresponding one of the plurality of second electrodes by a via electrodes.

5. The piezoelectric device according to claim 1, wherein the membrane portion has a circular or substantially circular shape; and a diameter of the membrane portion is about 0.5 mm or more and about 1.3 mm or less.

6. A piezoelectric device comprising: a substrate including a first main surface and a second main surface opposite to the first main surface; a piezoelectric element on the first main surface; and a cover on the first main surface, covering the piezoelectric element, and being spaced apart from the piezoelectric element on the first main surface side; wherein the piezoelectric element includes a base portion on the first main surface and having an annular external shape when viewed from the first main surface side and a membrane portion inside the annular base portion when viewed from the first main surface side; the cover includes a first through hole; the substrate includes a second through hole facing the membrane portion and extending between the first main surface and the second main surface; the substrate includes a peripheral side surface connecting the first main surface and the second main surface to each other; and the substrate includes a communication portion extending from the peripheral side surface so as to communicate with the second through hole.

7. An acoustic transducer comprising: a piezoelectric device including a substrate including a first main surface and a second main surface opposite to the first main surface, a piezoelectric element on the first main surface, and a cover on the first main surface, covering the piezoelectric element, and being spaced apart from the piezoelectric element on the first main surface side; a mounting substrate on which the piezoelectric device is mounted such that the mounting substrate faces the second main surface; and a housing accommodating the piezoelectric device and the mounting substrate and including a first wall and a second wall, the first wall being located on a side opposite to the mounting substrate side with respect to the piezoelectric device, and the second wall being located on a side opposite to the piezoelectric device side with respect to the mounting substrate; wherein the piezoelectric element includes a base portion on the first main surface and having an annular external shape when viewed from the first main surface side and a membrane portion inside the annular base portion when viewed from the first main surface side; the cover includes a first through hole; the substrate includes a second through hole facing the membrane portion and extending between the first main surface and the second main surface; the mounting substrate includes a third through hole facing the second through hole; the first wall includes a fourth through hole facing the first through hole; and the second wall includes a fifth through hole facing the third through hole.

8. The acoustic transducer according to claim 7, wherein the second through hole has a hole diameter that decreases from the first main surface side towards the second main surface side.

9. The acoustic transducer according to claim 7, wherein a hole diameter of the second through hole on the second main surface side is larger than a hole diameter of the second through hole on the first main surface side.

10. The acoustic transducer according to claim 7, wherein the substrate includes a peripheral side surface connecting the first main surface and the second main surface to each other; and the

substrate includes a communication portion extending from the peripheral side surface so as to communicate with the second through hole.

11. The acoustic transducer according to claim 7, wherein a porous material is provided at least at a portion of the first through hole or at a portion of the second through hole.

12. The acoustic transducer according to claim 7, wherein a thickness of the substrate is about 0.1 mm or more and about 0.3 mm or less.

13. The acoustic transducer according to claim 7, wherein a plurality of first electrodes are provided on the first main surface so as to be spaced apart from each other; and a plurality of second electrodes are provided on the second main surface so as to be spaced apart from each other.

14. The acoustic transducer according to claim 13, wherein the plurality of first electrodes are electrically connected to some of the plurality of second electrodes by via electrodes.

15. The acoustic transducer according to claim 7, wherein the membrane portion includes a slit extending therethrough in a direction normal to the first main surface.

16. The acoustic transducer according to claim 7, wherein the membrane portion has a circular or substantially circular shape; and a diameter of the membrane portion is about 0.5 mm or more and about 1.3 mm or less.