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(54) **BONE CONDUCTION DEVICE HAVING A MULTILAYER PIEZOELECTRIC ELEMENT**

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(21) Appl. No.: **16/396,895**

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Issued: **Sep. 16, 2014**
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Filed: **Mar. 25, 2010**

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(63) Continuation of application No. 15/254,237, filed on Sep. 1, 2016, now abandoned, which is an application for the reissue of Pat. No. 8,837,760.

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H04R 1/24 (2006.01)

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CPC ***H04R 17/00*** (2013.01); ***H04R 25/606*** (2013.01); *H04R 1/24* (2013.01); *H04R 2225/67* (2013.01); *H04R 2460/13* (2013.01)

(58) **Field of Classification Search**
CPC .. H04R 25/606; H04R 17/00; H04R 2460/13; H04R 2225/67; H04R 1/24
See application file for complete search history.

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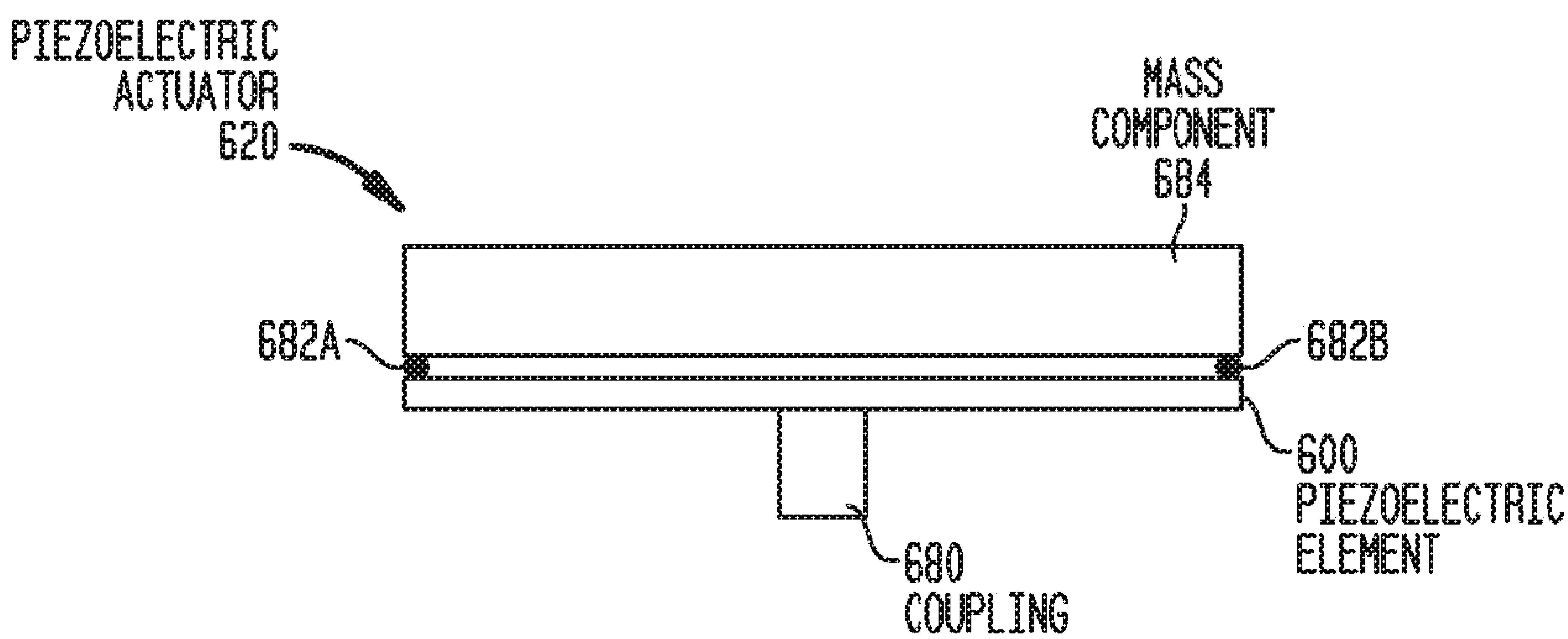
(57) **ABSTRACT**

A bone conduction device comprising a multilayer piezoelectric element. The multilayer piezoelectric element comprises two stacked piezoelectric layers, and a flexible passive layer disposed between the piezoelectric layers. The device also comprises a mass component attached to the multilayer piezoelectric element; and a coupling attached to the multilayer piezoelectric element configured to transfer mechanical forces generated by the multilayer piezoelectric element and the mass component to a recipient's skull.

25 Claims, 8 Drawing Sheets



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International Application No. PCT/AU2009/000358, Written Opinion mailed on Jul. 14, 2009, 6 Pages.

International Application No. PCT/AU2009/000372, International Preliminary Report on Patentability mailed on Oct. 5, 2010, 8 Pages.

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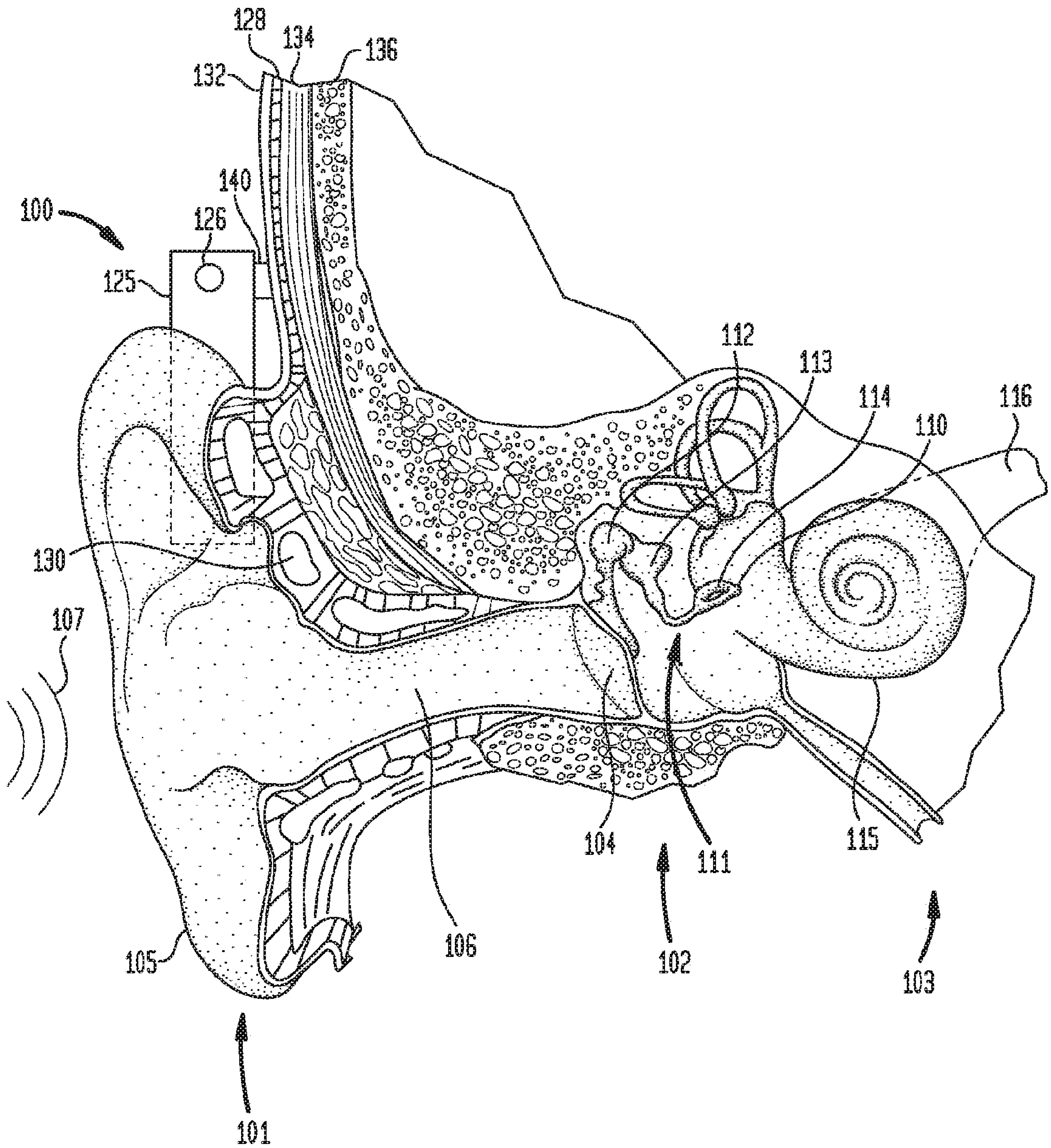
FIG. 1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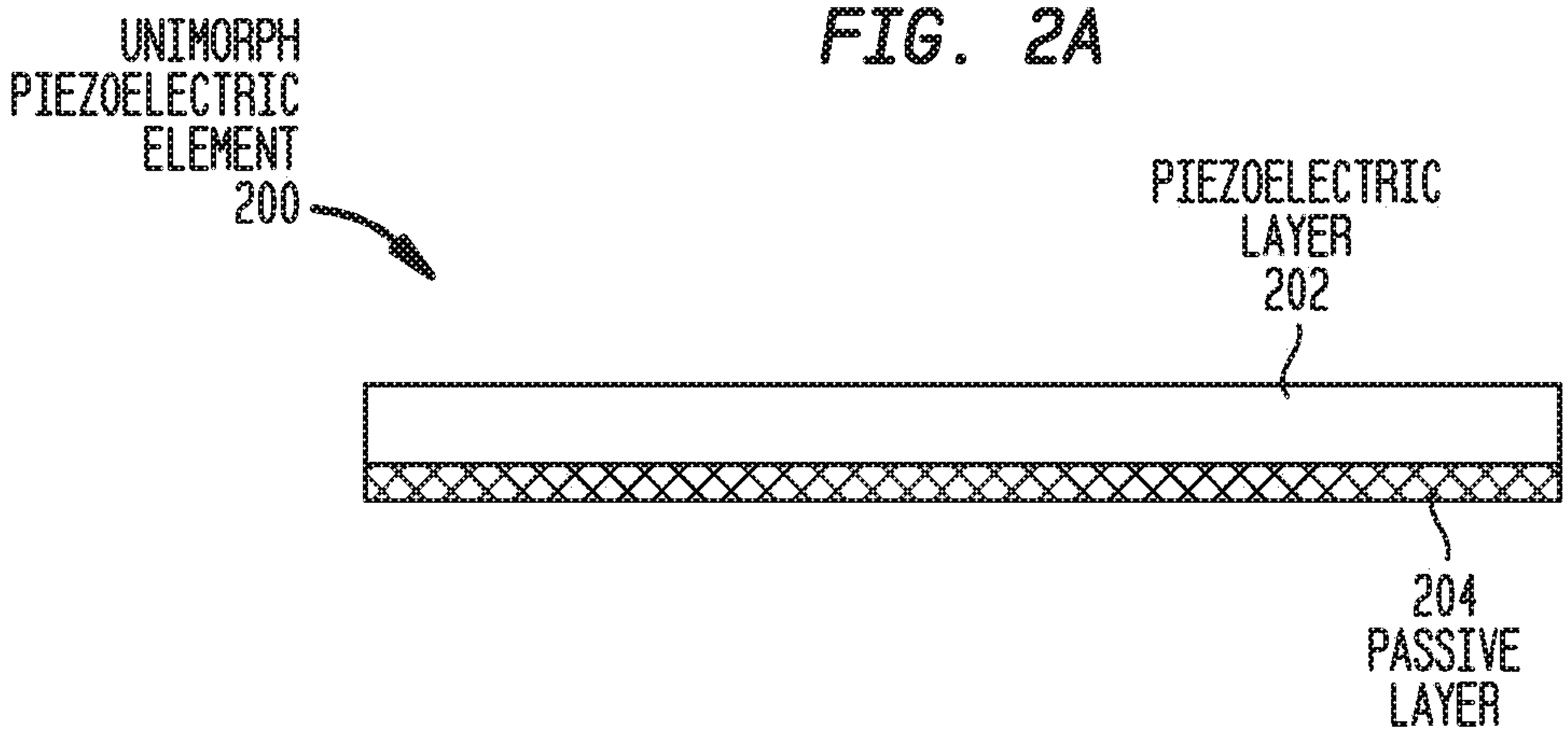
103
101

FIG. 2A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ELEMENT
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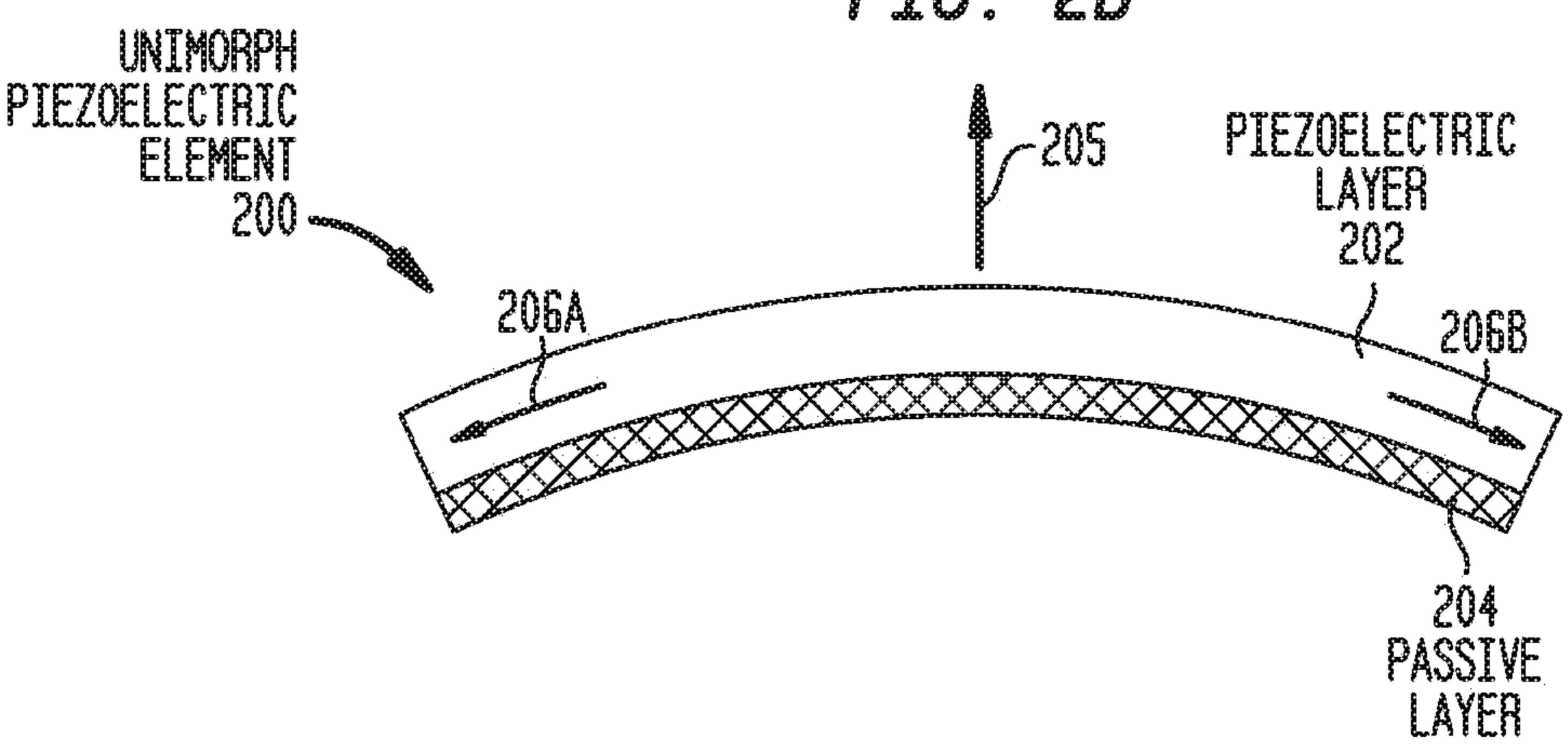
PIEZOELECTRIC
LAYER
202
204
PASSIVE
LAYER

FIG. 2B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LAYER
202
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206B
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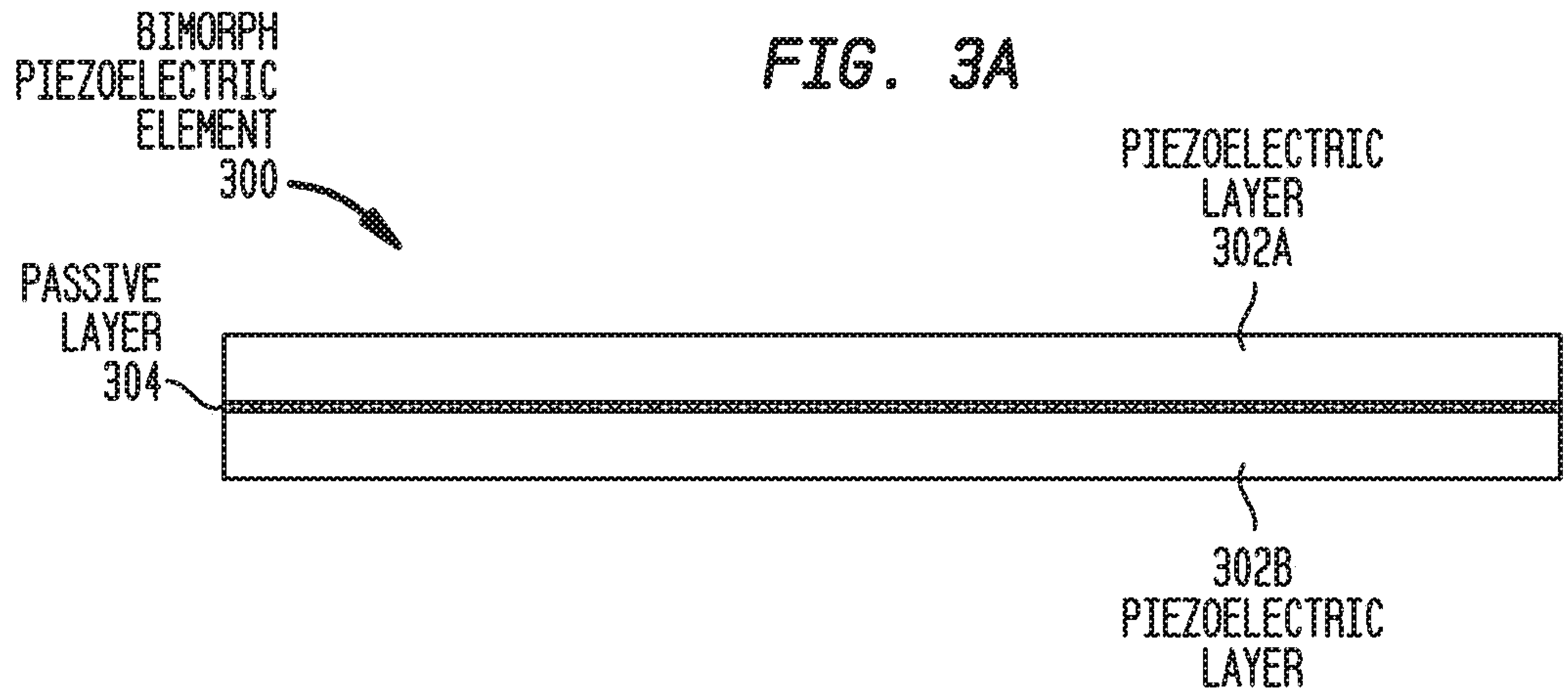
FIG. 3A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LAYER
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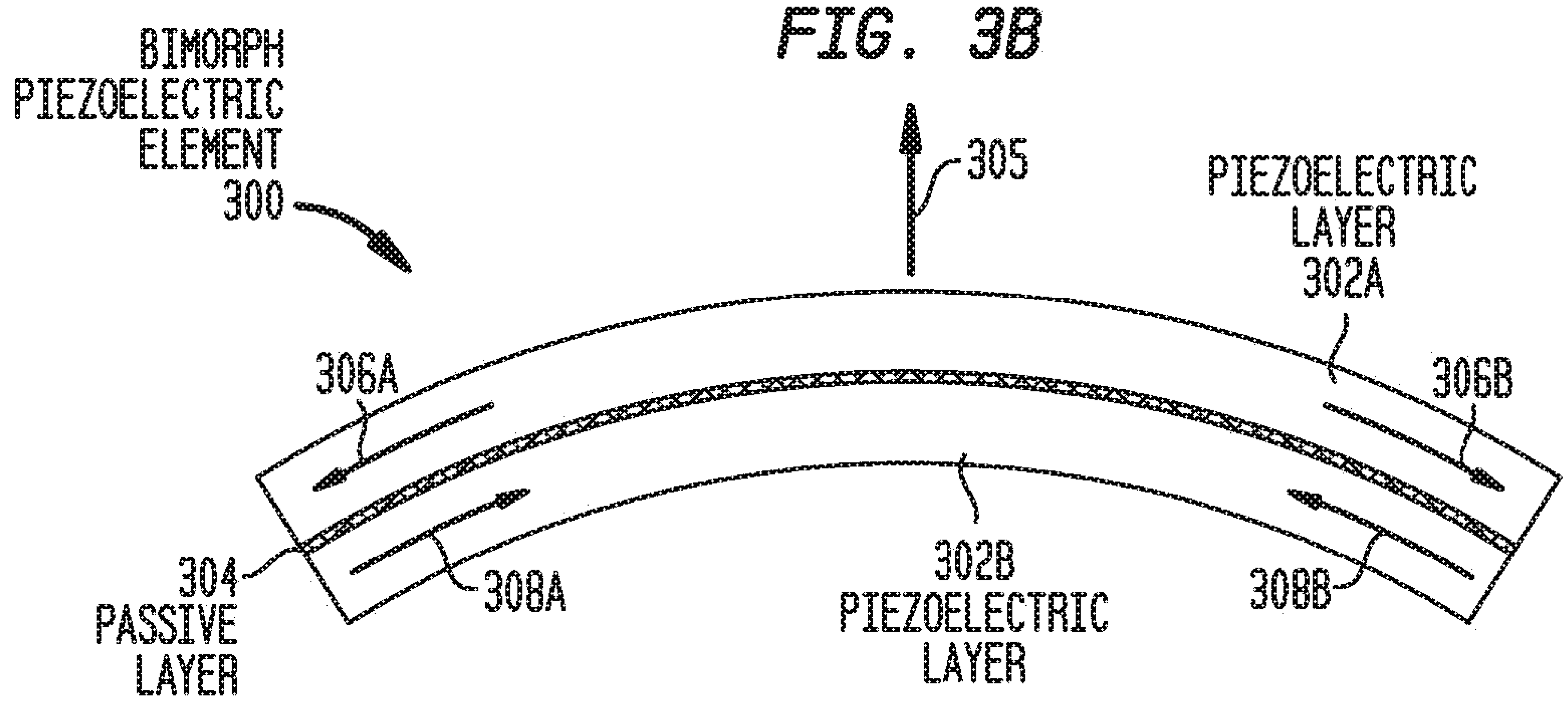
PIEZOELECTRIC
LAYER
302A
302B
PIEZOELECTRIC
LAYER

FIG. 3B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ELEMENT
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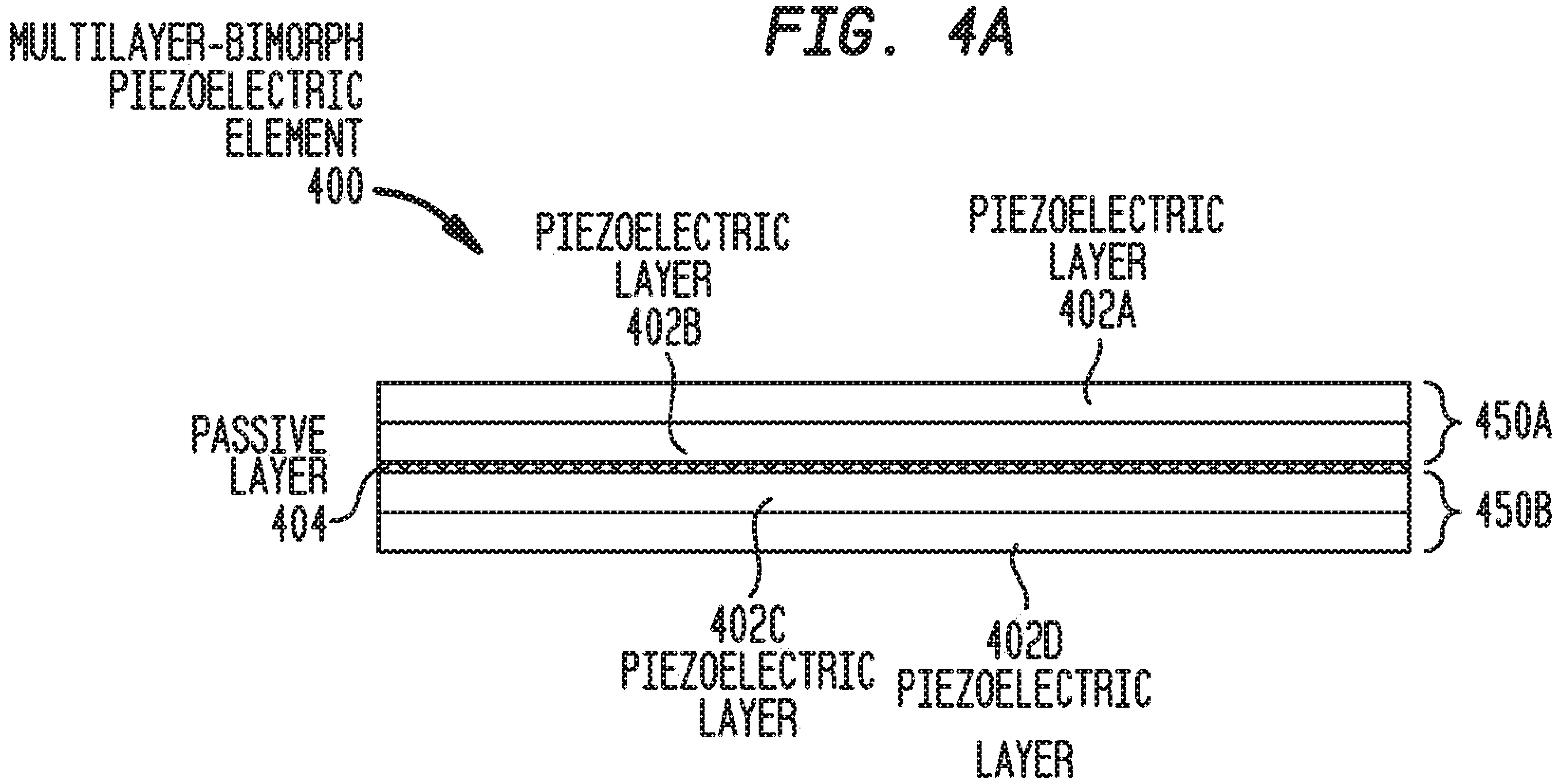
305
PIEZOELECTRIC
LAYER
302A
306A
306B
304
PASSIVE
LAYER
308A
302B
PIEZOELECTRIC
LAYER
308B

FIG. 4A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ELEMENT
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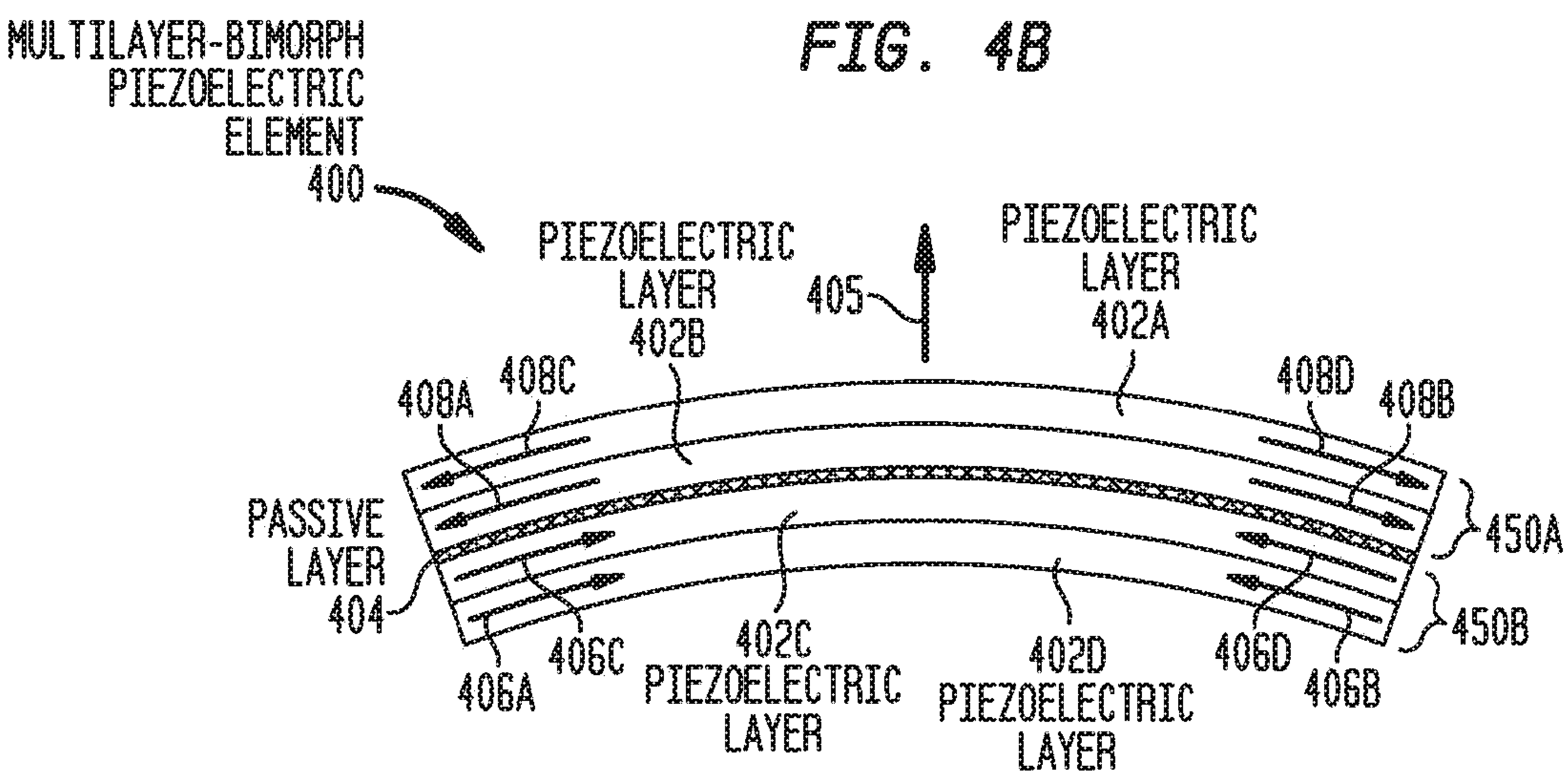
PIEZOELECTRIC
LAYER
402B
PIEZOELECTRIC
LAYER
402A
PASSIVE
LAYER
404
450A
450B
402C
PIEZOELECTRIC
LAYER
402D
PIEZOELECTRIC
LAYER

FIG. 4B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LAYER
402B
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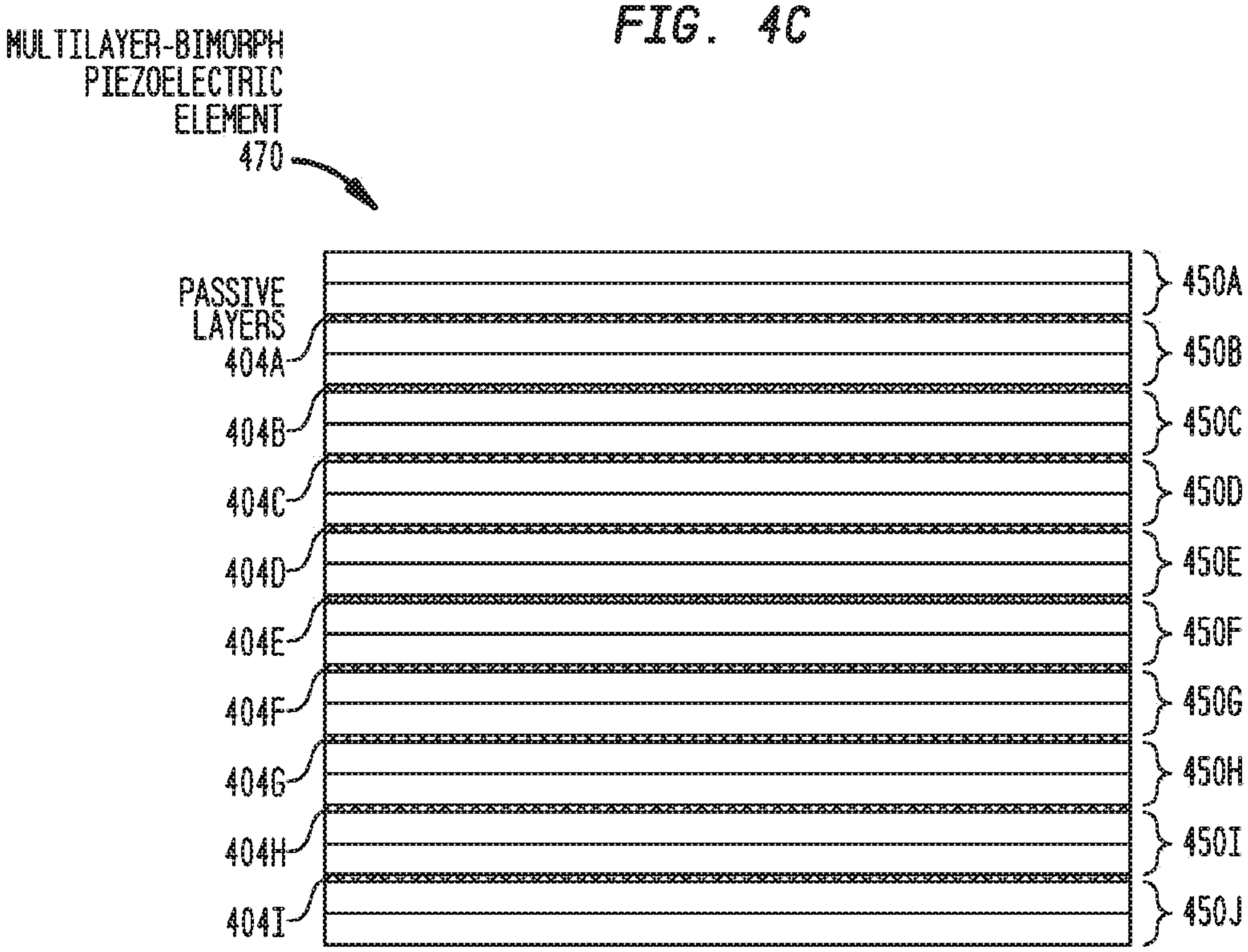
LAYER
402A
408A
408C
408D
408B
PASSIVE
LAYER
404
450A
450B
406A
406C
402C
PIEZOELECTRIC
LAYER
402D
PIEZOELECTRIC
LAYER
406D
406B

FIG. 4C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ELEMENT
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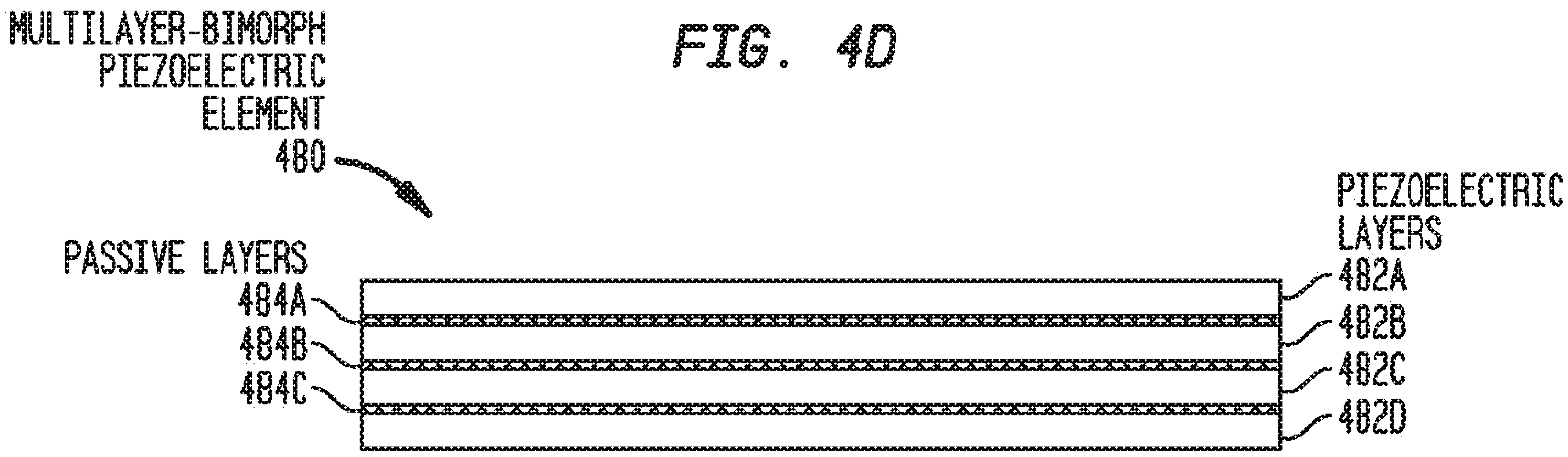
PASSIVE
LAYERS
404A
404B
404C
404D
404E
404F
404G
404H
404I
450A
450B
450C
450D
450E
450F
450G
450H
450I
450J

FIG. 4D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ELEMENT
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484A
484B
484C
PIEZOELECTRIC
LAYERS
482A
482B
482C
482D

FIG. 5

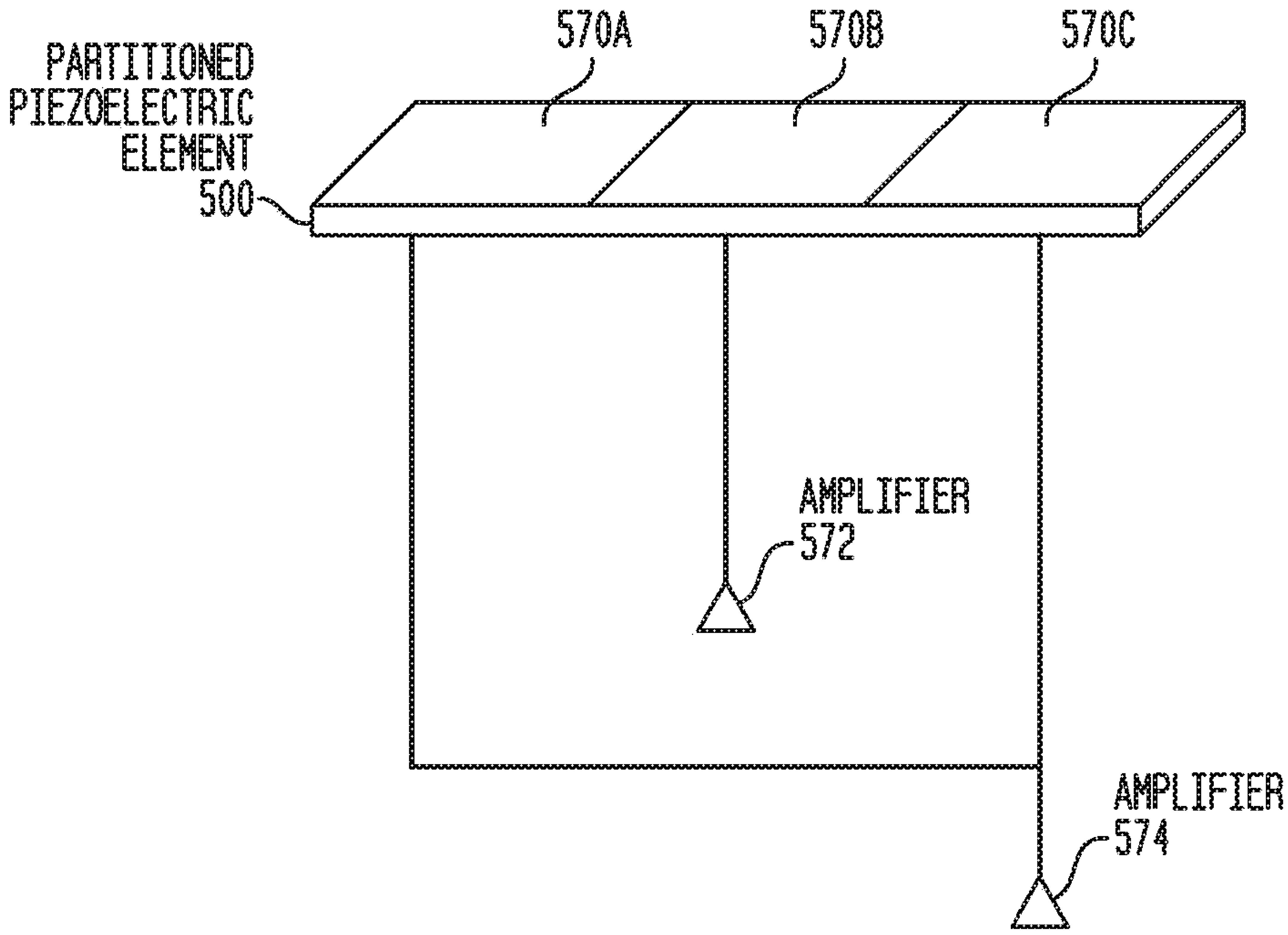

570A
570B
570C
PARTITIONED PIEZOELECTRIC ELEMENT 500
AMPLIFIER 572
AMPLIFIER 574

FIG. 6

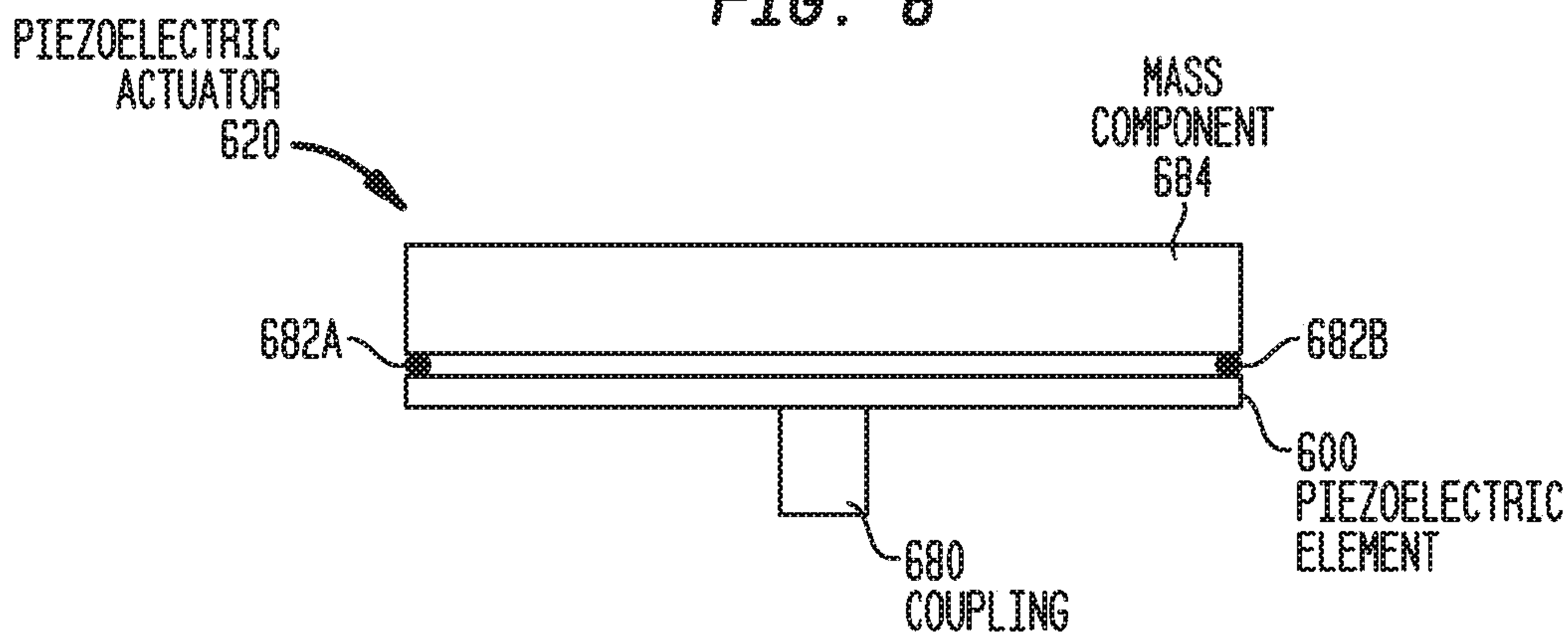
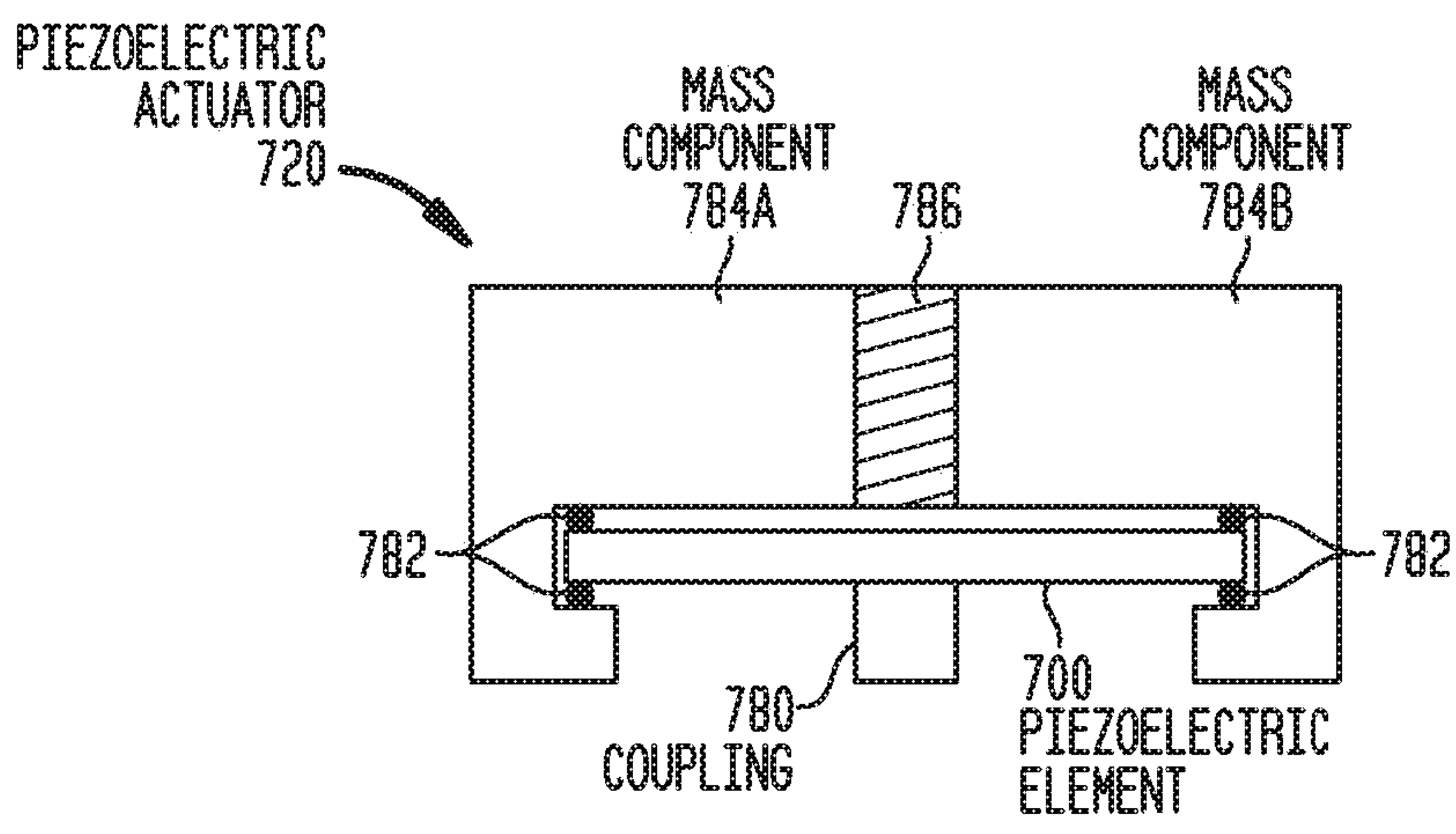

PIEZOELECTRIC
ACTUATOR
620
MASS
COMPONENT
684
682A
682B
600
PIEZOELECTRIC
ELEMENT
680
COUPLING

FIG. 7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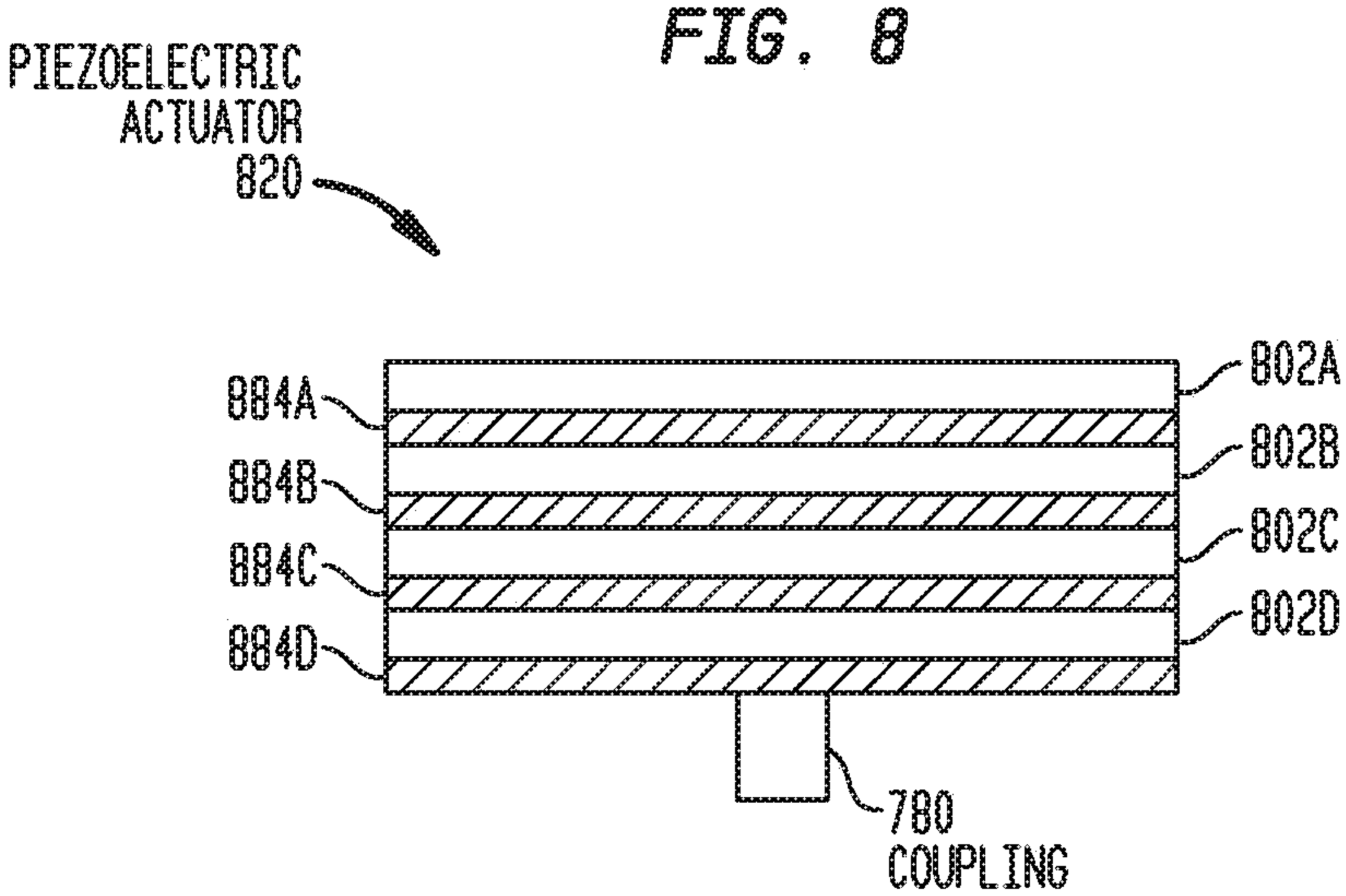
ACTUATOR
720
MASS
COMPONENT
784A
786
MASS
COMPONENT
784B
782
782
780
COUPLING
700
PIEZOELECTRIC
ELEMENT

FIG. 8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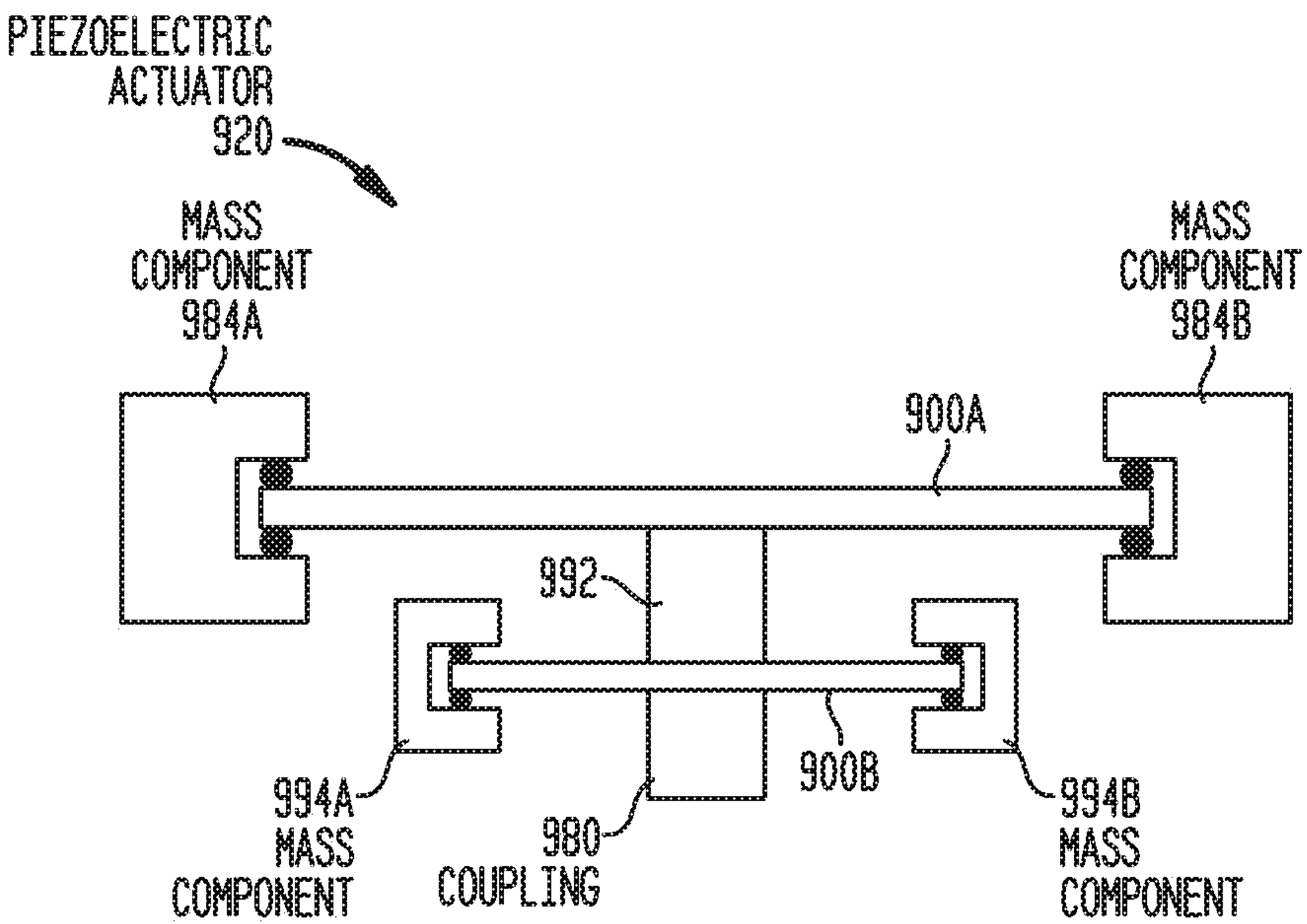
884B
884C
884D
802A
802B
802C
802D
780
COUPLING

FIG. 9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ACTUATOR
920
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COMPONENT
984A
MASS
COMPONENT
984B
900A
992
900B
994A
MASS
COMPONENT
980
COUPLING
994B
MASS
COMPONENT

BONE CONDUCTION DEVICE HAVING A MULTILAYER PIEZOELECTRIC ELEMENT

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority from German Patent Application No. 102009014770.5, filed Mar. 25, 2009, which is hereby incorporated by reference herein.

BACKGROUND

1. Field of the Invention

The present invention relates generally to bone conduction devices, and more particularly, to a bone conduction device having a multilayer piezoelectric element.

2. Related Art

Hearing loss, which may be due to many different causes, is generally of two types, conductive and sensorineural. Sensorineural hearing loss is due to the absence or destruction of the hair cells in the cochlea that transduce sound signals into nerve impulses. Various prosthetic hearing implants have been developed to provide individuals who suffer from sensorineural hearing loss with the ability to perceive sound. One such prosthetic hearing implant is referred to as a cochlear implant. Cochlear implants use an electrode array implanted in the cochlea of a recipient to bypass the mechanisms of the ear. More specifically, an electrical stimulus is provided via the electrode array directly to the auditory nerve, thereby causing a hearing sensation.

Conductive hearing loss occurs when the normal mechanical pathways that provide sound to hair cells in the cochlea are impeded, for example, by damage to the ossicular chain or ear canal. However, individuals suffering from conductive hearing loss may retain some form of residual hearing because the hair cells in the cochlea may remain undamaged.

Still other individuals suffer from mixed hearing losses, that is, conductive hearing loss in conjunction with sensorineural hearing. Such individuals may have damage to the outer or middle ear, as well as to the inner ear (cochlea).

Individuals suffering from conductive hearing loss are typically not candidates for a cochlear implant due to the irreversible nature of the cochlear implant. Specifically, insertion of the electrode assembly into a recipient's cochlea exposes the recipient to potential destruction of the majority of hair cells within the cochlea. Typically, destruction of the cochlea hair cells results in the loss of residual hearing in the portion of the cochlea in which the electrode assembly is implanted.

Rather, individuals suffering from conductive hearing loss typically receive an acoustic hearing aid, referred to as a hearing aid herein. Hearing aids rely on principles of air conduction to transmit acoustic signals to the cochlea. In particular, a hearing aid typically uses an arrangement positioned in the recipient's ear canal or on the outer ear to amplify a sound received by the outer ear of the recipient.

This amplified sound reaches the cochlea causing motion of the perilymph and stimulation of the auditory nerve.

Unfortunately, not all individuals who suffer from conductive hearing loss are able to derive suitable benefit from hearing aids. For example, some individuals are prone to chronic inflammation or infection of the ear canal thereby eliminating hearing aids as a potential solution. Other individuals have malformed or absent outer ear and/or ear canals resulting from a birth defect, or as a result of medical conditions such as Treacher Collins syndrome or Microtia. Furthermore, hearing aids are typically unsuitable for individuals who suffer from single-sided deafness (total hearing loss only in one ear). Hearing aids commonly referred to as "cross aids" have been developed for single sided deaf individuals. These devices receive the sound from the deaf side with one hearing aid and present this signal (either via a direct electrical connection or wirelessly) to a hearing aid which is worn on the opposite side. Unfortunately, this requires the recipient to wear two hearing aids. Additionally, in order to prevent acoustic feedback problems, hearing aids generally require that the ear canal be plugged, resulting in unnecessary pressure, discomfort, or other problems such as eczema.

As noted above, hearing aids rely primarily on the principles of air conduction. However, other types of devices commonly referred to as bone conducting hearing aids or bone conduction devices, function by converting a received sound into a mechanical force. This force is transferred through the bones of the skull to the cochlea and causes motion of the cochlea fluid. Hair cells inside the cochlea are responsive to this motion of the cochlea fluid and generate nerve impulses which result in the perception of the received sound. Bone conduction devices have been found suitable to treat a variety of types of hearing loss and may be suitable for individuals who cannot derive sufficient benefit from acoustic hearing aids, cochlear implants, etc, or for individuals who suffer from stuttering problems.

SUMMARY

In one aspect of the present invention, a bone conduction device for converting received acoustic signals into a mechanical force for delivery to a recipient's skull is provided. The bone conduction device comprises: a multilayer piezoelectric element comprising two stacked piezoelectric layers, and a flexible passive layer disposed between and mounted to the piezoelectric layers, wherein the piezoelectric layers are configured to deform in response to application thereto of electrical signals generated based on the received sound signals; a mass component attached to the multilayer piezoelectric element so as to move in response to deformation of the piezoelectric element; and a coupling configured to attach the device to the recipient so as to transfer mechanical forces generated by the multilayer piezoelectric element and the mass component to the recipient's skull.

In another aspect of the present invention, a bone conduction device for converting received acoustic signals into a mechanical force for delivery to a recipient's skull is provided. The bone conduction device comprises: a multilayer piezoelectric element comprising two stacked piezoelectric layers separated by a substantially flexible passive layer, wherein the piezoelectric layers have opposing directions of polarization such that application of electric signals, generated based on the sound signals, to both of the layers causes deflection of the piezoelectric element in a single direction; a mass component attached to the multilayer piezoelectric element so as to move in response to deformation of the piezoelectric element; and a coupling configured to attach the device to the recipient so as to transfer mechanical forces generated by the multilayer piezoelectric element and the mass component to the recipient's skull.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are described below with reference to the attached drawings, in which:

FIG. **1** is a perspective view of an exemplary bone conduction device worn behind a recipient's ear;

FIG. **2**A is a schematic side view of a unimorph piezoelectric element, shown prior to application of an electric field to the element;

FIG. **2**B is a schematic side view of the unimorph piezoelectric element of FIG. **2**A, shown after application of an electric field to the element;

FIG. **3**A is a schematic side view of a bimorph piezoelectric element which may be implemented in embodiments of the present invention, shown prior to application of an electric field to the element;

FIG. **3**B is a schematic side view of the bimorph piezoelectric element of FIG. **3**A, shown after application of an electric field to the element;

FIG. **4**A is a schematic side view of a multilayer-bimorph piezoelectric element which may be implemented in embodiments of the present invention, shown prior to application of an electric field to the element;

FIG. **4**B is a schematic side view of the multilayer bimorph piezoelectric element of FIG. **4**A, shown after application of an electric field to the element;

FIG. **4**C is a schematic side view of another multilayer-bimorph piezoelectric element which may be implemented in embodiments of the present invention;

FIG. **4**D is a schematic side view of a still other multilayer-bimorph piezoelectric element which may be implemented in embodiments of the present invention;

FIG. **5** is a schematic perspective view of a partitioned piezoelectric element which may be implemented in embodiments of the present invention;

FIG. **6** is a schematic side view of a multilayered piezoelectric actuator having a single counter-mass, in accordance with embodiments of the present invention;

FIG. **7** is a schematic side view of a multilayered piezoelectric actuator having a dual counter-mass system, in accordance with embodiments of the present invention;

FIG. **8** is schematic side view of a multilayered piezoelectric actuator having interspersed counter-mass layers, in accordance with embodiments of the present invention; and

FIG. **9** is a schematic side view of a piezoelectric actuator having independent multilayered piezoelectric elements, in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

Embodiments of the present invention are generally directed to a bone conduction device for converting a received sound signal into a mechanical force for delivery to a recipient's skull. The bone conduction device comprises a multilayer piezoelectric element having two or more stacked piezoelectric layers, and a flexible passive layer disposed between the piezoelectric layers. The piezoelectric layers are configured to deform in response to application thereto of electrical signals generated based on the received sound signals The bone conduction device also includes a mass component attached to the multilayer piezoelectric element so as to move in response to deformation of the piezoelectric element, and a coupling configured to attach the device to the recipient. The coupling transfers mechanical forces generated by the multilayer piezoelectric element and the mass component to the recipient's skull.

The voltage of an electric field or electrical signal utilized to actuate a multilayer element may be lower than the voltage utilized in to actuate a single layer piezoelectric device. That is, a higher voltage electric field is required to generate a desired deflection of a single piezoelectric element than is required to generate the same desired deflection of a multilayer piezoelectric element. As such, bone conduction devices having a multilayer piezoelectric element in accordance with embodiments of the present invention have the advantage of requiring less power lower to produce desired mechanical force for delivery to a recipient's skull.

As noted above, bone conduction devices have been found suitable to treat a variety of types of hearing loss and may suitable for individuals who cannot derive suitable benefit from acoustic hearing aids, cochlear implants, etc. FIG. **1** is a perspective view of a bone conduction device **100** in which embodiments of the present invention may be advantageously implemented. As shown, the recipient has an outer ear **101**, a middle ear **[105]** *102,* and an inner ear **[107]** *103*. Elements of outer ear **101**, middle ear **[105]** *102,* and inner ear **[107]** *103* are described below, followed by a description of bone conduction device **100**.

In a fully functional human hearing anatomy, outer ear **101** comprises an auricle **105** and an ear canal **106**. A sound wave or acoustic pressure **107** is collected by auricle **105** and channeled into and through ear canal **106**. Disposed across the distal end of ear canal **106** is a tympanic membrane **104** which vibrates in response to acoustic wave **107**. This vibration is coupled to oval window or fenestra ovalis **110** through three bones of middle ear **102**, collectively referred to as the ossicles **111** and comprising the malleus **112**, the incus **113** and the stapes **114**. Bones **112**, **113** and **114** of middle ear **102** serve to filter and amplify acoustic wave **107**, causing oval window **110** to articulate, or vibrate. Such vibration sets up waves of fluid motion within cochlea **115**. Such fluid motion, in turn, activates tiny hair cells (not shown) that line the inside of cochlea **115**. Activation of the hair cells causes appropriate nerve impulses to be transferred through the spiral ganglion cells and auditory nerve **116** to the brain (not shown), where they are perceived as sound.

FIG. **1** also illustrates the positioning of bone conduction device **100** relative to outer ear **101**, middle ear **102** and inner ear **103** of a recipient of device **100**. As shown, bone conduction device **100** may be positioned behind outer ear **101** of the recipient. In the embodiment illustrated in FIG. **1**, bone conduction device **100** comprises a housing **125** having a sound input element **126** positioned in, on or coupled to housing **125**. Sound input element **126** is configured to receive sound signals and may comprise, for example, a microphone, telecoil, etc. As described below, bone conduction device **100** may comprise a sound processor, a piezoelectric actuator and/or various other electronic circuits/devices which facilitate operation of the device. For example, as described further below, bone conduction device **100** comprises actuator drive components configured to generate and apply an electric field to the piezoelectric actuator. In certain embodiments, the actuator drive components comprise one or more linear amplifiers. For example, class D amplifiers or class G amplifiers may be utilized, in certain circumstances, with one or more passive filters. More particularly, sound signals are received by sound input element **126** and converted to electrical signals. The electrical signals are processed and provided to the piezoelectric element. As described below, the electrical signals cause deformation of the piezoelectric element which is used to output a force for delivery to the recipient's skull.

Bone conduction device **100** further includes a coupling **140** configured to attach the device to the recipient. In the specific embodiments of FIG. **1**, coupling **140** is attached to an anchor system (not shown) implanted in the recipient. In the illustrative arrangement of FIG. **1**, anchor system comprises a percutaneous abutment fixed to the recipient's skull bone **136**. The abutment extends from bone **136** through muscle **134**, fat **128** and skin **132** so that coupling **140** may be attached thereto. Such a percutaneous abutment provides an attachment location for coupling **140** that facilitates efficient transmission of mechanical force. A bone conduction device anchored to a recipient's skull is sometimes referred to as a bone anchored hearing aid (Baha). Baha is a registered trademark of Cochlear Bone Anchored Solutions AB (previously Entific Medical Systems AB) in Goteborg, Sweden.

It would be appreciated that embodiments of the present invention may be implemented with other types of couplings and anchor systems. Exemplary couplings and anchor systems that may be implemented in accordance with embodiments of the present invention include those described in the following commonly owned and co-pending U.S. patent application Ser. No. 12/167,796, entitled "SNAP-LOCK COUPLING SYSTEM FOR A PROSTHETIC DEVICE," U.S. patent application Ser. No. 12/167,851, entitled "TANGENTIAL FORCE RESISTANT COUPLING SYSTEM FOR A PROSTHETIC DEVICE," U.S. patent application Ser. No. 12/167,871, entitled "MECHANICAL FIXATION SYSTEM FOR A PROSTHETIC DEVICE," U.S. patent application Ser. No. 12/167,825, entitled, "TISSUE INJECTION FIXATION SYSTEM FOR A PROSTHETIC DEVICE," U.S. patent application Ser. No. 12/168,636, entitled "TRANSCUTANEOUS MAGNETIC BONE CONDUCTION DEVICE," U.S. patent application Ser. No. 12/168,603, entitled "HEARING DEVICE HAVING ONE OR MORE IN-THE-CANAL VIBRATING EXTENSIONS," and U.S. patent application Ser. No. 12/168,620, entitled "PIERCING CONDUCTED BONE CONDUCTION DEVICE." The contents of these applications are hereby incorporated by reference herein. Additional couplings and/or anchor systems which may be implemented are described in U.S. Pat. No. 3,594,514, U.S. Patent Publication No. 2005/0020873, U.S. Patent Publication No. 2007/0191673, U.S. Patent Publication No. 2007/0156011, U.S. Patent Publication No. 2004/0032962, U.S. Patent Publication No. 2006/0116743 and International Application No. PCT/SE2008/000336. The contents of these applications are hereby incorporated by reference herein.

As noted, a bone conduction device, such as bone conduction device **100**, utilizes a vibrator or actuator to generate a mechanical force for transmission to the recipient's skull. As described below, embodiments of the present invention utilize a multilayer piezoelectric element to generate the desired force. Specifically, the multilayer piezoelectric element comprises two or more active piezoelectric layers each mounted to a passive layer. The piezoelectric layers mechanically deform (i.e. expand or contract) in response to application of the electrical signal thereto. This deformation (vibration) causes motion of a mass component attached to the piezoelectric element. The deformation of the piezoelectric element and the motion of the mass component generate a mechanical force that is transferred to the recipient's skull. The direction and magnitude of deformation of a piezoelectric element in response to an applied electrical signal depends on material properties of the layers, orientation of the electric field with respect to the polarization direction of the layers, geometry of the layers, etc. As such, modifying the chemical composition of the piezoelectric layer or the manufacturing process may impact the deformation response of the piezoelectric element. It would be appreciated that various materials have piezoelectric properties and may implemented in embodiments of the present invention. One commonly used piezoelectric material is lead zirconate titanate, commonly referred to as (PZT).

FIGS. **2**A and **2**B are schematic side view of one piezoelectric element referred to as unimorph piezoelectric element **200**. FIG. **2**A illustrates unimorph piezoelectric element **200** prior to application of an electric field thereto, while FIG. **2**B illustrates the element after application of an electric field. For ease of illustration, electrodes for applying an electric field to piezoelectric element **200** have been omitted from FIGS. **2**A and **2**B.

Unimorph piezoelectric element **200** comprises a piezoelectric layer **202** mounted to a passive layer **204**. It would be appreciated that layer **204** may be any one or more of a number of different materials. In one embodiment, layer **204** is a metal layer. In the exemplary configuration of FIG. **2**A, layers **202**, **204** each have a generally planar orientation. However, when an electric field is applied to piezoelectric layer **202**, the layer expands longitudinally as illustrated by arrows **206**. Because passive layer **204** does not substantially expand, the centers of both layers **202** and **204** deflect in the direction illustrated by arrow **205** to take a concave orientation. As described elsewhere herein, the deflection of layers **202**, **204** is used to generate vibration of the recipient's skull.

Unimorph piezoelectric element **200** is shown as having a piezoelectric strip layer **202** having a generally rectangular geometry. However, piezoelectric layers **202** may comprise, for example, piezoelectric disks or piezoelectric plates. Additionally, layers **202** and **204** are shown having a planar configuration prior to application of an electric field to layer **202**. However, it would be appreciated that layers **202** and **204** may have a concave shape prior to application of the electric field.

FIGS. **3**A and **3**B are schematic side view of an exemplary multilayer piezoelectric element which may be implemented in embodiments of the present invention, referred to as bimorph piezoelectric element **300**. FIG. **3**A illustrates bimorph piezoelectric element **300** prior to application of an electric field thereto, while FIG. **3**B illustrates the element after application of an electric field. For ease of illustration, electrodes for applying an electric field to piezoelectric element **300** have been omitted from FIGS. **3**A and **3**B.

Bimorph piezoelectric element **300** comprises first and second piezoelectric layers **302** separated by a flexible passive layer **304**. Each piezoelectric layer **302** is mounted to opposing sides of passive layer **304**. It would be appreciated that passive layer **304** may be any one or more of a number of different materials. In one embodiment, layer **304** is a metal layer, and more specifically, a metal foil layer. In the illustrative arrangement of FIGS. **3**A and **3**B, passive layer **304** is substantially thinner and thus more flexible than layer **204** implemented in unimorph piezoelectric element **200**. In still other embodiments, passive layer **304** may comprises a plurality of couplings or connectors extending between piezoelectric layers **302**. In such embodiments, the connectors may be separated by air gaps and passive layer **304** may be partially or substantially formed by such air gaps.

In the exemplary configuration of FIG. **3**A, layers **302**, **304** each have a generally planar orientation. In these embodiments, layers **302**A and **302**B each have opposing directions of polarization. As such, when an electric field is applied to piezoelectric layers **302**, layer **302**A expands longitudinally as illustrated by arrows **306**, while layer **302**B contracts longitudinally as illustrated by arrows **308**. Due to the opposing expansion and contraction, the centers of layers **302** and **304** deflect in the direction illustrated by arrow **305**. As previously noted, due to the opposing expansion and contraction of layers **302**A and **302**B, bimorph piezoelectric element **300** generates more deflection than that provided by comparable unimorph piezoelectric elements. The deflection of layers **302**, **304** is used to output a mechanical force that generates vibration of the recipient's skull.

In the embodiments of FIGS. **3**A and **3**B, bimorph piezoelectric element **300** comprises two piezoelectric strip layers **302** having generally rectangular geometries. However, in accordance with other embodiments of the present invention, piezoelectric layers **302** may comprise, for example, piezoelectric disks or piezoelectric plates. Additionally, it would be appreciated that each piezoelectric layer may comprise one or a plurality of piezoelectric sheets having the same or different piezoelectric properties.

Additionally, FIGS. **3**A and **3**B illustrate embodiments in which the layers **302** and **304** are planar prior to application of an electric field to layers **302**. However, it would be appreciated that in alternative embodiments, layers **302** and **304** may have a concave shape prior to application of the electric field.

FIGS. **4**A and **4**B are schematic side view of another multilayer piezoelectric element which may be implemented in embodiments of the present invention, referred to as multilayer-bimorph piezoelectric element **400**. FIG. **4**A illustrates multilayer-bimorph piezoelectric element **400** prior to application of an electric field thereto, while FIG. **4**B illustrates the element after application of an electric field. For ease of illustration, electrodes for applying an electric field to piezoelectric element **400** have been omitted from FIGS. **4**A and **4**B.

Multilayer-bimorph piezoelectric element **400** comprise two pairs **450** of piezoelectric layers **402** each having, in the exemplary configuration of FIG. **4**A, a generally planar orientation . . . . A first pair **450**A of piezoelectric layers **402**A and **402**B are mounted to one another and have a first direction of polarization. The other pair **450**B of piezoelectric layers **402**C and **402**D are also mounted to one another, but have a second directional of polarization that is opposite to the first polarization direction. Pairs **450** are separated from one another by a passive layer **404**. Similar to the embodiments described above, passive layer may be any one or more of a number of different materials. In one embodiment, layer **404** is a metal layer, and more specifically, a metal foil layer. In the illustrative arrangement of FIGS. **4**A and **4**B, passive layer **404** is substantially thinner and thus more flexible than layer **204** implemented in unimorph piezoelectric element **200**. In still other embodiments, passive layer **404** may comprises a plurality of couplings or connectors extending between piezoelectric layers **402**. In such embodiments, the connectors may be separated by air gaps and passive layer **404** may be partially or substantially formed by such air gaps.

When an electric field is applied to piezoelectric layers **402**, layers **402**A and **402**B expand longitudinally as illustrated by arrows **408**, while layers **402**C and **402**D contract longitudinally as illustrated by arrows **406**. Due to the opposing expansion and contraction, the centers of layers **402** and **404** deflect in the direction illustrated by arrow **405**. As described elsewhere herein, the deflection of layers **402**, **404** is used to output a mechanical force that generates vibration of the recipient's skull.

In the embodiments of FIGS. **4**A and **4**B, multilayer-bimorph piezoelectric element **400** is shown comprising multiple piezoelectric strip layers **402** having generally rectangular geometries. However, in accordance with other embodiments of the present invention, piezoelectric layers **402** may comprise, for example, piezoelectric disks or piezoelectric plates. It would also be appreciated that the use of four layers in FIGS. **4**A and **4**B is merely illustrative, and additional layers may be added in further embodiments. Additionally, it would be appreciated that each piezoelectric layer may comprise one or a plurality of piezoelectric sheets having the same or different piezoelectric properties.

Additionally, FIGS. **4**A and **4**B illustrate embodiments in which the layers **402** and **404** are planar prior to application of an electric field to layers **402**. However, it would be appreciated that in alternative embodiments, layers **402** and **404** may have a concave shape prior to application of the electric field.

As noted above, FIGS. **4**A and **4**B illustrate a multilayer-bimorph piezoelectric element having two pairs **450** of piezoelectric elements separated by a passive layer **404**. It would be appreciated that these embodiments are merely illustrative and other arrangements may be implemented in embodiments of the present invention. FIG. **4**C illustrates one other such alternative arrangement for a multilayer-bimorph piezoelectric element **470** comprising ten (10) stacked pairs **450** of piezoelectric layers. Each of the pairs **450** are separated by a passive layer **404**. It would be appreciated that different numbers of stacked pairs **450** may be implemented in other embodiments.

Additionally, as noted above, FIGS. **4**A and **4**B illustrate embodiments in which layers **402**A and **402**B have the same direction of polarization, and are separated from layers **402**C and **402**D having an opposing polarization. FIG. **4**D illustrates a specific alternative embodiment of a multilayer-bimorph piezoelectric element **480** comprising a plurality of stacked piezoelectric layers **480**. In these embodiments, each of the layers **480** are separated by a flexible passive layer **484**. Passive layers **484** may be substantially similar to passive layer **404** described above.

FIG. **5** is a schematic perspective view of a partitioned piezoelectric element **500** in accordance with embodiments of the present invention. As shown, piezoelectric element **500** comprises three independently drivable, adjacent segments **570**. That is, piezoelectric element **500** is configured such that each segment **570** may be actuated substantially independently from the other adjacent segments. In the embodiments of FIG. **5**, piezoelectric element may comprise any of the piezoelectric elements described above with reference to FIGS. **2**-**4**B. In certain embodiments, piezoelectric element **500** comprises a partitioned multilayer piezoelectric element.

In the embodiments of FIG. **5**, segment **570**B is electrically connected to an amplifier **572** which is configured to apply an electric field to segment **570**B via one or more electrodes (not shown). However, segments **570**A and **570**C are each electrically connected to amplifier **574**. In certain circumstances, amplifier **572** and the electrodes may be operated to deliver an electric field to segment **570**B, while amplifier **574** remains inactive. In such circumstances, segment **570**B will deflect to generate a mechanical force for delivery to the recipient's skull. Similarly, amplifier **574** and the electrodes may be operated to apply an electric field to segments **570**A and **570**C, while amplifier **572** remains inactive. Again, in such circumstances, segments **570**A and **570**C will deflect to generate a mechanical force for delivery to the recipient's skull.

The determination of which segments **570** to actuate may be based on a number of factors. In one specific embodiment, amplifier **572**, and thus segment **570**B, is activated in response to receipt by the device of high frequency signals, while amplifier **574**, and thus segments **570**A and **570**C, is activated in response to low frequency signals. In such specific embodiments, the force generated by the deflection of segment **570**B causes perception of high frequency sound signals, while deflection of segments **570**A and **570**C result in perception of low frequency sound signals.

As noted above, in order to generate sufficient force to vibrate a recipient's skull, at least one mass component is mechanically attached to the piezoelectric element. FIG. **6** is a schematic diagram of a piezoelectric actuator **620** comprising a piezoelectric element **600** attached to a mass **684** by two connectors **682**. Connectors **682** may comprise, for example, hinges, clamps, adhesive connections, etc., which are connected to a first side of piezoelectric element **600**. Attached to the opposing second side of piezoelectric element **600** is a coupling **680**. It would be appreciated that any of the piezoelectric elements described above with reference to FIGS. **2**-**5** may be implemented as piezoelectric element **600**.

Similar to the embodiments described above, coupling **680** is utilized to transfer the mechanical force generated by piezoelectric actuator **620** to the recipient's skull. In certain embodiments, coupling **680** may comprise a bayonet coupling, a snap-in or on coupling, a magnetic coupling, etc.

In embodiments of the present invention, mass **684** is piece of material such as tungsten, tungsten alloy, brass, etc, and may have a variety of shapes. Additionally, the shape, size, configuration, orientation, etc., of mass **684** may be selected to optimize the transmission of the mechanical force from piezoelectric actuator **620** to the recipient's skull. In specific embodiments, mass **684** has a weight between approximately 3 g and approximately 50 g. Furthermore, the material forming mass **684** may have a density between approximately 6000 kg/m3 and approximately 22000 kg/m3.

FIG. **6** illustrates embodiments of the present invention in which one mass is attached to a piezoelectric element. FIG. **7** illustrates an alternative configuration for a piezoelectric actuator **720** utilizing a dual mass system. As shown, piezoelectric actuator **720** comprises a piezoelectric element **700** as described above with reference to any of FIGS. **2**-**5**. Two mass components **784**A, **784**B are attached to the ends of piezoelectric element **700** by connectors **782**. More particularly, first mass component **784**A is attached to a first end of piezoelectric element **700** by a first set of connectors **782**. Second mass component **784**B is independently attached to a second end of piezoelectric element **700** by a second set of connectors **782**. Piezoelectric actuator **720** further includes a mechanical damping member **786** disposed between mass components **784**. Damping member **786** may comprise a material that is designed to mechanically isolate mass components **784** from one another. Exemplary such materials include, but are not limited to, silicone, IsoDamp, ferrofluids, etc. IsoDamp is a trademark of Cabot Corporation. In an alternative arrangement, damping members may also be placed between piezoelectric element **700** and mass components **784**.

As shown, piezoelectric element **700** is also attached to coupling **780** which is utilized to transfer the mechanical force generated by piezoelectric actuator **720** to the recipient's skull. In certain embodiments, coupling **780** may comprise a bayonet coupling, a snap-in or on coupling, a magnetic coupling, etc.

FIG. **8** is a side view of another piezoelectric actuator **820** in accordance with embodiments of the present invention. As shown, piezoelectric actuator **820** comprises a plurality of stacked piezoelectric layers **802**. Disposed between each of the piezoelectric layers **802** are passive, non-rigid mass layers **884**. In these embodiments, passive layers **884** function to facilitate deflection of the piezoelectric layers, as described above with reference to FIGS. **2**-**5**. However, passive layers **884** are also configured to provide mass to piezoelectric actuator **820** so that sufficient force may be generated without the need for an additional attached mass.

FIG. **8** illustrates embodiments comprising four piezoelectric layers. It would be appreciated that the embodiments of FIG. **8** are not limiting and that different numbers of layers may be implemented. Additionally, it would be appreciated that each piezoelectric layer may comprise one or a plurality of piezoelectric sheets having the same or different piezoelectric properties.

FIG. **9** is side view of a still other piezoelectric actuator **920** which may be implemented in embodiments of the present invention. In these embodiments, piezoelectric actuator **920** comprises first and second piezoelectric elements **900**A, **900**B. Attached to the opposing ends of piezoelectric element **900**A are two mass components **984**. Similarly, attached to the opposing ends of piezoelectric element **900**B are mass components **994**. Piezoelectric elements **900** are connected to one another by interconnector **992**, and a coupling **980** extends from piezoelectric element **900**B.

In the exemplary arrangement of FIG. **9**, each of the piezoelectric elements **900** are operated in response to receipt of different frequencies of sound signals. Specifically, piezoelectric element **900**B is operable in response to receipt of high frequency sound signals, while piezoelectric element **900**A is operable in response to receipt of low frequency sound signals.

As noted, FIG. **9** illustrates the use of piezoelectric actuator for presentation of one of the two sound frequency ranges. However, it would be appreciated that both elements may operate in the same frequency range for use in, for example, single sided deaf patients who may require representation of only high frequency signals.

In the embodiments described above, the maximum deflection of the piezoelectric elements may be the same axis as the combined center of the mass components and/or along the axis of the coupling to the skull. Such a configuration results in a balanced device.

Additionally, a piezoelectric actuator for use in a direct bone conduction device may have one or more resonant peaks within the range of approximately 300 to approximately 12000 Hz. In a specific arrangement, a piezoelectric actuator may have two resonance peaks where one peak is at less than approximately 1000 Hz, and the other peak is within the range of approximately 4000 to approximately 12000 Hz.

In a still other specific example, a piezoelectric actuator may have a resonant peak at less than approximately 300 Hz. Such an actuator may be used to transmit a tactile sensation to a recipient, rather than an audio sensation.

While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation.

It will be apparent to persons skilled in the relevant art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents. All patents and publications discussed herein are incorporated in their entirety by reference thereto.

What is claimed is:

1. A bone conduction device for converting received sounds signals into a mechanical force for delivery to a recipient's skull, the device comprising:

- a plurality of separate, independently operable multilayer piezoelectric elements each comprising two stacked piezoelectric layers, and a passive layer disposed between and mounted to the piezoelectric layers so as to separate the piezoelectric layers from each other, wherein the piezoelectric layers are configured to deform in response to application thereto of electrical signals generated based on the received sound signals;
- **[**a mass component**]** *one or more mass components* attached to one or more of the multilayer piezoelectric elements so as to move in response to deformation of the one or more piezoelectric elements; and
- a coupling configured to attach the device to the recipient so as to transfer mechanical forces generated by the multilayer piezoelectric element and the mass component to the recipient's skull,
- wherein the device is configured to apply an electric signal to a first of the plurality of multilayer piezoelectric elements in response to receipt of a high frequency sound signal by the device, and wherein the device is configured to apply an electric signal to a second of the plurality of multilayer piezoelectric elements in response to receipt of a low frequency sound signal by the device.

2. The bone conduction device of claim **1**, wherein the at least two piezoelectric layers of one or more of the multilayer piezoelectric elements have opposing directions of polarization such that application of electrical signals to both of the layers causes deflection of the piezoelectric element in a single direction.

3. The bone conduction device of claim **1**, wherein each of the two stacked piezoelectric layers of one or more of the multilayer piezoelectric elements comprise two or more piezoelectric sheets.

4. The bone conduction device of claim **1**, wherein one or more of the multilayer piezoelectric elements comprises a bimorph piezoelectric element.

5. The bone conduction device of claim **1**, wherein one or more of the multilayer piezoelectric elements comprises a plurality of adjacent segments configured to be actuated substantially independently.

6. The bone conduction device of claim **5**, wherein the plurality of adjacent segments comprise three adjacent segments.

7. The bone conduction device of claim **5**, further comprising a plurality of amplifiers configured to selectively generate electrical signals for delivery to the plurality of adjacent segments.

8. The bone conduction device of claim **7**, wherein a first of the plurality of amplifiers is configured to generate an electric signal for application to a first of the plurality of segments in response to receipt of a high frequency sound signal by the device, and wherein a second of the plurality of amplifiers is configured to generate an electric signal for delivery to a second of the plurality of segments in response to receipt of a low frequency sound signal by the device.

9. The bone conduction device of claim **1**, wherein each of the piezoelectric layers comprise piezoelectric strips.

10. The bone conduction device of claim **1**, wherein each of the piezoelectric layers comprise piezoelectric disks.

11. The bone conduction device of claim **1**, wherein the **[**mass component**]** *one or more mass components* comprises a plurality of separate mass components *attached at different locations of the one or more piezoelectric elements*.

12. The bone conduction device of claim **11**, wherein the plurality of mass components are separated by a vibration damping element.

13. The bone conduction device of claim **1**, wherein the **[**mass components**]** *one or more mass components* comprise the passive layer disposed between the piezoelectric layers.

14. A bone conduction device for converting received sound signals into a mechanical force for delivery to a recipient's skull, the device comprising:

- a multilayer piezoelectric element comprising two stacked piezoelectric layers separated from each other by a non-conductive passive layer, wherein the piezoelectric layers have opposing directions of polarization such that application of electric signals, generated based on the sound signals, to both of the layers causes deflection of the piezoelectric element in a single direction and wherein the multilayer piezoelectric element comprises a plurality of adjacent segments configured to be actuated substantially independently;
- a plurality of amplifiers configured to selectively generate electrical signals for application to the plurality of adjacent segments;
- **[**a mass component**]** *one or more mass components* attached to the multilayer piezoelectric element so as to move in response to deformation of the piezoelectric element; and
- a coupling configured to attach the device to the recipient so as to transfer mechanical forces generated by the multilayer piezoelectric element and the mass component to the recipient's skull.

15. The bone conduction device of claim **14**, wherein each of the two stacked piezoelectric layers comprise two or more piezoelectric sheets.

16. The bone conduction device of claim **14**, wherein the multilayer piezoelectric element comprises a bimorph piezoelectric element.

17. The bone conduction device of claim **14**, wherein the plurality of adjacent segments comprise three adjacent segments.

18. The bone conduction device of claim **14**, wherein a first of the plurality of amplifiers is configured to generate an electric signal for application to a first of the plurality of segments in response to receipt of a high frequency sound signal by the device, and wherein a second of the plurality of amplifiers is configured to generate an electric signal for application to a second of the plurality of segments in response to receipt of a low frequency sound signal by the device.

19. The bone conduction device of claim **14**, wherein each of the piezoelectric layers comprise piezoelectric strips.

20. The bone conduction device of claim **14**, wherein each of the piezoelectric layers comprise piezoelectric disks.

21. The bone conduction device of claim **14**, wherein the **[**at least one mass component**]** *one or more mass components* comprises a plurality of separate mass components *attached at different locations of the one or more piezoelectric elements*.

22. The bone conduction device of claim **21**, wherein the plurality of mass components are separated by a vibration damping element.

23. The bone conduction device of claim **14**, wherein the **[**mass components**]** *one or more mass components* comprise the passive layer disposed between the piezoelectric layers.

24. The bone conduction device of claim **14**, further comprising:

a plurality of separate, independently operable multilayer piezoelectric elements.

25. The bone conduction device of claim **24**, wherein the device is configured to apply an electric signal to a first of the plurality of multilayer piezoelectric elements in response to receipt of a high frequency sound signal by the device, and wherein the device is configured to apply an electric signal to a second of the plurality of multilayer piezoelectric elements in response to receipt of a low frequency sound signal by the device.

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