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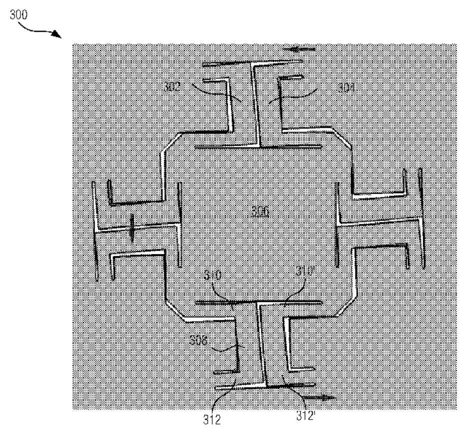


FIG. 3

(57) Abstract: An example include microelectromechanical die for sensing motion that includes a fixed portion, an anchor coupled to the fixed portion, a first nonlinear suspension member coupled to anchor on a side of the anchor, a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane and a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the fixed portion.

FLEXURE BEARING TO REDUCE QUADRATURE FOR RESONATING MICROMACHINED DEVICES

CLAIM OF PRIORITY AND RELATED APPLICATIONS

The present application claims the benefit of priority of U.S. Provisional Patent Application Serial No. 61/384,247, entitled “LOW-QUADRATURE SUSPENSION SYSTEM FOR MULTI-AXIS GYROSCOPES,” filed Sep 18, 2010 and U.S. Provisional Patent Application Serial No. 61/384,512, entitled “IMPROVED QUADRATURE REDUCTION STRUCTURE FOR RESONATING MICROMACHINED DEVICES,” filed Sep 20, 2010, each of which is incorporated by reference in its entirety.

The present application is related to U.S. Patent Application Serial No. 12/849,742, entitled “MICROMACHINED INERTIAL SENSOR DEVICES,” filed Aug 3, 2010; U.S. Patent Application Serial No. 12/849,787, entitled “MICROMACHINED DEVICES AND FABRICATING THE SAME,” filed Aug 3, 2010 and U.S. Provisional Patent Application Serial No. 61/384,240, entitled “MICROMACHINED MONOLITHIC 6-AXIS INERTIAL SENSOR,” filed Sep 18, 2010, each of which is incorporated by reference in its entirety.

BACKGROUND

Quadrature error is one of the primary factors that limit the performance of micromachined sensors such as gyroscopes. Considering the relative magnitudes of the drive and sense oscillations, even an extremely small part of the drive motion coupling into a sense-mode could dominate over the Coriolis response.

Practically, fabrication imperfections may result in less-than-ideal geometries in structures such as gyroscope structures. Less-than-ideal geometries can cause a drive oscillation to partially couple into a sense-mode. Even though several cross-coupling approaches exist, such as elastic, viscous and electrostatic coupling approaches, in certain cases the elastic coupling due to anisoelasticity in the suspension elements increases in magnitude beyond a desired level.

In sensor systems such as gyroscope systems with out-of-plane operational modes, anisoelasticity between the in-plane and out-of- plane directions is the dominating source of Quadrature error. Sidewall tilt or skew in deep reactive-ion etching (“DRIE”) can result in deviation of the cross-section of the flexure bearings from a rectangle to a parallelogram, causing the principle axes of elasticity of the suspension flexure bearings to deviate from parallel and orthogonal to the device surface. In an example, single or multi-axis micromachined sensor structures such as gyroscope structures can suffer from high-quadrature error caused at least in part by DRIE skew.

Additionally, prior resonators rely on simple straight flexure bearings to generate a flexing structure to allow the device to displace in resonance. This creates significant problems when etching creates a skew in the flexure bearing, causing large undesired displacement, often actuating a sense mechanism.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

FIG. 1 illustrates a sensor structure including a suspension structure, according to an example.

FIG. 2A illustrates a portion of a suspension, according to an example.

FIG. 2B illustrates the suspension of FIG. 8A, in a bending state in which a top portion is bent upward, in an example.

FIG. 2C illustrates the suspension of FIG. 8A, in a bending state in which a top portion is bent downward, in an example.

FIG. 3 illustrates torsional motion of a suspended structure about a z-axis, according to an example.

FIG. 4 illustrates torsional motion of a suspended structure about an x-axis, according to an example.

FIG. 5 illustrates torsional motion of a suspended structure about a y-axis, according to an example.

FIG. 6 illustrates a 2-Axis Gyroscope including a low quadrature error suspension, according to an example.

FIG. 7 illustrates a 3-Axis Gyroscope including a low quadrature error suspension, according to an example.

FIG. 8 illustrates quadrature error for an example suspension.

FIG. 9 illustrates a drive mode, according to an example.

FIG. 10 illustrates a four bend flexure bearing, according to an example.

FIG. 11 illustrates a flexure bearing including a flexing flexure bearing and a non-flexing flexure bearing, according to an example.

FIG. 12 illustrates a flexure bearing including a flexing flexure bearing shorter than the flexure bearing of FIG. 11, and a non-flexing flexure bearing shorter than the non-flexing flexure bearing of FIG. 11, according to an example.

FIG. 13A illustrates a suspension with large clearances, according to an example.

FIG. 13B illustrates stresses related to flexing of flexures bearings.

FIG. 14 illustrates a suspension including a switchback, according to an example.

FIG. 15 illustrates the suspension of FIG. 14 flexed in torsion around a z-axis, according to an example.

FIG. 16A illustrates the suspension of FIG. 14 flexed in torsion around a z-axis, according to an example.

FIG. 16B illustrates the suspension of FIG. 14 flexed about a y-axis, according to an example.

FIG. 16C illustrates the suspension of FIG. 14 flexed about the x-axis, according to an example.

FIG. 16D illustrates the suspension of FIG. 14 flexed in displacement along a y-axis, according to an example.

FIG. 17 shows a method of making a low-quadrature-error suspension, according to an embodiment.

DETAILED DESCRIPTION

Unwanted sidewall flex can negatively affect the performance of flexure bearings (“flexures”), such as flexure bearings that support one or more portions of a microelectromechanical systems (“MEMS”) structure such as a die. In an example, if one or more sidewalls have an angle error, an in-plane drive motion can cause out-of-plane motion, such as when the skew axis is along a flexure bearing or beam length. In an example, when skewed pliable or compliant flexure bearings or beams are located on opposite sides of a drive motion, a resulting out-of-plane deflection can cause or contribute to quadrature error. In an example, a low-quadrature suspension system aims at reducing or cancelling undesired out-of-plane motion.

FIG. 1 illustrates a sensor structure including a suspension structure, according to an example. Various examples disclose a low-quadrature suspension system for a sensor. In an example, a suspension structure can be utilized in a torsional multi-axis micromachined gyroscope system with a proof-mass such as a single proof-mass 104. In an example, a proof-mass 104 is suspended at its center with a single central anchor 106. In an example, one or more flexure bearings connect the anchor 106 to the proof-mass 104, such as to the proof-mass main frame 116. In an example, one or more flexures allow the proof-mass to oscillate torsionally about three perpendicular axes. In an example, suspension flexure bearings or beams provide in-plane and out-of-plane deflections, allowing the proof-mass to oscillate torsionally about the x, y, and z axes.

An example includes a fixed portion 118, wherein the anchor 106 is coupled to the fixed portion 118. In an example, a first nonlinear suspension member 108 is coupled to anchor 106 on a side of the anchor. In an example, a second nonlinear suspension member 120 coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane 122, such as a x-z plane. Various examples include a proof-mass 104 that is planar, the proof mass suspended at least in part by the first nonlinear suspension member 108 and the second nonlinear suspension member 120 such that the proof-mass is rotable about the anchor 106 and is slideable in a plane parallel to the fixed portion, such as in the x-y plane.

In an example, a C-shaped flexure bearing 108 includes a inner portion 110 coupled to the anchor 106 and extending toward the anchor bisecting plane 122, a center portion 114 having a proximal portion and a distal portion, with a proximal portion coupled to the inner portion 110 and a distal portion extending away from the anchor 106 along the anchor bisecting plane 122 and coupled to a outer portion 112 extending away from the anchor bisecting plane 122. In an example, the center portion 114 is perpendicular the inner portion 110 and the outer portion 112. In an examples, the center portion 114 is parallel the anchor bisecting plane 122.

In an examples, the anchor 106, the first nonlinear suspension member 108, the second nonlinear suspension member 120 and the proof-mass 104 are formed of a monolithic material. In an example, the fixed portion 118 comprises a fixed monolithic material other than the monolithic material of the anchor 106, the first nonlinear suspension member 108, the second nonlinear suspension member 120 and the proof-mass 104. In an example, the fixed portion 118 comprises a fixed monolithic material the same as the monolithic material of the anchor 106, the first nonlinear suspension member 108, the second nonlinear suspension member 120 and the proof-mass 104.

In an example, flexure bearings are disposed on each side of the central anchor, such as on opposite sides of the anchor. In an example, out-of-plane motion caused by each C-shaped flexure bearing on a side is cancelled out by its symmetric counterpart. Accordingly, in an example, the quadrature error induced on each flexure bearing is locally reduced or cancelled.

In an example, a central suspension structure 102 is utilized in a sensor, such as a 6 degree of freedom (“DOF”) sensor 100, such as a monolithic 6-DOF sensor, that is comprised of symmetric flexures bearings. In an example, the symmetric flexure bearings include “C-shaped flexure bearings” 108. In an example, each C-shaped flexure bearing includes inner 110 and outer 112 flexure bearings and a high-stiffness connection flexure bearing 114 between two flexure bearings. In an example, the inner flexure bearing 112 is connected to the anchor 106 on one end, and the outer flexure bearing 112 is connected to the proof mass 104 on another end. In an example, the suspension system 102 is formed by a total of eight C-shaped flexure bearings 108. In an example, two symmetric C-shaped flexure bearings are located on each of the four sides of a central anchor structure.

In an example, a suspension system provides three gyroscope operational modes: torsional in-plane about the z-axis for the drive motion; torsional out-of-plane about the x-axis for the y-axis gyroscope sense motion; and torsional out-of-plane about the y-axis for the x-axis gyroscope sense motion. In an example, the oscillation modes can be switched between each other.

FIG. 2A illustrates a portion of a suspension, according to an example. FIG. 2B illustrates the suspension of FIG. 2A, in a bending state in which a top portion is bent upward, in an example. FIG. 2C illustrates the suspension of FIG. 2A, in a bending state in which a top portion is bent downward, in an example. The examples shown illustrate the deformation profile in each direction of the suspension mechanism. In an example, bending occurs equal and opposite in both deformation cases illustrates in FIG. 2B and FIG. 2C. In an example, in each direction the two flexure bearings bend in opposite ways. In an example, by creating opposing out-of-plane deformations that cancel each other, the overall out-of-plane deformation from one end of the flexure to the other is minimized.

FIG. 3 illustrates torsional motion of a suspended structure about a z-axis, according to an example. In an example, a suspension system 300 comprises two symmetric C-shaped flexure bearings 302, 304 on each side of a central anchor structure 306. In an example, one or both of the C-shaped flexure bearings 302, 304 is formed of a high-stiffness connection flexure bearing 308 disposed between two flexure bearings 310, 312. In an example, during in-plane torsional motion, such as motion parallel to the plane of the figure, the out-of-plane motion caused by the deflection of the flexure bearings in each C-shaped flexure bearing on a side is cancelled out by a symmetric counterpart 310’, 312’. Accordingly, quadrature error induced on each flexure bearing is locally reduced or cancelled.

The illustrated example illustrates torsional motion about a Z-Axis, i.e. an axis extending into and out of the page. In an example, during the in-plane torsional motion, the inner 310 and outer 312 flexure bearings in each C-shaped flexure bearing bend in-plane. In an example, the high-stiffness connection bearings 308 do not experience significant bending. For a counterclockwise rotation of the proof-mass about the z-axis, top part of the proof mass moves left as shown. In an example, the high-stiffness connection bearings both move left. As a result, the inner and outer flexures on the right C-shaped flexure bearing bend down, while the ones on the left C-shaped flexure bearing bend up. Thus, in an example, the motion results in deflections in opposite directions in the symmetric C-shaped flexure bearing flexures. Since the flexures in symmetric C-shaped flexure bearings deflect in opposite directions, the out-of-plane motion caused by the deflection of the flexure bearings in each C-shaped flexure bearing on a side is cancelled out by its symmetric counterpart. Thus, the quadrature error induced on each flexure bearing is locally cancelled.

FIG. 4 illustrates torsional motion of a suspended structure about an x-axis, according to an example. In an example, a suspension structure can be utilized in a torsional multi-axis micromachined gyroscope system with a proof-mass such as a single proof-mass 404. In an example, a proof-mass 404 is suspended at its center with a single central anchor 406. In an example, one or more flexure bearings 402 connect the anchor 406 to the proof-mass 404. In an example, during the out-of-plane torsional motion about the x-axis, primarily the C-shaped suspension pairs 412, 412’ on the y-axis sides of the anchor deflect. In an example, the inner flexure bearings 410, 410’ in these C-shaped suspensions bend torsionally about the x-axis, acting as a torsional hinge.

In an example, the die is wafer shaped, with each of a first nonlinear suspension member 408 and a second nonlinear suspension member 412 having a substantially rectangular cross-section with the height of the cross-section smaller than the width.

FIG. 5 illustrates torsional motion of a suspended structure about a y-axis, according to an example. In an example, a suspension structure can be utilized in a torsional multi-axis micromachined gyroscope system with a proof-mass such as a single proof-mass 404. In an example, a proof-mass 404 is suspended at its center with a single central anchor 406. In an example, one or more flexure bearings 402 connect the anchor 406 to the proof-mass 404. In an example, during the out-of-plane torsional motion about the y-axis, primarily the C-shaped suspension pairs 412, 412’on the x-axis sides of the anchor deflect. The inner flexure bearings in these C-shaped flexure bearings 414, 414’ bend torsionally about the y-axis, acting as a torsional hinge.

FIG. 6 illustrates a 2-Axis Gyroscope including a low quadrature error suspension, according to an example. In an example, a structure 602 can be utilized in various torsional multi-axis micromachined gyroscope systems with a single proof-mass 604 that is suspended at its center with a single central anchor 606. The flexures 608 connect the anchor to the proof-mass 604, and allow the proof-mass to oscillate torsionally about all three axes. The illustrated example senses motion about each of the x-axis and the y-axis, and proves three gyroscope operational modes: torsional in-plane about the z-axis for the drive motion; torsional out-of-plane about the x-axis for the y-axis gyroscope sense motion; and torsional out-of-plane about the y-axis for the x-axis gyroscope sense motion. In an example, one or more comb electrodes 616 are coupled to a fix portion of the device and sense motion of comb electrodes 618 coupled to the proof mass 604. In an example, the comb teeth of the comb electrodes 618 are disposed along an axis that bisects an angle between the x-axis and the x-axis.

FIG. 7 illustrates a 3-Axis Gyroscope including a low quadrature error suspension, according to an example. In an example, a structure 702 can be utilized in various torsional multi-axis micromachined gyroscope systems with a single proof-mass 704 that is suspended at its center with a single central anchor 706. The flexures 708 connect the anchor to the proof-mass 704, and allow the proof-mass to oscillate torsionally about all three axes. In an example, a device function as an a three-axis (“X/Y/Z”) gyroscope. In an example, the suspension system 702 provides similar gyroscope operational modes to the device illustrated in FIG. 6. In an example, the illustrated device of FIG. 7 includes additional flexures 720 that provide for the Z-axis sense mode. In an example, one or more comb electrodes 716 are coupled to a fix portion of the device and sense motion of comb electrodes 718 coupled to the proof mass 704. In an example, the comb teeth of the comb electrodes 718 are disposed along an axis that bisects an angle between the x-axis and the x-axis.

FIG. 8 illustrates quadrature error for an example suspension. In an example, the angle of the flexure bearings has a significant effect on the quadrature. In an example, for each design the angle can be chosen to optimize the quadrature error arising from skew of the resonator flexure bearing flexures. In an example, for the desired implementation of the suspension system, the optimal angle is 15 degrees. In an example, the optimal angle is structure shape dependent, and is selected based on the structure of a respective device. In an example, for a desired structure, two flexure bearings are set at the same angular shift, but two flexure bearings could easily be set at different angles.

FIG. 9 illustrates a drive mode, according to an example. The inventors recognized that skew effect creates quadrature errors in suspension configurations including an anchor 906, and that they could minimize the effect by creating opposite skews on the same flexure 902 or flexure pair 904. Accordingly, there are two flexing flexure bearings separated by a frame, each of which deforms in the opposite direction in the drive mode of operation. The opposite directions of the deformation cause the skew to create out-of-plane deformation in opposite directions, which cancel each other out at the final connection to the moving component. This is used to replace an existing mechanism which only includes one flexure bearing, the skew of which causes deformation in only one direction, creating a lot of out-of-plane motion without any canceling.

However, in some examples, the inner 910, 910’ and outer 912, 912’ flexure bearings are rotated so that deformation causes one flexure bearing to bend up and one flexure bearing to bend downward during drive mode actuation. In an example, the drive mode is a rotational mode about a central anchor. In an example, for each of the four suspension pairs 404, the drive mode causes one to deform in one direction and the other in the other direction.

FIG. 10 illustrates a four bend flexure bearing, according to an example. In an example, the flexure 1002 can include more than one bend. In an example, this can allow for more tightly controlled out-of-plane motion. In an example, a number of switchbacks 1004 are included. In an example, the switchbacks define a zigzag that extends from the anchor 1006 to the proof-mass 1005. In an example, the zigzag includes switchbacks of a regular amplitude along the patter extending from the anchor 1006 to the proof-mass 1005. In additional embodiments, the amplitude varies. In an example, the switchbacks have a C-shape, with top 1008 and bottom 1014 members parallel to one another, but not parallel to a high-stiffness portion 1016.

FIG. 11 illustrates a flexure bearing including a flexing flexure bearing and a non-flexing flexure bearing, according to an example. In an example, a flexure 1102 can also be parameterized by lengthening or shortening the flexing flexure bearings 1110, 1114 or the non-flexing flexure bearing(s) 1112. In the example shown in FIG. 12, the outer flexing flexure bearing 1110 and non-flexing flexure bearing 1112 have been shortened.

FIG. 12 illustrates a flexure bearing including a flexing flexure bearing shorter than the flexure bearing of FIG. 11, and a non-flexing flexure bearing shorter than the non-flexing flexure bearing of FIG. 11, according to an example. The outer flexing flexure bearing 1210 and non-flexing flexure bearing 1212 have been shortened compared to the components of FIG. 11.

FIG. 13A illustrates a suspension with large clearances, according to an example. FIG. 13B illustrates stresses related to flexing of flexures bearings. In the examples, there are voids 1302 disposed between the flexure bearing 1304 and the proof-mass 1306.

FIG. 14 illustrates a die 1400 including a suspension including a switchback, according to an example. The switchback 1402 extends between the C-shaped flexure bearing 1406 and the proof mass 1408. The addition of the switchback 1402 further reduces quadrature error, at least because it reduces out-of-plane flexing due at least in part to DRIE etching.

In an example, the outer portion 1412 of a first nonlinear suspension member 1416 has a proximal portion coupled to the center portion 1420 of the first nonlinear suspension member 1416, and a distal portion extending away from the anchor bisecting plane 1422, with a fourth portion 1402 of the first nonlinear suspension member 1416 coupled to the distal portion of the outer portion at a proximal portion of the fourth portion 1402, and extending toward the anchor 1404 to a distal portion of the fourth portion that is coupled to a fifth portion 1424 of the first nonlinear suspension member that extends toward the anchor bisecting plane 1422. In an example, the inner portion 1410 and the outer portion 1412 are linear and parallel.

FIG. 15 illustrates the suspension of FIG. 14 flexed in torsion around a z-axis, according to an example. FIG. 16A illustrates the suspension of FIG. 14 flexed in torsion around a z-axis, according to an example. FIG. 16B illustrates the suspension of FIG. 14 flexed about a y-axis, according to an example. FIG. 16C illustrates the suspension of FIG. 14 flexed about the x-axis, according to an example. FIG. 16D illustrates the suspension of FIG. 14 flexed in displacement along a y-axis, according to an example.

FIG. 17 shows a method of making a low-quadrature-error suspension, according to an embodiment. At 1702 the method includes etching a material to define an anchor. At 1704, the method includes etching the material to define a first nonlinear suspension member coupled to anchor on a side of the anchor. At 1706, the method includes etching the material to define a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane. At 1708 the method includes etching the material to define a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the substrate.

Optional methods are possible, including methods in which etching includes deep reactive-ion etching. In some optional methods, the first nonlinear suspension member and the second nonlinear suspension member are part of a first set, comprising etching the material to define a second set of nonlinear suspension members opposite the first set. Some optional methods include etching a third set of nonlinear suspension members for coupling the anchor to the proof-mass and etching a fourth set of nonlinear suspension members for coupling the anchor to the proof-mass, wherein the third set and the fourth set have a similar for factor to the first set and the second set and are bisected by a second anchor bisecting plane perpendicular the first.

ADDITIONAL NOTES

The subject matter of the present document can be described using several examples. Example 1 includes a microelectromechanical die for sensing motion, that includes a fixed portion, an anchor coupled to the fixed portion, a first nonlinear suspension member coupled to anchor on a side of the anchor, a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane and a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the fixed portion.

Example 2 includes the subject matter of example 1, wherein the first nonlinear suspension member has a C-shape.

Example 3 includes the subject matter of example 2, wherein the C-shape includes a inner portion coupled to the anchor and extending toward the anchor bisecting plane, a center portion having a proximal portion and a distal portion, with a proximal portion coupled to the inner portion and a distal portion extending away from the anchor along the anchor bisecting plane and coupled to a outer portion extending away from the anchor bisecting plane.

Example 4 includes the subject matter of example 3, wherein the outer portion of the first nonlinear suspension member has a proximal portion coupled to the center portion of the first nonlinear suspension member, and a distal portion extending away from the anchor bisecting plane, with a fourth portion of the first nonlinear suspension member coupled to the distal portion of the outer portion at a proximal portion of the fourth portion, and extending toward the anchor to a distal portion of the fourth portion that is coupled to a fifth portion of the first nonlinear suspension member that extends toward the anchor bisecting plane.

Example 5 includes the subject matter of any of examples 3-4, wherein the inner portion and the outer portion are linear and parallel.

Example 6 includes the subject matter of example 5, wherein the center portion is perpendicular the inner portion and the outer portion.

Example 7 includes the subject matter of any of examples 3-6, wherein the center portion is parallel the anchor bisecting plane.

Example 8 includes the subject matter of any of examples 1-7, wherein the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass are formed of a monolithic material.

Example 9 includes the subject matter of example 8, wherein the fixed portion comprises a fixed monolithic material other than the monolithic material of the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass.

Example 10 includes the subject matter of any of examples 1-9, wherein the fixed portion comprises a fixed monolithic material the same as the monolithic material of the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass.

Example 11 includes the subject matter of any of examples 1-10, wherein the die is wafer shaped, with each of the first nonlinear suspension member and the second nonlinear suspension member have a substantially rectangular cross-section with the height of the cross-section smaller than the width.

Example 12 includes a that includes etching a material to define an anchor, etching the material to define a first nonlinear suspension member coupled to anchor on a side of the anchor, etching the material to define a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane and etching the material to define a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the substrate.

Example 13 includes the subject matter of example 12, wherein etching includes deep reactive-ion etching.

Example 14 includes the subject matter of any of examples 12-13, wherein the first nonlinear suspension member and the second nonlinear suspension member are part of a first set, comprising etching the material to define a second set of nonlinear suspension members opposite the first set.

Example 15 includes the subject matter of example 14, comprising etching a third set of nonlinear suspension members for coupling the anchor to the proof-mass and etching a fourth set of nonlinear suspension members for coupling the anchor to the proof-mass, wherein the third set and the fourth set have a similar for factor to the first set and the second set and are bisected by a second anchor bisecting plane perpendicular the first.

The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to herein as “examples.” All publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this document and those documents so incorporated by reference, the usage in the incorporated reference(s) should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

In this document, the terms “a” or “an” are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of “at least one” or “one or more.” In this document, the term “or” is used to refer to a nonexclusive or, such that “A or B” includes “A but not B,” “B but not A,” and “A and B,” unless otherwise indicated. In the appended claims, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein.” Also, in the following claims, the terms “including” and “comprising” are open-ended, that is, a system, device, article, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms “first,” “second,” and “third,” etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. The above description is intended to be illustrative, and not restrictive. In other examples, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description.

The Abstract is provided to comply with 37 C.F.R. §1.72(b), to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separate embodiment. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

WHAT IS CLAIMED IS:

1. A microelectromechanical die for sensing motion, comprising:

a fixed portion;

an anchor coupled to the fixed portion;

a first nonlinear suspension member coupled to anchor on a side of the anchor;

a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane; and

a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the fixed portion.

2. The die of claim 1, wherein the first nonlinear suspension member has a C-shape.

3. The die of claim 2, wherein the C-shape includes a inner portion coupled to the anchor and extending toward the anchor bisecting plane, a center portion having a proximal portion and a distal portion, with a proximal portion coupled to the inner portion and a distal portion extending away from the anchor along the anchor bisecting plane and coupled to a outer portion extending away from the anchor bisecting plane.

4. The die of claim 3, wherein the outer portion of the first nonlinear suspension member has a proximal portion coupled to the center portion of the first nonlinear suspension member, and a distal portion extending away from the anchor bisecting plane, with a fourth portion of the first nonlinear suspension member coupled to the distal portion of the outer portion at a proximal portion of the fourth portion, and extending toward the anchor to a distal portion of the fourth portion that is coupled to a fifth portion of the

first nonlinear suspension member that extends toward the anchor bisecting plane.

5. The die of any of claims 3-4, wherein the inner portion and the outer portion are linear and parallel.

6. The die of claim 5, wherein the center portion is perpendicular the inner portion and the outer portion.

7. The die of claim 3, wherein the center portion is parallel the anchor bisecting plane.

8. The die of claim 3, wherein the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass are formed of a monolithic material.

9. The die of claim 8, wherein the fixed portion comprises a fixed monolithic material other than the monolithic material of the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass.

10. The die of any of claims 8-9, wherein the fixed portion comprises a fixed monolithic material the same as the monolithic material of the anchor, the first nonlinear suspension member, the second nonlinear suspension member and the proof-mass.

11. The die of claim 1, wherein the die is wafer shaped, with each of the first nonlinear suspension member and the second nonlinear suspension member have a substantially rectangular cross-section with the height of the cross-section smaller than the width.

12. A method comprising:

etching a material to define an anchor;

etching the material to define a first nonlinear suspension member coupled to anchor on a side of the anchor;

etching the material to define a second nonlinear suspension member coupled to the anchor on the same side of the anchor, the second nonlinear suspension member having a shape and location mirroring the first nonlinear suspension member about an anchor bisecting plane; and

etching the material to define a proof-mass that is planar, the proof mass suspended at least in part by the first nonlinear suspension member and the second nonlinear suspension member such that the proof-mass is rotable about the anchor and is slideable in a plane parallel to the substrate.

13. The method of claim 12, wherein etching includes deep reactive-ion etching.

14. The method of any of claims 12-13, wherein the first nonlinear suspension member and the second nonlinear suspension member are part of a first set, comprising etching the material to define a second set of nonlinear suspension members opposite the first set.

15. The method of claim 14, comprising etching a third set of nonlinear suspension members for coupling the anchor to the proof-mass and etching a fourth set of nonlinear suspension members for coupling the anchor to the proof-mass, wherein the third set and the fourth set have a similar for factor to the first set and the second set and are bisected by a second anchor bisecting plane perpendicular the first.

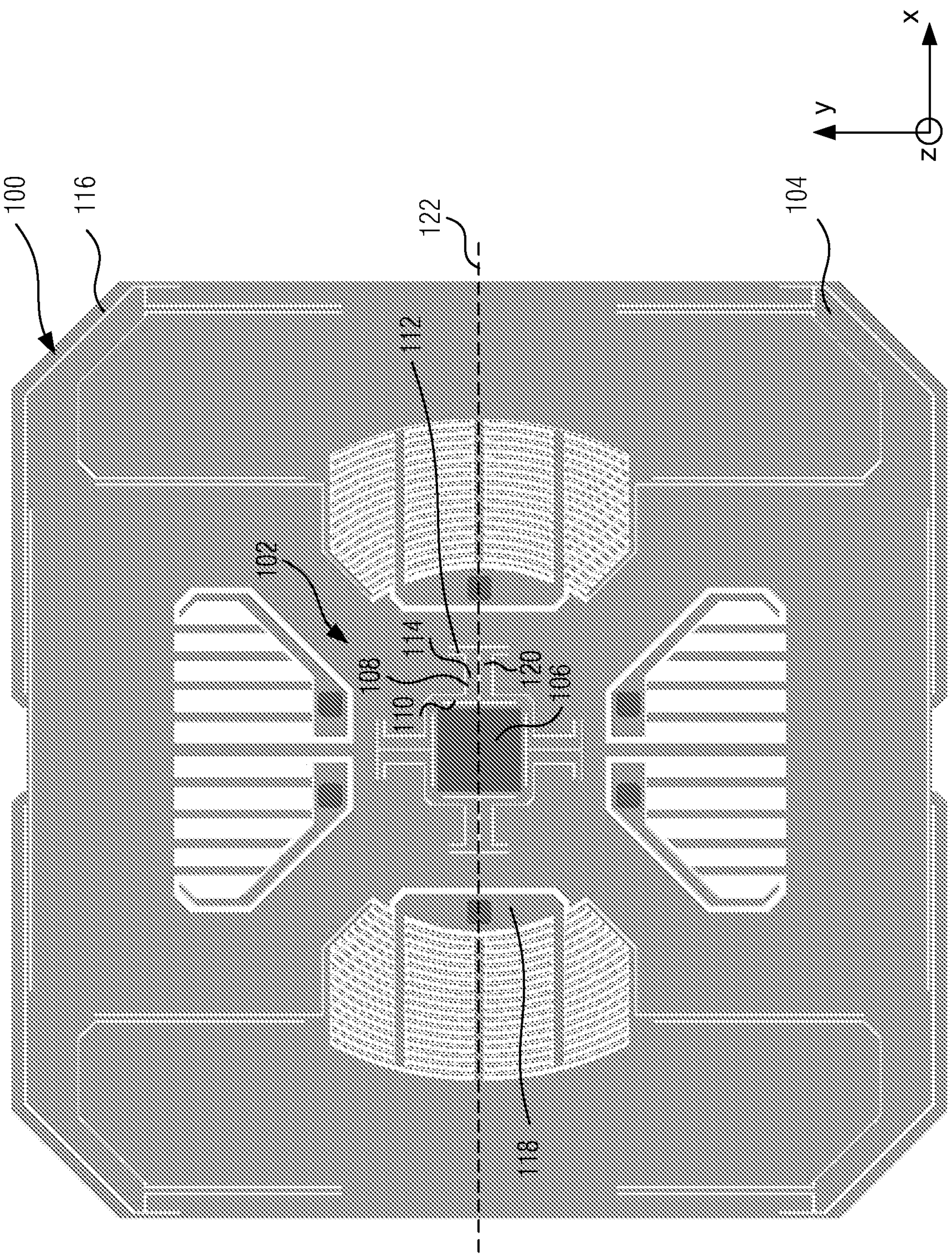


FIG. 1

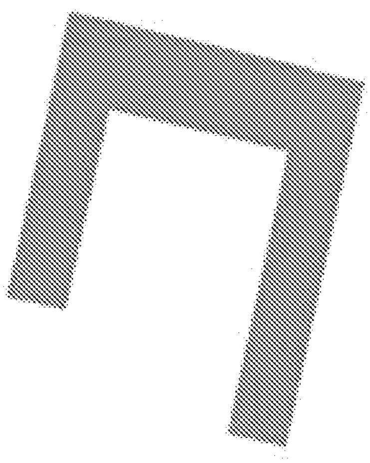


FIG. 2A

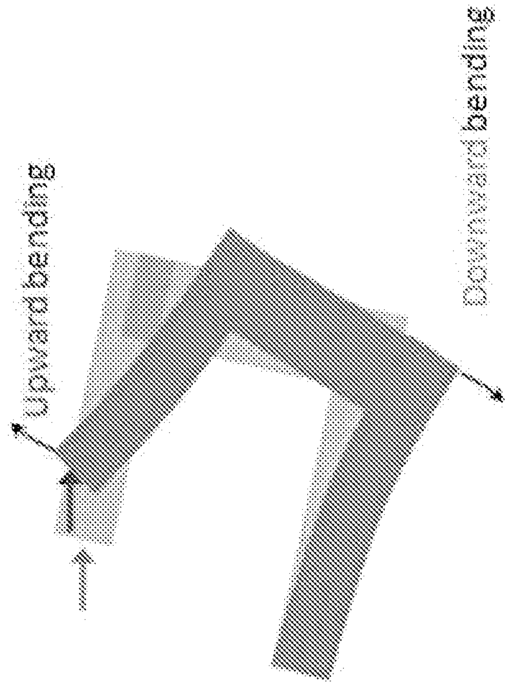


FIG. 2B

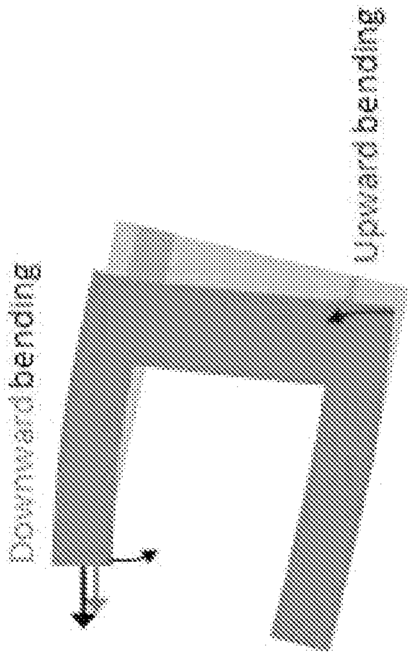


FIG. 2C

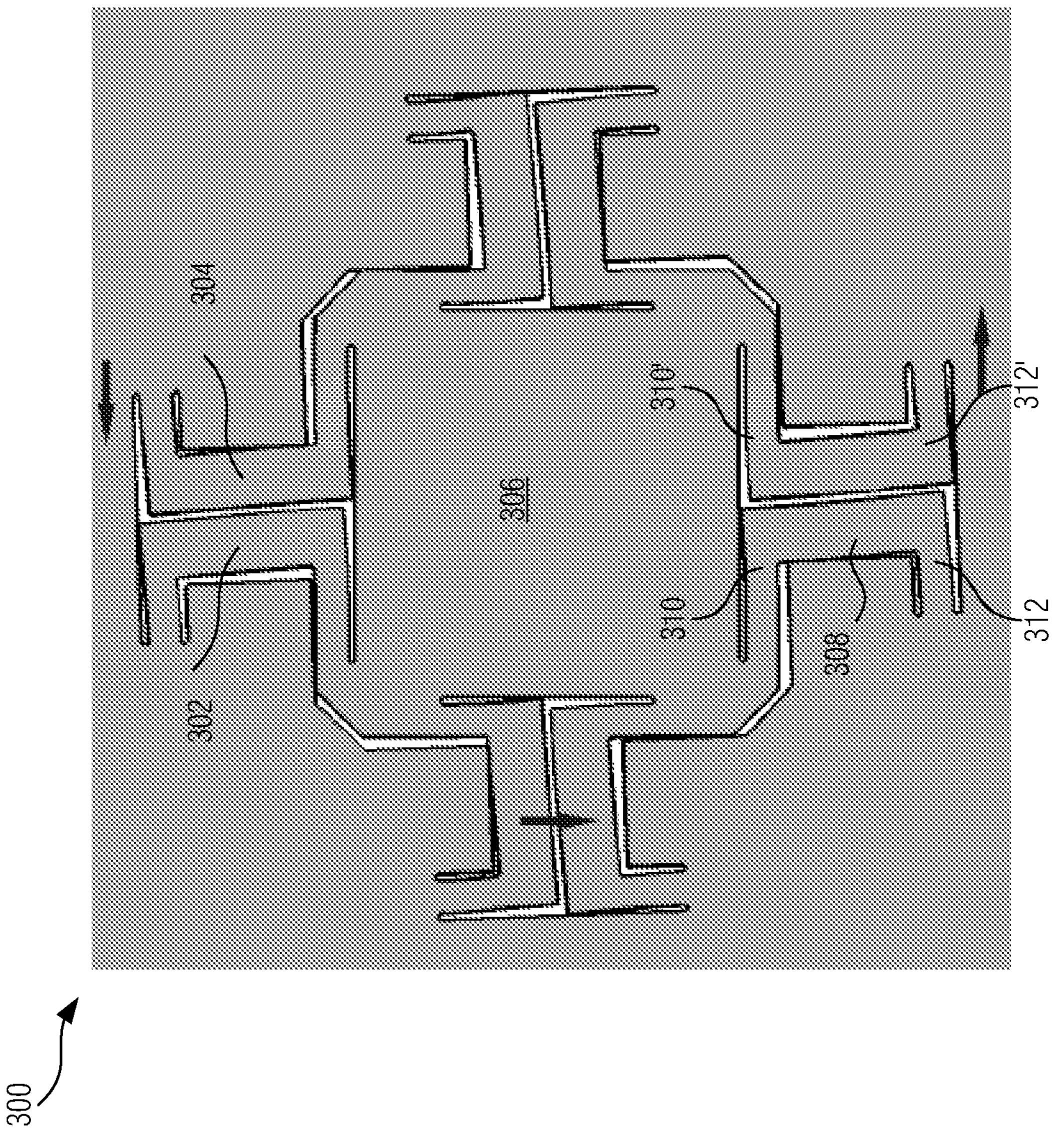
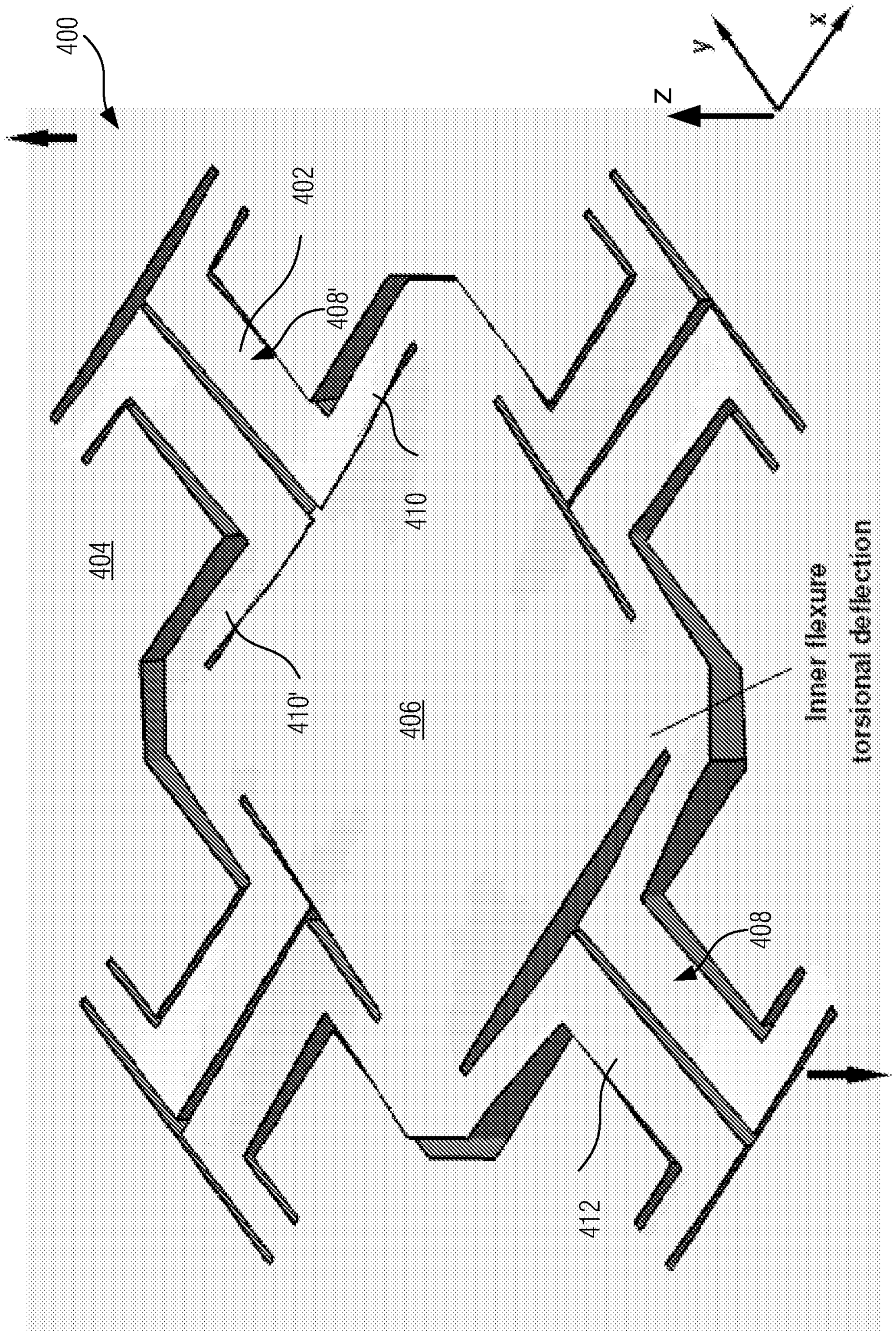


FIG. 3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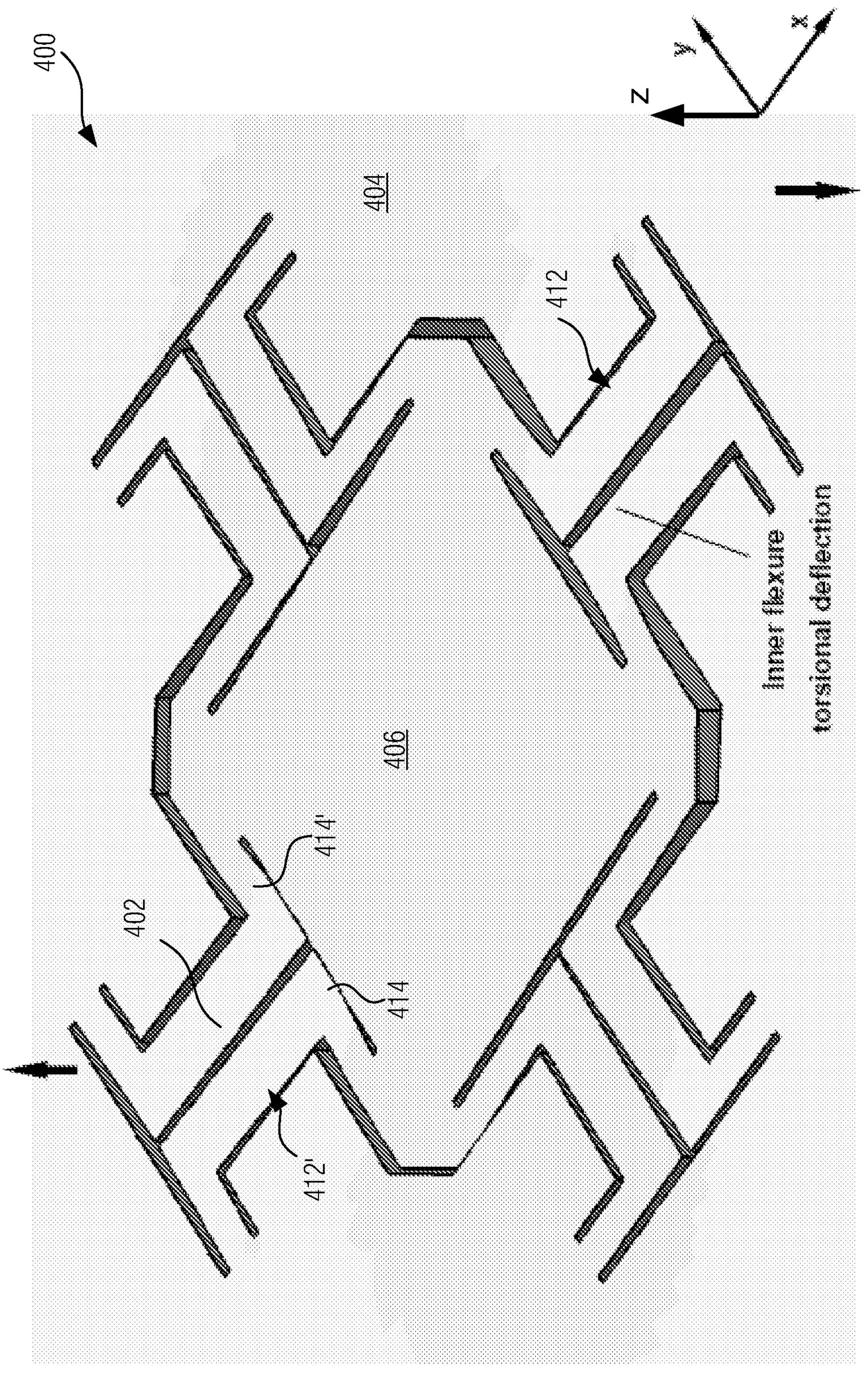
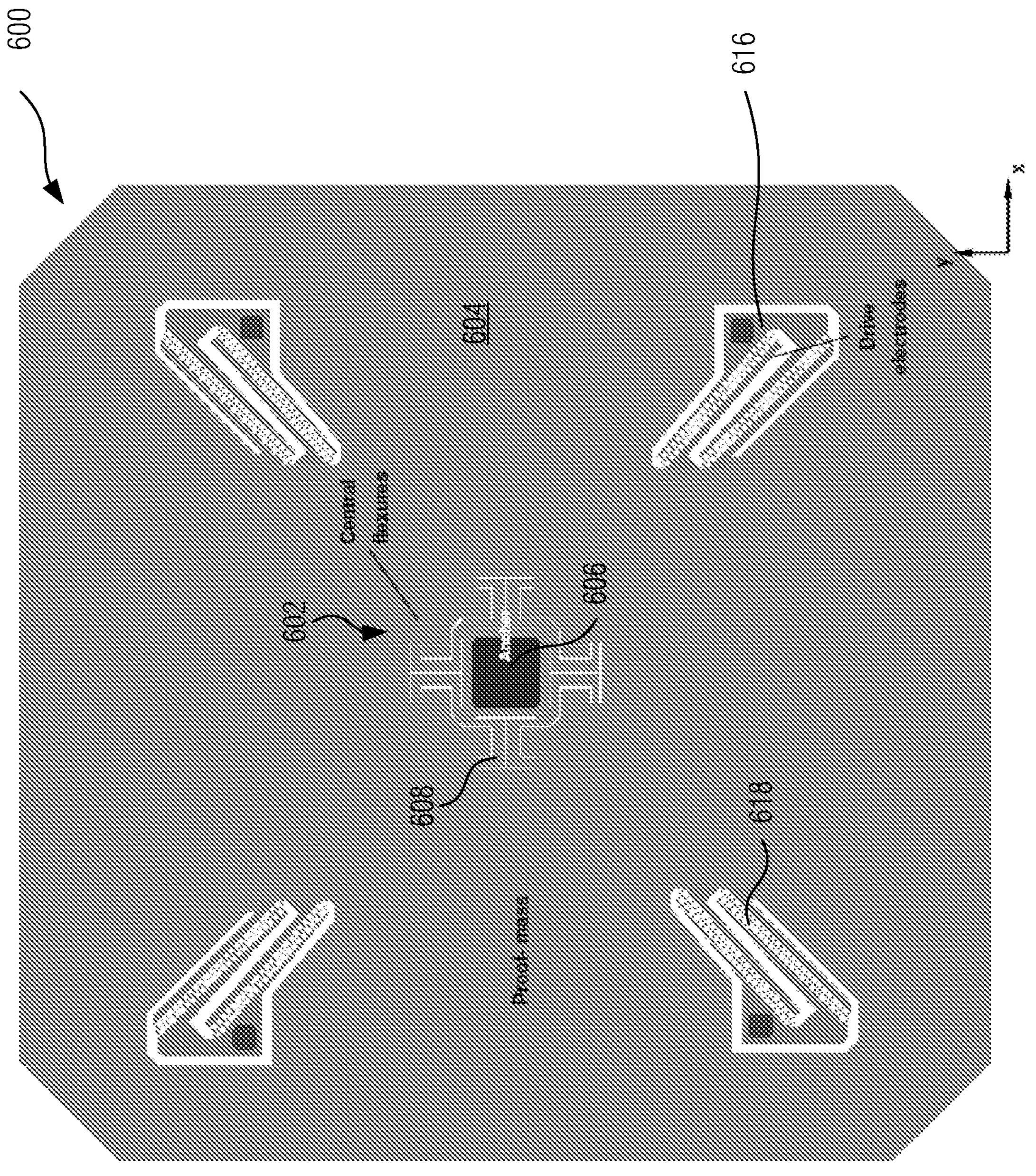
z
y
x
402
408'
410
404
410'
406
Inner flexure
torsional deflection
408
412

FIG. 4



400
404
406
402
412
412'
414
414'
Inner flexure
torsional deflection
x
y
z

FIG. 5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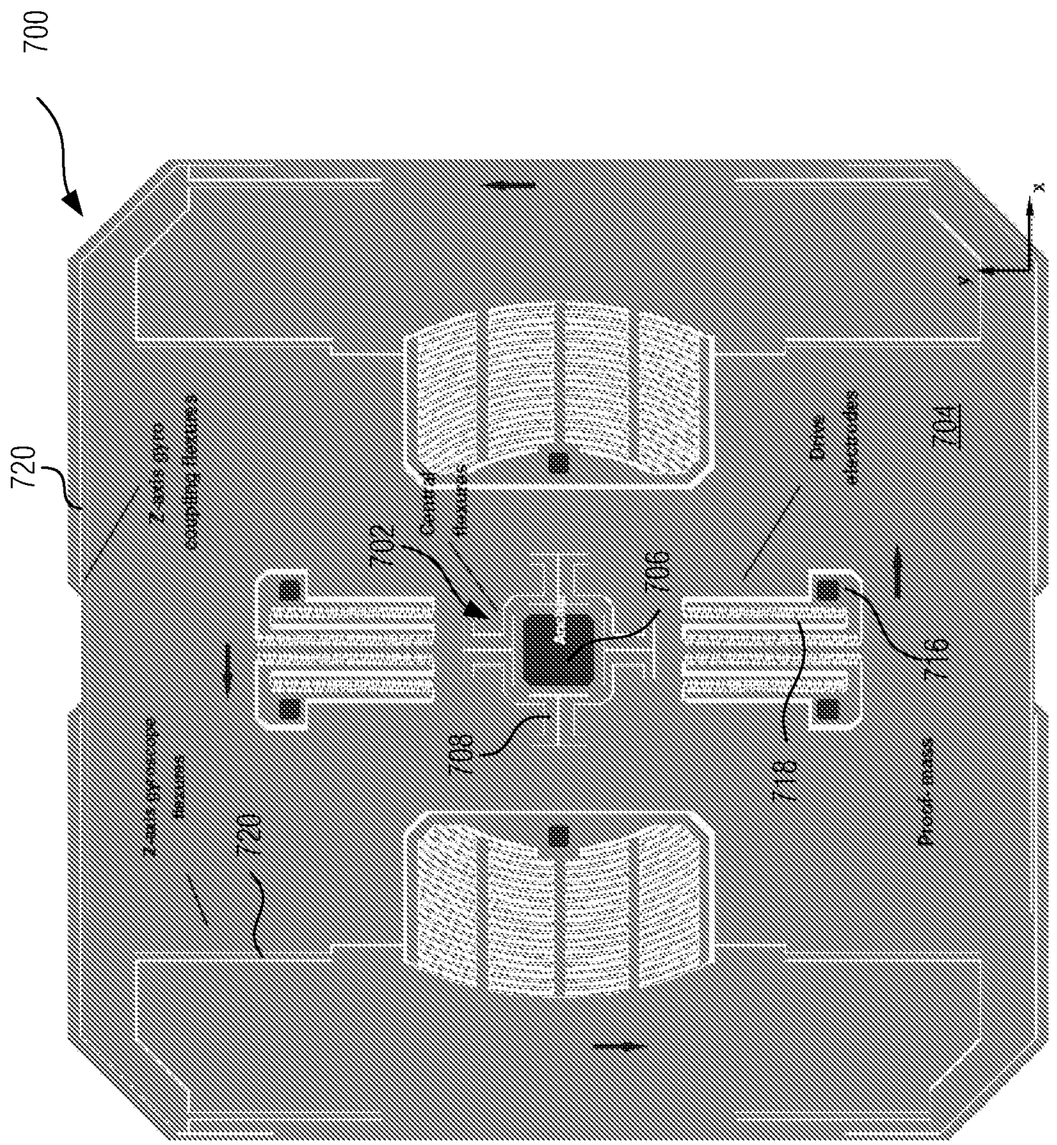
Central flexures
602
606
608
618
Proof mass

FIG. 6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Central flexures
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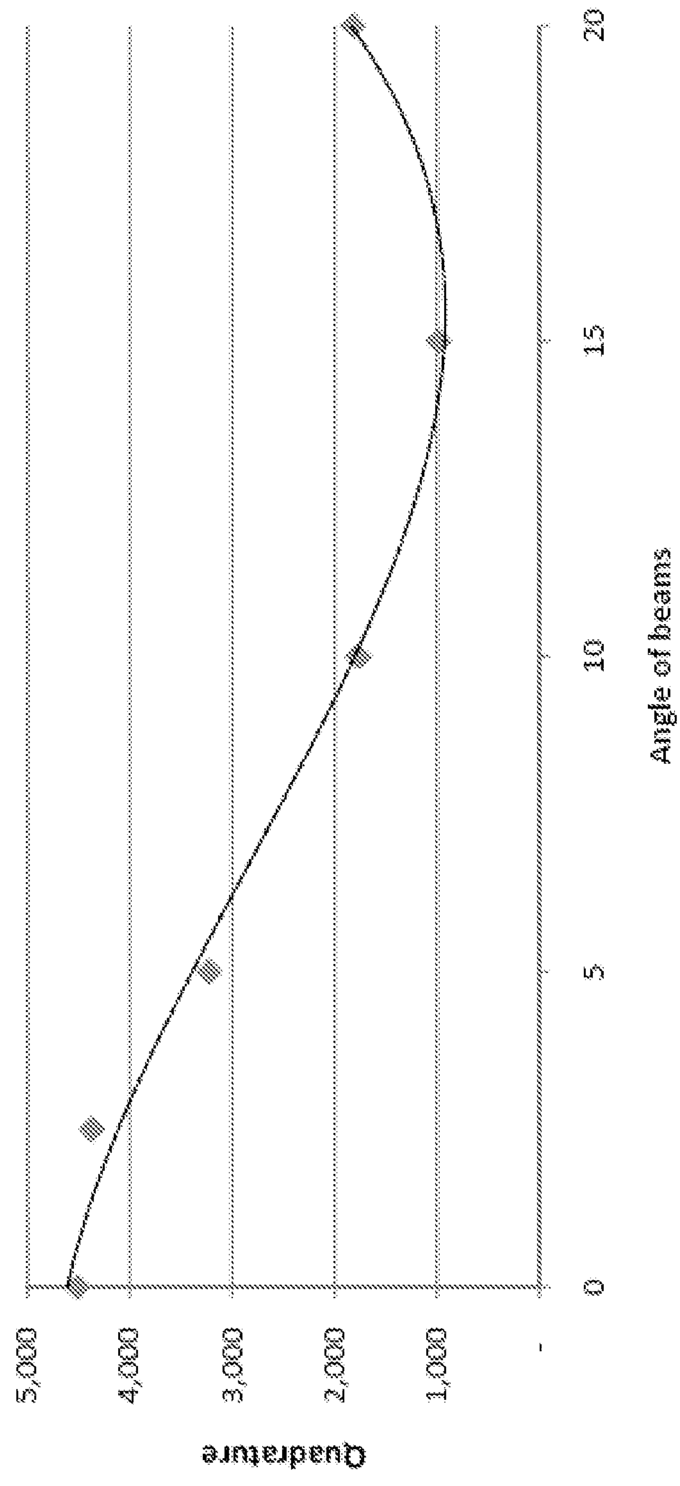
Drive electrodes
704
716
718
Proof mass
720
x
y

FIG. 7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5
10
15
20
Angle of beams

FIG. 8

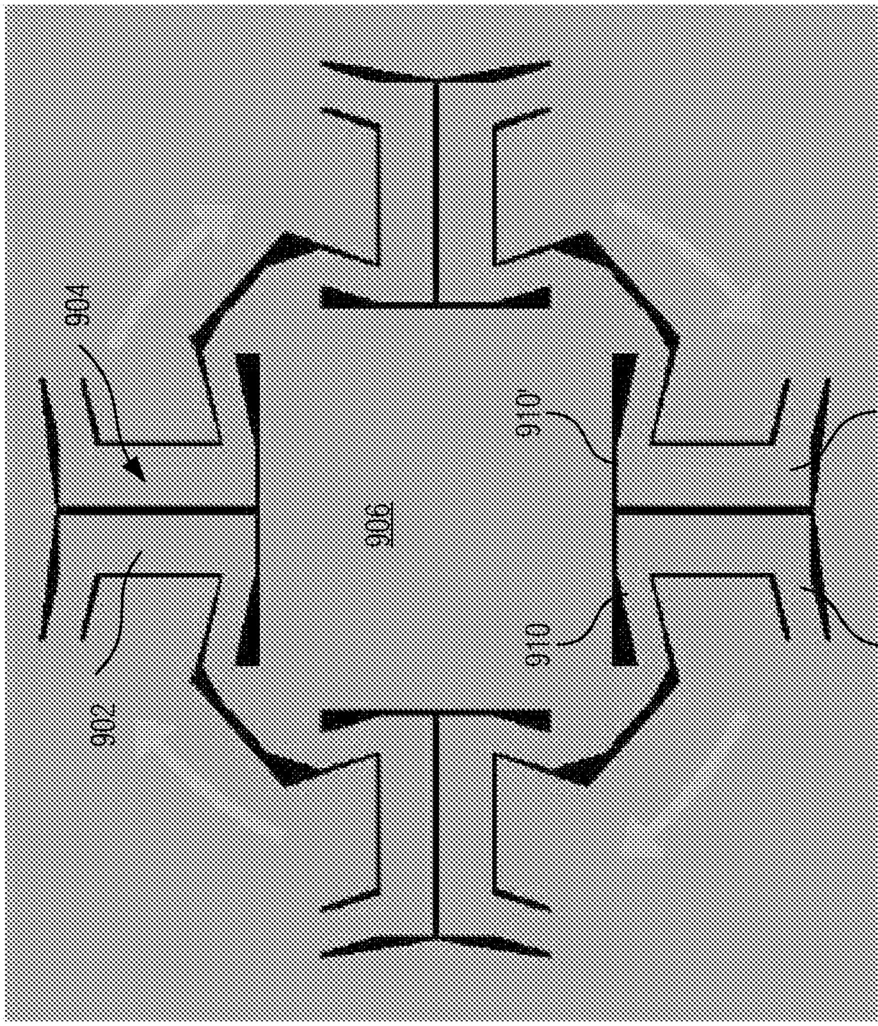

FIG. 9

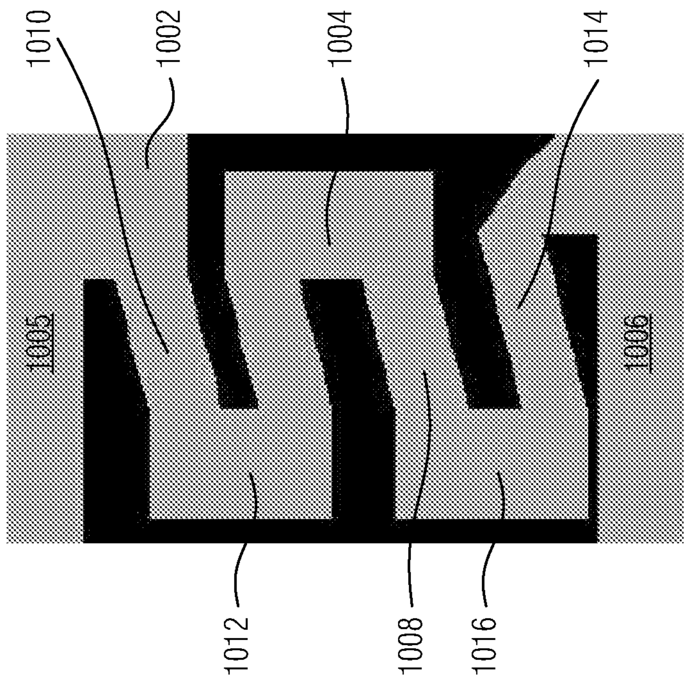

FIG. 10

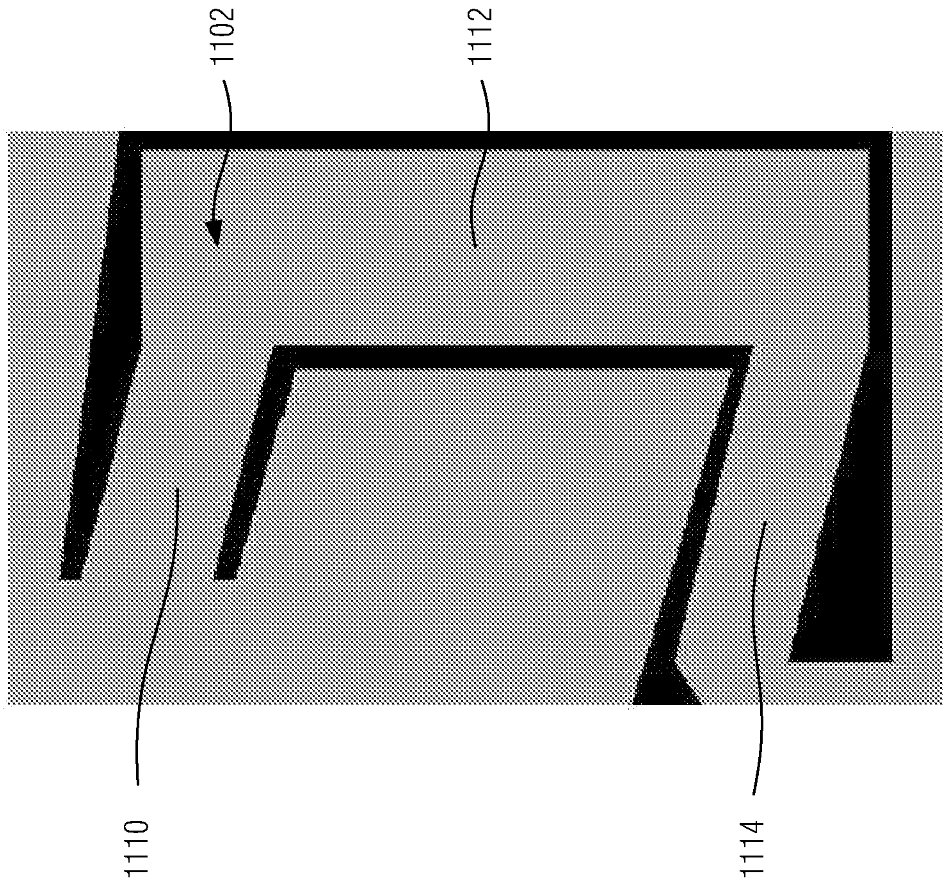

FIG. 11

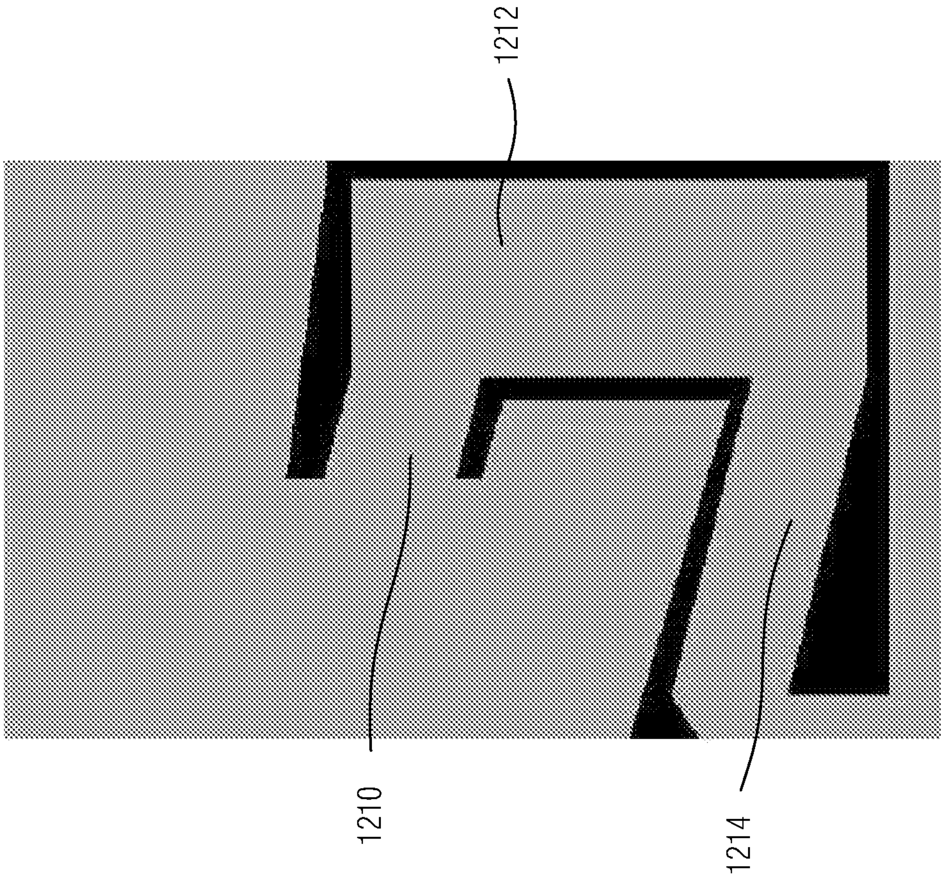

FIG. 12

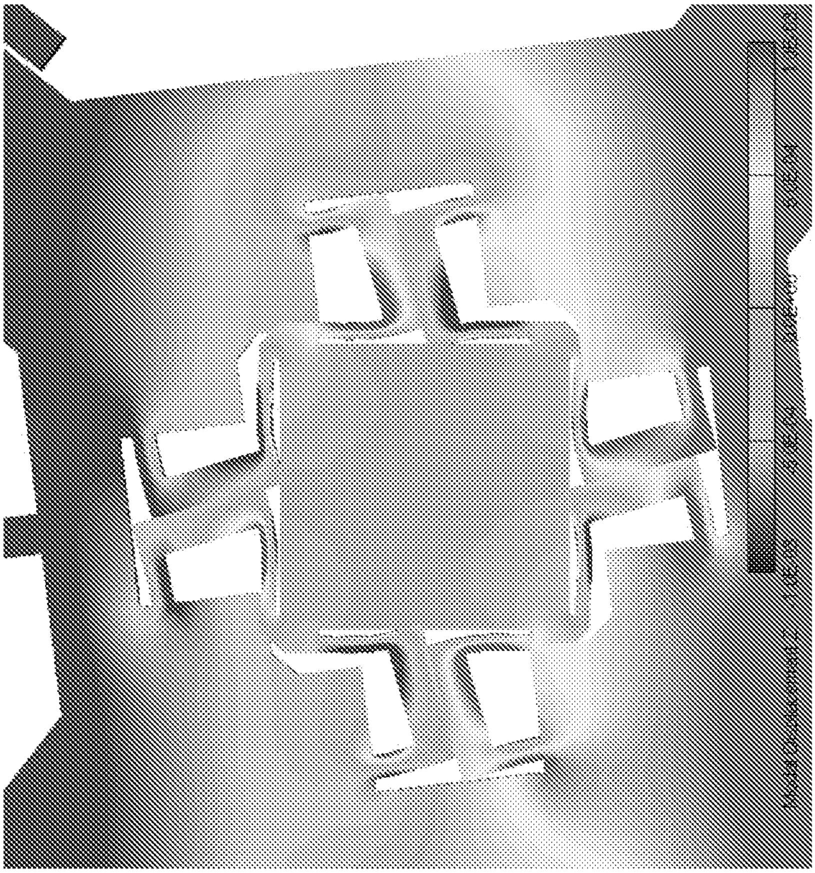

FIG. 13B

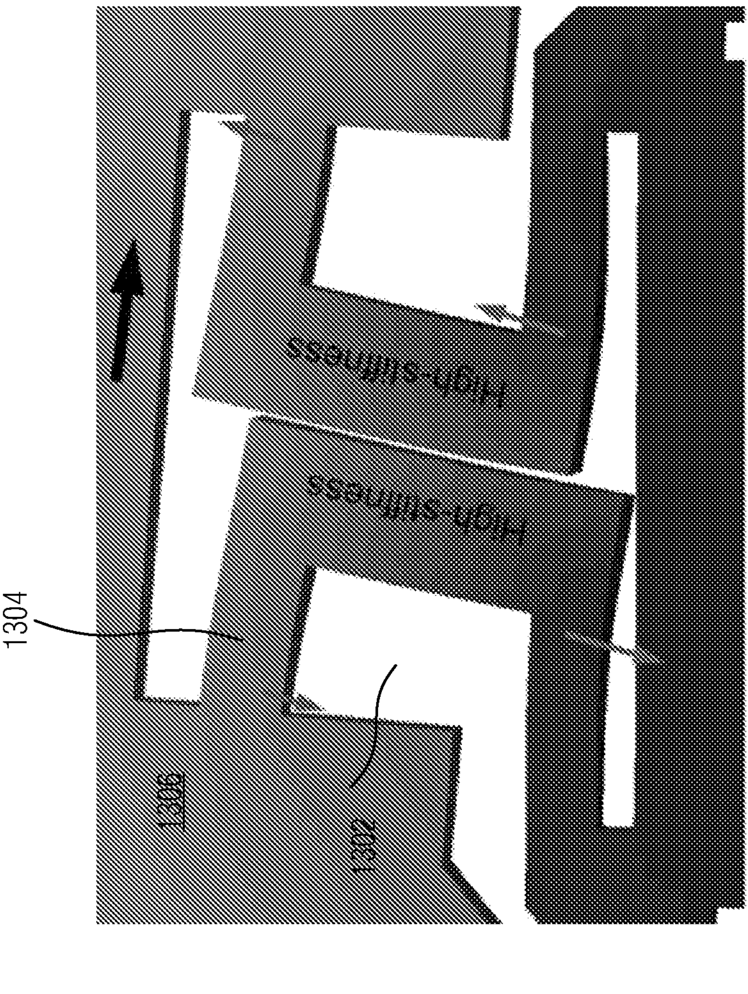

FIG. 13A

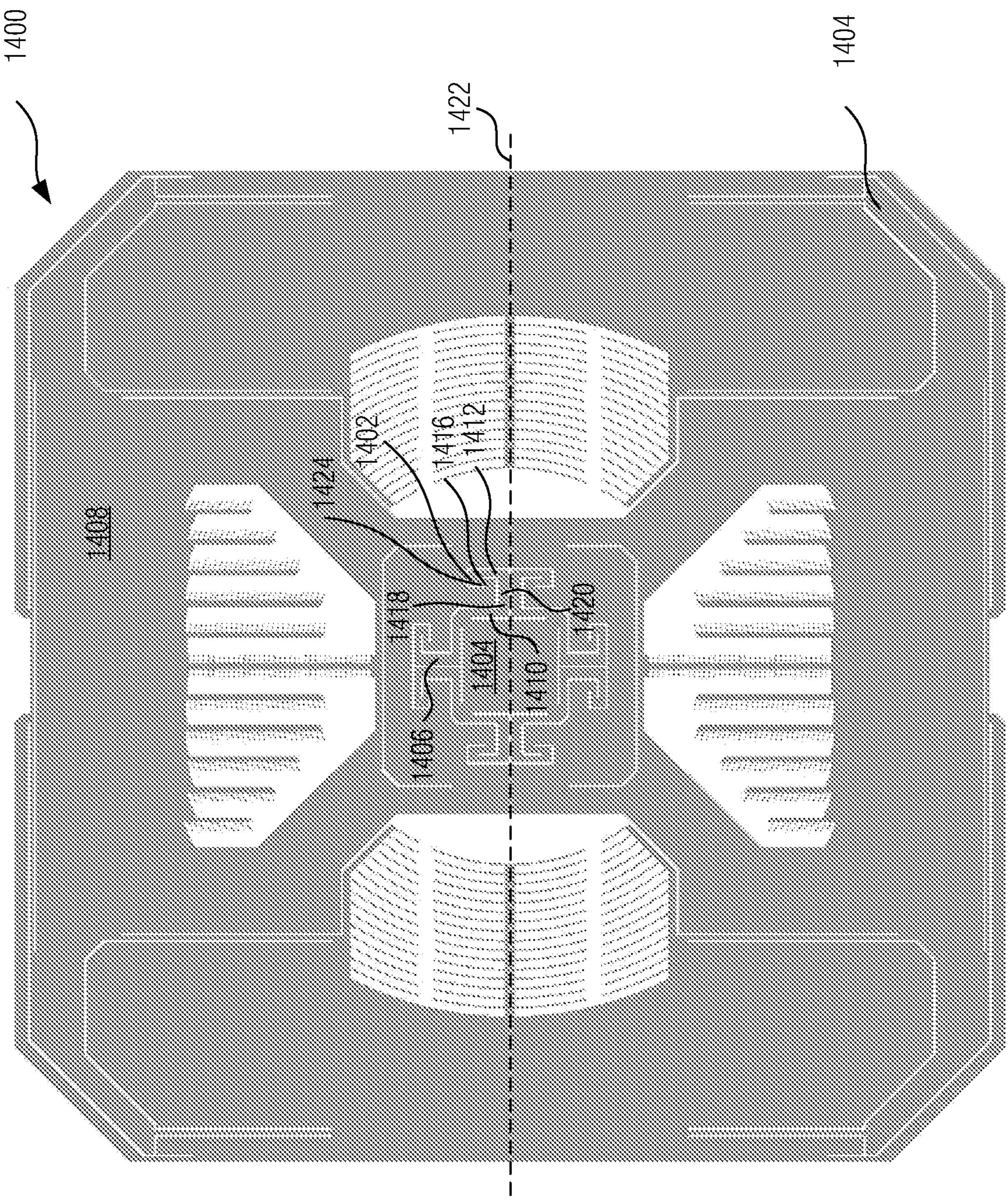
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FIG. 14

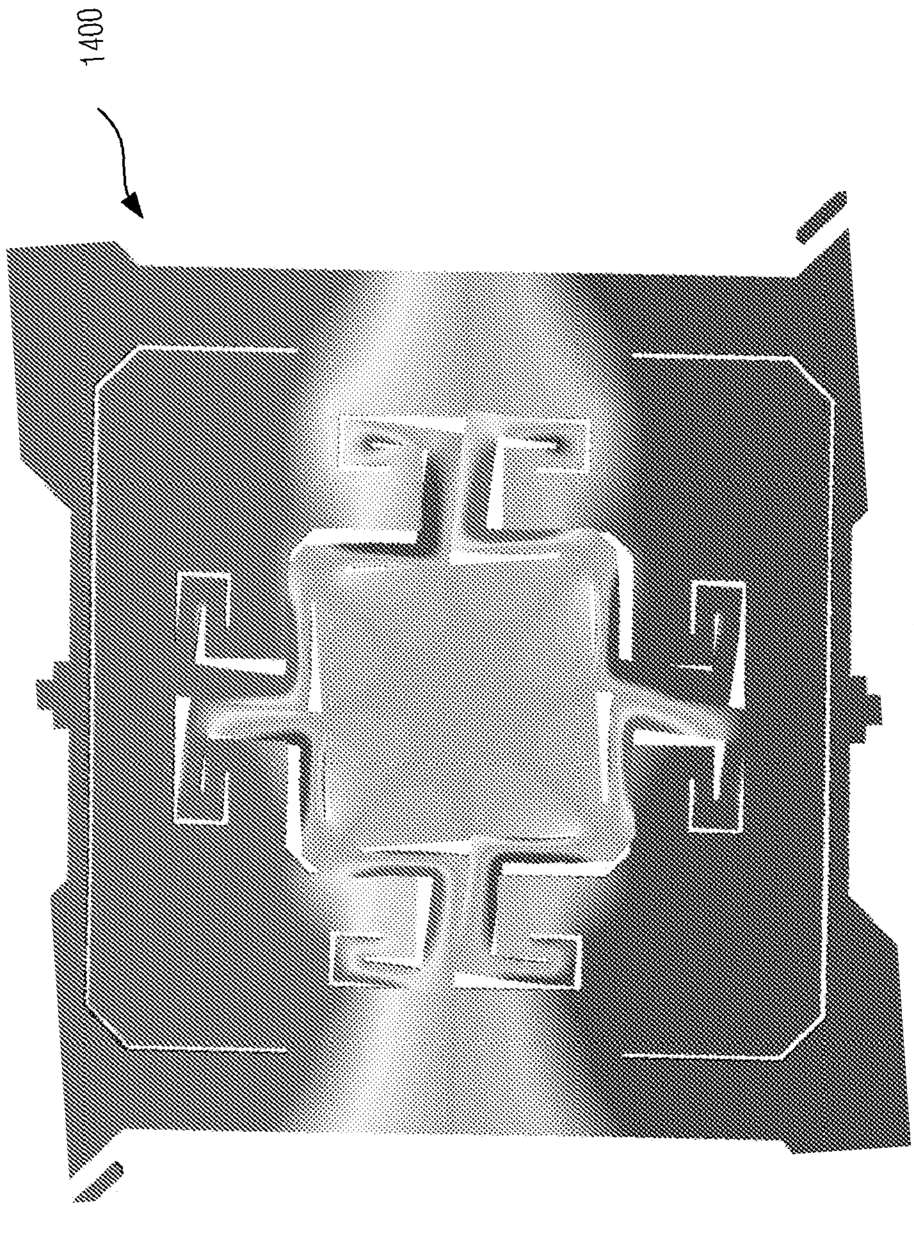

FIG. 15

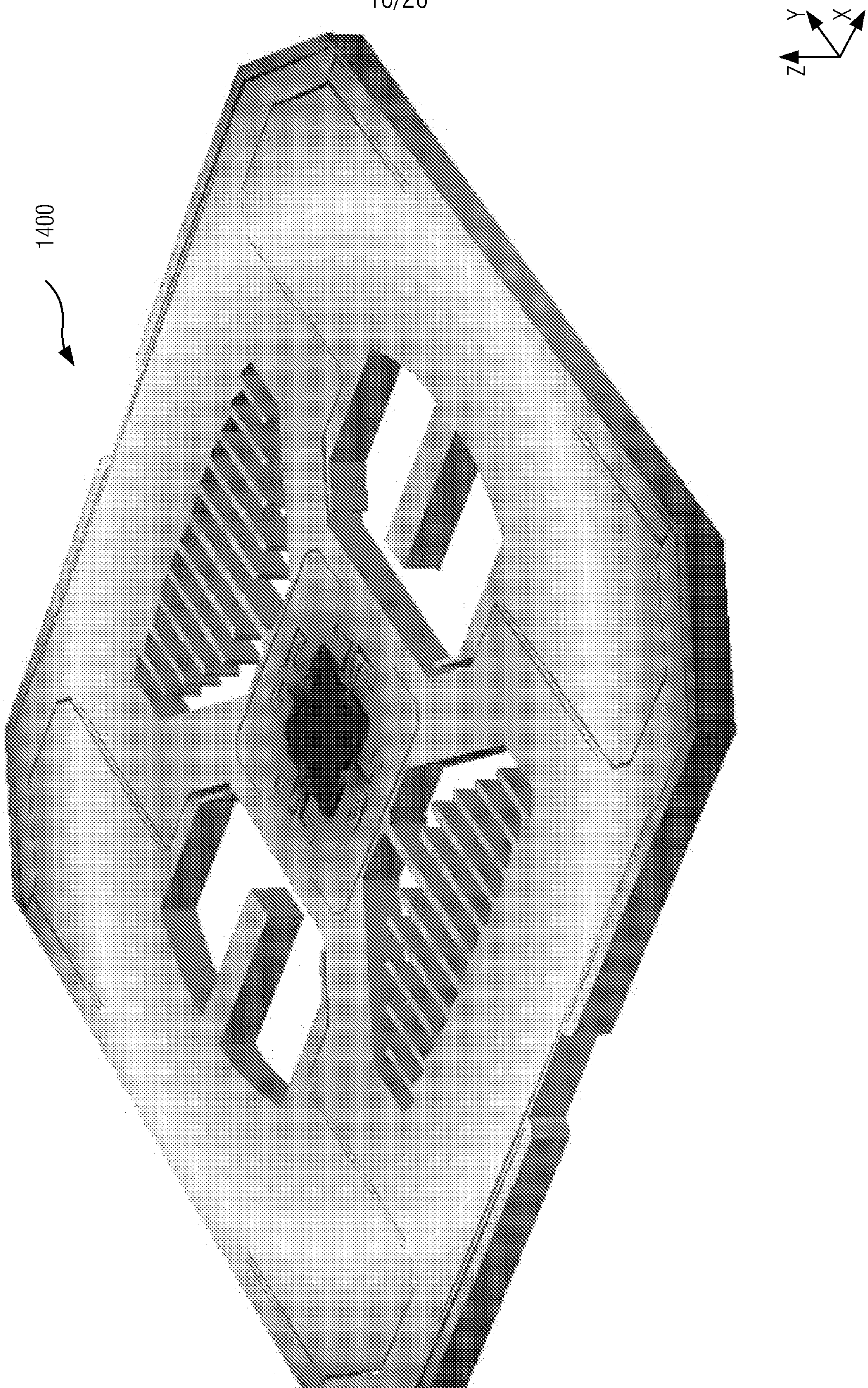

FIG. 16A

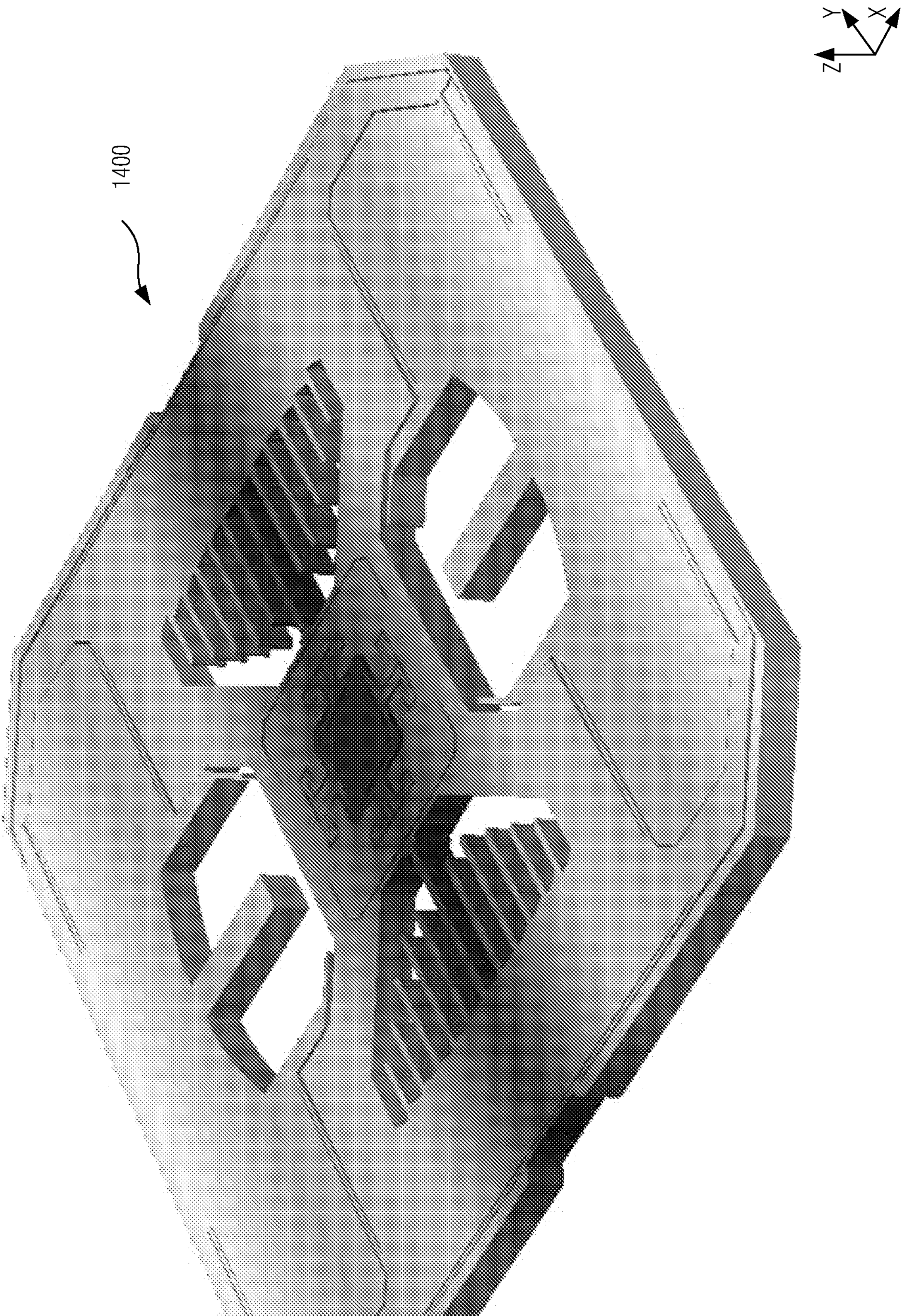

FIG. 16B

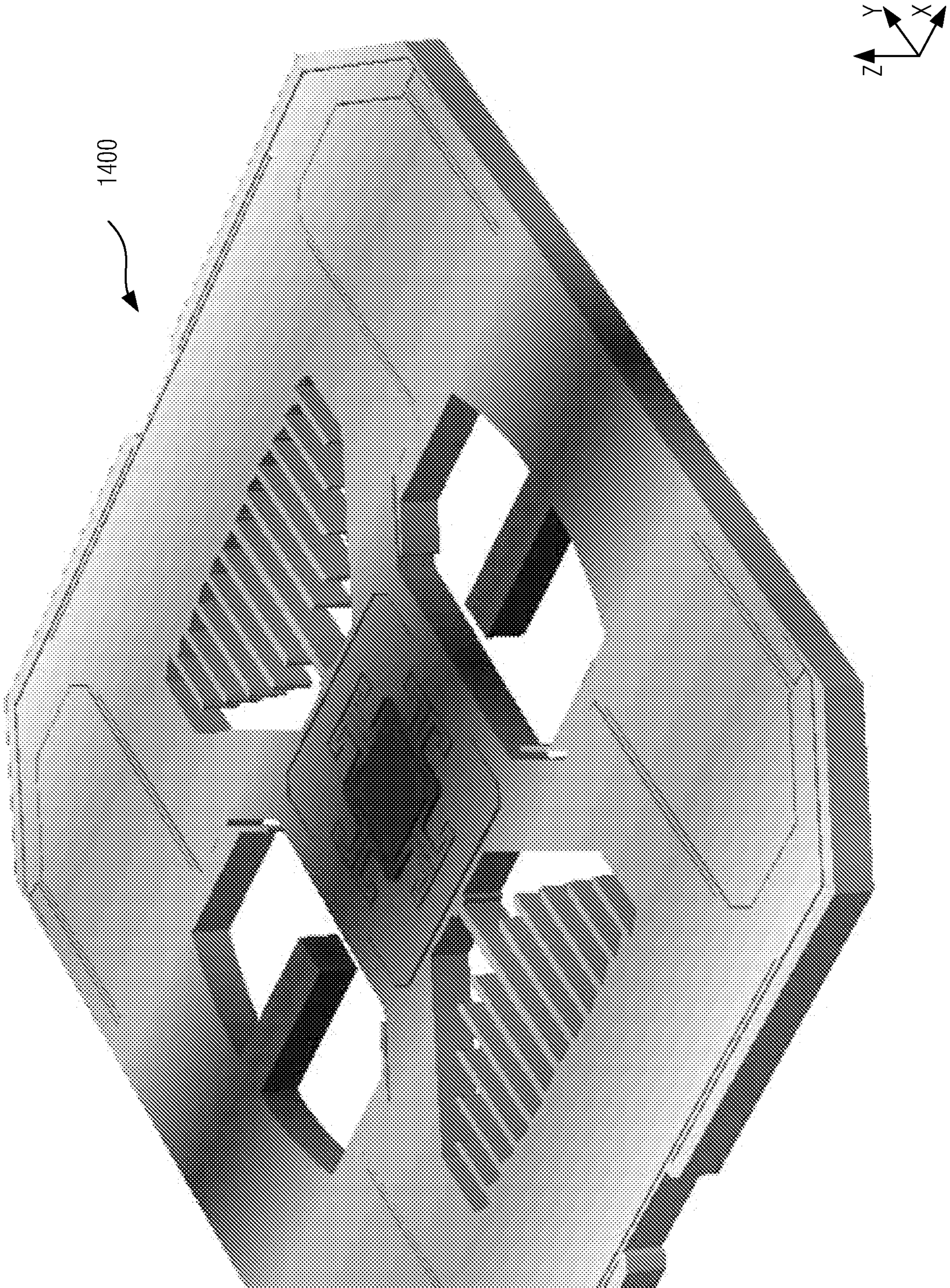

FIG. 16C

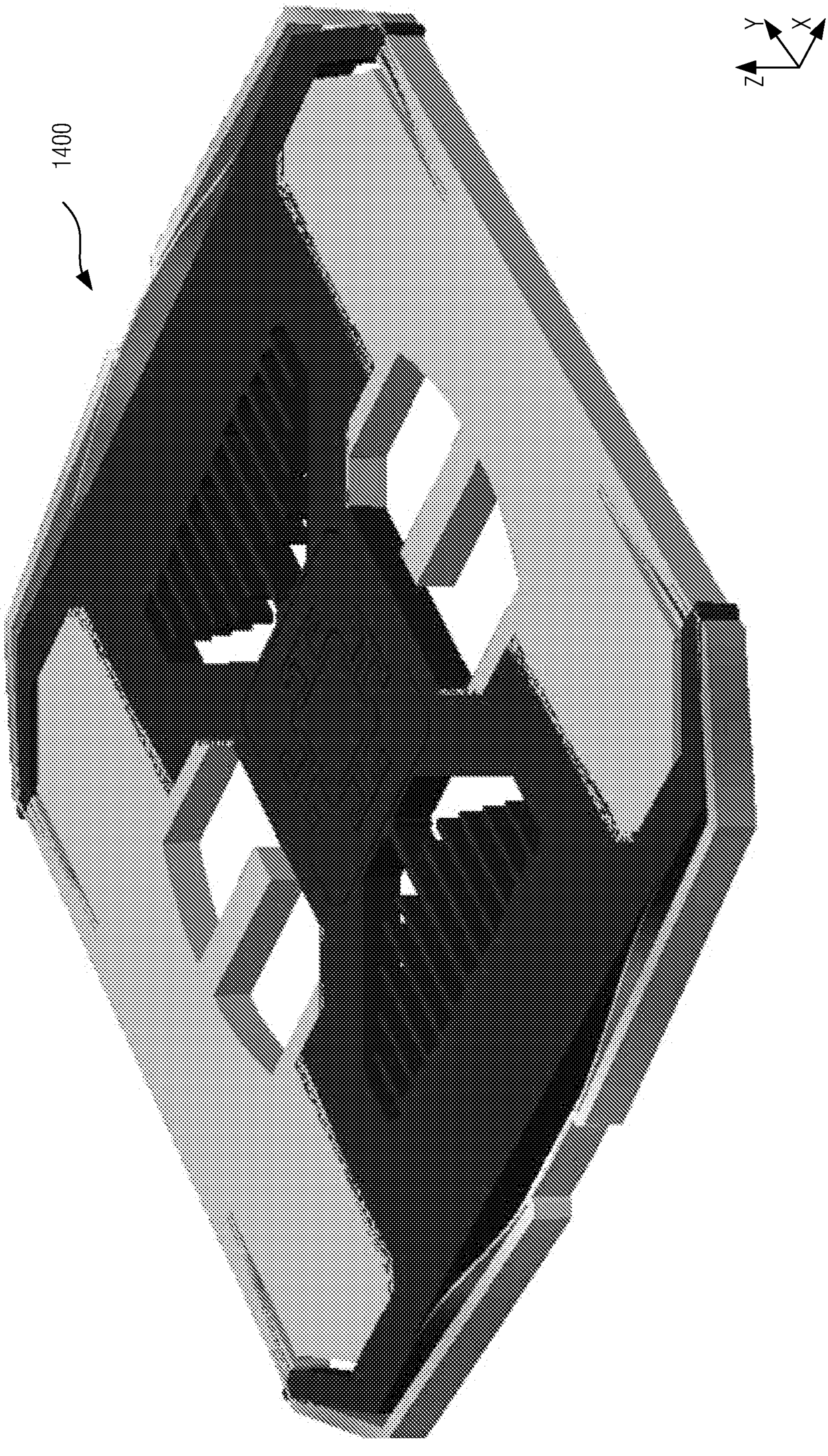

FIG. 16D

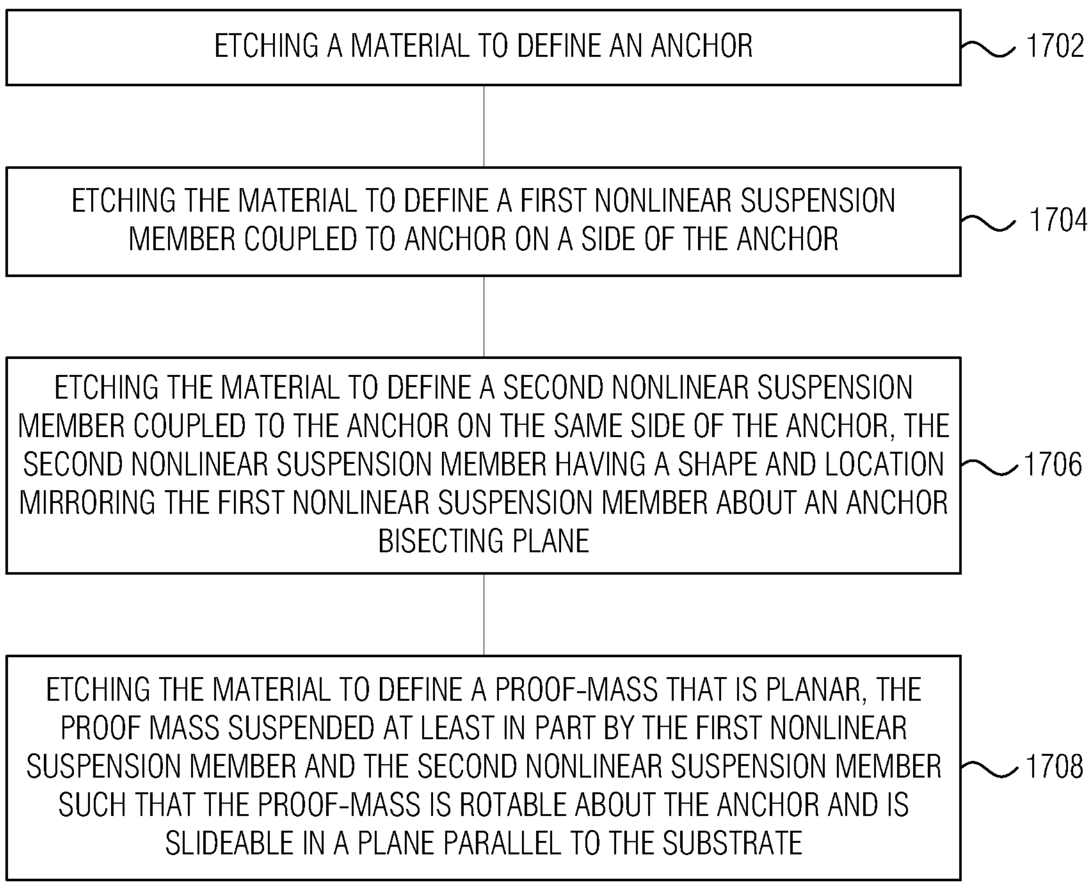
ETCHING A MATERIAL TO DEFINE AN ANCHOR
1702
ETCHING THE MATERIAL TO DEFINE A FIRST NONLINEAR SUSPENSION MEMBER COUPLED TO ANCHOR ON A SIDE OF THE ANCHOR
1704
ETCHING THE MATERIAL TO DEFINE A SECOND NONLINEAR SUSPENSION MEMBER COUPLED TO THE ANCHOR ON THE SAME SIDE OF THE ANCHOR, THE SECOND NONLINEAR SUSPENSION MEMBER HAVING A SHAPE AND LOCATION MIRRORING THE FIRST NONLINEAR SUSPENSION MEMBER ABOUT AN ANCHOR BISECTING PLANE
1706
ETCHING THE MATERIAL TO DEFINE A PROOF-MASS THAT IS PLANAR, THE PROOF MASS SUSPENDED AT LEAST IN PART BY THE FIRST NONLINEAR SUSPENSION MEMBER AND THE SECOND NONLINEAR SUSPENSION MEMBER SUCH THAT THE PROOF-MASS IS ROTABLE ABOUT THE ANCHOR AND IS SLIDEABLE IN A PLANE PARALLEL TO THE SUBSTRATE
1708

FIG. 17