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(54) Title: MICROMACHINED 3-AXIS ACCELEROMETER WITH A SINGLE PROOF-MASS

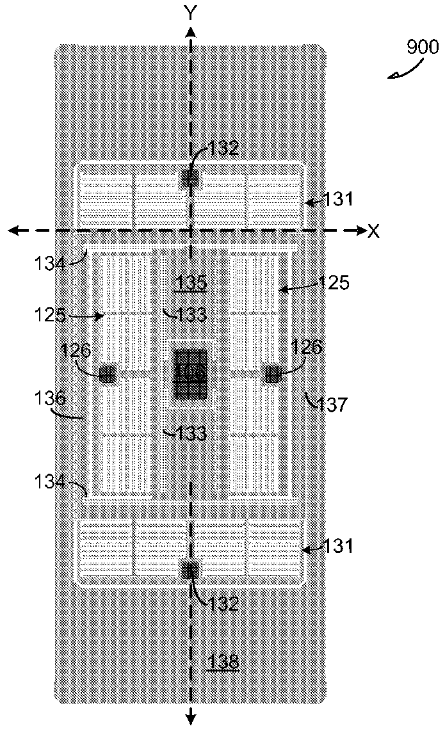

FIG. 9

(57) Abstract: This document discusses, among other things, an inertial measurement system including a device layer including a single proof-mass 3 -axis accelerometer, a cap wafer bonded to a first surface of the device layer, and a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3 -axis accelerometer. The single proof-mass 3 -axis accelerometer can be suspended about a single, central anchor, and can include separate x, y, and z-axis flexure bearings, wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor.

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MICROMACHINED 3-AXIS ACCELEROMETER WITH A SINGLE PROOF-MASS

CLAIM OF PRIORITY

This application claims the benefit of priority of Acar, U.S. Provisional Patent Application Serial No. 61/384,245, entitled “MICROMACHINED MONOLITHIC 3-AXIS GYROSCOPE WITH SINGLE DRIVE,” filed on September 18, 2010 (Attorney Docket No. 2921.100PRV), and the benefit of priority of Acar, U.S. Provisional Patent Application Serial No. 61/384,246, entitled “MICROMACHINED 3-AXIS ACCELEROMETER WITH A SINGLE PROOF-MASS,” filed on September 18, 2010 (Attorney Docket No. 2921.101PRV), each of which is hereby incorporated by reference herein in its entirety.

Further, this application is related to Acar et al., U.S. Patent Application Serial No. 12/849,742, entitled “MICROMACHINED INERTIAL SENSOR DEVICES,” filed on August 3, 2010 and to Marx et al., U.S. Patent Application Serial No. 12/849,787, entitled “MICROMACHINED DEVICES AND FABRICATING THE SAME,” filed Aug 3, 2010, each of which is hereby incorporated by reference herein in its entirety.

TECHNICAL FIELD

The present invention relates generally to inertial sensor devices and more particularly to micromachined inertial sensor devices.

BACKGROUND

Several single-axis or multi-axis micromachined gyroscope structures have been integrated into a system to form a 3-axis gyroscope cluster. However, the size and cost of such clusters consisting of separate sensors can be excessive for certain applications. Even though single or multi-axis gyroscopes can be fabricated on a single MEMS chip, separate drive and sense electronics are required for each sensor.

Further, the demand for three axis acceleration detection in consumer/mobile, automotive and aerospace/defense applications is constantly increasing. Many single-axis or multi-axis micromachined accelerometer structures have utilized separate proof-masses for each acceleration axis. Combining multiple sensors or multiple proof-masses on a die can drive up both the size and cost of the integrated three-axis accelerometer sensor.

OVERVIEW

This document discusses, among other things, an inertial measurement system including a device layer including a single proof-mass 3-axis accelerometer, a cap wafer bonded to a first surface of the device layer, and a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis accelerometer. The single proof-mass 3-axis accelerometer can be suspended about a single, central anchor, and can include separate x, y, and z-axis flexure bearings, wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor.

This overview is intended to provide an overview of subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the present patent application.

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 generally a schematic cross sectional view of a 3-degrees-of-freedom (3-DOF) inertial measurement unit (IMU).

FIG. 2 illustrates generally an example of a 3-axis gyroscope.

FIG. 3 illustrates generally an example of a 3-axis gyroscope in drive motion.

FIG. 4 illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the x-axis.

FIG. 5 illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the y-axis.

FIG. 6 illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the z-axis.

FIGS. 7 and 8 illustrate generally examples of a 3-axis gyroscope including a z-axis gyroscope coupling flexure bearing during anti-phase motion and in-phase motion, respectively.

FIG. 9 illustrates generally an example of a 3-axis accelerometer.

FIG. 10 illustrates generally an example of a 3-axis accelerometer in sense motion in response to an x-axis acceleration.

FIG. 11 illustrates generally an example of a 3-axis accelerometer in sense motion in response to a y-axis acceleration.

FIG. 12 illustrates generally an example of a 3-axis accelerometer in sense motion in response to a z-axis acceleration.

FIG. 13 illustrates generally an example of a system including via wafer electrode placement.

FIG. 14 illustrates generally an example side view of a 3-axis accelerometer including a single proof-mass.

FIG. 15 illustrates generally an example of a 3+3-degrees-of-freedom (3+3DOF) inertial measurement unit (IMU).

FIG. 16 illustrates generally an example of the central suspension at rest about an anchor.

FIG. 17 illustrates generally an example of a portion of the central suspension in drive motion.

DETAILED DESCRIPTION

The present inventor has recognized, among other things, a micromachined monolithic 3-axis gyroscope configured to utilize a single center-anchored proof-mass to detect angular rate about all three axes while effectively decoupling the response modes for each axis to minimize cross-axis sensitivity.

In an example, the unique proof-mass partitioning and flexure structure disclosed herein can allow 3-axis angular rate detection utilizing a single drive-mode oscillation, which can require only one drive control loop for all axes. Thus, in contrast to existing multi-axis gyroscopes that use three separate drive loops, complexity and cost of control electronics of the 3-axis gyroscope disclosed herein can be significantly reduced.

Further, the present inventor has recognized, among other things, a micromachined 3-axis accelerometer configured to utilize a single center-anchored proof-mass to detect accelerations about all three axes while effectively decoupling the response modes for each axis to minimize cross-axis sensitivity.

In an example, the unique proof-mass and flexure structure disclosed herein can allow 3-axis acceleration detection using a single center anchored proof-mass. Thus, in contrast to existing multi-axis accelerometers that utilize separate proof-masses for each acceleration axis, the overall die size and the total cost of the microelectromechanical system (MEMS) sensing element of the 3-axis accelerometer disclosed herein can be significantly reduced.

Device Structure

FIG. 1 illustrates generally a schematic cross sectional view of a 3-degrees-of-freedom (3-DOF) inertial measurement unit (IMU) 100, such as a 3-DOF gyroscope or a 3-DOF micromachined accelerometer, formed in a chip-scale package including a cap wafer 101, a device layer 105 including micromachined structures (e.g., a micromachined 3-DOF IMU), and a via wafer 103. In an example, the device layer 105 can be sandwiched between the cap wafer 101 and the via wafer 103, and the cavity between the device layer 105 and the cap wafer 101 can be sealed under vacuum at the wafer level.

In an example, the cap wafer 101 can be bonded to the device layer 105, such as using a metal bond 102. The metal bond 102 can include a fusion bond, such as a non-high temperature fusion bond, to allow getter to maintain long term vacuum and application of anti-stiction coating to prevent stiction that can occur to low-g acceleration sensors. In an example, during operation of the device layer 105, the metal bond 102 can generate thermal stress between the cap wafer 101 and the device layer 105. In certain examples, one or more features can be added to the device layer 105 to isolate the micromachined structures in the device layer 105 from thermal stress, such as one or more stress reducing grooves formed around the perimeter of the micromachined structures. In an example, the via wafer 103 can be bonded to the device layer 105, such as fusion bonded (e.g., silicon-silicon fusion bonded, etc.), to obviate thermal stress between the via wafer 103 and the device layer 105.

In an example, the via wafer 103 can include one or more isolated regions, such as a first isolated region 107, isolated from one or more other regions of the via wafer 103, for example, using one or more through-silicon-vias (TSVs), such as a first TSV 108 insulated from the via wafer 103 using a dielectric material 109. In certain examples, the one or more isolated regions can be utilized as electrodes to sense or actuate out-of-plane operation modes of the 6-axis inertial sensor, and the one or more TSVs can be configured to provide electrical connections from the device layer 105 outside of the system 100. Further, the via wafer 103 can include one or more contacts, such as a first contact 110, selectively isolated from one or more portions of the via wafer 103 using a dielectric layer 104 and configured to provide an electrical connection between one or more of the isolated regions or TSVs of the via wafer 103 to one or more external components, such as an ASIC wafer, using bumps, wire bonds, or one or more other electrical connection.

In certain examples, the 3-degrees-of-freedom (3-DOF) gyroscope or the micromachined accelerometer in the device layer 105 can be supported or anchored to the via wafer 103 by bonding the device layer 105 to a protruding portion of the via wafer 103, such as an anchor 106. In an example, the anchor 106 can be located substantially at the center of the via wafer 103, and the device layer 105 can be fusion bonded to the anchor 106, such as to eliminate problems associated with metal fatigue.

Gyroscope Device Structure

FIG. 2 illustrates generally an example of a 3-axis gyroscope 200, such as formed in a single plane of a device layer 105 of a 3-DOF IMU 100. In an example, the structure of the 3-axis gyroscope 200 can be symmetrical about the x and y axes illustrated in FIG. 2, with a z-axis conceptually coming out of the figure. Reference in FIG. 2 is made to structure and features in one portion of the 3-axis gyroscope 200. However, in certain examples, such reference and description can apply to unlabeled like portions of the 3-axis gyroscope 200.

In an example, the 3-axis gyroscope 200 can include a single proof-mass design providing 3-axis gyroscope operational modes patterned into the device layer 105 of the 3-DOF IMU 100, such as illustrated in the example of FIG. 1.

In an example, the single proof-mass can be suspended at its center using a single central anchor (e.g., anchor 106) and a central suspension 111 including symmetrical central flexure bearings ("flexures"), such as disclosed in the copending Acar et al., PCT Patent Application Serial No. US2011052006, entitled "FLEXURE BEARING TO REDUCE QUADRATURE FOR RESONATING MICROMACHINED DEVICES," filed on September 16, 2011, which is hereby incorporated by reference in its entirety. The central suspension 111 can allow the single proof-mass to oscillate torsionally about the x, y, and z axes, providing three gyroscope operational modes, including:

(1) Torsional in-plane drive motion about the z-axis (e.g., as illustrated in FIG. 3);

(2) Torsional out-of-plane y-axis gyroscope sense motion about the x-axis (e.g., as illustrated in FIG. 4); and

(3) Torsional out-of-plane x-axis gyroscope sense motion about the y-axis (e.g., as illustrated in FIG. 5).

Further, the single proof-mass design can be composed of multiple sections, including, for example, a main proof-mass section 115 and x-axis proof-mass sections 116 symmetrical about the y-axis. In an example, drive electrodes 123 can be placed along the y-axis of the main proof-mass section 115. In combination with the central suspension 111, the drive electrodes 123 can be configured to provide a torsional in-plane drive motion about the z-axis, allowing detection of angular motion about the x and y axes.

In an example, the x-axis proof-mass sections 116 can be coupled to the main proof-mass section 115 using z-axis gyroscope flexure bearings 120. In an example, the z-axis gyroscope flexure bearings 120 can allow the x-axis proof-mass sections 116 to oscillate linear anti-phase in the x-direction for the z-axis gyroscope sense motion.

Further, the 3-axis inertial sensor 200 can include z-axis gyroscope sense electrodes 127 configured to detect anti-phase, in-plane motion of the x-axis proof-mass sections 116 along the x-axis.

In an example, each of the drive electrodes 123 and z-axis gyroscope sense electrodes 127 can include moving fingers coupled to one or more proof-mass sections interdigitated with a set of stationary fingers fixed in position (e.g., to the via wafer 103) using a respective anchor, such as anchors 124, 128.

Gyroscope Operational Modes

FIG. 3 illustrates generally an example of a 3-axis gyroscope 300 in drive motion. In an example, the drive electrodes 123 can include a set of moving fingers coupled to the main proof-mass section 115 interdigitated with a set of stationary fingers fixed in position using a first drive anchor 124 (e.g., a raised and electrically isolated portion of the via wafer 103). In an example, the stationary fingers can be configured to receive energy through the first drive anchor 124, and the interaction between the interdigitated moving and stationary fingers of the drive electrodes 123 can be configured to provide an angular force to the single proof-mass about the z-axis.

In the example of FIG. 3, the drive electrodes 123 are driven to rotate the single proof-mass about the z-axis while the central suspension 111 provides restoring torque with respect to the fixed anchor 106, causing the single proof-mass to oscillate torsionally, in-plane about the z-axis at a drive frequency dependent on the energy applied to the drive electrodes 123. In certain examples, the drive motion of the single proof-mass can be detected using the drive electrodes 123.

X-Axis Rate Response

FIG. 4 illustrates generally an example of a 3-axis gyroscope 400 including a single proof-mass during sense motion in response to rotation about the x-axis, the single proof-mass including a main proof-mass section 115, x-axis proof-mass sections 116, and central suspension 111.

In the presence of an angular rate about the x-axis, and in conjunction with the drive motion of the 3-axis gyroscope 400 described in the example of FIG. 3, Coriolis forces in opposite directions along the z-axis can be induced on the x-axis proof-mass sections 116 because the velocity vectors are in opposite directions along the y-axis. Thus, the single proof-mass can be excited torsionally about the y-axis by flexing the central suspension 111. The sense response can be detected using out-of-plane x-axis gyroscope sense electrodes, e.g., formed in the via wafer 103 and using capacitive coupling of the x-axis proof-mass sections 116 and the via wafer 103.

Y-Axis Rate Response

FIG. 5 illustrates generally an example of a 3-axis gyroscope 500 including a single proof-mass during sense motion in response to rotation about the y-axis, the single proof-mass including a main proof-mass section 115, x-axis proof-mass sections 116, and central suspension 111.

In the presence of an angular rate about the y-axis, and in conjunction with the drive motion of the 3-axis gyroscope 400 described in the example of FIG. 3, Coriolis forces in opposite directions along the z-axis can be induced on the main proof-mass section 115 because the velocity vectors are in opposite directions along the x-axis. Thus, the single proof-mass can be excited torsionally about the x-axis by flexing the central suspension 111. The sense response can be detected using out-of-plane y-axis gyroscope sense electrodes, e.g., formed in the via wafer 103 and using capacitive coupling of the main proof-mass section 115 and the via wafer 103.

Z-Axis Rate Response

FIG. 6 illustrates generally an example of a 3-axis gyroscope 600 including a single proof-mass during sense motion in response to rotation about the z-axis, the single proof-mass including a main proof-mass section 115, x-axis proof-mass sections 116, central suspension, z-axis flexure bearings 120, and z-axis gyroscope coupling flexure bearings 121.

In the presence of an angular rate about the z-axis, and in conjunction with the drive motion of the 6-axis inertial sensor 400 described in the example of FIG. 3, Coriolis forces in opposite directions along the x-axis can be induced on the x-axis proof-mass sections 116 because the velocity vectors are in opposite directions along the y-axis. Thus, the x-axis proof-mass sections 116 can be excited linearly in opposite directions along the x-axis by flexing the z-axis flexure bearings 120 in the x-direction. Further, the z-axis gyroscope coupling flexure bearings 121 can be used to provide a linear anti-phase resonant mode of the x-axis proof-mass sections 116, which are directly driven by the anti-phase Coriolis forces. The sense response can be detected using in-plane parallel-plate sense electrodes, such as the z-axis gyroscope sense electrodes 127 formed in the device layer 105.

FIGS. 7 and 8 illustrate generally examples of a 3-axis gyroscope 700 including a z-axis gyroscope coupling flexure bearing 121 during anti-phase motion and in-phase motion, respectively. To improve the vibration rejection of the 3-axis gyroscope 700 due to x-axis acceleration, the z-axis gyroscope coupling flexure bearings 121 is configured to suppress in-phase motion of the x-axis proof-mass sections 116.

During the anti-phase motion, the connection beams that connect the two x-axis proof-mass sections 116 to the z-axis gyroscope coupling flexure bearing 121 apply forces in the same direction and the coupling beams undergo a natural bending with low stiffness.

In contrast, during the in-phase motion, the coupling beams of the z-axis gyroscope coupling flexure bearing 121 apply forces in opposite directions on the coupling beams, forcing the coupling beams into a twisting motion with a higher stiffness. Thus, the in-phase motion stiffness and the resonant frequencies are increased, providing better vibration rejection.

Accelerometer Device Structure

FIG. 9 illustrates generally an example of a 3-axis accelerometer 900, such as formed in a single plane of a device layer 105 of a 3-DOF IMU 100. In an example, the 3-axis accelerometer 900 can include a single proof-mass design, providing 3-axis accelerometer operational modes patterned into the device layer 105 of the 3-DOF IMU 100, such as illustrated in the example of FIG. 1.

In an example, the single proof-mass can be suspended at its center to a single central anchor (e.g., anchor 106) using a series of flexure bearings and frames that aim to decouple the response modes and reduce cross-axis sensitivities. In an example, the 3-axis accelerometer 900 can include x-axis flexure bearings 133 configured to couple the anchor 106 to the x-axis frame 135 and allow the x-axis frame 135 to deflect in response to acceleration along the x-axis. Further, the device can include y-axis flexure bearings 134 configured to couple the x-axis frame 135 to the y-axis frame 136 and allow the y-axis frame 136 to deflect with respect to the x-axis frame 135 in response to accelerations along the y-axis, and z-axis flexure bearings 137 configured to couple the y-axis frame 136 to the remainder of the proof mass 138. The z-axis flexure bearings 137 function as a torsional hinge, allowing the proof-mass to deflect torsionally out-of-plane about the axis that passes through the center of the beams.

Further, the 3-axis accelerometer 900 can include x-axis accelerometer sense electrodes 125 configured to detect in-phase, in-plane x-axis motion of the x-axis frame 135, or y-axis accelerometer sense electrodes 131 configured to detect in-phase, in-plane, y-axis motion of the y-axis frame 136. In an example, each of the x-axis and y-axis accelerometer sense electrodes 125, 131 can include moving fingers coupled to one or more frame sections interdigitated with a set of stationary fingers fixed in position (e.g., to the via wafer 103) using a respective anchor, such as anchors 126, 132.

X-Axis Accelerometer Response

FIG. 10 illustrates generally an example of a 3-axis accelerometer 1000 in sense motion in response to an x-axis acceleration, the 3-axis accelerometer including a single proof-mass, an anchor 106, x-axis flexure bearings 133, and an x-axis frame 135.

In the presence of an acceleration along the x-axis, the proof mass, the y-axis frame 136 and the x-axis frame 135 can move in unison with respect to the anchor 106. The resulting motion can be detected using the x-axis accelerometer sense electrodes 125 located on opposite sides of the proof-mass, allowing differential measurement of deflections. In various examples, a variety of detection methods, such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be used.

Y-Axis Accelerometer Response

FIG. 11 illustrates generally an example of a 3-axis accelerometer 1100 in sense motion in response to a y-axis acceleration, the 3-axis accelerometer including a single proof-mass, an anchor 106, y-axis flexure bearings 134, and a y-axis frame 136.

In the presence of an acceleration along the y-axis, the y-axis flexure bearings 134 that connect the y-axis frame 136 to the x-axis frame 135 deflect and allow the y-axis frame 136 to move along the y-axis in unison with the proof-mass, while the x-axis frame remains stationary. The resulting motion can be detected using the y-axis accelerometer sense electrodes 131 located on opposite sides of the proof-mass, allowing differential measurement of deflections. In various examples, a variety of detection methods, such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be used.

Z-Axis Accelerometer Response

FIG. 12 illustrates generally an example of a 3-axis accelerometer 1200 in sense motion in response to a z-axis acceleration, the 3-axis accelerometer including a single proof-mass 138, an anchor, and z-axis flexure bearings 137.

In the example of FIG. 12, the x-axis flexure bearings 137 are located such that the axis that passes through the center of the beam is offset from the center of the proof-mass 138. Thus, a mass imbalance is created, so that the portion of the mass that is located further from the pivot line generates a larger inertial moment than the portion located closer, rendering the proof-mass 138 sensitive to z-axis accelerations, deflecting torsionally out-of-plane about the pivot line. The x and y-axis flexure bearings 133, 134 are designed to have high out-of-plane stiffness. Accordingly, they remain stationary during z-axis acceleration.

FIG. 13 illustrates generally an example of a system 1300 including via wafer electrode placement. In an example, z-axis accelerometer electrodes 140 can be placed on the via wafer 103 under the device layer 105. The torsional response allows measurement of deflections differentially with only one layer of out-of-plane electrodes. In an example, a variety of detection methods such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be employed.

FIG. 14 illustrates generally an example side view of a 3-axis accelerometer 1400 including a single proof-mass, an illustrative "pivot", and z-axis accelerometer electrodes 140.

3+3DOF

FIG. 15 illustrates generally an example of a 3+3-degrees-of-freedom (3+3DOF) inertial measurement unit (IMU) 200 (e.g., a 3-axis gyroscope and a 3-axis accelerometer), such as formed in a single plane of a device layer 105 of an IMU. In an example, the 3+3 DOF can include a 3-axis gyroscope 1505 and a 3-axis accelerometer 1510 on the same wafer.

In this example, each of the 3-axis gyroscope 1505 and the 3-axis accelerometer 1510 have separate proof-masses, though when packaged, the resulting device (e.g., chip-scale package) can share a cap, and thus, the 3-axis gyroscope 1505 and the 3-axis accelerometer 1510 can reside in the same cavity. Moreover, because the devices were formed at similar times and on similar materials, the invention significantly lowers the risk of process variations, reduces the need to separately calibrate the sensors, reduces alignment issues, and allows closer placement than separately bonding the devices near one another.

Further, there is a space savings associated with sealing the resulting device. For example, if a 100um seal width is required, sharing the cap wafer and reducing the distance between devices allows the overall size of the resulting device to shrink. Packaged separately, the amount of space required for the seal width could double.

In an example, die size can be reduced to 2.48x1.8mm with a 100um seal width.

Drive and Detection Frequencies

In an example, the drive mode and the three gyroscope sense modes can be located in the 20kHz range. For open-loop operation, the drive mode can be separated from the sense-modes by a mode separation, such as 100Hz to 500Hz, which can determine the mechanical sensitivity of the gyroscopes. To increase sensitivity, the gyroscope operational resonant frequencies can be reduced if the vibration specifications of the application allow. If closed-loop sense operation is implemented, the mode separation can be reduced to increase mechanical sensitivity further.

Quadrature Error Reduction

FIG. 16 illustrates generally an example of the central suspension 111 at rest about an anchor 106, the central suspension 111 including symmetric "C-beams" configured to locally cancel quadrature error. The primary source of quadrature error in micromachined gyroscopes is the DRIE sidewall angle errors, which result in deviation of the etch profile from a straight sidewall. If sidewalls have an angle error, the in-plane drive motion can also cause out-of-plane motion when the skew axis is along beam length. Thus, when skewed compliant beams are located on opposite sides of the drive motion, the resulting out-of-plane deflections cause quadrature error.

FIG. 17 illustrates generally an example of a portion of the central suspension 111 in drive motion. The central suspension 111 utilizes symmetric "C-beams" on each side of the anchor 106. The out-of-plane motion caused by each C-beam on a side is cancelled out by its symmetric counterpart. Thus, the quadrature error induced on each beam can be locally cancelled.

Additional Notes and Examples

In Example 1, an inertial measurement system includes a device layer including a single proof-mass 3-axis accelerometer formed in an x-y plane, the single proof-mass 3-axis accelerometer suspended about a single, central anchor, the single proof-mass 3-axis accelerometer including separate x, y, and z-axis flexure bearings, wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor, a cap wafer bonded to a first surface of the device layer, and a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis accelerometer.

In Example 2, the 3-axis accelerometer of Example 1 optionally includes in-plane x and y-axis accelerometer sense electrodes.

In Example 3, the in-plane x and y-axis accelerometer sense electrodes of any one or more of Examples 1-2 are optionally symmetrical about the single, central anchor.

In Example 4, the 3-axis accelerometer of any one or more of Examples 1-3 optionally include out-of-plane z-axis accelerometer sense electrodes.

In Example 5, the 3-axis accelerometer of any one or more of Examples 1-4 is optionally rectangular in shape, longer about the y-axis than the x or z-axis.

In Example 6, the x, y, and z-axis flexure bearings of any one or more of Examples 1-5 optionally have high out-of-plane stiffness.

In Example 7, the single proof-mass of any one or more of Examples 1-6 optionally includes an outer portion surrounding in-plane x and y-axis accelerometer sense electrodes and x, y, and z-axis flexure bearings.

In Example 8, the 3-axis accelerometer of any one or more of Examples 1-7 optionally includes a micromachined, monolithic, 3-axis accelerometer.

In Example 9, the device layer of any one or more of Examples 1-8 optionally includes a 3-axis gyroscope formed in the x-y plane proximate the 3-axis accelerometer.

In Example 10, the cap wafer and the via wafer of any one or more of Examples 1-9 are optionally configured to encapsulate the single proof-mass 3-axis accelerometer and the 3-axis gyroscope.

In Example 11, the 3-axis accelerometer and the 3-axis gyroscope of any one or more of Examples 1-10 are optionally configured to share the same encapsulated cavity.

In Example 12, the device layer of any one or more of Examples 1-11 optionally includes a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including:

a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope sensor, a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor, and a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

In Example 13, any one or more of Examples 1-12 optionally include symmetrical x-axis proof-mass sections configured to move anti-phase along the x-axis in response to z-axis angular motion.

In Example 14, any one or more of Examples 1-13 optionally include a z-axis gyroscope coupling flexure bearing configured to couple the x-axis proof mass sections and to resist in-phase motion.

In Example 15, any one or more of Examples 1-14 optionally includes micromachined, monolithic inertial sensor apparatus, comprising a single proof-mass 3-axis accelerometer formed in an x-y plane of a device layer, suspended about a single, central anchor, the single proof-mass 3-axis accelerometer including separate x, y, and z-axis flexure bearings, wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor.

In Example 16, the 3-axis accelerometer of any one or more of Examples 1-15 optionally includes in-plane x and y-axis accelerometer sense electrodes.

In Example 17, the in-plane x and y-axis accelerometer sense electrodes of any one or more of Examples 1-16 are optionally symmetrical about the single, central anchor.

In Example 18, the 3-axis accelerometer of any one or more of Examples 1-17 optionally includes out-of-plane z-axis accelerometer sense electrodes.

In Example 19, any one or more of Examples 1-18 optionally includes a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope, a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor, and a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

In Example 20, any one or more of Examples 1-19 optionally includes a cap wafer bonded to a first surface of the device layer and a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis gyroscope and the single proof-mass 3-axis accelerometer in the same cavity.

In Example 21, a system or apparatus can include, or can optionally be combined with any portion or combination of any portions of any one or more of Examples 1-20 to include, means for performing any one or more of the functions of Examples 1-20, or a machine-readable medium including instructions that, when performed by a machine, cause the machine to perform any one or more of the functions of Examples 1-20.

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. An inertial measurement system, comprising:

a device layer including a single proof-mass 3-axis accelerometer formed in an x-y plane, the single proof-mass 3-axis accelerometer suspended about a single, central anchor, the single proof-mass 3-axis accelerometer including separate x, y, and z-axis flexure bearings;

wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor;

a cap wafer bonded to a first surface of the device layer; and

a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis accelerometer.

2. The system of claim 1, wherein the 3-axis accelerometer includes in-plane x and y-axis accelerometer sense electrodes.

3. The system of claim 2, wherein the in-plane x and y-axis accelerometer sense electrodes are symmetrical about the single, central anchor.

4. The system of claim 2, wherein the 3-axis accelerometer includes out-of-plane z-axis accelerometer sense electrodes.

5. The system of claim 1, wherein the 3-axis accelerometer is rectangular in shape, longer about the y-axis than the x or z-axis.

6. The system of claim 1, wherein the x, y, and z-axis flexure bearings have high out-of-plane stiffness.

7. The system of claim 1, wherein the single proof-mass includes an outer portion surrounding in-plane x and y-axis accelerometer sense electrodes and x, y, and z-axis flexure bearings.

8. The system of claim 1, wherein the 3-axis accelerometer includes a micromachined, monolithic, 3-axis accelerometer.

9. The system of claim 1, wherein the device layer includes a 3-axis gyroscope formed in the x-y plane proximate the 3-axis accelerometer.

10. The system of claim 9, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis accelerometer and the 3-axis gyroscope.

11. The system of claim 10, wherien the 3-axis accelerometer and the 3-axis gyroscope are configured to share the same encapsulated cavity.

12. The system of claim 1, wherein the device layer includes a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including:

a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope sensor;

a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor; and

a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

13. The system of claim 12, including symmetrical x-axis proof-mass sections configured to move anti-phase along the x-axis in response to z-axis angular motion.

14. The system of claim 12, including a z-axis gyroscope coupling flexure bearing configured to couple the x-axis proof mass sections and to resist in-phase motion.

15. A micromachined, monolithic inertial sensor apparatus, comprising:

a single proof-mass 3-axis accelerometer formed in an x-y plane of a device layer, suspended about a single, central anchor, the single proof-mass 3-axis accelerometer including separate x, y, and z-axis flexure bearings; and

wherein the x and y-axis flexure bearings are symmetrical about the single, central anchor and the z-axis flexure is not symmetrical about the single, central anchor.

16. The apparatus of claim 15, wherein the 3-axis accelerometer includes in-plane x and y-axis accelerometer sense electrodes.

17. The apparatus of claim 16, wherein the in-plane x and y-axis accelerometer sense electrodes are symmetrical about the single, central anchor.

18. The apparatus of claim 16, wherein the 3-axis accelerometer includes out-of-plane z-axis accelerometer sense electrodes.

19. The apparatus of claim 15, including:

a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including:

a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope;

a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor; and

a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

20. The apparatus of claim 19, including:

a cap wafer bonded to a first surface of the device layer; and a via wafer bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis gyroscope and the single proof-mass 3-axis accelerometer in the same cavity.

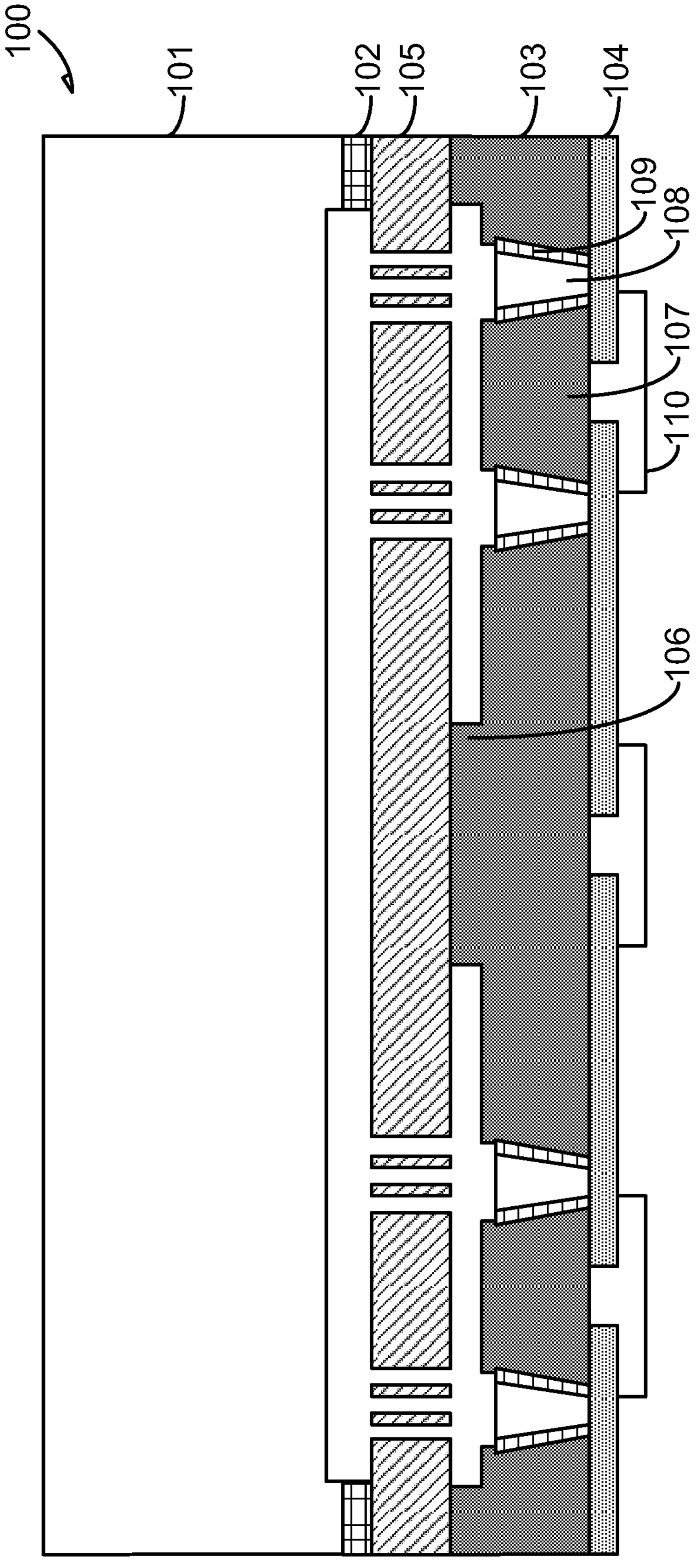

FIG. 1

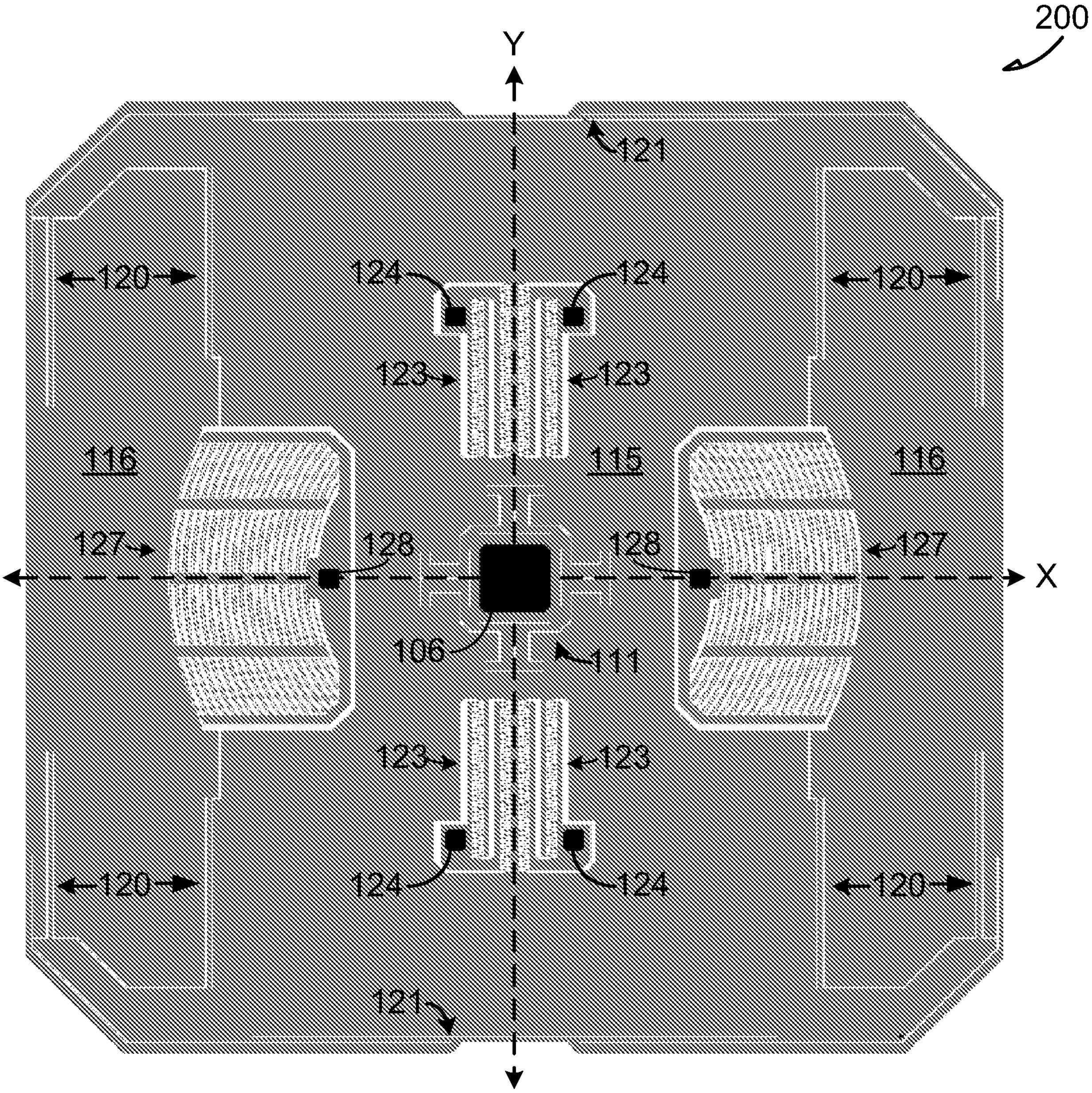
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FIG. 2

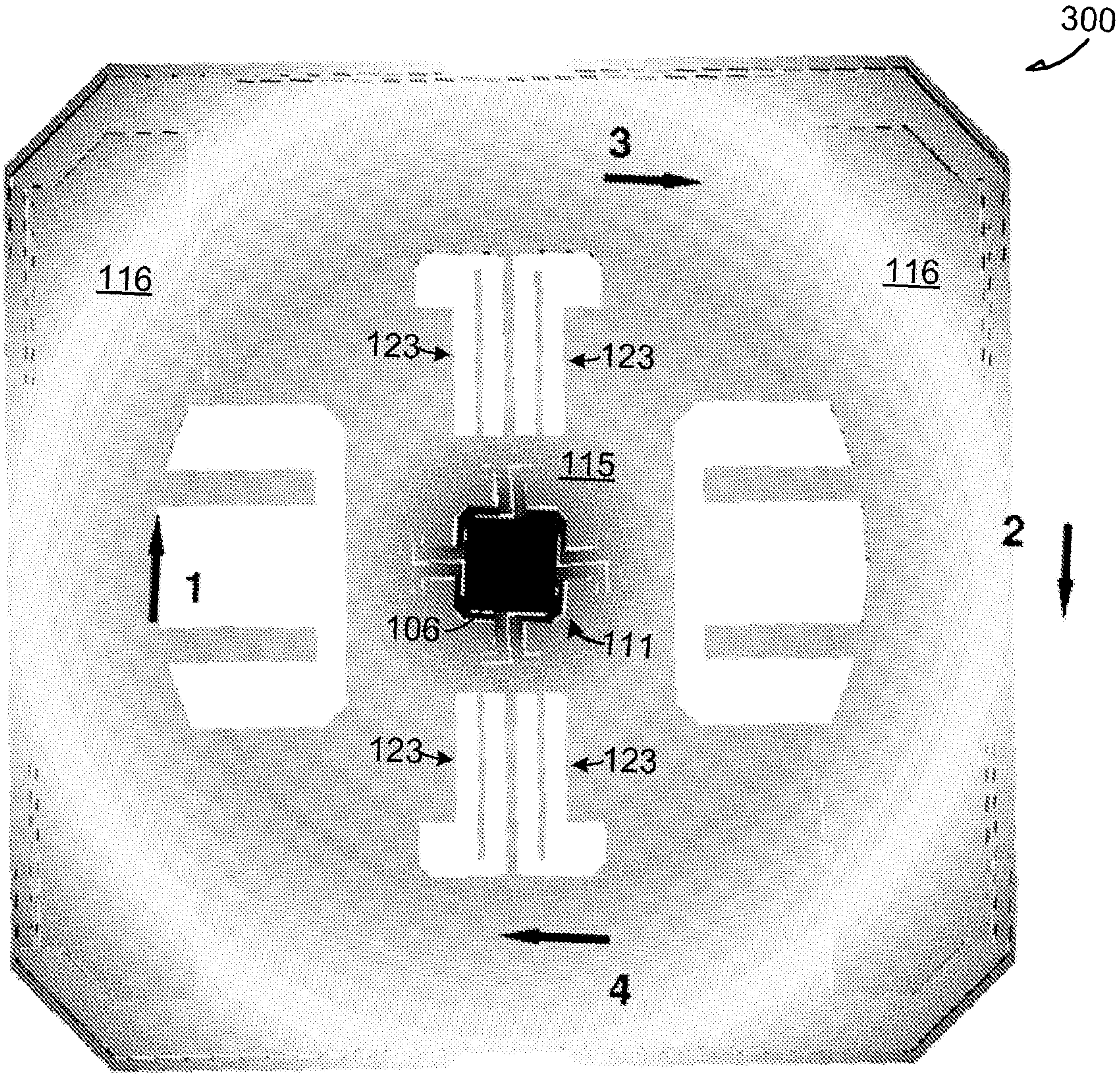


FIG. 3

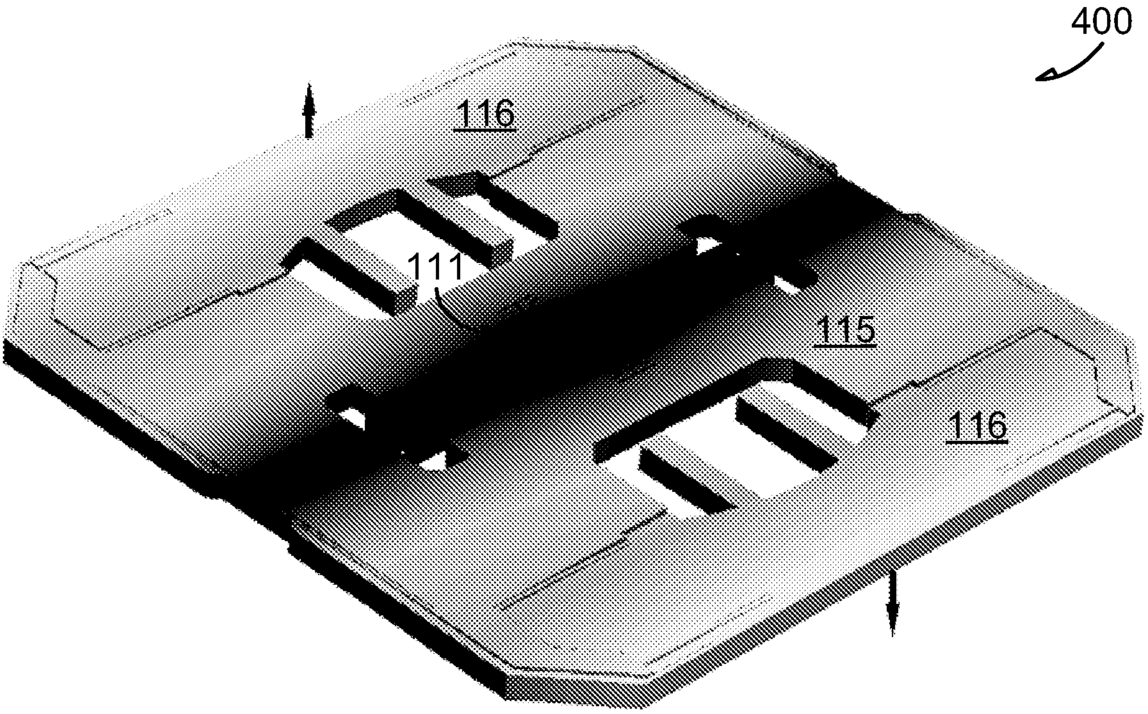
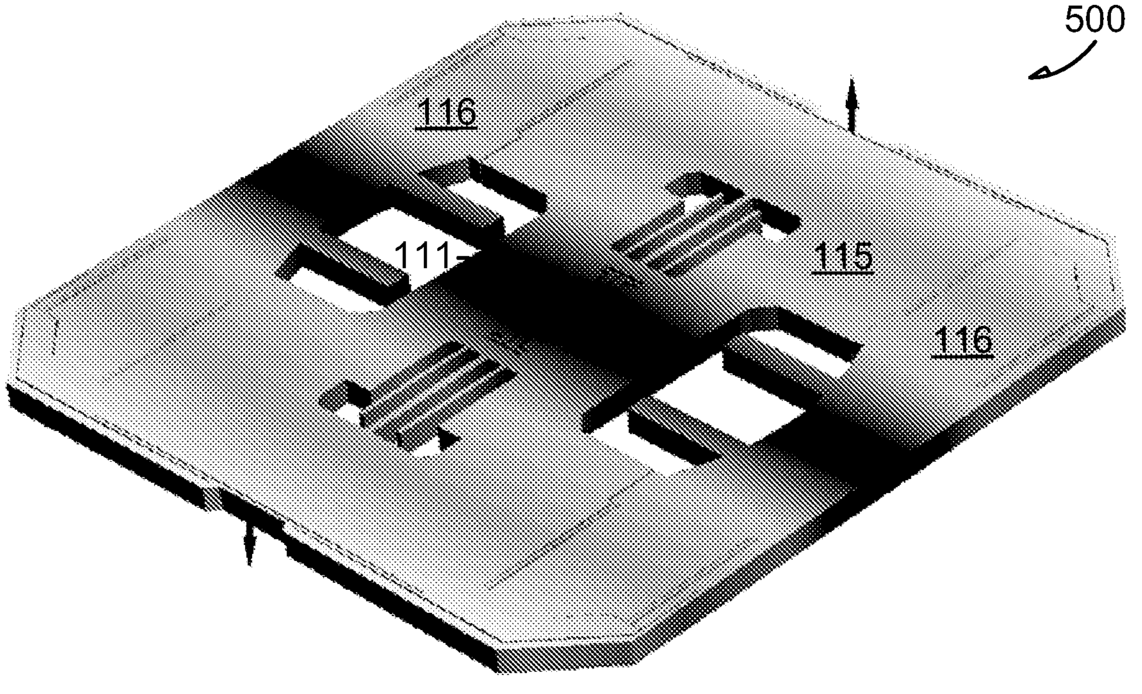


FIG. 4



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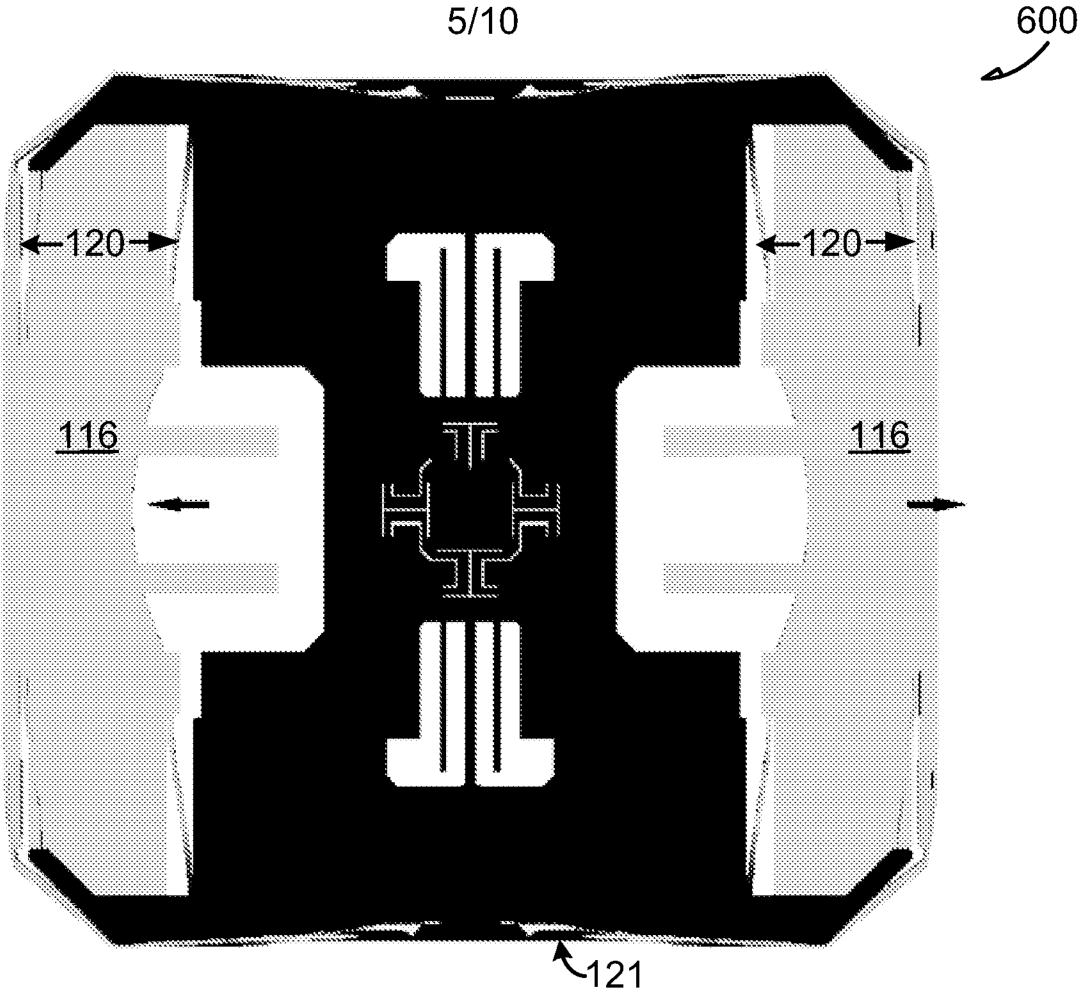

FIG. 6

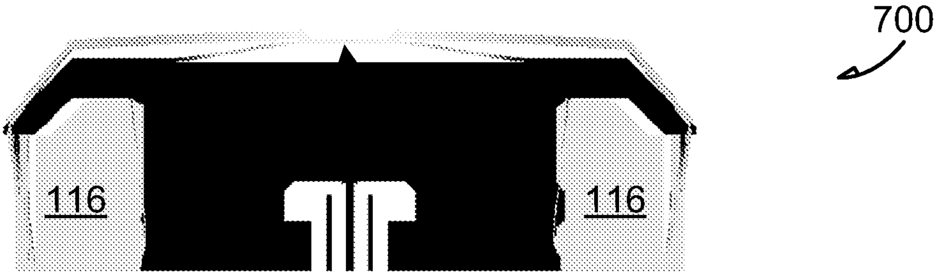

FIG. 7

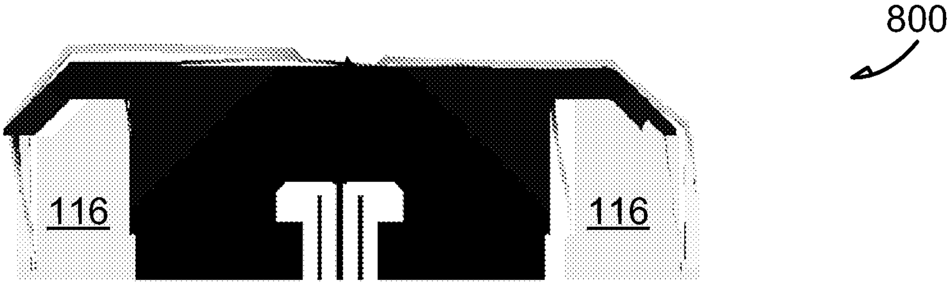

FIG. 8

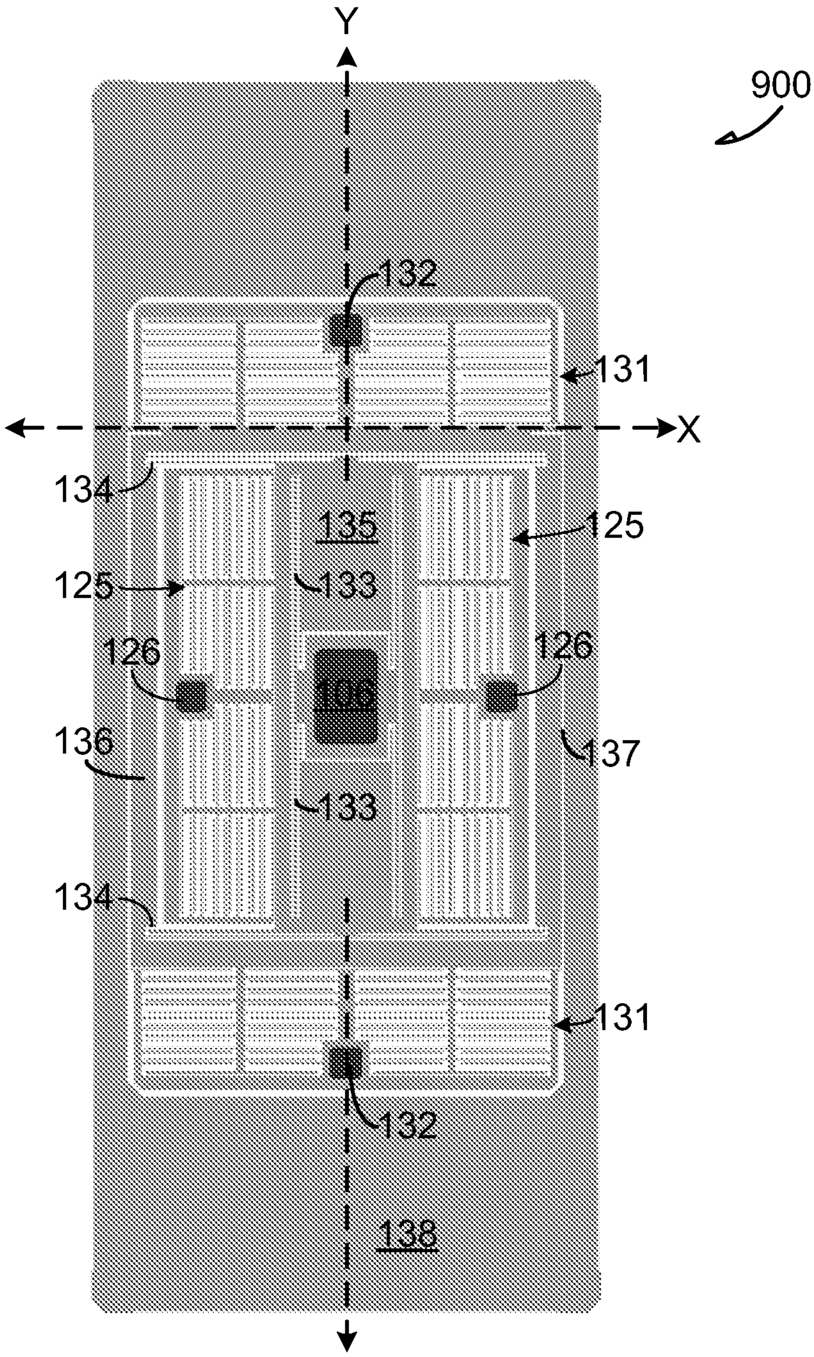
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FIG. 9

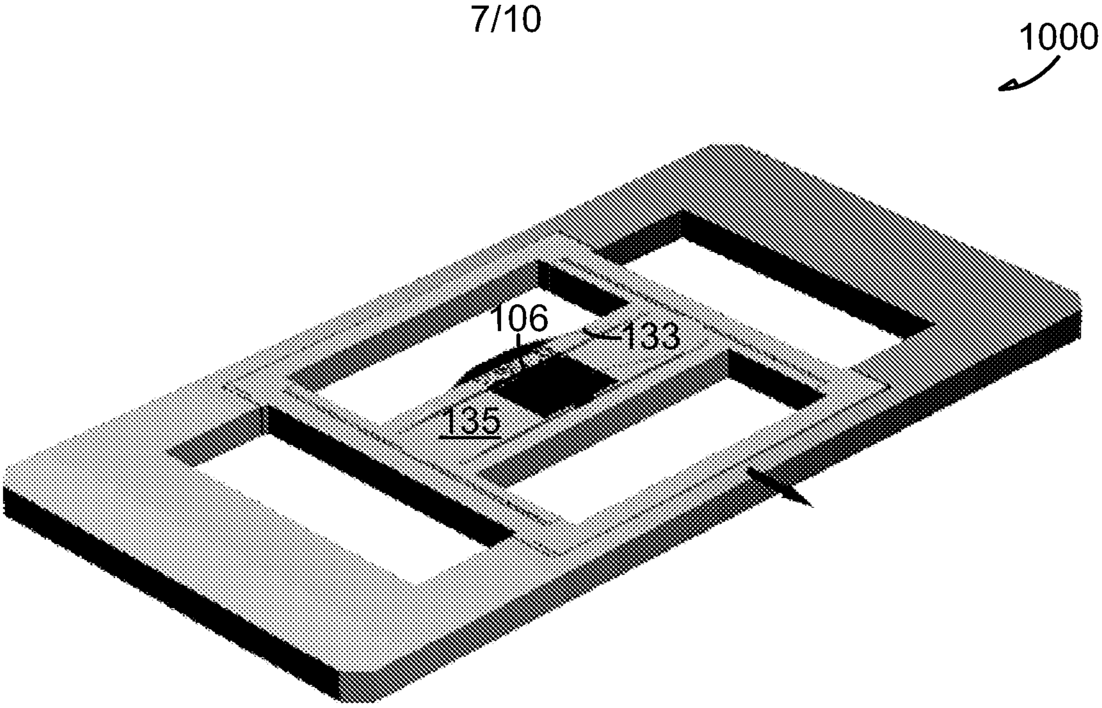

FIG. 10

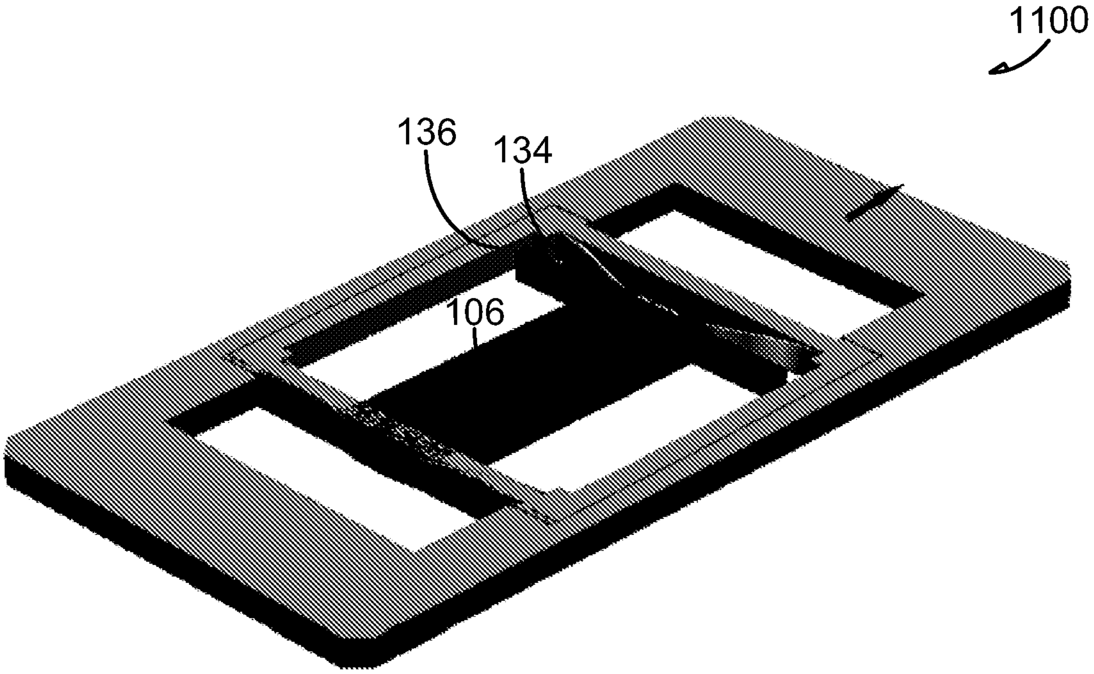

FIG. 11

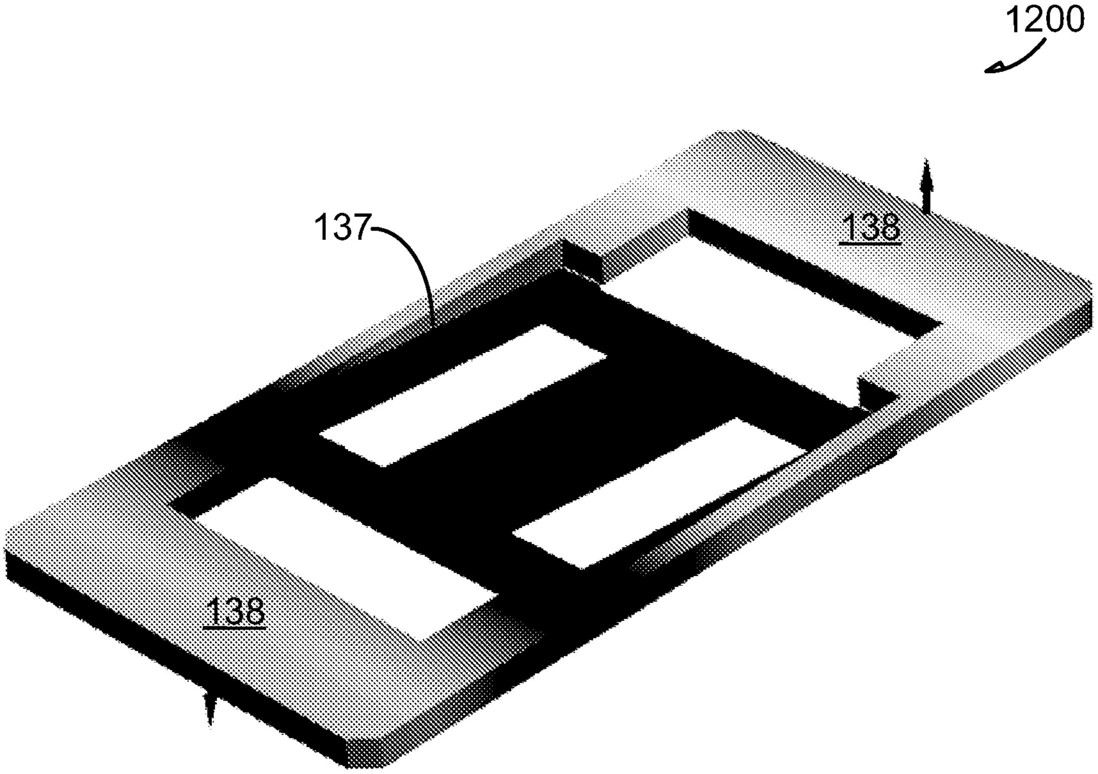

FIG. 12

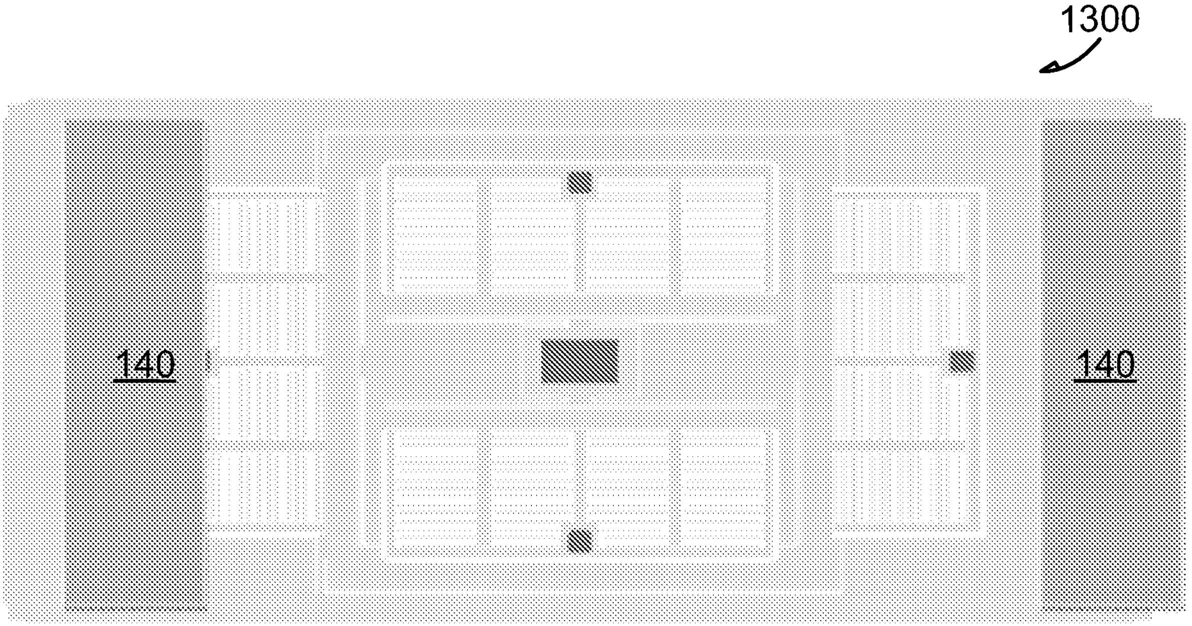

FIG. 13

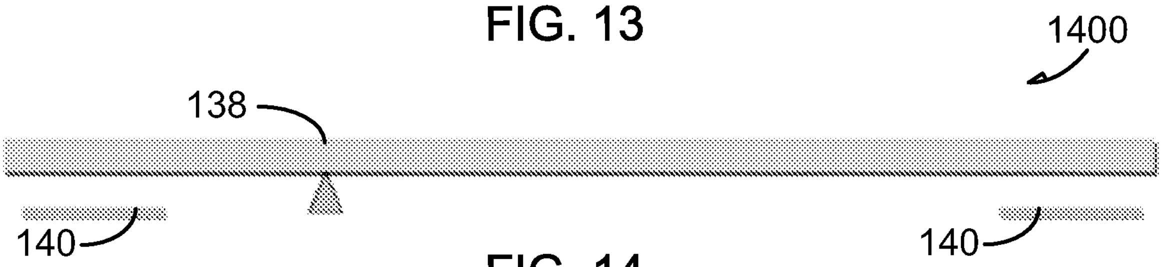

FIG. 14

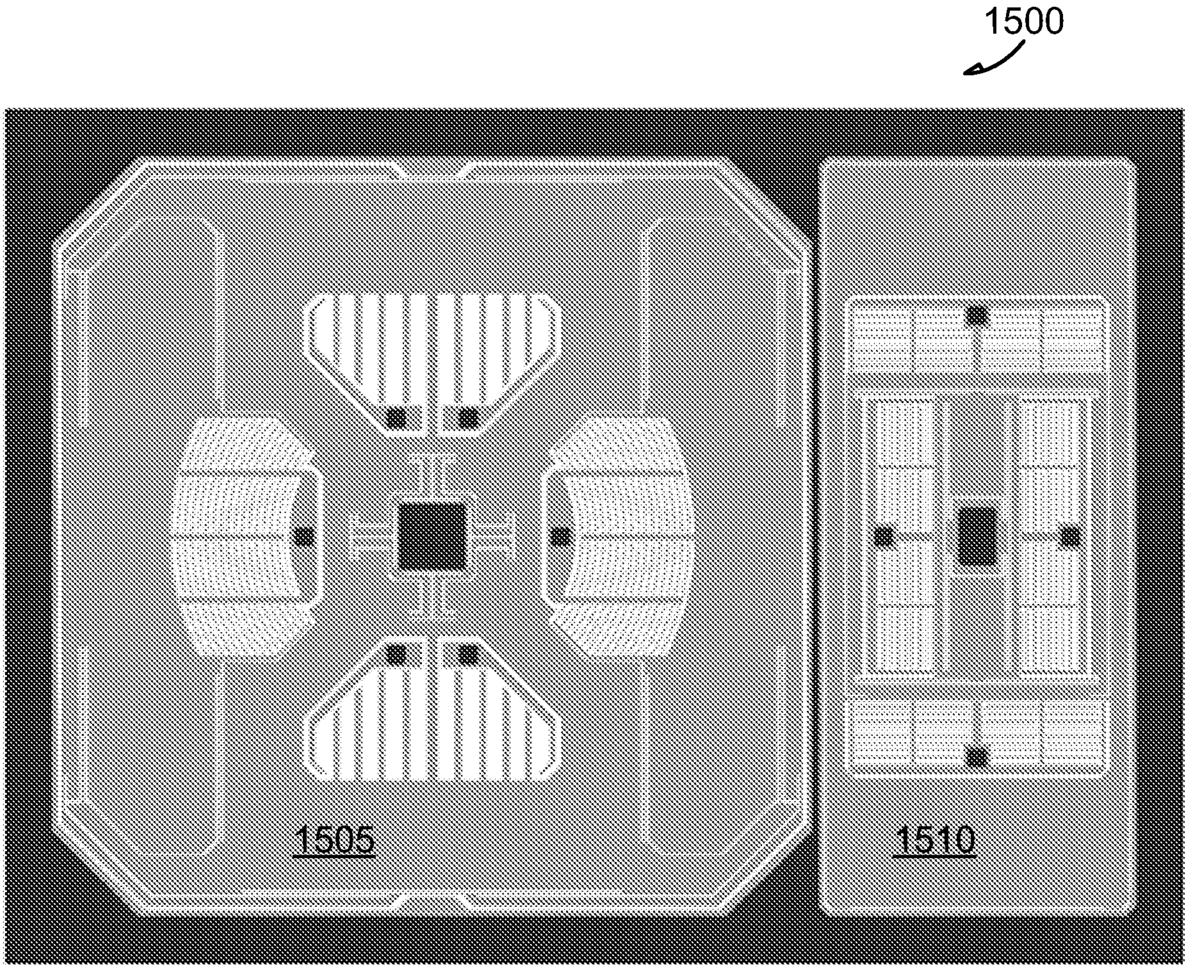

FIG. 15

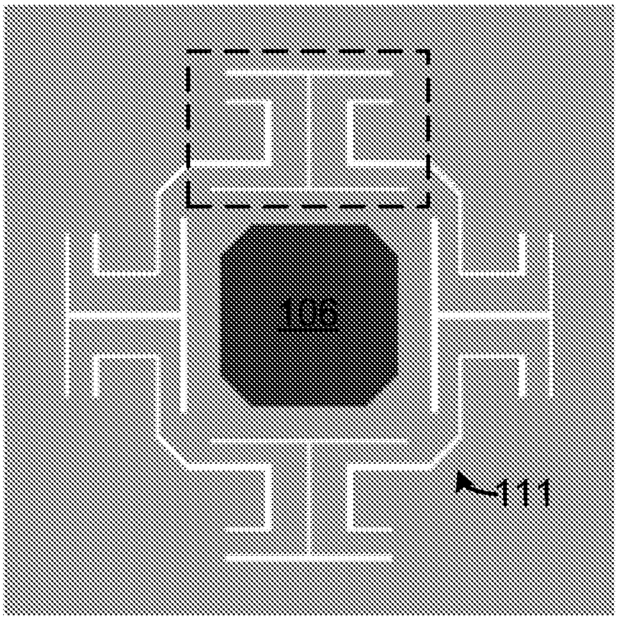

FIG. 16

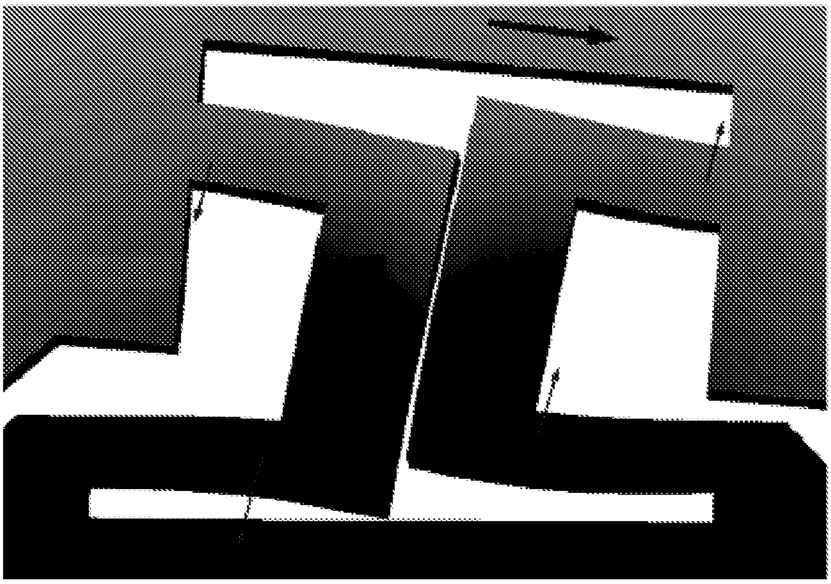

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/052064

A. CLASSIFICATION OF SUBJECT MATTER

G01P 15/02(2006.01)i, G01P 15/097(2006.01)i, G01C 19/56(2006.01)i, B81B 7/02(2006.01)i, B81C 1/00(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01P 15/02; G01P 15/18; G01P 15/125; G01P 15/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: acceleration, proof, mass

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2010-506182 A (FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.) 25 February 2010 See abstract, figure 1, claims 1-16.	1-20
A	US 2005-0005698 A1 (MCNEIL ANDREW C. et al.) 13 January 2005 See abstract.	1-20
A	US 2006-0213268 A1 (ASAMI KAZUSHI et al.) 28 September 2006 See abstract.	1-20

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 28 FEBRUARY 2012 (28.02.2012)	Date of mailing of the international search report **29 FEBRUARY 2012 (29.02.2012)**
Name and mailing address of the ISA/KR Korean Intellectual Property Office Government Complex-Daejeon, 189 Cheongsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea Facsimile No. 82-42-472-7140	Authorized officer KIM, Chang Ju Telephone No. 82-42-481-5676

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2010-506182 A	25.02.2010	CA 2670513 A1	17.04.2008
		DE 102006048381 A1	17.04.2008
		EP 2076783 A1	08.07.2009
		KR 10-2009-0101884 A	29.09.2009
		US 2010-0139401 A1	10.06.2010
		WO 2008-043831 A1	17.04.2008
US 2005-0005698 A1	13.01.2005	CN 1816747 A	09.08.2006
		CN 1816747 C0	26.11.2008
		EP 1646878 A1	19.04.2006
		JP 04-787746 B2	22.07.2011
		JP 2007-530914 A	01.11.2007
		KR 10-2006-0033779 A	19.04.2006
		US 2005-0097957 A1	12.05.2005
		US 6845670 B1	25.01.2005
		US 6936492 B2	30.08.2005
		WO 2005-017536 A1	24.02.2005
US 2006-0213268 A1	28.09.2006	JP 04-453587 B2	12.02.2010
		JP 2006-266873 A	05.10.2006
		US 7418864 B2	02.09.2008