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(54) **ISOLATED PLANAR GYROSCOPE WITH INTERNAL RADIAL SENSING AND ACTUATION**

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Related U.S. Application Data

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(51) **Int. Cl.**
G01P 9/04 (2006.01)
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See application file for complete search history.

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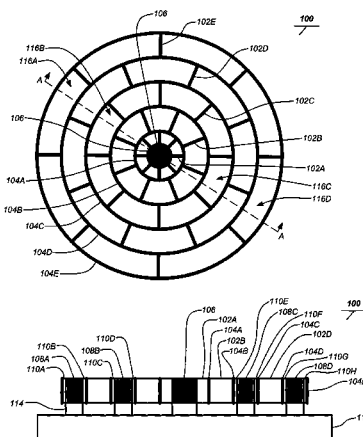
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(57) **ABSTRACT**

The present invention discloses an inertial sensor comprising a planar mechanical resonator with embedded sensing and actuation for substantially in-plane vibration and having a central rigid support for the resonator. At least one excitation or torquer electrode is disposed within an interior of the resonator to excite in-plane vibration of the resonator and at least one sensing or pickoff electrode is disposed within the interior of the resonator for sensing the motion of the excited resonator. In one embodiment, the planar resonator includes a plurality of slots in an annular pattern; in another embodiment, the planar mechanical resonator comprises four masses; each embodiment having a simple degenerate pair of in-plane vibration modes.

23 Claims, 36 Drawing Sheets

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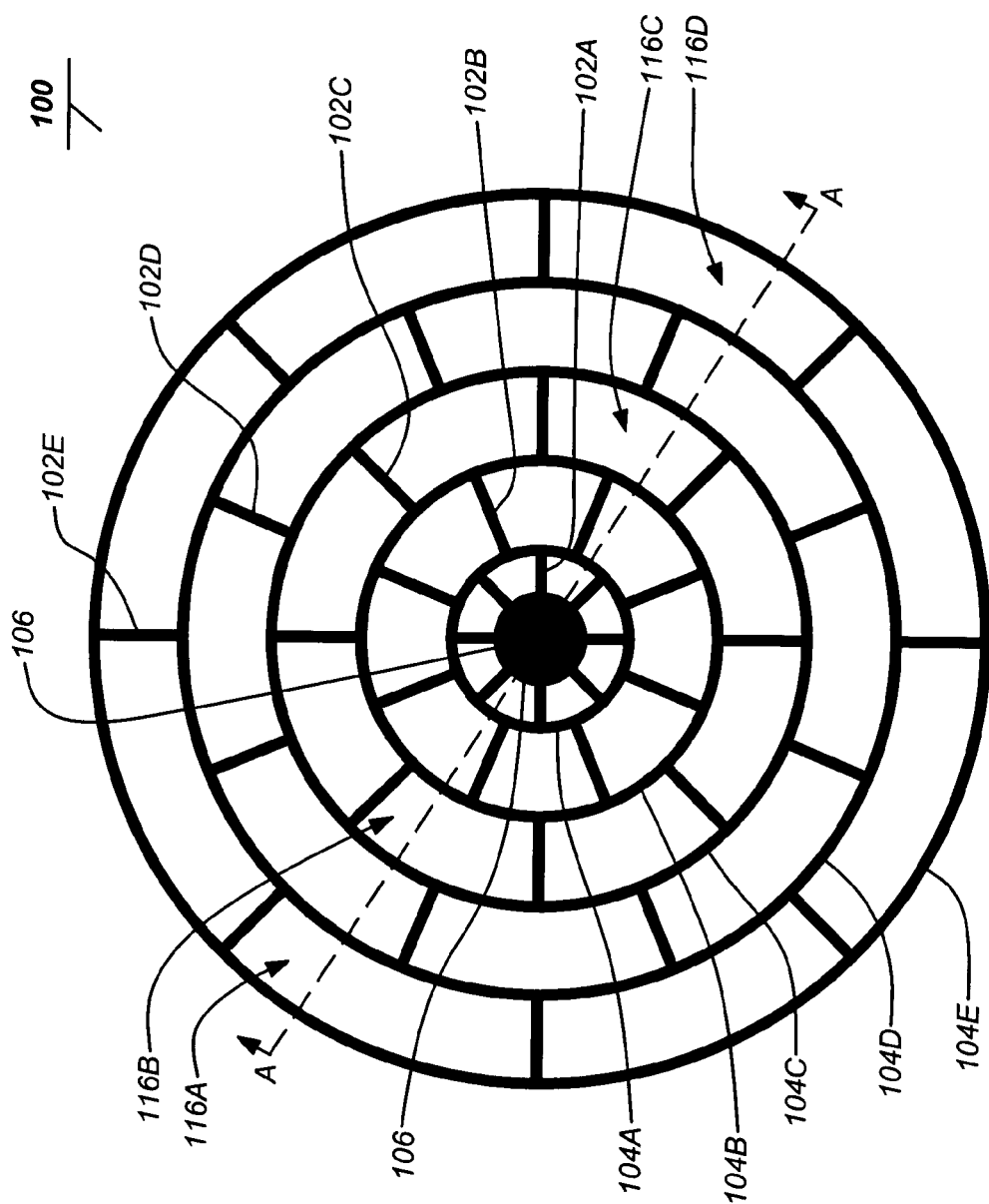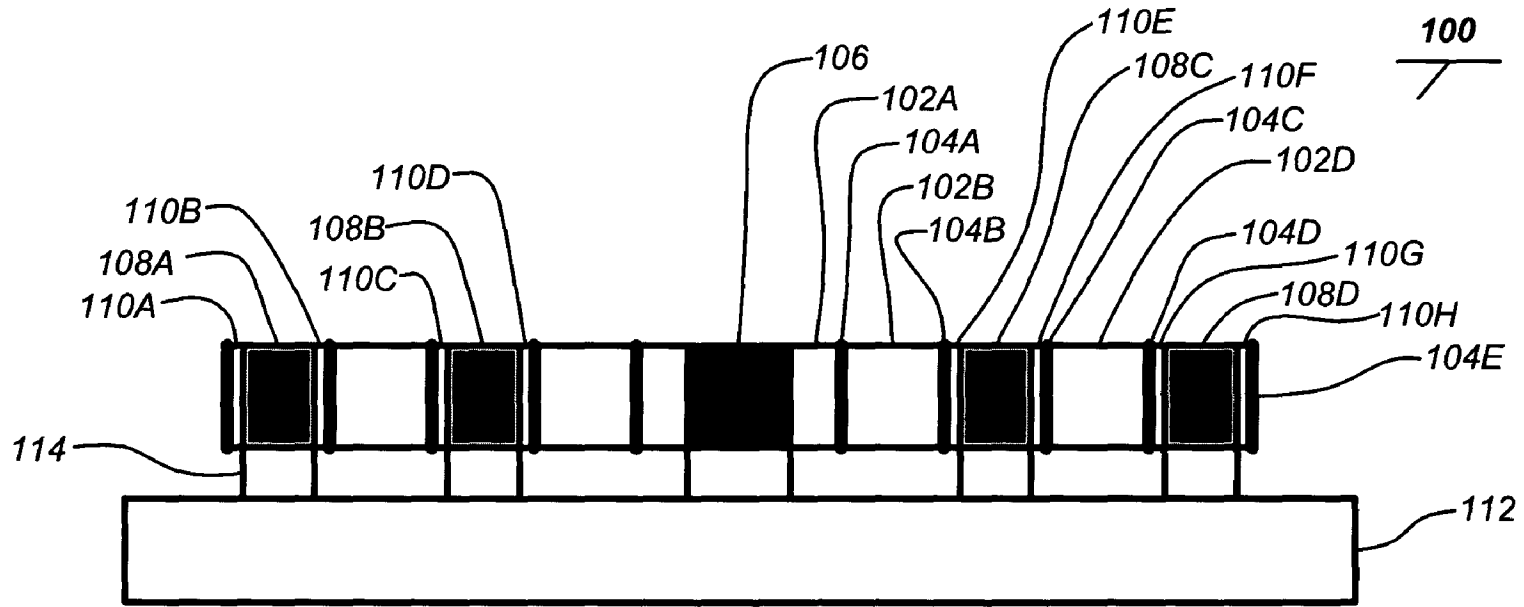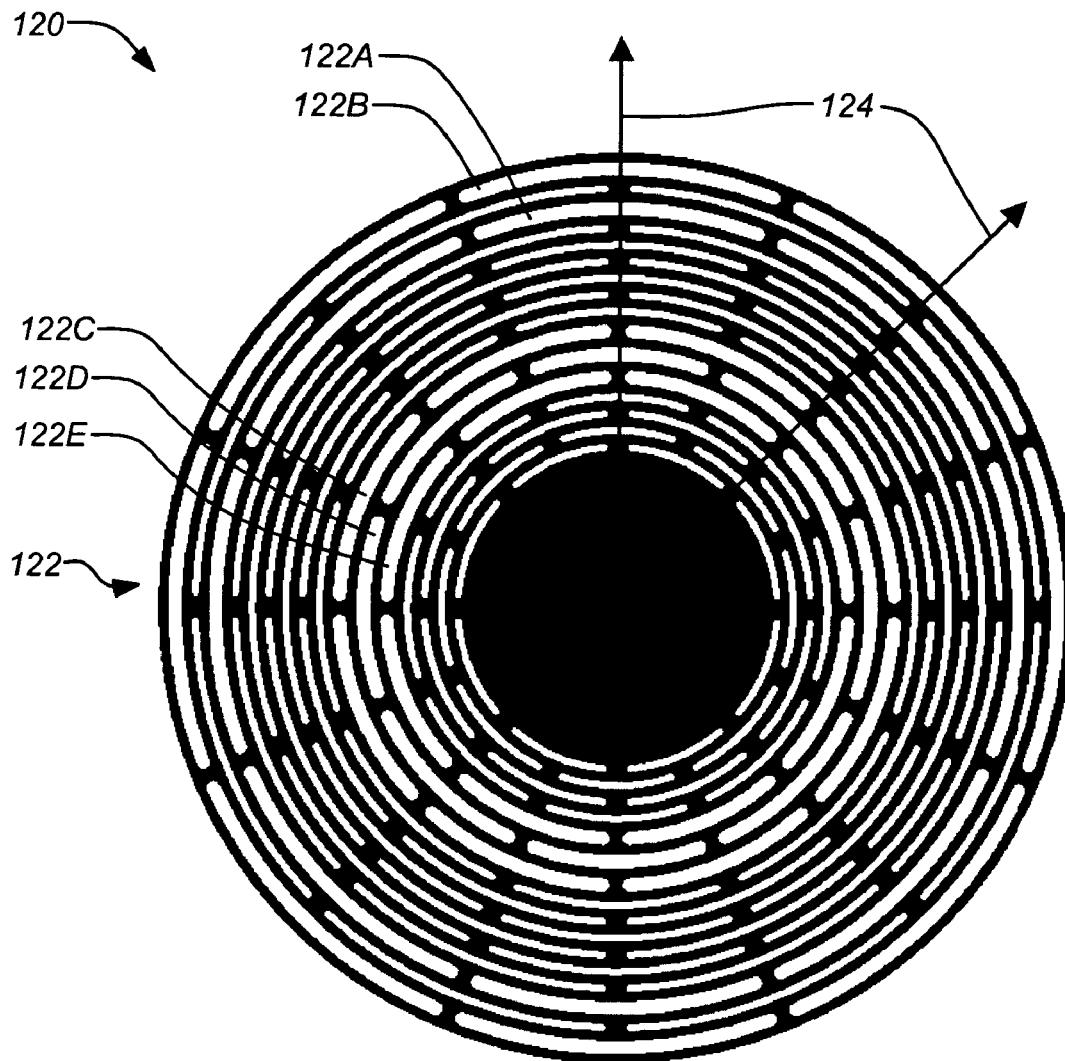
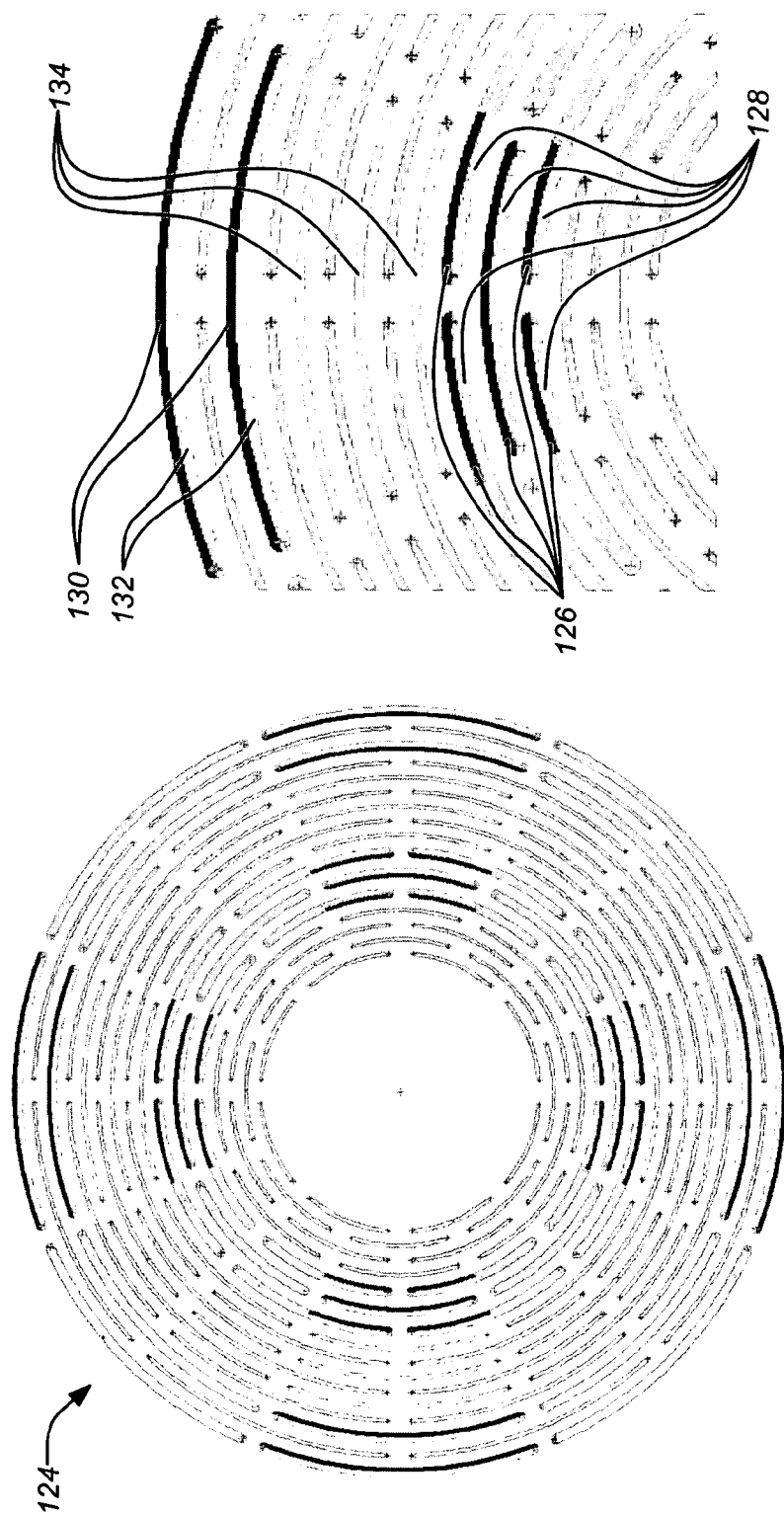* cited by examiner

FIG. 1A

FIG. 1B

FIG. 1C

FIG. 1D

2.456
2.303
2.15
1.997
1.844
1.692
1.539
1.386
1.233
1.081
0.928
0.775
0.622
0.469
0.317
0.164
0.011

Output Set: Mode 9, 43368.88 Hz
Deformed(382.9): Total Translation
Contour: Strain Energy Percent

FIG. 2A

V1

2.456	
2.303	
2.15	
1.997	
1.844	
1.691	
1.538	
1.385	
1.232	
1.079	
0.926	
0.773	
0.62	
0.467	
0.314	
0.161	
0.00825	

Y
Z   X

Output Set: Mode 10, 43371.54 Hz
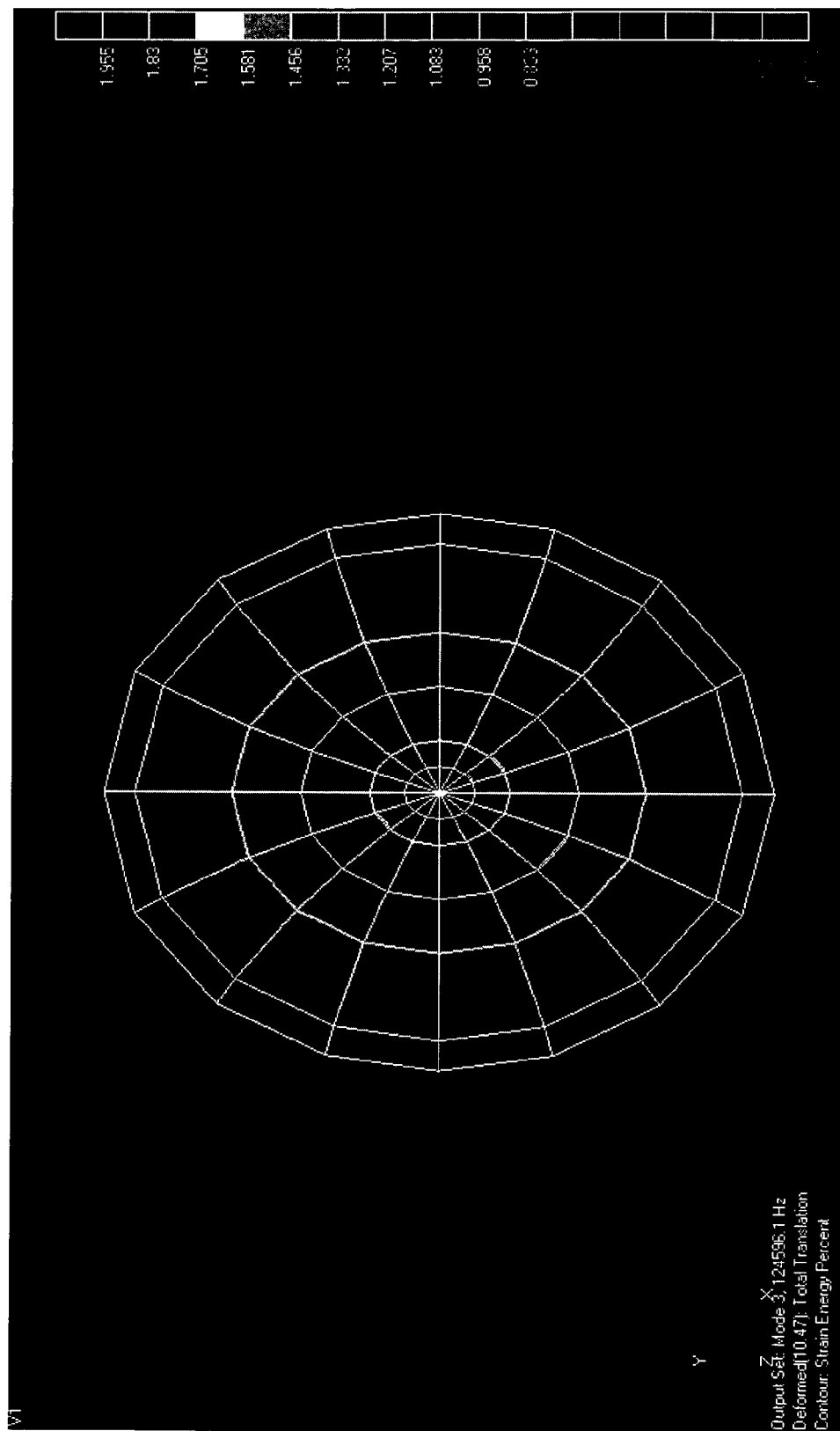Deformed(382.9): Total Translation
Contour: Strain Energy Percent

FIG. 2B

FIG. 3A

FIG. 3B

FIG. 3C

FIG. 3D

Output Set: Mode 4, 124596.1 Hz
Deformed(10.47): Total Translation
Contour: Strain Energy Percent

FIG. 3E

FIG. 3F

FIG. 3G

FIG. 3H

FIG. 31

FIG. 3J

FIG. 4A

FIG. 4B

FIG. 5A

508

510A
510B
510C
510D
510E
510F

512

FIG. 5B

FIG. 5C

FIG. 6A

FIG. 6B

612

614

616

FIG. 6C

FIG. 6D

FIG. 6E

700

Provide a planar mechanical resonator for substantially in-plane vibration and having a central mounting point.   *702*

Support the resonator at the central mounting point.   *704*

Provide at least one excitation electrode within an interior of the resonator to excite in-plane vibration of the resonator.   *706*

Provide at least one sensing electrode within the interior of the resonator for sensing the motion of the excited resonator.   *708*

FIG. 7

FIG. 8

FIG. 9A

FIG. 9B

FIG. 10A

1016
1018

1014
1016
1018

FIG. 10B

FIG. 10C

FIG. 10D

FIG. 10E

FIG. 10F

ISOLATED PLANAR GYROSCOPE WITH INTERNAL RADIAL SENSING AND ACTUATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. §119 (e) of the following U.S. Provisional Patent Applications, which are all incorporated by reference herein:

U.S. Provisional Patent Application No. 60/402,681, filed Aug. 12, 2002, and entitled "CYLINDER GYROSCOPE WITH INTEGRAL SENSING AND ACTUATION", by Kirill V. Shcheglov and A. Dorian Challoner; and

U.S. Provisional Patent Application No. 60/428,451, filed Nov. 22, 2002, and entitled "DESIGN AND FABRICATION PROCESS FOR A NOVEL HIGH PERFORMANCE MESOGYRO", by Kirill V. Shcheglov and A. Dorian Challoner.

This application is related to the following co-pending applications, which are all incorporated by reference herein:

U.S. patent application Ser. No. 09/928,279, filed Aug. 10, 2001, and entitled "ISOLATED RESONATOR GYROSCOPE", by A. Dorian Challoner;

U.S. patent application Ser. No. 10/370,953, filed Feb. 20, 2003, and entitled "ISOLATED RESONATOR GYROSCOPE WITH A DRIVE AND SENSE FRAME", by A. Dorian Challoner and Kirill V. Shcheglov;

U.S. patent application Ser. No. 10/423,459, filed Apr. 25, 2003, and entitled "ISOLATED RESONATOR GYROSCOPE WITH ISOLATION TRIMMING USING A SECONDARY ELEMENT", by A. Dorian Challoner and Kirill V. Shcheglov;
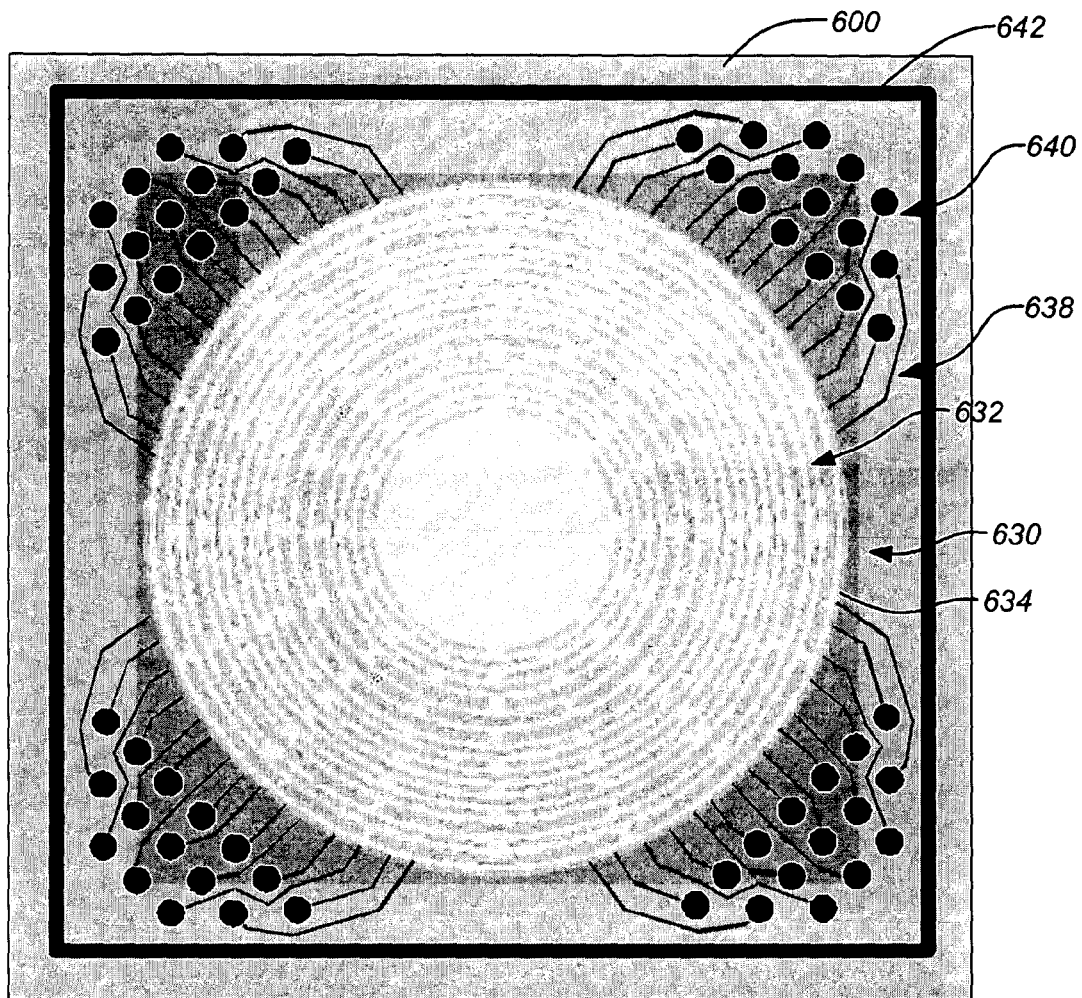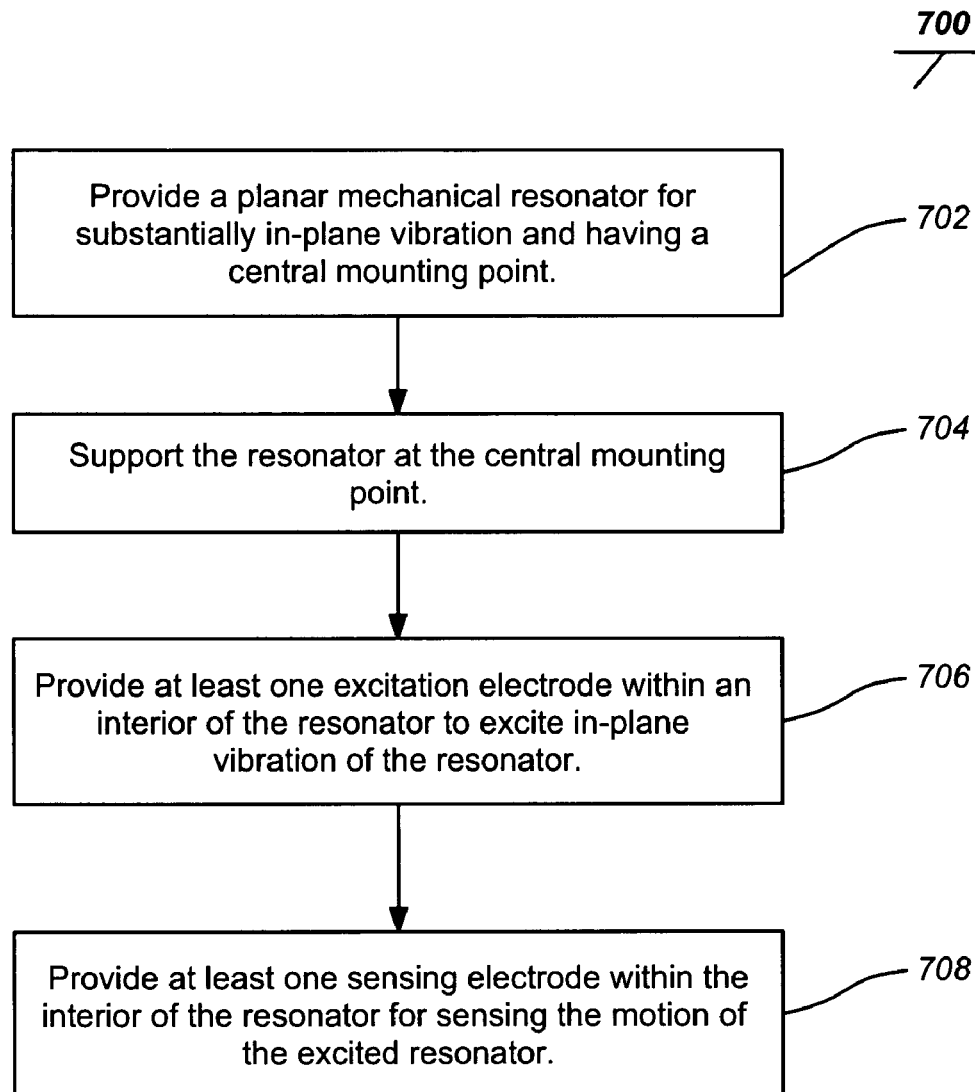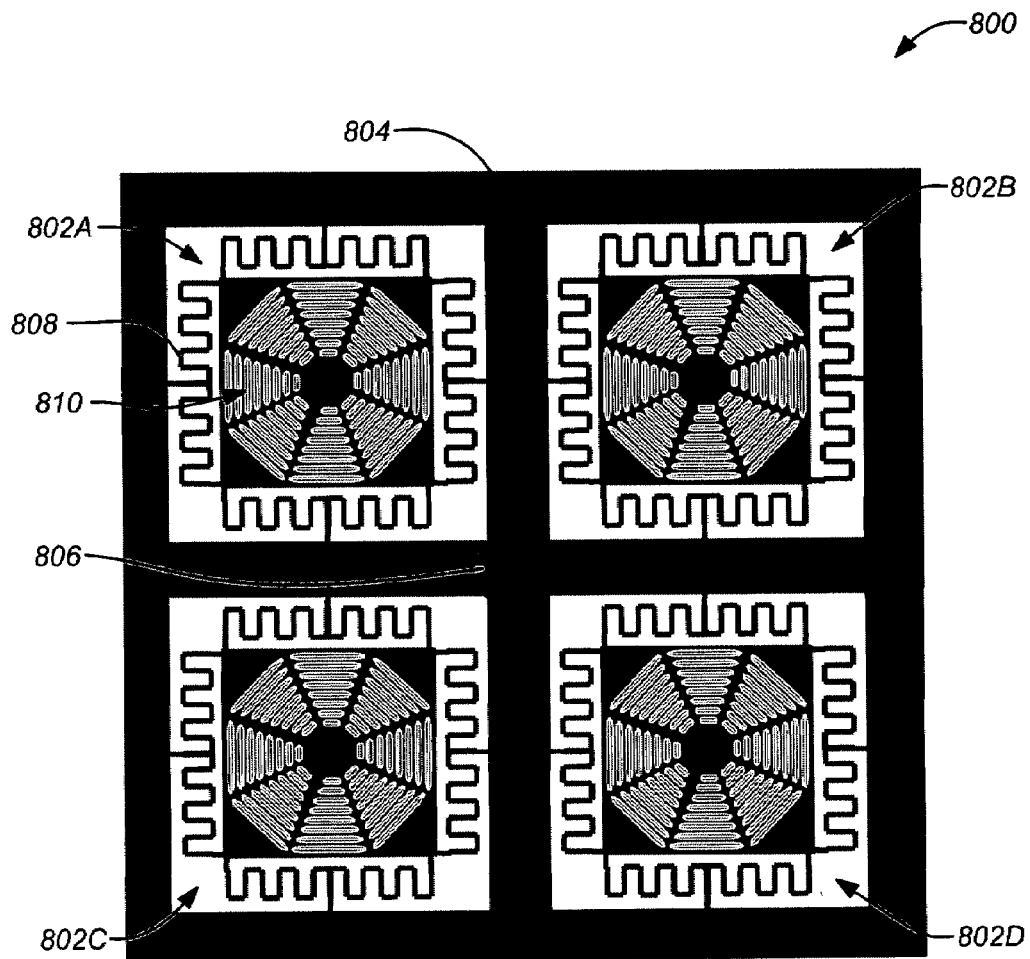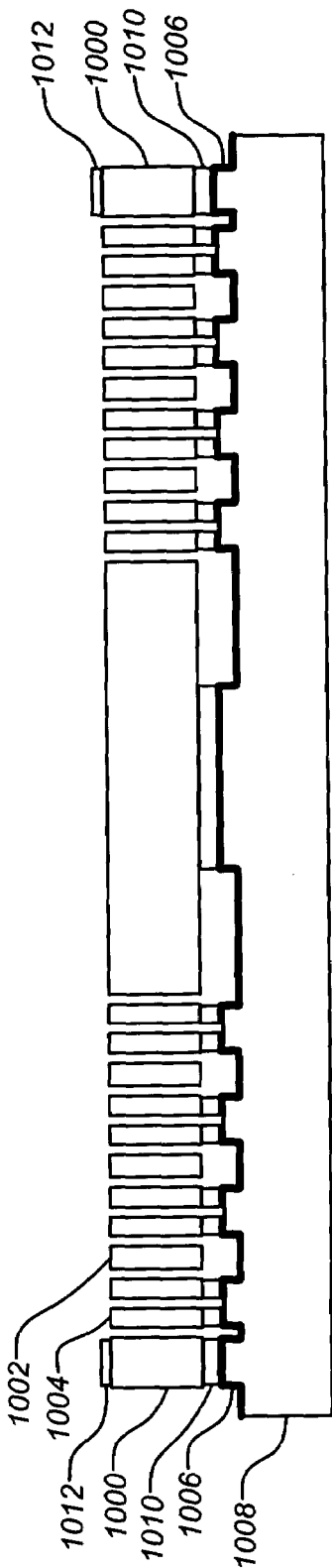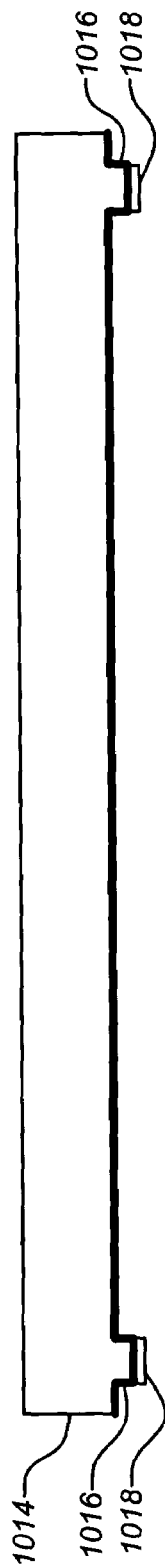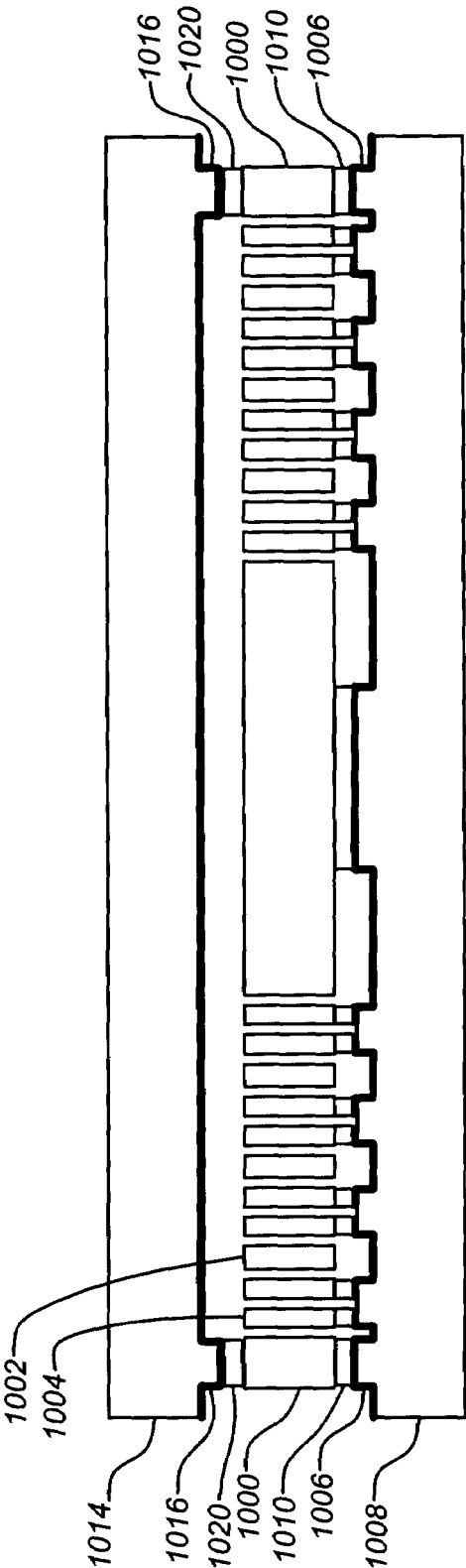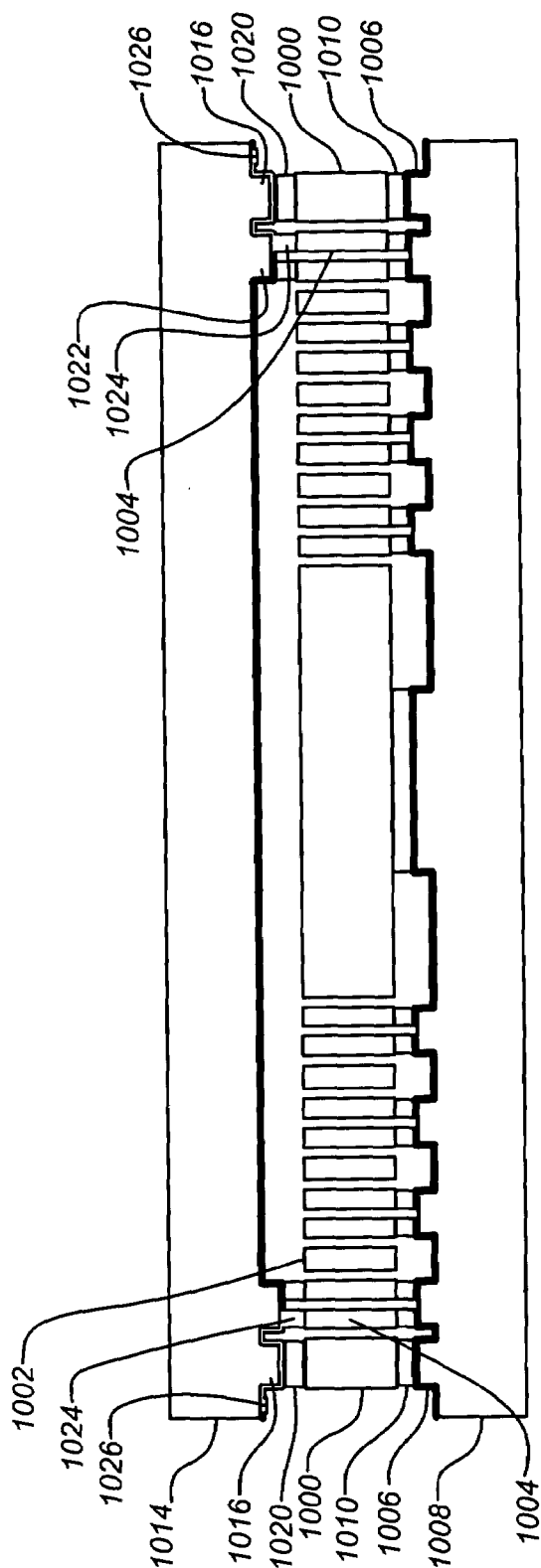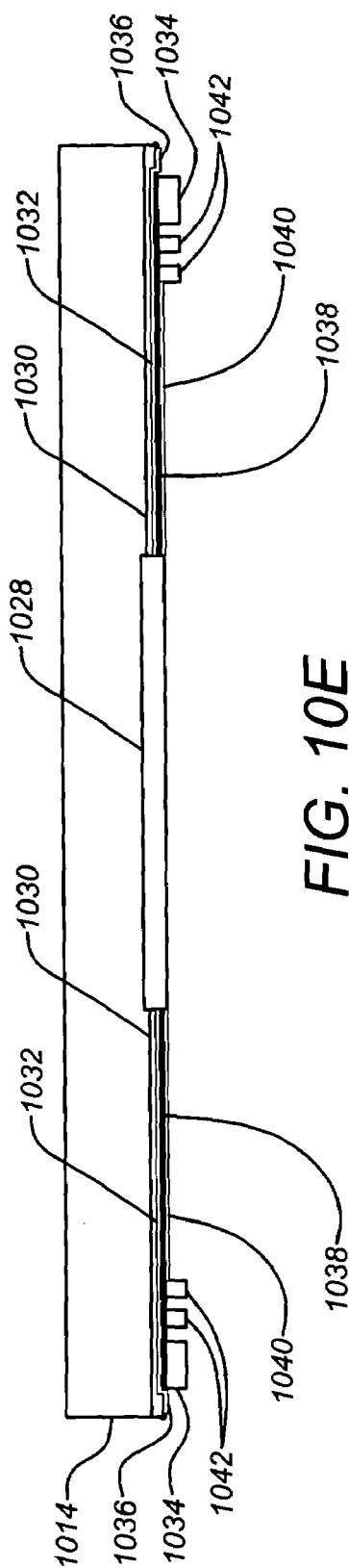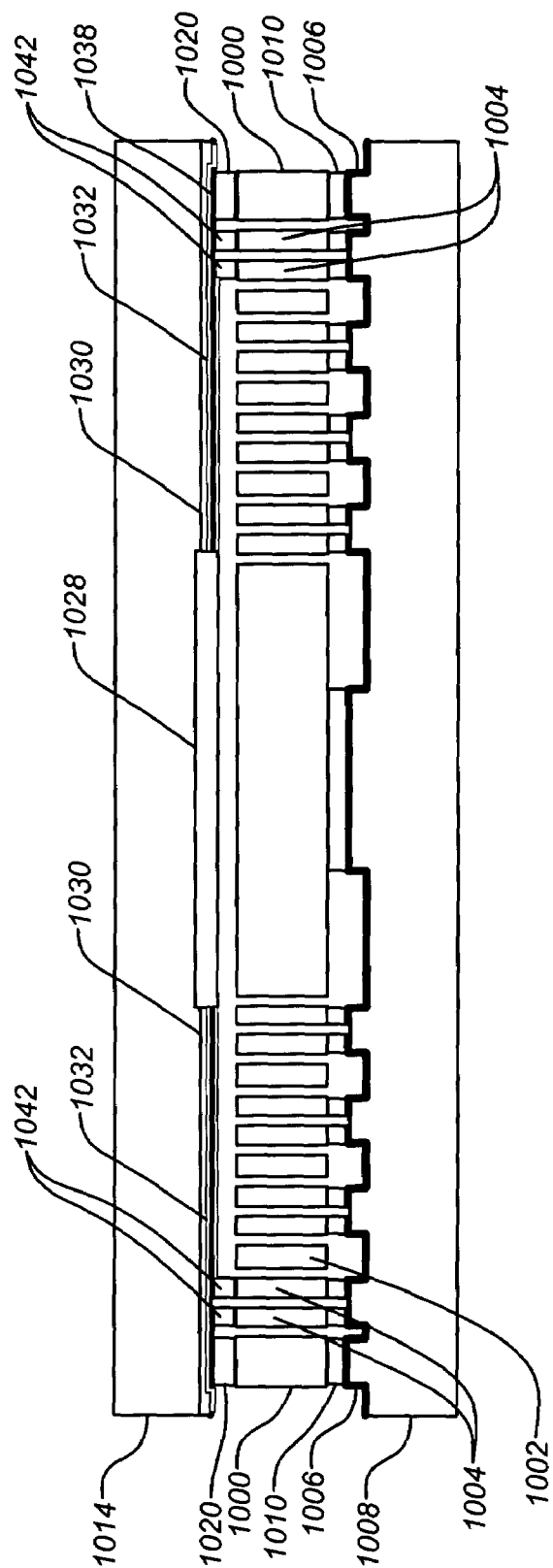
U.S. patent application Ser. No. 10/410,744, filed Apr. 10, 2003, and entitled "ISOLATED RESONATOR GYROSCOPE WITH COMPACT FLEXURES", by A. Dorian Challoner and Kirill V. Shcheglov;

U.S. patent application Ser. No. 10/285,886, filed Nov. 1, 2002, and entitled "MICROGYRO TUNING USING FOCUSED ION BEAMS", by Randall L. Kubena et al.;

U.S. patent application Ser. No. 10/603,557, filed Jun. 25, 2003, and entitled "INTEGRATED LOW POWER DIGITAL GYRO CONTROL ELECTRONICS", by Robert M'Closkey et al; and

U.S. patent application Ser. No. 10/639,135, filed on this same day herewith, and entitled "INTEGRAL RESONATOR GYROSCOPE", by Kirill V. Shcheglov et al.

STATEMENT OF GOVERNMENT RIGHTS

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to gyroscopes, and in particular to resonator microgyroscopes or inertial sensors and their manufacture. More particularly, this invention relates to isolated resonator inertial sensors and microgyroscopes.

2. Description of the Related Art

Mechanical gyroscopes are used to determine direction of a moving platform based upon the sensed inertial reaction of an internally moving proof mass. A typical electromechanical gyroscope comprises a suspended proof mass, gyroscope

case, pickoffs, or sensors, torquers, or actuators and readout electronics. The inertial proof mass is internally suspended from the gyroscope case that is rigidly mounted to the platform and communicates the inertial motion of the platform while otherwise isolating the proof mass from external disturbances. The pickoffs to sense the internal motion of the proof mass, the torquers to maintain or adjust this motion and the readout electronics that must be in close proximity to the proof mass are internally mounted to the case which also provides the electrical feedthrough connections to the platform electronics and power supply. The case also provides a standard mechanical interface to attach and align the gyroscope with the vehicle platform. In various forms gyroscopes are often employed as a critical sensor for vehicles such as aircraft and spacecraft. They are generally useful for navigation or whenever it is necessary to autonomously determine the orientation of a free object.

Older conventional mechanical gyroscopes were very heavy mechanisms by current standards, employing relatively large spinning masses. A number of recent technologies have brought new forms of gyroscopes, including optical gyroscopes such as laser gyroscopes and fiberoptic gyroscopes as well as mechanical vibratory gyroscopes.

Spacecraft generally depend on inertial rate sensing equipment to supplement attitude control. Currently this is often performed with expensive conventional spinning mass gyros (e.g., a Kearfott inertial reference unit) or conventionally-machined vibratory gyroscopes (e.g. a Litton hemispherical resonator gyroscope inertial reference unit). However, both of these are very expensive, large and heavy.

In addition, although some prior symmetric vibratory gyroscopes have been produced, their vibratory momentum is transferred through the case directly to the vehicle platform. This transfer or coupling admits external disturbances and energy loss indistinguishable from inertial rate input and hence leads to sensing errors and drift. One example of such a vibratory gyroscope may be found in U.S. Pat. No. 5,894,090 to Tang et al. which describes a symmetric cloverleaf vibratory gyroscope design and is hereby incorporated by reference herein. Other planar tuning fork gyroscopes may achieve a degree of isolation of the vibration from the baseplate, however these gyroscopes lack the vibrational symmetry desirable for tuned operation.

In addition, shell mode gyroscopes, such as the hemispherical resonator gyroscope and the vibrating thin ring gyroscope, are known to have some desirable isolation and vibrational symmetry attributes. However, these designs are not suitable for or have significant limitations with thin planar silicon microfabrication. The hemispherical resonator employs the extensive cylindrical sides of the hemisphere for sensitive electrostatic sensors and effective actuators. However its high aspect ratio and 3D curved geometry is unsuitable for inexpensive thin planar silicon microfabrication. The thin ring gyroscope (e.g., U.S. Pat. No. 6,282,958, which is incorporated by reference herein) while suitable for planar silicon microfabrication, lacks electrostatic sensors and actuators that take advantage of the extensive planar area of the device. Moreover, the case for this gyroscope is not of the same material as the resonator proof mass so that the alignment of the pickoffs and torquers relative to the resonator proof mass change with temperature, resulting in gyroscope drift.

Vibration isolation using a low-frequency seismic support of the case or of the resonator, internal to the case is also known (e.g., U.S. Pat. No. 6,009,751, which is incorporated by reference herein). However such increased isolation comes at the expense of proportionately heavier seismic

mass and/or lower support frequency. Both effects are undesirable for compact tactical inertial measurement unit (IMU) applications because of proof mass misalignment under acceleration conditions.

Furthermore, the scale of previous silicon microgyroscopes (e.g., U.S. Pat. No. 5,894,090) can not been optimized for navigation or pointing performance resulting in higher noise and drift than desired. This problem stems from dependence on out of plane bending of thin epitaxially grown silicon flexures to define critical vibration frequencies that are limited to 0.1% thickness accuracy. Consequently device sizes are limited to a few millimeters. Such designs exhibit high drift due to vibrational asymmetry or unbalance and high rate noise due to lower mass which increases thermal mechanical noise and lower capacitance sensor area which increases rate errors due to sensor electronics noise.

Scaling up of non-isolated silicon microgyros is also problematic because external energy losses will increase with no improvement in resonator Q and no reduction in case-sensitive drift. An isolated cm-scale resonator with many orders of magnitude improvement in 3D manufacturing precision is required for very low noise pointing or navigation performance.

Conventionally machined navigation grade resonators such as quartz hemispherical or shell gyros have the optimum noise and drift performance at large scale, e.g. 30 mm and 3D manufacturing precision, however such gyros are expensive and slow to manufacture. Micromachined silicon vibratory gyroscopes have lower losses and better drift performance at smaller scale but pickoff noise increases and mechanical precision decreases at smaller scale so there are limits to scaling down with conventional silicon designs. Conventional laser trimming of mechanical resonators can further improve manufacturing precision to some degree. However this process is not suitable for microgyros with narrow mechanical gaps and has limited resolution, necessitating larger electrostatic bias adjustments in the final tuning process.

There is a need in the art for small gyroscopes with greatly improved performance for navigation and spacecraft payload pointing. There is also a need for such gyros to be scalable to smaller, cheaper and more easily manufactured designs with lower mechanical losses in silicon and greater 3D mechanical precision for lower gyro drift. There is still further a need for such gyros to have desirable isolation and vibrational symmetry attributes while being compatible with planar silicon manufacturing. There is a need for the gyroscope resonator and case to be made of the same material, preferably silicon and allowing close proximity of pickoffs, torquers and readout electronics. Finally, there is a need for such gyros to provide adequate areas for sensing and drive elements in a compact form for lower gyro noise at small scale. As detailed below, the present invention satisfies all these and other needs.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide a planar resonator supported on a central rigid stem and with substantially increased sensing capability by utilizing a short solid cylindrical resonator or disc having a substantial useable internal resonator volume, allowing the incorporation of significantly more sensing for the measurement of desirable resonator internal motion. This use of a planar element, such as a disc, rather than a shell or ring results in substantial top and bottom surface areas and a large internal

volume for mounting additional sensors. A disc provides the same favorable modes for Coriolis sensing as a cylindrical or hemispherical shell.

A typical resonator of the invention for an inertial sensor includes a plurality of concentric rings and interleaved segments connecting the concentric rings. The rings are typically circular, but can also be in other closed shapes. Importantly, this resonator structure can be used with or without internal electrodes for actuation and sensing.

A typical embodiment of the present invention comprises an inertial sensor including a planar mechanical resonator for substantially in-plane vibration and having a central mounting point, a rigid support for the resonator at the central mounting point. Excitation elements are disposed within an interior of the resonator to excite in-plane vibration of the resonator and sensing elements are disposed within the interior of the resonator for sensing the internal motion of the excited resonator. In one embodiment, the planar resonator includes a plurality of slots in an annular pattern.

In one embodiment of the invention, multiple concentric alternating segments or slots can be cut or etched through the disc, reducing the in-plane stiffness of the resonator. In addition, the segmented or slotted disc also obtains an increased area available for capacitive sensing. The advantages of this structure include permitting larger deflections with increased sensitivity. Alternatively, in-plane strain gauges can be placed on the top and bottom surfaces of a solid disc to provide a constant sensing area, regardless of the disc thickness. However, this approach will produce a resonator with an increased in-plane stiffness when compared with the segmented or slotted approach.

Because the resonator is planar, it's manufacture is conveniently facilitated through known wafer manufacturing technologies. For example, the planar resonator can be produced by reactive ion etching (RIE) the resonator from silicon bonded in place on a supporting silicon baseplate. Electrode support pillars and interconnect wiring can be etched and deposited on the baseplate before bonding. The etching process can thus be used to simultaneously produce the torquer excitation and pickoff sensing electrodes along with the resonator and a portion of the gyroscope case, including a wall surrounding the resonator and an endplate. A third silicon wafer comprising the readout electronics and electrode interconnections can also be bonded to the resonator to complete the gyroscope case.

In addition, in further embodiments of the invention, the planar resonator can comprise four masses, each having a simple degenerate pair of in-plane vibration modes and all being centrally supported. The planar mechanical resonator can be designed with two degenerate in-plane system modes producing symmetric motion of the four masses for Coriolis sensing.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1A depicts a top view of an exemplary planar resonator gyroscope of the present invention;

FIG. 1B depicts a side view of an exemplary planar resonator gyroscope of the present invention;

FIG. 1C illustrates a pattern for an exemplary planar resonator of the present invention;

FIG. 1D illustrates electrode operation for a first mode of an exemplary resonator.

FIGS. **2A–2B** represent a finite element model of an exemplary segmented planar resonator gyroscope of the present invention;

FIGS. **3A–3J** illustrate strain energy within a finite element model of an exemplary solid planar resonator gyroscope in various modes;

FIGS. **4A** and **4B** depict another finite element model of an exemplary segmented planar resonator gyroscope of the present invention;

FIGS. **5A–5C** illustrate masks that can be used in producing an isolated resonator of the invention;

FIGS. **6A–6C** depicts various stages of an exemplary manufacturing process for the invention;

FIG. **6D** shows an exemplary resonator with a quarter cutaway to reveal the embedded electrodes;

FIG. **6E** shows an exemplary gyro without end cap readout electronics assembled

FIG. **7** is a flowchart of an exemplary method of producing a resonator according to the present invention;

FIG. **8** illustrates an alternate isolated planar resonator gyroscope embodiment comprising four masses vibrating in plane;

FIGS. **9A** and **9B** illustrate the Coriolis sensing modes of the four masses vibrating in plane;

FIG. **10A–10C** illustrate the integration of a end cap wafer with the baseplate including an integral vacuum cavity wall;

FIG. **10D** illustrates a further embodiment with electrical feedouts to the excitation sensing and bias electrodes provided on the end cap wafer;

FIG. **10E** illustrates yet another embodiment where the end cap wafer includes the control electronics for the gyro; and

FIG. **10F** illustrates the integrated end cap wafer including the control electronics.

DETAILED DESCRIPTION

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

1.0 Overview

Embodiments of the present invention generally describe an isolated planar vibratory gyroscope. Generally, embodiments of the invention employ embedded sensing and actuation providing a planar micromachined silicon gyroscope having desirable axisymmetric resonator with single central nodal support, integral (and distributed) proof mass and flexural suspension and extensive capacitive electrodes with large total area. Advantageously, the entire resonator, embedded electrodes and integral case wall of the present invention can be fabricated from a single wafer of silicon.

Silicon ring resonators (e.g., U.S. Pat. No. 6,282,958) do not have large area internal capacitive sensors and actuators and require flexible support beams. Other quartz hemispherical resonator gyroscopes are three dimensional so they cannot be micromachined and do not have embedded electrodes. Although post mass type resonator gyroscopes have high angular gain, large area sensing elements and hence superior noise performance to other designs, they do not have the optimized resonator isolation properties of a single central nodal support and often employ a discretely assembled post proof mass. Further, integrally made, fully

differential embedded electrodes as with the present invention, desirable for better thermal and vibration performance, are not possible with a discrete post proof mass resonator gyroscope or out of plane gyroscope.

The principal problems with ring gyroscopes are the inherently small sensor area around a thin ring and the flexibility or interaction of the support beams. A three dimensional hemispherical gyroscope has taller sides for large area capacitive sensing, but still requires assembly of a discrete circumferential electrode cylinder or cup for sensing and excitation. A tall cylinder with central support and circumferential electrodes also faces this problem. A short solid cylinder or disc with a central support and piezoelectric and/or electromagnetic wire sensors and actuators, mounted to the top or bottom surface of the disc solves the problem of non-embedded sensors with small area. However, a preferred embodiment of this invention is a multiply slotted disc resonator with capacitive sensing and actuation illustrated in exemplary embodiment described hereafter.

2.0 Exemplary Planar Resonator Gyroscope Embodiment

FIG. **1A** depicts a schematic top view of an isolated resonator for the gyroscope or inertial sensor embodiment of the present invention. The gyroscope comprises a unique planar resonator **100** which is supported by a rigid central support **106** and designed for in-plane vibration. In the exemplary embodiment, the resonator **100** comprises a disc that includes a number of slots, e.g. **116A–116D** (generally referenced as **116**) formed from concentric circumferential segments **104A–104E**. The circumferential segments **104A–104E** are supported by radial segments **102A–102E**. The overall diameter of the resonator can be varied depending upon the performance requirements. For example, a 16 mm diameter resonator can provide relatively high machining precision and low noise. Further refinement of the resonator can yield a resonator diameter of only 4 mm at significantly reduced cost.

FIG. **1B** depicts a schematic side view of an exemplary isolated resonator **100** of the present invention assembled into a baseplate **112**. The central support **106** supports the resonator **100** on the baseplate **112**. At least some of the slots **116** in the resonator **100** provide access for the embedded electrodes **108A–108D** which are also supported on pillars **114** on the baseplate **112**. The electrodes **108A–108D** form capacitive gaps **110A–110H** (outward gaps **110A**, **110C**, **110F** and **110H** and inward gaps **110B**, **110D**, **110E** and **110G**) with at least some of the circumferential segments **104A–104E** of the resonator **100**. These electrodes **108A–108D** provide for radial excitation of the resonator **100** as well as sensing motion of the resonator **100**. To facilitate this each of the electrodes **108A–108D** is divided into multiple separate elements to improve control and sensing of the resonator. For example, the annular electrode **108B** as shown can be divided into two or more elements, at least one acting across the outward gap **110C** and at least one acting across the inward gap **110D**. Vibration is induced in the resonator by separately exciting the elements to produce a biased reaction on the resonator **100** at the electrode **108B** location.

In general, the excitation electrodes **108B**, **108C** are disposed closer to the central support **106** (i.e., within inner slots of the resonator **100**) than the electrodes **108A**, **108D** (i.e. within outer slots of the resonator **100**) to improve sensing. However, the arrangement and distribution of the excitation and sensing electrodes **108A–108D** can be varied as desired. In further embodiments, additional electrodes can

also be used to bias the resonator **100** providing electrostatic tuning. Such biasing electrodes can also include multiple separate elements as the excitation and sensing electrodes.

FIG. 1C illustrates a pattern **120** for an exemplary planar resonator **100** of the present invention. This pattern **120** employs numerous concentric interleaved circumferential slots **122**. Some of the slots, e.g. **122A–122E** are wider to accommodate multiple element electrodes. For example, two of the outer rings of wider slots **122A**, **122B** are for the sensing electrodes and three of the inner rings of wider slots are for the driving electrodes. The remaining slots **122** can serve to structurally tune the resonator **100** (e.g., lower the frequency) and/or they may be occupied by bias electrodes which are used to actively bias the resonator in operation. The resonator and modal axes **124** are indicated; operation of the resonator identifies them as the pattern **120** is symmetric.

Although the exemplary resonator **100** is shown as a disc, other planar geometrics using internal sensing and actuation are also possible applying principles of the present invention. In addition, the single central support **106** is desirable, providing complete isolation of the resonator, however, other mounting configurations using one or more additional or alternate mounting supports are also possible. For example, although central mounting is desirable, in other embodiments of the invention the resonator can be alternately mounted circumferentially.

As employed in the resonator **100** described above, a centrally supported solid cylinder or disc has two degenerate in-plane modes suitable for Coriolis sensing, however the frequencies are very high (greater than 100 KHz) and the radial capacitance sensing area diminishes with cylinder height or disc thickness. However, the multi-slotted disc resonator **100**, shown in FIGS. **1A** and **1B** overcomes these problems. By etching multiple annular slots through the cylinder or disc two immediate benefits result: two degenerate modes suitable for Coriolis sensing with low frequency (less than 50 KHz) and large sense, bias and drive capacitance. The low frequency derives from the increased in-plane compliance provided by the slots. The large sense, bias and drive capacitance is a consequence of the large number of slots that can be machined into the resonator.

FIG. 1D illustrates electrode operation for a first mode of the resonator of FIG. 1C. The electrodes **124** that operate with a resonator **100** of the pattern **120** are shown in the left image. Four groups of electrodes **124** are used, each at a 90° interval around the circumference of the pattern. The positive excitation elements **126** and negative excitation elements **128**, paired elements of the excitation electrodes, are driven to excite the resonator **100**. These paired elements **126**, **128** share a slot with the positive elements **126** in the outward position and the negative elements **128** in the inward position. Note also that as shown some of the pairs share a common slot with other distinct electrode pairs, illustrating that multiple separately operable electrodes can share a common resonator slot. The sensing electrodes are disposed at a larger radial position and include positive sensing elements **130** and negative sensing elements **132** which together provide output regarding motion of the resonator **100**.

A uniform radial spacing between slots **116**, **122** can be employed, but other spacing may also be used, provided two degenerate in-plane modes suitable for Coriolis sensing are maintained. In addition, in further embodiments, some or all of the segments **104A–104E** can be further slotted such that a single beam segment is further divided into a composite segment including multiple parallel segments. Selective use

of such composite segments can be used to adjust the frequency of the resonator as well as eliminate harmful thermoelastic effects on drift performance as the segments are stressed in operation of the resonator. Generally, adding slots to form composite circumferential segments lowers the resonator frequency. The effect of machining errors is also mitigated with multiple slots. Although such composite segments are preferably applied to the circumferential segments **104A–104E**, the technique can also be applied to the radial segments **102A–102E** or other designs with other segments in other resonator patterns.

Employing the in-plane design described, embodiments of the present invention obtain many advantages over other out-of-plane gyros. For example, the central support bond carries no vibratory loads, eliminating any friction possibility or anchor loss variability. In addition, simultaneous photolithographic machining of the resonator and electrodes is achieved via the slots. Furthermore, diametral electrode capacitances can be summed to eliminate vibration rectification and axial vibration does not change capacitance to a first order. Modal symmetry is also largely determined by photolithographic symmetry not wafer thickness as with other designs. Isolation and optimization of sense capacitance (e.g., from the outer slots) and drive capacitance (e.g., from the inner slots) is achieved. Embodiments of the invention also achieve a geometric scalable design to smaller or larger diameters and thinner or thicker wafers. In addition, embodiments of the invention can be entirely defined by slots of the same width for machining uniformity and symmetry. Implementation of the present invention can also accommodate silicon anisotropy producing frequency splits. For example, a <111> silicon wafer and/or a varied slot width can be used.

As mentioned above, high thermoelastic damping due to vibration frequency proximity to thermal relaxation resonance can result in short resonance decay times and high gyro drift. However, the slot radial spacing can be adjusted to define an optimum beam width and a number of slots can be additionally etched in between the slots defining the electrode gaps to further reduce the vibrating beam width.

In further embodiments of the invention, the multiple ring structure with staggered or interleaved radial spokes or segments, such as illustrated in FIG. 1A can be used without internal sensing/actuation. This resonator architecture can provide the advantages of averaging of machining errors, higher natural frequency with thinner silicon rings, higher Q (lower thermoelastic damping) and higher angular gain when compared with resonators employing a single ring and "wagon wheel" spokes from a central hub, such as the ring resonator of U.S. Pat. No. 6,282,958. The utility of this resonator structure is to provide multiple thin silicon rings with useful sturdy support to a central hub. Such a resonator can be employed whether or not internal actuation and sensing is also used. Furthermore, although it is desirable to employ a central mounting point, this resonator architecture can alternately be mounted from its periphery (e.g. its circumference) or using one or more other mounting points. Staggering or interleaving the radial segments indicates not all the radial segments form straight lines from the center of the resonator to the periphery (although some may). It should also be noted that the term "ring" as used herein does not require a circular shape. For example, the circumferential segments forming the concentric "rings" of the resonator of FIG. **1A** actually form a polygon. Circular rings are desirable, but any closed shape can also be used.

3.0 Planar Isolated Resonator Model

FIGS. **2A** and **2B** depict a finite element model of an exemplary slotted disc planar resonator gyroscope of the present invention. FIGS. **3A–3J** illustrate strain energy within a finite element model of an exemplary cylinder resonator gyroscope in various modes. These various solid cylinder resonator modes illustrate radial strain patterns in a solid cylindrical resonator vibration, aiding in the development of the segmented embodiment of the present invention, such as shown in FIGS. **2A–2B**.

FIGS. **4A** and **4B** depict another finite element model of an exemplary segmented planar resonator gyroscope of the present invention. The multi-slotted disc Coriolis coupled modes are depicted. Strain contours are shown with a fixed central support in white. In this case, a larger number of segments are employed than in the model of FIGS. **2A** and **2B**.

4.0 Producing an Isolated Planar Resonator Gyroscope

FIGS. **5A–5C** illustrate masks that can be used in producing an isolated resonator of the invention. FIG. **5A** illustrates a top view of the multi-slotted disc resonator fabrication pattern **500**. The resonator pattern includes a large central area **502** which is bonded to the central support on the baseplate. The embedded electrodes, e.g. concentric annular electrodes **504A–504F**, are defined by the through etching process that simultaneously defines the structure **506** (radial and circumferential segments) of the resonator. FIG. **5B** illustrates a top view of the multi-slotted disc baseplate pattern **508** showing the bonding pads, e.g., electrode bonding pads **510A–510F** and the central support bonding pad **512**. FIG. **5C** illustrates a top view of the multi-slotted disc resonator bonded to the baseplate. To illustrate the alignment, the electrode bonding pads **510A–510F** and central support bonding pad **512** are shown through the electrodes and resonator structure **506**, respectively. Known silicon manufacturing processes can be employed.

For a mesoscale (16 mm) gyroscope, a 500 micron wafer, e.g. silicon, can be through-etched with circumferential slot segments to define a planar cylindrical resonator with embedded electrostatic sensors and actuators. Integral capacitive electrodes can be formed within these slots from the original resonator silicon during the through etch process. This can be accomplished by first bonding the unmachined resonator disc to a base silicon wafer that is specially prepared with circumferential bonding pillar segments to support the stationary electrodes and central resonator. The pillar heights may be defined by wet chemical etching and gold compression or gold-silicon eutectic bonding can be used to bond the resonator to the support pillars before the resonator and its electrodes are photolithographically machined using deep reactive ion etching (DRIE). In addition, for a microscale (4 mm) resonator a 100 micron thick silicon wafer or silicon on insulator (SOI) or epitaxial silicon layer is required for the resonator wafer. Alternatively, a thicker wafer can be bonded to the baseplate and ground down and polished to the desired thickness. The dense wiring can be photographed onto the baseplate before resonator bonding and wirebonded outside the device to a wiring interconnect grid on a ceramic substrate in conventional vacuum packaging or interconnected to a readout electronics wafer via vertical pins etched into the resonator for a fully integrated silicon gyroscope that does not require a package.

FIGS. **6A–6C** depicts various stages of an exemplary manufacturing process for the invention. FIG. **6A** shows a sequential development of the baseplate for the resonator gyroscope. The process begins with a wafer **600**, e.g. a 500

micron silicon wafer as shown in the first image. The wafer **600** is first etched to produce electrode pillars **602** as well as a central resonator support pillar **604**, such as for a single central support as shown in the second image. The etching process can include growing a wet oxide, e.g. silicon oxide, approximately 1500 Angstroms thick, followed by pillar mask lithography according to standard techniques (e.g. using an AZ 5214 resist) known in the art. This is followed by a buffered oxide etch (BOE) of the mask, such as with a Surface Technology Systems (STS) to a depth of approximately 20 microns (corresponding to approximately 5 to 6 minutes). The resist is then removed, using an O_2 ashing process for example. Next, the wafer **600** is BOE dipped for approximately 10 to 20 seconds to remove the native oxide. Following this is a potassium hydroxide (KOH) dip of approximately 1 minute at 90° C. The oxide is then removed with HF. The third image of FIG. **6A** shows an oxide layer **606** applied over the etched wafer **600**. This layer **606** can be applied by growing a wet oxide for approximately 3 days at approximately 1050° C. The oxide layer **606** can then be etched, e.g. using a AZ 5740 resist, BOE oxide etch for approximately 2 hours to get through approximately 5 microns of oxide. After removing the resist, a metalization layer is then applied to form bonding pads **608**, **610** on each of the pillars **602**, **604**, respectively, as shown in the fourth image of FIG. **6A**. Application of the metalization layer can be accomplished by mask lithography, depositing the mask (e.g. AZ 5214 at 2000 RPM for 20 seconds). The metal, e.g. 100 Angstroms Ti, 200 Angstroms Pt and 3500 Angstroms Au, is then deposited and the mask is lifted off to yield metal bonding pads **608**, **610** only on the surfaces of the pillars **602**, **604**. Finally, the processed wafer **600** is washed thoroughly with an O_2 ashing process prior to bonding with the resonator wafer.

Application of the metalization layer for the bonding pads can also include patterning of the electrical wiring from the electrodes photographed onto the baseplate, wirebonded outside the device to a wiring interconnect grid on a ceramic. Alternately, in further novel embodiments discussed hereafter, the electrical wiring can be alternately developed into an integral vacuum housing produced simultaneously with the resonator.

FIG. **6B** shows a sequential development of the resonator wafer for the gyroscope. The first image shows the uniform thickness wafer **612**, e.g. of silicon, used to form the resonator. The wafer **612** can first have the back side processed to produce alignment marks with mask lithography applying a resist. The alignment marks can be produce through a reactive ion etch (RIE) process using CF_4 and O_2 until a relief is clearly visible (approximately 5 to 10 minutes). Alternately, an STS process for approximately 1 minute can also be used. After removing the resist, metalization lithography used to apply a mask to the front side of the wafer **612** to produce bonding pads **614**, **616**. The metal, e.g. 30 Angstroms Cr and 3500 Angstroms Au or 100 Angstroms Ti, 200 Angstroms Pt and 3500 Angstroms Au, is applied and the mask is lifted off to reveal the bonding pads **614**, **616**.

FIG. **6C** shows integration of the resonator and baseplate wafers and formation of the functional resonator for the gyroscope. The preprocessed baseplate wafer **600** and resonator wafer **612** are bonded together as shown in the first image of FIG. **6C** after aligning the two wafers **600**, **612** to approximately 1 micron. Bonding fuses the metal bonding pads (the electrode pads **608**, **610** as well as the central support bonding pads **614** and **616**) to form single bonded metal joints **618** and can be performed at approximately

400° C. and 5000 N. Next, the complete resonator 630 and electrodes 632A, 632B (generally referenced as 632) are simultaneously formed directly from the bonded structure by through etching. The through etching process can be performed using deep reactive ion etch (RIE) such as a suitable STS process with a photolithographically defined mask, e.g. an AZ 5740 mask, approximately 6 to 8 microns thick. The mask can be made as thin as possible for through etching. The resonator wafer 612 is then through etched over the mask pattern to simultaneously produce the resonator 630 as well as the separate electrodes 632A, 632B from the original wafer 612. See also FIGS. 5A–5C. Note that single electrodes 632 can be formed by through etching, forming passages 622, 624, to isolate a section of the resonator wafer 612 attached to a bonded joint 618. In addition, as discussed above with respect to FIG. 1B, electrodes can also be divided into multiple separate elements. For example, through etching an additional passage 626 separates the electrode 632 into two isolated electrode elements 632A, 632B. In this case the passage 626 must penetrate the metal bonded joint 618 to isolate the separate electrode elements 632A, 632B. At the conclusion of the through etching process, the resonator 630 structure is only supported at the central resonator support pillar 604.

FIG. 6D shows an exemplary resonator 630 with a quarter cutaway to reveal the embedded electrodes 632. A dust ring 634 is also shown that can be etched along with the resonator 630. Intermittent gaps 636 in the dust ring can be made to accommodate metal traces to the electrodes 632 to operate the gyro.

Elements of the exemplary planar silicon resonator gyro embodiments presented herein can be assembled with conventional vacuum packaging and discrete electronics in a manner similar to previous gyros. An internal ceramic substrate wiring bonded to the silicon gyro baseplate can be changed to match the new and old designs to existing packages.

FIG. 6E shows an exemplary gyro in a typical packaging assembly. Metal traces 638 from the electrodes 632 of the resonator 630. The dust ring 634 with intermittent gaps 636 allows passage of the metal traces 638 on the baseplate wafer 600 to the electrodes 632. The metal traces 638 lead to vertical connect pins 640 which pass through the baseplate wafer 600 (providing a vacuum seal). In the exemplary architecture shown, the vertical connect pins 640 are disposed in the corners of the square baseplate wafer 600. A vacuum cavity wall 642 surrounds the entire assembly. The vacuum cavity wall 642 can be applied as a part of a conventional housing covering the resonator 630 and bonded to the baseplate wafer 600. Alternately, in further embodiments discussed hereafter, an vacuum cavity wall 642 can be produced simultaneously with the resonator.

FIG. 7 is a flowchart of an exemplary method of producing a resonator according to the present invention. The method 700 includes providing a planar mechanical resonator for substantially in-plane vibration and having a central mounting point at step 702. The resonator is supported at the central mounting point at step 704. At step 706, at least one excitation electrode is provided within an interior of the resonator to excite in-plane vibration of the resonator. Finally at step 708, at least one sensing electrode is provided within the interior of the resonator for sensing the motion of the excited resonator. As discussed above, in further embodiments the planar mechanical resonator can be provided and supported substantially simultaneously with providing the excitation and sensing electrodes by through etching.

Final mechanical trimming with a laser or a focused ion beam (FIB) of all embodiments described herein can be optionally used to achieve full performance over thermal and vibration environments. Such FIB tuning applied to gyro resonators is described in U.S. application Ser. No. 10/285,886 filed Nov. 1, 2002 by Kubena et al., which is incorporated by reference herein.

5.0 Alternate Isolated Planar Resonator Gyroscope

An exemplary centrally supported planar resonator having concentric circumferential slots with internal electrodes to produce substantially in-plane vibration is described above. However, it is important to note that other planar resonator patterns are also possible using the principles and procedures described.

FIG. 8 illustrates an alternate isolated planar resonator gyroscope embodiment comprising four masses vibrating in plane. In this embodiment, the resonator 800 comprises a plate including four sub resonator mass elements 802A–802D (generally referenced as 802) each occupying a separate pane of a supporting frame 804. The frame is attached to a baseplate (not shown) at a central support 806. Each sub resonator mass element 802A–802D, is attached to the frame 804 by one or more support flexures 808. In the exemplary resonator 800, four support flexures 808 each having a meander line shape are attached to each mass element 802A–802D, one attached to each of the four sides of the element 802. Each support flexure 808 is attached to two corners of the mass element 802 at its ends and attached to an adjacent side of the pane of the support frame 804 at its middle. Each mass element 802A–802D includes eight groups of linear electrodes 810 (each electrode including two elements) arranged in a pattern of increasing length from a central point of the mass element 802. Each sub resonator mass element 802A–802D has a pair of simple degenerate in-plane vibration modes to yield two degenerate in-plane system modes involving symmetric motion of all four elements 802A–802D, suitable for Coriolis sensing. Note that despite the significant differences in the architecture between this embodiment and that of FIGS. 1A–1B, both still utilize planar mechanical resonators for substantially in-plane vibration with internal excitation and sensing electrodes.

FIGS. 9A and 9B illustrate a model of the Coriolis sensing modes of the four masses vibrating in plane. There are some key advantages of this alternate in-plane design embodiment over other out-of-plane gyros. For example, this embodiment includes a central support 806 bond that carries no vibratory loads, virtually eliminating any possible friction. In addition, simultaneous photolithographic machining of the resonator and electrodes can be achieved via the slots. Further, with this embodiment diametral electrode capacitances can be summed to eliminate vibration rectification and axial vibration does not change capacitance to a first order. The modal symmetry is largely determined by photolithographic symmetry, not wafer thickness as with gyros employing out-of-plane vibration. Also, this embodiment employs isolation and optimization of the sense capacitance (e.g., the outer slots of each element) and the drive capacitance (e.g., the inner slots of each element) and provides a geometrically scalable design to smaller/larger diameters and thinner/thicker wafers. This embodiment can also be entirely defined by slots of the same width for machining uniformity and symmetry. Finally, with this embodiment four-fold symmetry applies to all the Si crystal orientations and an ideal angular gain approaches one.

Wiring can be photographed onto the baseplate and wire-bond outside the device to a wiring interconnect grid on a ceramic as discussed above. However, implementation of this alternate embodiment can require many electrodes and interconnect wiring. As discussed below, the electrical wir-ing for this embodiment can also be alternately developed into an integral vacuum housing produced simultaneously with the resonator. Such an implementation is detailed hereafter.

There is also a potential interaction with degenerate pairs of other system modes very close in frequency. However, these can be ignored if not coupled. In addition, the central support and frame compliance can be modified to shift any coupled modes away in frequency.

This embodiment can also employ final mechanical trim-ming with laser or FIB of all mesogyro designs can be used to achieve full performance over thermal and vibration environments. This technique is described in U.S. applica-tion Ser. No. 10/285,886 filed Nov. 1, 2002 by Kubena et al., which is incorporated by reference herein. It is also noted that the isolation of the degenerate modes used in present embodiments of the invention can also be trimmed electro-statically, as with the embodiments discussed above and other out-of-plane gyro designs.

This alternate embodiment can also be packaged using conventional techniques. However, as discussed hereafter, the resonator can also be integrated into a novel integrated vacuum housing formed by resonator baseplate, case wall and readout electronics.

6.0 Isolated Planar Resonator Gyroscope with Integral Case and Readout Electronics

In further embodiments of the invention, the isolated planar resonator with internal excitation and sensing elec-trodes can be produced in a novel gyroscope including integral vacuum housing that is developed along with the resonator. These further embodiments build upon the basic product and manufacturing procedure detailed above with respect to FIGS. 6A–7.

FIG. 10A illustrates development of a vacuum cavity wall 1000 along with the resonator 1002 and electrodes 1004. The vacuum cavity wall 1000 is produced by first etching a continuous low wall 1006 on the baseplate 1008 around the perimeter of the electrode pillars as well as a central reso-nator support pillar. A bonding line 1010 (e.g., Au) is then produced on the low wall 1006 (over the SiO$_2$ layer) along with the bonding pads of the electrodes and central support. The resonator 1002 is prepare with a matching bonding line that is fused to the bonding line 1010. The vacuum cavity wall 1000 is then through etched from the resonator wafer along with the resonator 1002 and the electrodes 1004. Another bonding line 1012 (e.g. Au) is produced on the top surface of the vacuum cavity wall 1000.

FIG. 10B illustrates development of an end cap wafer 1014 that can be used to vacuum seal a resonator 1002. Like the baseplate 1008 of FIG. 10A, the end cap wafer 1014 is etched with a continuous low wall 1016. A metal bonding line 1018 (e.g., Au) is also produced over the oxide layer on the end cap wafer 1014.

FIG. 10C illustrates the integration of the end cap wafer 1014 with the baseplate including the vacuum cavity wall 1000. The bonding line 1010 of the vacuum cavity wall 1000 and the bonding line 1018 of the end cap wafer 1014 are then fused to form a vacuum seal 1020. The development of the vacuum cavity wall 1000 along with the planar resonator eliminates the need for separate hardware packaging proce-

dures and costs. In further embodiments, this aspect of the present invention further integrates the device and packag-ing solution.

FIG. 10D illustrates a further embodiment with electrical feedouts to the excitation sensing and bias electrodes pro-vided on the end cap wafer. The end cap wafer 1014 is etched to include electrode pillars 1022. Similar to the embodiment shown in FIG. 6E with metal traces 638 (e.g., Au) formed on the baseplate wafer 600, metal traces 1026 are formed on the end cap wafer 1014 connected to fused bonding pads 1024 of the top of the electrode (formed along with the bonding line 1012) and of the electrode pillar 1022 (formed along with the bonding line 1018). In order to electrically isolate passage through the vacuum seal 1020, a second SiO$_2$ layer 1016 is applied over the metal trace 1026 at least in the area that passes through the seal 1020. Although the electrical connection is shown to only two electrodes, other or all electrodes 1004 of the resonator 1002 can be so connected, patterned onto the surface of the end cap wafer 1014 to pass through the finished vacuum cavity wall 1000. Alternately, more space can be provided between the vacuum cavity wall 1000 and the resonator so that vertical connect pins can be arranged to pass through the end cap wafer 1014 from a point within the vacuum cavity wall 1000, similar to the arrangement shown in FIG. 6E with the baseplate wafer 600. Also, the electrodes 1004 which are used connected to metal traces 1026 on the end cap wafer 1014 can be considered "vertical connect pins" because they can be used to connect metal traces on the baseplate wafer 1008 with metal traces 1026 on the end cap wafer 1014.

FIG. 10E illustrates yet another embodiment where the end cap wafer 1014 includes the control electronics 1028 for the gyro. The end cap wafer 1014 can be produced including the control electronics 1028, e.g. an CMOS application specific integrated circuit (ASIC) device. Application of the control electronics 1028 to the end cap wafer 1014 includes applying metal traces 1032 (e.g., Al) over a first SiO$_2$ layer 1030. The metal traces 1032 lead from the control electron-ics 1028 under the bonding line 1034 for the vacuum seal to contact pads 1036 which communicate electrical power and control and rate signals to and from the control electronics 1028. Alternately, the metal traces 1032 can be eliminated in favor of vertical connect pins (not shown) which pass through the end cap wafer 1014. In this case contacts are provided on the top side of the integrated device. A second SiO$_2$ layer 1038 is applied over the metal traces 1032 of the control electronics 1028 to isolate a second layer of metal traces 1040 which couple the control electronics 1028 to the excitation, sensing and bias electrodes through bonding pads 1042.

FIG. 10F illustrates the integrated end cap wafer 1014 including the control electronics 1028. As with previous embodiments, the bonding line 1034 is fused to form the vacuum seal 1020 around the perimeter of the integrated device. Similarly, the bonding pads 1042 are fused to the various excitation, sensing and bias electrodes 1004.

The specific feature of the device design that enables relatively seamless subsequent integration with the CMOS control electronics is the presence of the "vertical connect pins" that bring signal lines from the baseplate wafer where the connections to the electrodes are made to the top surface of the device wafer pair. The pins can be connected to the feed-through lines on the end cap wafer or to the relevant metallization on the CMOS electronics during the bonding process. The bonding process which makes these electrical connections also creates the vacuum sealed cavity that houses the gyroscope resonator. The bonding can be per-

formed with a solder reflow (such as Au—Sn) which ensures a vacuum-tight seal and a high quality electrical connection.

A proper choice of the device wafer pair and end cap wafer/device pair bonding methods is important to both ensure a tight vacuum seal and to maintain electrical connectivity and mechanical integrity. In particular, the device wafer pair should be bonded with a higher temperature process, such as a Au thermal compression or Au—Si eutectic, while the readout electronics wafer should be bonded with a lower temperature process, such as Au—Sn or Au—In. This is done to maintain the mechanical integrity of free-standing electrodes during the readout electronics wafer bonding phase.

Since the planar resonator to baseplate bond can be accomplished by a robust Au/Si eutectic bond, a solder seal ring approach can be used for end cap wafer to resonator wafer bond with a melting point of approximately 300° C. This will allow the gyro to operate in a temperature environment as high approximately 200° C. if needed. The silicon planar resonator wafer and baseplate pair can be bonded directly to a Si readout electronics wafer containing CMOS control electronics in order to reduce the induced capacitive variations in a high g-environment. By connecting the gyro sense and control electrodes directly to the control electronics on the Si readout electronics wafer using Au/Si eutectic bonding, the overall robustness to high g-loading and thermal variations can be increased. In addition, since the gyro structure will form part of the readout electronics wafer, the electronics integration and the wafer vacuum encapsulation is accomplished in one fabrication step.

The foregoing description of the preferred embodiment of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto. The above specification, examples and data provide a complete description of the manufacture and use of the invention. Since many embodiments of the invention can be made without departing from the scope of the invention, the invention resides in the claims hereinafter appended.

What is claimed is:

1. An inertial sensor, comprising:
   a planar mechanical resonator for substantially in-plane solid disc vibration with two isolated and degenerate resonator modes for Coriolis sensing having a central mounting point;
   a support for the planar mechanical resonator at the central mounting point;
   at least one excitation electrode within an interior of the planar mechanical resonator to excite vibration of the isolated and degenerate resonator modes; and
   at least one sensing electrode within the interior of the planar mechanical resonator for sensing the vibration of the isolated and degenerate resonator modes.

2. The inertial sensor of claim 1, wherein planar resonator vibration is substantially isolated from the support.

3. The inertial sensor of claim 1, wherein the in-plane vibration comprises substantially radial motion about the central mounting point.

4. The inertial sensor of claim 1, further comprising a baseplate supporting the support, excitation electrode and sensing electrode.

5. The inertial sensor of claim 4, wherein producing the sensor comprises the steps of:
   etching the baseplate;
   bonding a wafer to the etched baseplate; and
   through etching the wafer to form the resonator, excitation elements and sensing elements.

6. The inertial sensor of claim 5, further comprising grinding and polishing the through-etched wafer to a desired thickness.

7. The inertial sensor of claim 5, wherein through etching the wafer also forms a case wall for the inertial sensor.

8. The inertial sensor of claim 1, wherein the planar mechanical resonator comprises a plurality of slots.

9. The inertial sensor of claim 8, wherein the plurality of slots are arranged in an annular pattern around the central mounting point.

10. The inertial sensor of claim 8, wherein the plurality of slots are arranged with substantially uniform radial spacing around the central mounting point.

11. The inertial sensor of claim 8, wherein the plurality of slots are arranged in a symmetric pattern.

12. The inertial sensor of claim 8, wherein the at least one excitation electrode is disposed within one or more of the plurality of slots.

13. The inertial sensor of claim 12, wherein the at least one excitation electrode is disposed within one or more inner slots of the plurality of slots.

14. The inertial sensor of claim 8, wherein the at least one sensing electrode is disposed within one or more of the plurality of slots.

15. The inertial sensor of claim 14, wherein the at least one sensing electrode is disposed within one or more outer slots of the plurality of slots.

16. The inertial sensor of claim 1, wherein the planar mechanical resonator comprises four masses, each hawing a simple degenerate pair of in-plane vibration modes.

17. The inertial sensor of claim 16, wherein the planar mechanical resonator has two degenerate in-plane system modes producing symmetric motion of the four masses for Coriolis sensing.

18. The inertial sensor of claim 1, further comprising an integral case vacuum wall formed from a same wafer as the planar mechanical resonator.

19. The inertial sensor of claim 1, further comprising an end cap wafer bonded to a case wall with a vacuum seal.

20. The inertial sensor of claim 19, wherein the end cap wafer includes readout electronics for the inertial sensor.

21. The inertial sensor of claim 1, wherein the planar mechanical resonator comprises an internally vibrating solid disc.

22. The inertial sensor of claim 1, wherein the planar mechanical resonator comprises a plurality of internal surfaces to actuate and sense the two internal and degenerate resonator modes for Coriolis sensing with the at least one excitation electrode and the at least one sensing electrode respectively.

23. The inertial sensor of claim 1, wherein the planar mechanical resonator comprises an integral and distributed proof mass and flexural suspension for the substantially in-plane solid disc vibration.

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