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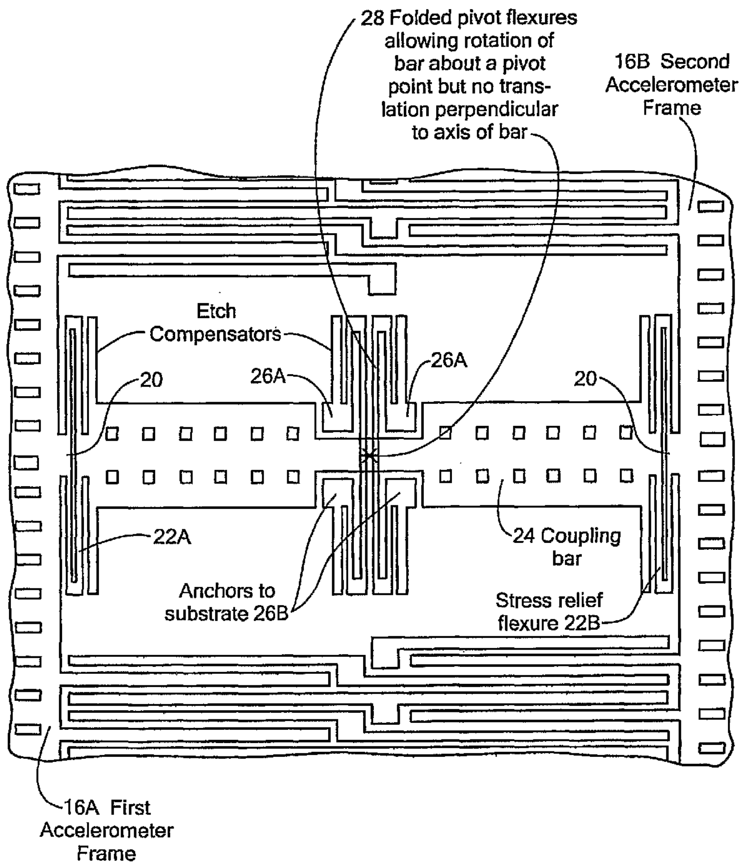
(54) Title: COUPLING APPARATUS FOR INERTIAL SENSORS



(57) Abstract: A coupling apparatus allows anti-phase movements of inertial sensor element frames along parallel axes but substantially prevents in-phase movements of the frames. The coupling apparatus includes a bar coupled between first and second sensor element frames and at least one supporting structure supporting the bar. The at least one structure is coupled to a substrate underlying the frames. The structures allow the bar to rotate at a pivot point when the frames move in anti-phase to one another along substantially parallel axes but substantially prevent in-phase movements of the frames.

WO 2005/103621 A1

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COUPLING APPARATUS FOR INERTIAL SENSORS

FIELD OF THE INVENTION

The invention generally relates to sensors and, more particularly, the invention relates to inertial sensors.

BACKGROUND OF THE INVENTION

Inertial sensors, such as MEMS gyroscopes, often are adversely affected by rotational vibration noise at the drive frequency (often referred to as "wobble"). In particular, MEMS gyroscopes can produce false readings if they are not capable of distinguishing between rotational vibration and the actual movement they are intended to detect.

Also, distortion of the geometry of a MEMS device having an oscillating mass, such as a gyroscope, can produce an imbalance in the forces transverse to a longitudinal drive finger. This imbalance can cause a net force that is indistinguishable from a Coriolis force. Consequently, a gyroscope can produce false outputs. There are at least two sources of these geometric distortions. One arises from surface shear of the substrate (e.g., from release/wafer curvature on dicing). Another arises from differential expansion of the package and applied accelerations (e.g., diagonally, G x G). Some causes of G x G error is discussed in Geen, J.A., "Progress in Integrated Gyroscopes," IEEE PLANS 2004 Proceedings, pp. 1-6, which is hereby incorporated herein by reference in its entirety.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide apparatus for coupling inertial sensor element frames so as to allow anti-phase movements of the inertial sensor element frames along parallel axes but substantially prevents in-phase movements of the frames.

In accordance with one aspect of the invention there is provided apparatus for coupling sensor elements of an inertial sensor. The apparatus includes a bar coupled between first and second sensor element frames and at least one supporting structure supporting the bar. The at least one structure is coupled to a substrate underlying the frames. The structures allow the bar to rotate at a pivot point when the frames move in anti-phase to one another along substantially parallel axes but substantially prevent in-phase movements of the frames.

In one exemplary embodiment, the apparatus further includes a first pair of short flexures extending from one of the frames and interconnected by a first long flexure and a second pair of short flexures extending from the other of the frames and interconnected by a second long flexure. The bar interconnects the first long flexure to the second long flexure substantially at the midpoints of the first and second long flexures. The at least one supporting structure includes an anchor flexure supporting the bar. The anchor flexure intersects with the bar substantially at the midpoints of the bar and the anchor flexure. Each end of the anchor flexure anchored to the substrate. Each of the long flexures is typically coupled so as to flex as the bar rotates.

In another exemplary embodiment of the invention, the apparatus further includes a first flexure extending from one of the frames and a second flexure extending from the other of the frames. The bar interconnects the first and second flexures. The at least one supporting structure includes at least one anchor flexure supporting the bar. Each anchor flexure includes a structure anchored at one end to the at least one substrate and folded back 180 degrees to meet with the bar. The at least one anchor flexure may include four anchor flexures positioned around the pivot point. Each of the anchor flexures is typically anchored to the substrate adjacent to the bar. Each of the first and second flexures may include two substantially parallel members coupled at both ends, with one of the members coupled to the frame and the other member coupled to the bar such that the members flex as the bar rotates.

In accordance with another aspect of the invention there is provided apparatus for coupling sensor elements of an inertial sensor. The apparatus includes coupling means for coupling first and second sensor element frames and supporting means for supporting the coupling means. The supporting means are coupled to a substrate underlying the frames. The supporting means allow the coupling means to rotate at a pivot point when the frames move in anti-phase to one another along substantially parallel axes but substantially preventing in-phase movements of the frames.

In a first exemplary embodiment, the coupling means include a first pair of short flexures extending from one of the frames and interconnected by a first long flexure; a second pair of short flexures extending from the other of the frames and interconnected by a second long flexure; and a bar that interconnects the first long flexure to the second long flexure substantially at the midpoints of the first and second long flexures. The supporting means may include an anchor flexure supporting the bar, the anchor flexure intersecting with the bar substantially at the midpoints of the bar and the anchor flexure, each end of the anchor flexure anchored to the substrate. Each of the long flexures may be coupled so as to flex as the bar rotates.

In another exemplary embodiment of the invention, the coupling means include a first flexure extending from one of the frames; a second flexure extending from the other of the frames; and a bar that interconnects the first and second flexures. The supporting means may include at least one anchor flexure supporting the bar, each anchor flexure including a structure anchored at one end to the at least one substrate and folded back 180 degrees to meet with the bar. The at least one anchor flexure may include four anchor flexures positioned around the pivot point. Each of the anchor flexures may be anchored to the substrate adjacent to the bar. Each of the first and second flexures may include two substantially parallel members coupled at both ends, one of the members coupled to the frame, the other member coupled to the bar, the members coupled so as to flex as the bar rotates.

In typical embodiments of the invention, rotation of the substrate about an axis normal to the plane causes the movements of the frames.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and advantages of the invention will be appreciated more fully from the following further description thereof with reference to the accompanying drawings wherein:

Figure 1 schematically shows a linear array of gyroscopes configured in accordance with illustrative embodiments of the invention;

Figure 2 schematically shows a coupling apparatus for coupling two frames shown in figure 1 in accordance with illustrative embodiments of the invention;

Figure 3 schematically shows additional details of an alternative embodiment of a first pair of gyroscopes;

Figure 4 shows more detail of the specific coupling apparatus used by the gyroscope pair shown in figure 3; and

Figure 5 shows more detail of specific balancers in accordance with illustrative embodiments of the invention.

The drawings are for illustrative purposes and may not be drawn to scale.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

In illustrative embodiments, an inertial sensor has a plurality of individual sensor components that all share a common centroid. Details of illustrative embodiments are discussed below.

Figure 1 schematically shows an array 10 of microelectromechanical systems (i.e., "MEMS") configured in accordance with illustrative embodiments of the invention. Specifically, the array 10 of MEMS devices together combine to effectively perform the function of a single gyroscope. To that end, the array 10 includes four MEMS gyroscopes 12A-D that all are secured to a common underlying substrate (not shown). Alternatively, the MEMS gyroscopes 12A-12D could be secured to different substrates.

Each gyroscope 12A-12D includes at least one oscillating mass (referred to herein as "resonator 14A, 14B, 14C, and 14D," respectively, or "resonator 14" generally) that 1) oscillates at a constant frequency along the X-axis and 2) is coupled with a single accelerometer frame (referred to herein as "frame 16A, 16B, 16C, or 16D," respectively, or "frame 16" generally). The resonator 14 illustratively is compliant in the X-direction only, while the frame 16 is compliant in the Y-direction only. Accordingly, rotation of any one of the gyroscopes 12A-12D about the Z-axis causes its resonator 14 to produce a Coriolis force that imparted to the accelerometer frame 16. Upon receipt of this Coriolis force, the frame 16 moves along the Y-axis. Capacitively coupled fingers 18 detect this Y-movement, which is translated into a signal representing the magnitude of the angular acceleration.

In illustrative embodiments, the gyroscopes 12A-12D are similar to those disclosed in U.S. patent numbers 6,505,511 and 6,122,961, the disclosures of which are incorporated herein, in their entireties, by reference. The gyroscopes 12A-12D also may be similar to those disclosed in co-pending U.S. patent application number 10/360,987, filed February 6, 2003, and naming John Geen as an inventor, the disclosure of which also is incorporated herein, in its entirety, by reference.

As noted above, in illustrative embodiments, the different gyroscopes 12A and 12D have a common centroid with the gyroscopes producing anti-phase signals 12B and 12C. The array 10 therefore is configured to position the gyroscopes 12A-12D and phase the respective resonators 14 in a manner that accomplishes this end. The specific placement, number of gyroscopes 12A-12D, and the phase of their resonators 14 thus are coördinated to ensure that they share a common centroid.

Figure 1 shows an exemplary arrangement that produces the desired result. In particular, the array 10 includes a first pair of gyroscopes 12A/B having the first and second gyroscopes 12A and 12B, and a second pair of gyroscopes 12 C/D having the third and fourth gyroscopes 12C and 12D. As shown, the resonators 14 in each pair operate 180 degrees out of phase and their frames 16 are coupled together in the manner discussed below. The first pair of gyroscopes 12A/B, however, is not coupled with the second pair 12C/D.

When positioned in the manner shown in figure 1, the first gyroscope 12A and the fourth gyroscope 12D resonate in phase, while the second and third gyroscopes 12B and 12C resonate in phase. Accordingly, the following equation is true:

$$V1+V4 = V2 +V3,$$

where:

V1 is the vector distance of the first gyroscope 12A to a point of rotation,

V2 is the vector distance of the second gyroscope 12B to a point of rotation,

V3 is the vector distance of the third gyroscope 12C to a point of rotation, and

V4 is the vector distance of the fourth gyroscope 12D to a point of rotation.

Note that a sign of the vector distance should be taken into account when considering this equation. When this relationship holds, the gyroscope as a whole becomes substantially insensitive to angular accelerations about that point of rotation to the extent that the responses of the frames match each other. The couplings overcome the mismatches induced by manufacturing tolerances and thereby improve the rejection of angular acceleration.

This arrangement nevertheless should not adversely affect the array 10 from detecting the underlying angular velocity for which it is designed.

Accordingly, embodiments of the invention should be substantially insensitive surface shear and also, as noted above, cause angular acceleration noise to cancel.

As noted above, the individual frames 16 within each pair are coupled in a manner that facilitates operation. Specifically, frames 16A and 16B are coupled by coupling 99AB, while frames 16C and 16D are coupled by coupling 99CD (referred to herein as "coupling apparatus 99" generally). In illustrative embodiments, each pair of frames 16 is coupled to ensure that they can move in anti-phase (i.e., 180 degrees out of phase) only, although the two pairs of frames are not interconnected. Figure 2 schematically shows more details of a mechanical coupling apparatus 99 for securing two of the frames. Although embodiments of the coupling apparatus 99 apply to any of the frames 16 shown, the frames 16 are identified in figure 2 as the first and second frames 16A and 16B for simplicity.

Specifically, the first frame 16A has a first pair of short flexures 20A that are coupled with a first long flexure 22A. In a corresponding manner, the second frame 16B has a second pair of short flexures 20B that are coupled with a second long flexure 22B. A bar 24 secures the first long flexure 22A to the second long flexure 22B. To provide some stability, a pair of anchors 26A and 26B extend on two sides of the bar 24 and couple with it by means of an anchor flexure 28.

This arrangement is substantially noncompliant when the two frames 16A and 16B are urged to move in phase. In contrast, this arrangement is substantially compliant when the two frames 16A and 16B are urged to move in anti-phase. In other words, when the first frame 16A is urged upwardly along the Y-axis, the second frame 16B is urged downwardly along the Y-axis. If both are urged upwardly along the Y-axis, however, this arrangement should be substantially non-compliant. In some embodiments, this arrangement permits the frames 16A and 16B to rotate to some extent as they move in the Y-direction.

Figure 3 schematically shows additional details of an alternative embodiment of the first pair of frames 16A and 16B. As shown, this embodiment also has the resonator 14, frame 16, coupling apparatus, and other components similar to those discussed above. Figure 4 shows more detail of the specific coupling apparatus shown in figure 3. Note that this coupling apparatus may be used with other gyroscope configurations, including those shown in figure 1.

As shown in Figure 4, the anchor flexure 28 actually extends outwardly and then folds back 180 degrees to meet with the bar 24. In addition, the coupling apparatus also has etch compensators. See the text in figure 4, which notes that the folded anchor flexure 28 allows rotation of the bar 24 about a pivot point, but no translation perpendicular to the axis of the bar 24. Also, rather than have a pair of short flexures 20 on each frame, this embodiment uses a single short flexure 20 on each frame.

In addition to ensuring that the frames 16A and 16B move in anti-phase, this flexure arrangement also reduces the potentially adverse effects of material shrinkage and G cross G error. This G cross G error arises when there is in-phase movement of the frames, and this is suppressed or reduced by the couplings.

The coupling apparatus 99 effectively add mass and stiffness to the movements of the frames 16. Since each frame is only coupled to an adjacent frame along one of its sides, the coupling apparatus 99 effectively unbalances the movements of each frame. Therefore, the array 10 preferably includes a number of balancers (referred to herein as "balancers 97A, 97B, 97C, and 97D," respectively, or "balancer 97" generally) to help offset the effects of the coupling apparatus 99. Specifically, a balancer 97 is preferably coupled to a side of each frame opposite the side with the coupling apparatus 99. Thus, balancer 97A is coupled to frame 16A along the side opposite the coupling 99AB, balancer 97B is coupled to frame 16B along the side opposite the coupling 99AB, balancer 97C is coupled to frame 16C along the side opposite the coupling 99CD, and balancer 97D is coupled to frame 16D along the side opposite the coupling 99CD. The configuration of each balancer 97 is typically the equivalent of half of a coupling apparatus 99 and therefore imparts substantially an equal but opposite mechanical effect on its respective frame 16.

Figure 5 shows more detail of specific balancers 97 (in this example, balancers 97B and 97C that sit between the two pairs of sensor elements) in accordance with illustrative embodiments of the invention. As shown, the configuration of each balancer 97 is essentially the equivalent of half of a coupling apparatus as shown in Figure 4. It should be noted that, unlike the coupling apparatus 99, there is no coupling between the two adjacent balancers 97B and 97C.

In illustrative embodiments, the accelerometers are run at about 17 volts.

The present invention may be embodied in other specific forms without departing from the true scope of the invention. The described embodiments are to be considered in all respects only as illustrative and not restrictive.

What is claimed is:

1. Apparatus for coupling sensor elements of an inertial sensor, the apparatus comprising:

a bar coupled between first and second sensor element frames; and

at least one supporting structure supporting the bar, the at least one structure coupled to a substrate underlying the frames, the structures allowing the bar to rotate at a pivot point when the frames move in anti-phase to one another along separate substantially parallel axes but substantially preventing in-phase movements of the frames.

2. Apparatus according to claim 1, further comprising:

a first pair of short flexures extending from one of the frames and interconnected by a first long flexure; and

a second pair of short flexures extending from the other of the frames and interconnected by a second long flexure, wherein the bar interconnects the first long flexure to the second long flexure substantially at the midpoints of the first and second long flexures, and wherein the at least one supporting structure includes an anchor flexure supporting the bar, the anchor flexure intersecting with the bar substantially at the midpoints of the bar and the anchor flexure, each end of the anchor flexure anchored to the substrate.

3. Apparatus according to claim 2, wherein each of the long flexures is coupled so as to flex as the bar rotates.

4. Apparatus according to claim 1, further comprising:

a first flexure extending from one of the frames; and

a second flexure extending from the other of the frames, wherein the bar interconnects the first and second flexures, and wherein the at least one supporting structure includes at least one anchor flexure supporting the bar, each anchor flexure including a structure anchored at one end to the at least one substrate and folded back 180 degrees to meet with the bar.

5. Apparatus according to claim 4, wherein the at least one anchor flexure includes four anchor flexures positioned around the pivot point.

6. Apparatus according to claim 4, wherein each of the anchor flexures in anchored to the substrate adjacent to the bar.

7. Apparatus according to claim 4, wherein each of the first and second flexures includes two substantially parallel members coupled at both ends, one of the members coupled to the frame, the other member coupled to the bar, the members coupled so as to flex as the bar rotates.

8. Apparatus according to claim 1, wherein rotation of the substrate about an axis normal to the plane causes the movements of the frames.

9. Apparatus for coupling sensor elements of an inertial sensor, the apparatus comprising:

coupling means for coupling first and second sensor element frames; and

supporting means for supporting the coupling means, the supporting means coupled to a substrate underlying the frames, the supporting means allowing the coupling means to rotate at a pivot point when the frames move in anti-phase to one another along separate substantially parallel axes but substantially preventing in-phase movements of the frames.

10. Apparatus according to claim 9, wherein the coupling means comprises:

a first pair of short flexures extending from one of the frames and interconnected by a first long flexure;

a second pair of short flexures extending from the other of the frames and interconnected by a second long flexure; and a bar that interconnects the first long flexure to the second long flexure substantially at the midpoints of the first and second long flexures.

11. Apparatus according to claim 10, wherein the supporting means comprises:

an anchor flexure supporting the bar, the anchor flexure intersecting with the bar substantially at the midpoints of the bar and the anchor flexure, each end of the anchor flexure anchored to the substrate.

12. Apparatus according to claim 10, wherein each of the long flexures is coupled so as to flex as the bar rotates.

13. Apparatus according to claim 9, wherein the coupling means comprises:

a first flexure extending from one of the frames;

a second flexure extending from the other of the frames; and

a bar that interconnects the first and second flexures.

14. Apparatus according to claim 13, wherein the supporting means comprises:

at least one anchor flexure supporting the bar, each anchor flexure including a structure anchored at one end to the at least one substrate and folded back 180 degrees to meet with the bar.

15. Apparatus according to claim 14, wherein the at least one anchor flexure includes four anchor flexures positioned around the pivot point.

16. Apparatus according to claim 14, wherein each of the anchor flexures is anchored to the substrate adjacent to the bar.

17. Apparatus according to claim 13, wherein each of the first and second flexures includes two substantially parallel members coupled at both ends,

one of the members coupled to the frame, the other member coupled to the bar, the members coupled so as to flex as the bar rotates.

18. Apparatus according to claim 9, wherein rotation of the substrate about an axis normal to the plane causes the movements of the frames.

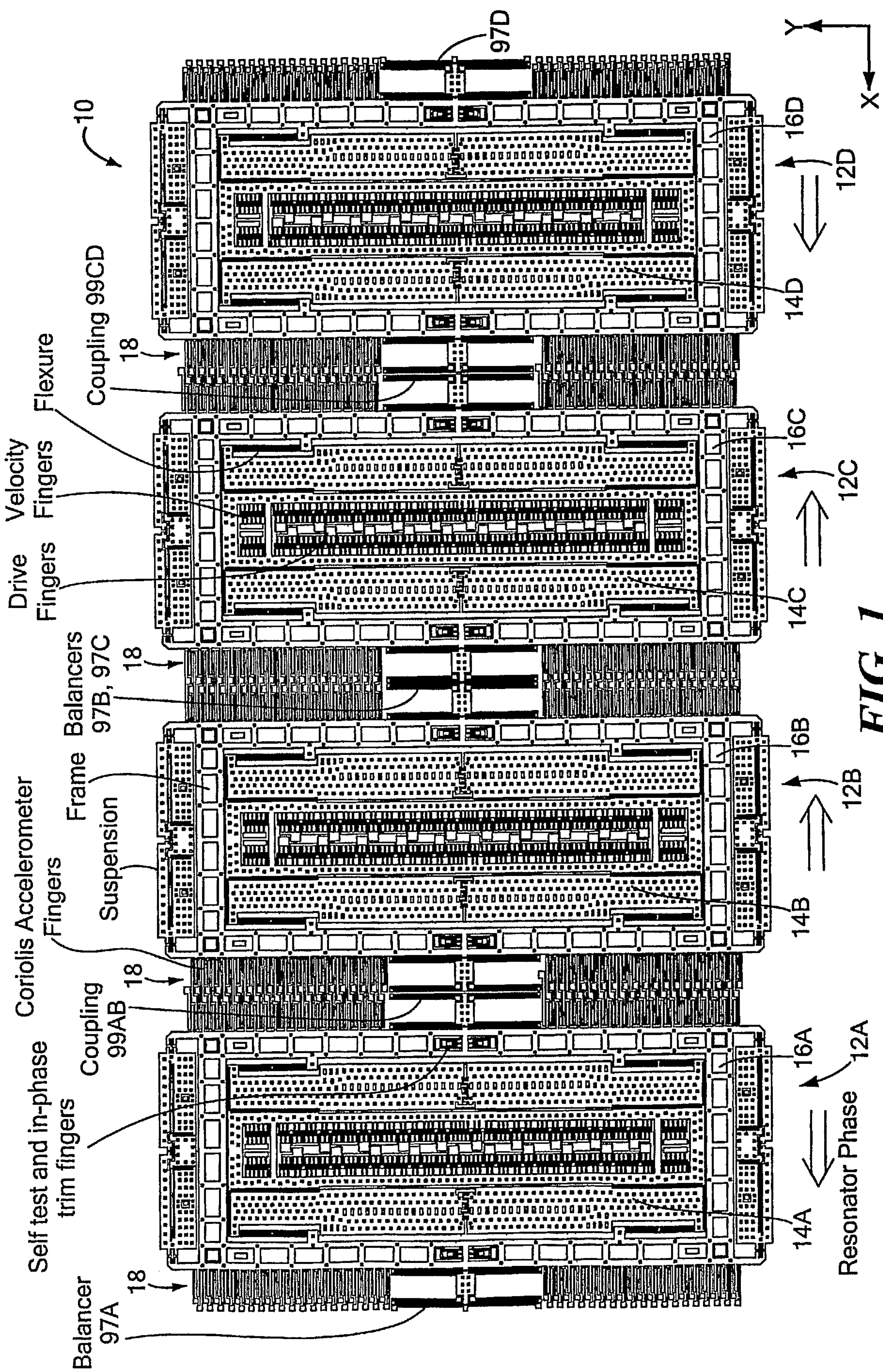
97D
Y
X
10
16D
12D
14D
Coupling 99CD
18
Flexure
Velocity Fingers
Drive Fingers
16C
12C
14C
Balancers 97B, 97C
18
Frame
Suspension
16B
12B
14B
Coriolis Accelerometer Fingers
18
Coupling 99AB
Self test and in-phase trim fingers
16A
12A
14A
Resonator Phase
18
Balancer 97A

FIG. 1

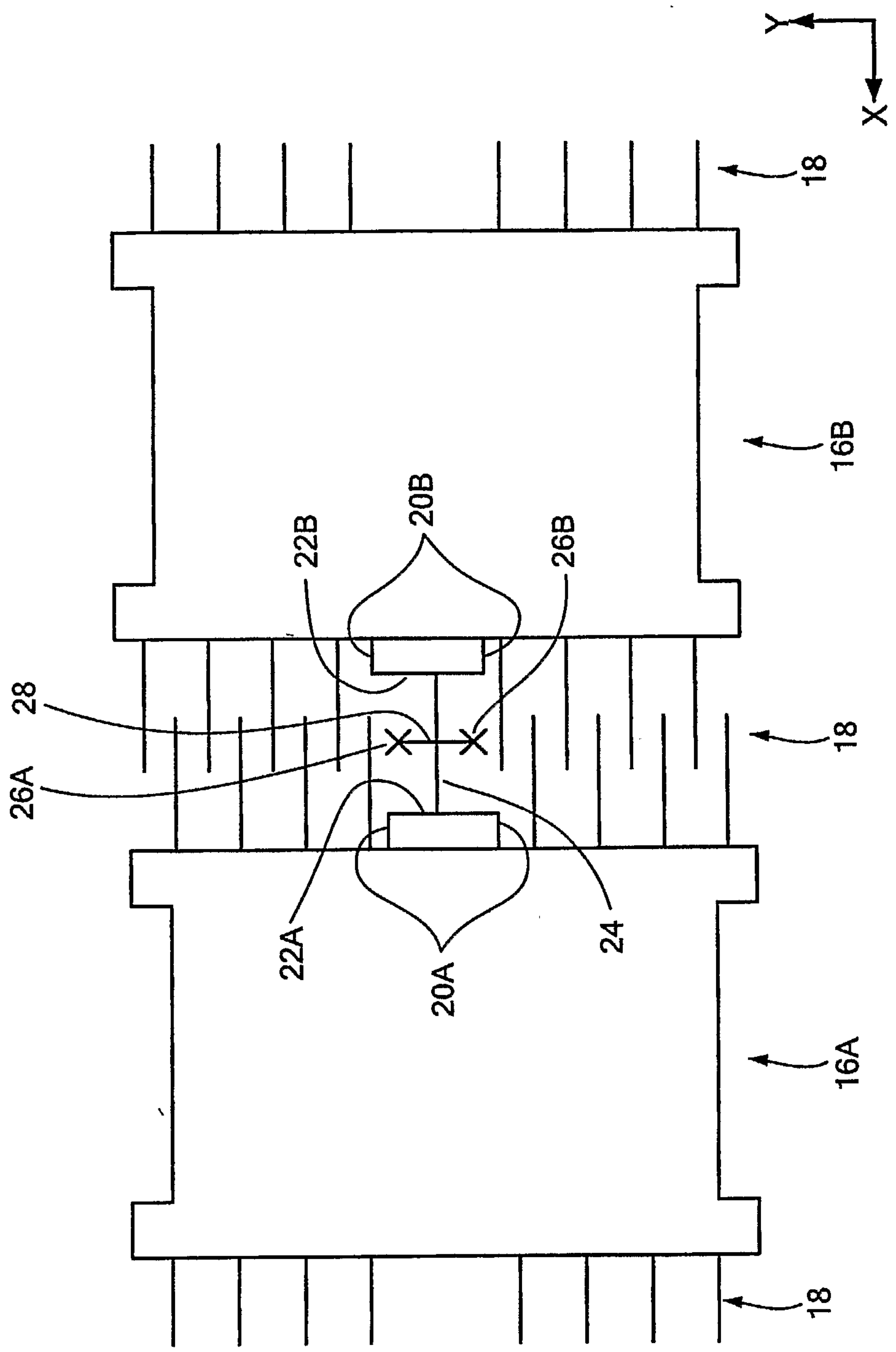

FIG. 2

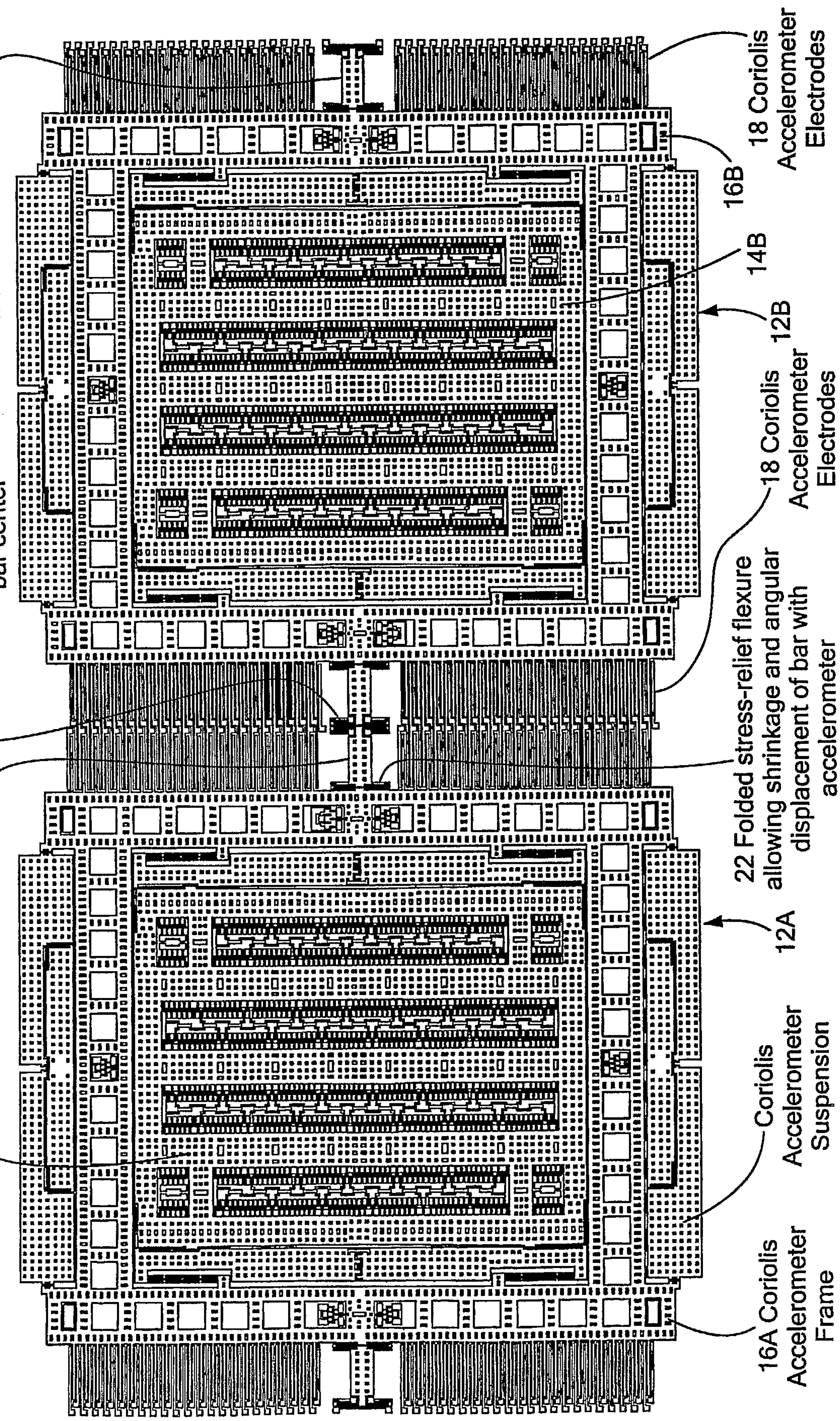
End bar to balance mass and stiffness 24
18 Coriolis Accelerometer Electrodes
16B
14B
12B
28 Folded pivot flexures anchored to define a fixed pivot point at the bar center
18 Coriolis Accelerometer Electrodes
22 Folded stress-relief flexure allowing shrinkage and angular displacement of bar with accelerometer
Coupling bar 24
12A
Driven resonator 14A
Coriolis Accelerometer Suspension
16A Coriolis Accelerometer Frame

FIG. 3

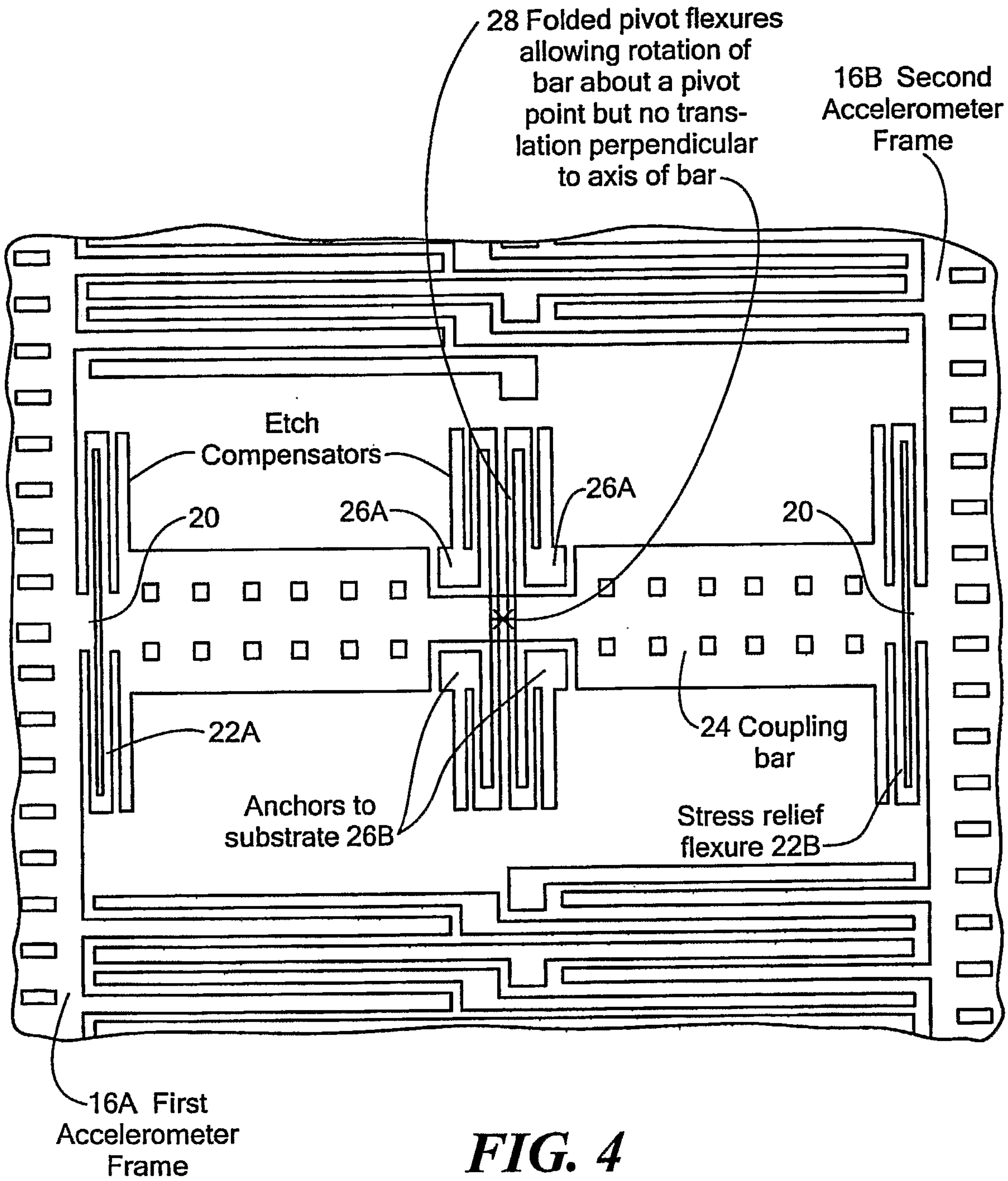
28 Folded pivot flexures allowing rotation of bar about a pivot point but no translation perpendicular to axis of bar
16B Second Accelerometer Frame
Etch Compensators
26A
26A
20
20
22A
24 Coupling bar
Anchors to substrate 26B
Stress relief flexure 22B
16A First Accelerometer Frame

FIG. 4

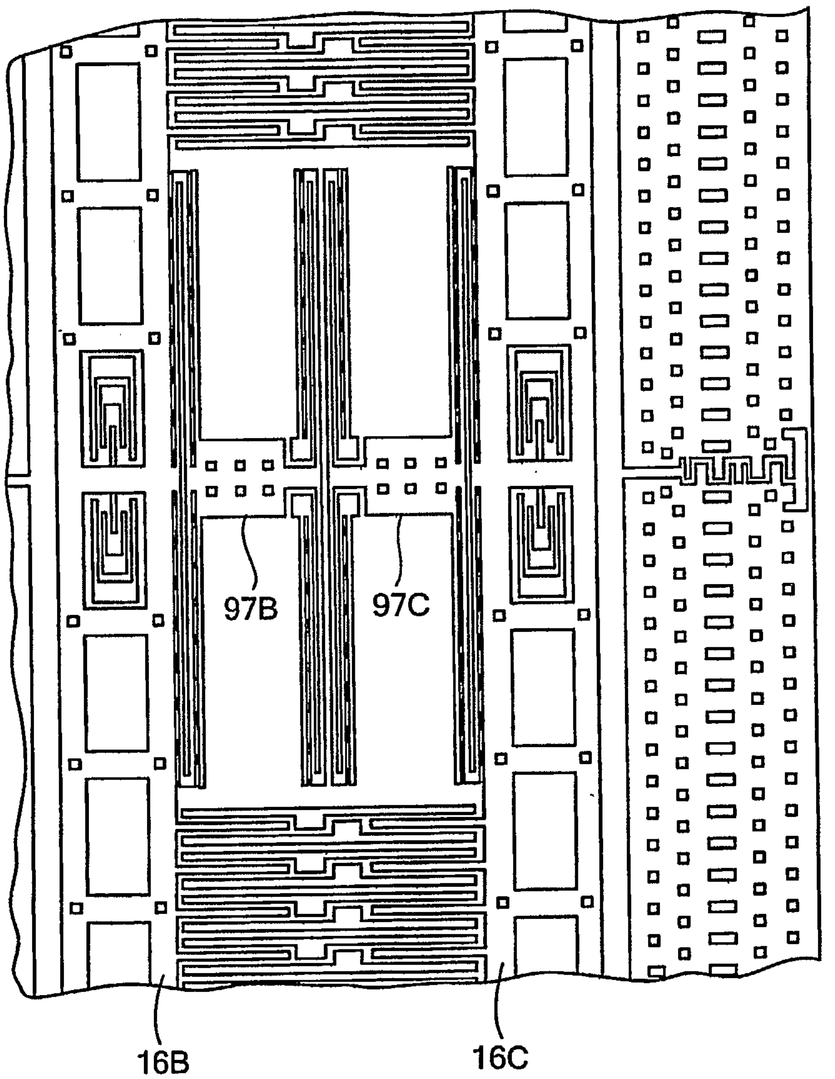

FIG. 5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/013109

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01C19/56

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)
IPC 7 G01C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 230 563 B1 (CLARK WILLIAM A ET AL) 15 May 2001 (2001-05-15) column 6, line 66 - column 7, line 17; figure 9 column 7, line 40 - line 53 claim 1	1-18
X	US 5 895 850 A (BUESTGENS ET AL) 20 April 1999 (1999-04-20) column 3, line 31 - line 43; figure 6 column 4, line 36 - line 53; claim 1	1,9,10

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"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	Date of mailing of the international search report
26 July 2005	03/08/2005

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Hunt, J

INTERNATIONAL SEARCH REPORT

ormation on patent family members

International Application No
PCT/US2005/013109

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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