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Xie

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(45) **Date of Patent: Aug. 21, 2007**

(54) **INTEGRATED MONOLITHIC TRI-AXIAL MICROMACHINED ACCELEROMETER**

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(21) Appl. No.: **11/363,293**

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Related U.S. Application Data

(63) Continuation of application No. 10/786,787, filed on Feb. 24, 2004, now abandoned.

(60) Provisional application No. 60/449,745, filed on Feb. 24, 2003.

(51) **Int. Cl.**
G01P 15/125 (2006.01)

(52) **U.S. Cl.** **73/514.32**; 73/510; 73/514.01; 73/514.16

(58) **Field of Classification Search** 73/510, 73/514.32
See application file for complete search history.

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Assistant Examiner—Samir M. Shah
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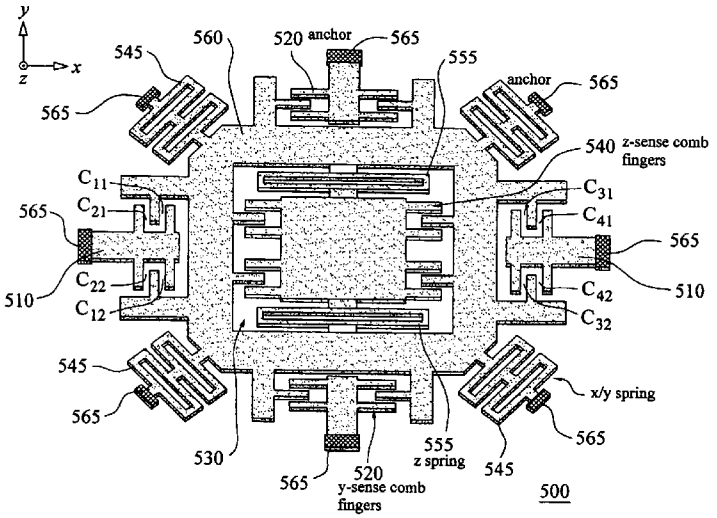
(57) **ABSTRACT**

A monolithic integrated 3-axis accelerometer chip includes a single crystal substrate, the substrate including at least one single crystal membrane layer portion. A single sensor microstructure made from the single crystal membrane senses acceleration in each of the three orthogonal directions. At least one electronic circuit can also be disposed on the chip, such as a circuit for driving, detecting, controlling and signal processing.

12 Claims, 8 Drawing Sheets



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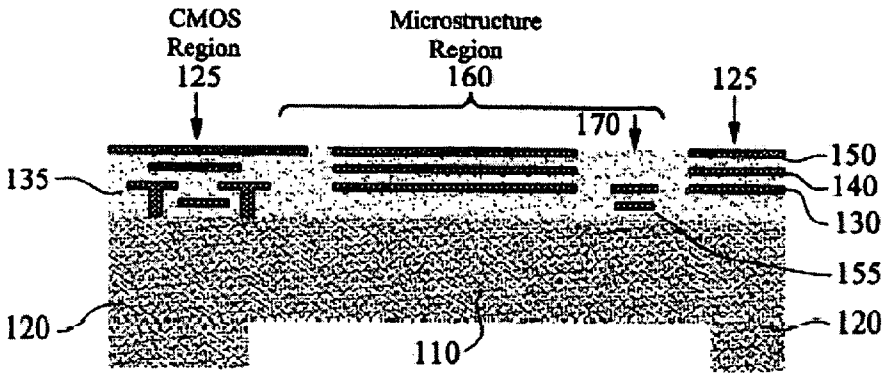

FIG. 1A

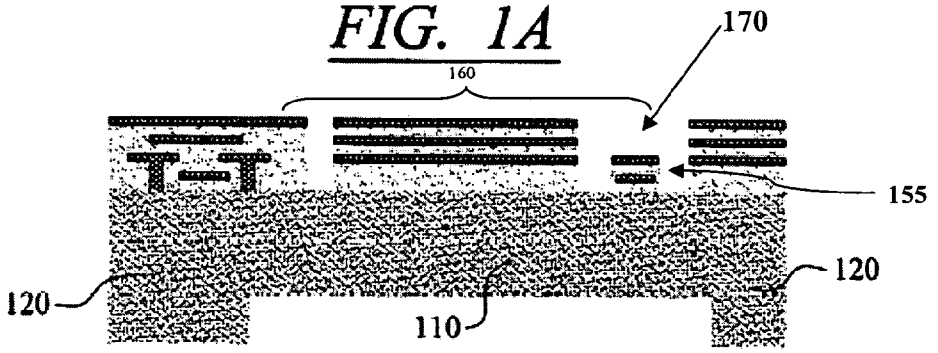

FIG. 1B

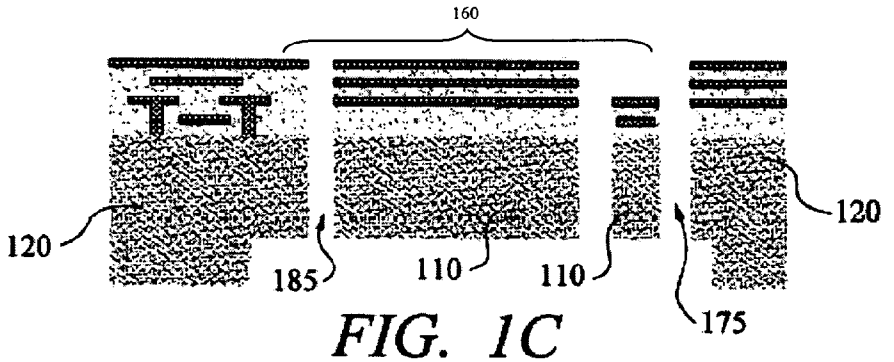

FIG. 1C

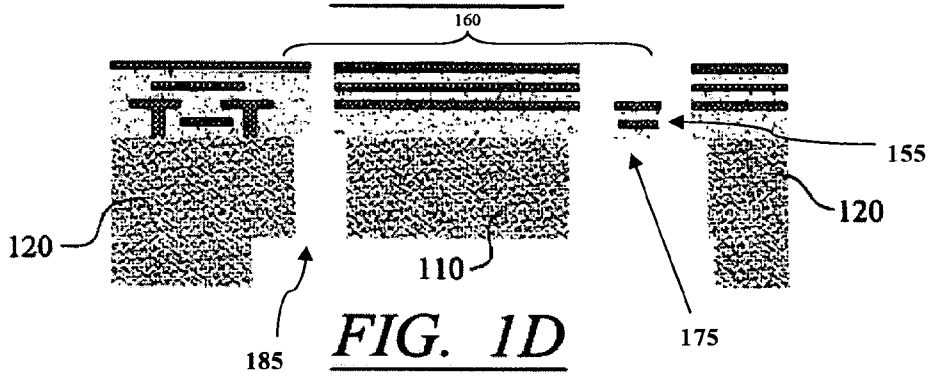

FIG. 1D

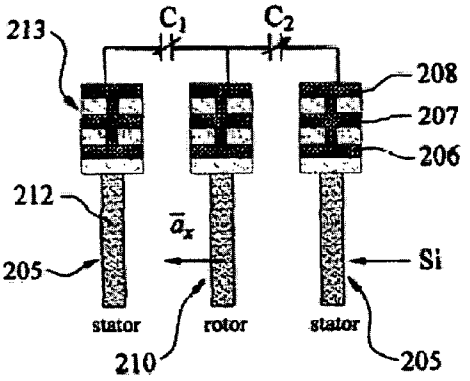

FIG. 2A

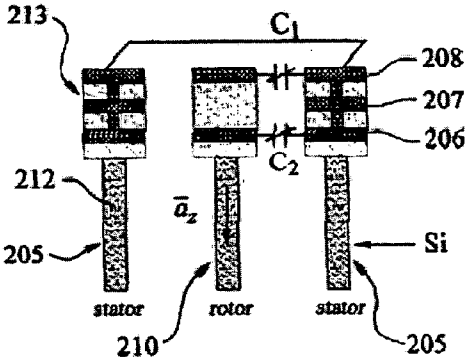

FIG. 2B

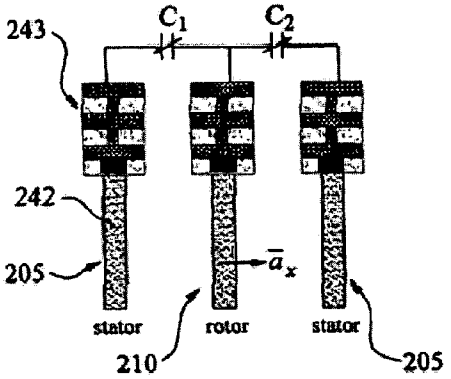

FIG. 2C

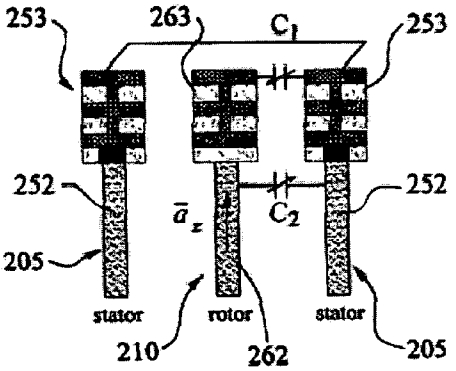

FIG. 2D

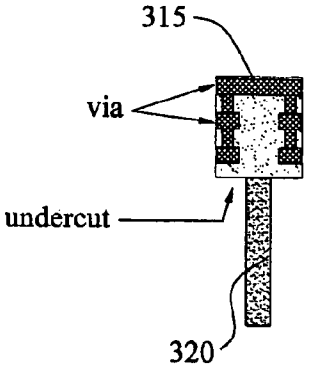

FIG. 3A

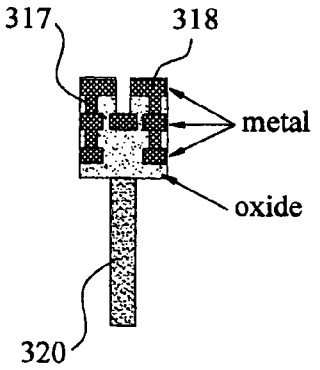

FIG. 3B

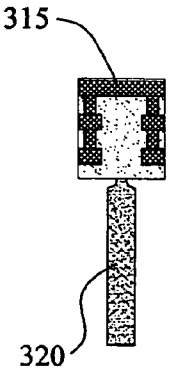

FIG. 3C

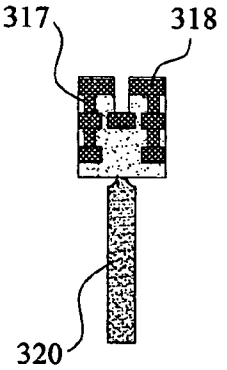

FIG. 3D

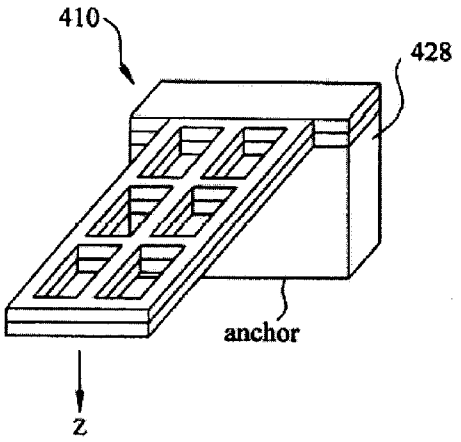

FIG. 4A

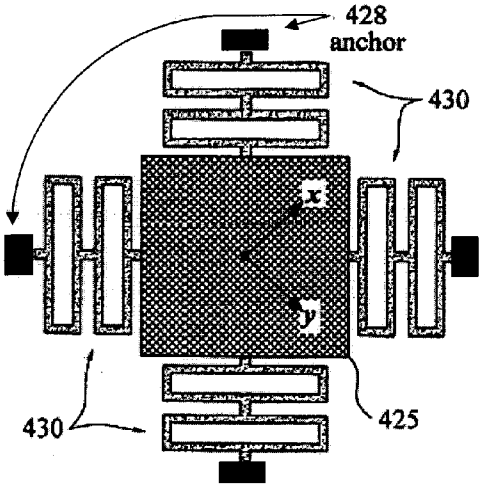

FIG. 4B

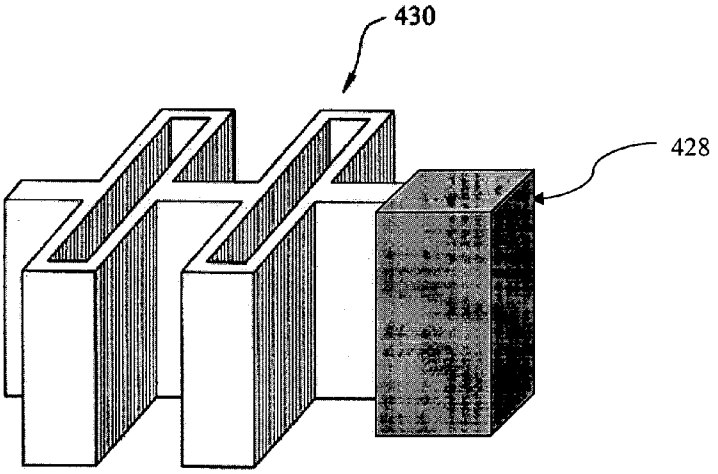

FIG. 4C

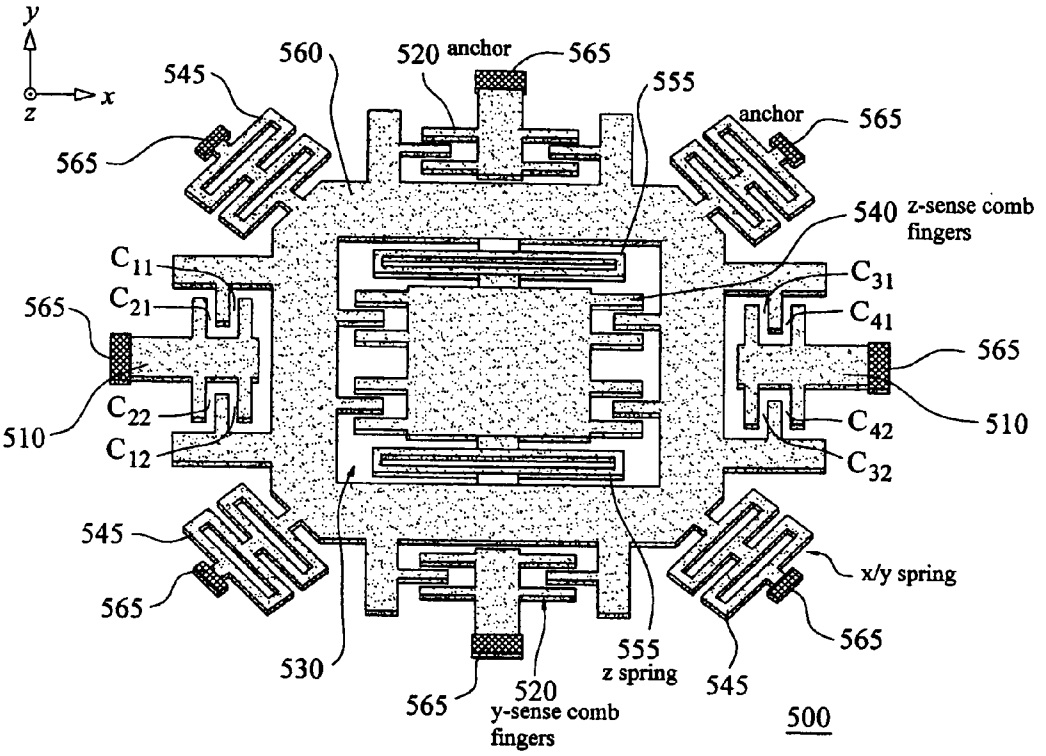
y
x
z
545
560
520 anchor
565
555
anchor
565
565
540 z-sense comb fingers
C11
C21
565
C31
C41
565
510
C22
C12
510
C42
C32
545
565
x/y spring
565
530
555 z spring
545
565
520 y-sense comb fingers
500

FIG. 5A

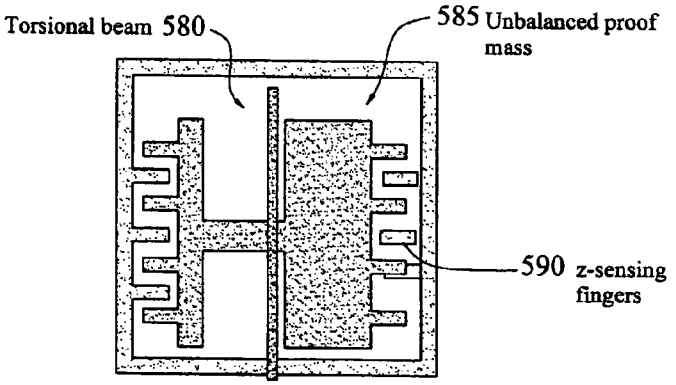
Torsional beam 580
585 Unbalanced proof mass
590 z-sensing fingers

FIG. 5B

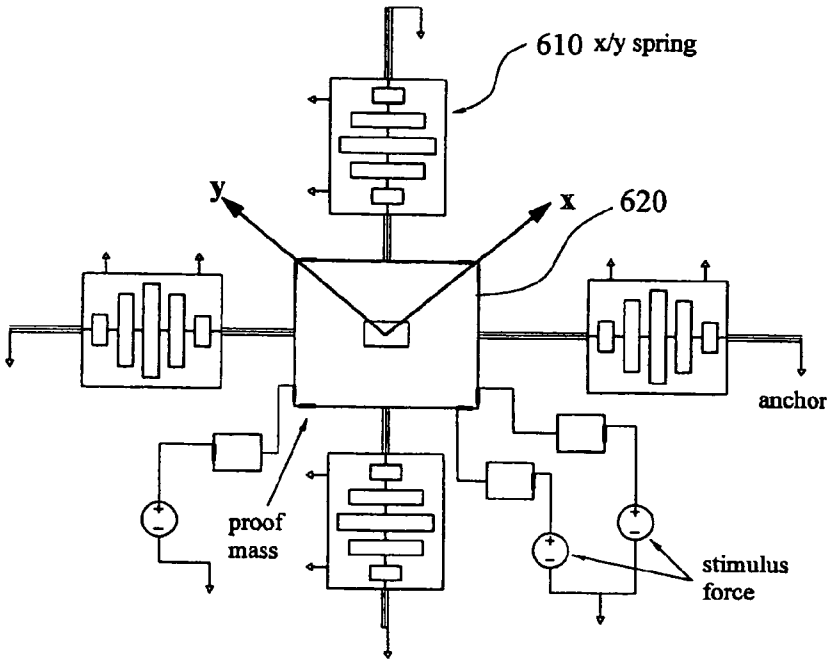
610 x/y spring
y
x
620
anchor
proof
mass
stimulus
force

FIG. 6A

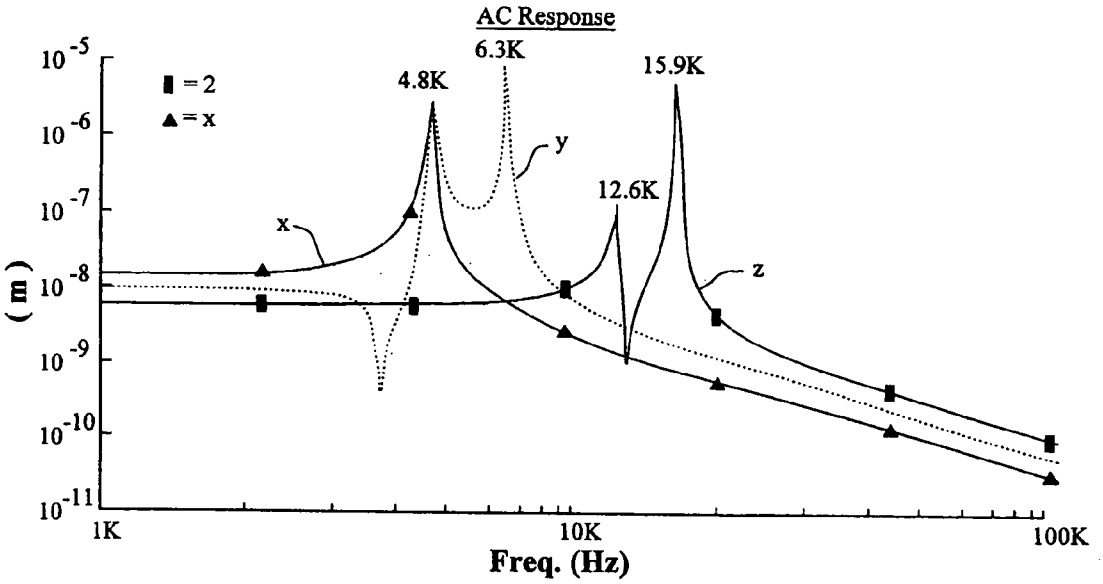
AC Response
6.3K
4.8K
15.9K
12.6K
▮ = 2
▲ = x
x
y
z
(m)
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1K
10K
100K
Freq. (Hz)

FIG. 6B

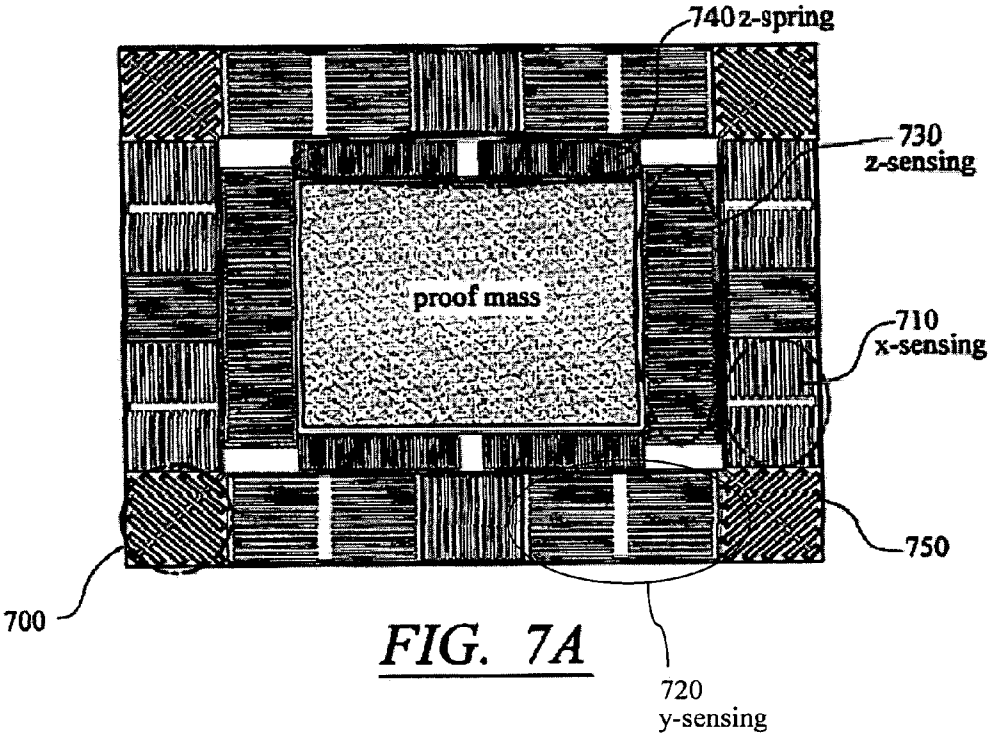

FIG. 7A

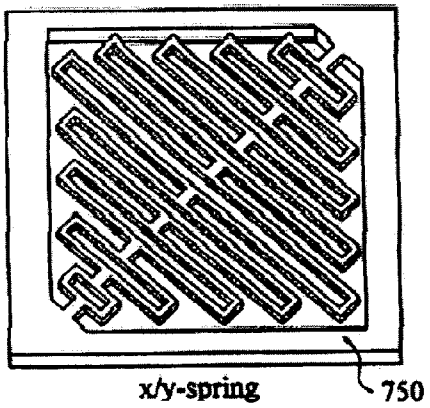

FIG. 7B

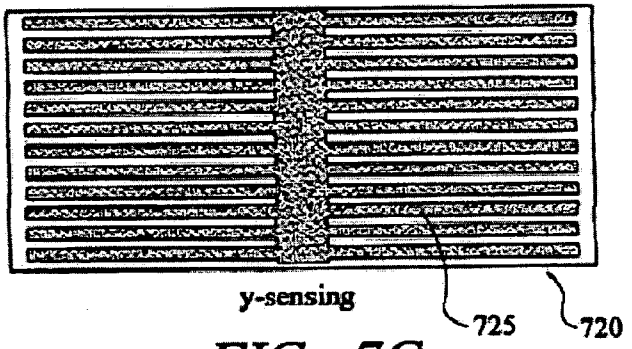

FIG. 7C

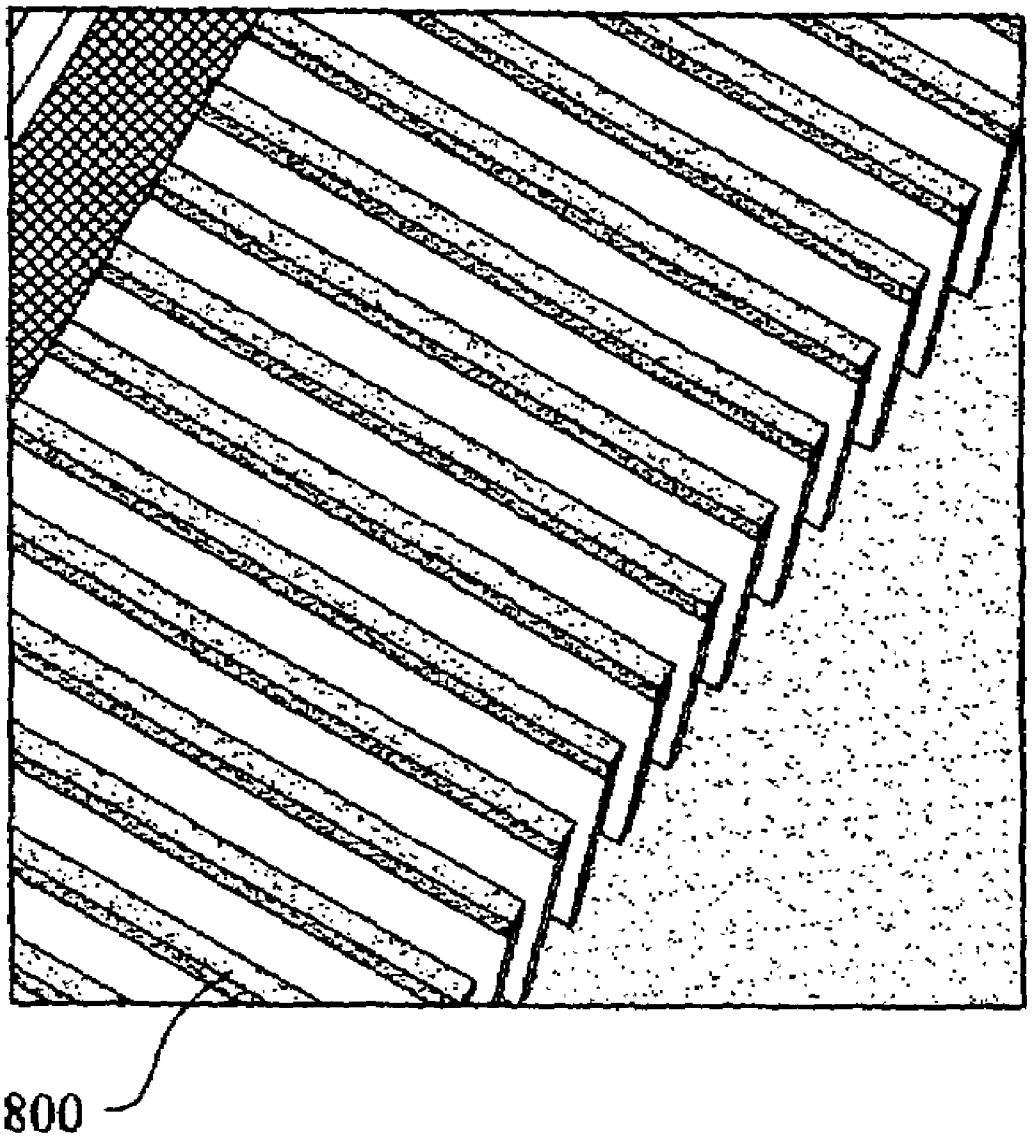

FIG. 8

INTEGRATED MONOLITHIC TRI-AXIAL MICROMACHINED ACCELEROMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 10/786,787 now abandoned entitled "INTEGRATED MONOLITHIC TRI-AXIAL MICROMACHINED ACCELEROMETER" filed on Feb. 24, 2004, which claims the benefit of U.S. Provisional Application No. 60/449,745 entitled "INTEGRATED MONOLITHIC TRI-AXIAL MICROMACHINED ACCELEROMETER" filed on Feb. 24, 2003, the entirety of which is incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The United States Government has rights in this invention pursuant to Agreements No. F30602-99-2-0545 and F30602-97-2-0323 between DARPA and Carnegie Mellon University.

FIELD OF THE INVENTION

The invention relates to sensors, and more particularly to monolithic integrated MEMS sensors.

BACKGROUND

Micromachined devices fabricated by complementary metal-oxide-semiconductor (CMOS)-compatible fabrication processes are attractive because of the ability to integrate high-performance on-chip signal conditioning circuits with sensing elements, expected multivendor accessibility and short design cycle times. Currently, most CMOS-compatible micromachining processes are polysilicon or polycrystalline silicon/germanium surface micromachining process based which use silicon dioxide as the sacrificial material and typically involve a wet etch step for releasing the micromechanical structures. Even though HF vapor can be used for release, protection of integrated circuits and sticking problems during release still remain major concerns.

Wiring on a single polysilicon microstructure is constrained to one electrode for each continuous microstructure which limits the design flexibility for electrostatic actuators and capacitive sensors. Moreover, the relatively large parasitic capacitance in polysilicon processes degrades performance of capacitive sensor designs. For example, a 50-finger comb drive with 30 μm overlap in the MUMP's polysilicon process has about 28 fF of sensing capacitance. The parasitic capacitance is 13 fF due to the fingers alone, 14 aF/μm from interconnect and 1.1 pF for a standard 78 μm by 78 μm square bond pad. Bond-wire or solder-bump connection to external electronics contributes additional parasitic capacitance.

Miniature three-axis accelerometers are often required in automobiles, navigation systems and for some medical applications, such for use with hemiplegic patients. There are two types of micromachining processes, surface micromachining and bulk micromachining. Most existing micromachined accelerometers are uni-axial or dual-axial and fabricated using surface micromachining processes.

In general, bulk micromachining creates large proof mass and is suitable for making z-axis accelerometers with capacitive parallel plates or piezoresistive beams. However, typically no CMOS circuitry is integrated on the sensor chip. Surface micromachining, on the other hand, can be compatible with CMOS processes and is suitable for fabricating lateral-axis accelerometers with capacitive interdigitated comb fingers. By assembling and orienting orthogonally two or three separate accelerometers, tri-axial acceleration sensing systems can be obtained, but both the package size and cost is high.

Some 3-axis accelerometers have been reported. Among them, bulk micromachined 3-axis accelerometers generally have large mass, but require wafer bonding, wet etching and two-side alignment. Surface micromachined tri-axial accelerometers can have integrated interface circuitry, but have small mass.

Lemkin et al. discloses a surface micromachined 3-axis accelerometer [Lemkin, et al. "A 3-Axis Force Balanced Accelerometer Using a Single Proof-Mass" Transducers '97, 1997 International Conference on Solid-State Sensors and Actuators, Chicago, Jun. 16-19, 1997, pgs. 1185-1188]. Lerikin's accelerometer uses single-crystal silicon as the substrate material, but the sensor microstructures are made of thin-film polysilicon. The x- and y-axis sensing elements disclosed by Lemkin are comb fingers, while the z-axis sensing capacitance is formed as a parallel plate pair between the proof mass and a ground polysilicon layer on the substrate. Thus, a separate fixed capacitor is used to realize a differential capacitive bridge for z-axis sensing. Significantly, the inherent large parasitic capacitance greatly reduces the obtainable signal-to-noise ratio. The residual stress of the thin-film materials also limits the size of the proof mass which limits the obtainable resolution of the Lemkin's accelerometer.

SUMMARY OF THE INVENTION

A monolithic integrated 3-axis accelerometer sensor "chip" includes a single crystal substrate, the substrate including at least one single crystal membrane layer portion. The membrane layer is thin as compared to the nominal thickness of the single crystal substrate. A single sensor microstructure based on capacitive sensing is formed using the membrane layer and senses acceleration in each of the three orthogonal directions (x, y and z). In one embodiment, all components comprising the sensor microstructure utilize the membrane layer.

As used above, the term "integrated" has a two-fold meaning. First, the 3-axis acceleration sensor is integrated on the single chip. Second, the sensor, and in a preferred embodiment electrical circuitry such as signal conditioning electronics, are also integrated on the chip. Although referred to as an acceleration sensor, the sensor is more broadly a motion sensor or a vibration sensor. The chip can also be used as a tilt sensor.

At least one interface electronic circuit is preferably provided on the chip for processing the sensor data. The sensor microstructure preferably utilizes comb finger sets, at least one comb finger set for sensing movement in one of the three orthogonal axes. The interface circuit can include a pre-amplifier, a demodulator, a low-pass filter, an A/D converter and/or a digital signal processor (DSP). The single crystal substrate can be used to provide at least one electrode. The single crystal membrane layer is preferably less than about 100 μm thick, such as 60 μm, 50 μm, or 40 μm.

The accelerometer can include a single proof mass, and the electronic circuit can be disposed on top of the proof mass. The comb finger sets for both x-sensing and y-sensing can provide fully differential capacitive bridges. The respec-

tive comb finger sets are preferably electrically isolated from one another and to other portions of chip.

The accelerometer can include a rigid frame for decoupling x-y sensing from z-sensing. In one embodiment, the structure for z-sensing can be disposed inside the rigid frame, wherein the frame together with said z-sensing structure is the effective proof mass for x-y sensing. The structure for x-y sensing can be disposed inside the frame, wherein the frame plus the x-y sensing structure is the effective proof mass for z-sensing.

The accelerometer chip can include differential z-axis capacitive sensing using sidewall capacitors formed by CMOS layers and the single crystal substrate. The single crystal substrate can comprise silicon and the electronic circuit comprises CMOS circuitry. A transceiver and integrated antenna may also be provided on chip to permit communications between the accelerometer chip and a remotely located system.

BRIEF DESCRIPTION OF THE DRAWINGS

A fuller understanding of the present invention and the features and benefits thereof will be accomplished upon review of the following detailed description together with the accompanying drawings, in which:

FIGS. **1**(A)-(C) illustrate cross sections of intermediate structures, while FIG. **1**(D) illustrates the cross section of a final monolithic integrated single crystal silicon (SCS) 3-axis accelerometer structure according to an embodiment of the invention, obtained using a DRIE CMOS-MEMS process.

FIG. **2**(A) illustrates a lateral axis comb finger sensor design, according to an embodiment of the invention.

FIG. **2**(B) illustrates a vertical axis comb finger sensor design, according to another embodiment of the invention.

FIG. **2**(C) illustrates a lateral axis comb finger sensor design, where the SCS layer is used as an active electrode, according to another embodiment of the invention.

FIG. **2**(D) illustrates a vertical axis comb finger sensor design, where the SCS layer is used as an active electrode, according to another embodiment of the invention.

FIGS. **3**(A) and (B) illustrate comb finger designs having electrodes at sidewall edges to reduce parasitic capacitance having one and two electrodes, respectively, according embodiments of the invention.

FIG. **3**(C) illustrates the single electrode sidewall comb finger design of FIG. **3**(A) modified to include an initial undercut of the membrane layer to further reduce parasitic capacitance, according to an embodiment of the invention.

FIG. **3**(D) illustrates the two electrode sidewall comb finger designs of FIG. **3**(B) modified to include an initial undercut of the membrane layer to further reduce parasitic capacitance, according to an embodiment of the invention.

FIG. **4**(A) illustrates a z-axis spring design, according to another embodiment of the invention.

FIG. **4**(B) illustrates a top view of x-y springs including a central plate, according to an embodiment of the invention.

FIG. **4**(C) illustrates a side view of a branch of the x-y spring shown in FIG. **4**(B).

FIG. **5**(A) illustrates the topology of an exemplary integrated 3-axis accelerometer, according to another embodiment of the invention.

FIG. **5**(B) illustrates the topology of another design for the central z-axis accelerometer, where the z-axis accelerometer includes a SCS torsional beam and a unbalanced proof mass.

FIG. **6**(A) illustrates a NODAS model for an x-y accelerometer according to an embodiment of the invention where the plate represents the proof of mass.

FIG. **6**(B) illustrates a NODAS simulation derived AC response for a three axis accelerometer according to an embodiment of the invention.

FIG. **7**(A) is a micrograph of a released three axis accelerometer; FIG. **7**(B) is a micrograph of an x-y spring from the accelerometer, while FIG. **7**(C) is a micrograph of y sensing comb fingers from the accelerometer, all according to embodiments of the invention.

FIG. **8** is a SEM showing a plurality of comb fingers according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A monolithic integrated 3-axis accelerometer "chip" includes a single crystal substrate, the substrate including at least one single crystal membrane layer portion. The sensor microstructure uses capacitive sensing to sense acceleration in each of the three orthogonal directions and is formed using the single crystal membrane layer. At least one electronic circuit is preferably also formed on the chip. The single crystal substrate is preferably silicon based, but can be any single crystal substrate material which is compatible with integrated circuit processing, such as Si/Ge or GaAs. When single crystal silicon substrates are described, such substrates, or portions thereof, are referred to herein as single crystal silicon (SCS).

The electronic circuits provided on the chip can include a pre-amplifier, demodulator, low-pass filter, A/D converter and DSP. A transceiver and integrated on-chip antenna can also be integrated for applications requiring communications between a plurality of the system according to the invention or between a system according to the invention and a remotely located system. Thus, the invention can integrate a SCS based sensor microstructure with CMOS electronics on a single chip. Previous work has integrated electronics with sensor microstructures made of polysilicon or other polycrystalline thin-film materials.

The single-crystal based microstructures comprising the sensor system are preferably all made using the SCS membrane layer, except for one disclosed embodiment of z-axis sensing which includes z-axis compliant springs. Accordingly, the proof mass is made of SCS and can be advantageously much larger than polysilicon-based microstructures, such as Lemkin's. Inherent residual stresses in thin-film polysilicon processes limit the area and thickness of polysilicon proof mass to avoid device degradation or failure resulting from curling or buckling of the proof mass. Therefore, the larger proof mass provided by the invention generates a correspondingly larger inertia which results in much higher sensitivity and enables higher resolution. In addition, use of SCS based microstructures provides improved robustness and temperature performance over otherwise analogous polysilicon microstructures.

In a preferred 3-axis accelerometer embodiment, separate comb finger sets are provided for x, y and z-axis acceleration sensing. The invention also discloses a new and improved comb finger design for acceleration sensing. In a preferred embodiment, the comb fingers have a metal/dielectric composite thin film layer ("CMOS layer") on top and single-crystal silicon (SCS) membrane layer. The SCS layer preferably has a cut adjacent to the joint (or anchor) of the comb fingers, resulting in the SCS layer underlying each comb finger being electrically isolated from the rest of the SCS,

and as a result, the comb fingers from one another. In one embodiment, the SCS layer is used as active electrodes.

Since the SCS membrane layer (e.g. 60 μm thick) is much thicker than CMOS layer disposed thereon (<5 μm), the resultant combs have much larger sensing capacitance. In addition, the parasitic capacitance of the microstructure is very small because there is no silicon substrate under the SCS membrane-based structures. Therefore, the signal-to-noise ratio is substantially improved.

The interface and sensor signal conditioning circuitry can be disposed on top of the proof mass. Placing the interface and signal conditioning circuitry on the proof mass can significantly reduce the chip size, which can reduce the cost of the monolithic sensor. The device can be fabricated by a post-CMOS micromachining process that utilizes only dry-etching and no extra masks, material deposition or wafer bonding. A noise floor of 1 $\mu g/Hz^{1/2}$ can be generally provided with a 2 mm by 2 mm device. A even lower noise floor is also achievable with a larger proof mass size and low-noise interface circuits.

The monolithic single-crystal based sensor can be formed using a deep reactive-ion-etch (DRIE) CMOS-MEMS process which can be implemented following standard CMOS processing during which interface and signal conditioning circuitry are also formed on-chip. The DRIE process is described in a paper by Xie et al., entitled "Post-CMOS Processing for High Aspect-Ratio Integrated Silicon Microstructures", Journal of Microelectromechanical Systems, Vol. 11, No. 2, April 2002 and U.S. Pat. No. 6,458,615 to Fedder et al. entitled "Method of Fabricating Micromachined Structures and Devices Formed Therefrom", both of which are hereby incorporated by reference in their entirety into this application. However, the invention is in no way limited to being formed using the DRIE CMOS-MEMS process.

An exemplary process flow, together with intermediate structures and a resulting exemplary accelerometer device according to the invention using the DRIE CMOS-MEMS process are shown in FIGS. **1**(A)-(C), and FIG. **1**(D), respectively. The CMOS wafer is etched from its back side, leaving a 10 to 100 μm-thick single-crystalline silicon (SCS) membrane layer **110** as shown in FIG. **1**(A) in the region labeled as the microstructure region **160**. Microstructure region **160** is where the sensors comprising the sensor microstructure will be formed. The Si thickness in the region labeled CMOS region **120** having one or more CMOS devices **125**, such as signal conditioning electronics, remains that of the wafer starting material, typically at least about 500 μm. Three layers of metal are shown in FIG. **1**(A), **150**, **140** and **130**, separated from each other and other conductive regions by an electrically insulating layer, such as silicon dioxide **135**.

The CMOS region **125** can include interface circuitry such as pre-amplifiers, demodulators, low-pass filters, A/D converters and a DSP, which are communicably connected (e.g. metal traces) to the sensors provided in the microstructure region **180**. In a preferred embodiment, the CMOS region **125** also includes a transceiver and integrated on-chip antenna to permit wireless transmission of sensor data from the accelerometer to one or more remote sites.

An optional polysilicon based region **170** is shown included within microstructure region **160**. Region **170** includes metal layer **130** and polysilicon layer **155**. The polysilicon layer **155** is typically only about 0.2 μm thick, thinner than typical oxide layers and (1 μm) and typical metal layers (0.8 μm).

Next, an anisotropic dielectric etch is performed from the front side using the top metal layers in the regions **125** and **160** as etch masks and results in the structure shown in FIG. **1**(B). Then, in contrast to other processes, an anisotropic instead of an isotropic silicon etch, is used to etch portions of the SCS membrane **110** and release microstructures **155** and **170** to produce the structure shown in FIG. **1**(C). A thick, stiff, single crystal layer **110** remains underneath the whole microstructure, resulting in a relatively flat released microstructure, especially when compared with multilayer thin-film CMOS-MEMS structures.

As used herein, the term "release" or the term "free" as applied to a microstructure refers to a microstructure portion which can move in one, two or even three directions. The release as described above is achieved by first forming a microstructure on top of a sacrificial layer, such as a silicon layer. After the sacrificial layer is removed, the microstructure is free to move. Although not shown, the microstructure is anchored to the substrate at one or more anchor points.

An optional isotropic timed Si etch step can be used to undercut the silicon comprising structures in region **160** to create z-compliant structures. As shown in FIG. **1**(D), structure **175** which includes polysilicon layer **155** has the Si totally undercut (removed). The silicon undercut is small (<1 μm) so that the silicon in the CMOS region **120** will remain, as will SCS membrane **110** beneath microstructures **185** as shown in FIG. **1**(D). This step provides both z-compliant structures and also achieves electrical isolation of the SCS membrane **110** between the respective sensing components comprising the microstructure.

Various comb designs according to the invention can be used to realize at least three comb sets on the same chip to provide capacitance-based acceleration sensing in the two lateral axes (x,y) as well as the vertical (z-axis), thus providing integrated full three axis sensing. The principle of lateral-axis and z-axis capacitive comb finger sensing is first illustrated in the cross sectional views shown in FIGS. **2**(A) and **2**(B), respectively. The SCS layer can be only a mechanical support layer as shown in FIGS. **2**(A) and **2**(B), or both a support and active electrode layer as shown in FIGS. **2**(C) and **2**(D).

SCS Layer as Mechanical Support Only

In this embodiment, the SCS membrane layer **212** comprising each finger is electrically isolated from the metal/dielectric stack **213** disposed on top of membrane layer **212**. If the respective metal layers **206**, **207** and **208** on stators **205** and rotor **210** are electrically connected, respectively, as shown in FIG. **2**(A), the CMOS comb drive functions analogously to a conventional lateral-axis polysilicon comb drive. If all three metal layers **206**-**208** on the stators are electrically connected while the metal layers **206** and **208** on rotor **210** are separately connected as shown in FIG. **2**(B), two sidewall capacitors, C_1 and C_2, will change values in opposite directions upon vertical (z-axis) movement of rotor **210**. Because of the high wiring flexibility, a fully differential capacitive bridge can be easily formed. All the comb fingers shown in FIGS. **2**(A) and (B) have a "T" shape cross-section due to the single crystal silicon undercut shown and described relative to FIG. **1**(D)).

SCS Membrane Layer as Active Electrodes (FIGS. **2**(C) and (D))

In this embodiment, the SCS membrane layer **242** comprising each finger can be electrically connected to the top metal/dielectric stack **243**, as shown in FIG. **2**(C) for lateral-axis acceleration sensing. This is similar to the cases shown in FIGS. **2**(A) and (B) where the SCS membrane layer **212**

only provides mechanical support. For z-axis acceleration sensing, the SCS membrane layer **252** on the stator fingers are shown electrically connected to the respective top metal/dielectric stack **253**, while the SCS layer on the rotor finger **262** is shown electrically isolated from the top metal/dielectric stack **263**. Similar to FIG. **2**(B), a differential capacitor pair comprising capacitors C_1 and C_2 is provided by the designs shown in FIGS. **2**(C) and (D).

FIGS. **3**(A) and **3**(B) show cross-sectional views of comb fingers with single electrodes **315** and two separate electrodes **317** and **318**, respectively, placed at the sidewall edges to reduce the parasitic capacitance overlap to the SCS beams **320**. The parasitics can be further reduced by narrowing the SCS beams **320**. The width of the SCS beams **320** is controlled by the silicon undercut step described relative to FIG. **1**(D). The SCS beams **320** should not be made too narrow (~2 μm), as the mechanical robustness may become compromised. An initial silicon undercut can be used to further reduce the overlap parasitic capacitance, as shown in the single electrode embodiment shown in FIG. **3**(C) and the two electrode embodiment shown in FIG. **3**(D). This initial silicon undercut should be performed between the steps shown in FIG. **1**(B) and FIG. **1**(C).

As with conventional accelerometers, movement of comb fingers is controlled by springs. A z-axis compliant spring **410** is shown in FIG. **4**(A), which can be realized by connecting multiple beams with short trusses and using beams with metal-**2** or metal-**3** on the top. Beams with metal-**1** on the top are even more compliant in the z-direction, but they have large out-of-plane curling. Narrow beams are used in the spring to guarantee the complete undercut of silicon to form a z-compliant thin-film structure. The multiple beams with short trusses can increase the stiffness in the lateral direction to reduce cross-axis sensitivity.

The x/y-axis spring can be obtained by symmetrically arranging four sub-springs **430** around a central plate **425** as shown in FIG. **4**(B). Springs are secured using anchor **428**. Each sub-spring shown consists of rectangularly closed beams in series which are flexible in both the x and y directions and anchored at a single point. The advantage of this x/y-axis spring design is that the spring constants in the x and y directions are equal. FIG. **4**(C) shows a side view of one x/y spring branch **430**. The torsional spring for the z-axis accelerometer shown in FIG. **5**(B) and described below is constructed using a long SCS beam with a rectangular cross section.

The topology of an exemplary 3-axis accelerometer according to an embodiment of the invention **500** is show in FIG. **5**(A). The comb fingers for x-axis sensing **510** form eight capacitors, i.e., four $C_i=C_{i1}+C_{i2}$, where i=1,2. Because of the symmetry, the C_i's are insensitive to y-axis acceleration to first order as C_1 and C_2 form a differential capacitive divider, and so do C_3 and C_4. Thus, a full differential capacitive bridge is obtained using the four C_1's. Since there is a SCS membrane (not shown) underneath spring beams for x-y springs **545**, the springs are much stiffer (about two orders of magnitude) in the z-direction than in the x- or y-direction, which significantly reduces the z-axis cross-sensitivity. The same rationale applies to the y-axis acceleration sensing provided by y-axis sensing comb fingers **520**. Springs **545** are secured by anchors **565**.

The z-axis acceleration sensing on the 3-axis accelerometer shown in FIG. **5**(A) is obtained by embedding a z-axis accelerometer **530** in the center of the structure including z-sense comb fingers **540**. As shown in FIG. **5**(A), the z-axis accelerometer **530** is disposed inside rigid frame **560**. Frame **560** together with the z-sensing structure provided by accelerometer **530** is an effective proof mass for x-y sensing. Although not shown in FIG. **5**(A), those having ordinary skill in the art will appreciate that the structure for x-y sensing can be disposed inside the frame. In this arrangement, the frame plus the x-y sensing structure is an effective proof mass for z-sensing.

The suspension of the z-axis accelerometer **530** is preferably in the form of the flexure shown in FIG. **4**(A), which is flexible in the z-direction. Again, the cross-axis acceleration contributions are rejected by the differential capacitive topology. It should be noted that the differential capacitors in the z-axis accelerometer **530** are preferably stacked vertically (as shown in FIG. **2**(B)) and separated into groups.

FIG. **5**(B) illustrates an alternate embodiment for the central z-axis accelerometer. This z-axis accelerometer design includes a SCS torsional beam (spring) **580**, an unbalanced proof mass **585**, and z-sense comb fingers **590**. In this arrangement, z-axis acceleration will generate a torque to tilt the unbalanced proof mass **585**. This tilt is proportional to the z-axis acceleration and can be detected by the same z-axis sensing comb fingers shown in FIG. **2**(B). This z-axis accelerometer can directly replace the z-axis accelerometer **530** shown in FIG. **5**(A) without changing anything else. The advantage of this embodiment is that the entire 3-axis accelerometer structure utilizes the SCS membrane, which results in more robust and superior temperature performance. One drawback is the non-linearity of the sensing capacitance versus the tilt. This nonlinearity may be overcome by employing closed-loop controlled force balancing.

EXEMPLARY APPLICATIONS FOR THE INVENTION:

As noted above, prior to the invention, three separate conventional single-axis accelerometers were generally required to monitor movement since acceleration is a vector quantity. Although single-axis accelerometers are typically small, assembling three single-axis accelerometers significantly increases the package size and cost. Therefore, integrated 3-axis accelerometers disclosed herein are much better suited for many accelerometer-related applications, particularly for such applications requiring small size, low power, low cost and high resolution.

In some applications, single-point acceleration detection may be not sufficient. For instance, if a given application requires simultaneous knowledge of the movement of head, arms, and legs of an individual, small size is even more crucial. The compact size and low cost of the monolithic 3-axis accelerometer thus makes systems according to the invention attractive to a wide variety of applications.

In one application, the impact on a football player's head can be real-time monitored by placing monolithic 3-axis accelerometers in the helmet. In a preferred embodiment as noted above, the monolithic 3-axis accelerometer-based system includes a wireless transmitter and on-chip signal processing, such as on the same monolithic chip, for transmitting the acceleration data to one or more remotely located monitoring stations. Thus, a football player can be warned of possible head injuries when measured accelerations are sensed as being above a certain predetermined threshold value. The data obtained can also help coaches in training and help helmet manufacturers to make better helmets to avoid head injuries. Although three (3) conventional accelerometers can generally be used for this particular application, as noted above assembling the three (3) single-axis accelerometers drastically increases the cost and size.

Although the overall size of three (3) conventional accelerometers may be suitable for a football player's helmet, it may be too large for other applications such as activity monitoring for babies and the elderly. Wireless monolithic 3-axis accelerometer-based systems according to the invention are adapted to be worn because of their small size, low power and wireless communication capability. The recorded movement data can be transmitted to a remotely located sight, such as a base station or directly to a doctor's office through a wireless network. Applications for wireless monolithic 3-axis accelerometer-based systems according to the invention include the following:

1. Motion monitoring for rehabilitation of patients.
2. Physical activity monitoring for athletes, babies and elderly.
3. Motion monitoring for identifying the pain sources of injured large animals.

In the above exemplary applications, the sensors must be wearable. Accordingly, the sensors must be small, low power and wireless. As noted above, each of these required features are provided by sensors according to the invention.

The same concept can be applied to civilian infrastructure monitoring and protection. Vibration monitoring for civilian infrastructures, such as bridges and buildings, can detect potential mechanical failures. Wireless sensor networks can be placed in skyscrapers. When extreme events such as earthquake, hurricane or terror attack occur, the sensor network can provide damage information at different locations of a skyscraper which can guide people inside the building to escape and help locate and rescue trapped survivors. The wireless sensors can also be disposed in a battlefield or a forest to monitor an enemy's activities. Oil exploration is another potential application, where oil sources can be identified by measuring the impact wave propagation in a field. In this application, a vibration wireless sensor network with high sensitivity and low power is a very effective and inexpensive solution.

Consumer electronics and automotives are also applications for the invention. For example, the vibration control of CD holders, airbags for collision protection and image stabilization are also demanding small-size, low-power and low-cost vibration sensors.

Three-axis accelerometers can be combined with gyroscopes can be used for navigation control for space and military applications. The portable navigation units are extremely useful for soldiers in a battlefield to accurately position themselves even when the GPS signal is jammed or not available.

EXAMPLES

The present invention is further illustrated by the following Examples. The examples are provided for illustration only and are not to be construed as limiting the scope or content of the invention in any way.

Example **1**

Structural Simulation

A structural simulation of a monolithic integrated three axis accelerometer according to an embodiment of the invention was performed using Nodal Design of Actuators and Sensors (NODAS) software. NODAS is a hierarchical cell library for behavioral modeling and nodal simulation of MEMS, was used [Q. Jing and G. K. Fedder, "A hierarchical circuit-level design methodology for microelectromechanical systems," IEEE Transactions on Circuits and Systems II, Vol. 46 (1999), pp. 1309-1315]. NODAS consists of symbols and models of elements commonly found in suspended MEMS designs, such as anchors, beams, plates and gaps. As shown in FIGS. **2**(A) and **2**(B), the cross-section of the DRIE beams is not rectangular. A DRIE beam has a wider CMOS layer on top of the silicon layer. This irregular cross section has been considered and adopted in the DRIE beam model in the NODAS library.

FIG. **6**(A) shows the NODAS model for an x-y accelerometer which includes x/y springs **610** and proof mass **620**. A plate represents the proof mass **620**. Each x-y spring **610** consists of a group of beams. Note that the model shown in FIG. **6** was rotated 45 degrees compared to structure shown in FIG. **5**(A).

The simulation results obtained are plotted in FIG. **6**(B). Table 1 below lists the design parameters for the 3-axis accelerometer simulated. The symmetry of the x/y springs **610** gives the same first resonance (4.8 kHz) for both x- and y-axes. A torsional force was also applied with respect to the y-axis which gives a 6.3 kHz torsional mode. The z-stiffness in the x/y springs is much larger because of the thick silicon layer. A 15.9 kHz resonance along the z-axis was obtained from the simulation. A similar NODAS model was used for an embedded z-axis accelerometer, in which the z-axis resonance was found to be at 4.2 kHz.

TABLE 1

Design parameters for the exemplary 3-axis accelerometer

	X	Y	Z
Proof mass (μg)	73	73	40
Resonance (kHz)	4.8	4.8	4.2

Example **2**

Fabrication Results

A released exemplary monolithic integrated three axis accelerometer **700** according to an embodiment of the invention is shown in FIG. **7**(A) comprising x-sensing accelerometer **710**, y-axis accelerometer **720** and z-axis accelerometer **730**, all disposed on the same chip. The x-axis accelerometer **710** y-axis accelerometer **720** are identical and orthogonally oriented, while the z-accelerometer **730** is embedded in the center of accelerometer **700**. The entire microstructure shown is about 1 mm by 1 mm in size. The SCS membrane layer was about 60 μm thick. Silicon underneath the z-spring beams **740** was completely undercut to maximize the z-compliance. Silicon underneath the x/y-spring beams **750** was just partially undercut to maintain the flatness of the whole structure. The silicon undercut on the comb fingers with small gaps was significantly reduced because of the known microloading effect.

FIG. **7**(B) shows a micrograph of an x/y spring **750**, while FIG. **7**(C) shows a micrograph of y-axis accelerometer **720** and its associated y-sensing comb fingers **725**. A SEM showing exemplary comb fingers **800** with one side stripped off is shown in FIG. **8**.

It is to be understood that while the invention has been described in conjunction with the preferred specific embodiments thereof, that the foregoing description as well as the examples which follow are intended to illustrate and not limit the scope of the invention. Other aspects, advantages

and modifications within the scope of the invention will be apparent to those skilled in the art to which the invention pertains.

I claim:

1. A monolithic integrated 3-axis accelerometer chip, comprising:

a single crystal substrate, said single crystal substrate including at least one single crystal membrane layer portion;

a single microstructure formed using said membrane layer, said single microstructure capacitively sensing and providing acceleration data for all three orthogonal axes, wherein said single microstructure comprises a plurality of comb finger sets including at least one comb finger set for motion sensing in each of said three orthogonal axes, said comb finger sets comprising a plurality of comb fingers, said comb finger sets for each of said three orthogonal axes include said membrane layer, and

at least one electronic circuit formed on said single crystal substrate for processing said acceleration data.

2. The accelerometer of claim **1**, wherein said single crystal substrate is preferably single crystal silicon, and said electronic circuit is preferably a CMOS circuit.

3. The accelerometer of claim **1**, wherein said electronic circuit comprises at least one selected from the group consisting of a pre-amplifier, a demodulator, a low-pass filter, an A/D converter and a DSP.

4. The accelerometer of claim **1**, wherein said accelerometer includes a proof mass and at least one flexure, at least a portion of said comb fingers being disposed on said proof mass, said flexure mechanically connecting said proof mass and said membrane layer.

5. The accelerometer of claim **1**, wherein said plurality of comb finger sets comprise a metal/dielectric composite thin film layer stack disposed on said membrane layer.

6. The accelerometer of claim **5**, wherein said metal in said metal/dielectric stack is electrically isolated from said membrane layer.

7. The accelerometer of claim **5**, wherein said metal in said metal/dielectric stack is electrically connected to said membrane layer, said membrane layer comprising at least one electrode of said structure for differential capacitive sensing.

8. The accelerometer of claim **5**, wherein said metal in said metal/dielectric stack is disposed in sidewalls of said metal/dielectric stack.

9. The accelerometer of claim **5**, wherein a cross sectional area of said membrane layer is less than a cross sectional area of said metal/dielectric stack.

10. The accelerometer of claim **9**, wherein said cross sectional area of said membrane layer is less than a cross sectional area of said metal/dielectric stack for said comb fingers including comb fingers which provide z-axis sensing.

11. The accelerometer of claim **1**, wherein said accelerometer includes a rigid frame disposed between structure for x-y sensing and structure for z-sensing.

12. The accelerometer of claim **11**, wherein said structure for z-sensing is disposed inside said rigid frame, wherein said structure for z-sensing includes a proof mass disposed inside said rigid frame by at least one element for decoupling z-sensing from x-y sensing, wherein said frame plus said z-sensing structure is an effective proof mass for said structure for x-y sensing.

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