EXHIBIT E

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Durante et al.

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(54) **INTEGRATED GYROSCOPE OF SEMICONDUCTOR MATERIAL WITH AT LEAST ONE SENSITIVE AXIS IN THE SENSOR PLANE**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 10/128,133, filed on Apr. 23, 2002, now Pat. No. 6,766,689.

(30) **Foreign Application Priority Data**

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May 21, 2002 (EP) 02425320

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(52) **U.S. Cl.** **73/504.04**; 73/514.32

(58) **Field of Search** 73/504.12, 504.16, 73/514.02, 514.32, 514.16, 504.02, 504.14

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,275,047 A		1/1994	Zabler et al.	73/505
5,604,312 A		2/1997	Lutz	73/504.14
5,635,638 A	*	6/1997	Geen	73/504.04
5,747,690 A		5/1998	Park et al.	73/504.12
5,780,739 A	*	7/1998	Kang et al.	73/504.16
5,792,954 A		8/1998	Corkum et al.	73/514.32
5,945,599 A		8/1999	Fujiyoshi et al.	73/504.12
5,955,668 A		9/1999	Hsu et al.	73/504.12
6,089,089 A		7/2000	Hsu	73/504.12
6,327,907 B1		12/2001	Park	73/504.12
6,349,597 B1		2/2002	Folkmer et al.	73/504
6,474,160 B1		11/2002	Stewart et al.	73/504.04
6,513,380 B2	*	2/2003	Reeds et al.	73/504.04
2002/0134154 A1		9/2002	Hsu et al.	73/504.04

FOREIGN PATENT DOCUMENTS

EP	0 911 606 A1	4/1999
EP	1 098 170 A2	1/2001
WO	WO 97/15066	4/1997
WO	WO 99/19734	4/1999
WO	WO 00/29855	5/2000

* cited by examiner

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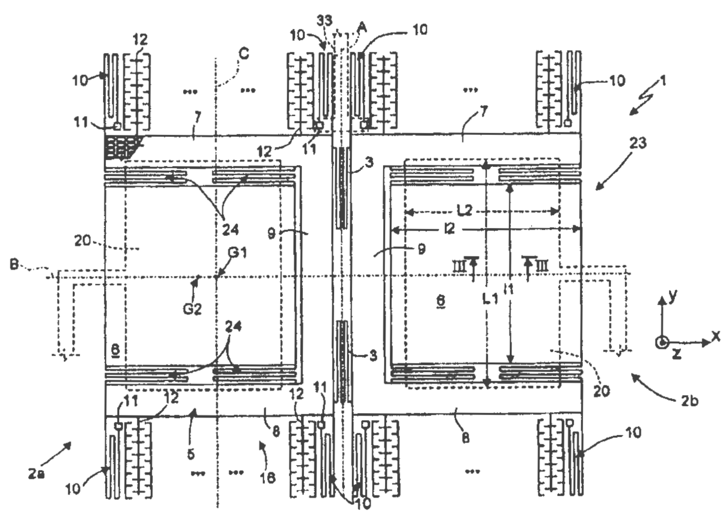
(57) **ABSTRACT**

An integrated gyroscope, including an acceleration sensor formed by: a driving assembly; a sensitive mass extending in at least one first and second directions and being moved by the driving assembly in the first direction; and by a capacitive sensing electrode, facing the sensitive mass. The acceleration sensor has an rotation axis parallel to the second direction, and the sensitive mass is sensitive to forces acting in a third direction perpendicular to the other directions. The capacitive sensing electrode is formed by a conductive material region extending underneath the sensitive mass and spaced therefrom by an air gap.

27 Claims, 6 Drawing Sheets



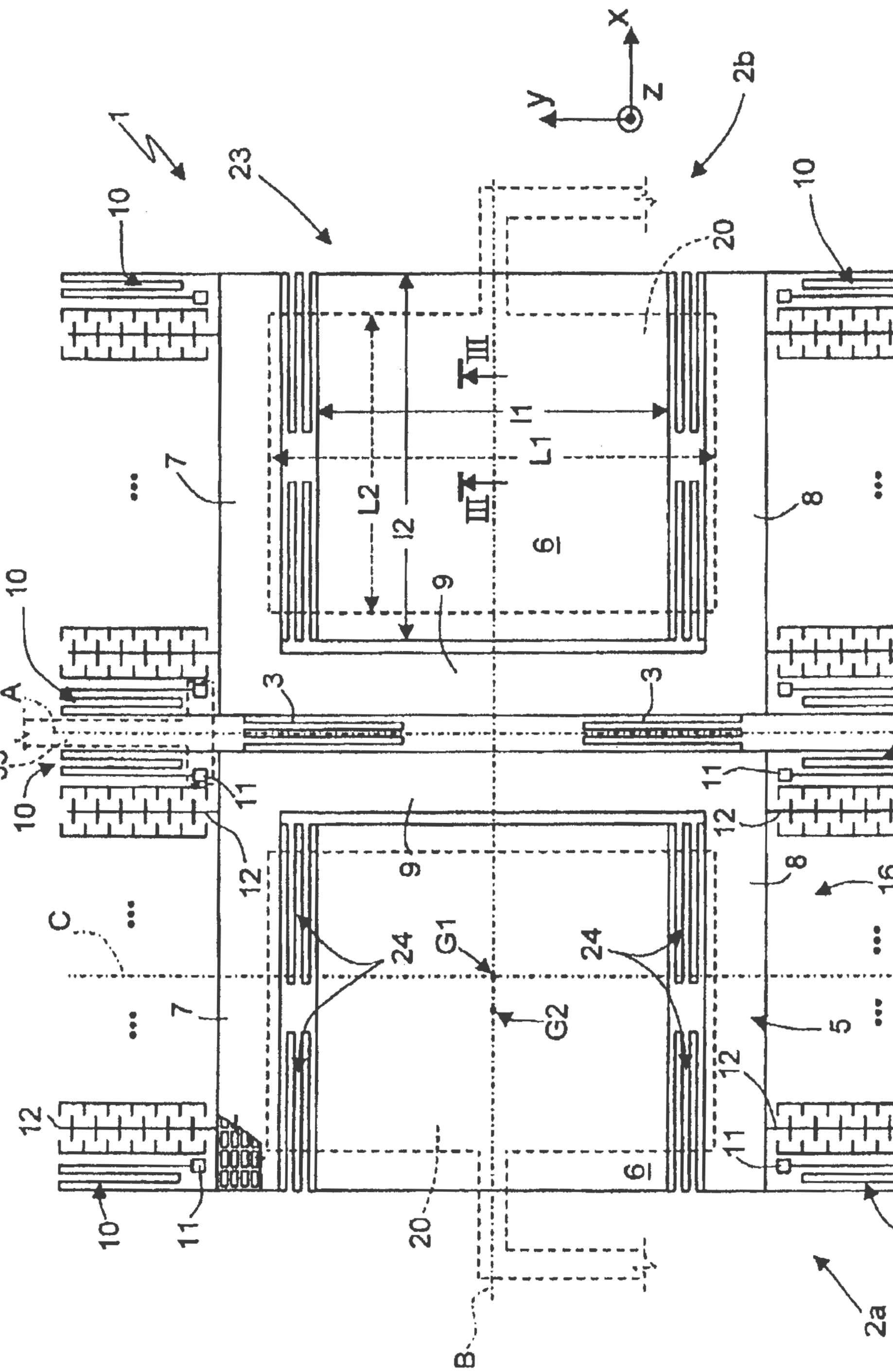


FIG. 1

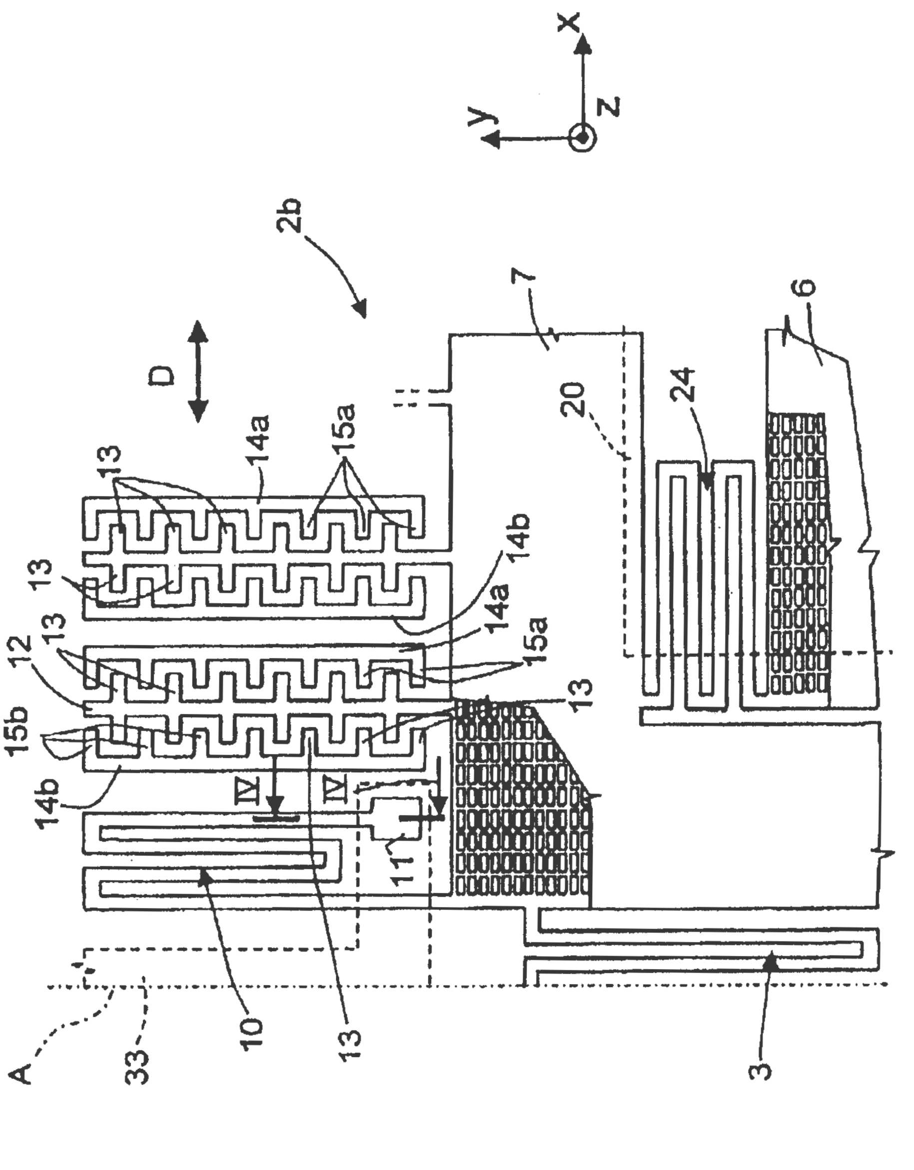


FIG. 2

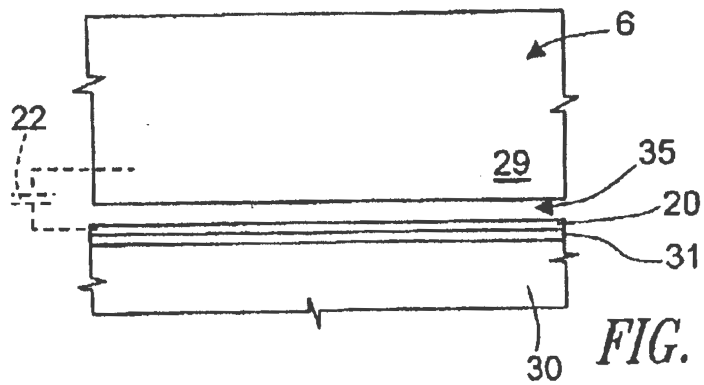
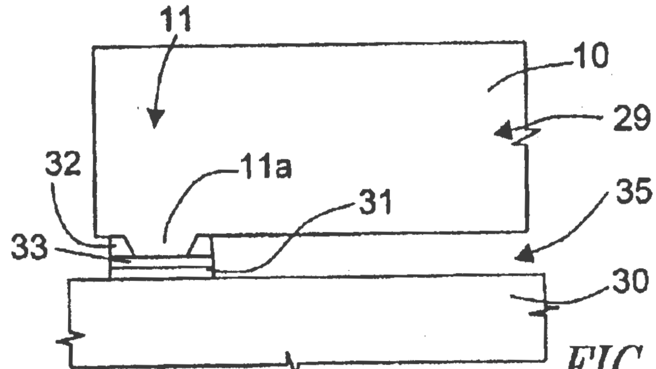


FIG. 3



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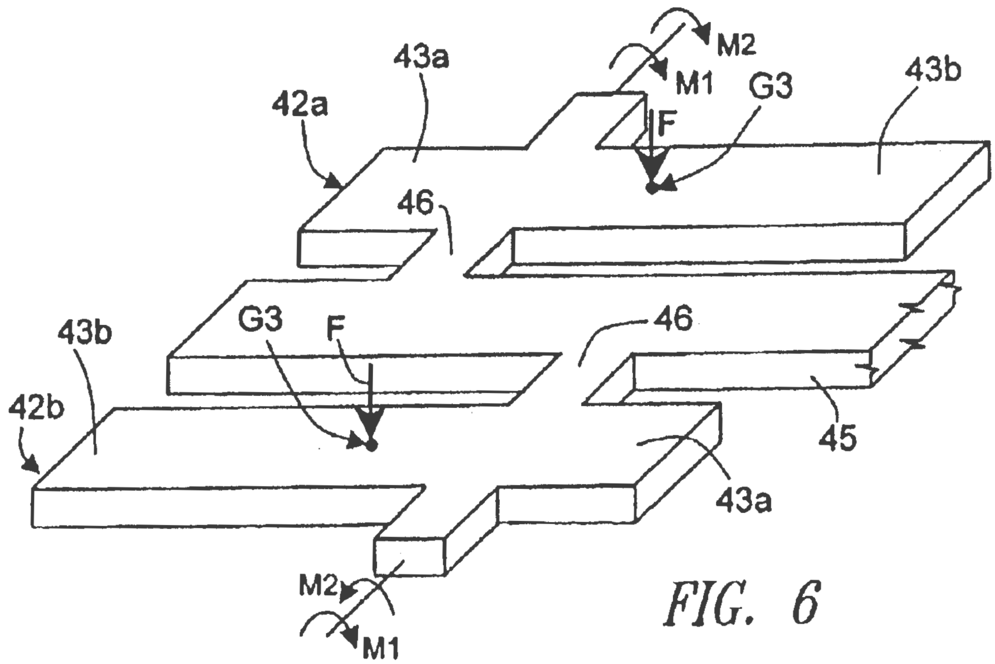


FIG. 6

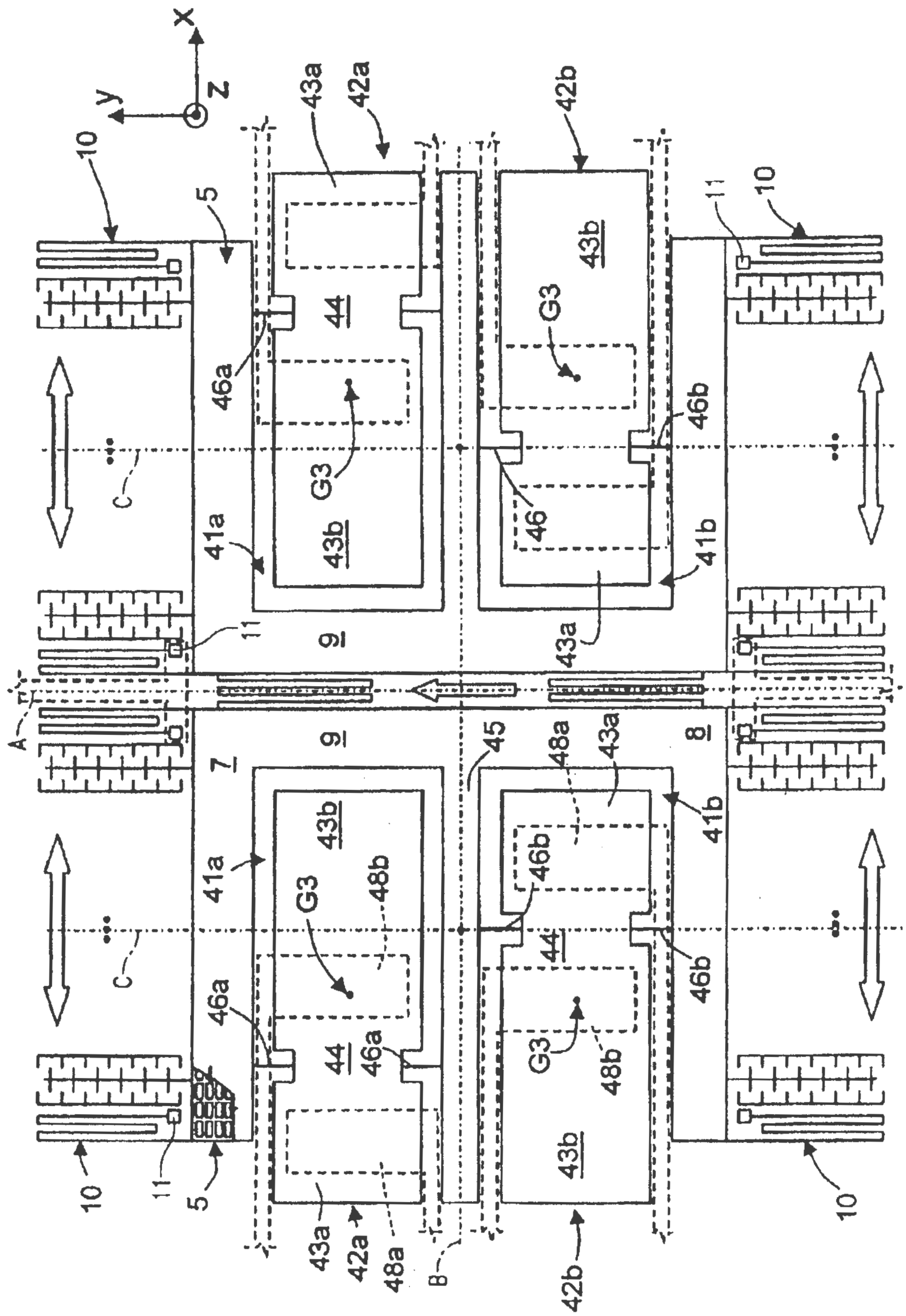
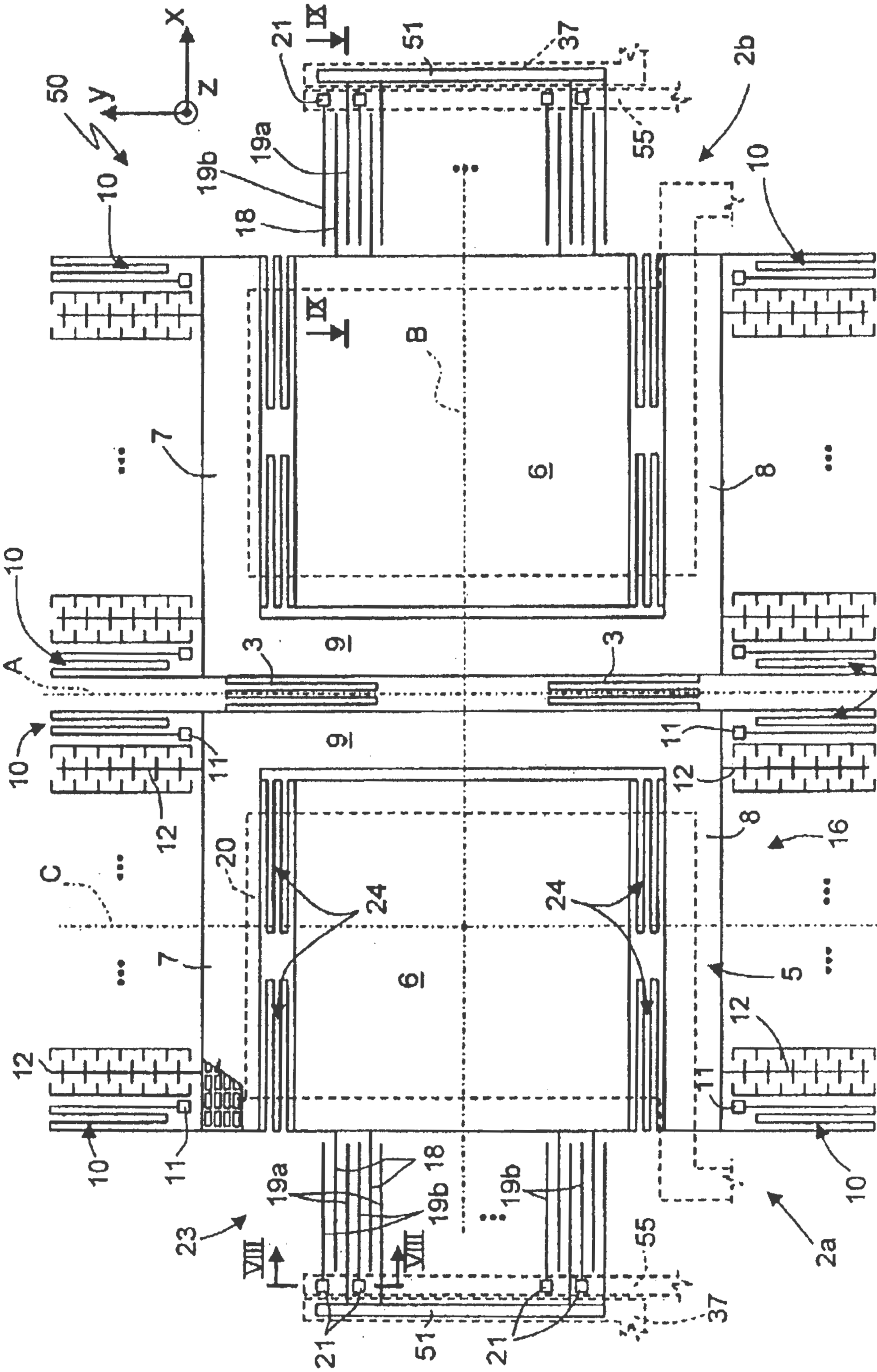

X
Y
Z
10
5
11
43a
42a
42b
43b
44
46a
46b
46
G3
41a
41b
9
7
8
45
48a
48b
A
B
C

FIG. 5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Y
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2b
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7
8
9
10
11
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16
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19a
19b
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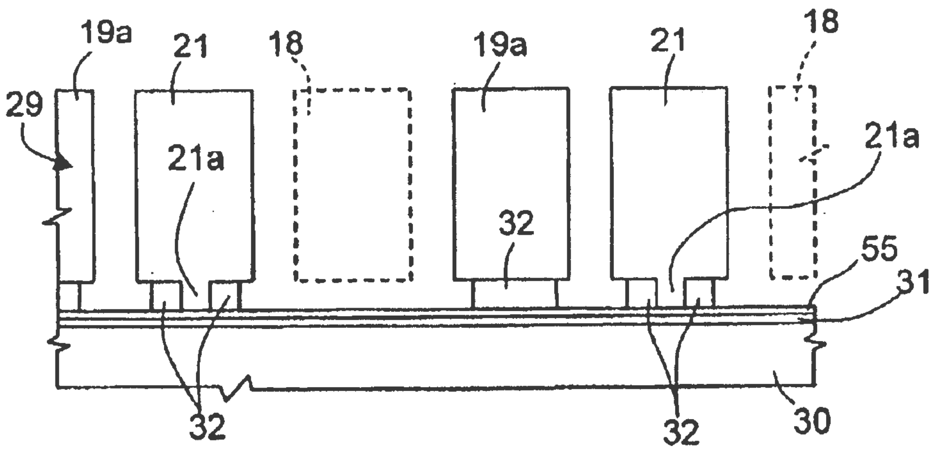
21
23
24
37
51
55
A
B
C
VIII
IX

FIG. 7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19a
21
18
29
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21a
32
55
31
32
32
30

FIG. 8

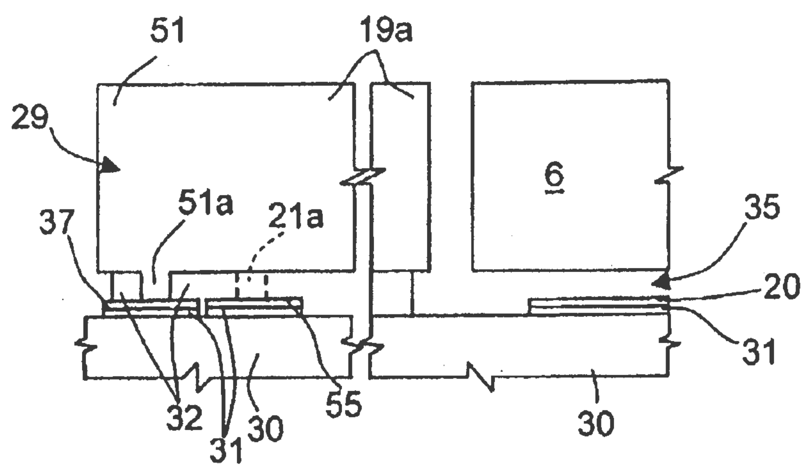
51
19a
29
6
51a
21a
37
35
20
31
32
31
30
55
30

FIG. 9

INTEGRATED GYROSCOPE OF SEMICONDUCTOR MATERIAL WITH AT LEAST ONE SENSITIVE AXIS IN THE SENSOR PLANE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application Ser. No. 10/128,133, filed Apr. 23, 2002, now U.S. Pat. No. 6,766,689, which application is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an integrated gyroscope of semiconductor material.

2. Description of the Related Art

As is known, integrated gyroscopes of semiconductor material, manufactured using MEMS (Micro-Electro-Mechanical Systems) technology, operate on the basis of the theorem of relative accelerations, exploiting Coriolis acceleration. In particular, when a linear velocity is applied to a movable mass rotating with angular velocity, the movable mass "feels" an apparent force, called Coriolis force, which determines a displacement thereof in a direction perpendicular to the linear velocity and to the axis of rotation. The apparent force can be hence detected by supporting the movable mass through springs which enable a displacement thereof in the direction of the apparent force. On the basis of Hooke's law, this displacement is proportional to the apparent force itself and, thus, detection of the displacement of the movable mass enables detection of Coriolis force and, hence, of the angular velocity.

In gyroscopes of the type considered, the displacement of the movable mass is detected capacitively, by measuring at resonance the variations in capacitance caused by the movement of movable detection electrodes integrally fixed to the movable mass and interfaced with, or comb-fingered to, fixed detection electrodes.

Examples of embodiment of integrated gyroscopes manufactured using MEMS technology are described, for example, in U.S. Pat. Nos. 5,604,312, 5,275,047 and WO 97/15066 in the name of Robert Bosch GmbH, and in U.S. Pat. No. 5,955,668, WO 99/19734 and WO00/29855 in the name of IRVINE SENSORS CORPORATION. However, the above gyroscopes present some drawbacks.

For example, U.S. Pat. No. 5,604,312 describes a gyroscope formed by an oscillating mass and a sensitive mass mounted upon the driving element. This known gyroscope involves a complicated fabrication process, which uses two different structural layers, with consequent high fabrication costs, low reliability, complication of alignment between the accelerometers and the oscillating masses, and complication in the connections.

U.S. Pat. No. 5,955,668 and WO 99/19734 provide for an external oscillating mass connected to an internal sensing mass and, i.e., two independent mechanical parts which can be appropriately calibrated. However, in case of the gyroscope of circular shape (described in the patent U.S. Pat. No. 5,955,668), the structure is sensitive to stresses due to the fabrication steps and to thermal drift, since the suspension springs of the sensing element internal to the oscillating external mass are very rigid in the direction of the axis of the angular velocity, and it is not possible to anchor the detection element centrally, in so far as the gyroscope would "feel" the velocity of a number of axes simultaneously and would become unusable. Instead, for the gyroscope of rectangular shape (described in the patent WO 99/19734), the system is not optimized since it uses suspension springs which involve undesired rotational contributions; moreover, the described gyroscope does not enable rejection of linear accelerations. In either case, but in particular in case of a translation gyroscope, numerous interconnections are present which pass underneath the mass, and the interconnections are quite long, with the risk of capacitive couplings with the sensing structures and hence of false or imprecise reading.

BRIEF SUMMARY OF THE INVENTION

According to an embodiment of the present invention, an integrated gyroscope of semiconductor material is provided, including an acceleration sensor having a driving assembly and a sensitive mass. The mass extends in a first direction and a second direction and is moved by the driving assembly in the first direction. The sensor further includes a capacitive sensing electrode, facing the sensitive mass. The acceleration sensor has a rotation axis parallel to the second direction, and the sensitive mass is sensitive to forces acting in a third direction perpendicular to the first and second directions.

The capacitive sensing electrode comprises a conductive material region extending underneath and at a distance, in the third direction, from the sensitive mass. The driving assembly has a driving element connected to the sensitive mass through a mechanical linkage, which enables a movement of at least to part of the sensitive mass in the third direction. The sensitive mass and the capacitive sensing electrode have a reciprocal facing area that is constant in presence of movements of the sensitive mass in the first direction or in said second direction, thus only movements of the sensitive mass in the third direction are detected.

According to another embodiment of the invention, a method of operation is provided, including oscillating a sensing mass in a first axis lying in a first plane relative to a surface of a semiconductor material body, the sensing mass mechanically couple to the body, moving the semiconductor material body about a second axis perpendicular to the first axis and lying in the same plane, and detecting the movement of the semiconductor material body by detecting changes in a capacitive coupling between the sensing mass and an electrode formed on the surface of the semiconductor body, due to movements of the body in an axis perpendicular to the first plane.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For an understanding of the present invention, preferred embodiments thereof will now be described, purely by way of non-limiting example, with reference to the annexed drawings, wherein:

FIG. 1 is a top plan view through the first embodiment, with single sensitive axis;

FIG. 2 illustrates a portion of the gyroscope of FIG. 1, at an enlarged scale;

FIG. 3 is a cross-section taken along line III—III of FIG. 1;

FIG. 4 is a cross-section taken along the line IV—IV of FIG. 2;

FIG. 5 is a top plan view through a second embodiment of the invention, with single sensitive axis;

FIG. 6 is a schematic illustration in perspective view of a detail of FIG. 5;

FIG. 7 is a top plan view through a third embodiment of the invention, with double sensitive axis;

FIG. 8 is a cross-section taken along the line VIII—VIII of FIG. 7; and

FIG. 9 is a cross-section taken along the line IX—IX of FIG. 7.

DETAILED DESCRIPTION OF THE INVENTION

U.S. patent application Ser. No. 10/128,133, filed on Apr. 23, 2002 and incorporated herein in its entirety, describes an integrated gyroscope comprising a sensor formed by a driving system, a sensitive mass and a mechanical linkage. The driving system is formed by a driving element having an open concave shape, and subject to a linear velocity directed in a first direction. The sensitive mass is also movable in a second direction perpendicular to the first direction and carries movable sensing electrodes. The mechanical linkage connects the driving elements to the sensitive mass. The gyroscope is sensitive to rotation about a third axis perpendicular to the former two and to the plane of the sensitive mass. The sensitive mass is surrounded on three sides by the driving element and has a peripheral portion not facing the latter. The movable sensing electrodes extend from the peripheral portion of the sensitive mass, not facing the driving element, and are comb-fingered to the fixed sensing electrodes. Thereby, there are no through electrical connections extending beneath the sensitive mass. In addition, the mechanical linkage is formed by springs arranged at equal distances with respect to the centroid of the sensitive mass, and the gyroscope is anchored to the substrate through anchoring springs arranged at equal distances with respect to the centroid of the ensemble formed by the driving system and the sensitive mass.

This previous gyroscope enables detection of the Coriolis force acting parallel to the second direction, in the sensor plane, and due to a rotation about an axis (hereinafter referred to as "sensitive axis") extending in the third direction, perpendicular to the sensor plane. By setting two gyroscopes rotated by 90° one with respect to the other on an appropriate board, it is possible to detect the apparent forces acting along two Cartesian axes parallel to the plane of the gyroscope, and hence the corresponding angular accelerations. It is not, however, possible to detect the apparent force and the corresponding angular acceleration along the third Cartesian axis, since in this case the third gyroscope should be mounted perpendicular to the board.

FIGS. 1 to 3 illustrate a gyroscope 1 according to a first embodiment of the invention. As shown in detail in FIG. 1, the gyroscope 1 comprises an acceleration sensor 23 formed by two parts 2*a*, 2*b*, which are symmetrical with respect to a central axis of symmetry designated by A and connected together by two central springs 3, configured to be symmetrical with respect to a horizontal centroidal axis designated by B. Furthermore, each part 2*a*, 2*b* has a vertical centroidal axis designated by C. The axes A and C are parallel to the axis Y, while the axis B is parallel to the axis X. The intersection between the horizontal centroidal axis B and the vertical centroidal axis C constitutes the centroid G1 of each part 2*a*, 2*b*.

The acceleration sensor 23 is sensitive to an angular velocity directed parallel to the axis Y.

Each part 2*a*, 2*b* comprises a driving element 5 of concave shape, here a square C shape, and a sensitive mass 6, completely housed inside the space delimited by the driving element 5 but having a peripheral portion not facing the driving element 5 itself. Both the driving element 5 and the sensitive mass 6 are perforated as shown only in part in FIG. 2.

Each driving element 5 is formed by a first and a second oscillating arms 7, 8, which are parallel to one another and are connected at one end by a central cross member 9 extending perpendicular to the oscillating arms 7, 8. The two cross members 9 of the parts 2*a*, 2*b* extend parallel to one another, face one another, and are connected by the central springs 3. The first oscillating arms 7 are aligned together, as also are the second oscillating arms 8.

Anchoring springs 10 extend from each end of the oscillating arms 7, 8 towards the outside of the respective driving elements 5. The anchoring spring 10, which can be seen more clearly in the detail of FIG. 2, are of a folded type, i.e., they comprise at least two non-aligned portions, one connected to the respective driving element 5 and one having an anchoring end 11 fixed to a fixed substrate (as described in greater detail hereinafter with reference to FIG. 3). The anchoring springs 10 are equal and are arranged in pairs symmetrically with respect to the centroidal vertical axis C and the centroidal horizontal axis B, so that the anchoring springs 10 are at equal distances from one another and balanced with respect to the centroid G1 of the respective part 2*a*, 2*b* of the gyroscope. The anchoring springs 10 are here made up of four portions extending orthogonally to the arms 7, 8 and connected, in pairs, via short connection portions at their ends.

Elongated expansions, hereinafter referred to as movable driving arms 12, extend towards the outside of the oscillating arms 7, 8, orthogonally to the arms, between pairs of anchoring springs 10, symmetrically with respect to both the centroidal horizontal axis B and the centroidal vertical axis C. Each movable driving arm 12 carries a plurality of movable driving electrodes 13, extending orthogonally from either side of the respective movable driving arms 12.

Associated to each movable driving arm 12 is a first and a second fixed driving arms 14*a*, 14*b* (see FIG. 2), which are parallel to the movable driving arms 12 and carry respective fixed driving electrodes 15*a*, 15*b*. The fixed driving electrodes 15*a*, 15*b* extend perpendicular to the fixed driving arms 14*a*, 14*b* towards the respective movable driving arms 12 and are comb-fingered to the movable driving electrodes 13. The first fixed driving arms 14*a* are arranged all on a same side of the respective movable driving arms 12 (in the example, on the right) and are all biased at a same first potential. Likewise, the second fixed driving arms 14*b* are all arranged on the other side of the respective movable driving arms 12 (in the example, on the left) and are all biased at a same second potential. For example, it is possible to use a push-pull biasing scheme.

The driving element 5, the movable driving arms 12, the movable driving electrodes 13, the fixed driving arms 14*a*, 14*b*, and the fixed driving electrodes 15*a*, 15*b* together form a driving system 16 for each part 2*a*, 2*b*.

The sensitive mass 6 has a basically plane shape, with the main extension in the direction of the axes X and Y. In the example illustrated, each sensitive mass 6 is rectangular in shape, with the length 11 in the Y direction, the width 12 in the X direction, and with a centroid G2, and is surrounded on three sides by the respective driving element 5.

Four coupling springs 24, of a folded type, extend between each sensitive mass 6 and the oscillating arms 7, 8 facing said mass 6, in a position symmetrical with respect to the centroid G2 of the sensitive mass 6.

The coupling springs **24** (see also FIG. **2**) extend mainly parallel to the oscillating arms **7**, **8** and are configured so as to connect rigidly the sensitive mass **6** to the driving element **5** in a direction parallel to the axis X, to enable a limited movement of the sensitive mass **6** in the event of application of a force in the direction parallel to the axis Y, as explained hereinafter, and to enable its displacement in a direction parallel to the axis Z under the action of the apparent force due to Coriolis acceleration.

Underneath each sensitive mass **6**, there extends a sensing electrode **20** of deposited doped polycrystalline silicon (for example, polysilicon deposited by low-pressure chemical vapor deposition LPCVD), the perimeter of the sensing electrode **20** being represented by a dashed line in FIG. **1**.

As may be seen from FIG. **3**, each sensitive mass **6** is separated from the respective sensing electrode **20** by an air gap **35** obtained by removal of a sacrificial material, such as deposited oxide. The sensitive mass **6** and the sensing electrode **20** thus form the plates of a capacitor **22** (represented by dashed lines in FIG. **3**), the dielectric whereof is formed by the air gap **35**.

Each sensing electrode **20**, of rectangular shape, has a length L1 in the Y direction that is greater than the length l1, and a width L2 in the X direction that is smaller than the length l2 of the respective sensitive mass **6**. In particular, the length L1 of the sensing electrode **20** exceeds the length l1 of the sensitive mass **6** by an amount such that any displacement in the direction Y of the sensitive mass **6** (due to forces acting in that direction) will not reduce the facing area between the sensitive mass **6** and the sensing electrode **20**. In addition, the width L2 of the sensing electrode **20** is smaller than the width l2 of the sensitive mass **6** by an amount such that any displacement of the latter in the direction X (due to the driving system **16** and/or to other forces acting in that direction) will not reduce the facing area between the sensitive mass **6** and the sensing electrode **20**. In this way, capacitive coupling between the sensitive mass **6** and the sensing electrode **20** does not change following upon movements in the directions X and Y; instead, it does change for movements along the axis Z, as described below.

FIG. **3** shows a cross-section through the gyroscope **1**. As may be noted, the sensitive mass **6** (as also the driving element **5**, the springs **10**, **24**, the movable driving arms **12**, and the fixed driving arms **14***a*, **14***b*) is formed in a structural layer, here constituted by an epitaxial layer **29** formed on top of a substrate **30** of monocrystalline silicon. The sensing electrode **20** is formed on top of an insulating layer **31**, for example, a deposited oxide layer, which is, in turn, formed on top of the substrate **30**.

FIG. **4** shows the cross-section of the gyroscope **1** at one anchoring end **11** of an anchoring spring **10**. In particular, the anchoring end **11** has, at the bottom, a reduced portion **11***a* overlying, and in direct electrical contact with, a first connection region **33** of conductive material, formed in the layer of polycrystalline silicon of the sensing electrode **20** and indicated by a dashed line in FIG. **1**. The first connection region **33** enables biasing of the anchoring spring **10** and, more in general, of the driving element **5** and of the sensitive mass **6** at the desired potential. FIG. **4** also shows the non-removed portions **32** of a sacrificial layer, which, where removed, forms the air gap **35**. In FIG. **4**, the insulating layer **31** and the sacrificial layer **32** extend only underneath the anchoring end **11**, and have been removed underneath the movable parts (here the anchoring spring **10**). Similar solutions of connection are used for the fixed driving elements **14***a*, **14***b*, where, however, the sacrificial area **22** is not generally removed.

The gyroscope **1** is able to detect the magnitude of the angular velocity which causes a rotation of the gyroscope about the axis Y and hence in the plane of the sensitive mass **6**. In this situation, in fact, as explained previously, the Coriolis force is directed along the axis Z and causes a displacement of the sensitive mass **6** in the same direction. Since the capacitance of the capacitor **22** formed by the sensitive mass **6** and by the sensing electrode **20** depends, in a known way, upon the distance between the plates, a special processing circuit (not shown) is able to detect the variation in capacitance and to find the magnitude of the angular velocity.

Thanks to the sizing, described above, of the sensitive mass **6** and of the sensing electrode **20**, it is moreover possible to reject any accelerations or forces lying in the plane of the sensitive mass **6** and parallel to the axis Y In fact, as indicated, the forces acting in the direction Y do not determine a modification of the facing area between the plates of the capacitor **22** and hence of its capacitance, and are not felt by the circuitry associated to the gyroscope **1**.

In this way, if two gyroscopes **1** of the type described are available in a single chip, the two gyroscopes being rotated through 90° (one with driving direction parallel to the axis X and the other with driving direction parallel to the axis Y) and hence having two sensitive axes in the plane of the sensitive mass **6**, but staggered by 90° with respect to one another, and if, moreover, there is available a gyroscope of a known type on the same chip, this gyroscope having a sensitive axis perpendicular to the plane of the sensitive mass **6**, it is possible with a single device to detect the angular velocities along all three Cartesian axes.

The gyroscope **1** has a high sensitivity thanks to the large facing area between the sensitive mass **6** and the sensing electrode **20** and supplies an output of a single-ended type.

FIG. **5** illustrates an embodiment of a gyroscope **40**, which supplies a differential reading of the angular velocity.

The gyroscope **40** of FIG. **5** still comprises a driving system **16** of the type described with reference to FIG. **1**, but each driving element **5** is here E-shaped and is provided with two concavities **41***a*, **41***b* facing outwards. In practice, each driving element **5** comprises, in addition to the oscillating arms **7**, **8** and the central cross member **9**, an intermediate arm **45**, extending parallel to the axis X. Each driving element **5** is also here supported and biased through an anchoring spring **10** of a folded type, the springs having an anchoring end **11** and being arranged symmetrically with respect to the vertical centroidal axis C.

A sensitive mass **42***a*, **42***b* arranged inside each concavity **41***a*, **41***b* has a generally rectangular shape and is supported in an eccentric way. In detail, each sensitive mass **42***a*, **42***b* is formed by a first smaller rectangular portion **43***a* and a second larger rectangular portion **43***b*, these portions being interconnected by a narrow portion **44**. Each sensitive mass **42***a*, **42***b* has an own centroid G3.

The sensitive mass **42***a* is supported by two supporting arms **46***a* extending parallel to the cross member **9** from the narrow portion **44** towards the oscillating arm **7** and towards the intermediate arm **45**. Likewise, the sensitive mass **42***b* is supported by two supporting arms **46***b* extending parallel to the cross member **9** from the narrow portion **44** towards the oscillating arm **8** and towards the intermediate arm **45**. The supporting arms **46***a* and **46***b* form torsion springs.

The supporting arms **46***a* of each sensitive mass **42***a* are aligned together, as are the supporting arms **46***b* of each sensitive mass **42***b*, but, in each part **2***a*, **2***b*, the supporting arms **46***a* of the sensitive mass **42***a* are misaligned with respect to the supporting arms **46***b* of the sensitive mass **42***b*. All of the supporting arms **46***a*, **46***b* extend at a distance from the centroid G3 of the respective sensitive mass **42***a*, **42***b*. Also here the suspended masses **42***a*, **42***b* of the two parts **2***a*, **2***b* of the gyroscope **40** are arranged symmetrically with respect to the central axis of symmetry A.

Respective sensing electrodes **48***a*, **48***b* extend underneath each portion **43***a*, **43***b* of the four suspended masses **42***a*, **42***b*. In detail, the sensing electrodes **48***a* face the smaller portions **43***a*, and the sensing electrodes **48***b* face the larger portions **43***b*. Also here the sensing electrodes **48***a*, **48***b* are formed by a polycrystalline silicon layer, separated from the respective portion **43***a*, **43***b* by an air gap, and are connected to a processing circuit (not shown).

In the gyroscope **40** of FIG. **5**, as illustrated in FIG. **6**, the Coriolis force F acting on the centroid G3 of each sensitive mass **42***a*, **42***b* determines opposite rotations of the suspended masses **42***a*, **42***b* connected to a same driving element **5**, since they have the centroid G3 on opposite sides with respect to the respective supporting elements **46***a*, **46***b*. This rotation determines an opposite variation in the capacitance of the capacitors formed by each portion **43***a*, **43***b* of the suspended masses **42***a*, **42***b* and the respective sensing electrode **46***a*, **46***b*.

With the structure described, it is possible to eliminate the influence of external momenta acting on the suspended masses **42***a*, **42***b*. In fact, as shown in the simplified diagram of FIG. **6** and as explained above, the couple generated by the Coriolis force F, designated by M2, has the same value, but opposite sign, in the two accelerometers **42***a*, **42***b* carried by the same driving element **5**. In particular, the couple M2 cause the more massive larger portions **43***b* of the suspended masses **42***a*, **42***b* to drop downward or rise upward together as they rotate in opposite directions about their respective support elements **46***a*, **46***b*. This results in opposite-polarity changes of the capacitance of the capacitors formed by the two accelerometers **42***a*, **42***b* and the respective sensing electrode **48***a*, **48***b*, and thus an opposite change in the signals supplied by the sensing electrodes **48***a*, **48***b* of each part **2***a*, **2***b*.

Instead, a possible external couple, designated by M1, acts in a concordant direction on both of the suspended masses **42***a*, **42***b*. In particular, the couple M1 will result in rotation of the suspended masses **42***a*, **42***b* about their respective supporting elements **46***a*, **46***b* in the same direction. This results in same-polarity changes of the capacitance of the capacitors formed by the two accelerometers **42***a*, **42***b* and the respective sensing electrode **48***a*, **48***b*, and thus a same change in the signals supplied by the sensing electrodes **48***a*, **48***b* of each part **2***a*, **2***b*.

Consequently, by subtracting the signals supplied by the sensing electrodes **48***a*, **48***b* of each part **2***a*, **2***b* of the gyroscope **40** from one another, the effect due to the external momentum M1 is cancelled, while the effect due to the Coriolis force is summed. In this way, it is possible to determine the magnitude of the angular velocity in the direction Y, eliminating the noise due to external momenta. In addition, a more symmetrical reading is obtained, which provides a non-negligible advantage during calibration and matching of the sensing resonance frequencies.

The gyroscope **40** illustrated in FIG. **5** is less sensitive than the gyroscope **1** of FIG. **1**, since the variation in capacitance due to rotation of the suspended masses **42***a*, **42***b* is less than the variation that may be obtained as a result of translation in the direction Z of the suspended masses **6**, given the same external force F. The gyroscope **40** is, however, less subject to electrostatic pull-in due to mechanical shocks. In fact, in the gyroscope of FIG. **1**, on account of the biasing of the driving elements **5** and the sensing electrodes **20**, it may happen that, following upon a mechanical shock, the driving elements **5** adhere to, and remain attracted by, the respective sensing electrodes **20**, this being facilitated by the large facing area. Instead, with the gyroscope **40**, a possible mechanical shock, such as might cause rotation of the suspended masses **42***a*, **42***b*, does not in general cause a condition of "sticking", given that in this case each sensitive mass **42***a*, **42***b* touches the respective sensing electrode **48***a*, **48***b* only along one edge instead of with the entire surface.

FIG. **7** presents an embodiment of the gyroscope **50** with double sensitive axis. In particular, the gyroscope **50** has a first sensitive axis extending in the plane of the sensitive mass **6**, parallel to the axis Y, as in the embodiment of FIG. **1**, and a second sensitive axis extending in a direction perpendicular to the plane of the sensitive mass **6** and parallel to the axis Z.

The gyroscope **50** has a basic structure similar to that of the gyroscope **1** of FIG. **1**, except for the fact that, in each part **2***a*, **2***b*, movable sensing electrodes **18** extend from the side of the sensitive mass **6** facing outwards, parallel to the oscillating arms **7**, **8**. The movable sensing electrodes **18** are comb-fingered to the fixed sensing electrodes **19***a*, **19***b*. In detail, each movable sensing electrode **18** is arranged between a fixed sensing electrode **19***a* and a fixed sensing electrode **19***b*. The fixed sensing electrodes **19***a* are all arranged on a first side of the movable sensing electrodes **18** and are electrically connected together at their outer ends through a first anchoring region **51**. The fixed sensing electrodes **19***b* are all arranged on a second side of the movable sensing electrodes **18** and are electrically connected together through respective second anchoring regions **21** formed at their outer ends and connected together through a second connection region **55**, represented by a dashed line in FIG. **7** and illustrated in FIG. **8**.

The fixed sensing electrodes **19***a*, **19***b* form, with the movable sensing electrodes **18**, capacitors, the capacitance of which depends upon the distance between them, in a known way. Consequently, any displacement in the direction Y of the sensitive mass **6**, due to an oscillation around axis Z, causes a variation of opposite sign in the voltages of the fixed sensing electrodes **19***a* and **19***b*, which is detected and processed by an appropriate circuit (not shown) in a known way.

FIG. **8** is a cross-sectional view through the gyroscope at the second anchoring region **21** of the fixed sensing electrodes **19***b*. Here the second anchoring regions **21**, which are formed in the same structural layer as the anchoring springs **10**, i.e., the epitaxial layer **29**, have at the bottom a reduced portion **21***a* formed by the epitaxial layer **29** itself, which overlies and is in direct electrical contact with the second connection region **55** formed in the same layer as the sensing electrodes **20** The second connection region **55** is formed on top of the insulating layer **31** and underneath the sacrificial layer **32**, of-which only some portions are visible, which have remained after the movable parts of the gyroscope **50** have been freed. The cross-section of FIG. **8** also shows the fixed sensing electrodes **19***a* and, in a plane set back with respect to the plane of the cross section, the movable sensing electrodes **18**, drawn with a dashed line.

FIG. **9** is a cross-section through the gyroscope **50** taken along a fixed sensing electrode **19***a*. As may be noted, the first anchoring region **51** is formed in the epitaxial layer **29** and has, at the bottom, a reduced portion **51***a* formed by the epitaxial layer **29**, which overlies and is in direct electrical contact with a third connection region **37** of conductive material, formed in the same layer as the sensing electrodes **20** and the second (polysilicon) connection region **55**, on top of the insulating layer **31** and underneath the sacrificial layer **32**.

The gyroscope **50** of FIGS. **7** to **9** is able to detect forces acting in the direction Z (sensitive axis parallel to the axis Y) as has been described with reference to FIG. **1**. In addition, the gyroscope is able to detect forces acting in the direction of the axis Y (sensitive axis parallel to the axis Z), in so far as any displacement in the direction Y is detected as a variation in capacitance between the movable sensing electrodes **18** and the fixed sensing electrodes **19***a*, **19***b*.

In the gyroscope **50** it is possible to distinguish the effects of forces or of components thereof acting in the three directions. In fact, the displacements in the direction X (due to driving or to external forces) are not detected by the sensing electrodes **20**, as mentioned with reference to FIG. **1**, and cause a same capacitive variation on the fixed sensing electrodes **19***a* and **19***b* and can thus be rejected. The displacements along the axis Y are not detected by the sensing electrodes **20**, as mentioned previously with reference to the embodiment of FIG. **1**, but are detected by the fixed electrodes **19***a* and **19***b*, as explained above. The displacements along the axis Z are detected by the sensing electrode **20**, as mentioned previously with reference to FIGS. **1**-**3**. Their effect on the fixed sensing electrodes **19***a* and **19***b* can, instead, be rejected since they detect a same capacitive variation with respect to the movable sensing electrodes **18**, as for the displacements in the direction X.

The advantages of the described gyroscope are the following. First, it is possible to have, on a single plane, the sensitive elements that are able to detect forces acting along three Cartesian axes, this enabling a reduction in the overall dimensions of a three-axes gyroscope. The advantage is all the greater in case of the third embodiment, where a single sensor **23** is able to measure forces acting in two perpendicular directions, and hence only two sensors are necessary for a three-dimension measure. The compactness of the sensors and the reduction in their number further enable reduction in costs for manufacturing the gyroscope.

Each sensor **23** and each sensing set is moreover sensitive only to the forces acting in the respective directions, and rejects actions in a perpendicular direction. Thus a high sensing precision is achieved. The sensing precision may be increased even further by designing the thicknesses of the various layers so as to assign different degrees of sensitivity in the different directions, in particular, in the third embodiment.

The first and the third embodiments have high sensitivity and hence are particularly suited in the case of low angular velocities; instead, the second embodiment, as mentioned previously, enables use of a simpler circuitry and makes it possible to avoid the risk of electrostatic pull-in.

Finally, it is clear that numerous modifications and variations may be made to the gyroscope described and illustrated herein, all falling within the scope of the invention as defined in the attached claims.

All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, are incorporated herein by reference, in their entirety.

What is claimed is:

1. An integrated gyroscope, including an acceleration sensor comprising:

a first driving assembly;

a first sensitive mass extending in a first direction and a second direction, said first sensitive mass being moved by said driving assembly in said first direction;

a first capacitive sensing electrode, facing said first sensitive mass, the first driving assembly, first sensitive mass, and first sensing electrode being components of a first part of the acceleration sensor;

a second driving assembly;

a second sensitive mass extending in the first direction and the second direction, said second sensitive mass being moved by said second driving assembly in said first direction; and

a second capacitive sensing electrode, facing said second sensitive mass, the second driving assembly, second sensitive mass, and second sensing electrode being components of a second part of the acceleration sensor, symmetrical to the first part, the first and second driving assemblies being connected by central springs;

wherein said acceleration sensor has a rotation axis parallel to said second direction, and said first and second sensitive masses are sensitive to forces acting in a third direction perpendicular to said first and second directions.

2. The gyroscope according to claim **1** wherein said first capacitive sensing electrode comprises a conductive material region extending underneath and at a distance, in said third direction, from said first sensitive mass.

3. An integrated gyroscope, including an acceleration sensor comprising:

a sensitive mass extending in a first direction and a second direction,

a driving assembly, said sensitive mass being moved by said driving assembly in said first direction, said driving assembly including a driving element connected to said sensitive mass through a mechanical linkage, which enables, at least to one part of said sensitive mass, a movement having a component in a third direction perpendicular to said first and second directions; and

a capacitive sensing electrode, facing said sensitive mass;

wherein said acceleration sensor has a rotation axis parallel to said second direction, and said sensitive mass is sensitive to forces acting in the third direction.

4. The gyroscope according to claim **3** wherein said sensitive mass can be translated parallel to said third direction.

5. The gyroscope according to claim **4** wherein said sensitive mass and said capacitive sensing electrode have a reciprocal facing area that is constant in presence of movements of said sensitive mass in said first direction or in said second direction.

6. The gyroscope according to claim **4** wherein said driving element surrounds, at least partially, said sensitive mass, said sensitive mass and said capacitive sensing electrode having a rectangular shape, a first one between said sensitive mass and said capacitive sensing electrode having a length in said first direction greater than another one between said sensitive mass and said capacitive sensing electrode, and a second one between said sensitive mass and said capacitive sensing electrode having a length in said second direction greater than another one between said sensitive mass and said capacitive sensing electrode.

7. The gyroscope according to claim 3 wherein said driving element has an open concave shape partially surrounding said sensitive mass, and said sensitive mass has a peripheral portion not facing said driving element.

8. The gyroscope according to claim 7, further comprising movable sensing electrodes extending from said peripheral portion of said sensitive mass in said first direction, said movable sensing electrodes being comb-fingered to fixed sensing electrodes for detecting movements of said sensitive mass in said second direction.

9. The gyroscope according to claim 3 wherein said sensitive mass can turn about an eccentric axis parallel to said second direction.

10. The gyroscope according to claim 9 wherein said driving element surrounds at least partially said sensitive mass, said sensitive mass has a first centroid, and said mechanical linkage comprises a first pair of supporting arms aligned to one another and defining said eccentric axis, said supporting arms of said first pair extending between said driving element and said at least one sensitive mass, eccentrically with respect to said first centroid.

11. The gyroscope according to claim 10 wherein said driving element is E-shaped and comprises first and second oscillating arms and an intermediate arm extending parallel to said first direction, said sensitive mass extending between said first oscillating arm and said intermediate arm, a second sensitive mass extending between said second oscillating arm and said intermediate arm, having a second centroid and being supported by a second pair of supporting arms, said supporting arms of said second pair extending eccentrically with respect to said second centroid.

12. The gyroscope according to claim 11 wherein said supporting arms of said second pair are misaligned with respect to said supporting arms of said first pair.

13. The gyroscope according to claim 11 wherein said sensitive mass and said second sensitive mass have a generally rectangular shape and comprise a first portion that is smaller and a second portion that is larger, arranged on opposite sides with respect to the respective supporting arms, and wherein a differential sensing electrode faces a respective one of said first and second portions of said sensitive mass and said second sensitive mass.

14. The gyroscope according to claim 3 wherein said driving element and said sensitive mass are formed in a same structural layer.

15. The gyroscope according to claim 14 wherein said driving element and said sensitive mass extend on top of a conductive material body and are spaced therefrom by an air gap, and said capacitive sensing electrode is formed by a semiconductor material region extending on top of said conductive material body and insulated therefrom, said semiconductor material region extending beneath said air gap.

16. The gyroscope according to claim 3 wherein said driving assembly further comprises a plurality of movable driving electrodes extending from said driving element and comb-fingered to a plurality of fixed driving electrodes.

17. An integrated gyroscope, including an acceleration sensor comprising:

a driving assembly;

a sensitive mass extending in a first direction and a second direction, said sensitive mass being moved by said driving assembly in said first direction; and

a capacitive sensing electrode, facing said sensitive mass;

wherein said acceleration sensor has a rotation axis parallel to said second direction, and said sensitive mass is sensitive to forces acting in a third direction perpendicular to said first and second directions;

the gyroscope comprising two symmetrical parts connected by central springs and each including an own driving assembly, an own sensitive mass, and an own capacitive sensing electrode.

18. A device, comprising:

a semiconductor substrate;

an electrode formed in a first layer of the substrate;

a driving element, mechanically coupled to the substrate and configured to oscillate along a first axis lying in a first plane parallel to the first layer; and

a sensing mass, mechanically coupled to the driving element and capacitively coupled to the first electrode, formed in a second layer of the substrate, the sensing mass being configured to oscillate with the driving element along the first axis lying in the first plane parallel to the first layer, and further configured to move along a second axis perpendicular to the first layer in response to angular movements of the substrate about a third axis perpendicular to the first axis and lying in the first plane.

19. The device of claim 18, further comprising a processing circuit configured to detect a magnitude of angular velocity of the substrate about the third axis by detecting changes in the capacitive coupling of the sensing mass and the electrode.

20. The device of claim 18, said sensing mass being further configured to oscillate along said third axis in response to angular movements of the substrate about said second axis.

21. A device, comprising:

a semiconductor substrate;

a first, second, third, and fourth electrodes formed in a first layer of the substrate;

a first sensing mass, mechanically coupled to the substrate and capacitively coupled to the first and second electrodes, formed in a second layer of the substrate, the first sensing mass being configured to oscillate along a first axis lying in a first plane parallel to the first layer, and further configured to oscillate about a second axis lying in the first plane in response to forces acting along a third axis perpendicular to the first and second axes, the first sensing mass and first and second electrodes forming first and second sensing capacitors; and

a second sensing mass, mechanically coupled to the substrate and capacitively coupled to the third and fourth electrodes, formed in the second layer of the substrate, the second sensing mass configured to oscillate along the first axis lying in the first plane, and further configured to oscillate about a fourth axis, parallel to the second axis, in response to forces acting along the third axis; the second sensing mass and third and fourth electrodes forming third and fourth sensing capacitors.

22. The device of claim 21, further comprising a processing circuit configured to process signals from the first, second, third, and fourth sensing capacitors to separate forces acting on the device due to coriolis effect from forces acting on the device due to momenta.

23. A method, comprising:

oscillating a driving element in a first axis lying in a first plane relative to a surface of a semiconductor material body, the driving element mechanically couple to the body;

moving the semiconductor material body about a second axis perpendicular to the first axis and lying in the same plane; and detecting the movement of the semiconductor material body by detecting changes in a capacitive coupling between a sensing mass mechanically coupled to the driving body and an electrode formed on the surface of the semiconductor body, due to movements of the body in an axis perpendicular to the first plane.

24. A device, comprising:

a semiconductor material body;

a driving element coupled to the semiconductor material body and movable with respect to the semiconductor material body in a first axis;

a sensing mass mechanically couple to the driving element and movable with respect to the driving element in a second axis, perpendicular to the first axis; and

a capacitive electrode positioned between the semiconductor material body and the sensing mass and configured to detect movement of the sensing mass in the second axis.

25. The device of claim **24** wherein the sensing mass is movable with respect to the driving element in a third axis, perpendicular to the first and second axes, the second axis being perpendicular to a face of the semiconductor material body, the device further comprising:

a plurality of sensing electrodes configured to detect movement of the sensing mass in the third axis.

26. The device of claim **24** wherein the driving element, sensing mass, and capacitive electrode are components of a first part of the device, the device further comprising:

a second part, symmetrical to the first part and coupled thereto by spring elements.

27. The device of claim **24** wherein the sensing mass is a first sensing mass and the capacitive electrode is a first capacitive electrode, the device further comprising:

a second sensing mass, the first and second sensing masses each being eccentrically, rotatably, coupled to the driving element, the first and second sensing masses configured to rotate around the second and a third axes, respectively, the second and third axes being parallel to each other; and

second, third, and fourth capacitive electrodes, the first and second capacitive electrodes being positioned between the semiconductor material body and the first sensing mass, and the third, and fourth capacitive electrodes being positioned between the semiconductor material body and the second sensing mass.

* * * * *

EXHIBIT F

US007450332B2

(12) **United States Patent**
Pasolini et al.

(10) **Patent No.: US 7,450,332 B2**
(45) **Date of Patent: Nov. 11, 2008**

(54) **FREE-FALL DETECTION DEVICE AND FREE-FALL PROTECTION SYSTEM FOR A PORTABLE ELECTRONIC APPARATUS**

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(73) Assignees: **STMicroelectronics, Inc.**, Carrollton, TX (US); **STMicroelectronics S.R.L.**, Agrate Brianza (IT)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 240 days.

(21) Appl. No.: **11/166,770**

(22) Filed: **Jun. 24, 2005**

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Related U.S. Application Data

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(30) **Foreign Application Priority Data**

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(51) **Int. Cl.**
G11B 21/02 (2006.01)
G11B 19/02 (2006.01)

(52) **U.S. Cl.** **360/75**; 360/69; 360/78.04

(58) **Field of Classification Search** .... None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,692,915	A	9/1987	Moriya et al.	
4,745,564	A	5/1988	Tennes et al.	
4,862,298	A	8/1989	Genheimer et al.	
4,862,394	A *	8/1989	Thompson et al.	702/166
4,873,871	A	10/1989	Bai et al.	
5,227,929	A	7/1993	Comerford	

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0 444 449 9/1991

(Continued)

OTHER PUBLICATIONS

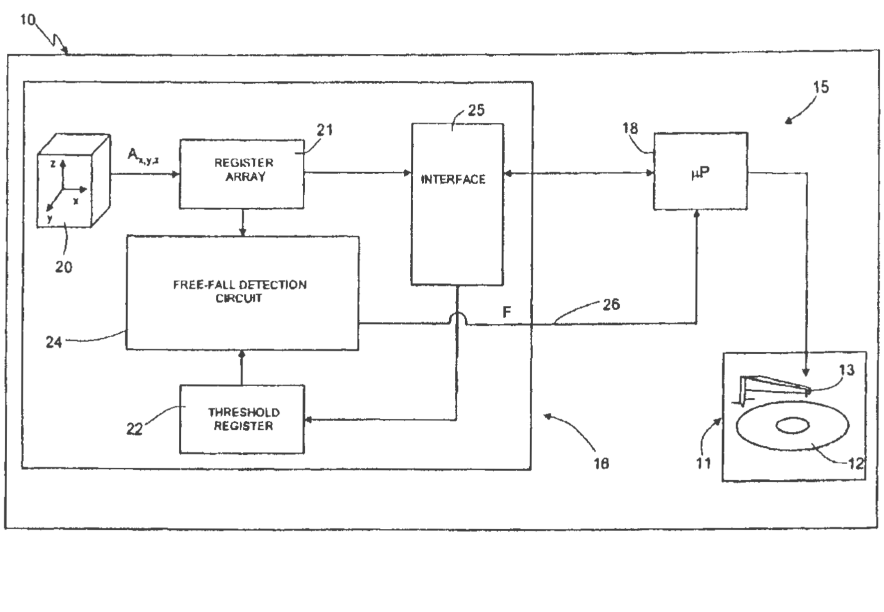
European Search Report EP 05 10 5662; Aug. 23, 2006.

Primary Examiner—Joseph Feild
Assistant Examiner—Jason Olson
(74) *Attorney, Agent, or Firm*—Hogan & Hartson LLP

(57) **ABSTRACT**

In an integrated free-fall detection device for a portable apparatus an acceleration sensor generates acceleration signals correlated to the components of the acceleration of the portable apparatus along three detection axes. A dedicated purely hardware circuit connected to the acceleration sensor generates a free-fall detection signal in a continuous way and in real-time. The free-fall detection signal has a first logic value in the event that the acceleration signals are simultaneously lower than a respective acceleration threshold, and is sent to a processor unit of the portable apparatus as an interrupt signal to activate appropriate actions of protection for the portable apparatus. Preferably, the acceleration sensor and the dedicated purely hardware circuit are integrated in a single chip and the acceleration sensor is made as a MEMS.

27 Claims, 5 Drawing Sheets



U.S. PATENT DOCUMENTS

5,235,472	A	8/1993	Smith	
5,299,075	A	3/1994	Hanks	
5,333,138	A	7/1994	Richards et al.	
5,452,612	A	9/1995	Smith et al.	
5,504,356	A	4/1996	Takeuchi et al.	
5,521,772	A	5/1996	Lee et al.	
5,723,789	A	3/1998	Shannon	
5,763,982	A *	6/1998	Tabota et al.	310/329
5,835,298	A	11/1998	Edgerton et al.	
5,982,573	A	11/1999	Henze	
6,003,374	A	12/1999	Vigna et al.	
6,046,877	A	4/2000	Kelsic	
6,115,200	A	9/2000	Allen et al.	
6,520,013	B1	2/2003	Wehrenberg	
6,738,214	B2	5/2004	Ishiyama et al.	
6,768,066	B2	7/2004	Wehrenberg	
2004/0125493	A1 *	7/2004	Shimotono et al.	360/75
2004/0252403	A1	12/2004	Wehrenberg et al.	

FOREIGN PATENT DOCUMENTS

EP	0 658 894 A1	7/1994
EP	0 826 967 A1	3/1998
JP	3252962	11/1991
JP	5198078	8/1993
JP	6275002	9/1994
WO	WO 2006/060077 A1	6/2006

* cited by examiner

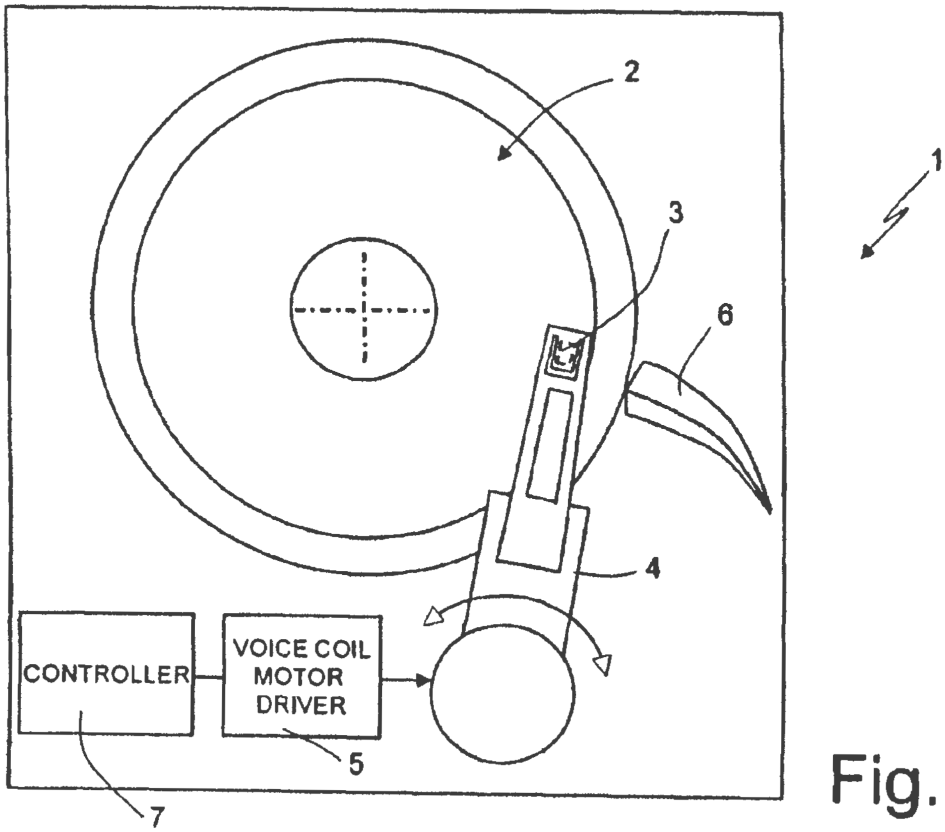


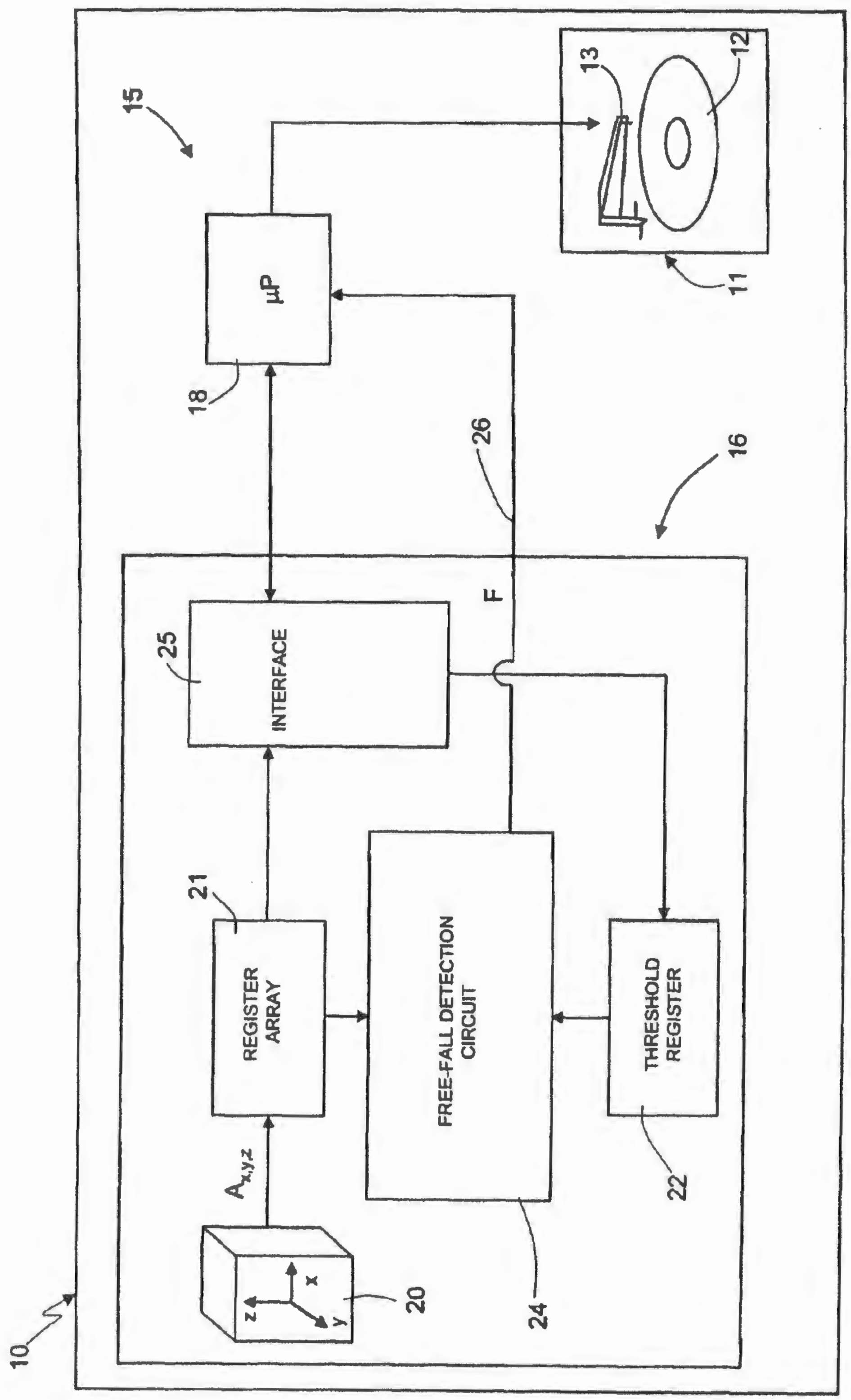
Fig.1

PRIOR ART

Impact Deceleration	Height (m)	Fall time (s)
170	0.102	0.1439
190	0.127	0.1609
208	0.152	0.1763
224	0.178	0.1904
240	0.203	0.2036
268	0.254	0.2276
379	0.508	0.3219
464	0.762	0.3942
536	1.016	0.4552
600	1.270	0.5089
657	1.524	0.5575
709	1.778	0.6022
758	2.033	0.6437
804	2.287	0.6828
848	2.541	0.7197

Fig.2

PRIOR ART



10
15
16
11
12
13
μP
18
26
F
INTERFACE
25
REGISTER ARRAY
21
FREE-FALL DETECTION CIRCUIT
24
THRESHOLD REGISTER
22
$A_{x,y,z}$
x
y
z
20

Fig.3

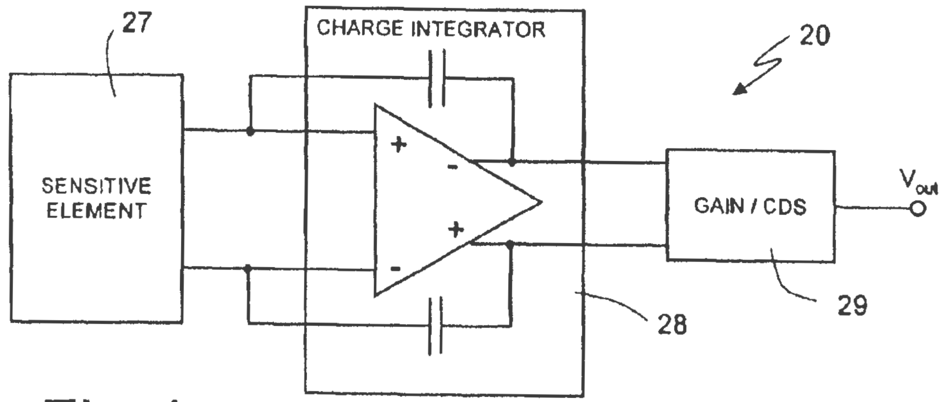


Fig.4

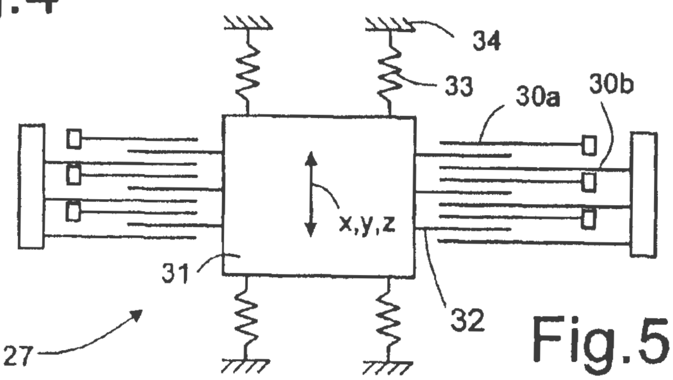


Fig.5

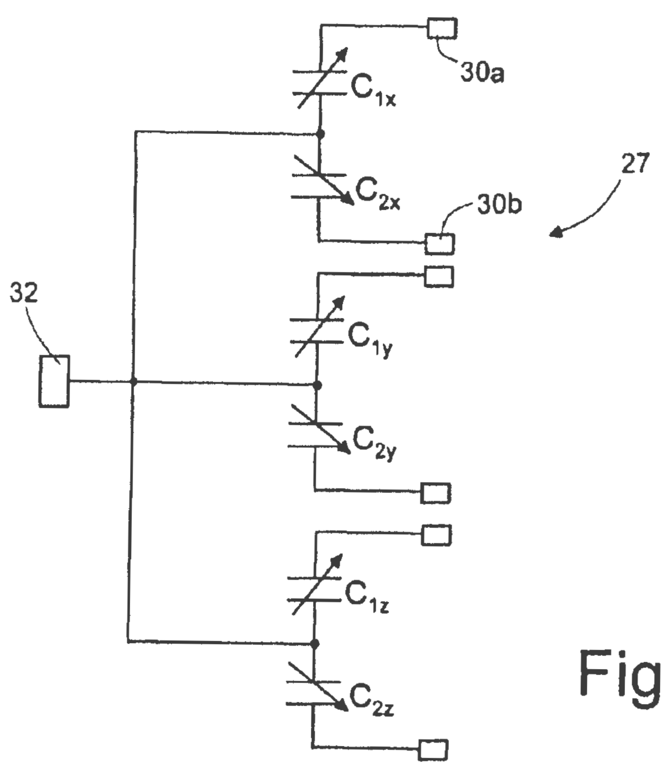


Fig.6

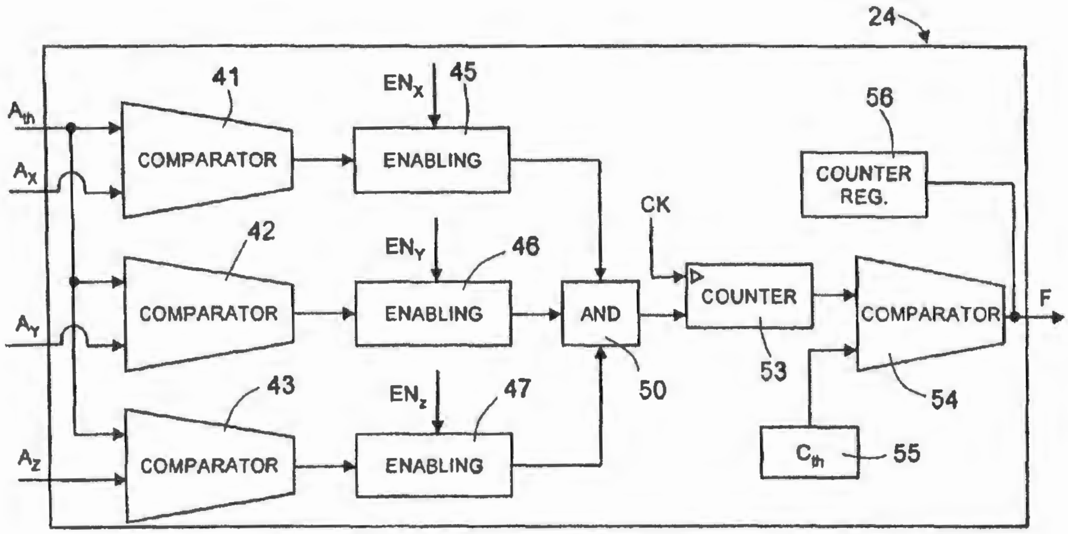

24
41
45
56
A_{th}
EN_X
COMPARATOR
ENABLING
COUNTER REG.
A_X
CK
42
EN_Y
46
A_Y
COMPARATOR
ENABLING
AND
COUNTER
COMPARATOR
F
53
50
54
43
EN_Z
47
A_Z
COMPARATOR
ENABLING
C_{th}
55

Fig.7

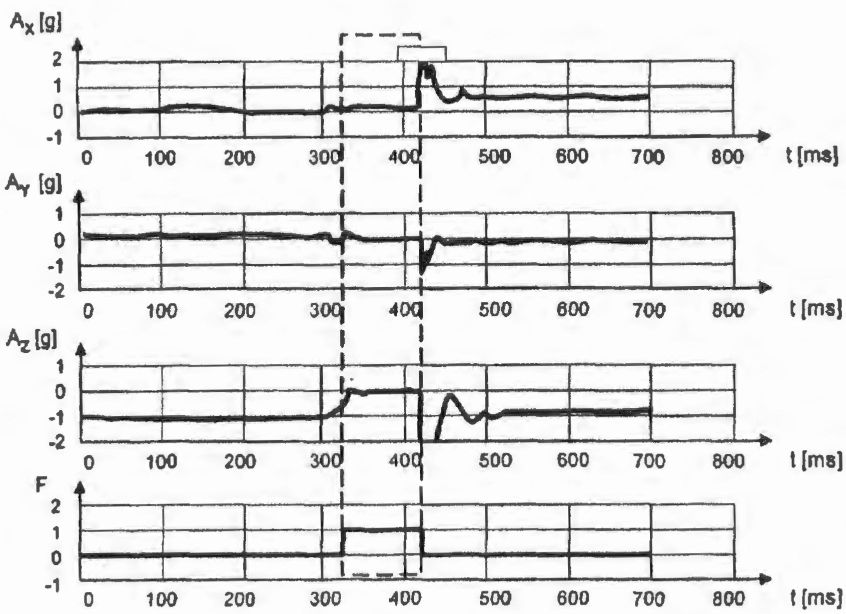

A_X [g]
A_Y [g]
A_Z [g]
F
t [ms]
0
100
200
300
400
500
600
700
800

Fig.8

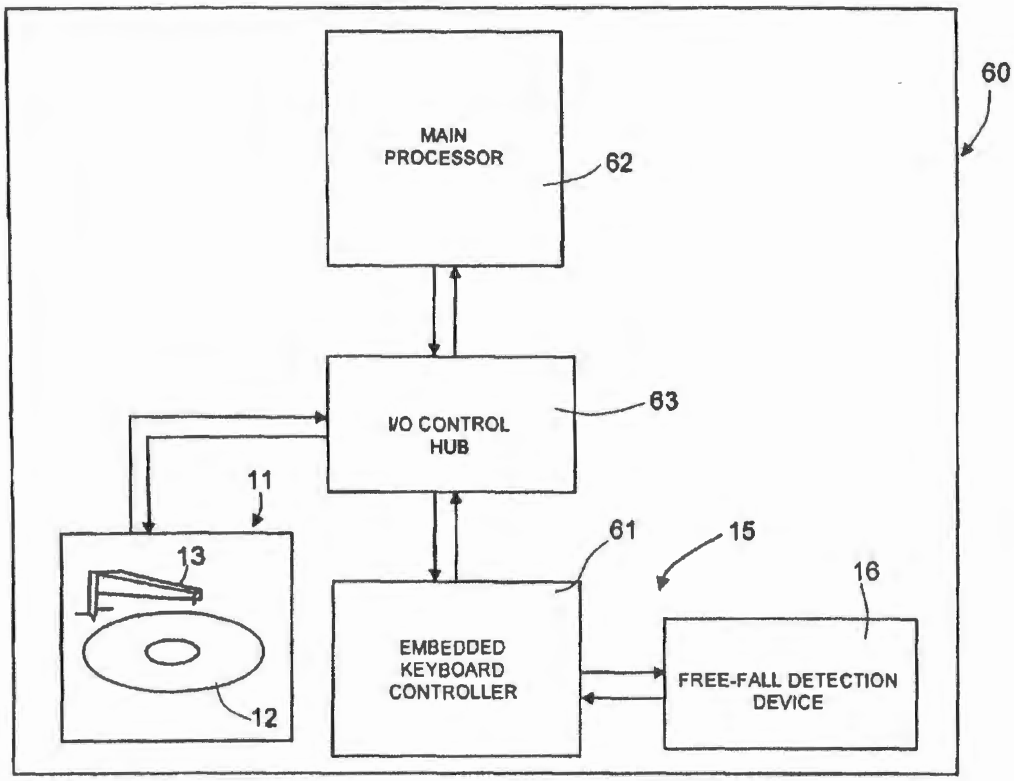

MAIN PROCESSOR
62
60
I/O CONTROL HUB
63
11
13
61
15
16
EMBEDDED KEYBOARD CONTROLLER
FREE-FALL DETECTION DEVICE
12

Fig.9

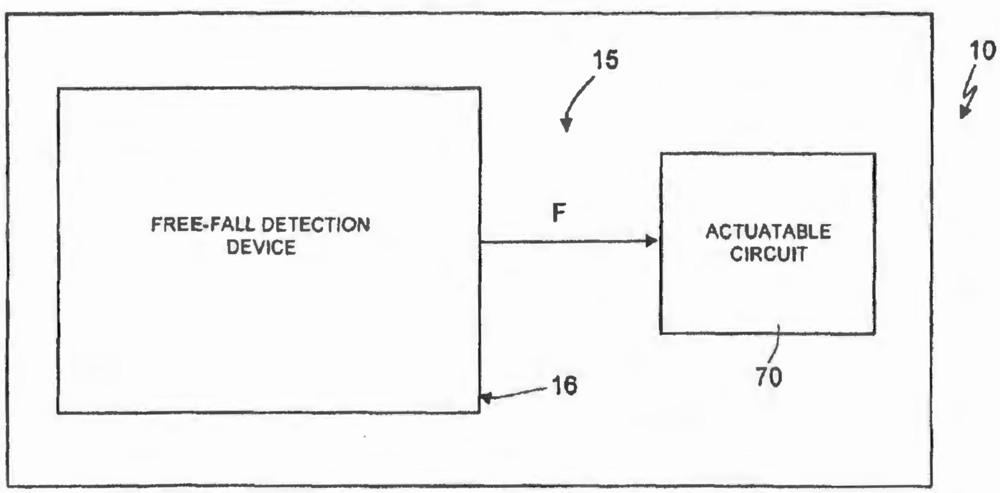

15
10
FREE-FALL DETECTION DEVICE
F
ACTUATABLE CIRCUIT
16
70

Fig.10

FREE-FALL DETECTION DEVICE AND FREE-FALL PROTECTION SYSTEM FOR A PORTABLE ELECTRONIC APPARATUS

RELATED APPLICATION

The present application claims priority of U.S. Provisional Patent Application No. 60/590,997 filed Jul. 26, 2004, entitled HDD FREE FALL PROTECTION SYSTEM IN PORTABLE PERSONAL ELECTRONIC DEVICES WITH 3 AXIS DIGITAL MEMS SENSOR, and also claims priority of Italian Patent Application No. TO2004A000436 filed Jun. 28, 2004, both applications being incorporated herein in their entireties by this reference.

FIELD OF THE INVENTION

The present invention relates to a free-fall detection device and to a free-fall protection system for a portable electronic apparatus, in particular for the protection of a mass-storage device (HDD—Hard Disk Drive) in the portable electronic apparatus, to which the following description will make explicit reference without this implying any loss of generality.

BACKGROUND OF THE INVENTION

As it is known, in portable mobile applications HDD devices are more and more frequently incorporated into personal electronic and personal computer products. This is because HDD high capacity, fast speed, and low price combination surpasses any other memory product, making them the best choice for data storage in portable apparatuses, such as laptop computers, Personal Data Assistants (PDAs), digital audio players, mobile phones, digital cameras, and the like.

FIG. **1** shows schematically the structure of a typical HDD device **1**. In a per se known manner, the HDD device **1** comprises: a rotating disk **2**, provided with a magnetic thin film as a data-storage medium and being rotated around an axis by a spindle motor (not shown); a read/write head **3** which is carried by an arm **4** and is suspended over the rotating disk **2**, and which comprises a magnetic transducer that magnetically transfers information to and from the data-storage medium; a voice coil motor driver **5** for moving and positioning the arm **4** over the rotating disk **2**; a parking ramp **6**; and a microprocessor controller **7** for controlling operation of the HDD device **1**, and particularly of the voice coil motor driver **5** and the spindle motor. When in operation, the read/write head **3** is positioned over specific locations of the rotating disk **2** for reading data from and writing data to the associated data-storage medium. Under certain circumstances, such as when the HDD device **1** is in power down or in low power consumption mode, the read/write head **3** is moved away from the surface of the rotating disk **2** and parked in a detent position at the parking ramp **6**.

Due to their portable nature, the above electronic portable apparatuses are accident prone and may easily undergo violent impacts, in particular in the case where they are dropped onto the floor during normal use. In the case of a fall, the impact of the portable apparatus with the ground has repercussions on the associated HDD device **1**, in the worst case producing damage and consequent permanent loss of data. In fact, the HDD device **1** is very sensitive to impact, in so far as, in order to ensure its proper operation, the read/write head **3** is normally kept at a very small distance from the associated data-storage medium. Consequently, in the case of an impact,

the read/write head **3** collides with and may get damaged together with the data-storage medium, causing irreversible loss of the data stored within.

To prevent, or at least limit, the occurrence of the above destructive events, HDD protection systems based upon the detection of a condition of free-fall of the portable apparatuses have been proposed.

As it is known, an object is considered to be in free-fall when it is falling under the only influence of gravity; in other words, any object which is moving and being acted upon the sole force of gravity is said to be in a state of free-fall. The following is the module of the free-fall equation of an object which is in free-fall condition, assuming a zero velocity at the beginning of the fall:

$$h = \frac{1}{2} \cdot g \cdot t^2$$

where h is the initial height of the fall, g is the acceleration of gravity (9.81 m/s^2), and t is the fall time. By way of example, and using the above equation, a fall time of about 378 ms can be calculated from a typical desktop height of about 0.7 m. An impact deceleration force can also be calculated using the following equation:

$$A = \frac{\pi \cdot R \cdot \sqrt{2 \cdot g \cdot h}}{2 \cdot t}$$

The table of FIG. **2** shows the impact deceleration force A (normalized to the g value), and fall time t based on the height h of the fall, assuming a rebound factor of 1.5 (where 1 means no rebound, and 2 means 100% rebound) and a shock duration of 2 ms.

In particular, following upon a free-fall detection, the above HDD protection systems issue appropriate actions for protecting the electronic portable apparatus, e.g. they command for retracting the read/write head **3** from the disk surface up to the positioning ramp **6**. As a result, upon impacting the ground of the HDD device **1**, the read/write head **3** and the rotating disk **2** do not collide, thus preventing the HDD device **1** from damage, or in any case limiting the extent of such damage.

For example, considering that a typical HDD device of a portable PC system can sustain 800 g non operating shocks and 225 g operating shocks, from the above table it follows that the HDD device can sustain impact if it falls from height below 0.178 m. The HDD device can not sustain impact if it falls from height above 2.282 m, because the impact deceleration force A is over the non operating shock level. With the above protection systems, the HDD device may sustain fall impact between 0.178 m to 2.282 m by placing the read/write head 3 to the ramp position, therefore greatly reducing the possibility of damage and loss of data.

In greater detail, the free-fall condition of the portable electronic apparatus is detected by using an acceleration sensor, fixed to the portable electronic apparatus. In particular, a free-fall condition is detected when the magnitude of the acceleration vector calculated from the acceleration sensor output falls within a preset range of values. In general, since it is not possible to determine the orientation of the portable apparatus during its free-fall, a three-axis acceleration sensor is used, the acceleration vector being the vector sum of the acceleration components along three mutually orthogonal axes.

To obtain an efficient protection against impact, the free-fall condition must be detected in the shortest time possible so as to enable subsequent activation of the appropriate actions of protection. In known HDD protection systems, a microprocessor is used to poll and to acquire the acceleration sensor outputs, to calculate the acceleration vector and its magnitude, and to compare the calculated magnitude against to a pre-programmed threshold value. In particular, the main microprocessor of the portable electronic apparatus that it is desired to protect or the controller of the HDD device, or even a dedicated microprocessor are used for this purpose.

A solution of this sort does not always enable detection of the condition of free-fall with a promptness sufficient to prevent damage to the portable electronic apparatuses. In fact, if the main microprocessor of the portable electronic apparatus, or the microprocessor of the HDD device controller are used, the same microprocessors must perform a plurality of functions, and are used in "time sharing" by the various resources and cannot dedicate the majority of their computing power and time to monitoring the output of the accelerometer. It follows that the free-fall event can occur during a time interval in which the microprocessor is occupied to manage other resources, and the free-fall can thus be detected too late to avoid damage to the portable electronic apparatus. Also, even if a dedicated microprocessor is used (solution that can be anyway too expensive for most applications), if the free-fall event happens in between two consecutive acquisition cycles, there is a latency time before the free-fall event can be reported (the worst latency time being a full sample time interval). In addition to this latency time, microprocessor instructions execution time (e.g. for the calculation of the vector sum and magnitude thereof) also needs to be accounted for the overall free-fall detection time.

The aim of the present invention is to provide a free-fall detection device and a free-fall protection system for a portable electronic apparatus which are free from the drawbacks referred to above and in particular operate in a more reliable way, and allow for a prompter detection of a free-fall condition of the portable electronic apparatus.

SUMMARY OF THE INVENTION

According to the present invention relates to a free-fall detection device for a portable apparatus which includes an acceleration sensor which generates a first acceleration signal and a second acceleration signal correlated to a respective component of a sensed acceleration along a respective detection axis, and also includes a free-fall detection module connected to the acceleration sensor. The device is configured to conduct a comparison between each of the first and second acceleration signals and a respective acceleration threshold and generate a free-fall detection signal according to the result of both comparisons.

The present invention further relates to a free-fall protection system for a portable apparatus which includes a free-fall detection device which issues a warning signal upon detecting a free-fall condition of the portable apparatus. The protection device which is connected to the free-fall detection device is configured to activate protection actions for the portable apparatus upon receiving the warning signal.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, preferred embodiments thereof are now described, purely by way of non-limiting example and with reference to the attached drawings, wherein:

FIG. **1** shows a schematic representation of a Hard Disk Drive device of a known type;

FIG. **2** is a table showing values of free-fall related quantities as a function of the height of the fall;

FIG. **3** is a block diagram of a portable electronic apparatus provided with a free-fall protection system according to the present invention;

FIGS. **4**-**6** are schematic representations of a linear accelerometer of a MEMS type ;

FIG. **7** is a more detailed block diagram of a free-fall detection circuit in the system of FIG. **3**;

FIG. **8** shows time plots of some quantities associated to the system of FIG. **3**;

FIG. **9** shows an example of application of the free-fall protection system according to the invention; and

FIG. **10** is a block diagram of a different embodiment of the free-fall detection system according to the present invention.

DETAILED DESCRIPTION

FIG. **3** is a schematic illustration of a portable electronic apparatus **10** provided with a Hard Disk Drive device **11** comprising in a known way a data-storage medium **12** and a read/write head **13**, and with a free-fall protection system **15**, which is connected to the HDD device **11** and is configured to protect the Hard Disk Drive device **11** from a free-fall event.

In detail, the free-fall protection system **15** comprises a free-fall detection device **16** and a processor unit **18**, connected to the free-fall detection device **16**, and to the Hard Disk Drive device **11**. The processor unit **18** can be a microprocessor, a digital signal processor (DSP), a microcontroller, a ASIC (Application Specific Integrated Circuit), or any other type of integrated processing unit. In particular, the free-fall detection device **16** is connected at output to an interrupt input of the processor unit **18**.

The free-fall detection device **16** comprises: an accelerometer **20** of the linear type; a register array **21** connected to the output of the accelerometer **20**; a threshold register **22**; and a free-fall detection circuit **24** connected to the register array **21** and to the threshold register **22**. The free-fall detection device **16** further comprises an interface **25** (e.g. a I2C/SPI interface), arranged between the processor unit **18** and the register array **21** and the threshold register **22**. In particular, all the components of the free-fall detection device **16** are conveniently integrated in a single chip of semiconductor material.

The accelerometer **20** is of a known type, including a MEMS (Micro-Electro-Mechanical-Systems) structure based on the semiconductor technology, and has three detection axes x, y and z so as to generate three acceleration signals A_x, A_y, A_z, each correlated to the acceleration detected along a respective detection axis. For example, the accelerometer **20** can be realized as described in "3-axis digital output accelerometer for future automotive applications", B. Vigna et al., AMAA 2004.

In brief, in a per se known manner, FIG. **4**, the accelerometer **20** is made up of a sensitive element **27**, which detects acceleration and generates an electrical signal correlated to the detected acceleration, and an electronic circuit for conditioning the electrical signal, which typically comprises a charge integrator **28** and a gain and noise-cancelling stage **29** (in particular, using the Correlated Double Sampling or CDS technique), which supplies an output signal V_{out}. As illustrated schematically in FIG. 5 (that refers to a uniaxial MEMS accelerometer for sake of clarity of illustration), the sensitive element 27 comprises a stator, of which only first and second fixed electrodes 30a, 30b are illustrated, and a rotor formed by a moving element 31 and mobile electrodes 32 fixed to the moving element 31, and each arranged between a respective first fixed electrode 30a and a respective second fixed electrode 30b. The moving element 31 is suspended by means of springs 33 to anchorage elements 34, so as to be movable along a detection axis.

As illustrated in FIG. 6, the electrical equivalent circuit of the sensitive element 27 can be represented schematically with first capacitors C_{1x}, C_{1y}, C_{1z} and second capacitors C_{2x}, C_{2y}, C_{2z}, one for each detection axis x, y, z; each one of the first capacitors being arranged in series with a respective one of the second capacitors, the capacitances of which being variable according to the distance between the mobile electrodes 32 and the fixed electrodes 30a, 30b and hence according to the displacement of the rotor with respect to the stator.

When the linear accelerometer 20 is subjected to an acceleration along a detection axis x, y, z, the moving element 31 moves along said axis, consequently a capacitive unbalancing is generated between the related first and second capacitors. This capacitive unbalancing is detected by the conditioning electronic circuit, which hence supplies at output the signal V_{out}.

In particular, the displacement of the moving element 31 occurs also in presence of a static acceleration (for example the acceleration of gravity), generating a corresponding capacitive unbalancing which is detected by the conditioning electronic circuit. It follows that, even in the resting condition, a non-zero acceleration is detected. Instead, during a free-fall, the displacement of the moving element 31 with respect to a reference system fixed with respect to the stator, which is also in free-fall, is zero (the mobile electrodes 32 remain centered with respect to the respective fixed electrodes 30a, 30b), so that the detected acceleration is almost (due to air friction) equal to zero.

In particular, the accelerometer 20 senses the movements of the electronic portable apparatus 10 and generates the corresponding acceleration signals A_x, A_y, A_z, which are sampled and hold in the register array 21. As will be described in greater detail hereinafter, the free-fall detection circuit 24 compares each one of the acceleration signals A_x, A_y, A_z with a preset acceleration threshold A_{th}, stored in the threshold register 22, and generates a free-fall detection signal F, if certain conditions are met which are indicative of a free-fall event. The free-fall detection signal F is then sent to an output 26 of the free-fall detection device 16, to be sent in real time to the processor unit 18, as an interrupt signal for immediately activating appropriate actions for protecting the portable electronic apparatus 10. A typical action is to issue a command to the HDD device 11 through an industrial standard interface (such as ATA or SATA), for controlling a forced parking of the read/write head 13 in a safe position of the HDD device 11. Therefore, upon impacting the ground, the read/write head 13 and the data-storage medium 12 will not collide against each other, and damage to the HDD device 11 will be prevented.

The processor unit 18 can also access the data stored in the register array 21 through the interface 25, and program the acceleration threshold A_{th} by writing in the threshold register 22.

In detail, as shown in FIG. 7, the free-fall detection circuit 24 comprises a first threshold comparator 41, a second threshold comparator 42, and a third threshold comparator 43. The threshold comparators 41-43 receive at their inputs a respective acceleration signal A_x, A_y, A_z from the accelerometer 20, and the acceleration threshold A_{th} from the threshold register 22. The threshold comparators 41-43 compare the absolute value of the respective acceleration signal A_x, A_y, A_z with the acceleration threshold A_{th} and output a respective logic signal, for example of a high value, if the absolute value of the respective acceleration signal A_x, A_y, A_z is smaller than the acceleration threshold A_{th}.

The free-fall detection circuit 24 further comprises three enabling stages 45, 46 and 47. In detail, each enabling stage 45-47, preferably made using logic gates, receives at its input the output of a respective threshold comparator 41-43 and an enabling signal EN_x, EN_y, EN_z, of a logic type. When the enabling signal EN_x, EN_y, EN_z assumes a first logic value, for example high, the respective enabling stage 45-47 outputs the logic signal received by the respective threshold comparator 41-43. Otherwise, when the enabling signal EN_x, EN_y, EN_z assumes a second logic value, in the example low, the enabling stage 45-47 outputs a constant logic signal of a high value.

The free-fall detection circuit 24 further comprises a three-input AND logic gate 50, receiving the outputs of the enabling stages 45-47; a counter 53, receiving the logic signal outputted by the AND logic gate 50 as count-enable signal and a clock signal CK generated in a per se known manner; and a threshold comparator 54, receiving the count signal generated by the counter 53 and a count threshold C_{th}, the latter being settable by writing in a dedicated register 55. In particular, the counter 53 is reset when the logic signal at the output of the AND logic gate 50 has a first logic value, for example low, while it is enabled for counting when the logic signal at the output of the AND logic gate 50 has a second logic value, for example high. The threshold comparator 54 outputs the free-fall detection signal F, which is supplied to the output 26 (FIG. 3) of the free-fall detection device 16, connected to the processor unit 18.

Finally, the free-fall detection circuit 24 comprises a counter register 56 connected to the output of the threshold comparator 54 for storing the free-fall detection signal F.

Operation of the free-fall detection circuit 24 is described hereinafter.

In particular, the principle of operation of the detection circuit 24 follows from the observation that, for any object in steady state, and thus subject to the only acceleration of gravity, it cannot happen that the acceleration along three mutually orthogonal axes x, y and z is lower than $1/\sqrt{3}\cdot g$ (0.577 g) at the same time. This is valid independently of the object orientation in the three-dimensional space. In fact, the magnitude A of the acceleration vector acting on the free-falling object can be calculated from the acceleration components along the three mutually orthogonal axes (acceleration signals A_x, A_y, A_z), with the following equation:

$$A=\sqrt{A_x^2+A_y^2+A_x^2}$$

Since the object is subject to the only acceleration of gravity, the value of the magnitude A must be equal to 1 g, and the minimum value that added three times gives 1 g is the afore said amount $1/\sqrt{3}\cdot g$ of 0.577 g. That is, in case the acceleration along one of the three orthogonal axes is lower than 0.577 g, the acceleration along at least one of the other two axes must be bigger than the above value 0.577 g to satisfy the equation.

The obtained number thus constitutes a good acceleration threshold A_{th} for free-fall detection. In fact, to detect a free-fall event it is enough to acquire the acceleration values for the three detection axes x, y and z and check that their absolute values are at the same time lower than 0.577 g. Of course this value must be considered as a theoretical upper limit and a safeguard is needed to avoid false detections. Taking into account accelerometer offset accuracy and offset thermal drift, the value of the acceleration threshold A_{th} is preferably set to 0.350 g. This value enables identification of the free-fall condition for any direction of free-fall of the portable apparatus **10** and it is at the same time insensitive to offsets due, for example, to temperature variations, component ageing, etc. In order for the above considerations to apply, the accelerometer **20** is preferably to be mounted close to the center of mass of the portable electronic apparatus **10**, to reduce any centripetal acceleration, if the apparatus rotates during the free-fall.

It follows that during free-fall, each one of the acceleration signals A_x, A_y, and A_z has an absolute value which is smaller than the acceleration threshold A_{th} set via the threshold register **22**. Therefore, the outputs of the threshold comparators **41-43**, and hence the logic signal at the output of the AND logic gate **50** assume a high logic value. The counter **53** is enabled for counting, increasing the count signal at each switching of the clock signal CK. When the generated count signal exceeds the count threshold C_{th}, the signal at the output of the threshold comparator **54**, i.e., the free-fall detection signal F, switches to the high logic state. The microprocessor circuit **18** then receives the free-fall detection signal F as interrupt signal, and consequently issues a control signal for undertaking the appropriate actions to protect the portable apparatus **10**, and particularly the HDD device **11** from impact.

By appropriately setting the count threshold C_{th}, possible false indications of free-fall, due for example to vibrations of the table on which the portable electronic apparatus **10** is resting or to movements of the person who is using the portable electronic apparatus **10**, do not cause switching of the free-fall detection signal F, and hence undesired parking of the read/write head **13**. In fact, said false indications of free-fall have a duration smaller than the time interval corresponding to the count threshold C_{th}, and hence the free-fall detection signal F at the output of the threshold comparator **54** does not switch to the high logic value. For example, the count threshold C_{th} can be set to a value corresponding to 8 ms.

In addition, via the enabling signals EN_x, EN_y, EN_z supplied to the enabling stages **45-47** it is possible to disable detection of acceleration along a respective detection axis. In fact, only when said enabling signals EN_x, EN_y, EN_z assume a given logic value, for example high, is the logic signal at output from the respective threshold comparator **41-43** sent to the AND logic gate **50**. This is useful when it is certainly known what the orientation assumed by the portable electronic apparatus **10** will be during free-fall, in order to disable the detection axis or axes that is or are not important for the purposes of free-fall detection.

FIG. **8** illustrates by way of example time plots of the acceleration signals A_x, A_y, and A_z and of the free-fall detection signal F during a free-fall event of a portable electronic apparatus which is dropped from a typical desk height (about 70 cm). In particular, the free-fall event is highlighted by a dashed rectangle, while the following time interval corresponds to the portable electronic apparatus impacting to the ground.

The response times of the free-fall detection device **16** are very short and enable suitable actions for protecting the portable apparatus **10** to be carried out promptly.

Consider, by way of example, the case of a portable apparatus provided with hard disk which drops onto the floor from a height of one meter. The fall time t is calculated using the equation:

$$t = \sqrt{2 \cdot \frac{h}{g}}$$

where h is the initial height of the fall. Substituting the numeric values, a fall time of approximately 450 ms is obtained.

The response time of the free-fall detection device **16** for detecting the free-fall event is approximately 5 ms, the waiting time to prevent false free-fall indications is set to 8 ms (a value corresponding to the count threshold C_{th}), and the time necessary for the processor unit **18** to receive the free-fall detection signal F and to issue an appropriate signal for controlling parking in a safe position of the read/write head **13** of the hard disk **11** is approximately 2 ms. Considering moreover a time approximately of 30 ms for parking the read/write head **13**, it follows that the time necessary for bringing the portable electronic apparatus **10** into a safe position is equal to approximately 45 ms, i.e., much less than the fall time calculated previously.

FIG. **9** illustrates by way of example the application of the free-fall protection system **15** in a typical architecture of a portable PC **60**. Since the above architecture is of a known type, only the elements directly related to the operation of the free-fall protection system **15** are illustrated.

In detail, the free-fall detection device **16** is connected to an embedded keyboard controller **61** provided internally with a microprocessor (corresponding to the processor unit **18**). The embedded keyboard controller **61** is connected to a main processor **62** of the portable PC **60**, through a I/O control hub **63** (e.g. ICH4-M). The main processor **62** is connected to HDD device **11** of the portable PC **60** through the I/O control hub **63** and a standard interface, for example an ATA interface.

At power on, the embedded keyboard controller **61** initializes the free-fall detection device **16**, programs the acceleration threshold A_{th} through the interface **25**, and enables the interrupt feature. Then, upon detecting a free-fall event, the free-fall detection device **16** causes the free-fall detection signal F to switch to the high logic level, and issues it as interrupt signal to the microprocessor of the embedded keyboard controller **61**. The latter interrupts the main processor **62**, which immediately issues an unload command to the HDD device **11** through the I/O control hub **63** and the standard interface, to park the read/write head **13**. Then, the main processor **62** executes code to monitor the free-fall condition. In particular, no access to the HDD device **11** is allowed during the period preceding the predicted ground impact. After the impact, the main processor **62** monitors the settlement of the electronic portable apparatus **10**, through the accelerometer **20** of the free-fall detection device **16** and unparks the read/write head **13** when it is considered safe to resume operations.

The free-fall detection device described above has the following advantages.

First, it is possible to detect a free-fall event with extremely short response times, so as to ensure an efficient protection for the portable apparatuses, and in particular for the associated data-storage devices. In fact, the free-fall detection device operates in real time mode, since the free-fall detection is executed by a purely hardware circuit and all the operations linked to free-fall detection are incorporated in a single integrated device, so that further processing by a processor unit in the portable apparatus is not required. In particular, the digital data provided by the accelerometer **20** are compared with the acceleration threshold A_{th} and the free-fall detection signal F is generated completely by hardware without any instructions latency. Therefore, the operating frequency of the processor unit **18** is not critical and there is no lengthy instruction execution time, as compared to known systems (in particular for the acquisition in polling of the acceleration data, and the pretty cumbersome computation of the acceleration magnitude). The generated free-fall detection signal F is issued in real time as an interrupt digital signal to the processor unit **18**, and so there is no interface delay between the processor unit **18** and the free-fall detection device **16**.

Furthermore, the free-fall detection device makes it possible to distinguish and ignore any false detection of free-fall, thus rendering the detection of free-fall extremely reliable.

The described free-fall detection device can advantageously be used for proving the occurrence of an impact following upon a free-fall. This is useful for example in the analysis of apparatuses returned for technical assistance on account of operating faults. It is in fact possible, by reading the contents of the counter register **56**, wherein the free-fall detection signal F is stored, to verify whether the presumed faults are in fact due to a destructive event. In the case where the above register is a counter, it is also possible to know the number of impacts that the portable apparatus has undergone.

Furthermore, the free-fall detection device can be used for gathering the height from the ground from which the portable apparatus has fallen, by calculating in a known way the duration of the free-fall (for example, by starting a counter at the instant of detection of free-fall, which corresponds to the switching of the free-fall detection signal F, and stopping it at the instant of impact with the ground, which can be detected in a known way).

Even though the free-fall detection device must be permanently supplied, its circuit simplicity renders power consumption practically negligible, i.e., such as not to influence significantly the consumption of the battery that supplies it. In particular, it is possible to place the system in power saving mode, in order to minimize power consumption.

Also, the use of a three-axis accelerometer for the detection of the free-fall event, allows for a successful free-fall detection independently of the spatial orientation that the portable electronic apparatus may have when it starts falling.

Finally, it is clear that modifications and variations may be made to what has been described and illustrated herein, without thereby departing from the scope of the present invention, as defined in the attached claims.

In particular, the processor unit **18** can be implemented by a dedicated processor, or any other processor unit, such as the main processor in the portable electronic apparatus, or the HDD device controller. Also, the parking command for the read/write head **13** of the HDD device **11** can be issued by another processor alerted by processor unit **18**.

The components of the free-fall detection device **16** could be integrated in different dice of semiconductor material, which could be assembled in a single package.

Furthermore, even if a count threshold C_{th} has been provided to avoid possible free-fall false detections, it is possible to provide for an immediate detection of the free-fall event, by directly connecting the output of the AND logic gate **50** to the interrupt input of the processor unit **18**, in order to further reduce the response time of the free-fall detection device **16**.

Also, even if a three-axis accelerometer is in general required to detect the free-fall event independently of the spatial orientation that the portable electronic apparatus may have when it starts falling, theoretically a two- or even single axis accelerometer could be used, in case the above orientation is known and forced. If cost is a concern for the overall free-fall protection system, an analog accelerometer could be used, with the drawback of a certain performance degradation in terms of response time.

Furthermore, the free-fall detection signal F generated in a continuous way by the free-fall detection device **16** could not be used as interrupt for a processor unit, but directly activate appropriate protection actions. For example, the above signal could directly control a switch designed to disable a given function within the portable electronic apparatus, or else control turning-on of a warning light, or emission of an alarm sound signal upon detection of the free-fall. In general, as shown in FIG. **10**, the free-fall detection signal F could directly control an actuatable circuit **70** in the portable electronic apparatus **10**, configured to activate appropriate protection actions for the portable electronic apparatus **10**.

The entire free-fall protection system could also be arranged inside the HDD device **11**. In this case, the chip of the free-fall detection device **16** is mounted to a printed circuit board of the HDD device **11**, together with the control circuit of the HDD device **11**. The free-fall detection signal F could directly be received and interpreted by the control circuit of the HDD device **11**, to instantaneously park the read/write head **13**.

In addition, different acceleration thresholds can be used for the various detection axes. Also, the accelerometer **20** could be different from the one described.

Two threshold comparators for each detection axis can be used, one for the free-fall detection, as described previously, and the other, in a known way, for the detection of impact ("shock detector") so as to integrate in a single device all functions required for protecting mass-storage devices in portable apparatuses.

Finally, the protection actions initiated by the free-fall protection system are not limited to the parking of the read/write head of the HDD device. For example, upon detecting of the free-fall condition, the spindle motor of the HDD device could be controlled to stop the rotating disk spinning movement, or, as another example, for a portable PC designed for rugged environment, air bag technology employed in automotive industry could be applied.

While there have been described above the principles of the present invention in conjunction with specific components, circuitry and bias techniques, it is to be clearly understood that the foregoing description is made only by way of example and not as a limitation to the scope of the invention. Particularly, it is recognized that the teachings of the foregoing disclosure will suggest other modifications to those persons skilled in the relevant art. Such modifications may involve other features which are already known per se and which may be used instead of or in addition to features already described herein. Although claims have been formulated in this application to particular combinations of features, it should be understood that the scope of the disclosure herein also includes any novel feature or any novel combination of features disclosed either explicitly or implicitly or any generalization or modification thereof which would be apparent to persons skilled in the relevant art, whether or not such relates to the same invention as presently claimed in any claim and whether or not it mitigates any or all of the same technical problems as confronted by the present invention. The applicants hereby reserve the right to formulate new claims to such features and/or combinations of such features during the prosecution of the present application or of any further application derived therefrom.

The invention claimed is:

1. A free-fall detection device for a portable apparatus comprising:

an acceleration sensor generating first, second, and third acceleration signals correlated to a respective component of a sensed acceleration along a respective detection axis; and

a free-fall detection module coupled to said acceleration sensor, wherein said free-fall detection module is configured to carry out a comparison between each one of said first, second, and third acceleration signals and a respective acceleration threshold, and to generate a free-fall detection signal according to the result of all three comparisons, wherein said free-fall detection signal has a first logic value indicative of a free-fall condition in the event that said first, second and third acceleration signals are all simultaneously lower than the respective acceleration threshold.

2. The device of claim 1, wherein said respective acceleration threshold is not higher than $1/\sqrt{3}\cdot g$.

3. The device of claim 2, wherein said respective acceleration threshold is equal to 350 mg.

4. The device of claim 1, wherein said free-fall detection module comprises a dedicated hardware circuit generating in a continuous way and in real-time said free-fall detection signal.

5. The device of claim 4, wherein said acceleration sensor and said dedicated hardware circuit are integrated in a single chip, said acceleration sensor being made as a Micro-Electro-Mechanical-System.

6. The device of claim 4 for a portable apparatus provided with a processor unit, wherein said dedicated hardware circuit has an output supplying said free-fall detection signal and configured to be connected to said processor unit.

7. The device of claim 4, wherein said dedicated hardware circuit comprises a comparison stage to carry out said comparison, and a detection stage connected to said comparison stage and generating said free-fall detection signal.

8. The device of claim 7, wherein said comparison stage comprises a threshold comparator for each of said acceleration signals, each of said threshold comparators receiving one respective of said acceleration signals and said respective acceleration threshold, and generating at output a respective logic signal; and wherein said detection stage comprises an AND logic gate receiving said logic signals.

9. The device of claim 8, wherein said detection stage further comprises false-detection rejecting means, connected to said AND logic gate and outputting said free-fall detection signal.

10. The device of claim 9, wherein said false-detection rejecting means comprise a counter receiving a clock signal and the logic signal outputted by said AND logic gate as count-enable signal; and a threshold comparator receiving the count signal generated by said counter and a count threshold, said threshold comparator generating said free-fall detection signal.

11. The device of claim 10, further comprising a first storage means for storing said respective acceleration threshold.

12. The device of claim 4, wherein said dedicated hardware circuit further comprises an enabling stage, which is connected to said comparison stage and receives an enabling signal for each of said detection axes; said enabling stage being configured to enable/disable detection of free-fall along each of said detection axes.

13. The device of claim 4, wherein said dedicated hardware circuit further comprises second storage means for storing the occurrence of said free-fall detection signal.

14. A free-fall protection system for a portable apparatus, comprising:

(a) a free-fall detection device configured to issue a warning signal upon detecting a free-fall condition of said portable apparatus, including:

(i) an acceleration sensor generating first, second, and third acceleration signals correlated to a respective component of a sensed acceleration along a respective detection axis; and

(ii) a free-fall detection module coupled to said acceleration sensor, to carry out a comparison between each one of said first, second, and third acceleration signals and a respective acceleration threshold, and to generate a free-fall detection signal according to the result of all three comparisons for generating a free-fall detection signal, wherein said free-fall detection signal has a first logic value indicative of a free-fall condition in the event that said first, second and third acceleration signals are all simultaneously lower than the respective acceleration threshold; and

(b) a protection device connected to said free-fall detection device and configured to activate protection actions for said portable apparatus upon receiving said warning signal.

15. The system of claim 14, wherein said protection device comprises a processor unit connected to an output of said free-fall detection device and having an interrupt input, said processor unit receiving at said interrupt input said warning signal for activating said protection actions.

16. The system of claim 15, wherein said free-fall detection device comprises first storage means for storing said respective acceleration threshold, and wherein said processor unit is further connected to said first storage means to program said respective acceleration threshold.

17. The system of claim 14 further comprising a data-storage device, wherein said protection device is configured to be connected to said data-storage device and said protection actions are intended to protect said data storage device from damage due to said free-fall condition.

18. The system of claim 17, wherein said data-storage device comprises a read/write head, and said protection actions comprise issuing a command for parking said read/write head in a safe position of said data-storage device.

19. A portable apparatus, comprising:

(a) a free-fall detection device configured to issue a warning signal upon detecting a free-fall condition of said portable apparatus, comprising:

(i) an acceleration sensor generating first, second, and third acceleration signals correlated to a respective component of a sensed acceleration along a respective detection axis; and

(ii) a free-fall detection module coupled to said acceleration sensor, to carry out a comparison between each one of said first, second, and third acceleration signals and a respective acceleration threshold, and to generate a free-fall detection signal according to the result of all three comparisons for generating a free-fall detection signal, wherein said free-fall detection signal has a first logic value indicative of a free-fall condition in the event that said first, second and third acceleration signals are all simultaneously lower than the respective acceleration threshold; and

(b) a protection device connected to said free-fall detection device and configured to activate protection actions for said portable apparatus upon receiving said warning signal.

20. The apparatus of claim **19**, further comprising a data storage device having a read/write head and wherein said protection device further comprises a processor unit, wherein said processor until controls a displacement of said read/write head according to said warning signal.

21. The apparatus of claim **20**, wherein said free-fall detection device and said protection device are arranged within said data-storage device.

22. The apparatus of claim **21**, wherein said apparatus is selected from the group consisting of laptop computers, personal data assistants, digital audio players, mobile phones, and digital cameras.

23. A data storage device comprising:

(I) a data storage medium;

(II) a read/write head associated with said data storage medium; and

(III) a free-fall protection system comprising:

(a) a free-fall detection device configured to issue a warning signal upon detecting a free-fall condition of said data-storage device, comprising:

(i) an acceleration sensor generating first, second, and third acceleration signals correlated to a respective component of a sensed acceleration along a respective detection axis; and

(ii) a free-fall detection module coupled to said acceleration sensor to carry out a comparison between each one of said first, second, and third acceleration signals and a respective acceleration threshold and to generate a free-fall detection signal, wherein said free-fall detection signal has a first logic value indicative of a free-fall condition in the event that said first, second and third acceleration signals are all simultaneously lower than the respective acceleration threshold; and

(b) a protection device connected to said free-fall detection device and configured to activate protection actions for said data storage device upon receiving said warning signal.

24. The data storage device of claim **23**, wherein said free-fall protection system controls a parking of said read/write head in a safe position upon detecting said free-fall condition.

25. A method for protecting a portable electronic apparatus from a free-fall event comprising:

detecting a free-fall condition of said portable electronic apparatus based on an acceleration of said portable electronic apparatus; wherein said detecting a free-fall condition comprises:

acquiring first, second, and third acceleration signals correlated to a respective component of said acceleration along a respective detection axis;

comparing each one of said first, second, and third acceleration signals with a respective acceleration threshold;

detecting said free-fall condition according to the result of all three comparisons;

activating protection actions for said portable apparatus upon detection of said free-fall condition; and

generating a free-fall detection signal, wherein said free-fall condition is detected in the event that all three said acceleration signals are simultaneously lower than the respective acceleration threshold.

26. The method according to claim **25**, wherein said free-fall condition is detected in the event said acceleration signals are simultaneously lower than the respective acceleration threshold for a preset time interval.

27. The method according to claim **25**, wherein said portable apparatus includes a processor unit and the activating step includes issuing an interrupt to said processor unit.

* * * * *

EXHIBIT G

US007409291B2

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Pasolini et al.

(10) **Patent No.:** **US 7,409,291 B2**
(45) **Date of Patent:** **Aug. 5, 2008**

(54) **DEVICE FOR AUTOMATIC DETECTION OF STATES OF MOTION AND REST, AND PORTABLE ELECTRONIC APPARATUS INCORPORATING IT**

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(22) Filed: **Feb. 26, 2004**

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(51) **Int. Cl.**
G01C 21/00 (2006.01)

(52) **U.S. Cl.** .... **701/220**; 700/245; 74/5 R

(58) **Field of Classification Search** .... 700/245, 700/258, 108, 67; 701/220; 74/5 R, 5.34, 74/5.46

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,490,719 A *	1/1970	Volpe et al.	....	244/169
4,823,626 A *	4/1989	Hartmann et al.	....	74/5.34
5,788,273 A *	8/1998	Jeenicke et al.	....	280/735
6,320,822 B1 *	11/2001	Okeya et al.	....	368/66
6,463,347 B1	10/2002	Nevruz et al.		
6,463,357 B1 *	10/2002	An et al.	....	700/245
6,512,310 B1 *	1/2003	Ohnishi	....	307/121
6,738,214 B2 *	5/2004	Ishiyama et al.	....	360/75
6,858,810 B2 *	2/2005	Zerbini et al.	....	200/61.08
2002/0033047 A1 *	3/2002	Oguchi et al.	....	73/514.16

* cited by examiner

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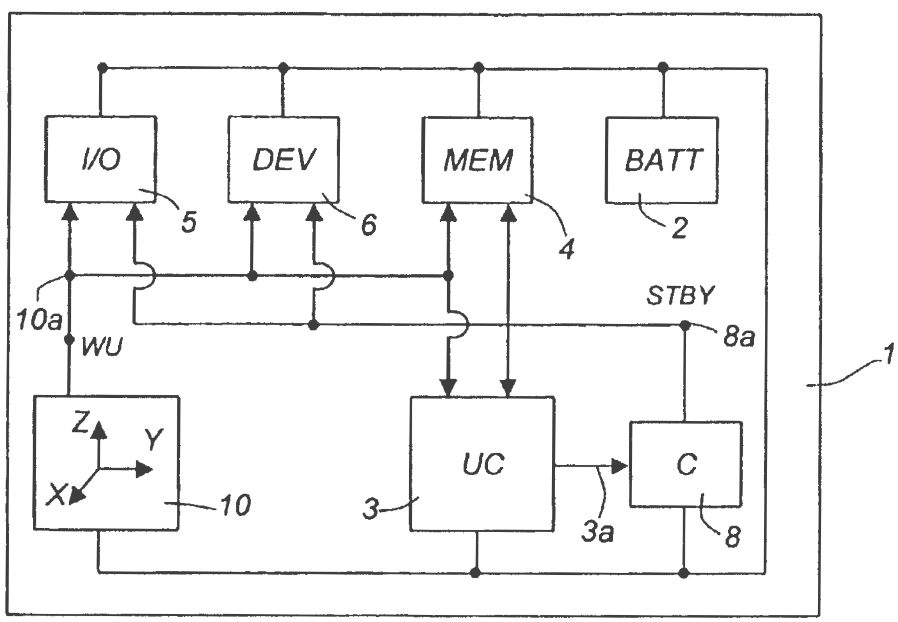
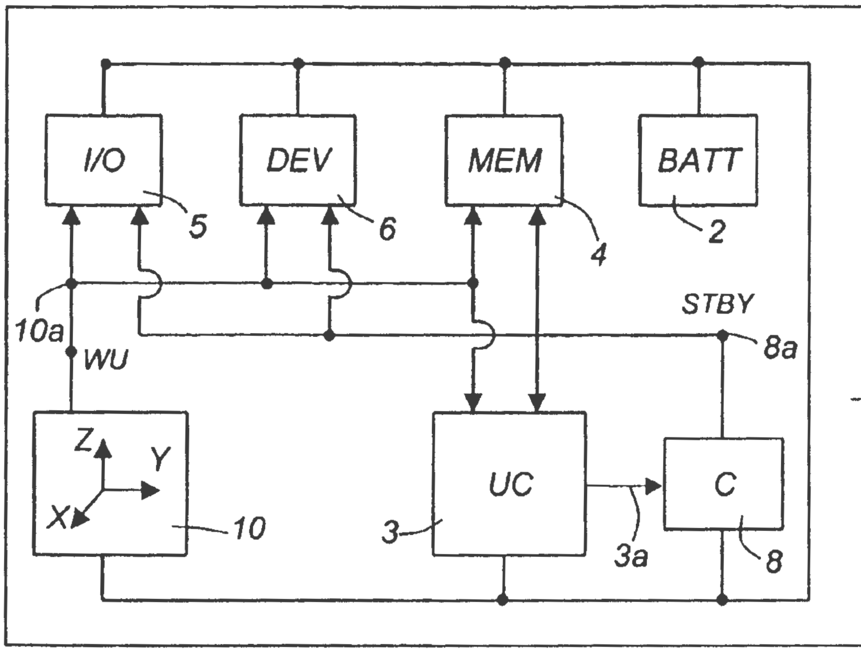
(57) **ABSTRACT**

A device for automatic detection of states of motion and rest includes at least one inertial sensor, having at least one preferential detection axis, and a converter, which is coupled to the inertial sensor and supplies a first signal correlated to forces acting on the first inertial sensor according to the preferential detection axis; the device further includes at least one processing stage for processing the first signal, which supplies a second signal correlated to a dynamic component of the first signal, and at least one threshold comparator, which supplies a pulse when the second signal exceeds a pre-determined threshold.

28 Claims, 2 Drawing Sheets

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DEV
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BATT
5
6
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C
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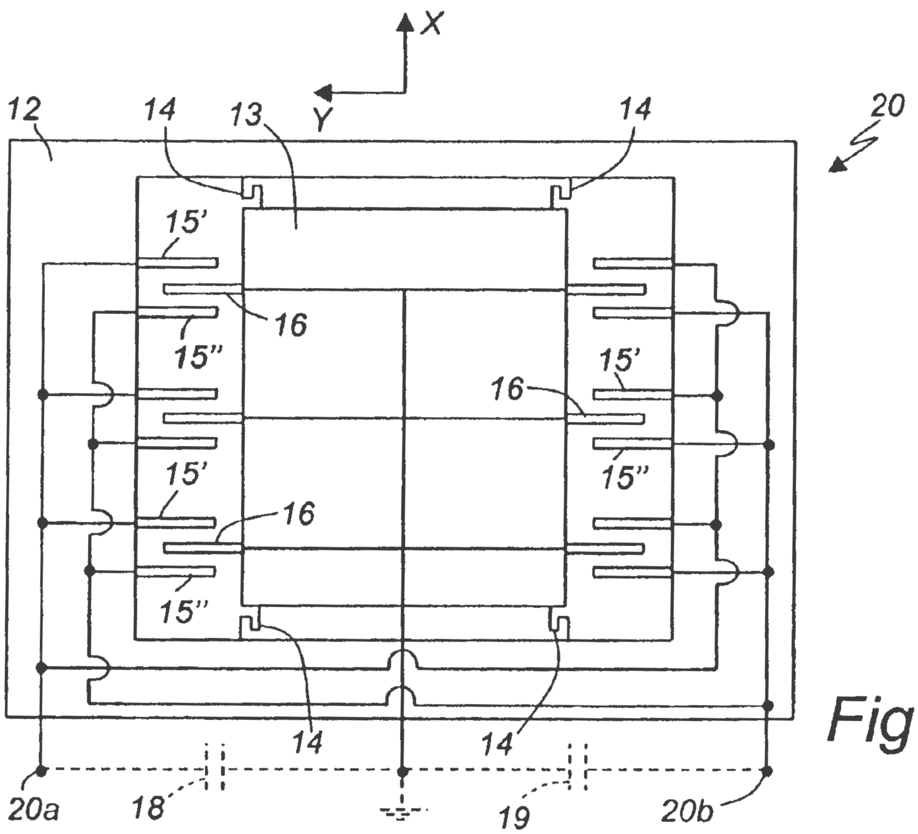
Fig. 1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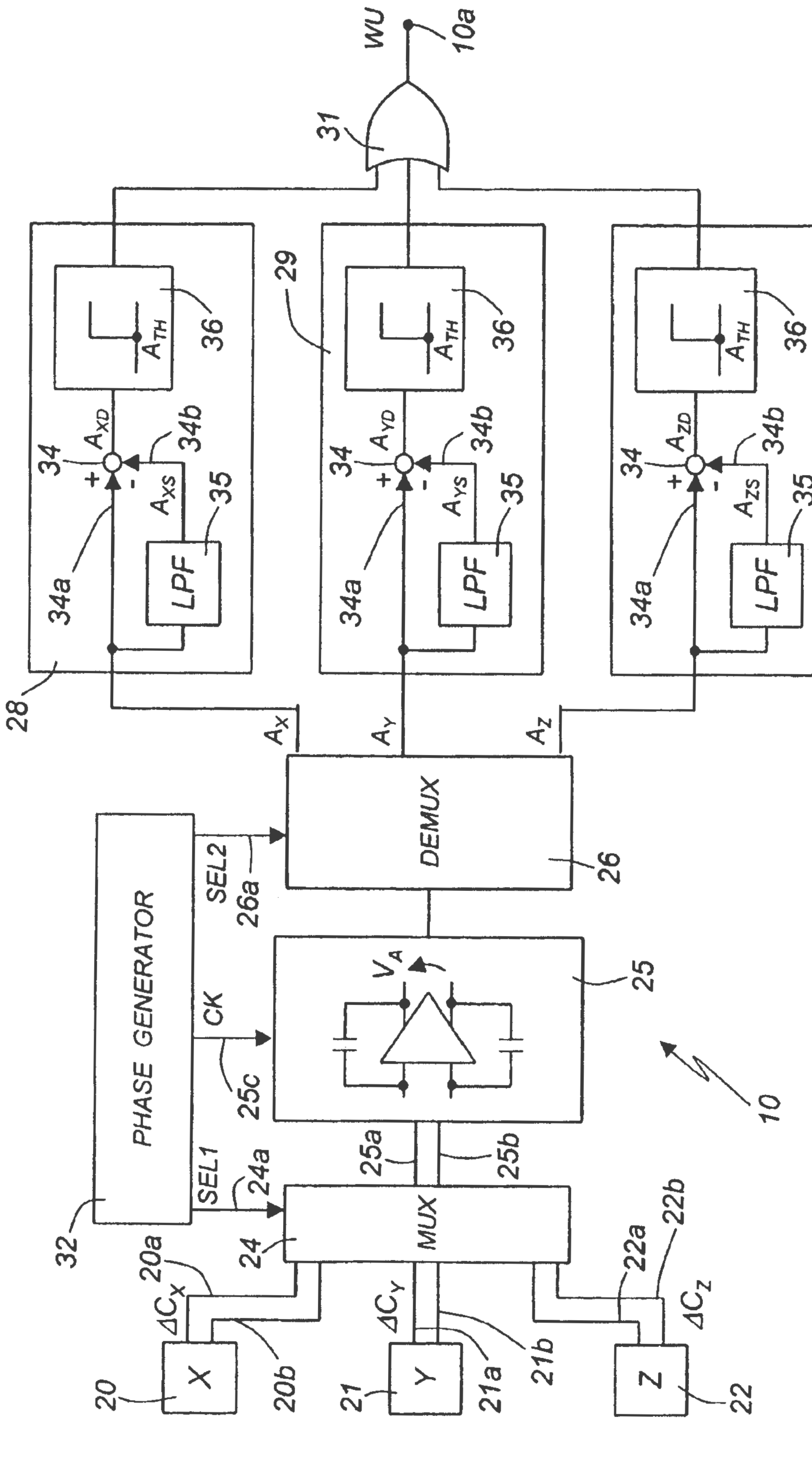
20a
18
19
20b

Fig. 2



WU
10a
31
28
29
30
36
A_{TH}
34
34a
34b
35
LPF
A_{XD}
A_{YD}
A_{ZD}
A_{XS}
A_{YS}
A_{ZS}
A_X
A_Y
A_Z
DEMUX
26
SEL2
26a
PHASE GENERATOR
32
CK
25c
V_A
25
25a
25b
10
SEL1
24a
MUX
24
ΔC_X
ΔC_Y
ΔC_Z
20a
20b
21a
21b
22a
22b
X
Y
Z
20
21
22

Fig.3

DEVICE FOR AUTOMATIC DETECTION OF STATES OF MOTION AND REST, AND PORTABLE ELECTRONIC APPARATUS INCORPORATING IT

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a device for automatic detection of states of motion and rest and to a portable electronic apparatus incorporating it.

2. Description of the Related Art

As is known, reduction of power consumption is one of the main objectives in any sector of modern microelectronics. In some fields, however, power consumption has an even determining importance in the evaluation the quality of a product. Many widely used electronic devices, in fact, are provided with a stand-alone battery supply and are normally disconnected from the mains supply; this is, for example, the case of cell phones and cordless phones, of palm-top computers and radio frequency pointer devices for computers (mouses and trackballs). It is clear that the reduction both of supply voltages and of currents advantageously involves an increase in the autonomy of the device and hence a greater convenience of use.

Furthermore, frequently the cited above devices are effectively used just for brief periods, whereas for most of the time in which they are on they remain inactive. Consider, for example, the ratio between the duration of a call from a cell phone and the average time between two successive calls. It is clear that, for almost the entire period of operation, the cell phone remains inactive, but is in any case supplied and thus absorbs a certain power. In effect, the autonomy of the device is heavily limited.

Some devices, after a pre-determined interval of inactivity, can be automatically set in a wait state (stand-by), in which all the functions not immediately necessary are deactivated; for example, in a cell phone it is possible to turn off the screen and all the circuitry that is not involved in identifying an incoming call.

To reactivate the devices from stand-by, it is advantageous to exploit a signal linked to an event (such as, for example, reception of a call signal, in the case of cell phones). However, since it is not always possible to associate a signal to an event (for example, in the case where it is the user who wants to make a call), normally a reactivation key is provided, that the user can press for bringing back the device into a normal operative state.

In this case, however, one drawback lies in that the device is not immediately ready for use: the user must in fact pick up the device, press the reactivation key and wait for the extinction of a transient in which the functions previously deactivated are restored. Although this transient is relatively brief (at the most in the region of one second), it is not however negligible and in some cases can render the device altogether inefficient. For example, in a radio frequency mouse, the restore time would be so long that the advantage of having low consumption in stand-by would be basically nullified by the lower efficiency of use.

It would, instead, be desirable to have available a device incorporated in an apparatus that is able to generate automatically a reactivation signal when the apparatus is to be used.

BRIEF SUMMARY OF THE INVENTION

One embodiment of the present invention provides a device and an apparatus that enables the problem described above to be solved.

One embodiment of the present invention is a device for automatic detection of states of motion and rest. The device

includes an inertial sensor having a preferential detection axis and a converter coupled to the inertial sensor and supplying a first signal correlated to forces acting on the first inertial sensor according to the preferential detection axis. The device also includes a processing stage structured to process the first signal and supply a second signal correlated to a dynamic component of the first signal; and a threshold comparator supplying a pulse when the second signal exceeds a predetermined threshold.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention, an embodiment thereof is now described, purely by way of non-limiting example and with reference to the attached drawings, in which:

FIG. **1** illustrates a simplified block diagram of an apparatus incorporating a device made according to the present invention;

FIG. **2** illustrates a more detailed circuit block diagram of the device according to the present invention; and

FIG. **3** is a schematic plan view of a detail of the device of FIG. **2**.

DETAILED DESCRIPTION OF THE INVENTION

With reference to FIG. **1**, designated, as a whole, by the reference number **1** is a portable electronic apparatus, which, in the example illustrated herein, is a palm-top computer; this must not, however, be considered in any way limiting, in so far as the apparatus **1** could also be of a different type. The apparatus **1** comprises at least one battery **2**, a control unit **3**, a memory **4**, an input/output (I/O) unit **5** (for example an infrared serial port), a screen **6**, a counter **8** and an activation device **10**.

An output **2***a* of the battery **2**, which supplies a supply voltage V_{DD}, is connected to respective supply inputs of the control unit **3**, the memory **4**, the I/O unit **5**, the screen **6**, the counter **8** and the activation device **10**.

Furthermore, the control unit **3**, the memory **4**, the I/O unit **5** and the screen **6** have: respective stand-by inputs connected to an output **8***a* of the counter **8**, which supplies stand-by pulses STBY; and respective activation inputs, connected to an output **10***a* of the activation device **10**, which supplies activation pulses WU ("Wake-Up"). Furthermore, the counter **8** has a counting input connected to an output **3***a* of the control unit **3**, which supplies a counting signal CT. In the presence of a first value of the counting signal CT, the counter **8** is disabled; when the counting signal CT switches from the first value to a second value, the counter **8** is reset and then incremented at each clock cycle. If the counter **8** reaches a predetermined threshold counting value, a stand-by pulse STBY is generated.

During normal operation of the apparatus **1** (active state), the control unit **3** maintains the counting signal CT at the first value, disabling the counter **8**. When, instead, the control unit **3** recognizes a condition in which the apparatus **1** is turned on, but is not used (for example, when the control unit **3** must execute only wait cycles), the counting signal is set at the second value, and the counter **8** is thus activated. After a pre-determined period of inactivity, the counter **8** reaches the threshold counting value and supplies at output a stand-by pulse STBY; in this way, the control unit **3**, the screen **6**, the I/O unit **5** and the memory **4** are set in a stand-by state, i.e., in an inoperative mode in which power consumption is minimized.

The activation device **10**, the structure of which will be described in detail hereinafter, detects the accelerations to which the apparatus **1** is subjected, preferably along a first axis X, a second axis Y and a third axis Z orthogonal to one another and fixed to the apparatus **1**. More precisely, the activation device **10** detects both the static accelerations (due to constant forces, like the force of gravity) and dynamic accelerations (due to non-constant forces) to which the apparatus **1** is subjected.

When the apparatus **1** is not used, it usually remains substantially immobile or in any case subjected to forces of negligible intensity, for example because it is resting on a shelf. As has been mentioned previously, after a pre-determined time interval, the apparatus **1** goes into a stand-by state. In these conditions, the activation device **10** detects dynamic accelerations which are practically zero and maintains its output **10***a* constant at a resting logic value; the apparatus **1** thus remains in stand-by.

When the dynamic accelerations directed along at least one of the three axes X, Y, Z exceed a pre-determined threshold, the activation device **10** generates an activation pulse WU thus bringing its output **10***a* to an activation logic value. In the presence of an activation pulse WU, any possible standby pulses STBY are ignored, and the control unit **3**, the screen **6**, the I/O unit **5** and the memory **4** are set in the active state. The activation pulse WU terminates when all the dynamic accelerations along the first axis X, the second axis Y and the third axis Z return below the pre-determined threshold.

The activation device **10** is based upon capacitive-unbalance linear inertial sensors, made using MEMS (Micro-Electro-Mechanical Systems) technology. For greater clarity, FIG. **2** illustrates a first inertial sensor **20**, having a preferential detection axis parallel to the first axis X.

In detail, the first inertial sensor **20** comprises a stator **12** and a moving element **13**, connected to one another by means of springs **14** in such a way that the moving element **13** may translate parallel to the first axis X, whereas it is basically fixed with respect to the second axis Y and the third axis Z (in FIG. **2**, the third axis Z is orthogonal to the plane of the sheet).

The stator **12** and the moving element **13** are provided with a plurality of first and second stator electrodes **15'**, **15"** and, respectively, with a plurality of mobile electrodes **16**, which extend basically parallel to the plane Y-Z. Each mobile electrode **16** is comprised between two respective stator electrodes **15'**, **15"**, which it partially faces; consequently, each mobile electrode **16** forms with the two adjacent fixed electrodes **15'**, **15"** a first capacitor and, respectively, a second capacitor with plane and parallel faces. Furthermore, all the first stator electrodes **15'** are connected to a first stator terminal **20***a* and all the second stator electrodes **15"** are connected to a second stator terminal **20***b*, while the mobile electrodes **16** are connected to ground. From the electrical standpoint, hence, the first inertial sensor **11** can be idealized by means of a first equivalent capacitor **18** and a second equivalent capacitor **19** (illustrated herein with a dashed line), having first terminals connected to the first stator terminal **20***a* and to the second stator terminal **20***b*, respectively, and second terminals connected to ground. Furthermore, the first and second equivalent capacitors **18**, **19** have a variable capacitance correlated to the relative position of the moving element **13** with respect to the rotor **12**; in particular, the capacitances of the equivalent capacitors **18**, **19** at rest are equal and are unbalanced in the presence of an acceleration oriented according to the preferential detection axis (in this case, the first axis X).

With reference to FIG. **3**, the activation device **10** comprises, in addition to the first inertial sensor **20**, a second inertial sensor **21** and a third inertial sensor **22**, identical to the first inertial sensor **20** and having preferential detection axes parallel to the second axis Y and to the third axis Z, respectively. Moreover, the activation device **10** comprises: a multiplexer **24**; a capacitance-voltage (C-V) converter **25**; a demultiplexer **26**; a first detection line **28**; a second detection line **29** and a third detection line **30**, associated respectively to the first inertial sensor **20**, to the second inertial sensor **21** and to the third inertial sensor **22**; an output logic gate **31**; and a phase generator **32**.

First stator terminals **20***a*, **21***a*, **22***a* and second stator terminals **20***b*, **21***b*, **22***b* respectively of the first, second and third inertial sensors **20**, **21**, **22** are selectively connectable in sequence to detection inputs **25***a*, **25***b* of the C-V converter **25** via the multiplexer **24**. For this purpose, a control input **24***a* of the multiplexer **24** is connected to a first output of the phase generator **32**, which supplies a first selection signal SEL**1**.

The C-V converter **25** is based upon a differential charge-amplifier circuit, of a type in itself known, and has a timing input **25***c*, connected to a second output of the phase generator **32**, which supplies timing signals CK, and an output **25***d*, which supplies, in sequence, sampled values of a first acceleration signal A_X, a second acceleration signal A_Y and a third acceleration signal A_Z, correlated to the accelerations along the first, second and third axes X, Y, Z, respectively.

The demultiplexer **26** connects the output of the C-V converter **25** selectively and in sequence to respective inputs of the first, second and third detection lines **28**, **29**, **30**, which thus receive respectively the first, second and third acceleration signals A_X, A_Y, A_Z. For this purpose, the demultiplexer **26** has a control input **26***a* connected to a second output of the phase generator **32**, which supplies a second selection signal SEL**2**.

Each of the detection lines **28**, **29**, **30** comprises a subtractor node **34**, a filter **35**, of a low-pass type, and a threshold comparator **36**. In greater detail, the input of each detection line **28**, **29**, **30** is directly connected to a non-inverting input **34***a* of the adder node **34** and is moreover connected to an inverting input **34***b* of the adder node **34** itself through the respective filter **35**.

In practice, the filters **35** extract the d.c. components of the acceleration signals A_X, A_Y, A_Z and supplies at output a first static-acceleration signal A_{XS}, a second static-acceleration signal A_{YS} and a third static-acceleration signal A_{ZS}, respectively. The subtractor nodes **34** subtract the static-acceleration signals A_{XS}, A_{YS}, A_{ZS} from the corresponding acceleration signals A_X, A_Y, A_Z. A first dynamic-acceleration signal A_{XD}, a second dynamic-acceleration signal A_{YD} and a third dynamic-acceleration signal A_{ZD}, which are correlated exclusively to the accelerations due to variable forces, are thus provided on the outputs of the subtractor nodes **35** of the first, second and third detection lines **28**, **29**, **30**, respectively.

The threshold comparators **36** have inputs connected to the outputs of the respective subtractor nodes **34** and outputs connected to the logic gate **31**, which in the embodiment described is an OR gate. Furthermore, the output of the logic gate **31** forms the output **10***a* of the activation device **10** and supplies the activation pulses WU. In particular, an activation pulse WU is generated when at least one of the dynamic-acceleration signals A_{XD}, A_{YD}, A_{ZD} is higher than a pre-determined threshold acceleration A_{TH} stored in the threshold comparators **36**; the activation pulses WU terminate when all the dynamic-acceleration signals A_{XD}, A_{YD}, A_{ZD} return below the threshold acceleration A_{TH}. The threshold acceleration A_{TH} is moreover programmable and is preferably so selected as to be exceeded in the presence of the stresses that the user impresses on the apparatus **1** during normal use.

In practice, the C-V converter **25** reads the capacitive unbalancing values ΔC_X, ΔC_Y, ΔC_Z of the inertial sensors **20**, **21**, **22**, to which it is sequentially connected and converts the capacitive unbalancing values ΔC_X, ΔC_Y, ΔC_Z into a voltage signal V_A, which is then sampled. The first, second and third acceleration signals A_X, A_Y, A_Z hence comprise respective sequences of sampled values of the voltage signal V_A generated when the C-V converter **25** is connected respectively to the first, the second and the third inertial sensor **20**, **21**, **22**; moreover, the first, second and third acceleration signal A_X, A_Y, A_Z indicate the sum of all the accelerations that act respectively along the first, second and third axes X, Y, Z.

The static-acceleration signals A_{XS}, A_{YS}, A_{ZS} supplied by the filters **35**, which basically correspond to the d.c. components of the acceleration signals A_X, A_Y, A_Z, are correlated to the accelerations due to constant forces, such as for example the force of gravity. Note that, since the apparatus **1** can be variously oriented both during use and when it is not in use, not necessarily are the components of the force of gravity along the axes X, Y, Z always constant and they may be non-zero even when the apparatus **1** is not moved. However, as long as the apparatus **1** remains at rest, the force of gravity supplies constant contributions to the acceleration signals A_X, A_Y, A_Z. The static-acceleration signals A_{XS}, A_{YS}, A_{ZS} take into account also all the causes that can determine, in the inertial sensors **20**, **21**, **22**, a permanent displacement of the moving element **13** from the position of rest with respect to the stator **12** (FIG. **2**). Amongst these causes, for example, there are fabrication offsets and deviations that can be caused by the fatiguing of the materials, especially in the springs **14**. Subtraction of the static-acceleration signals A_{XS}, A_{YS}, A_{ZS} from the acceleration signals A_X, A_Y, A_Z advantageously enables compensation of said offsets.

The dynamic-acceleration signals A_{XD}, A_{YD}, A_{ZD} are exclusively correlated to the accelerations due to variable forces and, in practice, are different from zero only when the apparatus **1** is moved, i.e., when it is picked up to be used. Consequently, at the precise moment when the user picks up the apparatus **1**, at least one of the dynamic-acceleration signals A_{XD}, A_{YD}, A_{ZD} exceeds the threshold acceleration A_{TH} of the respective threshold comparator **36**, and an activation pulse WU is supplied, which brings the control unit **3**, the memory **4**, the I/O unit **5** and the screen **6** back into the active state. Note that, in this case, also the force of gravity can advantageously provide a contribution to the dynamic-acceleration signals A_{XD}, A_{YD}, A_{ZD}, as far as the apparatus **1** can be rotated by the user so as to change the orientation of the axes X, Y, Z with respect to the vertical direction (i.e., with respect to the direction of the force of gravity). Consequently, the movement due to the intervention of the user is more readily detected.

Some advantages of the invention are evident from the foregoing description. In the first place, the activation device **10** enables the apparatus **1** to be brought back automatically into the active state from the stand-by state, since it is based just upon the forces that are transmitted by the user when he picks up the apparatus **1** to use it. In practice, the activation device **10** is able to distinguish a condition of use from a condition of rest by simply detecting a state of motion from a state of substantial rest. Consequently, the apparatus **1** is reactivated as soon as it is picked up by the user and the transients of exit from the stand-by state are exhausted when the user is terminating the movement of picking up the apparatus **1**. The troublesome delays, that can reduce or eliminate the advantages deriving from the use of portable apparatus with stand-alone supply, are thus prevented. Furthermore, the use of inertial sensors of the MEMS type, which are extremely sensitive, have small overall dimensions and can be made at relatively low costs, is advantageous. Above all, however, the MEMS sensors have a virtually negligible consumption: consequently, the energy accumulated in the batteries is almost entirely available for active use of the apparatus **1**, the effective autonomy whereof is significantly increased.

Finally, it is clear that modifications and variations can be made to the device described herein, without thereby departing from the scope of the present invention. In particular, the activation device **10** could comprise two inertial sensors (for example, in the case of a radio frequency mouse, which in use is displaced just in one plane) or even just one inertial sensor; inertial sensors of a different type could also be used, for example rotational inertial sensors or else inertial sensors with more than one degree of freedom (i.e., having at least two preferential non-parallel detection axes). Furthermore, there can be provided a C-V converter for each inertial sensor used; in this case, use of the multiplexer and demultiplexer is not required.

All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, are incorporated herein by reference, in their entirety.

From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.

The invention claimed is:

1. A device for automatic detection of states of motion and rest, comprising:

a first inertial sensor having a first preferential detection axis;

a converter coupled to said first inertial sensor and supplying a first signal correlated to forces acting on said first inertial sensor according to said first preferential detection axis;

a first processing stage structured to process said first signal and supply a second signal correlated to a dynamic component of said first signal wherein said first processing stage comprises a filter, supplying a third signal correlated to a static component of said first signal, and a subtractor element, for subtracting said third signal from said first signal; and

a first threshold comparator supplying a pulse when said second signal exceeds a threshold.

2. The device according to claim **1** wherein said first inertial sensor is a micro-electro-mechanical sensor with capacitive unbalancing.

3. The device according to claim **1**, further comprising a second inertial sensor having a second preferential detection axis, the first and second inertial sensors being of a micro-electro-mechanical type with capacitive unbalancing, the first preferential detection axis and the second preferential detection axis being orthogonal to one another.

4. The device according to claim **3** said first inertial sensor and said second inertial sensor are selectively connectable in sequence to said converter.

5. The device according to claim **4**, comprising a third inertial sensor of a micro-electro-mechanical type with capacitive unbalancing, having a third preferential detection axis, orthogonal to said first preferential detection axis and to said second preferential detection axis.

6. The device according to claim **5**, further comprising a switch device positioned to selectively connect said first inertial sensor, said second inertial sensor and said third inertial sensor in sequence to said converter.

7. The device according to claim 1, further comprising a second inertial sensor having a second preferential detection axis that is transverse to the first preferential detection axis.

8. The device according to claim 7, further comprising:

a multiplexer connected between the inertial sensors and the converter to selectively electrically connect each of the inertial sensors to the converter, the converter supplying a third signal correlated to forces acting on said second inertial sensor according to said second preferential detection axis;

a second processing stage structured to process said third signal and supply a fourth signal correlated to a dynamic component of said third signal;

a second threshold comparator supplying a pulse when said fourth signal exceeds the threshold; and

a demultiplexer connected between the converter and the first and second processing stages to selectively supply the first and third signals to the first and second processing stages, respectively.

9. The device according to claim 8, further comprising:

a phase generator connected to the multiplexer, converter, and demultiplexer and structured to provide timing signals that coordinate operations of the multiplexer, converter, and demultiplexer.

10. A portable electronic apparatus, comprising:

a supply source;

a plurality of user devices alternatively connected to said supply source in a first operative state, and disconnected from said supply source in a second operative state;

deactivation means connected to said user devices for setting said user devices in said second operative state; and

activation means for setting the user devices in the first operative state, said activation means including:

a first inertial sensor having a preferential detection axis,

a converter coupled to said first inertial sensor and supplying a first signal correlated to forces acting on said first inertial sensor according to said preferential detection axis;

a first processing stage structured to process said first signal and supply a second signal correlated to a dynamic component of said first signal, and

a first threshold comparator supplying an activation pulse when said second signal exceeds a threshold.

11. An apparatus according to claim 10 wherein, in the presence of the activation pulse, said user devices are in said first operative state.

12. The apparatus according to claim 10 wherein said first processing stage comprises a filter, supplying a third signal correlated to a static component of said first signal, and a subtractor element, for subtracting said third signal from said first signal.

13. The apparatus according to claim 10 wherein said first inertial sensor is a micro-electro-mechanical sensor with capacitive unbalancing.

14. The apparatus according to claim 10, wherein said activation means further include a second inertial sensor having a second preferential detection axis, the first and second inertial sensors being of a micro-electro-mechanical type with capacitive unbalancing, the first preferential detection axis and the second preferential detection axis being orthogonal to one another.

15. The apparatus according to claim 14, wherein said activation means further include a third inertial sensor of a micro-electro-mechanical type with capacitive unbalancing, having a third preferential detection axis, orthogonal to said first preferential detection axis and to said second preferential detection axis.

16. The apparatus according to claim 10, wherein said activation means further include a second inertial sensor having a second preferential detection axis that is transverse to the first preferential detection axis.

17. The apparatus according to claim 16, wherein said activation means further include:

a multiplexer connected between the inertial sensors and the converter to selectively electrically connect each of the inertial sensors to the converter, the converter supplying a third signal correlated to forces acting on said second inertial sensor according to said second preferential detection axis;

a second processing stage structured to process said third signal and supply a fourth signal correlated to a dynamic component of said third signal;

a second threshold comparator supplying a pulse when said fourth signal exceeds the threshold; and

a demultiplexer connected between the converter and the first and second processing stages to selectively supply the first and third signals to the first and second processing stages, respectively.

18. The apparatus according to claim 10, wherein said activation means further include:

a phase generator connected to the multiplexer, converter, and demultiplexer and structured to provide timing signals that coordinate operations of the multiplexer, converter, and demultiplexer.

19. A method for automatic detection of motion of a portable electronic device, comprising:

sensing motion of the device along a first preferential detection axis;

supplying a first signal correlated to forces acting on the device according to the preferential detection axis;

processing the first signal and supplying a second signal correlated to a dynamic component of the first signal wherein the processing comprises filtering the first signal to create a third signal correlated to a static component of the first signal, and subtracting the third signal from the first signal to create the second signal; and

supplying an activation pulse when the second signal exceeds a first threshold.

20. The method of claim 19, further comprising

sensing motion of the device along a second preferential detection axis that is orthogonal to the first preferential detection axis;

supplying a third signal correlated to forces acting on the device according to the second preferential detection axis;

processing the third signal and supplying a fourth signal correlated to a dynamic component of the third signal; and

supplying the activation pulse when the fourth signal exceeds a second threshold.

21. The method of claim 19, further comprising:

receiving the activation pulse at an operation circuit of the device, the operation circuit being in a stand-by condition prior to receiving the activation pulse; and

activating the operation circuit into an active condition in response to receiving the activation pulse.

22. A device, comprising:

a first inertial sensor having a first preferential detection axis;

a converter coupled to the first inertial sensor and supplying a first signal correlated to forces acting on the first inertial sensor according to the first preferential detection axis;

a first processing stage structured to process the first signal and supply a second signal correlated to a dynamic component of the first signal;

a first threshold comparator supplying a pulse when the second signal exceeds a threshold;

a second inertial sensor having a second preferential detection axis that is transverse to the first preferential detection axis;

a multiplexer connected between the inertial sensors and the converter to selectively electrically connect each of the inertial sensors to the converter, the converter supplying a third signal correlated to forces acting on the second inertial sensor according to the second preferential detection axis;

a second processing stage structured to process the third signal and supply a fourth signal correlated to a dynamic component of the third signal;

a second threshold comparator supplying a pulse when the fourth signal exceeds the threshold; and

a demultiplexer connected between the converter and the first and second processing stages to selectively supply the first and third signals to the first and second processing stages, respectively.

23. The device of claim **22**, further comprising:

a phase generator connected to the multiplexer, converter, and demultiplexer and structured to provide timing signals that coordinate operations of the multiplexer, the converter, and the demultiplexer.

24. The device of claim **22** wherein the first inertial sensor is a micro-electro-mechanical sensor with capacitive unbalancing.

25. A method for automatic detection of motion of a portable electronic device, comprising:

sensing motion of the device along a first preferential detection axis;

supplying a first signal correlated to forces acting on the device according to the preferential detection axis;

processing the first signal and supplying a second signal correlated to a dynamic component of the first signal;

supplying an activation pulse when the second signal exceeds a first threshold;

sensing motion of the device along a second preferential detection axis that is orthogonal to the first preferential detection axis;

supplying a third signal correlated to forces acting on the device according to the second preferential detection axis;

processing the third signal and supplying a fourth signal correlated to a dynamic component of the third signal; and

supplying the activation pulse when the fourth signal exceeds a second threshold.

26. The method of claim **25**, further comprising:

sensing motion of the device along a third preferential detection axis that is orthogonal to the first preferential detection axis and the second preferential detection axis;

supplying a fifth signal correlated to forces acting on the device according to the third preferential detection axis;

processing the fifth signal and supplying a sixth signal correlated to a dynamic component of the fifth signal; and

supplying the activation pulse when the sixth signal exceeds a third threshold.

27. A method for automatic detection of motion of a portable electronic device, comprising:

sensing motion of the device along a first preferential detection axis;

supplying a first signal correlated to forces acting on the device according to the preferential detection axis;

processing the first signal and supplying a second signal correlated to a dynamic component of the first signal;

supplying an activation pulse when the second signal exceeds a first threshold;

receiving the activation pulse at an operation circuit of the device, the operation circuit being in a stand-by condition prior to receiving the activation pulse; and

activating the operation circuit into an active condition in response to receiving the activation pulse.

28. The method of claim **27**, further comprising terminating the activation pulse in response to the second signal being lower than the first threshold.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,409,291 B2
APPLICATION NO. : 10/789240
DATED : August 5, 2008
INVENTOR(S) : Fabio Pasolini et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page, item [30]
Foreign Application Priority Data, should read
-- Feb. 28, 2003...(IT)...TO2003A 000141 --

Signed and Sealed this

Twenty-first Day of October, 2008

JON W. DUDAS
Director of the United States Patent and Trademark Office

EXHIBIT H

US005874850A

United States Patent [19]

Pulvirenti et al.

[11] **Patent Number: 5,874,850**

[45] **Date of Patent: Feb. 23, 1999**

[54] **MOS VOLTAGE ELEVATOR OF THE CHARGE PUMP TYPE**

[75] Inventors: **Francesco Pulvirenti**, Acireale; **Roberto Gariboldi**, Lacchiarella, both of Italy

[73] Assignee: **STMicroelectronics S.r.l.**, Agrate Brianza, Italy

[21] Appl. No.: **919,592**

[22] Filed: **Aug. 5, 1997**

Related U.S. Application Data

[63] Continuation of Ser. No. 513,293, Aug. 10, 1995, abandoned.

[30] **Foreign Application Priority Data**

Aug. 12, 1994 [EP] European Pat. Off. 94830402

[51] **Int. Cl.^{6}** **G05F 1/10**

[52] **U.S. Cl.** **327/536**; 327/537; 363/60; 363/61; 307/110

[58] **Field of Search** 327/536, 537, 327/543, 548; 307/110; 363/60, 61, 147

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,029,973	6/1977	Kobayashi et al.	307/264
4,068,295	1/1978	Portmann	363/60
4,740,715	4/1988	Okada	327/537
4,961,007	10/1990	Kumanoya et al.	327/543
4,982,317	1/1991	Mauthe	363/60
5,093,586	3/1992	Asari	327/536
5,172,013	12/1992	Matsumura	327/537
5,247,208	9/1993	Nakayama	327/537
5,266,842	11/1993	Park	327/537
5,436,587	7/1995	Cernea	327/536
5,444,362	8/1995	Chung et al.	323/313
5,519,557	5/1996	Kopera, Jr. et al.	361/84

FOREIGN PATENT DOCUMENTS

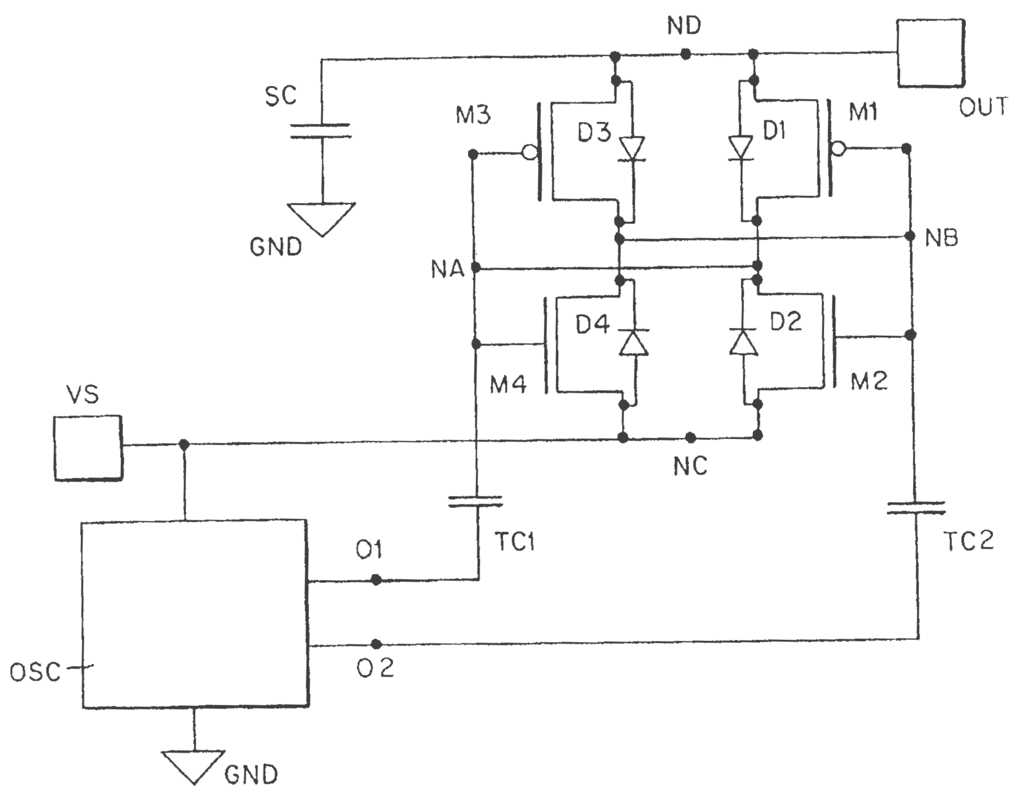
a-2 261 307	5/1923	United Kingdom	G11C 11/40

Primary Examiner—Timothy P. Callahan
Assistant Examiner—Jung Ho Kim
Attorney, Agent, or Firm—Wolf, Greenfield & Sacks, P. C.

[57] **ABSTRACT**

A charge pump MOS voltage booster has reduced voltage drops and ripple. This voltage booster is advantageously used in two applications. The voltage has four MOS transistors instead of diodes in a classical voltage booster, which exhibit an undesired voltage drop. The voltage booster also has an oscillator with two outputs and two corresponding charge transfer capacitors. In this manner, the undesired voltage drops and ripple are reduced without complicating the circuitry structure.

19 Claims, 3 Drawing Sheets



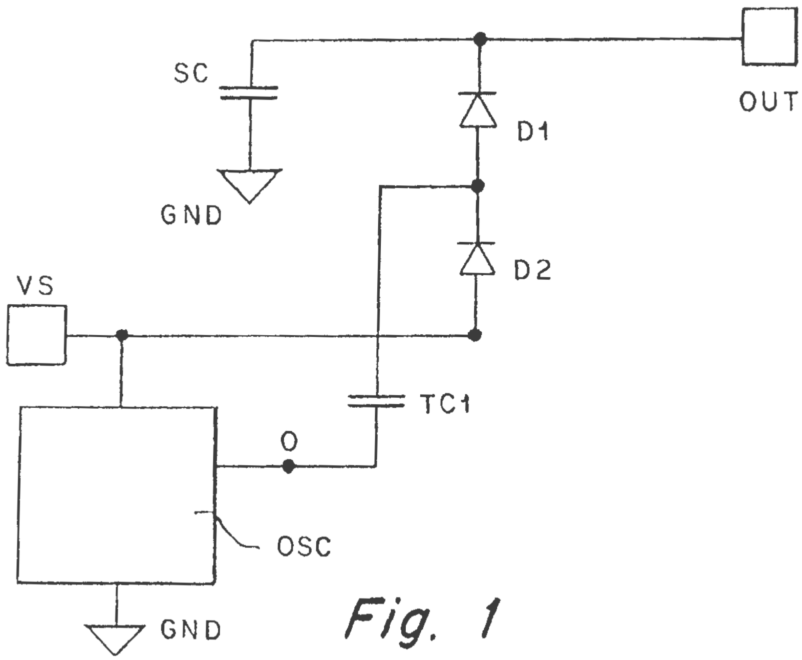


Fig. 1
(PRIOR ART)

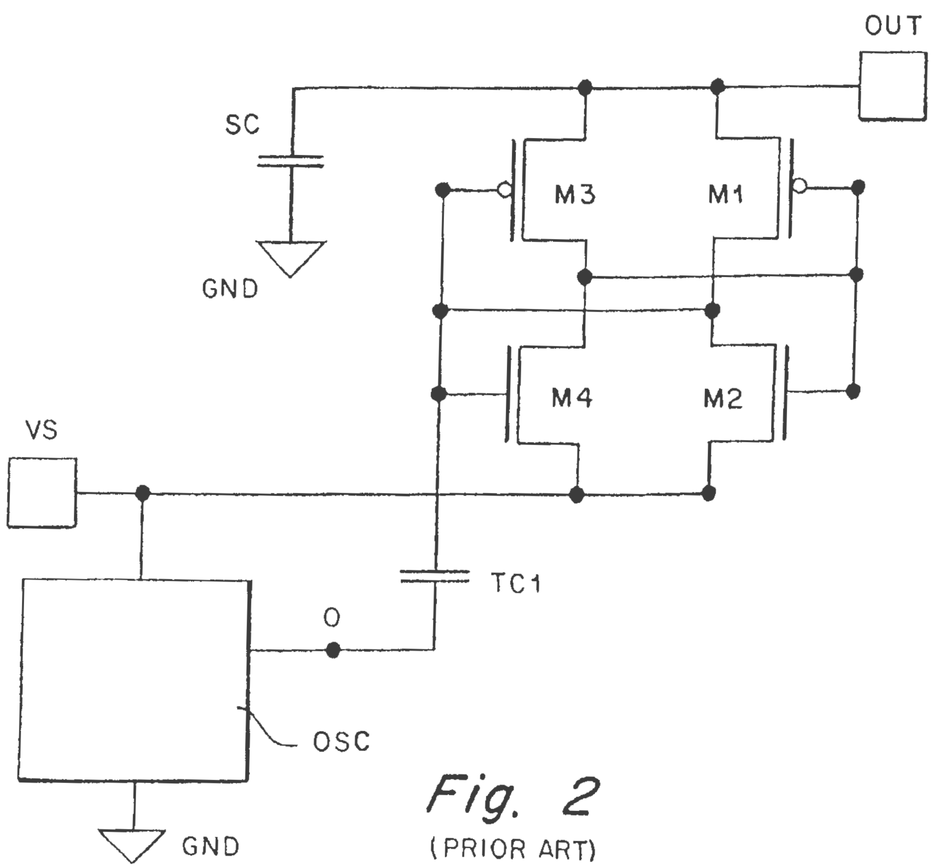
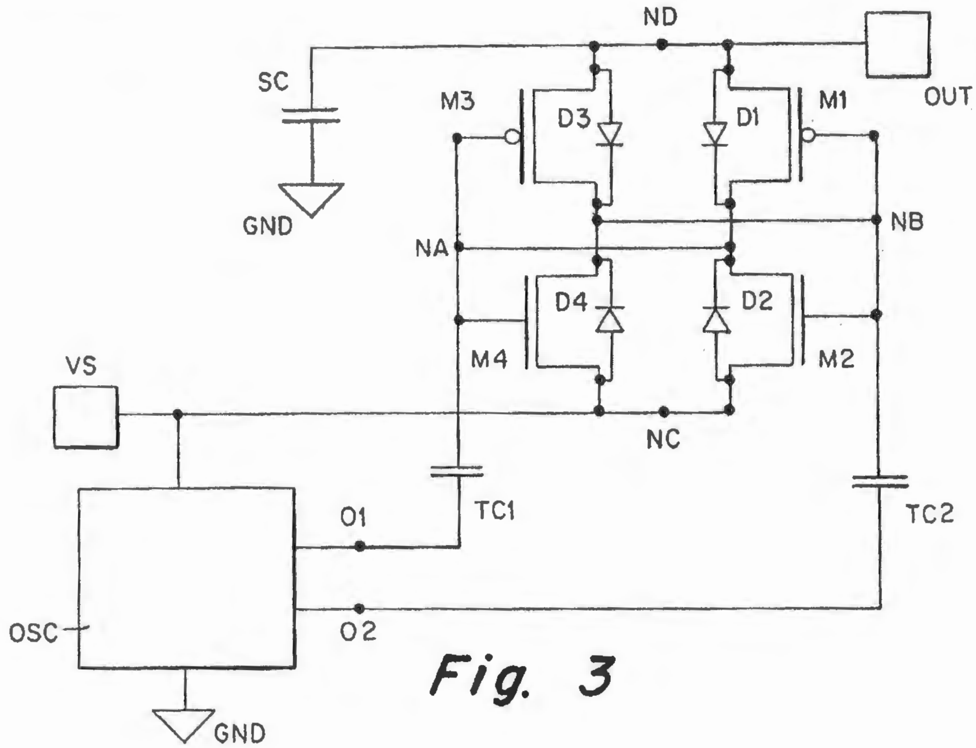
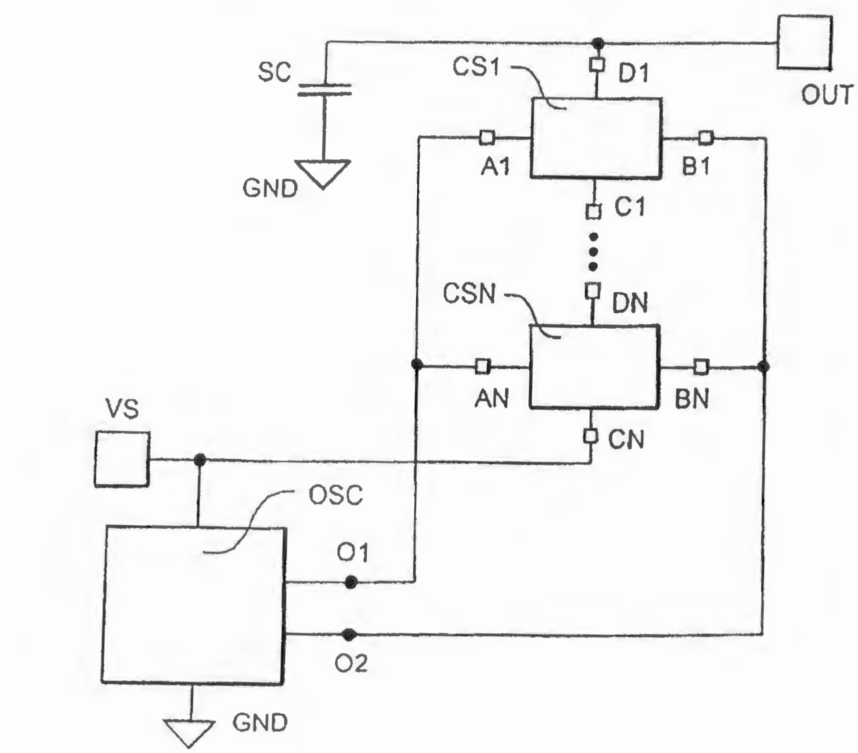


Fig. 2
(PRIOR ART)



ND
SC
M3
D3
D1
M1
OUT
GND
NB
NA
D4
D2
M4
M2
VS
NC
TC1
TC2
O1
OSC
O2
GND

Fig. 3



SC
CS1
D1
OUT
GND
A1
B1
C1
CSN
DN
AN
BN
VS
CN
OSC
O1
O2
GND

Fig. 4

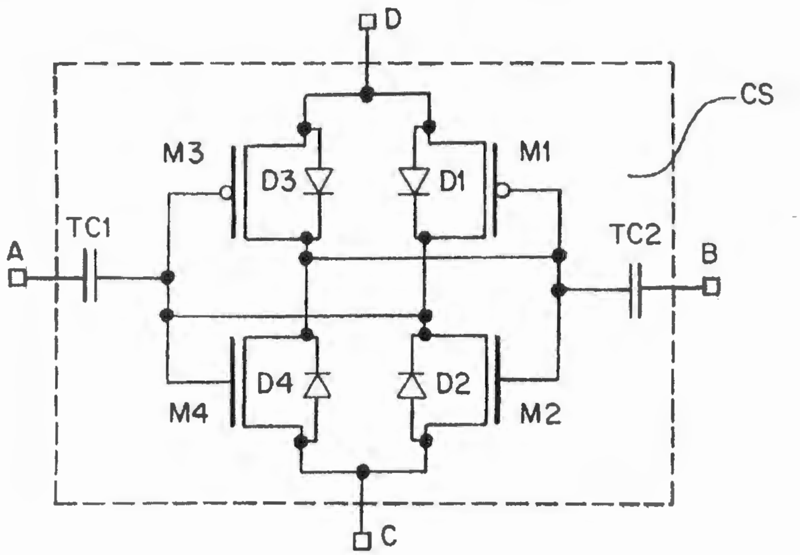

D
CS
M3
M1
D3
D1
TC1
TC2
A
B
D4
D2
M4
M2
C

Fig. 5

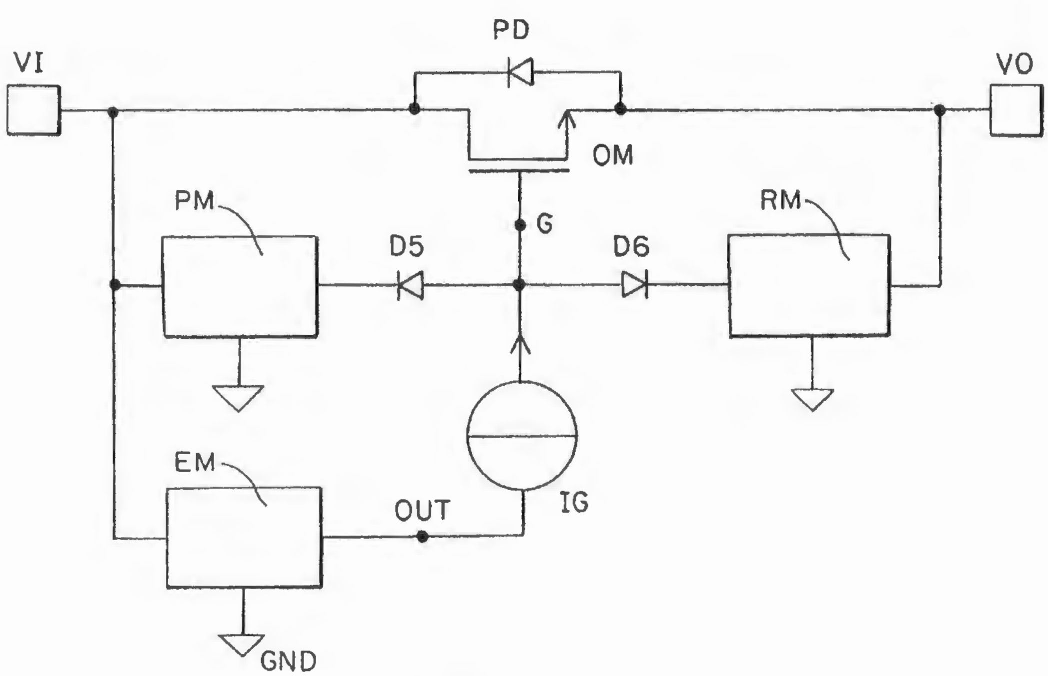

PD
VI
VO
OM
PM
RM
G
D5
D6
EM
OUT
IG
GND

Fig. 6

MOS VOLTAGE ELEVATOR OF THE CHARGE PUMP TYPE

This application is a continuation of application Ser. No. 08/513,293, filed Aug. 10, 1995, abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a charge pump MOS voltage booster and to two applications where said type of booster can find advantageous use.

2. Discussion of the Related Art

The increasing need for devices which operate in equipment having one continuous very low power voltage (down to 1V), such as telecommunications line equipment, portable units, etc., requires efficient and simple continuous voltage boosters.

One well known structure of a charge pump doubler is illustrated in FIG. 1. It includes an oscillator OSC typically with square wave and powered with a continuous power voltage VS and connected to ground GND and having an output O. The output O is connected to the first terminal of a first charge transfer capacitor TC1. The second terminal of the charge transfer capacitor TC1 is connected to the cathode of a diode D2. The anode of the diode D2 is connected to the power voltage VS. The cathode of the diode D2 is also connected to the anode of another diode D1. The cathode of the diode D1 is connected to the output OUT of the doubler and to the second terminal of a charge accumulation capacitor SC whose first terminal is connected to ground GND.

In this circuit the output voltage (without load) is equal to double the power voltage decreased by double the starting voltage (approximately 0.7V) of the diodes D1 and D2. When the power voltage is very low, e.g. between 1.2V and 3.5V, this reduction becomes significant and unacceptable.

To solve this problem it has bee proposed, e.g. in French patent application FR-A-2 321 144, to replace the diodes D1 and D2 with two MOS transistors M1 and M2 as shown in FIG. 2. Naturally threshold transistors M1 and M2 need to be appropriately piloted. This was achieved, as shown in said document, by means of two other MOS transistors M3 and M4.

The circuit of FIG. 2 solves the problem of voltage drop on the diodes since the voltage drop on the channel of the MOS transistors is extremely small but exhibits, as also the circuit of FIG. 1, a certain ripple at the output OUT.

SUMMARY OF THE INVENTION

The purpose of the present invention is to supply a voltage booster with simple, efficient circuitry and without large voltage drops in relation to the theoretical high value and with ripple limited at the output.

This purpose is achieved through the doubler having the characteristics set forth in claims 1 or 3 or the booster having the characteristics set forth in claim 6. Additional advantageous aspects of the present invention are set forth in the dependent claims.

By using an oscillator in the doubler or elevator having two outputs in phase opposition and two corresponding charge transfer capacitors in addition to a bridge of controlled switches, it is possible to charge the accumulation capacitor during a first half-period through one of the two capacitors and during the following half-period charge the accumulation capacitor through the other of the two capacitors and reduce ripple at the output.

Advantageously, instead of using four additional MOS transistors, the second charge transfer capacitor can be connected directly to the first four transistors symmetrically in relation to the first charge transfer capacitor.

In accordance with another aspect the present invention concerns also an electrical circuit in accordance with claim 13 and a voltage regulator in accordance with claim 14, both comprising and using such a voltage booster.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is clarified by the description given below with reference to the annexed drawings.

In the drawings:

FIG. 1 shows a diode voltage booster in accordance with the known art,

FIG. 2 shows an MOS-transistor voltage booster in accordance with the known art,

FIG. 3 shows a voltage doubler in accordance with the present invention,

FIG. 4 shows a voltage booster in accordance with the present invention,

FIG. 5 shows a loading section to be used in the voltage booster of FIG. 4, and

FIG. 6 shows a voltage regulator in accordance with the present invention.

DETAILED DESCRIPTION

The circuit of FIG. 3 is quite similar to that of FIG. 2 but differs therefrom in some important elements.

The oscillator OSC exhibits, in addition to the first output 01, a second output 02 in phase opposition in relation to the first. The second output is connected to the first terminal of a second charge transfer capacitor TC2. The second terminal of said second capacitor is connected directly to the four transistors M1,M2,M3,M4 symmetrically in relation to the first capacitor TC1.

The transistors M1,M2,M3,M4 thus give rise to two inverters connected together in a loop so as to form a flip-flop having respective inputs connected to the second terminals of the capacitors TC1 and TC2 which are negative power terminals connected together to the voltage VS and positive power terminals connected together to the second terminal of the capacitor SC.

The signal generated by the oscillator OSC varies between the potential of the reference GND a nd the potential of the continuous power voltage VS in accordance with a square wave both at the output 01 and the output 02.

Such an oscillator can include an oscillator having a single output referred to the potential reference GND, in particular ground, from an inverting buffer and from a non-inverting buffer having virtually equal delays.

FIG. 3 shows the bulk diodes D1,D2,D3,D4 of the four MOS transistors M1,M2,M3,M4 respectively. The cathodes of D1 and D3 are connected to the output OUT of the doubler and the anodes of D2 and D4 are connected to the continuous power voltage VS. These connections are very important for correct starting of the circuit and subsequent rated operation as explained more clearly in the following description.

Naturally, considering the perfect symmetry of the circuit thus achieved, the inverters including the transistors M1,M2, M3,M4 preferably must be equal.

To explain the operation of this circuit it is necessary to follow the evolution of the voltage at the output OUT of the doubler from the time power voltage is applied to achievement of rated operating voltage.

At the instant the power voltage is applied, the accumulation capacitor SC is discharged and the output moves to potential VS−2 * VD, where VD is a starting voltage of the bulk diodes of the MOS transistors, approximately 0.7V.

During this first phase the four MOS transistors are all off and the capacitor SC charges through the bulk diodes. When the difference between voltage at output and power voltage becomes greater than the threshold voltage of the MOS transistors, the transistors M1,M2,M3,M4 begin to conduct and cooperate in "pumping" charge into the capacitor SC until completely replacing the bulk diodes at rated operation.

Operation during the transient is as follows:

During the half-period in which the output **01** of the oscillator OSC is low, i.e. grounded, the first capacitor TC1 charges through the diode D2. While the output **02** is high, the charge transfer capacitor TC2 supplies its energy to the capacitor SC through the diode D3.

During the half-period in which the output **01** of the oscillator OSC is high, i.e. at power potential, the capacitor TC1 supplies its energy to the capacitor SC through the diode D1. While the output **02** is low, the charge transfer capacitor TC2 charges through the diode D4.

In the absence of the MOS transistors, with only a bridge of the diodes (D1,D2,D3,D4), the voltage at the output OUT would rise to:

$$2*VS-2*VD-2*RD*IL-IL*T/C; \quad [1]$$

where RD is the series resistance of the bulk diodes, IL is the average current absorbed by the load, T is the period of the square wave generated by the oscillator OSC, and C is the capacity of the capacitors TC1 and TC2, which are assumed to be equal. This is true only if SC>>TC1 and SC>>TC2, so as to disregard ripple.

The first of the three contributions subtracted is due to the diode starting voltage and is present even when no current is absorbed by the load, e.g. in "High Side Driver" applications where the load to be piloted is a MOS transistor, i.e., a pure capacity.

The second contribution is due to the potential drop in the series resistance of said diodes. By appropriately dimensioning the diodes, this contribution is almost always negligible.

The third contribution is due to the loss of charges of the capacitors TC1 and TC2. This contribution cannot be eliminated and should be allowed for if the charge transfer capacitors are integrated, or it can be minimized if it is possible to connect very large discrete capacitors outside the chip. In any case, for applications in which no average current is absorbed on the load, this contribution is zero.

Rated operation is as follows:

During the half-period in which the output **01** is low, i.e. grounded, the nodes NA and NB are at potential VS and VOUT respectively, M1 and M4 are off, M2 and M3 are on. In this condition, the first capacitor TC1 charges through the N-channel MOS transistor M2 and the charge transfer capacitor TC2 charges the capacitor SC through the P-channel MOS transistor M3.

During the half-period in which the output **01** is high, i.e. at power potential, the nodes,NA and NB are at potential VOUT and VS respectively, M1 and M4 are on, M2 and M3 are off. In this condition, the first capacitor TC1 charges the capacitor SC through the P-channel MOS transistor M1 and the charge transfer capacitor TC2 charges through the N-channel MOS transistor M4.

In rated operation, assuming the output resistance of the oscillator OSC to be null, the output voltage will be:

$$2*VS-2*RDS\_ON*IL-IL*T/C; \quad [2]$$

where RDS_ON is the series resistance of the MOS transistors, which are assumed to be equal.

From a comparison of formulas [1] and [2] the advantage achieved by use of the MOS transistors is clear. This advantage is especially relevant in applications in which, in rated operation, the term IL becomes null, e.g. when the load to be piloted is an MOS transistor.

During the initial transient operating condition, when the node NA goes low, the bulk diode D2 of the N-channel MOS transistor M2 (this applies also to D4 and M4) goes into conduction triggering an NPN parasite transistor which has for emitter the drain diffusion of the N-channel MOS transistor M2, for base the bulk diffusion of the N-channel MOS transistor M2, and for collector the pocket containing the N-channel MOS transistor **M2**. If the pocket of the N-channel MOS transistor M2 is polarized at the voltage VOUT the intervention of this parasite transistor would discharge the capacitor SC and prevent reaching of rated condition. Hence, if the circuit is integrated in the same chip, it is advisable to place the transistors **M1**, **M2**, **M3**, **M4** in separated pockets and polarize the pocket of the N-channel MOS transistors at the same bulk potential, i.e. VS.

When the node NA goes high the bulk diode D1 of the P-channel MOS transistor M1 (this also applies for D3 and M3) goes into conduction triggering a parasite PNP transistor which has for emitter the drain diffusion of the P-channel MOS transistor M1, for base the pocket of the P-channel MOS transistor M1, and for collector the substrate and the insulation. The presence of this parasite transistor would slow reaching of the rated condition. Therefore it is advisable to minimize said undesired effect by surrounding the MOS transistors M1 and M2 with a deep highly doped type N diffusion.

Another important point to be mentioned concerns dimensioning of the four MOS transistors and the output resistance of the oscillator OSC.

The MOS transistors should be constructed allowing first for the RDS_ON because the voltage drop on it is to be subtracted from the output voltage, but without excessive reduction of this parameter which causes an opposite increase in the cross current lost during each switching and affects conversion efficiency.

In addition, in rated operating condition, if the transfer capacitors TC1 and TC2 are sufficiently large that the charge lost can be considered negligible, the potential at the nodes NA and NB during a rising or falling front will be determined by the resistive divider made up of the RDS_ON of the MOS transistors and the output resistance of the oscillator OSC. Normally even the oscillator OSC has its output stage provided by MOS inverters.

Therefore, assuming half the switching threshold of the inverters made up of the pairs of MOS transistors M1,M2 and M3,M4, for said inverters to be able to switch, the oscillator must have an output resistance smaller than the RDS_ON of the MOS transistors.

It must also be noted that the MOS transistors work in the voltage space between VOUT and VS and must be constructed in such a manner as to withstand this potential difference while the pocket containing them must hold the highest voltage VOUT.

FIG. **4** shows a block diagram of a voltage booster in accordance with the present invention also based on an oscillator OSC having two outputs **01** and **02** in phase opposition and at least one pair of charge transfer capacitors so that the accumulation capacitor SC is loaded during both half-periods of the wave, usually square, generated by the oscillator OSC.

This booster includes generically N loading sections CS indicated as CS 1-CSN. In the circuit of FIG. 4, the voltage at the output OUT is equal to N+1 times the continuous power voltage VS, hence in the case of a single loading section the booster will be a doubler.

The generic loading section CS is illustrated in FIG. 5 and is a device with four terminals, i.e. a first side terminal A, a second side terminal B, a power input terminal C, and a charge output terminal D. All the first side terminals A1-AN are connected to the output 01 and all the second side terminals B1-BN are connected to the output 02. In the case of a single loading section CS the terminal D is connected to the output OUT and to the capacitor SC and the terminal C to a potential reference, in the case of FIG. 4, the continuous power voltage VS. In the case of N loading sections CS1-CSN these are connected in series by the input terminals C1-CN and the output terminals D1-DN. The first output terminal (D1) of the series connection is connected to the output OUT and to the capacitor SC, and the last input terminal (CN) of the series connection is connected to a potential reference, in the case of FIG. 4, the continuous power voltage VS.

Each of the loading sections CS includes:

- a first charge transfer capacitor TC1 and a second charge transfer capacitor TC2 having first terminals connected to the first A and second B side terminals respectively, and
- two inverters connected together in a loop in such a way as to form a flip-flop having respective inputs connected to second terminals of the first charge transfer capacitor TC1 and of the second charge transfer capacitor TC2, negative power terminals connected together to the power input terminal C and positive power terminals connected together to the charge output terminal D.

The first inverter is made up of the MOS transistors M1 and M2 and the second inverter of the MOS transistors M3 and M4. Again in FIG. 5 the bulk diodes D1,D2,D3,D4 are shown (basically for operation of the circuit), the cathodes of the diodes D1 and D3 are connected to the charge output terminal D, while the anodes of the diodes D2 and D4 are connected to the power input terminal C.

In FIG. 4, a terminal of the capacitor SC is connected to ground GND. Naturally a different potential reference could be chosen with no consequence on the potential at the output OUT.

Again in FIG. 4, the continuous power voltage VS is supplied as an input both to the oscillator OSC and the terminal CN. Again in this case the terminal CN could be connected to a different potential reference. The output voltage would then be equal to N times the continuous power voltage VS of the oscillator OSC increased by the reference potential.

As already mentioned, there are various electrical circuits which require voltage booster circuits for the environment in which they operate.

A first example are Flash EPROM memory devices. These devices require a relatively low read voltage, e.g. 3 to 5V, but relatively high programming and reading voltages, 12V. Naturally, it is rather inconvenient to have, only for these devices, a 12V power source, and it is convenient to insert a booster in the memory device.

A second example are voltage regulators with a low voltage drop between input and output, and an MOS power transistor as an output regulation element.

Such a regulator is shown in FIG. 6. This is a device basically with three terminals, an input terminal VI, an output terminal VO, and a potential reference terminal GND which is usually connected to ground.

The input terminal VI is connected to the drain terminal of a P-channel MOS power transistor OM, and the output terminal VO is connected the source terminal of the P-channel MOS power transistor OM. In parallel with the channel of the P-channel MOS power transistor OM is a protection diode PD.

The output terminal VO is also connected to regulation means RM whose output is connected to the gate terminal G of the P-channel MOS power transistor OM through a diode D6.

The input terminal VI can also be connected to protection means PM against current overloads whose output is again connected to the gate terminal G of the P-channel MOS power transistor OM through another diodes D5.

The input terminal VI must also be connected to voltage booster means EM whose output OUT is connected to the gate terminal G of the P-channel MOS power transistor OM through a current generator IG. The current generator fulfils principally a function of limiting the current generated by the voltage booster means EM and also permits letting the potential of the gate terminal G vary.

The voltage booster means EM provides the gate terminal G with a potential greater at least than the threshold voltage present on the output terminal VO by at least one volt. If the regulator has a low voltage drop, the potential on the output terminal VO will be greater only by a few tenths of a volt and would not be sufficient to pilot the gate terminal G of the P-channel MOS power transistor OM. Therefore, the voltage booster is needed.

Having thus described at least one illustrative embodiment of the invention, various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description is by example only and is not intended as limiting. The invention is limited only as in the following claims and the equivalents thereto.

What is claimed is:

1. A voltage doubler receiving at an input a continuous power voltage and supplying at an output a voltage having a value virtually double that of said continuous power voltage, the voltage doubler comprising:

a. an oscillator, powered by said continuous power voltage having a first output, and a second output in phase opposition to the first output.

b. a charge accumulation condenser having a first terminal connected to a potential reference and a second terminal connected to the output of the doubler,

c. a first charge transfer condenser having a first terminal connected to said first output of said oscillator, and

d. two CMOS inverters connected together in a loop to form a flip-flop having a first input connected to a second terminal of said first condenser, negative power terminals connected together to said continuous power voltage and positive power terminals connected together to said second terminal of said charge accumulation condenser, and

e. a second charge transfer condenser having a first terminal connected to said second output of said oscillator and a second terminal connected to a second input of said inverters.

2. The voltage doubler in accordance with claim 1, wherein said inverters include MOS transistors which are

virtually equal, and wherein corresponding bulk terminals of said MOS transistors are connected in such a manner as to create a one-way conduction path between said negative terminals and said positive terminals of said inverters.

3. A voltage doubler receiving at an input a continuous power voltage and supplying at an output a voltage having a value virtually double that of said continuous power voltage, the voltage doubler comprising:

a. an oscillator powered by said continuous power voltage and having two outputs in phase opposition,

b. a charge accumulation condenser having a first terminal connected to a potential reference and a second terminal connected to the output of the doubler,

c. a first charge transfer condenser and a second charge transfer condenser having first terminals respectively connected to the outputs of said oscillator,

d. a bridge comprising four transistors and corresponding bulk diodes of the transistors, the transistors being arranged so that the four bulk diodes form a bridge, said bridge having a positive terminal connected to the second terminal of said charge accumulation condenser, a negative terminal connected to said continuous power voltage and two intermediate terminals respectively connected to second terminals of said first charge transfer condenser and said second charge transfer condenser, and

the four transistors hiving principal conduction paths connected in parallel with said tour diodes and control terminals connected to the first charge transfer condenser and the second charge transfer condenser in such a way as to lower a voltage drop along branches of the bridge when the doubler reaches a steady state.

4. The voltage doubler in accordance with claim 3, wherein said four transistors are MOS type and are virtually equal.

5. A voltage booster receiving at an input a continuous power voltage and supplying at an output a voltage higher than the continuous power voltage, the voltage booster comprising:

a. an oscillator powered by said continuous power voltage, having two outputs in phase opposition,

b. a charge accumulation condenser having a first terminal connected to a first potential reference and a second terminal connected to the output of the booster, and

c. at least one charging section having a charge output terminal, a power input terminal, a first side terminal and a second side terminal respectively connected to the outputs of said oscillator, and said at least one charging section being connected in series with the output terminal connected to the second terminal of said charge accumulation condenser and the input terminal connected to the continuous power voltage,

wherein the at least one charging section comprises:

a first charge transfer condenser and a second charge transfer condenser having respective first terminals connected to said first and second side terminals, and

a bridge of four controlled switches having two intermediate terminals connected to respective second terminals of said first charge transfer condenser and said second charge transfer condenser a negative terminal connected to said power input terminal and a positive terminal connected to said charge output terminal,

and wherein the value of the voltage of the output corresponds to said continuous power voltage plus the product of said continuous power voltage and a number of the at least one charging section.

6. The voltage booster in accordance with claim 5, wherein the switches of said bridge form two CMOS inverters connected together in a loop to form a flip-flop, having inputs connected to respective second terminals of said first charge transfer condenser and said second charge transfer condenser, negative power terminals connected together to said power input terminal and positive power terminals connected together to said charge output terminal.

7. The voltage booster in accordance with claim 6, wherein said switches include MOS transistors.

8. The voltage booster in accordance with claim 7, wherein corresponding bulk terminals of said MOS transistors are connected in such a way as to create a one-way conduction path between said power input terminal and said charge output terminal when the switches are not conducting.

9. The voltage booster in accordance with claim 6, wherein said inverters are virtually equal.

10. The voltage booster in accordance with claim 5, wherein said power input terminal is connected to said continuous power voltage.

11. An electrically programmable and delectable non-volatile memory device of a type powered with a low voltage comprising:

a. an oscillator powered by said low voltage, having two outputs in phase opposition,

b. a charge accumulation condenser having a first terminal connected to a first potential reference and a second terminal connected to an output of the memory device and

c. at least one charging section having a charge output terminal, a power input terminal, a first side terminal and a second side terminal respectively connected to the outputs of said oscillator and said at least one charging section being connected in series with the output terminal connected to the second terminal of said charge accumulation condenser and the input terminal connected to the low voltage,

wherein the at least one charging section comprises:

a first charge transfer condenser and a second charge transfer condenser having respective first terminals connected to said first and second side terminals, and

a bridge of four controlled switches having two intermediate terminals connected to respective second terminals of said first charge transfer condenser and said second charge transfer condenser, a negative terminal connected to said power input terminal and a positive terminal connected to said charge output terminal,

and wherein the value of the voltage of the output corresponds to said low voltage plus the product of said low voltage and a number of the at least one charging section.

12. A voltage regulator having a low voltage drop between an input and an output of a type having a MOS power transistor as an output regulation element and a voltage booster means having an output coupled to a control terminal of said power transistor to maintain a conduction condition on the power transistor when operating conditions of the regulator change, wherein the voltage booster means includes:

a. an oscillator powered by a continuous power voltage, having two outputs in phase opposition,

b. a charge accumulation condenser having a first terminal connected to a first potential reference and a second terminal connected to the output of the voltage booster means, and

c. at least one charging section having a charge output terminal, a power input terminal, a first side terminal and a second side terminal respectively connected to the outputs of said oscillator and said at least one charging section being connected in series with the output terminal connected to the second terminal of said charge accumulation condenser and the input terminal connected to the continuous power voltage,

wherein the at least one charging section comprises:

a first charge transfer condenser and a second charge transfer condenser having respective first terminals connected to said first and second side terminals, and

a bridge of four controlled switches having two intermediate terminals connected to respective second terminals of said first charge transfer condenser and said second charge transfer condenser, a negative terminal connected to said power input terminal and a positive terminal connected to said charge output terminal,

and wherein the value of the voltage of the output corresponds to said continuous power voltage plus the product of said continuous power voltage and a number of the at least one charging section.

13. The voltage multiplier of claim **12**, wherein the output means includes a charge accumulation condenser connected between the multiplied voltage and a potential reference.

14. The voltage multiplier of claim **13**, wherein the output voltage is outputted at the connection between the charge accumulation condenser and the multiplied voltage.

15. The voltage multiplier of claim **14**, wherein the oscillator is powered by the constant voltage.

16. A voltage multiplier receiving a constant voltage comprising:

an oscillator providing two outputs in phase opposition,

multiplying means connected to the constant voltage and the oscillator outputs for generating a multiplied voltage which is a multiple of the constant voltage; and

output means receiving the multiplied voltage for outputting a substantially constant output voltage which is a multiple of the constant voltage;

wherein the multiplying means includes:

at least one first charge transfer condenser connected to one output of the oscillator;

at least one second charge transfer condenser connected to another output of the oscillator;

at least one bridge circuit of four controlled switches having an input coupled to the constant voltage, an output providing the multiplied voltage, and at least two side inputs respectively coupled to the at least one first charge transfer condenser and the at least one second charge transfer condenser.

17. The voltage multiplier of claim **16**, wherein:

the at least one first charge transfer condenser includes a plurality of first charge transfer condensers, each being connected to said one output of the oscillator;

the at least one second charge transfer condenser includes a plurality of second charge transfer condensers corresponding to the plurality of first charge transfer condensers, each of the second charge transfer condensers being connected to said another output of the oscillator;

the at least one bridge circuit includes a plurality of series connected bridge circuits corresponding to the plurality of first charge transfer condensers and plurality of second charge transfer condensers, each bridge circuit having two side inputs connected to a respective first charge transfer condenser and a respective second charge transfer condenser.

18. The voltage multiplier of claim **16**, wherein the at least one bridge circuit includes:

four diodes in a bridge arrangement such that a positive terminal is connected to the output of the bridge circuit, a negative terminal is connected to the input of the bridge circuit, and two intermediate terminals are connected to the side inputs of the bridge circuit; and

four transistors having principal conduction paths connected in parallel with the four diodes and control terminals connected to the side inputs.

19. The voltage multiplier of claim **17**, wherein each of the plurality of series connected bridge circuits includes:

four diodes in a bridge arrangement such that a positive terminal is connected to the output of the bridge circuit, a negative terminal is connected to the input of the bridge circuit, and two intermediate terminals are connected to the side inputs of the bridge circuit; and

four transistors having principal conduction paths connected in parallel with the four diodes and control terminals connected to the side inputs.

* * * * *

EXHIBIT I

US005986861A

United States Patent [19]

Pontarollo

[11] **Patent Number: 5,986,861**

[45] **Date of Patent: Nov. 16, 1999**

[54] **CLAMP**

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[73] Assignee: **SGS-Thomson Microelectronics S.A.**, Saint Genis, France

[21] Appl. No.: **08/653,958**

[22] Filed: **May 22, 1996**

[30] **Foreign Application Priority Data**

May 24, 1995 [FR] France 95 06405

[51] **Int. Cl.^{6}** **H02H 9/00**

[52] **U.S. Cl.** **361/56**; 361/91.5

[58] **Field of Search** 361/18, 56, 58, 361/91, 111, 118, 119; 257/355–365

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,636,385	1/1972	Koepp	361/56
5,023,542	6/1991	Banura	361/18
5,239,440	8/1993	Merrill	361/91
5,345,357	9/1994	Pianka	361/56
5,400,202	3/1995	Metz et al.	361/56
5,418,411	5/1995	Michel et al.	327/313
5,452,171	9/1995	Metz et al.	361/56
5,526,214	6/1996	Takata et al.	361/56
5,745,323	4/1998	English et al.	361/56
5,825,601	10/1998	Statz et al.	361/56
5,838,146	11/1998	Singer	361/56

OTHER PUBLICATIONS

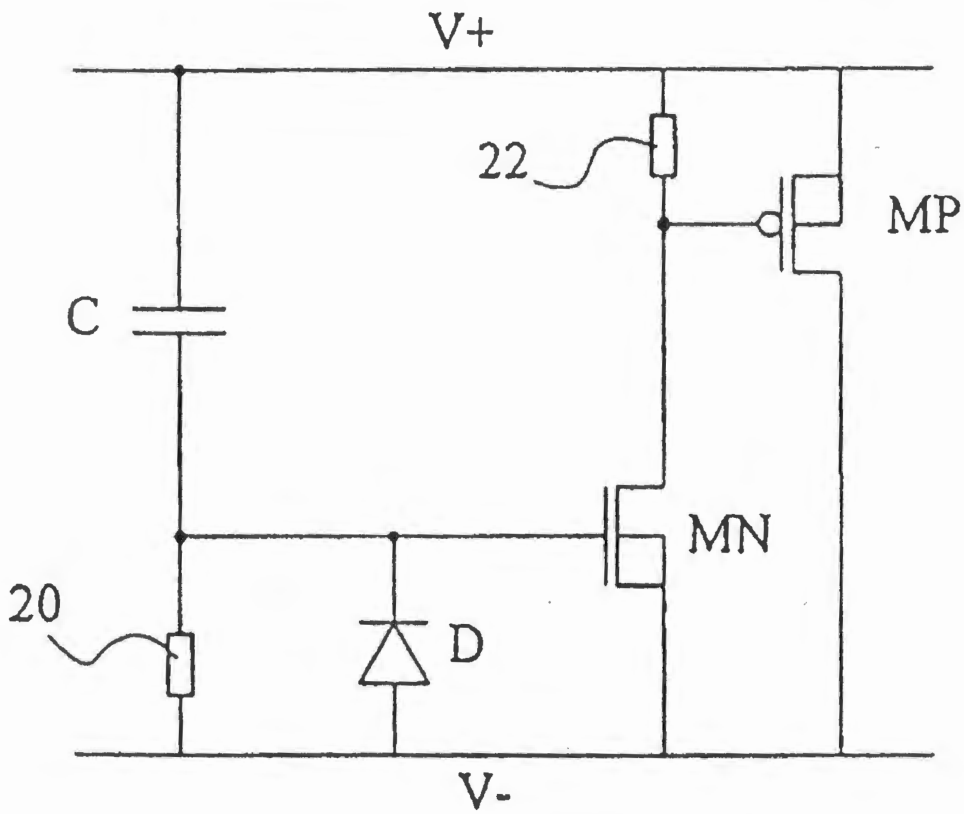
French Search Report from French Patent Application No. 95 06405, filed May 24, 1995.

Primary Examiner—Ronald W. Leja
Attorney, Agent, or Firm—Wolf, Greenfield & Sacks, P.C.

[57] **ABSTRACT**

This invention relates to a device for protecting a circuit against voltage surges, including a MOS transistor of a first type connected to first and second supply terminals by its source and its drain, respectively; a MOS transistor of a second type connected between the second supply terminal and the gate of the first type transistor, by its source and its drain, respectively; and a capacitor having a first terminal connected to the first supply terminal and a second terminal connected to the gate of the second type transistor.

24 Claims, 2 Drawing Sheets



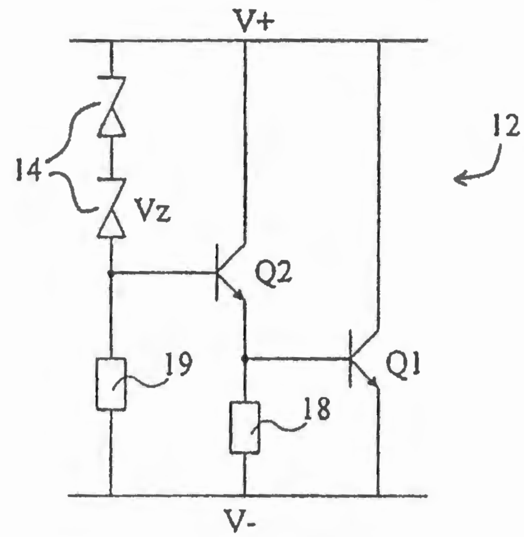


FIG. 1
(PRIOR ART)

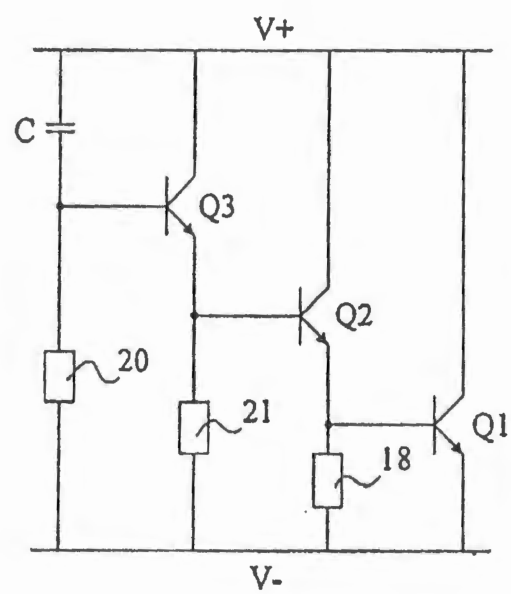


FIG. 2

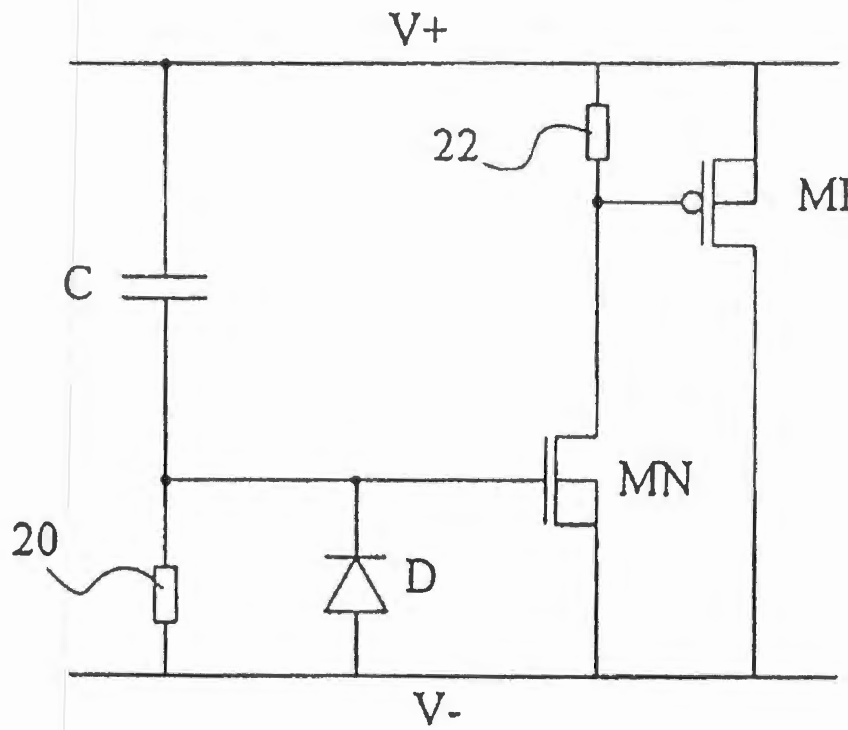


FIG. 3

CLAMP

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a clamp for protecting an integrated circuit against voltage surges which may occur between two terminals of the integrated circuit.

Voltage surges applied between two terminals of an integrated circuit can destroy the circuit. These voltage surges most often result from electrostatic discharges which can be inadvertently applied to the terminals of the integrated circuit in various circumstances. These circumstances may be a mere manipulation of the circuit by an operator whose fingers are brought to high electrostatic potentials by friction phenomena.

2. Discussion of the Related Art

FIG. **1** shows a conventional clamp **12**. This device includes a bipolar NPN shunt transistor Q1 connected by its collector to terminal V^+ and by its emitter to terminal V^-. One or more Zener diodes **14** may be used to define the limit voltage between terminals V^+ and V^-, beyond which transistor Q1 turns on. The anode voltage of the Zener diodes **14** is applied to the base of transistor Q1 through a bipolar NPN follower transistor Q2. The bases of transistors Q1 and Q2 are connected to terminal V^- through respective resistors **18** and **19**.

With this configuration, transistor Q1 is turned on when the voltage between terminals V^+ and V^- becomes higher than the value Vz+2Vbe, where Vz is the sum of the voltages of Zener diodes **14** and 2Vbe is the sum of the base-emitter voltages of transistors Q1 and Q2.

Transistor Q1 is chosen with a particularly low on-resistance. It has a size of, for example, 300 elementary transistors. Follower transistor Q2 is used to supply a base current sufficient for transistor Q1 and includes for this purpose, for example, 100 elementary transistors.

A drawback of this clamp is the difficulty in obtaining a well known Zener voltage Vz. This Zener voltage must be higher than the nominal supply voltage of the circuit but must be lower than the maximum admissible voltage before circuit breakdown.

This range is relatively narrow and it often happens that, from the construction, the Zener voltage obtained is too low so that the clamp starts operating as soon as the circuit is normally supplied. It also often happens that, during circuit operation, by mere thermal drift or aging, the Zener voltage decreases and activates the clamp while the circuit is normally supplied.

Another drawback of this clamp is that transistor Q1 can be destroyed by a long voltage surge, which, however, is insufficient to damage the circuit the clamp protects. As a result, transistor Q1 is permanently short-circuited, which makes the circuit inoperable, even though it is in working order.

Most prior art clamps used in fast technologies are implemented by means of bipolar transistors. An electrostatic discharge has an almost vertical voltage leading edge followed by a progressive decrease. It is essentially this initial voltage value that must be reduced. For this purpose, the clamp must be able to react almost instantaneously. Up to now, it has not been possible to obtain an efficient clamp in slow CMOS technologies (for example, HC1PA).

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an efficient clamp for slow CMOS technology, which eliminates the problem of ensuring an accurate and stable triggering voltage.

To achieve this and other objects, the present invention provides a device for protecting a circuit against voltage surges, including a MOS transistor of a first type connected to first and second supply terminals by its source and its drain, respectively; a MOS transistor of a second type connected between the second supply terminal and the gate of the transistor of the first type, by its source and its drain, respectively; and a capacitor having a first terminal connected to the first supply terminal and a second terminal connected to the gate of the transistor of the second type.

According to an embodiment of the present invention, the device includes a reverse connected diode between the gate and the source of the transistor of the second type.

According to an embodiment of the present invention, the transistor of the first type is a P-channel transistor, the first supply terminal being a positive supply terminal.

These objects, features and advantages, as well as others, of the present invention will be discussed in detail in the following description of specific embodiments, taken in conjunction with the following drawings, but are not limited by them.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**, previously described, shows a conventional clamp;

FIG. **2** shows an embodiment of a clamp which avoids the problem of ensuring a stable and accurate triggering voltage; and

FIG. **3** shows an embodiment of a clamp according to the present invention.

DETAILED DESCRIPTION

FIG. **2** shows a clamp including, like the clamp of FIG. **1**, a transistor Q1, controlled by a follower transistor Q2, for short-circuiting supply terminals V^+ and V^-.

According to an aspect of the invention, a capacitor C is connected between terminal V^+ and the base of follower transistor Q2 via, optionally, an NPN follower transistor Q3. Capacitor C and the base of transistor Q3 are connected to terminal V^- through a resistor **20**. The base of transistor Q1 is connected to terminal V^- through a resistor **18**, as in FIG. **1**, and the base of transistor Q2 is connected to terminal V^- through a resistor **21**.

With this configuration, the clamp is triggered, that is, transistor Q1 is turned on, when the voltage across resistor **20** becomes higher than 3Vbe (sum of the base-emitter voltages of transistors Q1 to Q3).

The voltage across resistor **20** essentially corresponds to the derivative of the voltage between terminals V^+ and V^-. Thus, the faster the voltage between terminals V^+ and V^- increases, the higher the voltage across resistor **20**.

In an electrostatic discharge, capacitor C does not have the time to charge through resistor **20**, that is, the base voltage of transistor Q3 increases at a rate similar to the voltage on terminal V^+. In this case, transistor Q1 is turned on almost as soon as the voltage between terminals V^+ and V^- becomes higher than 3Vbe, which results in eliminating a voltage surge.

Conversely, if the voltage between terminals V^+ and V^- increases relatively slowly, for example when the circuit being protected is normally turned on, the voltage across resistor **20** remains under 3Vbe and the clamp is not triggered.

When a permanent voltage surge is applied, the clamp is not triggered either, at least not after the voltage between terminals V^+ and V^- has reached a stable value. Therefore, transistor Q1 is not destroyed during permanent voltage surges which do not damage the circuit being protected.

The rate of the increase of voltage between terminals V^+ and V^- which triggers the clamp is determined by the values of capacitor C, resistor **20**, the turn-on voltage (3Vbe in FIG. **2**) of transistor Q1, and the gain of transistors Q1 to Q3. A rate is chosen, for instance, which is higher than the rate of increase during normal turn-on of the circuit being protected.

In order to adapt the clamp for use in slow CMOS technology, such as the HC1PA technology, the bipolar transistors of the structure of FIG. **2** could be replaced by MOS transistors. However, the device thus obtained has proven to be inefficient because the circuit it is supposed to protect is destroyed in most cases, under normalized test conditions (a 100 picofarads capacity charged at 2 to 4 kilovolts and discharged in the circuit through a 1500 ohms resistance). This inefficiency is due to the clamp's inability to react to a surge quickly enough. The efficiency of the MOS shunt transistor which replaces transistor Q1 directly depends on its gate-source voltage. However, this gate-source voltage is lower than one third of the voltage across resistor **20**, which follows the voltage of a voltage surge. Therefore, the voltage surge will have time to destroy the circuit before this gate-source voltage reaches a sufficient value for the shunt transistor to absorb the voltage surge.

It has been found that, in CMOS technologies, bipolar NPN transistors with a vertical structure can be utilized, the only restriction being that the collectors of these NPN transistors correspond to the substrate, that is, to positive supply terminal V^+. The circuit of FIG. **2**, with bipolar transistors, can thus be realized in pure CMOS technology. However, tests have shown that the clamp obtained in this manner still is too slow to be efficient, due to the low speed of vertical bipolar transistors.

FIG. **3** shows a clamp according to the present invention which is efficient even if implemented in slow CMOS technology. This device includes a P-channel MOS transistor MP connected between supply terminals V^+ and V^- by its source and its drain, respectively. An N-channel MOS transistor MN is connected between the gate of transistor MP and terminal V^- by its drain and its source, respectively. The gate of transistor MN is connected to terminal V^+ through a capacitor C. The gate and the source of each of transistors MN and MP are interconnected through a resistor, respectively **20** and **22**, which serves to discharge the gate-source capacitance of the transistor.

During a voltage surge, capacitor C does not have the time to charge through resistor **20**, that is, the gate voltage of transistor MN increases at a rate similar to the voltage on terminal V^+. As soon as this gate voltage reaches the threshold voltage of transistor MN, transistor MN turns on and draws the gate voltage of transistor MP towards voltage V^-. Thus, transistor MP also turns on and short-circuits terminals V^+ and V^- to alleviate the voltage surge.

A reason for which the circuit of FIG. **3** is particularly fast is that the gate-source voltage of transistor MP quickly reaches a high value (equal to the circuit supply voltage) which makes it conductive enough to alleviate the voltage surge. Indeed, as soon as the gate voltage of transistor MN becomes greater than the transistor's threshold voltage by a given value, much lower than the value of the voltage surge, transistor MN enters a linear mode, that is, it behaves as a low value resistance, and brings the gate voltage of transistor MP almost back to voltage V^-. Transistor MN rapidly enters a linear mode, since the gate-source capacitance of this transistor constitutes, with capacitor C, a capacitive divider bridge which causes the gate voltage of transistor MN to vary proportionally to the voltage surge, the proportionality coefficient increasing with the increase of capacitor C.

In order to obtain a good compromise between the size of capacitor C and the turn-on speed of transistor MN, this transistor MN preferably is relatively small. As a result, transistor MN is not able to absorb the voltage surge which must be absorbed by the much larger transistor MP.

As an example, in a device according to the invention capable of absorbing voltage surges of 4 kV, transistor MN has a W/L ratio of 1,500/5, transistor MP a W/L ratio of 10,000/5, and capacitor C has a value of 8 picofarads. Resistors **20** and **22** have, for example, a value of 6 Kohms. If a voltage capacity of 2 kV is desired, the W/L ratio of transistor MP can be reduced to 5,000/5.

A device according to the invention, as that of FIG. **2**, is triggered as soon as the voltage between terminals V^+ and V^- changes rapidly. As previously indicated, in the device of FIG. **2**, the components are chosen so that the device is not triggered for a normal turn-on. However, the circuit's supply source generally has a particularly low impedance, which could cause the destruction of the clamp if the device should be triggered.

Despite a judicious selection of the components, it is always possible to encounter the case where a normal turn-on triggers the device, and causes its destruction if it is constituted by bipolar transistors. Indeed, a saturated bipolar transistor has a very low on-resistance, and regardless of the current flowing through it, this resistance decreases as the transistor heats up, which quickly tends to destroy the bipolar transistor.

Conversely, the fact that the clamp according to the invention, as shown in FIG. **3**, formed with MOS transistors, triggers during normal turn-on, is not a nuisance. MOS transistor MP tends to behave as a current source with a value determined by its gate-source voltage. Thus, the current which flows through it never goes over this value and, as long as it is lower than this value, transistor MP behaves as a low value resistance. Further, a MOS transistor has a positive thermal coefficient which tends to decrease the current which flows through the transistor when its temperature increases. These combined characteristics make the clamp according to the invention particularly robust.

Alternatively, the types of transistors MN and MP can be reversed, by inverting the polarities of the supply terminals V^+ and V^-. This has the advantage of reducing the surface occupied by the circuit, since the transistor which must bear the voltage surge is then an N-channel transistor which is approximately three times smaller than a P-channel transistor with the same characteristics. However, an N-channel MOS transistor has the disadvantage of having a parasitic bipolar transistor between its drain and its source. This parasitic bipolar transistor, bearing the current of the MOS transistor, decreases the robustness of the circuit because of its negative thermal coefficient.

As shown, a diode D is reverse connected between the gate and the source of transistor MN. This diode D prevents the gate voltage of transistor MN from becoming too negative with respect to voltage V^-. The gate voltage of transistor MN is equal to the voltage on terminal V^+ minus the voltage across capacitor C. Thus, if voltage V^+ quickly resumes its initial value, after a voltage surge, capacitor C does not have time to discharge through resistor **20**, which causes a negative voltage surge between the gate and the source of transistor MN, which can lead to its destruction.

Of course, the present invention is likely to have various alterations and modifications, which will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and the scope of the invention. Accordingly, the foregoing description is by way of example only and is not intended to be limiting. The invention is limited only as defined in the following claims and equivalents thereto.

What is claimed is:

1. A device for protecting a circuit against voltage surges, comprising:

an MOS transistor of a first type directly connected to first and second supply terminals by its source and its drain, respectively;

an MOS transistor of a second type directly connected between the second supply terminal and the gate of the transistor of the first type by its source and its drain, respectively; and

a capacitor having a first terminal directly connected to the first supply terminal and a second terminal directly connected to the gate of the transistor of the second type.

2. The protection device according to claim **1**, wherein a resistor interconnects the gate and the source of the MOS transistor of the first type.

3. The protection device according to claim **2**, wherein the transistor of the first type is a P-channel transistor, and the first supply terminal is a positive supply terminal.

4. A device for protecting a circuit against voltage surges, comprising:

an MOS transistor of a first type directly connected to first and second supply terminals by its source and its drain respectively;

an MOS transistor of a second type directly connected between the second supply terminal and the gate of the transistor of the first type by its source and its drain respectively;

a capacitor having a first terminal directly connected to the first supply terminal and a second terminal directly connected to the gate of the transistor of the second type; and

a reverse connected diode between the gate and the source of the transistor of the second type.

5. The protection device according to claim **3**, wherein the transistor of the first type is a P-channel transistor, and the first supply terminal is a positive supply terminal.

6. The protection device according to claim **1**, wherein the transistor of the first type is a P-channel transistor, the first supply terminal being a positive supply terminal.

7. The protection device according to claim **1**, wherein a resistor interconnects the gate and the source of the MOS transistor of the second type.

8. A protection device according to claim **7**, further comprising a reverse connected diode between the gate and the source of the transistor of the second type and wherein the transistor of the second type has a faster turn-on rate than the transistor of the first type.

9. A protection device according to claim **7**, further comprising a reverse connected diode between the gate and the source of the transistor of the second type and wherein the transistor of the second type has a smaller capacitance than the transistor of the first type.

10. A protection device according to claim **7**, further comprising a reverse connected diode between the gate and the source of the transistor of the second type and wherein the transistor of the second type has a smaller W/L ratio than the transistor of the first type.

11. A protection device according to claim **1**, wherein the transistor of the second type has a faster turn-on rate than the transistor of the first type.

12. A protection device according to claim **1**, wherein the transistor of the second type has a smaller capacitance than the transistor of the first type.

13. A protection device according to claim **1**, wherein the transistor of the second type has a smaller W/L ratio than the transistor of the first type.

14. A device for protecting a circuit from voltage surges comprising:

a first means for switching coupled to a first power supply and directly connected to a second power supply;

a second means for switching directly connected between said first power supply and said second power supply;

a capacitor directly connected between said first means for switching and said first power supply;

a first resistor directly connected between said first means for switching and said second power supply; and

a second resistor directly connected between said second means for switching and said first power supply;

wherein, upon the occurrence of a voltage surge on said first power supply, said first means for switching closes, thereby supplying a voltage to said second means for switching, which also closes, thereby causing a short-circuit between said first and second power supplies.

15. The device of claim **14**, further comprising a third means for switching coupled between said first means for switching and said second power supply.

16. The device of claim **15**, wherein said first means for switching comprises a transistor of a first type, said second means for switching comprises a transistor of a second type and said third means for switching comprises a diode.

17. The device of claim **16**, wherein said transistor of a first type comprises an N-channel MOS transistor.

18. The device of claim **17**, wherein said transistor of a second type comprises a P-channel MOS transistor.

19. The device of claim **18**, wherein the transistor of the first type has a faster turn-on rate than the transistor of the second type.

20. The device of claim **18**, wherein the transistor of the first type has a smaller capacitance than the transistor of the second type.

21. The device of claim **18**, wherein the transistor of the first type has a smaller W/L ratio than the transistor of the second type.

22. The device of the claim **14**, wherein the first means for switching has a faster turn-on rate than the second means for switching.

23. The device of claim **14**, wherein the first means for switching has a smaller capacitance than the second means for switching.

24. The device of claim **14**, wherein the first means for switching has a smaller W/L ratio than the second means for switching.

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