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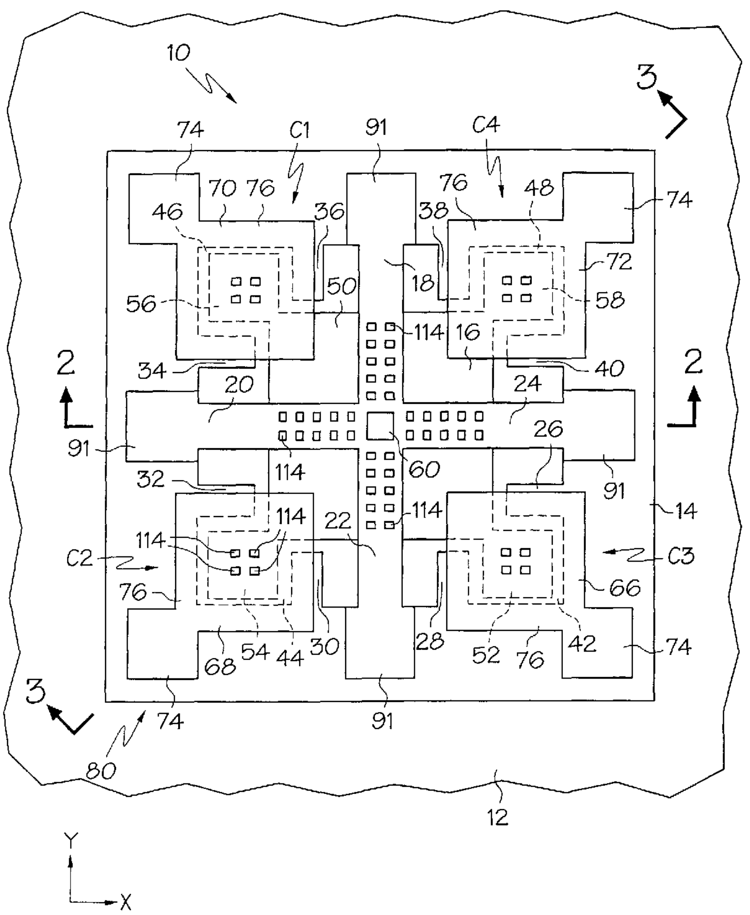

(57) Abstract: A method for forming an accelerometer including the steps of providing a wafer of doped silicon, growing an oxide layer on the wafer, and forming an aperture in the oxide layer. The method further includes the steps of forming a layer of polysilicon on the wafer such that a portion of the polysilicon passes through the aperture and contacts the wafer, and etching the layer of polysilicon to form a beam and a capacitor plate. The wafer is then etched to form a response mass and a support, at least part of the response mass being located below the capacitor plate. Finally, the oxide layer is etched to separate the response mass from the support and from the capacitor plate, the response mass being coupled to the beam by polysilicon received through the aperture.

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THREE AXIS ACCELEROMETER

The present invention is directed to a three axis accelerometer and a method for making a three axis accelerometer, and more particularly, to an accelerometer having generally uniform sensitivity along three axes, as well as a method for making an accelerometer having generally uniform sensitivity along three axes.

BACKGROUND OF THE INVENTION

Accelerometers are used in a wide variety of mechanisms, including vehicles, aircraft, machinery and the like, to sense the acceleration experienced by the mechanism or to sense acceleration experienced by certain components of the mechanism. In many cases, the accelerometers must be quite small (i.e. on the order of a few square millimeters) to be mounted onto the desired component. These small-scale accelerometers are often formed by etching a silicon wafer, using surface micromachining techniques, to form a number of accelerometers on the wafer. Each accelerometer may then be removed from the wafer and mounted to the desired component. However, due to the relatively shallow depth of etching that can be achieved using surface micromachining techniques, accelerometers produced by surface micromachining can typically sense acceleration accurately only along two axes (i.e. the axes lying in the plane of the surface of the accelerometer). An additional, separate accelerometer is typically required if it is desired to accurately sense acceleration along a third, orthogonal axis. Accordingly, there is a need for a small scale accelerometer formed out of a silicon wafer that can accurately sense acceleration along three axes, as well as a method for forming such an accelerometer.

SUMMARY OF THE INVENTION

The present invention is an accelerometer formed from a silicon wafer that can accurately sense acceleration along three axes, as well as a method for making such an accelerometer. The bulk of the wafer is etched using deep reactive ion etching to form a response mass of the accelerometer, which provides a response mass having a large thickness. The accelerometer of the present invention can measure acceleration along all three axes, and can measure acceleration with generally equal sensitivity along all three axes.

In a preferred embodiment, the invention is a method for forming an accelerometer including the steps of providing a wafer of doped silicon, growing an oxide layer on the wafer, and forming an aperture in the oxide layer. The method further includes the steps of forming a layer of polysilicon on the wafer such that a portion of the polysilicon passes through the aperture and contacts the wafer, and etching the layer of polysilicon to form a beam and a capacitor plate. The wafer is then etched to form a response mass and a support, at least part of the response mass being located below the capacitor plate. Finally, the oxide layer is etched to separate the response mass from the support and from the capacitor plate, the response mass being coupled to the beam by polysilicon received through the aperture.

In another embodiment, the invention is an accelerometer including a conductive response mass, a support, a beam coupled to the support and to the response mass such that the response mass is supported by the beam, and a displacement sensor coupled to the support, the displacement sensor including at least three capacitor plates, each capacitor plate being located adjacent to the response mass to form a capacitor with the response mass, wherein acceleration of the accelerometer causes the response mass to be displaced relative the support, the displacement of the response mass relative the support causing a change in capacitance in at least two of the capacitors that is sensed by the displacement sensor.

Other objects and advantages of the present invention will be apparent from the following description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a top view of a one embodiment of the accelerometer of the present invention;

Fig. 2 is section view of the accelerometer of Fig. 1 taken along line 2-2 of Fig. 1;

Fig. 3 is a section view of the accelerometer of Fig. 1 taken along line 3-3 of Fig. 1;

Fig. 4 is a schematic representation of the accelerometer of the present invention experiencing acceleration in the Z direction;

Fig. 5 is a schematic representation of the accelerometer of the present invention experiencing acceleration in the X direction;

Fig. 6A is a top view of the support and response mass of the accelerometer of Fig. 1;

Fig. 6B is a detail view of a capacitor plate of the accelerometer of Fig. 1;

Fig. 6C is a top view of the support and an alternate embodiment of the response mass;

Figs. 7-13 are a series of section views showing a method for manufacturing the accelerometer of Fig. 1;

Figs. 14-20 are a series of section views showing a method for manufacturing an alternate embodiment of the accelerometer of Fig. 1;

Fig. 21 is a circuit configuration for monitoring the acceleration of an accelerometer;

Fig. 22 is a timing diagram for achieving desired outputs from the circuit of Fig. 21;

Fig. 23 is an amplifier output table corresponding to the amplifiers of the circuit configuration of Fig. 21; and

Figs. 24-30 are a series of section views showing an alternate method for manufacturing the accelerometer of Figs. 1-3.

DETAILED DESCRIPTION

As shown in Fig. 1, the sensor or accelerometer 10 of the present invention can be coupled to a component 12 to measure the acceleration experienced by the component 12. The accelerometer 10 includes a support 14, a set of capacitors C1, C2, C3 and C4, a response mass 16, and a set of beams 18, 20, 22, 24 extending from the support to the response mass. As shown in Fig. 6A, the support 14 extends around the perimeter of the response mass 16, and is generally square in top view. Each side of the support 14 preferably has a length ranging from between about 1.5 mm and about 2.5 mm. The support 14 also includes a set of inwardly extending arms 26, 28, 30, 32, 34, 36, 38, 40. Adjacent arm pairs form a set of four cavities 42, 44, 46, 48 in the support 14, each cavity being located adjacent a corner of the support.

The response mass 16 is located within the support 14, and includes a central portion 50 and four corner protrusions 52, 54, 56, 58. Each protrusion 52, 54, 56, 58 is closely received within a cavity 42, 44, 46, 48. As shown in Figs. 1 and 2, each beam 18, 20, 22, 24 is connected at one end to the support 14, and at the other end to the center of the response mass 16. A nonconductive layer, such as an oxide layer 61, is located between each beam 18, 20, 22, 24 and the support 14 (Figs. 2 and 3). The beams 18, 20, 22, 24 are located at the top of the support 14 and coupled to the top of the response mass 16 by an anchor 60 such that the response mass is suspended from the beams. The beams 18, 20, 22, 24 may also be located below the response mass 16. In either case, the beams 18, 20, 22, 24 support the response mass 16. Although not shown in Figs. 2-3, the lower edge 15 of the response mass 16 is spaced above the lower edge 17 of the support 14 such that the response mass 16 is suspended from, and supported by, the beams 18, 20, 22, 24. The anchor 60 also provides an electrical contact between the suspension beams 18, 20, 22, 24 and the response mass 16.

The accelerometer 10 includes four capacitor plates 66, 68, 70, 72, each capacitor plate having an end portion 74 and an overhang portion 76. Each capacitor plate 66, 68, 70, 72 is located over a cavity 42, 44, 46, 48 of the support 14 and the associated protrusion 52, 54, 56, 58 of the response mass 16. A non-conductive layer, such as an oxide layer 61, is located between each capacitor plate 66, 68, 70, 72 and the support 14 (see Fig. 3). When the capacitor plates 66, 68, 70, 72 are coupled to the support 14, as shown in Fig. 1, the end portion 74 of each capacitor plate is coupled to the support 14, and the overhang portions 76 are located over the associated protrusion and cavity. Parts of the overhang portions 76 of each capacitor plate are coupled to the arms 26, 28, 30, 32, 34, 36, 38, 40 of the support 14 to further attach the capacitor plates to the support. The arms help to support the capacitor plates 66, 68, 70, 72 to limit the deflection of the plates. For example, parts of the overhang portion 76 of capacitor plate 66 are attached to the arms 26, 28, parts of the overhang portion 76 of capacitor plate 68 are attached to the arms 30, 32, parts of the overhang portion 76 of capacitor plate 70 are attached to the arms 34, 36, and parts of the overhang portion 76 of capacitor plate 72 are attached to the arms 38, 40. Alternately, the capacitor plates may be located below the response mass 16.

The response mass 16, capacitor plates 66, 68, 70, 72, support 14 and beams 18, 20, 22, 24 are made of conductive materials, and each capacitor plate is electrically isolated from the support (i.e. by the oxide layer 61). Accordingly, each capacitor plate/protrusion pairing forms a capacitor, shown as capacitors C1, C2, C3 and C4 in Fig. 1. The materials and size of the capacitors C1, C2, C3 and C4 are preferably matched such that the nominal capacitance value of each capacitor is equal.

When the accelerometer 10 experiences an acceleration, the response mass 16 moves relative the support 14. Movement of the response mass 16, in turn, causes a change in capacitance of the capacitors C1, C2, C3 and C4. The change in capacitance in the capacitors is inversely proportional to the applied acceleration. The change in capacitance can be sensed in a manner well known in the art, and the acceleration can then be calculated. For example, with reference to the coordinate system shown in Figs. 1-3, when the accelerometer 10 experiences acceleration in the +Z direction, the response mass 16 moves downwardly (in the -Z direction) to its position shown in solid lines in Fig. 4 (the position of the response mass at rest being shown in hidden lines). The acceleration force is balanced by a spring force in the suspension beams 18, 20, 22, 24. Because the response mass 16 is moved further away from the capacitor plates 66, 68, 70, 72, the capacitance of the capacitors C1, C2, C3 and C4 changes accordingly. By sensing the change in the capacitance of the capacitors C1, C2, C3 or C4, the deflection of the response mass 16 can be measured. The measured displacement of the response mass 16 can then be converted into an acceleration.

As shown in Fig. 5, when the accelerometer experiences acceleration in the +X direction, the response mass 16 tilts from its rest position (shown in hidden lines) to a displaced position (shown in solid lines). When the accelerometer 10 experiences acceleration in the Y direction, the response mass 16 tilts in the same manner (although around a different axis) as shown in Fig. 5. Thus, acceleration in the Y direction is governed by the same equations that are used when the accelerometer 10 experiences acceleration along the X axis. Although not shown in Figs. 2-3, the lower edge 15 of the response mass 16 is spaced above the lower edge 17 of the support 14 sufficiently to enable the response mass 16 to move downwardly without engaging (i.e. "bottoming out on") the component 12.

When the accelerometer experiences acceleration in the X direction, the deflection and acceleration of the response mass is directly proportional to (1/C2 - 1/C3), where C2 is the capacitance of the capacitor C2 and C3 is the capacitance of the capacitor C3. As shown in Fig. 1, the capacitors C2 and C3 form a line or axis that extends along the X axis. Of course, the capacitance of any two capacitors that are spaced along the X axis may be used to measure X acceleration. The value of (1/C2 - 1/C3) changes only under X acceleration, and does not change under any other accelerations.

Similarly, when the accelerometer experiences acceleration in the Y direction, the deflection and acceleration of the response mass is directly proportional to (1/C1 - 1/C2), where C1 is the capacitance of the capacitor C1. The capacitors C1 and C2 form a line or axis that extends along the Y axis. Again, the capacitance of any two capacitors spaced along the Y axis may be used, and the value of (1/C1 - 1/C2) is only responsive to Y acceleration.

Finally, when the accelerometer is accelerated in the Z direction, the displacement and acceleration of the response mass is directly proportional to 1/C1, 1/C2 or 1/C3. However, in a preferred embodiment, the displacement in the Z direction is calculated based upon (1/C1 + 1/C3). The value of (1/C1+ 1/C3) is responsive to Z acceleration only.

While the following description refers to the preferred embodiment of processing circuitry useful in monitoring the capacitors of the accelerometer, it is recognized that other suitable processing circuitry could be developed or utilized in combination with the accelerometer structure described herein. A preferred circuit configuration 200 for monitoring the accelerometer is shown in Fig. 21, which depicts a switched-capacitor circuit approach. Three switched capacitor amplification stages 202, 204 and 206 with respective op-amps 203, 205 and 207 are provided in the circuit 200. A final stage 208 of the circuit 200 is made up of four track and hold circuit modules T/H1, T/H2, T/H3 and T/H4. Each track and hold circuit module includes a respective sampling trigger input 210-1, 210-2, 210-3 and 210-4 for controlling when the respective module samples the voltage output level of amplification stage 206, and also includes a respective output 212-1, 212-2, 212-3 and 212-4.

Capacitors C1, C2 and C3 of the accelerometer are connected in parallel in the feedback path of amplification stage 202, and are designated as capacitors Cx1, Cx2 and Cx3 respectively. Each capacitor Cx1, Cx2 and Cx3 is connected in series with a respective electronic switch S3, S4 or S5 for switching the capacitors into and out of the circuit. An electronic switch S12 is connected in series between the capacitors and a reference voltage V0. Electronic switch S6 is also provided in the feedback path of amplification stage 202. Accordingly, there are four potential feedback paths for amplification stage 202 which are selected to achieve desired circuit outputs.

An input to amplification stage 202 is provided through switching circuit 214 which may be a 2 to 2 multiplexer. In particular a reference voltage Vref, such as 1.25 volts, is selectively applied to amplification stage 202 by controlling switching circuit 214 and electronic switches S1 and S2. Switches S1 and S2 are controlled to switch the input to amplification stage 202 between the upper and lower outputs of the switching circuit 214. A control input P to the switching circuit 214 controls which output of the switching circuit is high (1.25 volts) and which output is low (GND).

The second and third amplification stages 204 and 206 each include selectable feedback paths. One of the selectable paths includes a capacitor C6 in series with an electronic switch S8 or S11 and the other of which is formed by a straight connection through an electronic switch S7 or S10. Reference voltage V0 is also selectively applicable to the capacitive feedback paths through electronic switches S9 and S12.

Referring now to Fig. 22, a timing diagram 220 for achieving desired outputs from circuit 200 is shown. Timing circuitry (not shown) for generating the illustrated clock signals can be easily developed by those of skill in the art. Signal Ch1 controls switch S5; signal Ch2 controls switch S4; signal Ch3 controls switch S3; signal P controls the output state of switching circuit 214; signal ϕ12 controls switch S13; signal ϕ13 controls switch S1; signal ϕ14 controls switch S2; signal Comp is provided as an input to second stage 204; signal ϕ21 controls switches S7 and S9; signal ϕ22 controls switch S8; signal ϕ3 controls switches S10 and S12; signal ϕ32 controls switch S11; signal Track1 is applied to T/H1 input 210-1; signal Track2 is applied to T/H2 input 210-2; signal Track3 is applied to T/H3 input 210-3; and signal Track4 is applied to T/H4 input 210-4.

By utilizing the timing signals illustrated in Fig. 22 during an acceleration event, the X, Y and Z acceleration components can be determined. In particular, referring to Fig. 23 the voltage output of each amplification stage resulting from the sequential switching of capacitors Cx1 and Cx2 into the feedback path of amplification stage 202 is shown at table segment 230. The resulting third stage output includes the desired (1/C1 - 1/C2) component. Similarly, table segment 232 shows the amplification stage outputs when capacitors Cx3 and Cx1 are sequentially switched into the feedback path of amplification stage 202. The third stage output includes the desired (1/C3 + 1/C1) component. Notably, timing signal P goes high as capacitor Cx1 is switched into the feedback path to assure that the critical third stage output component is additive rather than subtractive. Table segment 234 shows the amplification stage outputs when capacitors Cx2 and Cx3 are sequentially switched into the feedback path of amplification stage 202. The third stage output includes the desired component (1/C1 - 1/C3). Table segment 236 shows the circuit output when none of the capacitors are in the feedback path of amplification stage 202. G1 and G2 represent the gain constants of stages 204 and 206 respectively and are known per the electronic components used.

In each amplifier stage, during clock phase 1 the amplifier is reset and the output is set to V0. During clock phase 2, the amplifier amplifies the voltage change in the input compared to the voltage value right at the moment the reset switch is open. The clock frequencies for first stage 202, second stage 204 and third stage 206 are *f*, *f/2* and *f/4* as shown in the timing diagram 220. The frequency *f* is preferably in the range of tens of KHz. For clock signals "high" means a switch is closed and "low" means a switch is open.

In the first stage 202 the operation repeats every two cycles. During the first cycle a stimulation signal is applied to the input and therefore the first stage output is the sum of (VrefCo)/Cx and some circuit offset errors. During the second cycle no stimulation signal is applied to the input and the first stage output is simply the offset error. In every cycle of the second stage 204 the op-amp amplifies the output difference between the two cycles of the first stage. By doing this, the output of the second stage 204 is a signal that represents one of the sense capacitors without offset errors. The unwanted sensor offset is canceled by intentionally applying negative offset by applying signal "Comp" to C4. In a preferred arrangement the gain of the second stage is about 5. In every cycle of the third stage 206 the circuit calculates and amplifies the difference between the outputs produced in the two cycles of the second stage 204. Ideally, the output of the second stage corresponds to 1/Cx without any offset error. The switched-capacitor circuit itself can only perform subtraction. Thus, in order to get the desired component (1/C3 + 1/C1) the polarity of the stimulus applied to the first stage is changed using switching circuit 214 when C1 is selected.

Each of the track and hold modules (column 6 of Fig. 23) is controlled to sample the third stage output when the voltage at the output corresponds to the value shown in adjacent column 5 of the illustrated table. Thus, at the end of a acceleration monitoring sequence each track and hold module stores a respective acceleration indicative output. Module T/H1 stores the Y-direction acceleration indicative value, module T/H2 stores the Z-direction acceleration indicative value and module T/H3 stores the X-direction acceleration indicative value. As shown in column 5, the acceleration indicative third stage outputs all include a component "offset 2". Module T/H4 stores the value "offset 2" allowing it to be subtracted from each of the acceleration indicative outputs to provide final outputs which are directly proportional to acceleration. Thus, for example, the value in module T/H4 can be subtracted from the value in module T/H1 and the resulting final value can be used to reference a stored acceleration map to determine the Y-direction acceleration. Alternatively, the resulting final value could be used to directly calculate the Y-direction acceleration. In either case, suitable processing circuitry 240 is provided to perform these functions as is known in the art. Similar operations are performed to determine X-direction acceleration and Z-direction acceleration.

The capacitors C1, C2 and C3 and associated circuitry together form a displacement sensor 80 (Fig. 1). The displacement sensor 80 can determine the acceleration experienced by the accelerometer based upon a change in capacitance of the capacitors. In order to sense acceleration along three axis, each capacitor C1, C2, C3 is preferably located at a corner of the accelerometer 10. In this manner, capacitors C1 and C2 form a line that is perpendicular to a line formed by capacitors C2 and C3. This enables the accelerometer 10 to sense acceleration along all three axes.

Returning to Fig. 1, the accelerometer 10 may include a fourth capacitor plate 72 that forms a capacitor C4 with the response mass 16. The capacitor C4 is preferably used as an actuator that is used to implement a self-test mechanism. In order to initiate the self test, a DC voltage is applied to the capacitor plate 72, which causes the response mass 16 to be deflected (i.e. upwardly in the +Z direction). The deflection of the response mass 16 can then be sensed by the sense capacitors C1, C2 and C3, and the measured deflection can be analyzed to check whether the sensed displacement of the response mass correlates with the expected displacement.

It is often desired to achieve uniform tri-axial sensitivity of the accelerometer; that is, for a given acceleration along the X, Y, or Z axis, the displacement of the response mass 16 is the same in each case. The deflection of the response mass 16 in the Z direction upon an acceleration in the Z direction is governed by the following equation:

$$\Delta D_z = \frac{(1-\gamma^2)L^3 m a_z}{4Ebh^3} \qquad (1)$$

Where E is the Young's modulus of the beams 18, 20, 22, 24; γ is Poisson's ratio of the beams; b, h, and L are the width, thickness and length of the beams, respectively; m is the mass of the response mass 16; and a_z is the acceleration in the Z direction. By selecting different combinations of b, h, L and m, wide ranges of sensitivity of the accelerometer 10 can be achieved.

When the accelerometer 10 experiences acceleration in the X or Y direction, the deflection of the response mass relative the center point of a sense capacitor plate can be expressed as:

$$\Delta D_{X(Y)} = \frac{3(1-\gamma^2)\, Lde\, ma_{X(Y)}}{2Ebh^3} \qquad (2)$$

Where d is the distance from the end of each beam 18, 20, 22, 24 (i.e. the anchor 60) to the center of the sense capacitor plate (shown in Fig. 2); e is the distance between the center of gravity of the response mass and the center of gravity of the suspension beam (shown in Fig. 2); and a_X is the acceleration in the X direction. In order achieve uniform sensitivity for the accelerometer 10, the response mass should be deflected the same distance in all three directions under the same acceleration. Thus, assuming equal accelerations, $a_{X(Y)} = a_z$, $\Delta D_{X(Y)}$ (Equation (1)) is set equal to ΔD_z (Equation (2)). Canceling out common terms in the equations, it is seen that:

$$L^2=6de \qquad (3)$$

Thus, in order to achieve uniform triaxial sensitivity, the conditions of Equation (3) must be met in the design of the accelerometer. In typical surface micromachined accelerometer, e is very small (on the order of microns), such that the condition of Equation (3) cannot be practically achieved. That is, L cannot be made small enough and d cannot be made large enough to compensate for the small value of e. However, when using deep reactive ion etching (DRIE), e can be on the same order of magnitude as L, such that uniform sensitivity over three axes is achievable. In the equation $L^2=Ade$, the constant A is preferably about 6, but the value may deviate, up to an integer or more from 6 (i.e., from about 4 to about 8), while still providing acceptable sensitivities.

The accelerometer is illustrated using four beams 18, 20, 22, 24. However, only a single beam (or other similar structure) may be used to support the response mass. In this case, the beam and response mass may be shaped to provide an accelerometer having uniform sensitivity. However, an equation other than $L^2=Ade$ would be used to determine the shape of the beam and response mass.

As noted previously, it is assumed that the change of (1/C1 - 1/C2) is equal to the change of (1/C1 + 1/C3) when $\Delta D_x = \Delta D_z$. However, the movement of the response mass in the Z direction is a translatory movement, (see Fig. 4) whereas the movement of the response mass under X acceleration is a rotational movement (see Fig. 5). Accordingly, the assumption that $\Delta(1/C1 - 1/C2) = \Delta(1/C1 + 1/C3)$ when $\Delta D_X = \Delta D_z$ is not completely accurate. However, due to the geometry of the accelerometer, the resultant error is expected to be within acceptable ranges. From a mechanical point of view, good linearity of the accelerometer can be achieved when the full range of deflection of the response mass is less than 30% of the thickness of the beams. Using the present design, the full range of deflection of the response mass can be 4% or less of the thickness of the beams.

A preferred process for forming the accelerometer shown in Figs. 1-6 is shown in Figs. 7-13 and discussed below. As shown in Fig. 7, the process begins with a silicon wafer 100 that is preferably heavily doped, the wafer typically being about 400 to 600 microns thick. The wafer may be made of other materials besides silicon such as glass, silicon carbide, polysilicon, or any number of ceramics. The wafer 100 can etched to simultaneously form a plurality of accelerometers on the wafer using batch processing techniques well known in the art. For example, up to 1000 or more accelerometers may be fabricated on a four inch diameter wafer. However, for ease of illustration Figs. 7-20 and 24-30 show the forming of only a single accelerometer on a wafer 100.

A top 102 and a bottom 104 oxide layer (such as silicon dioxide) are then grown onto the silicon wafer 100. Although the thickness of the oxide layers 102, 104 may vary, the oxide layers are typically about one micron thick. The top oxide layer 102 is then patterned by forming an aperture 106 in the center of the oxide. Either dry or wet etching techniques may be used to pattern the top oxide layer 102. The aperature 106 will ultimately be the location of the anchor 60 where the beams 18, 20, 22, 24 are attached to the response mass 16. Next, as shown on Fig. 9, a top layer 110 and a bottom layer 111 of polysilicon are deposited on top of the oxide layers 102, 104. The deposition of the bottom layer of polysilicon 111 is not necessary to the manufacturing process, but is a byproduct of depositing the top layer of polysilicon 110 and will subsequently be removed. The top polysilicon layer 110 is preferably heavily doped (such as n-type) to improve its conductivity, and may be from about 5-10 microns thick. Other materials besides polysilicon such as amorphous silicon, heavily doped silicon, glass, silicon carbide, polysilicon, ceramics, sapphire, single crystal silicon, metal, polyimid, silicon-on-insulator and the like may also be used.

As shown in Fig. 10, the top layer of polysilicon 110 is then patterned to form the desired shape of the suspension beams 18, 20, 22, 24 and capacitor plates 66, 68, 70, 72 (i.e. the shape of the suspension beams and capacitor plates shown in Figs. 1-3 and 6B). A series of release holes 114 are formed in the suspension beams 18, 20, 22, 24 (as shown in Fig. 10) and in the capacitor plates 66, 68, 70, 72 (not shown in Fig. 10) during this step. The release holes 114 can be seen in Fig. 1 and will be used as a conduit for a wet etching materials, as will be discussed in greater detail below. The mask used to etch the top layer of polysilicon 110 during the step shown in Fig. 10 may be varied to change the size and shape of the suspension beams 18, 20, 22, 24, capacitor plates 66, 68, 70, 72 and release holes 114. Various techniques of etching the top layer of polysilicon 110 may be used, although dry etching, such as reactive ion etching, is preferred.

Next, as shown in Fig. 11, the bottom layer 111 of polysilicon is removed. As shown in Fig. 12, the bottom oxide layer 104 is then removed, and the back side of the wafer 100 is etched (preferably using DRIE) to define the shape of the support 14 and the response mass 16, including the protrusions 52, 54, 56, 58 and cavities 42, 44, 46, 48, as shown in Figs. 6A or 6C. Again, the size and shape of the support 14 and response mass 16 can be controlled during this step to produce desired qualities in the accelerometer 10. For example, if desired the response mass 16 may be shaped as the response mass shown in Fig. 6A or 6C, which provides differing values of L and b. Finally, the device is released by removing the upper oxide layer 102 between the response mass 16 and the suspension beams 18, 20, 22 and 24, and between the response mass 16 and the capacitor plates 66, 68, 70, 72 , as shown in Fig. 13. The portions of the upper oxide layer 102 are preferably removed with a wet etch material, such as hydrofluoric acid (HF). The wet etch material is passed through the release holes 114 and the gaps 120 shown in Fig. 12 to etch away the oxide 102 connecting the suspension beams 18, 20, 22, 24 and the support 12, and the capacitor plates 66, 68, 70, 72 and the response mass 16. The etch release time during this step must be carefully controlled to ensure that contact remains between the response mass 16 and the beams 18, 20, 22, 24 (i.e. the anchor 60), and between the beams and the support 14 (i.e. the oxide layer 61). A buffered hydrofluoric acid may be used to provide greater control over the etching process during this step. The anchor 60 is preferably at least about 50 microns, and the distance between the release holes is preferable about 25 microns.

The process described above is a preferred method for forming the accelerometer 10 shown in Figs. 1-3, although different steps may be used to form the accelerometer without departing from the scope of the invention. A number of accelerometers 10 may be simultaneously etched onto a single, larger wafer (not shown). If this is the case, each accelerometer must then be released from the large wafer in a manner commonly known to those skilled in the art, for example through dicing. After the accelerometer 10 is released, it is packaged within a housing or packaging (not shown). A set of wires are then electrically coupled to the accelerometer 10 to couple the accelerometer to a signal conditioning circuit or a microprocessor, and the ends of the wire extend outside of the packaging. The end portions 74 of the capacitor plates 66, 68, 70, 72 act as bonding pads, and provide a convenient surface upon which wires may be soldered, bonded or otherwise attached. Each beam 18, 20, 22, 24 also includes a bonding pad 91 upon which a wire may be soldered, bonded, or otherwise attached. A wire that is coupled to one of the bonding pads 91 of one of the beams is electrically coupled to the response mass 16, because the beams are electrically coupled to the response mass by the anchor 60 (Fig. 2). Furthermore, the beams 18, 20, 22, 24 are electrically isolated from the support 14 due to the oxide layer 61 between the beams and the support 14 (Fig. 3).

The mass of the response mass 16 may be selected during the manufacturing process to adjust the characteristics of the accelerometer 10 to the expected operating conditions. That is, the size, shape and mass of the response mass 16 may be adjusted to adapt the accelerometer to the expected range of acceleration. For example, a larger, more massive response mass 16 is desired when relatively low acceleration is expected. In contrast, when larger accelerations are expected, a smaller, lighter response mass 16 is desired. One advantage provided by the present invention is that the shape and mass of the response mass is not determined until relatively late in the manufacturing process. This provides flexible manufacturing benefits.

For example, if the desired size of the response mass 16 is not known in advance, a number of accelerometers may be partially formed and stored. When the desired parameters for the response mass are known, the stored, partially completed accelerometers may be pulled from storage and quickly processed to completion. For example, a manufacturer may process a number of wafers up through the processing step shown in Fig. 11, and then store the partially completed wafers. When an order is received from a customer, the desired shape and size of the response mass 16 may be calculated based upon the accelerometer specifications supplied by the customer. The partially completed wafers may then be pulled from storage, and processed according to the customer specifications. This provides flexibility and quick response time to the manufacturer.

As noted above, the size, shape, thickness and materials of various components of the accelerometer 10 may be varied to adapt the accelerometer to the expected operating characteristics. For example, the size and shape of the response mass 16 may be varied to adapt the response mass to the expected range of accelerations. Fig. 6C illustrates a response mass 16 that is small compared to the response mass 16 of Fig. 6A. However, in some cases it may be desired to reduce mass of the response mass 16 even beyond that shown in Fig. 6C, and this is accomplished by etching the back side of the response mass 16, including those sections of the response mass forming the arms 19 (Fig. 6C) and the protrusions 52, 54, 56, 58.

Fig. 20 illustrates an alternate embodiment 10' of the accelerometer 10 wherein the back side of the response mass 16 is etched to reduce the mass of the response mass. This embodiment is used when an accelerometer is needed to measure high accelerations, and where the response mass 16 needs to be decreased beyond the size of the response mass that can be made according to the process shown in Figs. 7-13. In this case, an additional DRIE etch may be applied to the response mass 16 to etch away the back side of the response mass under the protrusions 52, 54, 56, 58. The etching of the back side of the protrusions 52, 54, 56, 58 must be carefully controlled to ensure that the top parts of the protrusions 52, 54, 56, 58 remain to form the capacitors C1, C2, C3, C4.

Figs. 14-20 illustrate one manner in which the mass of the response mass 16 may be additionally reduced. After the top polysilicon 110 has been patterned and the bottom layer of polysilicon 111 is removed, the wafer 100 of Fig. 7 has the configuration shown in Fig. 11, as also shown in Fig. 14 (Figs. 14-20 illustrate a "diagonal" cross section of the wafer 100 , for example, taken along lines 3-3 of Fig. 1, whereas Figs. 7-13 illustrate a side cross section taken along lines 2-2 of Fig. 1).

The bottom oxide layer 104 is then patterned with a first wet or dry etch, as shown in Fig. 15. Next, a photoresist 126 is coated on the top of the bottom oxide 104 and patterned as shown in Fig. 16. It is advantageous to add the photoresist 126 on top of the bottom oxide 104 at this point as will be explained below. The extra mass that is desired to be etched from the under side of the wafer 100 is not covered by the photoresist 126. The wafer 110 is then time etched using DRIE and the areas of the wafer 110 that are not covered by the bottom oxide 104 and not covered by the photoresist 126 are etched away to a predetermined depth (about 50 microns in one embodiment) (Fig. 17).

Because the photoresist 126 was placed onto the wafer 100 before the bulk of the wafer 100 was etched, the photoresist need not be placed onto the wafer after this etching step. This is advantageous because the newly etched areas 113 (Fig. 17) of the wafer would be coated by a photoresist if it were added after the wafer 100 were etched.

After this first etch, the wafer 110 is then put into a liquid etch material to etch the exposed oxide 104 (i.e. the oxide not covered by the photoresist, Fig. 18). After the bottom oxide 104 is removed, a second DRIE timed etch is employed to etch away the extra mass in the mass 16 to a predetermined depth, as shown in Fig. 19. The areas etched away during this step is controlled by the photoresist layer 126. Care must be taken to ensure that the response mass 16 is not etched all the way through, to ensure that parts of the response mass are located below each capacitor plate to act as an electrode of the capacitors C1, C2, C3 and C4. The top oxide layer 102, photoresist 126 and bottom oxide layer 104 are then removed to form the accelerometer 10' shown in Fig. 20.

The resultant accelerometer 10' has a response mass 16 with removed portions 13 (portions that are removed compared to the accelerometer 10 of Figs. 1-3). The center section 50, arms 19 and protrusions portions 52, 54, 56, 58 can be etched to their minimum required thickness to reduce the mass of the response mass. This reduces the weight of the response mass 16, which means that the accelerometer 10' is can sense higher accelerations. The additional etching steps of Figs. 14-20 changes *e*, and an appropriate compensation in the external processor or circuit is required to achieve uniform sensitivity of the accelerometer. Of course, other methods of etching the back side of the wafer to reduce the response mass may be used without departing from the scope of the present invention.

Figs. 24-30 illustrate a method for forming an accelerometer similar to the accelerometer 10 of Figs. 1-3. As shown in Fig. 24, the process begins with a wafer 140 having a top silicon layer 142 and a middle oxide layer 144. The wafer 140 is preferably heavily doped silicon, and the top silicon layer 142 is preferably about 5-10 microns thick and also heavily doped. The middle oxide layer 144 is preferably about 1 micron thick.

As shown in Fig. 25, the top silicon layer 142 is patterned to form the top capacitor plates 66, 68, 70, 72, suspension beams 18, 20, 22, 24, release holes 114 and an opening 148 for the anchor 60. Next, as shown in Fig. 26, a photoresist layer 150 is coated onto the top silicon layer 142, and is patterned to open a window 152 at the anchor area and opening 148. As shown in Fig. 27, the portion of the oxide layer 144 located below the opening 148 is removed, and the photoresist 150 is then removed. Next a conductor, such as metal, is deposited into the opening 148 (Fig. 28) to form an anchor 60' that ensures electrical contact between the suspension beams 18, 20, 22, 24 and the portion of the wafer 140 that will be formed as the response mass. If metal is used to form the anchor 60', the metal is preferably resistant to HF.

As shown in Fig. 29, the back side of the wafer 140 is etched to form the support 14 and the response mass 16. The response mass 16 is then released by etching the oxide layer 144 to form the accelerometer 10" as shown in Fig. 30. The accelerometer 10" may then be packaged and shipped to a customer, as described above.

Having described the invention in detail and by reference to the preferred embodiments, it will be apparent that modifications and variations thereof are possible without departing from the scope of the invention.

What is claimed is:

CLAIMS

1. A method for forming an accelerometer comprising the steps of:

providing a conductive wafer;

growing an oxide layer on said wafer;

forming an aperture in said oxide layer;

forming a layer of conductive material on said wafer such that a portion of said layer of conductive material passes through said aperture and contacts said wafer;

etching said layer of conductive material to form a beam and a capacitor plate;

etching into said wafer to form a response mass and a support, at least part of said response mass being located adjacent said capacitor plate; and

etching said oxide layer to release said response mass from said capacitor plate, said response mass being coupled to said beam by said portion of said layer of conductive material passed through said aperture.

2. The method of claim 1 wherein said first etching step includes etching said conductive material such that said beam is electrically isolated from said capacitor plate.

3. The method of claim 1 wherein said wafer is doped silicon and said conductive material is polycrystalline silicon.

4. The method of claim 3 wherein said second etching step includes etching into the bulk of said doped silicon wafer.

5. The method of claim 4 wherein the etching of said doped silicon of said wafer includes using deep reactive ion etching.

6. The method of claim 1 wherein said second etching step including etching said wafer such that said response mass is movable relative said support and said capacitor plate is coupled to said support such that said response mass and said capacitor plate form a capacitor.

7. The method of claim 1 wherein a plurality of release holes are formed in said layer of polysilicon during said first etching step, and wherein said oxide layer is etched with a wet etch material in said third etching step, and wherein said wet etch material flows through said release holes to separate said response mass from said capacitor plates during said third etching step.

8. The method of claim 1 wherein said third etching step is controlled such that a layer of oxide remains between said capacitor and said support to couple said support to said capacitor and to electrically isolate said support relative said capacitor.

9. The method of claim 1 wherein said first etching step includes forming said capacitor plate such that said capacitor plate is laterally spaced apart from said beam, and wherein said second etching step includes etching said support such that said support is spaced from said response mass but connected to said response mass by said oxide layer.

10. The method of claim 1 further comprising the step of etching said response mass using reactive ion etching, after said second etching step, to reduce the mass of said response mass.

11. The method of claim 10 wherein said response mass is etched on a side of said response mass opposite the side of response mass facing said capacitor plate to reduce the mass of said response mass.

12. The method of claim 11 wherein said etching of response mass to reduce the mass of said response mass includes forming an oxide on said wafer, etching said oxide, locating a photoresist on said oxide, patterning said oxide and etching said wafer in areas of said wafer not covered by said oxide or said photoresist.

13. The method of claim 12 wherein said etching of said response mass to reduce the mass of said response further includes removing exposed portions of said oxide, and etching said wafer in areas of said wafer not covered by said oxide or said photoresist.

14. The method of claim 1 wherein said second forming step includes forming doped polysilicon on said wafer, and wherein said capacitor plate is located to form a capacitor with said response mass.

15. The method of claim 1 wherein said first etching step includes forming at least three capacitor plates, said second etching step including etching said wafer to form said response mass such that at least part of said response mass is located below each capacitor plate, and said third etching step includes etching said oxide layer to separate said response mass from each capacitor plate.

16. The method of claim 15 wherein said first etching step includes forming a first, second and third capacitor plates, and wherein said first and said second capacitor plates lie along a first axis and said second and third capacitor plates lie along a second axis that is generally perpendicular to said first axis.

17. The method of claim 15 wherein said second etching step includes etching said support such that said support includes at least three cavities, and wherein said response mass includes at least three protrusions, each cavity receiving a protrusion therein, and wherein a capacitor plate is located over each of said at least three cavities.

18. The method of claim 1 wherein said second etching step includes etching said support such that said support extends around the perimeter of said response mass.

19. The method of claim 1 wherein said second etching step including forming a support having a generally square outer perimeter , each side of said support having a length of between about 1.5 mm and about 2.5 mm.

20. The method of claim 1 wherein said first etching step includes etching an actuating capacitor plate, and wherein said third etching step includes separating said response mass from said actuating capacitor plate.

21. The method of claim 1 wherein said first etching step includes etching said layer of conductive material to form a plurality of beams, and wherein said response mass is coupled to and suspended from said plurality of beams.

22. The accelerometer of claim 1 wherein said accelerometer can sense acceleration along three independent, orthogonal axes, and wherein said accelerometer has relatively uniform sensitivity along each of said three axes.

23. The method of claim 1 wherein first etching step includes forming three additional beams, and wherein each beam and said response mass are formed during said first and said second etching steps such that

$$L^2=Ade$$

wherein L is the length of each beam, A is a constant that is about 6, d is the distance from the center of said response mass to the center of each capacitor plate, and e is the distance between the center of gravity of said response mass and the center of gravity of each beam.

24. The method of claim 1 further comprising the steps of storing said wafer after said first etching step until an order having product specifications is received, and determining the parameters of said second etching step based upon said product specifications.

25. The method of claim 1 wherein said second etching step includes etching said response mass such that at least part of said response mass is located below said capacitor plate.

26. A method for forming an accelerometer comprising the steps of:

providing a conductive wafer;

forming a layer of conductive material on said wafer;

etching said layer of conductive material to form a beam and at least three capacitor plates; and etching said wafer to form a response mass and a support, said beam being coupled to said support and to said response mass such that said beam supports said response mass, wherein each capacitor plate is coupled to said support and located above or below said response mass to form a capacitor such that said accelerometer can sense acceleration along three orthogonal axes.

27. The method of claim 26 wherein said etching step includes etching said beam and said response mass such that said response mass is suspended from said beam.

28. A method for forming an accelerometer comprising the steps of:

providing a conductive wafer having an oxide layer thereon and a layer of conductive material located on top of said oxide layer;

etching said layer of conductive material to form a hole, a beam and a capacitor plate;

forming a hole in said layer of oxide, said hole in said oxide being aligned with said hole in said layer of conductive material;

depositing a conductive material in said hole in said layer of conductive material and in said hole in said layer of oxide such that said deposited conductive material contacts said wafer;

etching into the bulk of said wafer to form a response mass and a support, at least part of said response mass being located adjacent said capacitor plate; and

etching said oxide layer to release said response mass from said capacitor plates, said response mass being coupled to said beam by said deposited conductive material.

29. An accelerometer comprising:

a conductive response mass;

a support located adjacent said response mass;

a beam coupled to said support and to said response mass such that said response mass is supported by said beam; and

at least three capacitor plates coupled to said support, each capacitor plate being located adjacent to said response mass to form a capacitor with said response mass, wherein the displacement of said response mass relative to said support causes a change in capacitance in at least two of said capacitors.

30. The accelerometer of claim 29 further comprising a processing circuit connected to said three capacitors for producing an output which varies according to the capacitances of said capacitors.

31. The accelerometer of claim 30 wherein said processing circuit includes a switched-capacitor amplification circuit having a first amplification stage, each of said three capacitors being switchably connectable into a feedback path of said first amplification stage.

32. The accelerometer of claim 31 wherein said switched-capacitor amplification circuit includes second and third amplification stages, an output of the third amplification stage being connected to a track and hold circuit stage.

33. The accelerometer of claim 31 further comprising a processor coupled to said processing circuit for determining the displacement of said response mass, and thereby the applied acceleration, based upon said output of said processing circuit.

34. The accelerometer of claim 29 wherein said beam is coupled to the top of said response mass such that said response mass is suspended from said beam.

35. The accelerometer of claim 29 wherein said at least three capacitor plates include first, second and third capacitor plates, and wherein said first and said second capacitor plates lie along a first axis and said second and third capacitor lie along a second axis that is generally perpendicular to said first axis.

36. The accelerometer of claim 35 wherein said first, second, and third capacitor plates form first, second, and third capacitors, respectively, with said response mass, wherein said first and said second capacitors are used to sense acceleration along a first direction, said first and said third capacitors are used to sense acceleration along a second direction

perpendicular to said first direction, and said second and third capacitors are used to sense acceleration along a third direction perpendicular to said first axis and said second directions.

37. The accelerometer of claim 29 wherein said response mass and said support are made of doped silicon.

38. The accelerometer of claim 29 wherein said beam and said capacitor plates are made of doped polysilicon.

39. The accelerometer of claim 29 wherein said support extends around the perimeter of said response mass.

40. The accelerometer of claim 39 wherein said support is generally square in top view and includes at least three cavities, and wherein said response mass includes at least three protrusions, each cavity of said support receiving a protrusion therein, and wherein a capacitor plate is located over each cavity.

41. The accelerometer of claim 40 wherein each side of said support has a length of between about 1.5 mm and about 2.5 mm.

42. The accelerometer of claim 40 further comprising three auxiliary beams extending from said support to said response mass and supporting said response mass, each of said beams extending from one side of the sides of said support to a center of said response mass.

43. The accelerometer of claim 29 further comprising an actuator including an actuating capacitor plate coupled to said support and located adjacent to said response mass, said actuating capacitor plate being capable of receiving a voltage to cause said response mass to be deflected relative said support.

44. The accelerometer of claim 29 further comprising a plurality of beams extending from said support to said response mass and supporting said response mass.

45. The accelerometer of claim 29 wherein said accelerometer can sense acceleration along three independent, orthogonal axes.

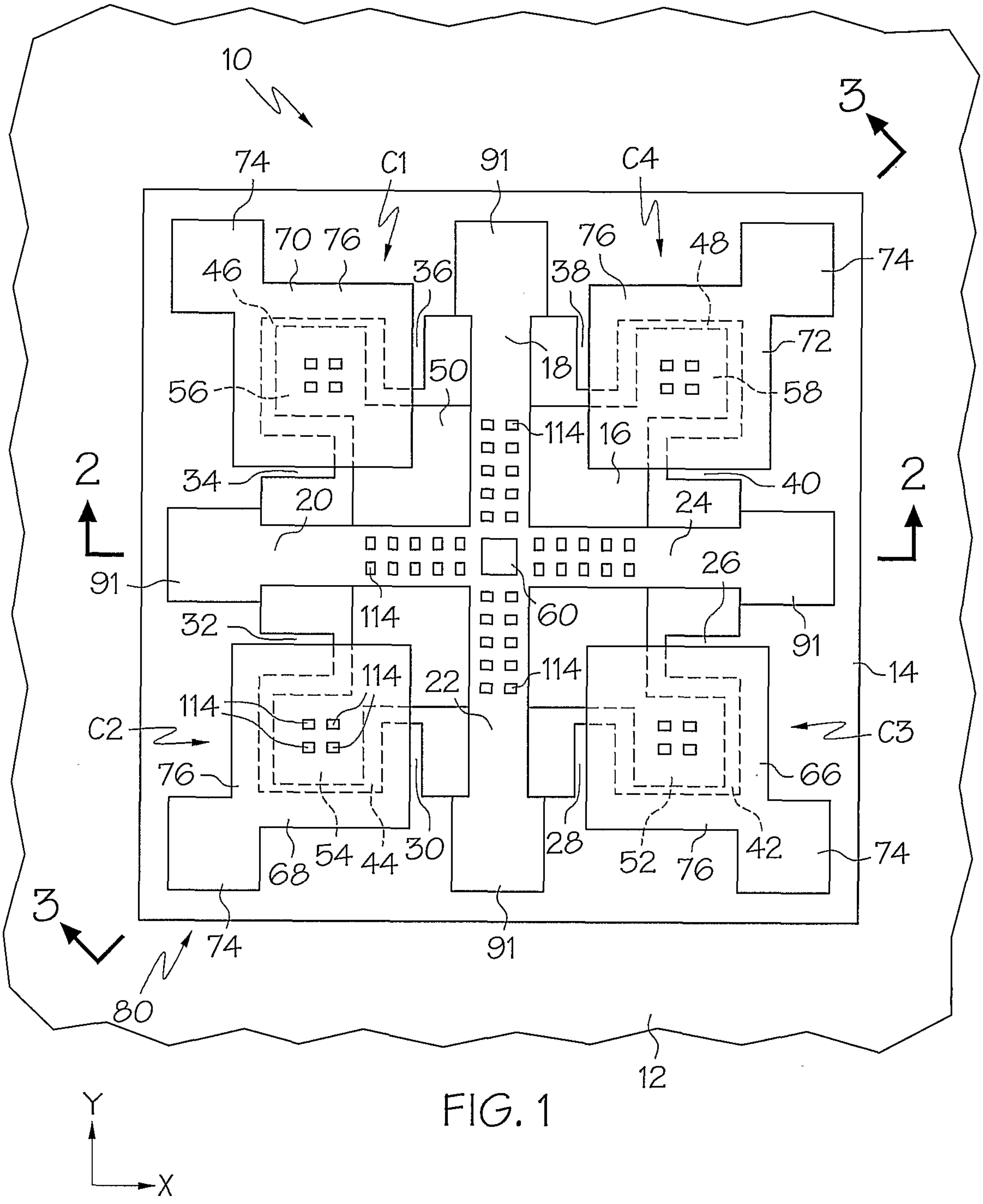
46. The accelerometer of claim 45 wherein said accelerometer has relatively uniform sensitivity along each of said three axes.

47. The accelerometer of claim 29 further comprising three additional beams coupled to said support and to said response mass such that said response mass is supported by each beam, wherein the dimension of each beams and said response mass are selected such that

$$L^2=Ade$$

wherein L is the length of each beam, A is a constant that is about 6, d is the distance from the center of said response mass to the center of each capacitor plate, and e is the distance between the center of gravity of said response mass and the center of gravity of each beam.

48. The accelerometer of claim 29 wherein at least part of said response mass is located below said capacitor plate.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C1
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C4
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34
40
2
2
20
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114
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114
14
C2
C3
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X

FIG. 1

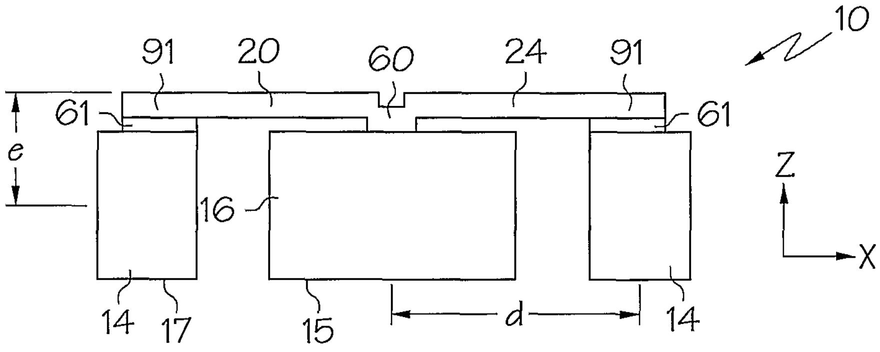


FIG. 2

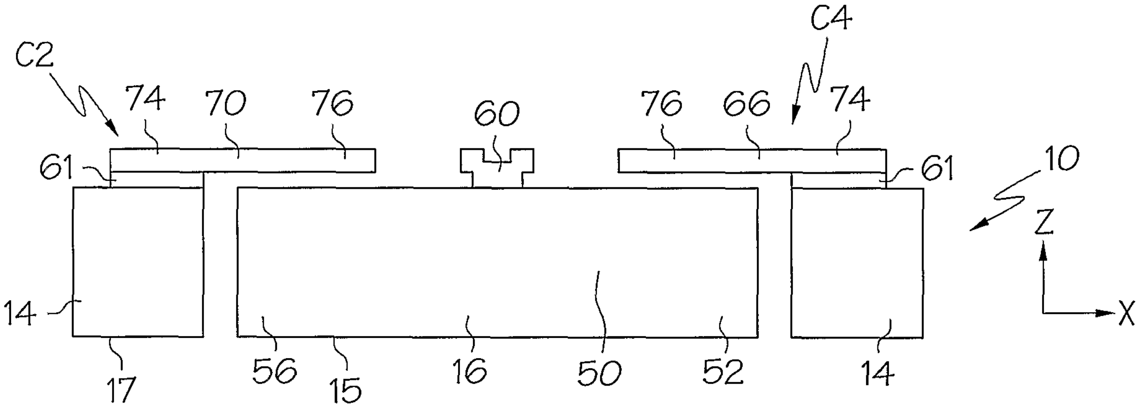


FIG. 3

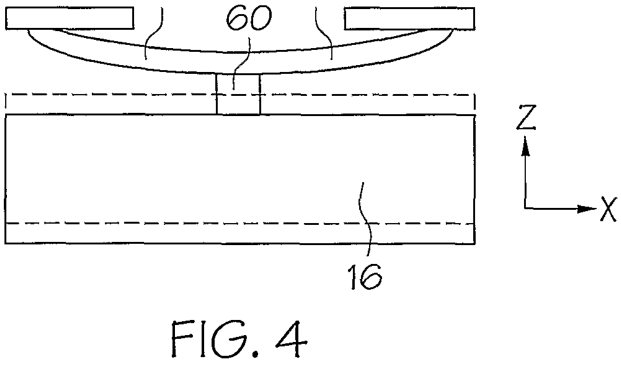
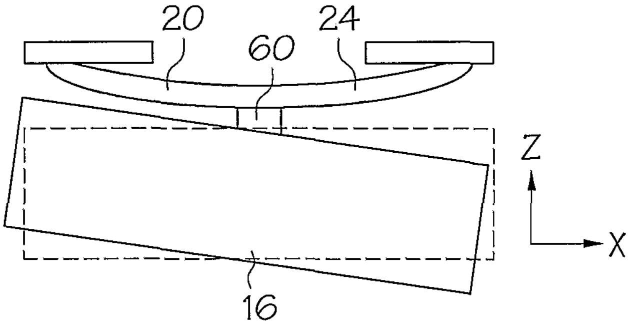


FIG. 4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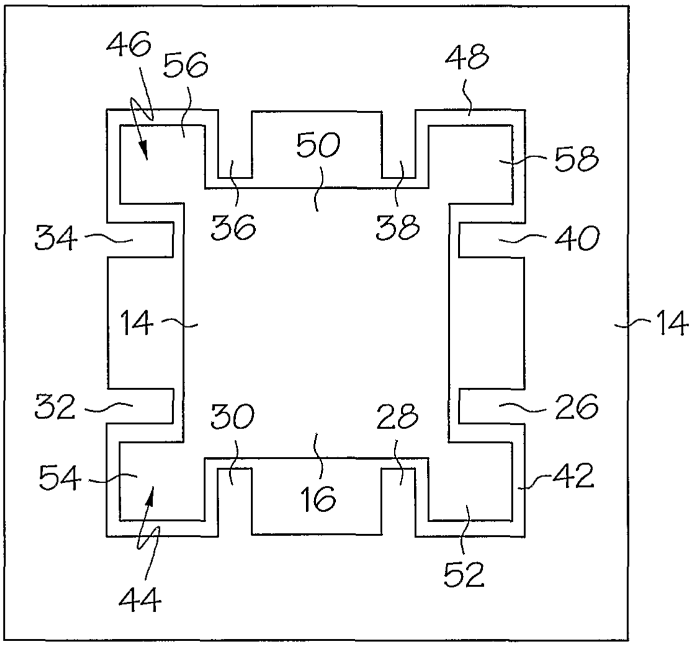
Z
X
16

FIG. 5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52
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FIG. 6A

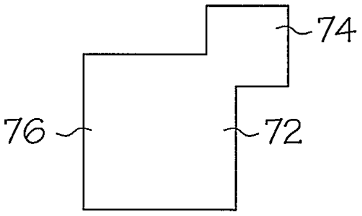
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FIG. 6B

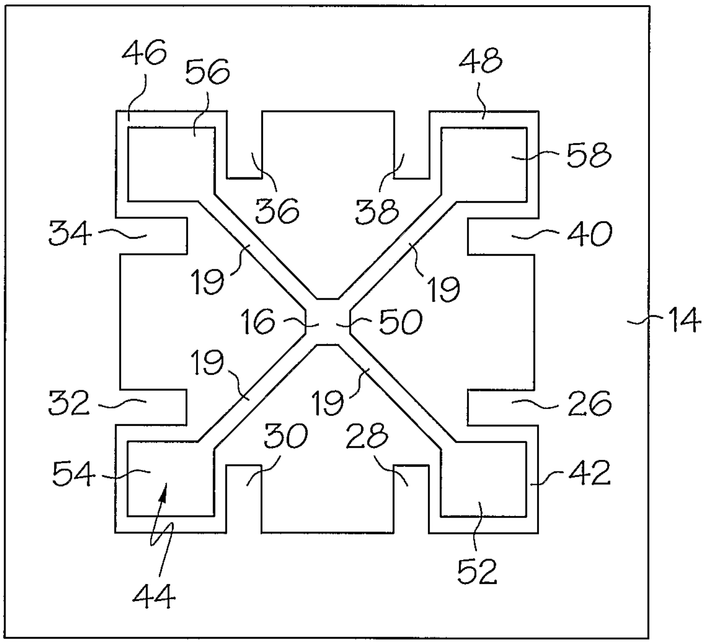
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FIG. 6C

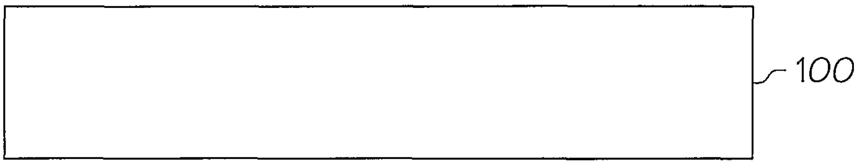

FIG. 7

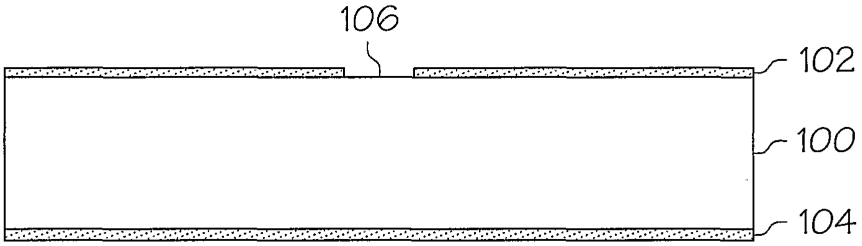

FIG. 8

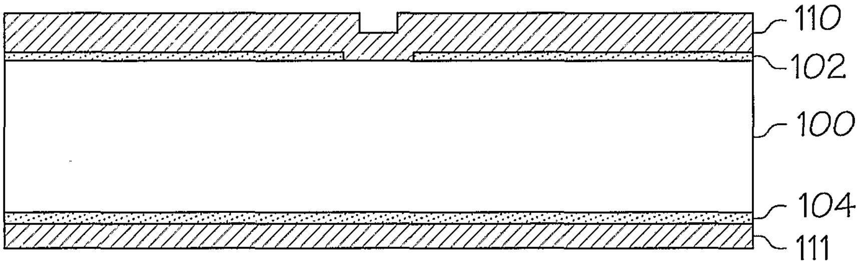

FIG. 9

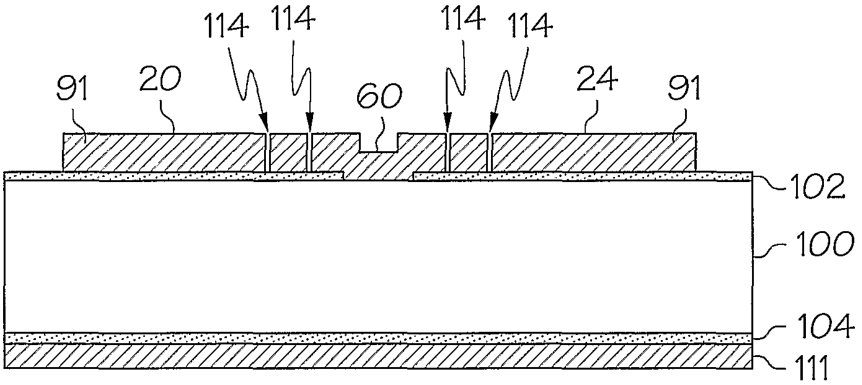

FIG. 10

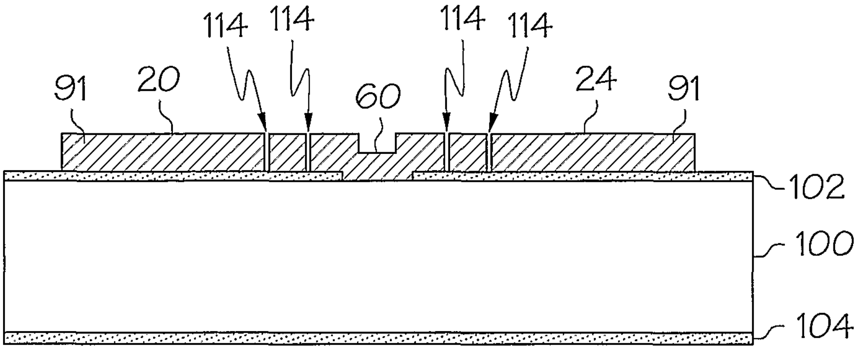

FIG. 11

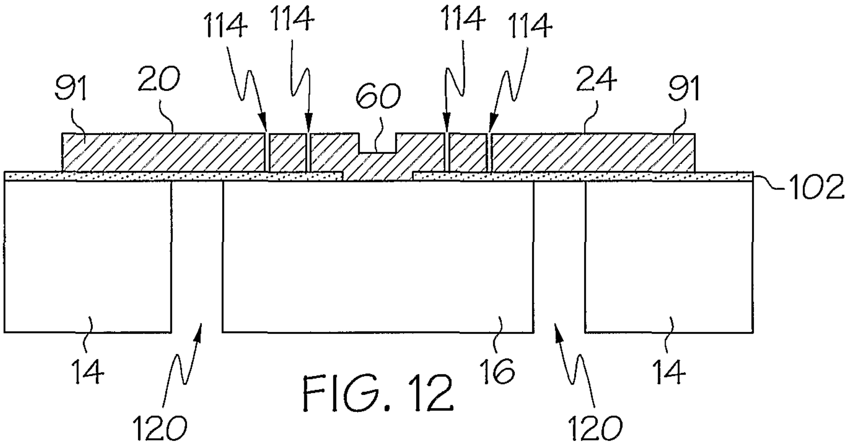

FIG. 12

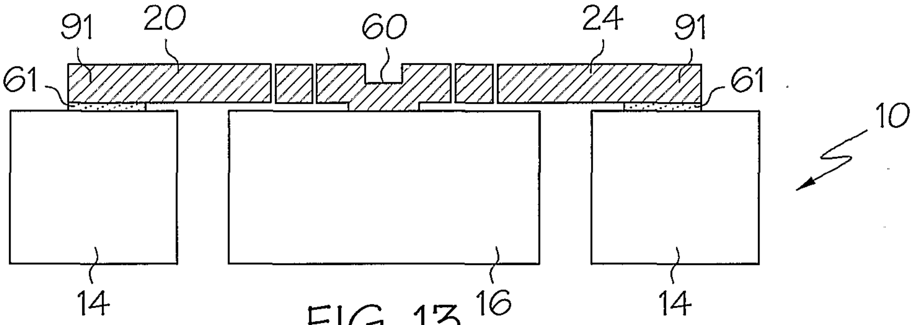

FIG. 13

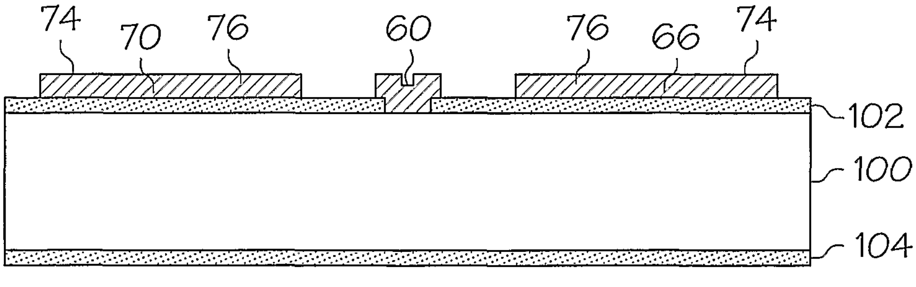

FIG. 14

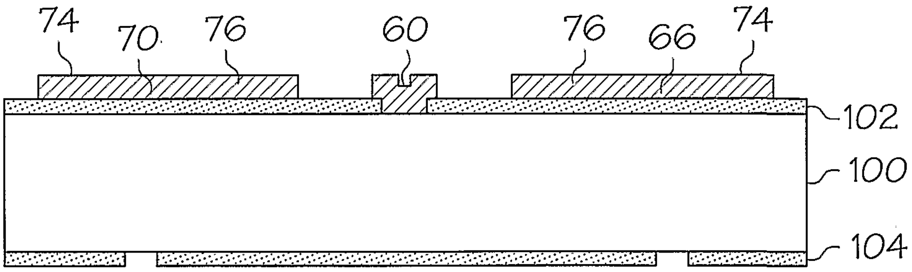

FIG. 15

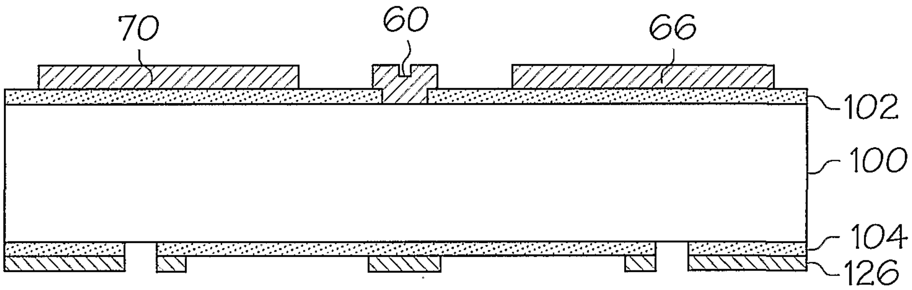

FIG. 16

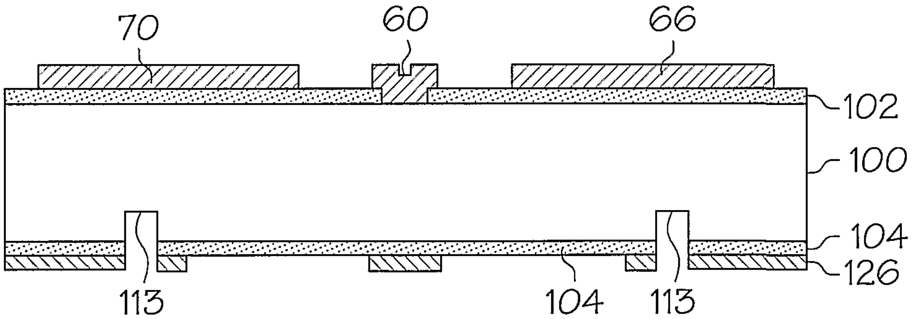

FIG. 17

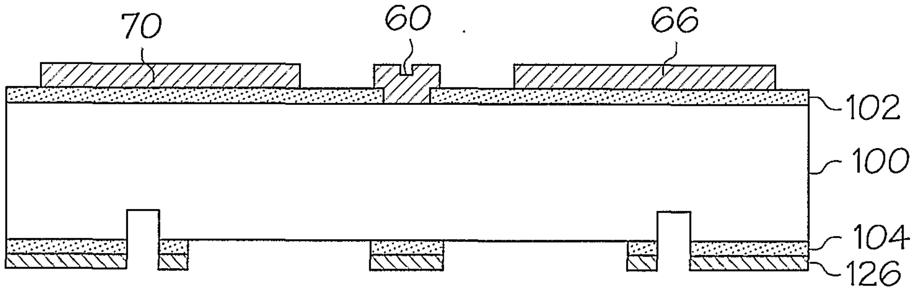

FIG. 18

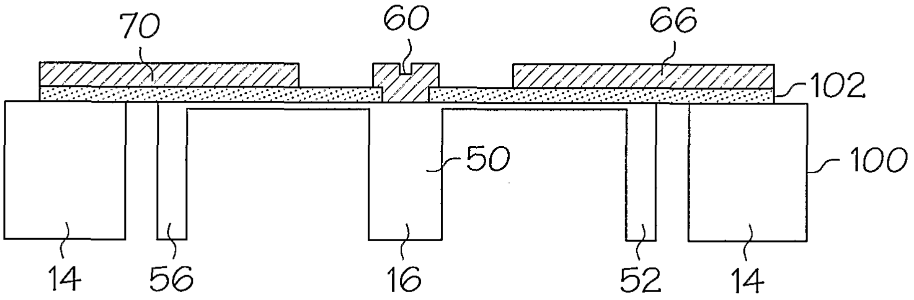

FIG. 19

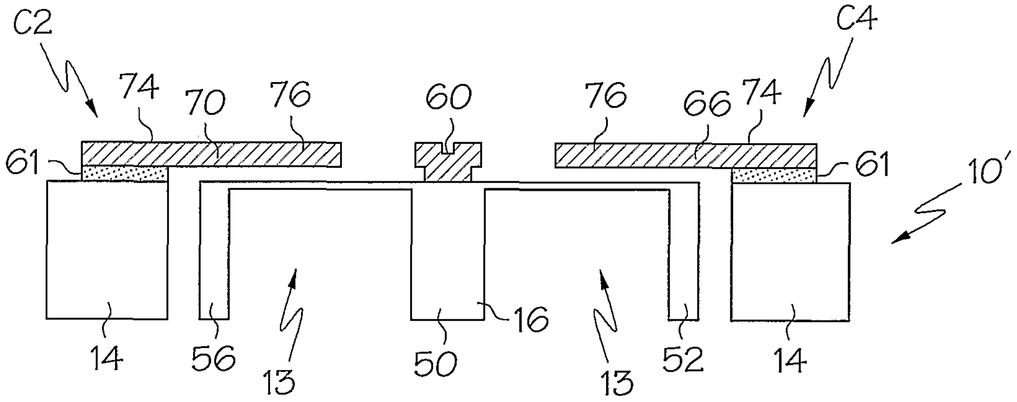

FIG. 20

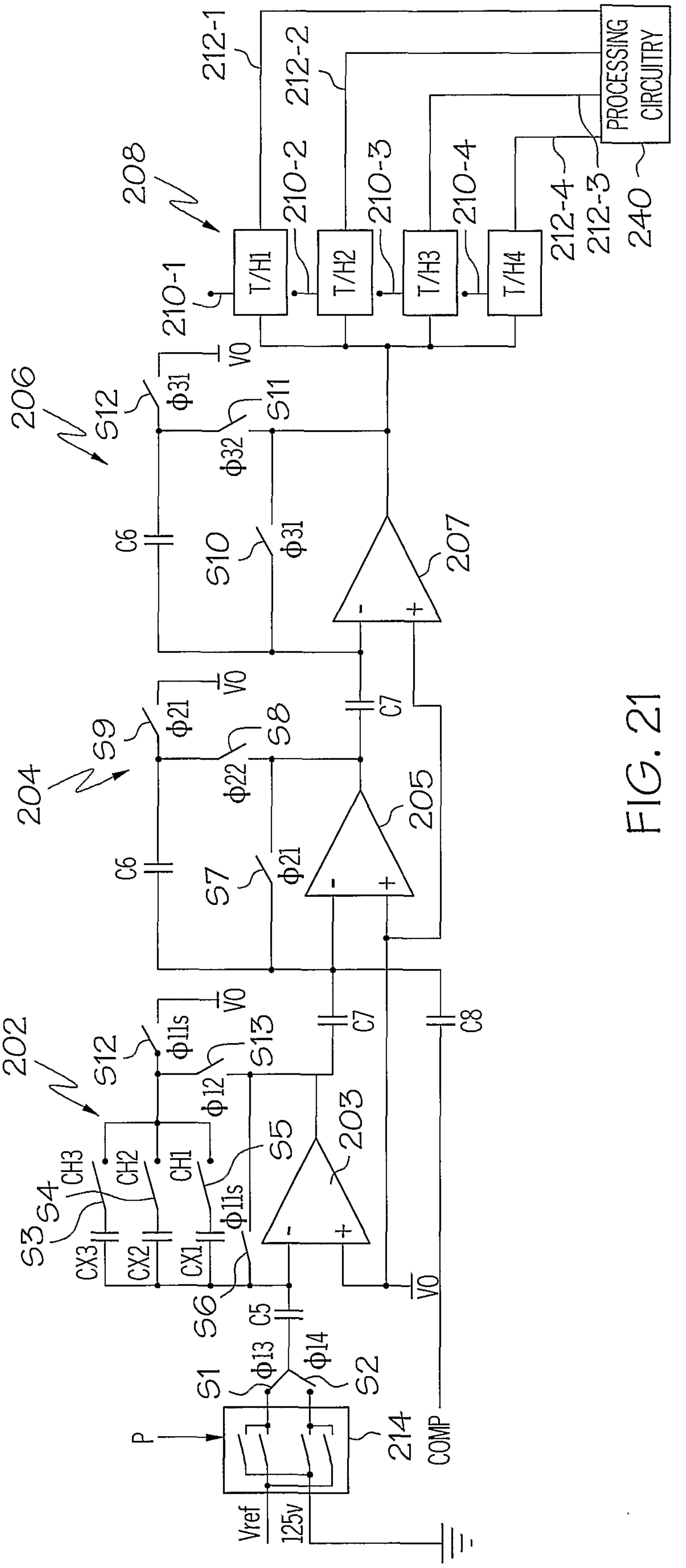
200
212-1
212-2
PROCESSING CIRCUITRY
240
212-3
212-4
208
210-1
T/H1
210-2
T/H2
210-3
T/H3
210-4
T/H4
206
S12
Φ31
V0
S11
Φ32
C6
S10
Φ31
207
204
S9
Φ21
V0
S8
Φ22
C6
S7
Φ21
C7
205
202
S12
Φ11s
V0
S13
Φ12
C7
C8
CH3
CH2
CH1
S5
S3
S4
CX3
CX2
CX1
Φ11s
203
S6
C5
V0
S1
Φ13
Φ14
S2
P
214
Vref
125v
COMP

FIG. 21

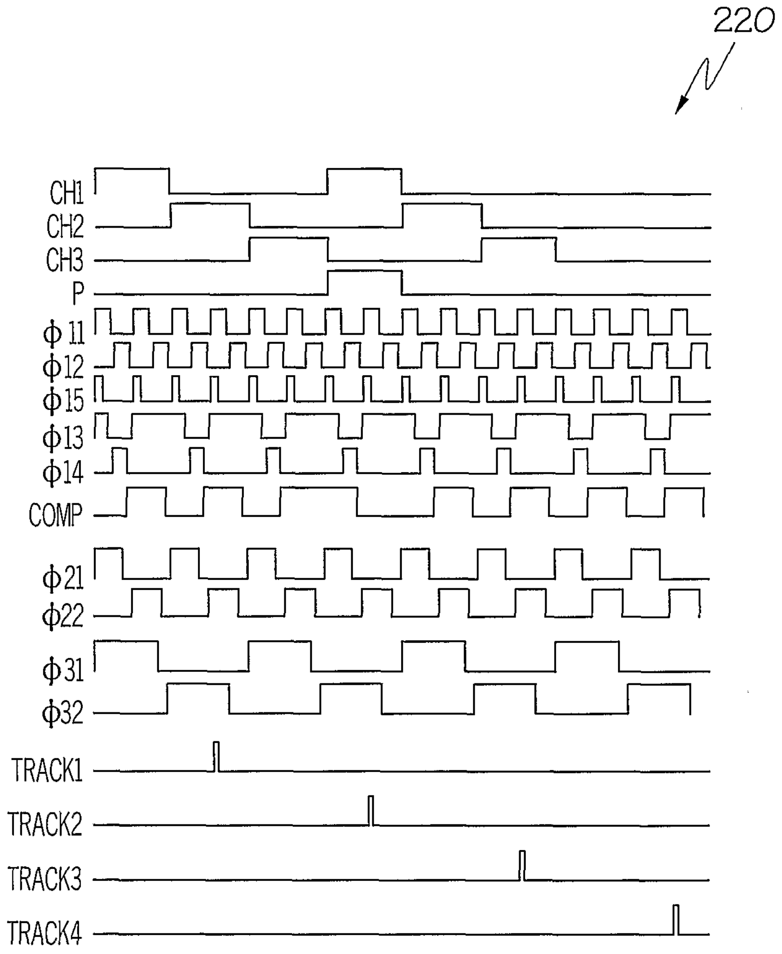
220
CH1
CH2
CH3
P
ϕ11
ϕ12
ϕ15
ϕ13
ϕ14
COMP
ϕ21
ϕ22
ϕ31
ϕ32
TRACK1
TRACK2
TRACK3
TRACK4

FIG. 22

			202	204	206	
	1	2	3	4	5	6
	SENSE CAPACITOR	POLARITY	FIRST STAGE	SECOND STAGE	THIRD STAGE	TRACK AND HOLD STAGE
230	C1 [C_{X1}]	POSITIVE	VrefCo/C1+offset offset	G1(VrefCo/C1-Voff)	G1G2VrefCo(1/C1-1/C2) +offset2	T/H1
	C2 [C_{X2}]	POSITIVE	VrefCo/C2+offset offset	G1(VrefCo/C2-Voff)		
232	C3 [C_{X3}]	POSITIVE	VrefCo/C3+offset offset	G1(VrefCo/C3-Voff)	G1G2VrefCo(1/C3+1/C1) +offset2	T/H2
	C1 [C_{X1}]	NEGATIVE	-VrefCo/C1-offset -offset	-G1(VrefCo/C1-Voff)		
234	C2 [C_{X2}]	POSITIVE	VrefCo/C2+offset offset	G1(VrefCo/C2-Voff)	G1G2VrefCo(1/C2-1/C3) +offset2	T/H3
	C3 [C_{X3}]	POSITIVE	VrefCo/C3+offset offset	G1(VrefCo/C3-Voff)		
236	NONE	POSITIVE	X X	X	offset2	T/H4
	NONE	POSITIVE	X X	X		

FIG. 23

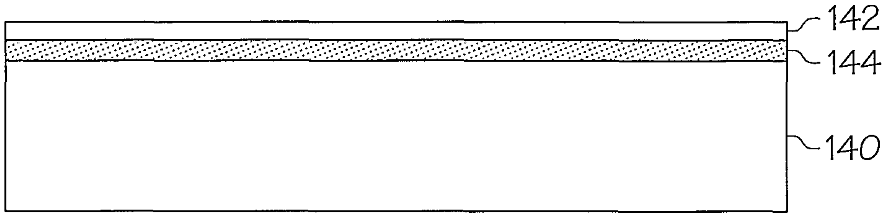

FIG. 24

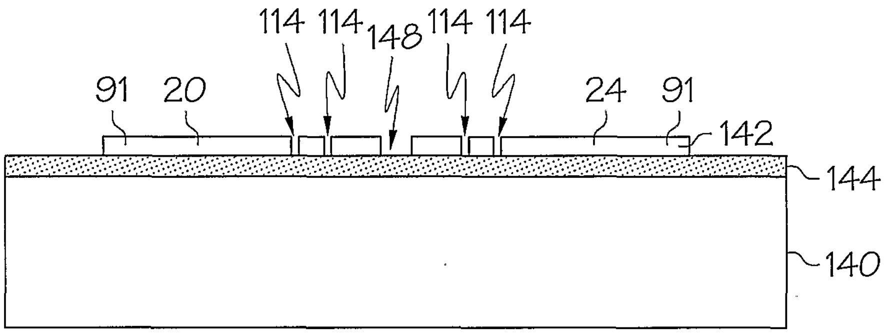

FIG. 25

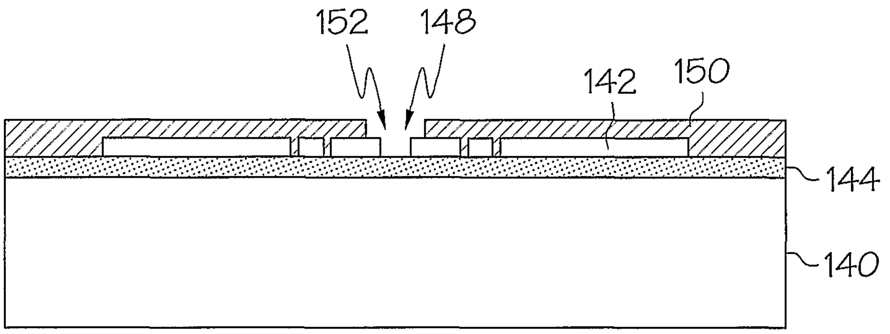

FIG. 26

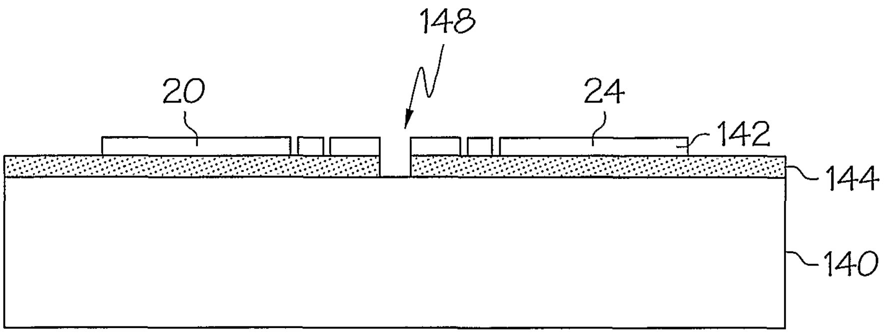

FIG. 27

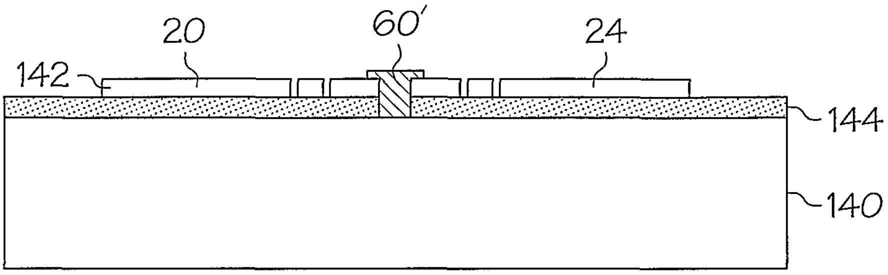

FIG. 28

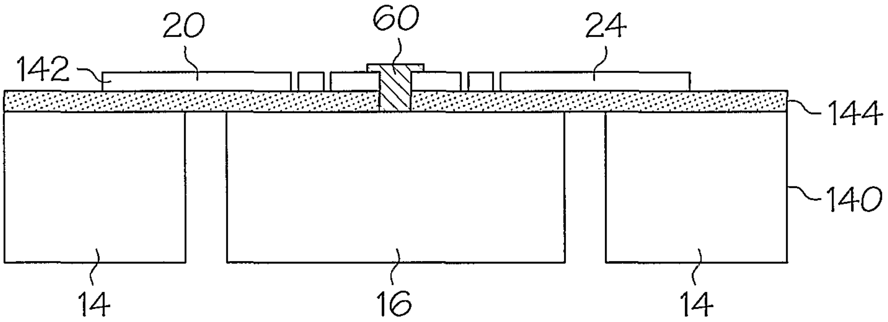

FIG. 29

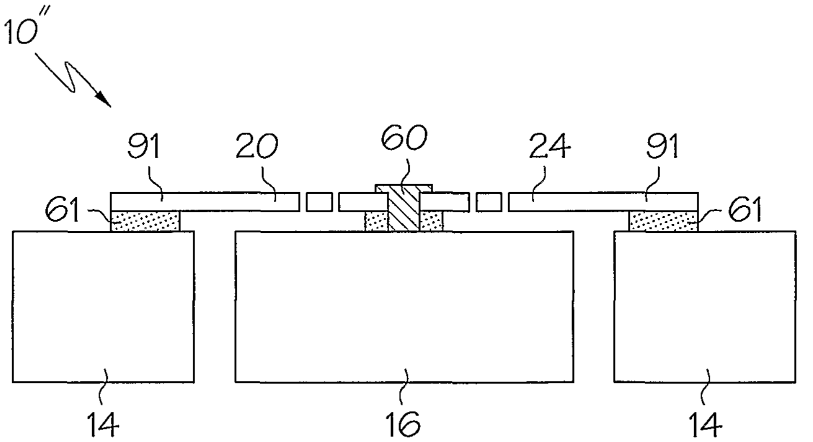

FIG. 30