

ACCELEROMETERS AND METHODS OF FABRICATING THEREOF

Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 201203234-8 (filed on 2 May 2012), the contents of which being hereby incorporated by reference in its entirety for all purposes.

Technical Field

[0002] Embodiments relate generally to accelerometers and methods of fabricating thereof.

Background

[0003] Capacitive sensing is widely used in accelerometers due to the many advantages, such as higher sensitivity, good dc response low drift, low temperature sensitivity, low-power dissipation and simplicity, over other methods. Differential sensing is desirable to minimize the effect of common mode noise. Close-loop operation is used to achieve higher linearity.

[0004] In the case of x- and y-axis accelerometers, the proof mass moves in the plane of the wafer, and it is easy to place to comb structures at the two ends for differential sensing as well as force feedback. However, in the case of z-axis accelerometers, the proof mass moves out of the wafer plane, which poses difficulties for fabricating differential arrangements. Several different methods have been proposed to achieve differential sensing for z-axis accelerometers.

[0005] For example, in a capacitance z-axis accelerometer, a series of fixed and movable rectangular plates were stacked alternatively above one another, forming a highly

sensitive, differential capacitor array. However, fabrication of this structure is rather complicated.

[0006] In other examples, two vertically offset comb structures were proposed to achieve differential sensing. This requires two DRIE etch stages, which increases both wafer-to-wafer and across-wafer variations.

[0007] In one example, a proof mass suspended by flexures such that only rotation about the y-axis (i.e. movement along z-axis) was proposed. Differential sensing was achieved by etching through the comb tines to create upper and lower tines, which is an unreliable process. Another solution is to bond multiple wafers to fabricate top and bottom electrodes on either side of the proof mass. However, it is difficult to precisely control the electrode gap through bonding, which affects the robustness of the manufacturing process. A method of accurately spacing z-axis electrode and achieving precise gaps was proposed in an example. The sidewall capacitors formed by multiple CMOS interconnect metal layers has also been used for differential displacement sensing as described in yet another example.

[0008] In one example, a torsional z-axis capacitive accelerometer with a comb capacitor and a flexural mode proof mass was described. The comb has different finger heights which allow differential measurement. Composite mask etching/dual etching was used for fabricating the torsional z-axis capacitive accelerometer.

[0009] Current methods of fabricating electrodes for differential capacitive sensing of acceleration along the z-axis are not robust. Large mass required for high resolution, but also has high damping.

[0010] Thus, there is a need to provide a MEMS capacitive accelerometer having novel structure that enables differential sensing and feedback for close loop operation for very high resolution acceleration sensing in the z-axis and that does not require multi-wafer bonding or multiple DRIE stages; thereby addressing the problems mentioned above.

Summary of the Invention

[0011] According to an embodiment, an accelerometer is provided. The accelerometer includes a pivot arm having a first end region and a second end region opposite to the first end region; a pivot coupled to the pivot arm; an annular predefined mass having a peripheral part coupled to the first end region or the second end region of the pivot arm; a first capacitive sensor located at the first end region of the pivot arm; and a second capacitive sensor located at the second end region of the pivot arm such that the pivot is arranged between the first capacitive sensor and the second capacitive sensor. The predefined mass may be configured to move in response to an acceleration force along a predefined direction. The first capacitive sensor and the second capacitive sensor may be configured to determine a differential capacitance value which relates to the acceleration force.

[0012] According to an embodiment, a method of fabricating an accelerometer is provided. The method includes forming on a device layer of a wafer respective trenches for forming a first and a second capacitive sensors, and a pivot of the accelerator therebetween; depositing a first polysilicon into the respective trenches to form comb structures of electrodes of the first and the second capacitor sensors, and the pivot; forming on the first polysilicon and the device layer respective cavities to provide a gap between the comb structures of electrodes formed by the first polysilicon and interleaving comb structures of electrodes of the first and the second capacitor sensors disposed on the device layer, and to provide a spacing between the pivot and a pivot arm of the accelerometer such that the pivot arm is movable about the pivot; depositing a second polysilicon over the first polysilicon and the device layer to form a predefined mass and the pivot arm, wherein the pivot arm is configured to couple respectively to the predefined mass, the comb structures of electrodes and the pivot; patterning the second polysilicon to obtain a structure of the accelerometer.

Brief Description of the Drawings

[0013] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. The dimensions of the various features/elements may be arbitrarily expanded or reduced for clarity. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0014] FIG. 1 shows a schematic diagram of a conceptual z-axis accelerometer, in accordance to various embodiments;

[0015] FIG. 2 shows a schematic diagram of an accelerometer, in accordance to various embodiments;

[0016] FIG. 3A shows a plot illustrating the relationship between normalized squeeze damping and the ratio of the inner annular diameter to the outer diameter, in accordance to various embodiments;

[0017] FIG. 3B shows a plot illustrating the relationship between damping and the ratio of the inner annular diameter to the outer diameter, in accordance to various embodiments;

[0018] FIG. 3C shows a plot illustrating the relationship between noise and scaling, in accordance to various embodiments;

[0019] FIG. 4 shows a perspective view of an exemplary accelerometer, in accordance to various embodiments;

[0020] FIG. 5A shows a perspective view of another exemplary accelerometer, in accordance to various embodiments;

[0021] FIG. 5B shows a perspective view of the exemplary accelerometer of FIG. 5A experiencing a $-z$ acceleration force, in accordance to various embodiments;

[0022] FIG. 6A shows a perspective view of the exemplary accelerometer of FIG. 5A with desired mode shape of the fundamental resonance mode, in accordance to various embodiments;

[0023] FIG. 6B shows a perspective view of the exemplary accelerometer of FIG. 5A at a “rocking” motion, in accordance to various embodiments;

[0024] FIG. 7A shows an example of a ANSYS (ANSYS, Inc., US) simulated maximum displacement along the x-axis when an input of 1G acceleration is applied along the x-axis direction, in accordance to various embodiments;

[0025] FIG. 7B shows an example of a ANSYS (ANSYS, Inc., US) simulated maximum displacement along the y-axis corresponding to FIG. 7A, in accordance to various embodiments;

[0026] FIG. 7C shows an example of a ANSYS (ANSYS, Inc., US) simulated maximum displacement along the z-axis corresponding to FIG. 7A, in accordance to various embodiments;

[0027] FIG. 8 shows a schematic diagram of a closed loop system model, in accordance to various embodiments;

[0028] FIG. 9A shows graph of (i) output differential measurement and (ii) input acceleration, in accordance to various embodiments;

[0029] FIG. 9B shows a partial expanded view of FIG. 9A, in accordance with various embodiments;

[0030] FIG. 10 shows a flow diagram of a method of fabricating an accelerometer, in accordance to various embodiments;

[0031] FIG. 11A shows a side view of a schematic diagram illustrating trench forming on an SOI wafer, in accordance to various embodiments;

[0032] FIG. 11B shows a perspective view of FIG. 11A, in accordance to various embodiments;

[0033] FIG. 11C shows another perspective view of FIG. 11A, in accordance to various embodiments;

[0034] FIG. 12A shows a side view of a schematic diagram illustrating oxide deposition, in accordance to various embodiments;

[0035] FIG. 12B shows a perspective view of FIG. 12A, in accordance to various embodiments;

[0036] FIG. 13A shows a side view of a schematic diagram illustrating oxide etchback, in accordance to various embodiments;

[0037] FIG. 13B shows a partial top view of FIG. 13A, in accordance to various embodiments;

[0038] FIG. 13C shows another partial top view of FIG. 13A, in accordance to various embodiments;

[0039] FIG. 14A shows a side view of a schematic diagram illustrating refilling of polysilicon with in situ doping, in accordance to various embodiments;

[0040] FIG. 14B shows a perspective view of FIG. 14A, in accordance to various embodiments;

[0041] FIG. 15A shows a side view of a schematic diagram illustrating chemical mechanical polishing of the polysilicon, in accordance to various embodiments;

[0042] FIG. 15B shows a perspective view of FIG. 15A, in accordance to various embodiments;

[0043] FIG. 15C shows a partial top view of FIG. 15A, in accordance to various embodiments;

[0044] FIG. 16A shows a side view of a schematic diagram illustrating etching of shallow cavities, in accordance to various embodiments;

[0045] FIG. 16B shows a perspective view of FIG. 16A, in accordance to various embodiments;

[0046] FIG. 16C shows a partial top view of FIG. 16A, in accordance to various embodiments;

[0047] FIG. 17A shows a side view of a schematic diagram illustrating oxide deposition, in accordance to various embodiments;

[0048] FIG. 17B shows a perspective view of FIG. 17A, in accordance to various embodiments;

[0049] FIG. 18A shows a side view of a schematic diagram illustrating chemical mechanical polishing of the deposited oxide, in accordance to various embodiments;

[0050] FIG. 18B shows a perspective view of FIG. 18A, in accordance to various embodiments;

[0051] FIG. 18C shows a partial top view of FIG. 18A, in accordance to various embodiments;

[0052] FIG. 19A shows a side view of a schematic diagram illustrating low-pressure chemical vapour deposition of polysilicon with in situ doping, in accordance to various embodiments;

[0053] FIG. 19B shows a perspective view of FIG. 19A, in accordance to various embodiments;

[0054] FIG. 20A shows a side view of a schematic diagram illustrating patterning of the polysilicon, in accordance to various embodiments;

[0055] FIG. 20B shows a perspective view of FIG. 20A, in accordance to various embodiments;

[0056] FIG. 20C shows a top view of FIG. 20A, in accordance to various embodiments;

[0057] FIG. 20D shows a partial top left view of FIG. 20C, in accordance to various embodiments;

[0058] FIG. 20E shows a partial perspective view of FIG. 20A, in accordance to various embodiments;

[0059] FIG. 20F shows another partial perspective view of FIG. 20A, in accordance to various embodiments;

[0060] FIG. 21A shows a side view of a schematic diagram illustrating releasing the accelerometer, in accordance to various embodiments;

[0061] FIG. 21B shows a perspective view of FIG. 21A, in accordance to various embodiments;

[0062] FIG. 21C shows a partial perspective view of FIG. 21A, in accordance to various embodiments;

[0063] FIG. 21D shows a partial cross-sectional view as seen from line A-A' of FIG. 21C, in accordance to various embodiments;

[0064] FIG. 21E shows a cross-sectional view as seen from line A-A' of FIG. 21C, in accordance to various embodiments; and

[0065] FIG. 21F shows a cross-sectional view as seen from line B-B' of FIG. 21C, in accordance to various embodiments.

Detailed Description

[0066] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0067] Embodiments described in the context of a method are analogously valid for a device, and vice versa.

[0068] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element includes a reference to one or more of the features or elements.

[0069] In the context of various embodiments, the phrase “at least substantially” may include “exactly” and a reasonable variance.

[0070] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0071] Various embodiments may provide a z-axis closed loop accelerometer.

[0072] The concept of a z-axis accelerometer 100 is to suspend a proof mass 102 from a pivot arm 104 that has comb structures 106 on either side, as shown in FIG. 1. Fundamentally, z-axis sensitivity requires out-of plane motion of the proof mass 102. If a non-compliant pivot arm 104 is used (i.e. if it does not bend), as the proof mass 102 moves in response to z-axis acceleration (as denoted by a directional arrow 108), the two comb structures which provide differential sense/actuate electrodes will move in opposite directions about a pivot 110. This allows differential sensing as well as bidirectional force feedback.

[0073] Various embodiments aim to achieve a high resolution differential capacitive signal in response to accelerations (nano G range, where $G = 9.81 \text{ m/s}^2$) in the z-axis.

Structural features may be optimized. For example, an annular proof mass, non-compliant pivot beams, link springs and torsion springs may be used to provide a differential comb structure sensitive to z-axis acceleration.

[0074] In order that the invention may be readily understood and put into practical effect, particular embodiments will now be described by way of examples and not limitations, and with reference to the figures.

[0075] FIG. 2 shows a schematic block diagram 200 of an accelerometer 202, according to various embodiments. The accelerometer 202 includes a pivot arm 204 having a first end region and a second end region opposite to the first end region; a pivot 206 coupled to the pivot arm 204 ; an annular predefined mass 208 having a peripheral part coupled to the first end region or the second end region of the pivot arm 204; a first capacitive sensor 210 located at the first end region of the pivot arm 204; and a second capacitive sensor 212 located at the second end region of the pivot arm 204 such that the pivot 206 is arranged between the first capacitive sensor 210 and the second capacitive sensor 212, wherein the predefined mass 208 is configured to move in response to an acceleration force along a predefined direction; and wherein the first capacitive sensor 210 and the second capacitive sensor 212 are configured to determine a differential capacitance value which relates to the acceleration force.

[0076] In other words, the accelerometer 202 has the annular predefined mass 208 coupled to the pivot arm 204 and when the predefined mass 208 moves due to an acceleration force in the predefined direction, for example, the z-axis direction, the pivot arm 204 rotates about the pivot 206 such that the first end region of the pivot arm 204 is positioned at an offset along the predefined direction from the second (opposite) end region of the pivot arm 204. That is, the first end region is not on the same z-plane as the second end region. With this, the first capacitor sensor 210 measures the capacitance value at the first end region and the second capacitor sensor 212 measures the capacitance value at the second end region. The difference between these two measured capacitance values is evaluated to provide a measure of the acceleration force acted on the predefined mass 208.

[0077] As used herein, the term “accelerometer” refers to a device that determines an acceleration of motion of a structure.

[0078] The term “pivot arm” may refer to an elongate pivot arm or pivot beam. The “end region” of the pivot arm 204 may refer to an end of the pivot arm 204, or a part that includes the end of the pivot arm 204 extending toward the pivoted point of the pivot arm 204 but not including the pivoted point, or a part that is located substantially toward the end of the pivot arm 204. It should be appreciated and understood that in some embodiments, the pivoted point may be located at the midpoint or centre of the pivot arm 204. In other embodiments, the pivoted point may be located at an offset from the midpoint or centre of the pivot arm 204.

[0079] The term “capacitive sensor” refers to electrodes that create one or more capacitors, which are then connected to a circuit that determines the capacitance value. In an embodiment, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code such as e.g., Java. Any other kind of implementation of the respective functions which will be described in more detail below may also be understood as a “circuit” in accordance with an alternative embodiment.

[0080] The term “determine” may refer to “measure”, “evaluate”, “compute”, or “assess”.

[0081] The term “differential capacitance” refer to the mathematical operation of subtraction of at least two capacitance values, for example, the capacitance value measured by the first capacitive sensor 210 and the capacitance value measured by the second capacitive sensor 212.

[0082] In the context of various embodiments, the term “annular predefined mass” may refer to a mass of known weight (mass) that has a ring-like structure. The ring-like structure may be round or polygonal in shape. For example, the annular predefined mass 208 may be but is not limited to a rectangular-frame, or a square-frame or a circular-frame. In one embodiment, the annular predefined mass 208 may be at least one of an annular circular predefined mass or an annular rectangular predefined mass. The annular predefined mass 208 may be interchangeably referred to as an annular proof mass.

[0083] For example, the accelerometer 202 may be the z-axis accelerometer 100 of FIG. 1. For example, the pivot arm 204 may refer to the pivot arm 104 of FIG. 1, the pivot 206 may refer to the pivot 110 of FIG. 1, and the annular predefined mass 208 may refer to the proof mass 102 of FIG. 1. For example, the first capacitor sensor 210 may refer to the (right side) comb structure 106 of FIG. 1, and the second capacitor sensor 212 may refer to the (left side) comb structure 106 of FIG. 1.

[0084] The resolution of an accelerometer (e.g., the accelerometer 202) may be limited by the total noise of the system. In some examples involving differential sensing and bidirectional force feedback, there may be a limitation on the achievable mechanical noise level. The noise of the system may be classified into mechanical noise and electrical noise. For simplicity, the mechanical noise is described in this context. Mechanical noise is generally dominated by Brownian noise. The Brownian-noise-limited mechanical resolution of an accelerometer is given by

$$g_{n,B} = \sqrt{4k_B T C} / m \quad (1)$$

where m is the proof mass, T is the absolute temperature, C is the total damping and k_B is the Boltzmann constant. Equation (1) shows that a larger mass and lower damping are required to achieve a low mechanical noise level.

[0085] The total air damping includes two components namely squeeze film damping and slide film damping. The squeeze film damping is given by

$$C_{squeeze} = \frac{\mu L w^3}{d^3} \cdot \beta(n) \quad (2)$$

where μ is the viscosity of air, L and w are the length and width of the proof mass respectively, and d is the air gap. The function $\beta(n)$ is a correction factor to account for the shape of the shape, where $n=w/L$, and $0.4 < \beta(n) < 1$.

[0086] The slide film damping is given by

$$C_{slide} = \frac{\mu A}{d} \quad (3)$$

where $A=Lw$ is the area of the proof mass. For typical dimensions where $w \gg d$, the squeeze film damping is much larger compared to slide film damping.

[0087] The proof mass (e.g. the annular predefined mass 208) may be increased by increasing its thickness, without affecting squeeze film damping. However, patterning of thick proof mass may be limited by Deep Reactive-Ion Etching (DRIE) tool capabilities. Therefore, the area of the proof mass also has to be increased to obtain a higher mass. Large areas may result in higher squeeze film damping as seen from Equation (2), which lowers the device resolution.

[0088] If the width of the mass w is decreased while keeping the area $A=Lw$ constant, squeeze film damping may be reduced. Thus a proof mass in the form of one or more long, narrow strips may have a lower damping than a square-shaped segment having an identical mass. However, such a structure may be highly fragile and asymmetrical. The fragility and asymmetry may be overcome by forming the narrow mass into an annular ring. The ring may be either circular or square shaped. In its annular form, a heavier proof mass may be allowed while maintaining low squeeze damping (or squeeze film damping).

[0089] For example, in optimizing damping and size of the proof mass, higher sensitivity and resolution require heavier proof mass. The resolution may be proportional to (total damping)^{0.5} divided by mass (i.e., Resolution $\propto$ (total damping)^{0.5}/mass)). Larger mass

increases damping. In the use of the annular proof mass, the outer-radius:inner-radius ratio determines the squeeze damping. This ratio may be made to approximately 1 to minimize the damping and maximizes the resolution. The total structure may be scaled down till squeeze damping is about 10 times slide damping without affecting resolution. In other words, resolution may be dominated by the squeeze damping.

[0090] FIG. 3A shows a graph 300 depicting the relationship between squeeze film damping and the ratio of the inner annular diameter to the outer diameter. In FIG. 3A, as the inner diameter approaches the outer diameter, squeeze damping decreases. FIG. 3B shows a graph 302 depicting the relationship between the squeeze and slide damping, and the ratio of the inner annular diameter to the outer diameter. In FIG. 3B, as the inner diameter approaches the outer diameter, the squeeze and slide damping decrease. FIG. 3C shows a graph 304 depicting the relationship between noise resolution and scaling. In FIG. 3C, as scaling increases, noise decreases exponentially.

[0091] In various embodiments, the pivot arm 204 may include a non-compliant pivot arm. In other words, the pivot arm 204 is unable to bend or is not flexible.

[0092] The peripheral part of the predefined mass 208 may be coupled to the first end region or the second end region of the pivot arm 204 via a compliant connector. The compliant connector may be a resilient material.

[0093] This is in contrast to an annular proof mass used in torsional mode (e.g., in gyroscopes), or more specifically, torsional mode z-axis accelerometers where the annular proof mass cannot be directly connected with a non-compliant beam as the ring (or annular proof mass) may attempt to twist which limits the displacement of the combs (e.g., the comb structures 106 of FIG. 1, or a comb structure that is located at the first end region of the pivot arm 204 of FIG. 2 and another comb structure that is located at the second end region of the pivot arm 204 of FIG. 2).

[0094] In one embodiment, the compliant connector may include or may be a link spring.

[0095] The term “link spring” may generally refer to a spring that connects or links two parts together. In this context, the link spring may connect the annular predefined mass 208 to the pivot arm 204. The link spring advantageously allows the annular predefined mass 208 and the combs of the capacitive sensors 210, 212 (which are described in detail

below) to translate vertically (in the z-axis direction) while maintaining the rigidity of the pivot arm 204 for differential measurement. That is to say, the link spring allows the annular predefined mass 208 to move like a guided mass, and for the pivot arm 204 to lever about a torsion spring (e.g., the pivot 206). The link spring and the torsion spring are designed to allow the pivot arm 204 to lever and to control mode shapes and frequencies.

[0096] For example, the link spring may have a mode shape of a fundamental resonance mode where the predefined mass 208 moves along the predefined direction.

[0097] The term “mode shape” refers to the link spring having a predefined shape corresponding to the shape of one of the modes of vibration the undeformed link spring can take in response to a force.

[0098] For example, the mode shape of the fundamental resonance mode may be the mode of vibration at the lowest possible frequency the undeformed link spring can take in response to a force.

[0099] In one embodiment, the fundamental resonance mode may be of a predetermined mode separation from high-order resonant modes.

[00100] The term “mode separation” may refer to a frequency separation between two adjacent modes.

[00101] In some example, the predetermined mode separation may be, but not limited to, between about 50 Hz to about 1000 Hz. For example, the predetermined fundamental resonance may be 1500 Hz and the next mode at 2000 Hz. In some examples, the predetermined mode separation may be but is not limited to the range of about 50 Hz to about 500 Hz, about 200 Hz to about 700 Hz, or about 500 Hz to about 1000 Hz. For example, the predetermined mode separation may be but is not limited to about 50 Hz, about 500 Hz, about 750 Hz, or about 1000 Hz.

[00102] In one embodiment, the predetermined mode separation may be 400Hz. In other embodiments, the mode separation may be higher or lower than this value.

[00103] In various embodiments, the predefined mass 208 may be configured to move in response to a z-axis acceleration.

[00104] The z-axis acceleration may be in the direction as shown by the directional arrow 108 of FIG. 1.

[00105] In various embodiments, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned within an inner region enclosed by the annular predefined mass 208.

[00106] For example, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned along at least a portion of the wall of the annular predefined mass 208 facing the enclosed inner region.

[00107] In one example, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned near the compliant connector, or more specifically the link spring.

[00108] In one example, the first capacitive sensor 210 or the second capacitive sensor 212 may be coupled to the compliant connector, or more specifically the link spring.

[00109] In other examples, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned along at least part of an exterior region of the annular predefined mass 208, the exterior region being opposite to the inner region enclosed by the annular predefined mass 208 or the exterior region being defined as the portion of the annular predefined mass 208 that is not defined as the inner region.

[00110] For example, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned along at least a portion of the wall of the annular predefined mass 208 facing the exterior region. In one example, the first capacitive sensor 210 or the second capacitive sensor 212 may be positioned near the compliant connector, or more specifically the link spring. In one example, the first capacitive sensor 210 or the second capacitive sensor 212 may be coupled to the compliant connector, or more specifically the link spring.

[00111] In one embodiment, the pivot 206 may be arranged within the inner region enclosed by the annular predefined mass 208.

[00112] In another embodiment, the pivot 206 may be arranged outside the inner region enclosed by the annular predefined mass 208. For example, the pivot 206 may be arranged in the exterior region as described above.

[00113] In various embodiments, the first capacitive sensor 210 and the second capacitive sensor 212, each includes an upper comb structure of electrodes and a lower comb structure of electrodes, wherein the upper comb structure of electrodes interleaves with the lower comb structure of electrodes such that a displacement formed between the upper comb structure of electrodes and the lower comb structure of electrodes determines a capacitive value.

[00114] In one embodiment, the electrodes may be configured to position along a plane parallel to the predefined direction (e.g. the z-axis direction).

[00115] In one embodiment, the pivot 206 may be coupled to the pivot arm 204 in the same plane as the pivot arm 204. For example, the pivot arm 204 may have a grooved part into which the pivot 206 may be slotted such that the pivot 206 may be coupled to the pivot arm 204 in an overlapping manner to be in the same plane.

[00116] In various embodiments, the accelerometer 202 may further include a plurality of pivot arms, wherein respective peripheral part of the predefined mass is coupled to respective first end region or second end region of each pivot arm.

[00117] For example, each of the plurality of pivot arms may refer to the pivot arm 204.

[00118] In various embodiments, the pivot arms may be spaced apart along radial axes of the predefined mass. For example, the pivot arms may be spaced or spanned equidistantly along the radial axes of the predefined mass. In other examples, the pivot arms may be spaced or spanned non-equidistantly along the radial axes of the predefined mass.

[00119] In various embodiments, the accelerometer 202 may further include a plurality of first and second capacitive sensors, wherein each of the plurality of first capacitive sensors and each of the plurality of second capacitive sensors is located at the respective first end region of each pivot arm and the respective second end region of each pivot arm, respectively.

[00120] For example, each of the plurality of first capacitive sensors may refer to the first capacitive sensor 210 and each of the plurality of second capacitive sensors may refer to the second capacitive sensor 212.

[00121] In various embodiments, the pivot 206 may include a torsion spring.

[00122] In various embodiments, the accelerometer 202 may be configured to produce a bidirectional force feedback signal when the predefined mass 208 moves in response to the acceleration force.

[00123] For example, when the predefined mass 208 moves in response to the positive z-axis acceleration force, the bidirectional force feedback signal may provide but is not limited to provide a feedback signal of positive polarity. In another example, when the predefined mass 208 moves in response to the negative z-axis acceleration force, the bidirectional force feedback signal may provide but is not limited to provide a feedback signal of negative polarity.

[00124] An annular ring proof mass (e.g. the annular predefined mass 208) in accordance with various embodiments for out-of-plane motion is the basic structure used. While annular rings may have been widely used in devices having rotational motion, they have not been known to be used in devices having out-of-plane translational motion. FIG. 4 shows a perspective view of an exemplary structure 400 having annular proof mass 402 that is suspended by multiple, radial pivot arms 404. The pivot arms 404 may be non-compliant to achieve differential motion. However, the non-compliant or stiff arm 404 may attempt to “twist” the proof mass 402 which in turn may cause little (or insufficient) displacement due to the stiff proof mass ring 402.

[00125] For example, the annular proof mass 402 may refer to the annular predefined mass 208.

[00126] For clarity, fixed digits of the comb structures are not shown in FIG. 4. Under z-axis acceleration, the proof mass 402 attempts to move along the z-axis (directional arrow 406). The proof mass motion pulls the pivot arms 404, attempting to rotate the arms 404 about the hinges 408. This may only be possible if the pivot arm 404 is connected to the proof mass 402 by a flexible hinge. If the connection is rigidly, the motion may be prevented.

[00127] Therefore, springs may be placed along the proof mass to allow compression and expansion. For example, a flexible link spring may be used to connect the pivot arms to the proof mass. Then, as the proof mass moves in response to acceleration, the link springs bend, pulling the pivot arms (or may be interchangeably referred to as linkage arms). This allows the proof mass to move vertically as a guided mass. In a similar manner, link springs may be used to connect the pivot arms to the inner combs (e.g., as in FIG. 5A). For example, the proof mass may also be connected to a rigid pivot arm using flexible springs.

[00128] FIG. 5A shows a perspective view of an exemplary accelerometer 500 in accordance with various embodiments. For example, the accelerometer 500 may refer to the accelerometer 202 of FIG. 2 or the structure 400 of FIG. 4.

[00129] In FIG. 5A, a set of comb structures (outer comb 502 and inner comb 504) is connected to an annular proof mass 506. The proof mass 506 is connected to the outer side of radial (non-compliant) pivot arms 508 by link springs 510. The inner sides of the pivot arms 508 are connected to the inner comb structure 504 using link springs 510. The pivot arms 508 are hinged by folded torsion springs 512. Such a design of the accelerometer 500 allows for easier fabrication, lower stresses at joints and larger response due to the low stiffness.

[00130] For example, the annular proof mass 506 may refer to the annular predefined mass 208 or the annular proof mass 402, each or at least one of the pivot arms 508 may refer to the pivot arm 204 or the pivot arm 404, and each or at least one of the torsion springs 512 may refer to the pivot 206 or the pivot 410 of FIG. 2 or FIG. 4, respectively.

[00131] The design of the link springs 510 may also be significant for the proper operation of the device (i.e., the accelerometer 500). The inclusion of link springs 510 may add more degrees of freedom of motion. The design ensures that the fundamental oscillation mode has the desired mode shape and this will be discussed later on below.

[00132] It should also be appreciated that if the pivot arms 404 are placed on top of pivots 410 (FIG. 3), there may be high stresses at the joints. Such a structure may also be difficult to fabricate. Therefore, the pivot arms 508 may be hinged by torsion springs 512

in the same plane as the pivot arm 508 (e.g., in FIG. 5A). These torsion springs 512 may be folded to increase the length, for greater response or higher sensitivity.

[00133] FIG. 5B shows the accelerometer 500 of FIG. 5A moved in response to an upward (+z) acceleration as indicated by a directional arrow 520.

[00134] In FIG. 5B, the annular proof mass 506 has moved up and the inner comb 504 has moved down. This way, a differential capacitance may be determined based on the measurements (capacitance value) at the outer comb 502 and the inner comb 504.

[00135] The performance of the accelerometer (e.g., the accelerometer 202 of FIG. 2 or the accelerometer 500 of FIGs. 5A and 5B) was evaluated through simulations. The damping, spring constant and displacement of the comb structure was studied and optimized. The cross axis sensitivity was also studied by applying acceleration along the x-axis and measuring the displacements along other axes (see with reference to, for example, FIG. 5B). A summary of measurements are given in Table 1.

[00136] Table 1

Parameter	Simulated result
Device size	3.5mm x 3.5mm
Total mass	0.75×10^{-6} kg
Fundamental Resonance	1520 Hz
Minimum mode separation	450 Hz
Vacuum level	7.5 Torr (1000Pa)
Brownian noise	28 ng/ $\sqrt{\text{Hz}}$
Displacement at 1G	Approximately 50nm
Static capacitance	Approximately 50pF
Capacitance change	Approximately 25fF/g (w/o fringing effect)
Dynamic range	± 2 G
Cross axis sensitivity	X: -28dB (3.6%) Y: -20dB (9.2%) Z: -46dB (0.46%)

[00137] The design of the link springs was also studied through simulations. FIG. 6A shows a perspective schematic view of the accelerometer 500 with the desired mode shape of the fundamental resonance mode (i.e., the desired lowest mode shape), where the proof mass 506 has a vertical (harmonic) motion. If the link springs 510 are made narrower (i.e., decreasing their torsion spring constants) the fundamental mode shape becomes a rocking motion, as shown in FIG. 6B. Such a rocking motion may provide “rocking” mode shapes as the lowest modes. Thus the link springs 510 may have to be designed in a manner to ensure the fundamental mode has the desired mode shape, as well as having a sufficient frequency separation from the higher resonant modes. In other words, the mode shapes and mode separation may be adjusted by the link springs’ 510 design. A mode separation of 400Hz was achieved through simulations. With possible design optimisation, a larger mode separation may be obtainable.

[00138] In determining the cross-axis sensitivity, an input of 1G acceleration was applied along the x-axis direction. The measured outputs (i.e., maximum displacements) along the major axes are obtained from the simulation diagrams 700, 702 and 704 of FIGs. 7A (for X-axis), 7B (for Y-axis) and 7C (for Z-axis), respectively, and are summarized as follow:

- X-axis: 1.8 nm
- Y-axis: 4.6 nm
- Z-axis: 0.23 nm

[00139] The z-axis sensitivity was 50nm/G. The Z-axis displacement is differential and may be minimized or eliminated by a readout circuit.

[00140] The closed loop operation of the device was studied through system level modeling using Matlab (The Mathworks, Inc., US). A second order feedback system was used for the application-specific integrated circuit (ASIC), which may be inherently stable. The system level model 800 of the closed loop accelerometer (e.g., the accelerometer 500 of FIGs. 5A and 5B) is shown in FIG. 8. In FIG. 8, the system level model 800 includes a sine wave 802 or a ramp 804 input to simulate the input

acceleration. The accelerometer 808 is modelled as having a second order transfer function of

$$\frac{9.81}{s^2 + b/m \cdot s + k/m} \quad (4)$$

where b is the damping coefficient, m is the mass, and k is the spring stiffness and based on 1G acceleration. The system is modelled to operate in a closed-loop with force feedback applied to the accelerometer.

[00141] For example, the accelerometer 808 may refer to the accelerometer 202 of FIG. 2 or the accelerometer 500 of FIGs. 5A and 5B. The measurement made by the accelerometer 808 is fed to a modulator 810 which applies a saturation function on the measurement to provide limitations on the maximum displacement value to be input to a capacitive sensor unit 812 that translates the displacement value (X) to a corresponding capacitive values (C+ and C-). For example, the capacitive sensor unit 812 may refer to the first capacitive sensor 210 and the second capacitive sensor 212 of FIG. 2. For example, the capacitive sensor 812 may be provided by the outer comb 502 and the inner comb 504 of FIG. 5A. The capacitive values (C+ and C-) are fed to a converter 814 which converts these values to voltage levels (V+ and V-) which are conditioned by a buffer 816. The difference between the conditioned voltage levels (Vcomp+ and Vcomp-) are evaluated by the differential amplifier 818 and can be observed using a scope 820. The input acceleration 802, 804 may also be fed into the scope 820 as a reference. The difference output from the differential amplifier 818 is fed as a force feedback signal 820 into a comparator 806 for the second order closed loop system level model 800.

[00142] FIG. 9A shows (i) the output pulse width modulated (PWM) signal and (ii) the input acceleration from the scope 820. It can be observed that saturation of the output PWM signal occurs when the input sine wave acceleration reaches its maximum and minimum peaks. FIG. 9B shows an expanded view of a marked area 902.

[00143] Using the device parameters, it was observed that the closed loop accelerometer 808 may operate in a dynamic range of ± 2 G without saturation.

[00144] The accelerometer in accordance with various embodiments (e.g., the accelerometer 202 of FIG. 2, the accelerometer 500 of FIGs. 5A and 5B, or the accelerometer 808 of FIG. 8) advantageously provide fully differential capacitive sensing and uses robust processes for critical parameters as described below. In such a design of the accelerometer, a number of resonant modes due to multiple degrees of freedom in the structure may exist and differential capacitances may not be identical. The inner comb structure (e.g., the inner comb 504 of FIG. 5A) may be provided within the inner region (or area) enclosed by the annular proof mass 506 of FIGs. 5A and 5B. The closed loop dynamic range and its limitations may also be determined or estimated by simulations.

[00145] The accelerometer in accordance with various embodiments (e.g., the accelerometer 202 of FIG. 2, the accelerometer 500 of FIGs. 5A and 5B, or the accelerometer 808 of FIG. 8) has industrial applicability, for example, in areas of navigation and geographical mapping. It may also be used in projects requiring high resolution 3-axis acceleration sensing.

[00146] The accelerometer in accordance with various embodiments (e.g., the accelerometer 202 of FIG. 2, the accelerometer 500 of FIGs. 5A and 5B, or the accelerometer 808 of FIG. 8) may be implemented as a closed loop feedback system design and integrated with ASIC. Key modules and fabrication may be developed in establishing principles for scaling of the device and achieving 30 nG resolution ($1G = 9.81 \text{ ms}^{-1}$ acceleration) and $\pm 2 \text{ G}$ dynamic range.

[00147] Table 2 shows a performance comparison between the accelerometer 808 of FIG. 8 and other accelerometers currently available in the market.

[00148] Table 2

Company/ Product	Type/ Techn.	Range (g)	Sens. (mv/g)	Resolutio n	Non- linearity	Cross Sens.	Pkg. (mm)	Remarks
Colibrys SF1500	Si Bulk MM, capa.	3	1200/2400	3 μ g	<1%	rejection > 46 dB	25x25x14	MIL-883 PKG
Honeywell QA- 3000	Quartz	60	1.20~1.46 mV/g	<1 μ g			Ø25x25	Vs=13~28
STM LIS344ALH	Surf MM, capacitive	±2, ±6	660/220	<1mg	±0.5%	±2%	4x4x1.5	Vs=3.3V
ADI ADXL337	Poly, SMM, capacitive	3.6	300	tunable	+/- 0.3%	+/- 1%	3x3x1.5	Vs=3V
Bosch BMA 180		±1 - ±16	2 - 8192 LSB/g	0.25mg	±0.15% - 0.75%	±1.75%	3x3x0.9	VDD: 2.4/1.8V
Freescall MMA7455L	Surf MM, capacitive	±2, ±4, ±8	64/32/16 count/g		±1%	±5%	3x5x1	Digital
MEMSIC MXR9150	Thermal	±5	150	0.5 mg	0.5%	±2%	7x7x1.8	
NTU-Taiwan		6	3.9 (x,y) 1.9(z)		1.06% (x,y) 1.81% (z)	1~3% (x,y) 5~8% (z)		CMOS MEMS, NEMS'08
Kyoto U			1fF/g				> 1.22mm ²	Transducer'07
ITRI, Taiwan		+/-5	~300	16Bits	<0.35%	<1.02		2009
U. Michigan		+/-1	490 (x,y) 960 (z)	μ g level				JMEMS'05
Accelerometer 808	SOI, z-axis	+/-2	25fF/g	30ng		0.46% (-46dB)		

[00149] It can be seen from Table 2 that the accelerometer 808 provides a comparative high resolution of about 30 ng (or nG). It also provides a higher sensitivity of 25fF/g as compared to that of the product from Kyoto University.

[00150] It should be appreciated that instead of link springs (e.g., the link springs 510 of FIGs. 5A and 5B), hinges may be used. However, microelectromechanical systems (MEMS) hinges tend to have space for movement or have a "play". Perfect MEMS hinges are currently not known in the art. The structural features of the accelerometer 808 may be easily identified by reverse engineering (SEM/FIB imaging etc), thereby providing traceability.

[00151] There is also improved performance with high resolutions being achieved without requiring high-vacuum packaging.

[00152] FIG. 10 shows a flow diagram of a method of fabricating an accelerometer 1000, according to various embodiments. At 1002, respective trenches for forming a first and a second capacitive sensors, and a pivot of the accelerator therebetween may be formed on a device layer of a wafer. At 1004, a first polysilicon may be deposited into the respective trenches to form comb structures of electrodes of the first and the second

capacitor sensors, and the pivot. At 1006, respective cavities may be formed on the first polysilicon and the device layer to provide a gap between the comb structures of electrodes formed by the first polysilicon and interleaving comb structures of electrodes of the first and the second capacitor sensors disposed on the device layer, and to provide a spacing between the pivot and a pivot arm of the accelerometer such that the pivot arm is movable about the pivot. At 1008, a second polysilicon may be deposited over the first polysilicon and the device layer to form a predefined mass and the pivot arm, wherein the pivot arm may be configured to couple respectively to the predefined mass, the comb structures of electrodes and the pivot. At 1010, the second polysilicon may be patterned to obtain a structure of the accelerometer.

[00153] In other words, the method of fabricating the accelerometer 1000 involves forming trenches into which polysilicon may be deposited to form structures on which cavities are then formed to provide for gaps or spacing between the underlying polysilicon and a next coat of deposited polysilicon, and patterning the overlying polysilicon. As used herein, the term “trenches” may refer to “vias”.

[00154] In various embodiments, the first polysilicon may be of the same material as the second polysilicon.

[00155] In the context of various embodiments, the term “accelerometer” may be as defined above. For example, the accelerator fabricated by the method 100 in accordance with various embodiments may refer to the accelerator 202 of FIG. 2.

[00156] The terms “first capacitive sensor”, “second capacitive sensor”, “pivot”, “comb structure”, “pivot arm”, and “predefined mass” may be as defined above. For example, the first capacitive sensor may refer to the first capacitive sensor 210, the second capacitive sensor may refer to the second capacitive sensor 212, the pivot arm may refer to the pivot arm 204, and the predefined mass may refer to the annular predefined mass 208 of FIG. 2.

[00157] As used herein, the term “polysilicon” may interchangeably be referred to as “polycrystalline silicon” composed of a number of smaller crystals of silicon. It should be appreciated and understood that polysilicon differs from single-crystal silicon,

typically used for electronics and solar cells, and from amorphous silicon, typically used for thin film devices and solar cells.

[00158] The term “wafer” may be a wafer used in semiconductor manufacturing. For example, the wafer may be a silicon wafer or a silicon-on-insulator (SOI) wafer.

[00159] In various embodiments, forming the trenches at 1002 may include using deep reactive-ion etching (DRIE) on the device layer of the wafer. DRIE is a highly anisotropic etch process used to create deep penetration, steep-sided holes and trenches in wafers/substrates, typically with high aspect ratios. It is used in fabricating MEMS devices.

[00160] In various embodiments, prior to depositing the first polysilicon at 1004, the method 1000 may include forming oxide layers over walls of the trenches; and prior to depositing the second polysilicon at 1008, the method 1000 may include forming oxide layers over the cavities of the first polysilicon; and patterning the second polysilicon at 1010 may further include removing the oxide layers to release the structure of the accelerometer.

[00161] An indicative process flow to fabricate the accelerator may be as follow. The process (e.g., the method 1000 of FIG. 10) starts with an SOI wafer 1102 (with the insulator or oxide layer 1106) as seen in a side view schematic diagram 1100 of FIG. 11A. First, trenches 1104 are formed on the silicon device layer of the wafer 1102, using DRIE. FIG. 11B shows a perspective view 1110 of FIG. 11A. FIG. 11C shows a top view 1112 of FIG. 11A. For example, the side view schematic diagram 1100 may be obtained from forming trenches on a device layer of a wafer at 1002 of FIG. 10.

[00162] FIG. 12A shows a side view schematic diagram 1200 depicting a thin conformal oxide layer 1202 deposited using low-pressure chemical vapor deposition (LPCVD). FIG. 12B shows a perspective view 1210 of FIG. 12A.

[00163] FIG. 13A shows a side view schematic diagram 1300 depicting the oxide layer 1202 being then etched back to remove the top surface 1302, leaving oxide 1202 only at the sidewalls 1304. FIG. 13B shows a partial top view 1310 of FIG. 13A depicting the area illustrating the pivot arm structure 1312, the pivot structure 1314, and a part of the annular predefined mass structure 1316. FIG. 13C shows another partial top

view 1320 of FIG. 13A depicting the area illustrating the pivot arm structure 1312, the pivot structure 1314, and a part of the annular predefined mass structure 1316 as well as the inner comb structure 1322.

[00164] FIG. 14A shows a side view schematic diagram 1400 depicting an LPCVD polysilicon layer 1402 next being deposited with in-situ doping to refill the trenches 1104. FIG. 14B shows a perspective view 1410 of FIG. 14A. For example, the side view schematic diagram 1400 may be obtained from depositing a first polysilicon into the respective trenches at 1004 of FIG. 10.

[00165] FIG. 15A shows a side view schematic diagram 1500 depicting the LPCVD polysilicon layer 1402 being subject to polysilicon chemical mechanical polishing (CMP). The top surface of LPCVD polysilicon layer 1402 is removed via polysilicon CMP and the LPCVD polysilicon layer 1402 is only remained in the filled trenches 1402. FIG. 15B shows a perspective view 1510 of FIG. 15A. FIG. 15C shows a partial top view 1520 of FIG. 15A depicting the area illustrating the pivot arm structure 1522, the pivot structure 1524, a part of the annular predefined mass structure 1526, and the inner comb structure 1528.

[00166] FIG. 16A shows a side view schematic diagram 1600 depicting shallow cavities 1602 being etched on the silicon 1604 and desired parts of the LPCVD polysilicon layer 1402. FIG. 16B shows a perspective view 1610 of FIG. 16A. FIG. 16C shows a partial top view 1620 of FIG. 16A depicting the shallow cavities 1602. For example, the side view schematic diagram 1600 may be obtained from forming cavities at 1006 of FIG. 10.

[00167] FIG. 17A shows a side view schematic diagram 1700 depicting an oxide deposition 1702. FIG. 17B shows a perspective view 1710 of FIG. 17A.

[00168] FIG. 18A shows a side view schematic diagram 1800 depicting planarization (or etch back) of the deposited oxide 1702 to form a plane with the silicon 1802. FIG. 18B shows a perspective view 1810 of FIG. 18A. FIG. 18C shows a partial top view 1820 of FIG. 18A depicting the deposited oxide 1702 filled in the shallow cavities 1602.

[00169] FIG. 19A shows a side view schematic diagram 1900 depicting that a second polysilicon layer 1902 is then deposited using LPCVD with in-situ doping. FIG. 19B shows a perspective view 1910 of FIG. 19A. For example, the side view schematic diagram 1900 may be obtained from depositing a second polysilicon over the first polysilicon at 1008 of FIG. 10.

[00170] FIG. 20A shows a side view schematic diagram 2000 depicting that the polysilicon layer 1902 is then patterned. For example, patterning may involve the removal of the polysilicon layer 1902 as shown in an encircled area 2002. FIG. 20B shows a perspective view 2010 of FIG. 20A. FIG. 20C shows a top view 2020 of FIG. 20A. FIG. 20D shows an expanded partial (top left) view 2030 of FIG. 20C. FIG. 20E shows a partial perspective view 2040 of FIG. 20A depicting the patterning of the deposited oxide polysilicon layer 1902 as indicated in the encircled area 2002. FIG. 20F shows another orientation of a partial perspective view 2050 of FIG. 20E. For example, the side view schematic diagram 2000 may be obtained from patterning the second polysilicon at 1010 of FIG. 10.

[00171] FIG. 21A shows a side view schematic diagram 2100 depicting the final step of releasing the device using vapor hydrofluoric acid (VHF). By releasing, all oxide layers are removed to provide the gaps 2102 to form the accelerometer structure. FIG. 21B shows a perspective view 2110 of FIG. 21A. FIG. 21C shows a partial top view 2120 of FIG. 21A depicting the area illustrating the pivot arm structure 2122, the pivot structure 2124, a part of the annular predefined mass structure 2126, the inner comb structure 2128, and the link spring 2130. FIG. 21D shows a partial cross-sectional view 2140 as seen from line A-A' of FIG. 21C. FIG. 21E shows a cross-sectional view 2150 as seen from line A-A' of FIG. 21C. FIG. 21F shows a cross-sectional view 2160 as seen from line B-B' of FIG. 21C, which is at an offset from line A-A'.

[00172] In accordance with various embodiments, a novel design for a z-axis accelerometer has been proposed. The performance of this device has been evaluated through simulations. The proposed structure is capable of fully differential capacitive sensing and force feedback close-loop operation, using robust processes. High mechanical resolutions may be achieved with this device, with $30\text{ng}/\sqrt{\text{Hz}}$ achieved in an

indicative design in an ambient vacuum level of 1000Pa, in other words, predicted through simulations at a low vacuum ambient. The accelerometer in accordance with various embodiments provides attractiveness, for example, high reliability as critical dimensions are defined using robust process. High resolutions are achievable, with low vacuum packaging. The design of the accelerometer in accordance with various embodiments provides a scalable and generic design in terms of form factor, resolution, durability. The annular proof mass of the accelerometer in accordance with various embodiments is used in translational motion with link springs being connected to pivot arm (or pivot-beam) with proof mass and inner combs. The design of the link springs achieves desired mode shapes and mode separations and the system design achieves desired performance levels.

[00173] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An accelerometer comprising:
 - a pivot arm having a first end region and a second end region opposite to the first end region;
 - a pivot coupled to the pivot arm;
 - an annular predefined mass having a peripheral part coupled to the first end region or the second end region of the pivot arm;
 - a first capacitive sensor located at the first end region of the pivot arm; and
 - a second capacitive sensor located at the second end region of the pivot arm such that the pivot is arranged between the first capacitive sensor and the second capacitive sensor,
 - wherein the predefined mass is configured to move in response to an acceleration force along a predefined direction; and
 - wherein the first capacitive sensor and the second capacitive sensor are configured to determine a differential capacitance value which relates to the acceleration force.
2. The accelerometer of claim 1, wherein the pivot arm comprises a non-compliant pivot arm and wherein the peripheral part of the predefined mass is coupled to the first end region or the second end region of the pivot arm via a compliant connector.
3. The accelerometer of claim 2, wherein the compliant connector comprises a link spring.
4. The accelerometer of claim 3, wherein the link spring has a mode shape of a fundamental resonance mode where the predefined mass moves along the predefined direction.

5. The accelerometer of claim 4, wherein the fundamental resonance mode is of a predetermined mode separation from high-order resonant modes.
6. The accelerometer of claim 5, wherein the predetermined mode separation is 400Hz.
7. The accelerometer of any one of claims 1 to 6, wherein the predefined mass is configured to move in response to a z-axis acceleration.
8. The accelerometer of any one of claims 1 to 7, wherein the first capacitive sensor or the second capacitive sensor is positioned within an inner region enclosed by the annular predefined mass.
9. The accelerometer of any one of claims 1 to 8, wherein the first capacitive sensor and the second capacitive sensor, each comprises an upper comb structure of electrodes and a lower comb structure of electrodes, wherein the upper comb structure of electrodes interleaves with the lower comb structure of electrodes such that a displacement formed between the upper comb structure of electrodes and the lower comb structure of electrodes determines a capacitive value.
10. The accelerometer of claim 9, wherein the electrodes are configured to position along a plane parallel to the predefined direction.
11. The accelerometer of any one of claims 1 to 10, wherein the pivot is coupled to the pivot arm in the same plane as the pivot arm.
12. The accelerometer of any one of claims 1 to 11, wherein the accelerometer further comprises a plurality of pivot arms, wherein respective peripheral part of the predefined mass is coupled to respective first end region or second end region of each pivot arm.

13. The accelerometer of claim 12, wherein the pivot arms are spaced apart along radial axes of the predefined mass.

14. The accelerometer of claim 12 or 13, further comprising a plurality of first and second capacitive sensors, wherein each of the plurality of first capacitive sensors and each of the plurality of second capacitive sensors is located at the respective first end region of each pivot arm and the respective second end region of each pivot arm, respectively.

15. The accelerometer of any one of claims 1 to 14, wherein the pivot comprises a torsion spring.

16. The accelerometer of any one of claims 1 to 15, wherein the accelerometer is configured to produce a bidirectional force feedback signal when the predefined mass moves in response to the acceleration force.

17. The accelerometer of any one of claims 1 to 16, wherein the annular predefined mass comprises an annular circular predefined mass or an annular rectangular predefined mass.

18. A method of fabricating an accelerometer, the method comprising:
forming on a device layer of a wafer respective trenches for forming a first and a second capacitive sensors, and a pivot of the accelerometer therebetween;
depositing a first polysilicon into the respective trenches to form comb structures of electrodes of the first and the second capacitor sensors, and the pivot in between the first second capacitive sensor and the second capacitive sensor;
forming on the first polysilicon and the device layer respective cavities to provide a gap between the comb structures of electrodes formed by the first polysilicon and interleaving comb structures of electrodes of the first and the second capacitor sensors

disposed on the device layer, and to provide a spacing between the pivot and a pivot arm of the accelerometer such that the pivot arm is movable about the pivot;

depositing a second polysilicon over the first polysilicon and the device layer to form a predefined mass and the pivot arm, wherein the pivot arm is configured to couple respectively to the predefined mass, the comb structures of electrodes and the pivot;

patterning the second polysilicon to obtain a structure of the accelerometer.

19. The method of claim 18, wherein forming the trenches comprises using deep reactive-ion etching (DRIE) on the device layer of the wafer.

20. The method of claim 18 or 19, wherein prior to depositing the first polysilicon, the method comprises forming oxide layers over walls of the trenches; and wherein prior to depositing the second polysilicon, the method comprises forming oxide layers over the cavities of the first polysilicon; and wherein patterning the second polysilicon further comprises removing the oxide layers to release the structure of the accelerometer.