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(54) MULTI-AXIAL FORCE SENSOR, METHOD OF MANUFACTURING THE MULTI-AXIAL FORCE SENSOR, AND METHOD FOR OPERATING THE MULTI-AXIAL FORCE SENSOR

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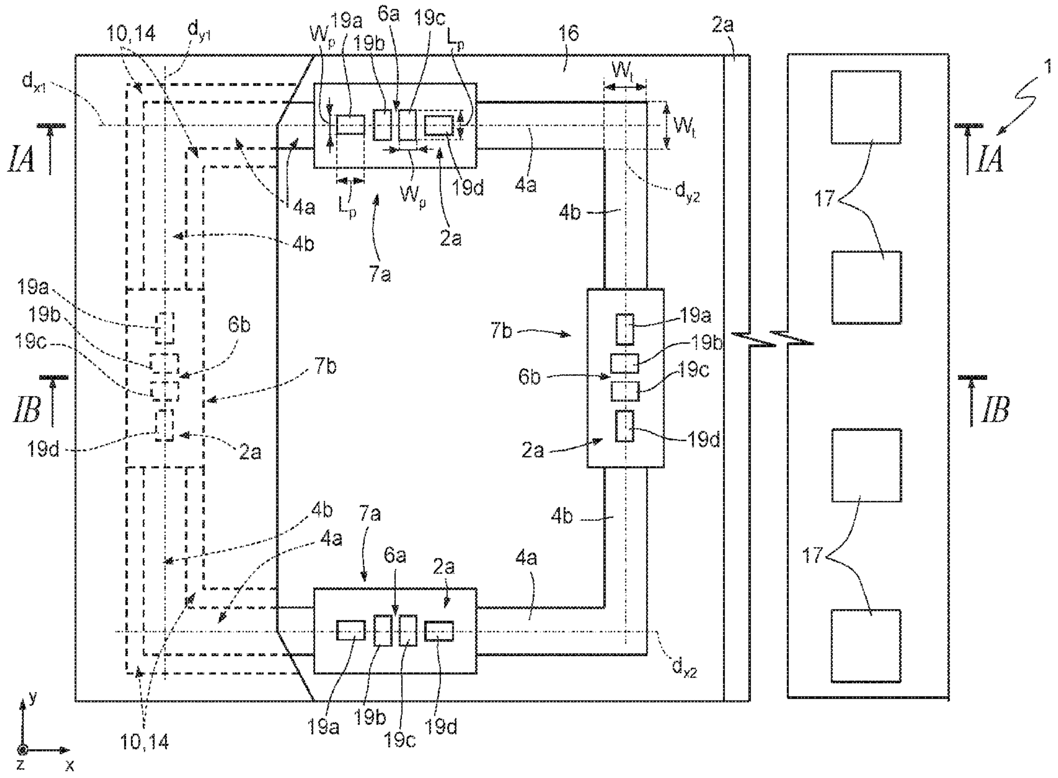
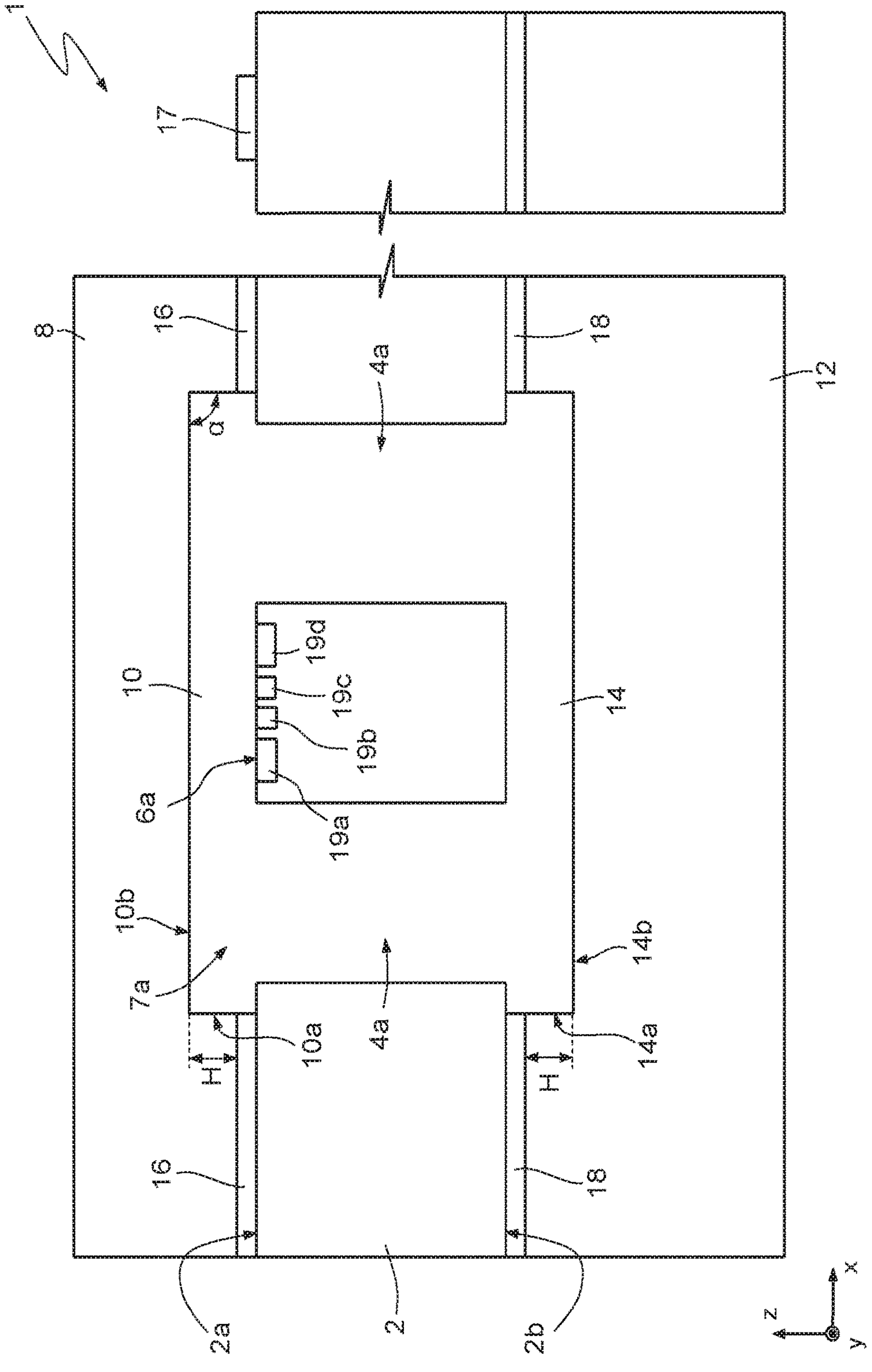
CPC *G01L 1/18* (2013.01)

(57) **ABSTRACT**

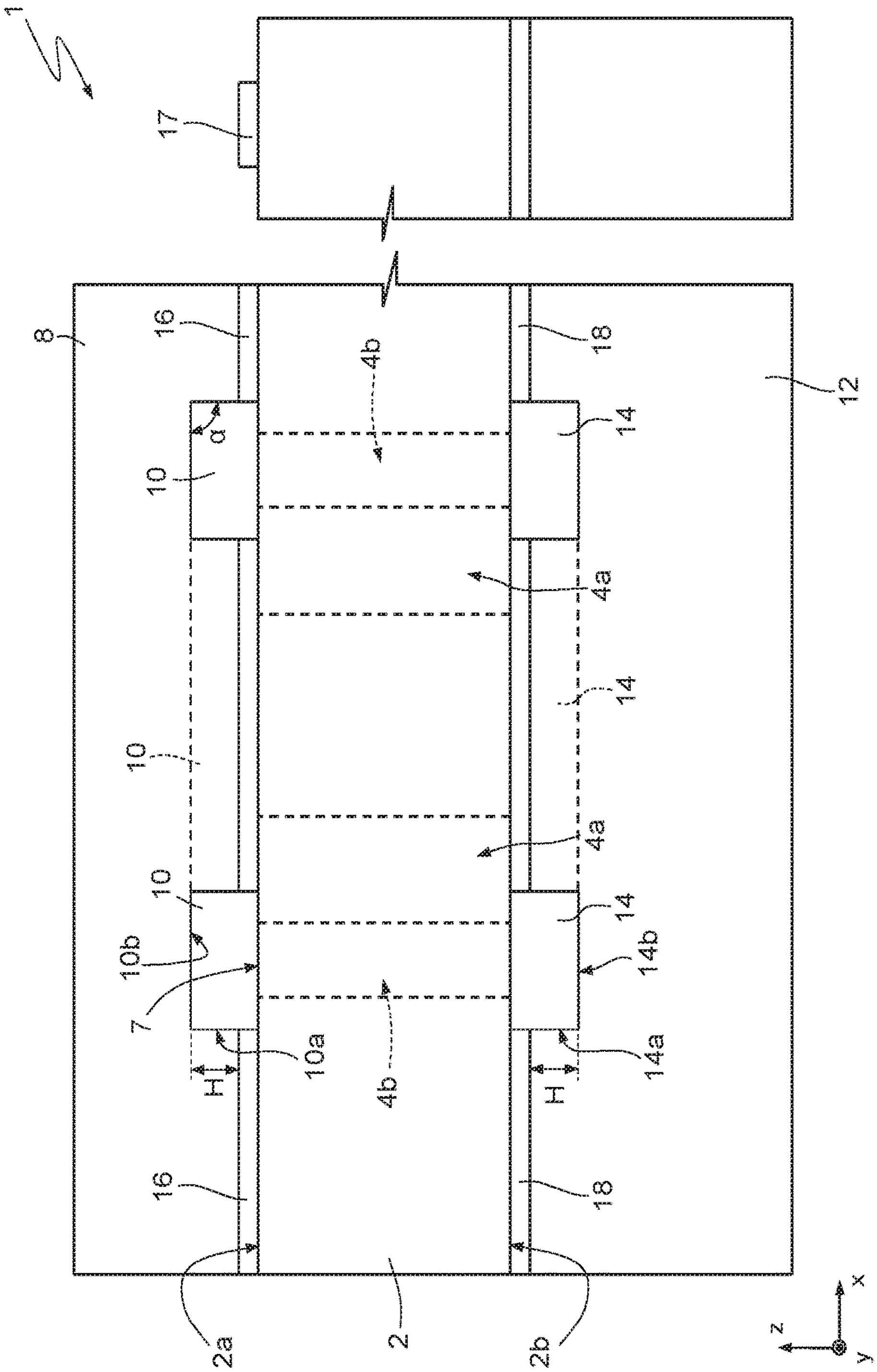
A microelectromechanical transducer includes a semiconductor body having first and second surfaces opposite to one another. A plurality of trenches extend in the semiconductor body from the first surface towards the second surface, including a first pair of trenches having a respective main direction of extension along a first axis, and a second pair of trenches having a respective main direction of extension along a second axis orthogonal to the first axis. A first piezoresistive sensor and a second piezoresistive sensor extend at the first surface of the semiconductor body respectively arranged between the first and second pair of trenches. The first piezoresistive sensor, the second piezoresistive sensor and the plurality of trenches form an active region. A first structural body is mechanically coupled to the first surface of the semiconductor body to form a first sealed cavity which encloses the active region.





(Cross-Section of figure 2 at IA)

FIG. 1A



(Cross-Section of figure 2 at IB)

FIG. 1B

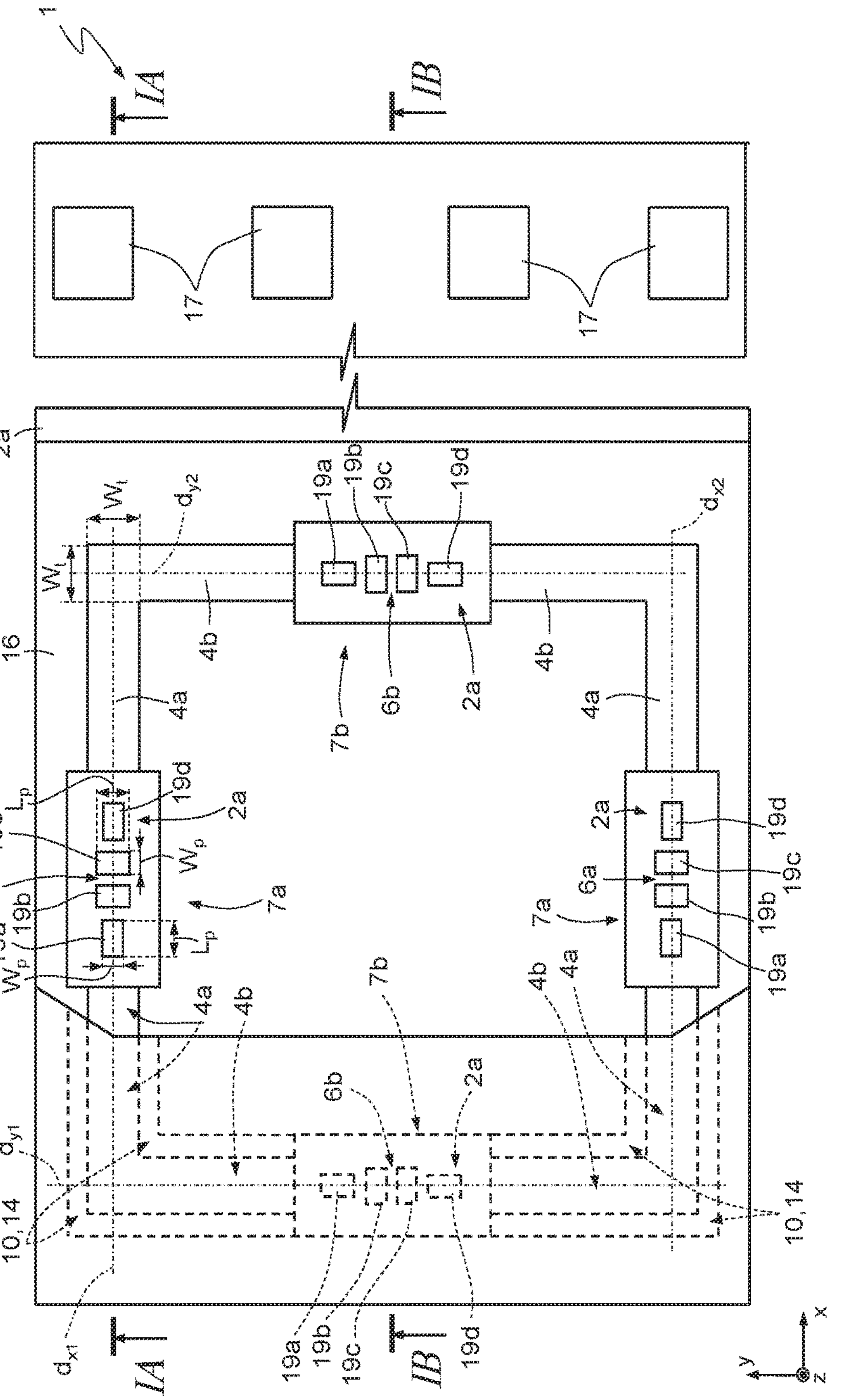


FIG. 2

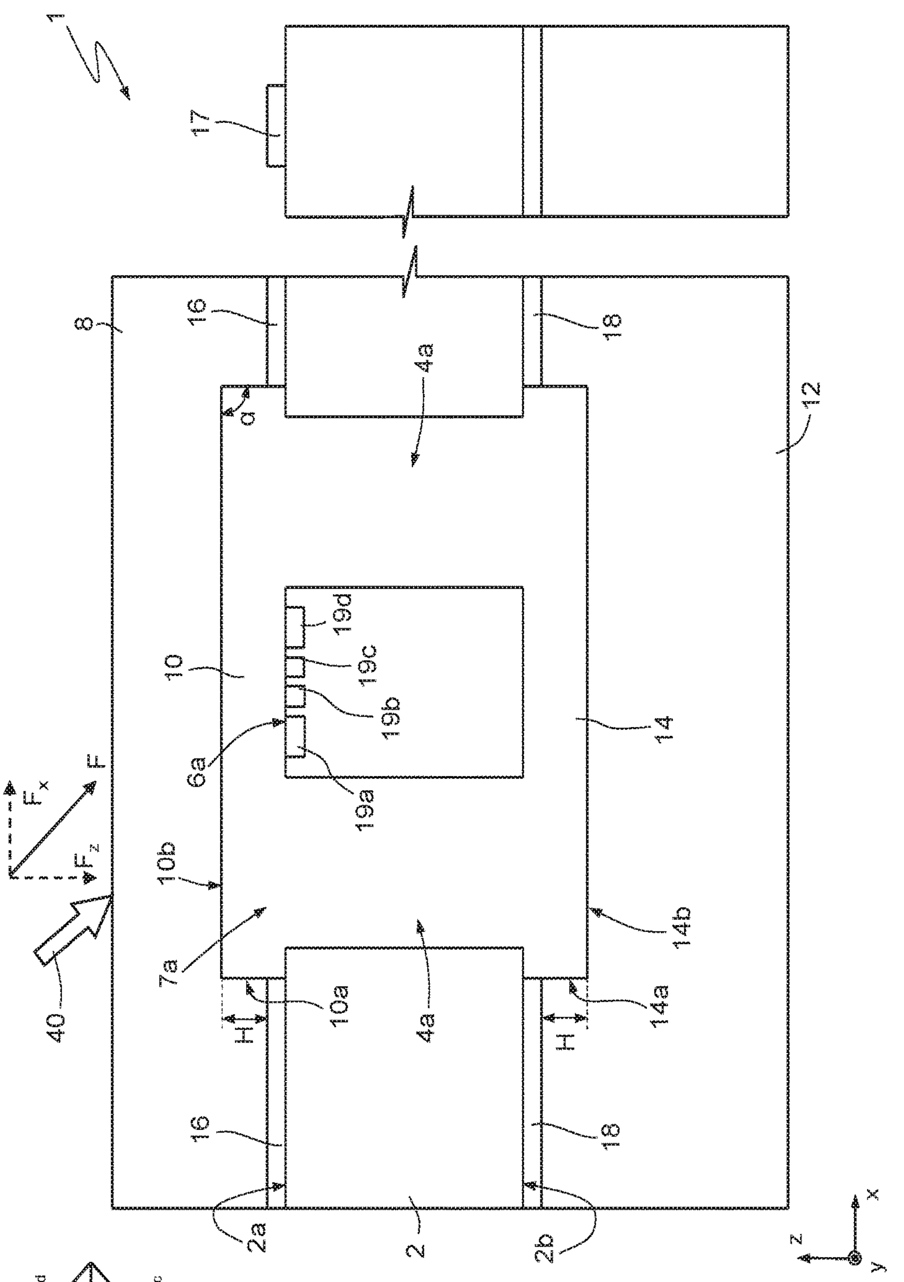

1
17
8
16
18
4a
12
α
10
19d
19c
19b
19a
6a
14
F
F_x
F_z
10b
14b
7a
40
H
10a
14a
2a
2
2b
z
x
y

FIG. 4

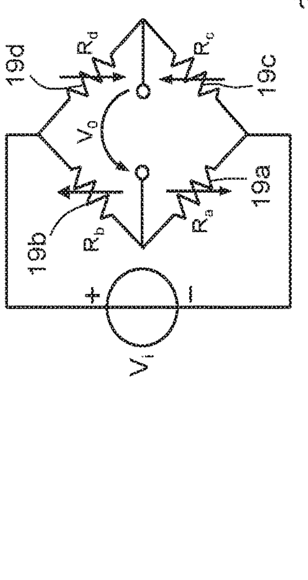

19d
R_d
R_c
19c
V_0
19a
R_a
R_b
19b
+
−
V_i

FIG. 3

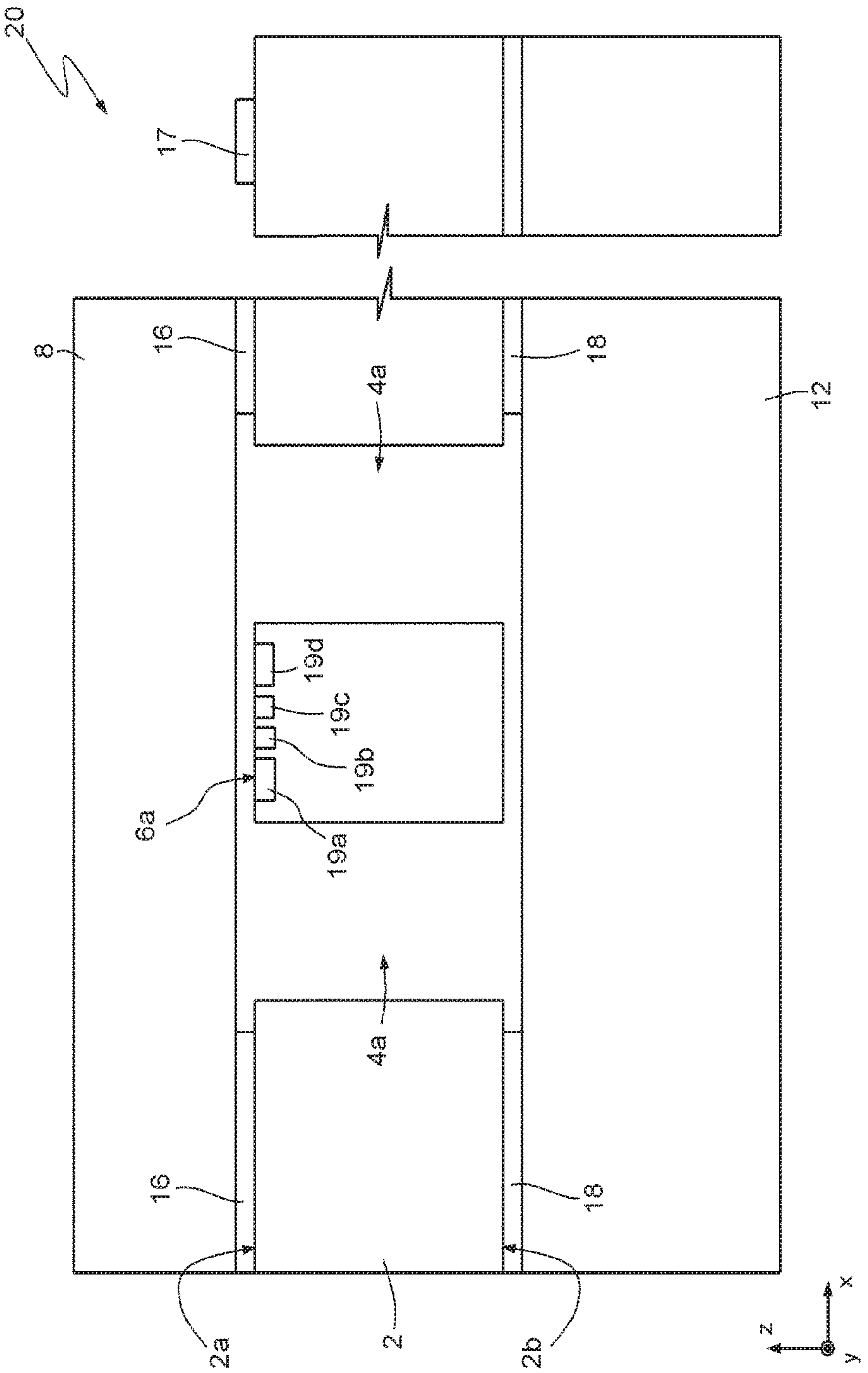


FIG. 5

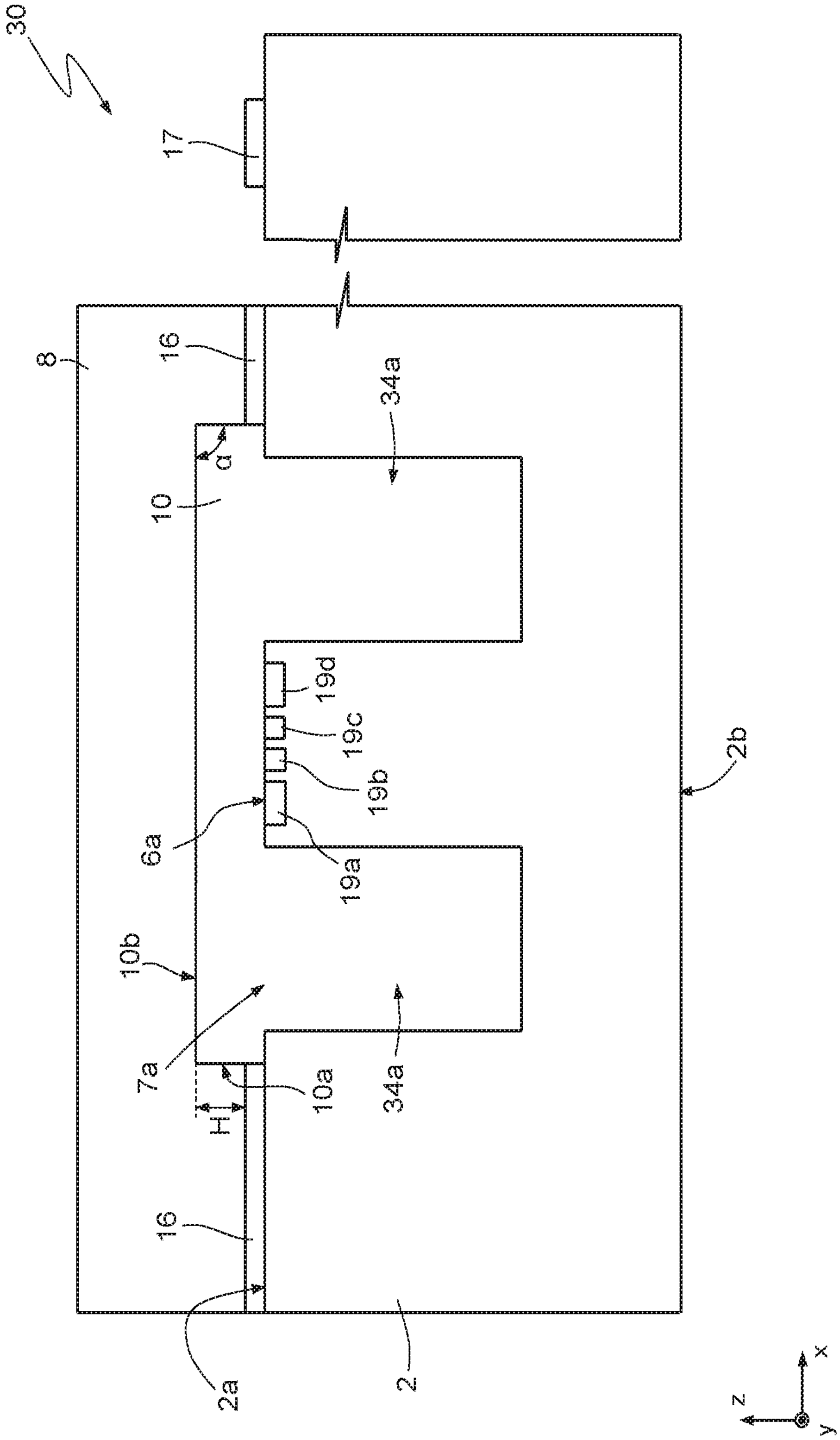


FIG. 6

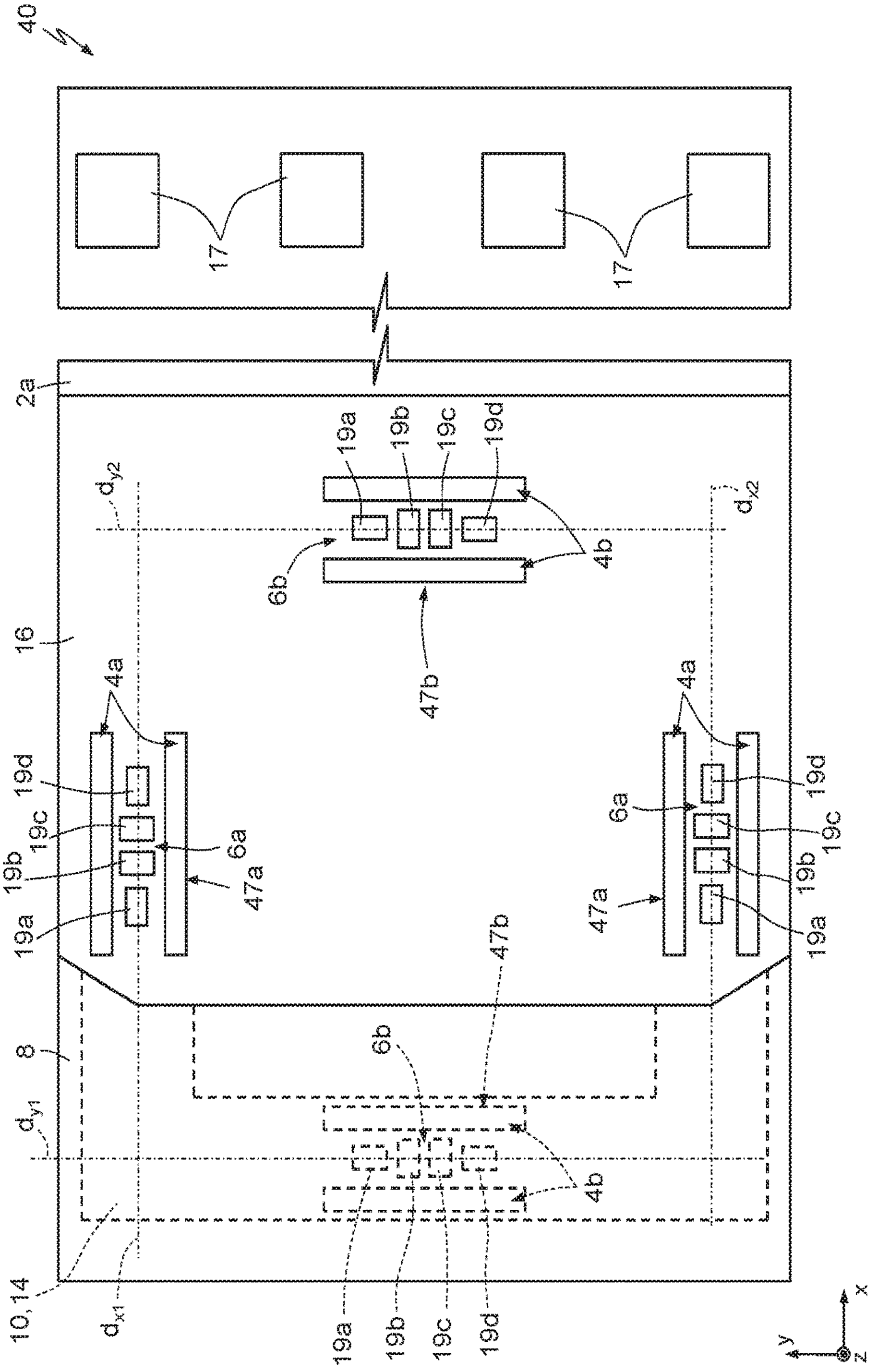
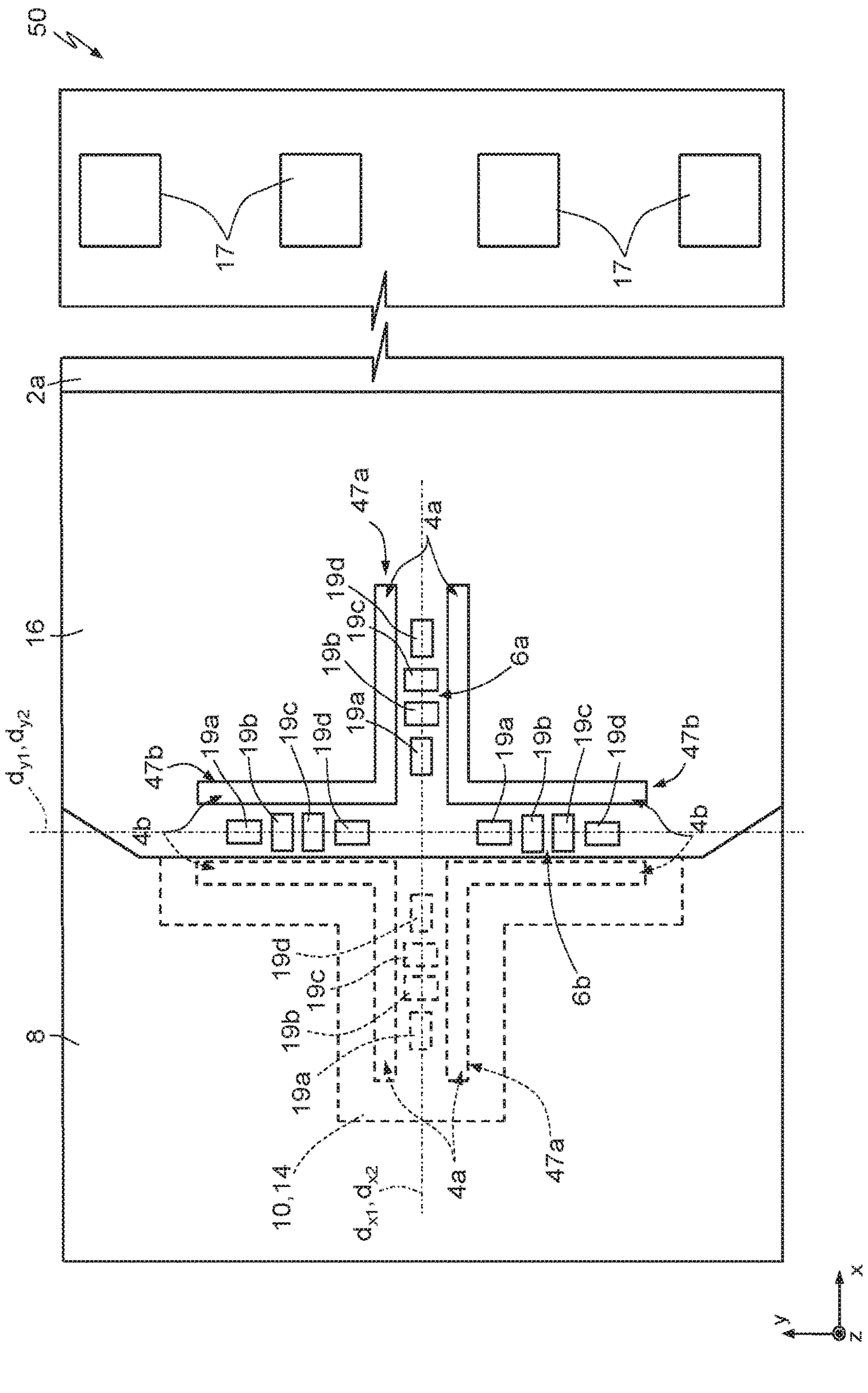

40
17
17
2a
16
8
10,14
19a
19b
19c
19d
6a
6b
4a
4b
47a
47b
d_{y1}
d_{y2}
d_{x1}
d_{x2}
x
y
z

FIG. 7



50
17
17
2a
16
8
47a
4a
19d
19c
19b
19a
6a
47b
4b
6b
10,14
d_{x1}, d_{x2}
d_{y1}, d_{y2}
x
y
z

FIG. 8

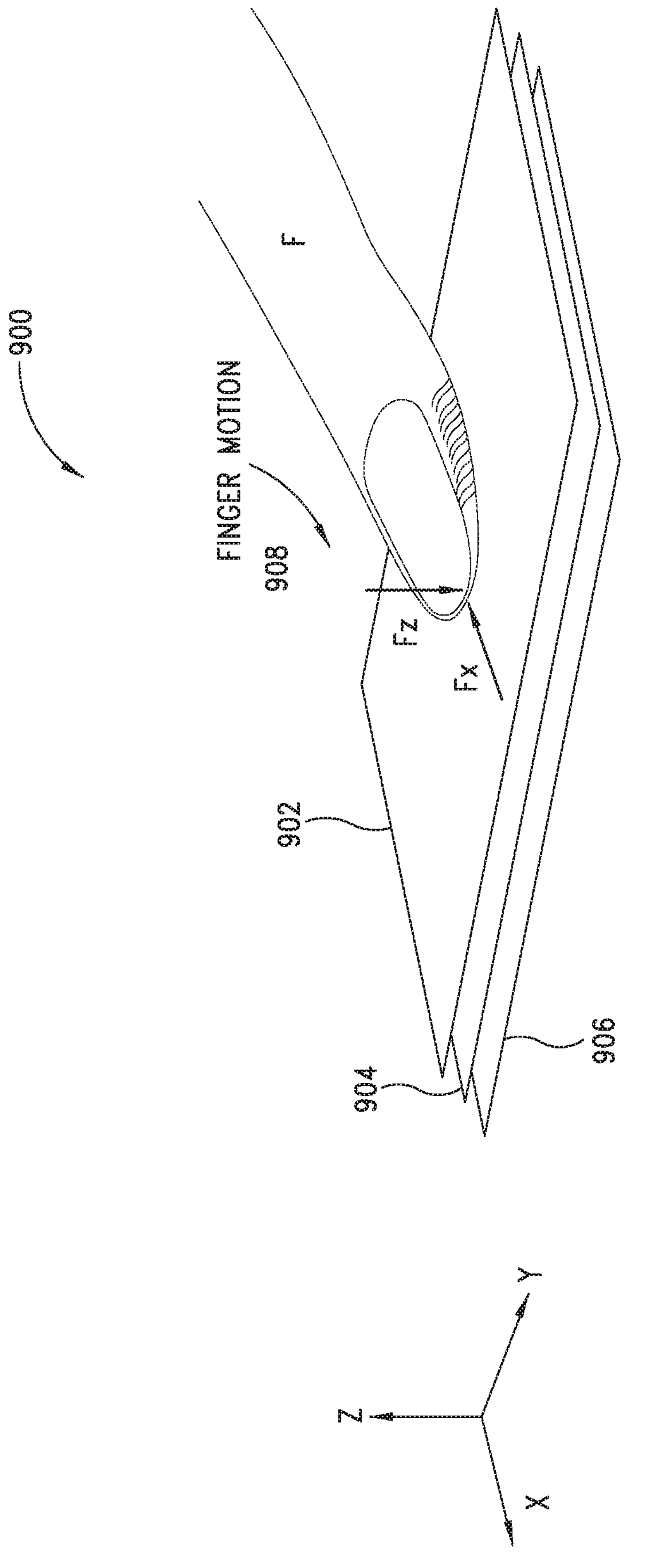


FIG. 9

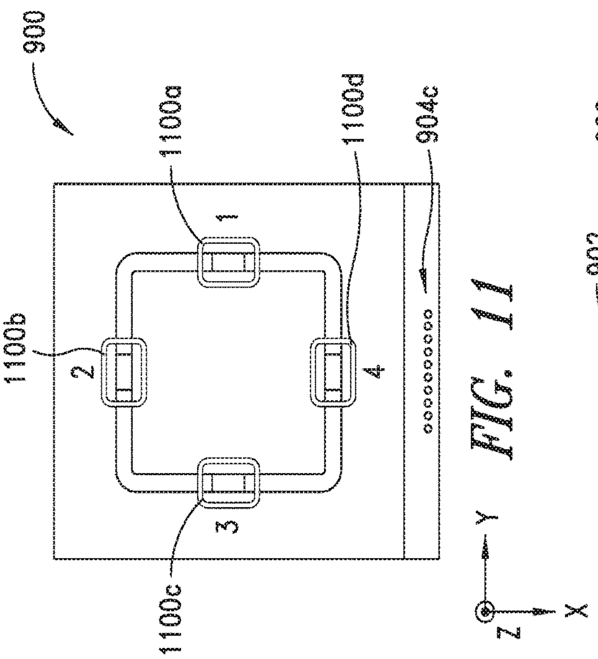


FIG. 11

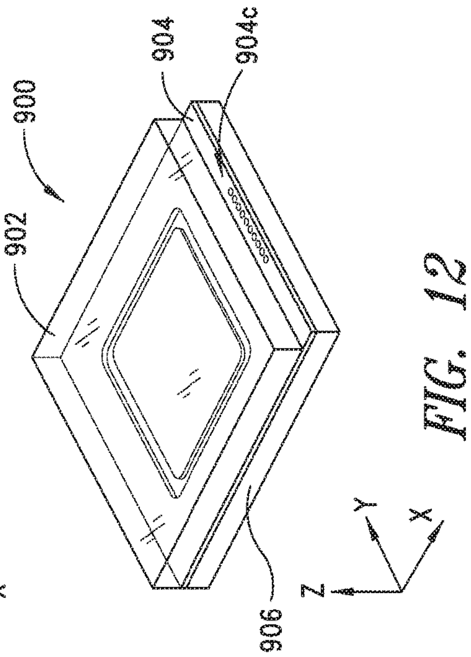


FIG. 12

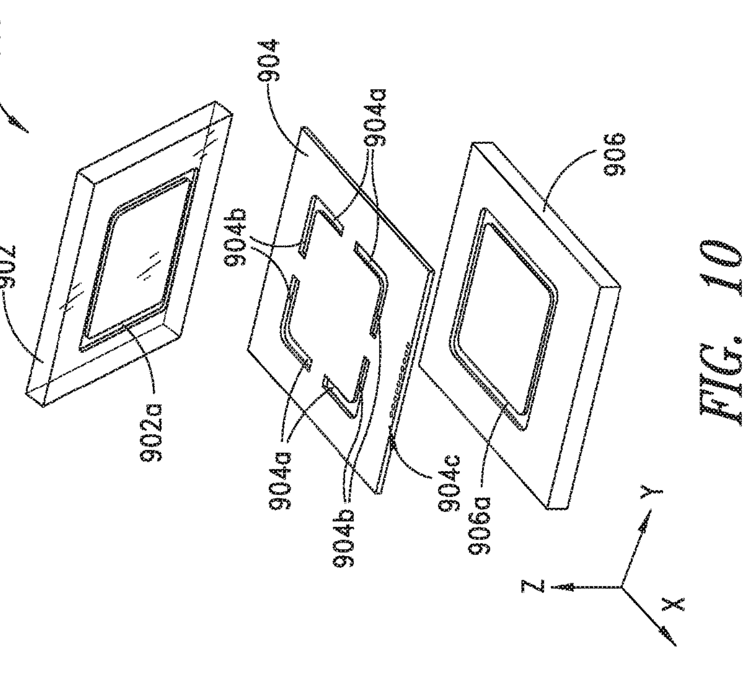


FIG. 10

MULTI-AXIAL FORCE SENSOR, METHOD OF MANUFACTURING THE MULTI-AXIAL FORCE SENSOR, AND METHOD FOR OPERATING THE MULTI-AXIAL FORCE SENSOR

BACKGROUND

Technical Field

[0001] The present disclosure relates to a microelectromechanical transducer, a method of manufacturing the microelectromechanical transducer, and a method for operating the microelectromechanical transducer.

Description of the Related Art

[0002] As is known, integrated force sensors can be manufactured with micromachining techniques. These sensors typically comprise a thin membrane, or diaphragm, suspended over a cavity provided in a silicon body. Formed within the membrane are piezoresistive elements connected together to form a Wheatstone bridge. When subjected to a force, the membrane undergoes deformation, causing a variation of resistance of the piezoresistive elements, and thus an unbalancing of the Wheatstone bridge. As an alternative, capacitive sensors are available, where the membrane provides a first plate of a capacitor, whereas a second plate is provided by a fixed reference. During use, deflection of the membrane generates a variation of the capacitance of the capacitor, which may be detected and associated with the pressure exerted on the membrane.

[0003] However, these semiconductor sensors may not in themselves be used for measuring high pressures in so far as they typically have low full-scale values. Thus, for high-pressure and high force applications, they need quite a complex package to support the applied load.

[0004] Moreover, typical semiconductor force sensors are designed to measure mainly one component of force (e.g. the normal force), but not a combination of normal component with in-plane components (e.g. shear forces). As a consequence, there is a need for a low-cost and versatile technology for the fabrication of semiconductor force sensors that sense multi-axial loads, able to measure or compensate different applied load components or non-homogeneous residual stresses induced on the sensor structure.

[0005] Multi-axial force sensors have been implemented exploiting other technologies, such as metallic load cells and ceramic load cells. However, multi-axial force sensors based on metallic load cells have issues related to low sensitivity, high cost, big size (especially for high-load applications) and high energy requirements (caused by the use of metallic strain gauges). Multi-axial force sensors based on ceramic load cells have other drawbacks, related to the technology of making resistors; screen printing for thick film resistors is the technology being used with limitations in miniaturization and flexibility in design. To make a multi-axial ceramic force sensor it is necessary to make use of complex mechanical features within the sensor layout. For this reason, multi-axial force sensors based on ceramic load cells need a complex package, increasing their cost. Moreover, force sensors based on ceramic load cells like the metallic ones have typically low resolution for high full scale ranges.

BRIEF SUMMARY

[0006] The present disclosure provides a microelectromechanical transducer, a method of manufacturing the microelectromechanical transducer, and a method for operating the microelectromechanical transducer to overcome at least some of the problems previously discussed. In particular, embodiments of the present disclosure provide a semiconductor microelectromechanical transducer based on piezoresistive transduction, configured to work both as a uni-axial force sensor or a multi-axial force sensor.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0007] For a better understanding of the present disclosure, preferred embodiments thereof are now described, purely by way of non-limiting example and with reference to the attached drawings, wherein:

[0008] FIG. **1**A is a first cross-sectional view of a microelectromechanical transducer of FIG. **2** according to an embodiment of the present disclosure;

[0009] FIG. **1**B is a second cross-sectional view of the microelectromechanical transducer of FIG. **2**;

[0010] FIG. **2** is a top view of the microelectromechanical transducer of FIGS. **1**A and FIG. **1**B;

[0011] FIG. **3** is a circuit representation of a Wheatstone bridge employed as read-out circuit of the microelectromechanical transducer of FIG. **1**A, FIG. **1**B and FIG. **2**;

[0012] FIG. **4** is a cross-sectional view of the microelectromechanical transducer of FIG. **1**A during use as a force sensor;

[0013] FIG. **5** is a cross-sectional view of a microelectromechanical transducer according to another embodiment of the present disclosure;

[0014] FIG. **6** is a cross-sectional view of a microelectromechanical transducer according to a further embodiment of the present disclosure;

[0015] FIG. **7** is a top view of a microelectromechanical transducer according to another embodiment of the present disclosure;

[0016] FIG. **8** is a top view of a microelectromechanical transducer according to a further embodiment of the present disclosure;

[0017] FIG. **9** is a simplified perspective view of a multi-axial sensor showing the multi-layered structure of sensors according to embodiments of the present disclosure;

[0018] FIG. **10** is a more detailed perspective exploded view showing the multiple layers of the multi-layered multi-axial sensor of FIG. **9** according to an embodiment of the present disclosure;

[0019] FIG. **11** is a top view of the multi-axial sensor of FIG. **10** looking through the cap layer and showing the piezo-resistive groups in the sensor body layer; and

[0020] FIG. **12** is a perspective view of the multi-axial sensor of FIGS. **10** and **11** showing the cap layer, sensor body layer and substrate layer positioned on top of one another in the assembled multi-axial sensor.

DETAILED DESCRIPTION

[0021] FIGS. **1**A, **1**B show respective cross-sectional views of a microelectromechanical transducer, in particular a multi-axial force sensor, **1** according to an embodiment of the present disclosure. FIG. **2** shows a top view of the multi-axial force sensor **1** of FIGS. **1**A, **1**B in an xy-plane.

FIG. **1**A shows a cross-sectional view of the multi-axial force sensor **1** at the cross-section labeled IA in FIG. **2** while FIG. **1**B shows a cross-sectional view of the multi-axial force sensor at the cross-section labelled IB in FIG. **2**. The multi-axial force sensor **1** in FIGS. **1**A, **1**B and **2** is represented in a system of spatial coordinates defined by three axes x, y, z, orthogonal to one another. The cross-sectional view of FIG. **1**A is taken along the line I-I shown in FIG. **2**, while the cross-sectional view of FIG. **1**B is taken along the line II-II shown in FIG. **2**.

[0022] Referring to FIGS. **1**A, **1** B and **2**, the multi-axial force sensor **1** comprises a sensor body **2** having a front surface **2***a* and rear surface **2***b*, extending in parallel with the plane xy. A plurality of trenches **4** extends throughout the sensor body **2** from the front surface **2***a* to the rear surface **2***b*, in particular parallel to the z axis.

[0023] According to one aspect of the present disclosure, the plurality of trenches **4** includes first trenches **4***a* and second trenches **4***b*. The first trenches **4***a* have a main direction of extension, parallel to the plane xy, parallel to a first direction. The second trenches **4***b* have a main direction of extension, parallel to the plane xy, parallel to a second direction, different from the first direction. In particular, in the multi-axial force sensor **1** of FIGS. **1**A, **1**B and **2** the main direction of extension, on the plane xy, of the first trenches **4***a* is the x axis, while the main direction of extension on the plane xy of the second trenches **4***b* is the y axis. Therefore, according to the embodiment of FIGS. **1**A, **1**B and **2**, the first direction of the first trenches **4***a* is orthogonal to the second direction of the second trenches **4***b*.

[0024] As shown in FIG. **2**, a plurality of piezoresistive groups **6***a*-**6***b* is arranged at the front surface **2***a* of the substrate or body **2**. In particular, each first piezoresistive group **6***a* is arranged between a respective pair of first trenches **4***a*, whereas each second piezoresistive group **6***b* is arranged between a respective pair of second trenches **4***b*. Each of the first piezoresistive groups **6***a* and the second piezoresistive groups **6***b* include piezoresistive elements **19***a*-**19***d*. Therefore, the piezoresistive elements **19***a*-**19***d* of each piezoresistive group **6***a* are arranged one next to the other along a respective direction parallel to the x axis, at a distance from each other and from the trenches **4***a*, whereas the piezoresistive elements **19***a*-**19***d* of each piezoresistive group **6***b* are arranged one next to the other along a respective direction parallel to the y axis, at a distance from each other and from the trenches **4***b*. The trenches **4** and the piezoresistive groups **6***a*-**6***b* define an active region **7** of the multi-axial force sensor **1**.

[0025] According to one aspect of the present disclosure, the sensor body **2** is of a semiconductor material and in particular silicon. More specifically, the sensor body **2** is made of n-type single-crystal (100) silicon and the piezoresistors **6** are p+implanted regions.

[0026] With reference to FIGS. **1**A, **1**B, **2**, a first structural body **8** having the function of a cap is coupled to the front surface **2***a* of the sensor body **2** through a first coupling region **16**. For clarity of representation only, the first structural body **8** is only partially shown in FIG. **2**, covering only one piezoresistive group **6***b*, and exposing the other piezoresistive groups **6***a*-**6***b*. In the following, the first structural body **8** is referenced as "cap." The cap **8** has a recess **10** facing the front surface **2***a* in correspondence of the active region **7**. The recess **10** is delimited by lateral walls **10***a* of height H, and a bottom wall **10***b*. Exemplary values of the height H of the lateral walls **10***a* are in the range of 1-500 μm. The lateral walls **10***a* and the bottom wall **10***b* are adjacent to one another, forming an angle α. According to an aspect of the present disclosure, to improve the mechanical coupling between the cap **8** to the sensor body **2**, the angle α is greater than or equal to 90°. In further embodiments, the angle a may be lower than 90°.

[0027] The lateral walls **10***a* surround the active region **7** and the bottom wall **10***b* extends at a distance from the front surface **2***a* of the sensor body **2**. In this way, the recess **10** of the cap **8** defines a sealed cavity, wherein the active region **7** is housed. The cavity is sealed by means of the first coupling region **16**, made for instance of glass, metal bonding like Al/Ge or Au/Ge alloys, bi-adhesive layers, in general wafer bonding materials. The first coupling region **16** may be formed by wafer-to-wafer bonding techniques (e.g., glass frit bonding). A plurality of pads **17** are arranged on a region of the sensor body **2** not covered by the cap **8**, to allow electrical access to the multi-axial force sensor **1**, for instance by wire bonding. The pads **17** form electrical contact terminals for the piezoresistive groups **19***a*-**19***d* connected in the Wheatstone bridge configuration. The pads are connected to the piezoresistive groups **19***a*-**19***d* by conductive paths passing through the cap **8** and/or the sensor body **2**. The pads **17** may be of any suitable material, for instance Aluminum.

[0028] A second structural body **12** having the function of a supporting element or substrate is coupled to the rear surface **2***b* of the sensor body **2** through a second coupling region **18**. In the following, the second structural body **12** is referenced as "substrate." The substrate **12** has a recess **14** facing the rear surface **2***b* in correspondence of the area in which the trenches **7** extend. The recess **14** is delimited by lateral walls **14***a* and a bottom wall **14***b*. The lateral walls **14***a* surround the trenches **4** and the bottom wall extends at a distance from the rear surface **2***b* of the sensor body **2**. In this way, the recess **14** of the substrate **12** defines a sealed cavity. In particular, according to one aspect of this embodiment, the recesses **14** and **10** are at least partially aligned along the z-axis. In particular, the recesses **14** and **10** are overlapping, as it can be seen from a top view on the xy-plane.

[0029] The recess **14** is sealed by means of the second coupling region **18**, made for instance of glass, metal bonding materials like Al/Ge alloys or bi-adhesive layers. Analogously to the first coupling region **16**, the second coupling region **18** may be formed by wafer-to-wafer bonding techniques (e.g., glass frit bonding).

[0030] The cap **8** and the substrate **12** may be of any suitable material, such as semiconductor materials, ceramics, steel or metallic alloys (e.g., Invar, or FeNiCo alloys).

[0031] With reference to FIG. **2**, a first sensing unit **7***a* includes a first piezoresistive group **6***a* and the respective pair of first trenches **4***a* between which the first piezoresistive group **6***a* is arranged, and a second sensing unit **7***b* includes a second piezoresistive group **6***b* and the respective pair of second trenches **4***b* between which the second piezoresistive group **6***b* is arranged.

[0032] Two first sensing units **7***a* extend at a distance from one another with a respective main direction dx**1**, dx**2** of extension parallel to the x axis. Two second sensing units **7***b* extend at a distance from one another with a respective main direction dy**1**, dy**2** of extension parallel to the y axis.

[0033] According to an embodiment of the present disclosure, each first trench **4***a* is seamlessly connected to one respective second trench **4***b;* more in particular, first trenches **4***a* and second trenches **4***b* are connected at one of their ends, forming a right angle, and extend continuously from a first piezoresistive group **6***a* to a second piezoresistive group **6***b*.

[0034] According to other embodiments of the present disclosure, first trenches **4***a* of first sensing units **7***a* are not connected to second trenches **4***b* of second sensing units **7***b*.

[0035] From a top view on the xy-plane shown in FIG. **2**, the trenches **4** have a substantially rectangular shape, for instance with rounded corners. Longer sides of the rectangles define the length of the trenches **4**, whereas the shorter sides define the width W_t of the trenches **4**.

[0036] Each piezoresistive element **19***a*-**19***d* of the piezoresistive groups **6***a*-**6***b* has a substantially rectangular or oval or elliptical shape, with a major axis defining a length L_p of the piezoresistive element **19***a*-**19***d* and a minor axis defining a width W_p of the piezoresistive element **19***a*-**19***d*. Exemplary values of the dimensions of the piezoresistive elements **19***a*-**19***d* are in the range of 5-100 μm for the length L_p, for instance L_p=30 μm, and in the range of 1-50 μm for the width W_p, for instance W_p=10 μm.

[0037] Exemplary values of the dimensions of the trenches **4** are in the range of 10-1000 μm for the length, and in the range of 5-500 μm for the width W_t, provided that the width W_t of the trench is higher than the length L_p of the piezoresistive elements **19***a*-**19***d*.

[0038] In each sensing units **7***a*-**7***b*, piezoresistive elements **19***a*-**19***d* may be arranged in such a way that their length L_p is parallel or perpendicular to the length L_t of the trenches **4***a*, **4***b* of the respective sensing unit **7***a*-**7***b*. In this embodiment, each piezoresistive group **6***a*-**6***b* includes four piezoresistive elements **19***a*-**19***d*, which are electrically connected in a Wheatstone bridge configuration, as schematically shown in FIG. **3**. To achieve a proper functioning of the Wheatstone bridge (as detailed in the following), two piezoresistive elements **19***a*, **19***d*, are arranged in such a way that their length L_p is parallel to the length L_t of the trenches **4***a* (**4***b*) of the respective sensing unit **7***a* (**7***b*), whereas the other two piezoresistors **6***b*, **6***c*, are arranged in such a way that their length L_p is perpendicular to the length L_t of the trenches **4***a* (**4***b*) of the respective sensing unit **7***a* (**7***b*).

[0039] FIG. **4** illustrates the multi-axial force sensor **1** in a working condition. More in particular, FIG. **4** shows the multi-axial force sensor **1**, in the cross-sectional view of FIG. **1**A, when subject to a multi-axial force F represented by an arrow **40**. The force F can be expressed in terms of its components Fx, Fy, Fz, respectively along the x, y, z axes. Due to the fact that the cap **8** is anchored to the sensor body **2** through the first coupling region **16**, the relative expansion of the cap **8** on the sensor body **2** caused by the applied force induces a shear load and thus a planar stress distribution at the surface **2***a* of the sensor body **2**, and therefore on the piezoresistive units **19***a*-**19***d*.

[0040] In this example, the multi-axial force F presents non-zero components along all axes x, y, z, therefore it can be considered a superposition of normal forces and out of plane forces (with respect to the surface **2***a*).

[0041] The force components Fx, Fy, Fz of the multi-axial force F induce a planar mechanical stress σ at the surface **2***a* of the sensor body **2**. The arrangement of the trenches **4** affects the value of the components of the planar stress σ in the regions where the piezoresistive groups **6***a*-**6***b* are located. In particular, for each sensing unit **7***a*-**7***b*, the respective trenches **4***a*-**4***b* limit the effect of the force components parallel to the respective main direction of extension dx**1**, dx**2**, dy**1**, dy**2**.

[0042] In particular, force component Fx induces a planar stress σ which is maximized in the regions where the piezoresistive groups **6***b* are located, whereas force component Fy induces a planar stress σ which is maximized in the regions where the piezoresistive groups **6***a* are located. The force component Fz induces an equal planar stress distribution on all the piezoresistive groups **6***a*-**6***b*.

[0043] When subject to the planar stress σ, the i-th piezoresistive unit **19***a* . . . **19***d* changes its resistance value R_i according to the known equation (1) of piezo-resistivity effect of silicon:

$$\frac{\Delta R_i}{R_i} = \frac{\Delta \rho_i}{\rho_i} = \pi_l \sigma_{li} + \pi_t \sigma_{ti} + \pi_z \sigma_{zi} \tag{1}$$

where ρ_i is the resistivity of the i-th piezoresistive unit **19***a*; . . . ; **19***d*; π_l, π_t and π_z are respectively the longitudinal (parallel to the length L_p), transversal (parallel to the width W_p) and normal (parallel to z axis) components of the piezoresistive coefficient matrix of the region of the sensor body **2** where the piezoresistive units **19***a*-**19***d* are located; σ_{li}, σ_{ti} and σ_{zi} are respectively the longitudinal, transversal and normal components of the stress with respect to the i-th piezoresistive units **19***a*-**19***d*. More in particular, since the piezoresistive units **19***a*-**19***d* are exclusively subject to a planar stress σ at the surface **2***a* of the sensor body **2**, the normal component σ_{zi} becomes zero. As an example, in the case of p-type silicon on crystalline plane (001) and crystalline direction <110>, equation (1) is simplified as:

$$\frac{\Delta R_i}{R_i} = \frac{\Delta \rho_i}{\rho_i} = \pi_{in\text{-}plane}(\sigma_{li} - \sigma_{ti}) \tag{2}$$

where π_{in_plane} is about one half of the silicon piezoresistive coefficient π_{44} ($\pi_{in\_plane} \approx 70 \times 10^{-11}$ Pa^{-1}).

[0044] In the first sensing units **7***a*, first piezoresistive groups **6***a* are arranged between a pair of first trenches **4***a* along a direction dx**1**, dx**2**, parallel to the x axis. Thus, the effect of force component Fx on the planar stress σ is reduced (due to the first trenches **4***a*), and the effect of forces Fy is increased. Therefore, the piezoresistive units **19***a*-**19***d* of the first sensing units **7***a* are subject to a planar stress σ with main component parallel to the y axis. Since the piezoresistive units **19***b* and **19***c* of the first sensing units **7***a* have a main direction of extension parallel to the y axis, σ_{li} is much higher in module than σ_{ti}. To the contrary, since the piezoresistive units **19***a* and **19***d* of the first sensing units **7***a* have a main direction of extension parallel to the x axis, σ_{ti} is much higher in module than σ_{li}.

[0045] For instance, if the force component Fy has positive sign in the considered reference system, the piezoresistive group **6***a* arranged along the dx**1** direction is subject to a compressive stress acting along the y axis, while the piezoresistive group **6***a* arranged along the dx**2** direction is subject to a tensile stress. Considering that compressive stress has a negative sign, within the meaning of equation

(1), there is an increase of the resistance values R_a, R_d of the piezoresistive units **19***a*, **19***d* of the piezoresistive group **6***a* arranged along the dx**1** direction, while there is a decrease of the resistance values R_b, R_c of the piezoresistive units **19***b*, **19***c* of the piezoresistive group **6***a*. Instead, considering that tensile stress has a positive sign, within the meaning of equation (1), there is a decrease of the resistance values R_a, R_d of the piezoresistive units **19***a*, **19***d* of the piezoresistive group **6***a* arranged along the dx**2** direction, while there is an increase of the resistance values R_b, R_c of the piezoresistive units **19***b*, **19***c* of the piezoresistive group **6***a*.

[0046] If instead the force component Fy has negative sign, the piezoresistive group **6***a* arranged along the dx**1** direction is subject to a tensile stress acting along the y axis, while the piezoresistive group **6***a* arranged along the dx**2** direction is subject to a compressive stress. Considering that compressive stress has a negative sign, there is an increase of the resistance values R_a, R_d of the piezoresistive units **19***a*, **19***d* of the piezoresistive group **6***a* arranged along the dx**2** direction, while there is a decrease of the resistance values R_b, R_c of the piezoresistive units **19***b*, **19***c* of the piezoresistive group **6***a*. Instead, considering that tensile stress has a positive sign, there is a decrease of the resistance values R_a, R_d of the piezoresistive units **19***a*, **19***d* of the piezoresistive group **6***a* arranged along the dx**1** direction, while there is an increase of the resistance values R_b, R_c of the piezoresistive units **19***b*, **19***c* of the piezoresistive group **6***a*.

[0047] In any case, the force component Fy has negligible effect on the resistance values of the piezoresistive units **19***a*-**19***d* of the second piezoresistive groups **6***b*. This is mainly due to two reasons. From a mechanical point of view, the low sensitivity of the second piezoresistive groups **6***b* is due to the presence of the trenches **4***b* and the fact that the two edges of the cap **8** in contact with the sensing units **7***b* are parallel to the orientation of the sensing units **7***b*, which is also parallel to the direction of the force component Fy.

[0048] Similar considerations are valid, mutatis mutandis, for the effects of force component Fx on the resistance values of the piezoresistive units **19***a*-**19***d*.

[0049] Changes of resistance values in the piezoresistive units **19***a*-**19***d* connected in a Wheatstone bridge result in a change of the output voltage V_o of the Wheatstone bridge biased by the input voltage V_i as shown in FIG. **3**, according to the known equation (2):

$$\frac{V_o}{V_i} = \frac{2\Delta R_{a,d} - 2\Delta R_{b,c}}{4R + 2(2\Delta R_{a,d} + 2\Delta R_{b,c})} = \frac{\Delta R_{a,d} - \Delta R_{b,c}}{2R + 2(\Delta R_{a,d} + \Delta R_{b,c})} \quad (2)$$

[0050] In presence of the following condition:

$$\Delta R_a = \Delta R_d = -\Delta R_b = -\Delta R_c = \Delta R$$

$$R_a = R_b = R_c = R_d = R \quad (3)$$

equation (2) is simplified to:

$$\frac{V_o}{V_i} = \Delta R/R \quad (4)$$

[0051] Therefore, the output voltage Vo of the first sensing units **7***a* is correlated to the force component Fy parallel to the y axis, while the output voltage Vo of the second sensing units **7***b* is correlated to the force component Fx parallel to the x axis.

[0052] Force component Fz induces an equal compressive stress distribution on all the piezoresistive groups **6***a*-**6***b*, and therefore an equal effect on the piezoresistive units **19***a*-**19***d*. In general, the sign of each Wheatstone bridge output does not only depend on the type of induced stress over the corresponding zone, but it depends also on the configuration of electrical connections between the piezoresistive units **19***a*-**19***d*.

[0053] Moreover, the fact that the force component Fy has negligible effect on the resistance values of the piezoresistive units **19***a*-**19***d* of the second piezoresistive groups **6***b* is also due to the fact that the piezoresistive units **19***a*-**19***d* of the second piezoresistive groups **6***b* are positioned symmetrically with respect to a line parallel to the x-axis and passing by the centroid of the active region **7**. As a consequence, the corresponding Wheatstone bridge is insensitive with respect to loads that induce either the same stress contribution over both piezoresistive groups **6***b* or an opposite stress contribution for the piezoresistive units **19***a* and **19***b* in comparison to the piezoresistive units **19***c* and **19***d*.

[0054] In conclusion, the force components Fx, Fy, Fz, of the multi-axial force F can be obtained from the output voltages of the sensing units **7***a*-**7***b* using the following equations:

$$F_x = \frac{S_x}{2 \cdot V_{in}}(-V_1 + V_3)$$

$$F_z = \frac{S_z}{4 \cdot V_i}(V_1 + V_2 + V_3 + V_4),$$

where V**1**, V**2**, V**3** and V**4** are respectively the output

$$F_y = \frac{S_y}{2 \cdot V_i}(-V_2 + V_4)$$

voltages of the Wheatstone bridge of the sensing unit **7***b* along the direction dy**2**, the sensing unit **7***a* along the direction dx**1**, the sensing unit **7***b* along the direction dy**1** and the sensing unit **7***a* along the direction dx**2**; and Sx, Sy, Sz are the sensitivities of the multi-axial force sensor **1** respectively along the x, y, z axes, which can be obtained by standard calibration protocols. Moreover, standard optimization procedures for the calculation of the force components may be adopted to take into account non-idealities of the sensing units.

[0055] An exemplary method for manufacturing the multi-axial force sensor of FIGS. **1**A, **1**B and **2** is now described.

[0056] First, an n-type single-crystal (100) silicon wafer comprising the sensor body **2** is provided. A first photoresist mask is formed on top of the front surface **2***a*, by standard optical lithography techniques. Openings in the photoresist mask correspond to the regions where the piezoresistive units **19***a*-**19***d* should be formed. The piezoresistive units **19***a*-**19***d* may be formed by implantation or diffusion of p-type dopant elements, for instance boron. The techniques to form the piezoresistive units **19***a*-**19***d*, as well as their connection in a Wheatstone bridge, are known and thus they will not be described in further detail. After removing the first photoresist mask, a second photoresist mask is formed on top of the front surface **2***a*. The openings in the second photoresist mask correspond to the areas in which the trenches **4** should be formed, at a distance from the areas in which the piezoresistive units **19***a*-**19***d* were formed. Using the second photoresist mask, the sensor body **2** is etched selectively through its whole thickness, until openings at the rear surface **2***b* are formed. The etching step to form the trenches **4** is a standard bulk micromachining technique and it may be of a wet or dry type. The second photoresist mask is then removed.

[0057] A second wafer of silicon or any other suitable material is provided, comprising the cap **8**. A third photoresist mask is formed on the front side of the second wafer by standard optical lithography techniques. The openings on the third photoresist mask correspond to the position of the recess **10**. The area of the openings on the third photoresist mask should be defined in such a way that it includes the area of the openings of both the first and the second photoresist mask when they are aligned to one another. Using the third photoresist mask, the cap **8** is etched selectively up to a depth lower than its thickness. Then, the third photoresist mask is removed.

[0058] A third wafer of silicon or any other suitable material is provided, comprising the substrate **12**. A fourth photoresist mask is formed on the front side of the third wafer by standard optical lithography techniques. The openings on the fourth photoresist mask correspond to the position of the cavity **14**. The area of the openings on the fourth photoresist mask should be defined in such a way that it includes the area of the openings of both the first and the second photoresist mask when they are aligned to one another. Using the fourth photoresist mask, the substrate **12** is etched selectively up to a depth lower than its thickness. Then, the fourth photoresist mask is removed.

[0059] Next, the first wafer, comprising the sensor body **2**, and the second wafer, comprising the cap **8**, are coupled to one another at the surface **2***a* through the coupling region **16**, obtained by known wafer-to-wafer bonding techniques, for instance glass frit.

[0060] Next, the first wafer, comprising the sensor body **2**, and the third wafer, comprising the substrate **12**, are coupled to one another at the surface **2***b* through the coupling region **18**, obtained by known wafer-to-wafer bonding techniques, for instance glass frit.

[0061] In this way, the active region **7** is not exposed to the environment.

[0062] FIG. **5** shows a multi-axial force sensor **20** according to a further embodiment of the present disclosure. Differently from the multi-axial force sensor **1** illustrated in FIGS. **1**A, **1**B, **2**, the recesses **10** and **14** are not present. All other elements are in common to the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2**, and designated by the same reference numbers, thus they are not described any further. As in the case of the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2**, the cap **8** and the substrate **12** are at a distance from the front surface **2***a* and rear surface **2***b*, respectively, by means of the coupling regions **16** and **18**. The multi-axial force sensor **20** of FIG. **5** is easier to be manufactured than the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2**, because it does not include the etching steps of the cap **8** and the substrate **12** to form the recesses **10** and **14**.

[0063] During use of the multi-axial force sensors **1**, **20**, a pressure or force applied along the z-axis may cause the cap **8** and the substrate **12** to bend towards the sensor body **2** in correspondence of their respective free surfaces facing the sensor body **2**. To ensure protection and a proper functioning of the active region **7**, neither the cap **8** nor the substrate **12** should come into direct contact, while bending, with the piezoresistive groups **6***a*-**6***b*. The multi-axial force sensor **20** can withstand lower forces applied to the z axis with respect to the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2** since the stress concentration in the region where the cap **8** and the substrate **12** come in contact with the sensor body **2** is higher compared to the multi-axial force sensor **1**.

[0064] FIG. **6** shows a multi-axial force sensor **30** according to a further embodiment of the present disclosure. Differently from the multi-axial force sensor **1** illustrated in FIGS. **1**A, **1**B, **2**, the substrate **12** is not present. Furthermore, trenches **34**, functionally corresponding to the trenches **4** of the multi-axial force sensor **1**, extend in the sensor body **2** at a depth lower or less than the thickness of the sensor body **2**. In other words, the trenches **34** end within the sensor body **2**, at a distance from the rear surface **2***b*. Exemplary values of the depth of the trenches **34** range from 5 to 100 μm. The trenches **34** of the multi-axial force sensor **30** include first trenches **34***a* having main direction of extension parallel to the x axis and second trenches **34***b* having main direction of extension parallel to the y axis, analogously respectively to the first trenches **4***a* and the second trenches **4***b* of the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2**. All other elements are in common to the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2** and designated by the same reference numbers, thus they are not described any further.

[0065] The multi-axial force sensor **30** has a lower thickness and lower manufacturing cost than the multi-axial force sensors **1** and **20**.

[0066] According to a further embodiment, not shown in the figures, the recess **10** of the cap **8** of the multi-axial force sensor **30** may not be present, analogously to what described above with reference to FIG. **5**.

[0067] FIG. **7** shows a top view of a multi-axial force sensor **40** according to a further embodiment of the present disclosure. The multi-axial force sensor **40** includes two first sensing units **47***a* and two second sensing units **47***b*. Each first sensing unit **47***a* includes two first trenches **4***a* and one first piezoresistive group **6***a*. Each second sensing unit **47***b* includes two second trenches **4***b* and one first piezoresistive group **6***a*.

[0068] Each first trench **4***a* has a main direction of extension parallel to the x axis. In each first sensing unit **47***a*, a first piezoresistive group **6***a* extends between respective first trenches **4***a*, along a direction parallel to the main direction of extension of the first trenches **4***a* and at a distance from the first trenches **4***a*. Therefore, for each first sensing unit **47***a*, the first piezoresistive group **6***a* extends along a main direction **dx1**, **dx2**, parallel to the x axis and two first trenches **4***a* extend along respective main directions which are parallel to, and distinct from, the main direction **dx1** (**dx2**). The piezoresistive group **6***a* and the trenches **4***a* of a same first sensing unit **47***a* are aligned to one another along the y axis. More in particular, both first sensing units **47***a* are aligned to one another along the y axis and are symmetric with respect to a line parallel to the x axis and passing by the centroid of the active region **7** (FIG. **1**B).

[0069] In each second sensing unit **47***b*, a second piezoresistive group **6***b* extends between respective second trenches

4*b*, along a direction parallel to the main extension of the second trenches **4***b*, and at a distance from the second trenches **4***b*. Therefore, for each second sensing unit **47***b*, the second piezoresistive group **6***b* extends along a main direction dy**1**, dy**2**, parallel to the y axis and two second trenches **4***b* extend along respective directions which are parallel to, and distinct from, the main direction dy**1** (dy**2**). The piezoresistive group **6***b* and the trenches **4***b* of a same second sensing unit **47***b* are aligned to one another along the x axis. More in particular, both second sensing units **47***b* are aligned to one another along the x axis and are symmetric with respect to a line parallel to the y axis and passing by the centroid of the active region **7** (FIG. **1**B).

[0070] The first sensing units **47***a* do not overlap with the second sensing units **47***b*.

[0071] All other elements are in common to the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2** and designated by the same reference numbers, thus they are not described any further. The variations described with reference to FIGS. **5** and **6** applies to the embodiment of FIG. **7** as well.

[0072] In use, a shear force component Fy parallel to the y axis will induce a tensile planar stress σ_x parallel to the x axis on the first piezoresistive groups **6***a*, while a shear force component Fx parallel to the x axis will induce a tensile planar stress σ_y, parallel to the y axis on the second piezoresistive groups **6***b*.

[0073] FIG. **8** shows a top view of a multi-axial force sensor **50** according to a further embodiment of the present disclosure. The multi-axial force sensor **50** includes two first sensing units **47***a* and two second sensing units **47***b*, which have elements in common to the multi-axial force sensor **40** of FIG. **7**.

[0074] In this embodiment, the main directions dx**1**, dx**2** of extension of the first piezoresistive groups **6***a* are coincident with one another and with the x axis. Analogously, also the main directions dy**1**, dy**2** of extension of the second piezoresistive groups **6***b* are coincident with one another and with the y axis.

[0075] The main directions dx, dy of extension of the sensing units **47***a*-**47***b* are chosen in a way such that the sensing units **47***a*-**47***b* are arranged in the shape of a cross; moreover, the main directions dx, dy of extension of the sensing units **47***a*-**47***b* are chosen in order to seamlessly connect a first trench **4***a* of a first sensing unit **47***a* to a respective second trench **4***b* of a second sensing unit **47***b*, and the other first trench **4***a* of the first sensing unit **47***a* to a respective second trench **4***b* of the other second sensing unit **47***b*.

[0076] All other elements are in common to the multi-axial force sensor **1** of FIGS. **1**A, **1**B, **2** and designated by the same reference numbers, thus they are not described any further. The variations described with reference to FIGS. **5** and **6** applies to the embodiment of FIG. **7** as well.

[0077] The advantages of embodiments of the disclosure described previously, according to the various embodiments, emerge clearly from the foregoing description.

[0078] In particular, the spatial configuration of the trenches **4** and the piezoresistive units **19***a*-**19***d* allow obtaining a multi-axial force sensor based on silicon technology, able to measure both normal forces and out-of-plane shear forces. Moreover, the spatial configuration of the trenches **4** and the piezoresistive units **19***a*-**19***d* allows accurate measurements in the case of non-homogenous or partially concentrated loads.

[0079] Finally, it is clear that modifications and variations may be made to what has been described and illustrated herein, without thereby departing from the scope of the present disclosure.

[0080] For instance, the cap **8**, the sensor body **2** and the substrate **12** may be of any suitable size and shape.

[0081] Moreover, the piezoresistive groups **6***a*, **6***b* may include only one or two piezoresistive elements.

[0082] Furthermore, the trenches may have different shapes than the rectangular, or substantially rectangular, shape described above. For instance, the trenches may have a rounded shape, a generic polygonal shape, etc.

[0083] Furthermore, the main directions of extension of the first and second trenches may also be non-orthogonal to one another, i.e., the main directions of extension of the first and second trenches intersect to one another forming an angle different from 90 degrees.

[0084] Moreover, the size of the cap and of the active region can be enlarged in order to increase the full scale of the multi-axial force sensor, according to the needs of the application.

[0085] FIG. **9** is a simplified perspective view of a multi-axial sensor **900** showing the multi-layered structure of sensors according to embodiments of the present disclosure. The multi-axial sensor **900** includes a cap layer **902** that corresponds to the cap **8** in the multi-axial force sensor **1** of FIGS. **1**A, **1**B and **2** in one embodiment of the multi-axial sensor. A sensor body layer **904** corresponds to the sensor body **2** and a substrate layer **906** corresponds to the substrate **12** in the multi-axial force sensor **1** of FIGS. **1**A, **1**B and **2** in an embodiment of the multi-axial sensor **900**. A finger F is illustrated moving in a finger motion direction indicated by arrow **908** and applying a force to the cap layer **902**. A normal component $\vec{fe}$ and a tangential component $\overline{fr}$ associated with the force applied to the cap layer **902** by the finger F are illustrated in FIG. **9**. As discussed above in relation to multi-axial force **40** in relation to FIG. **4**, multi-axial sensors according to embodiments of the present disclosure sense forces normal to surface of the sensor (XY plane in FIG. **9**) and normal to this plane (along the Z-axis in FIG. **9**.

[0086] FIG. **10** is a more detailed perspective exploded view showing the multiple layers of the multi-layered multi-axial sensor **900** of FIG. **9** according to an embodiment of the present disclosure. The cap layer **902** includes a recess **902***a*, which corresponds to the recess **10** in the cap **8** in the embodiment of FIGS. **1**A, **1**B and **2**. The sensor body layer **904** includes trenches **904***a* and **904***b* corresponding to the trenches **4***a* and **4***b*, respectively, formed in the sensor body **2** in the embodiment of FIGS. **1**A, **1**B and **2**. The substrate layer **906** includes a trench **906***a*, which corresponds to the trench **14** in the substrate **12** in the embodiment of FIGS. **1**A, **1**B and **2**. The sensor **900** includes electrical contacts or pads **904***c* formed on a surface of the sensor body layer **904** which correspond to the electrical pads **17** in the embodiment of FIGS. **1**A, **1**B and **2**.

[0087] FIG. **11** is a top view of the multi-axial sensor **900** of FIG. **10** looking through the cap layer **902** and showing piezo-resistive groups **1100***a*-**1100***d* formed in the sensor body layer **904**. The piezo-resistive groups **1100***a*-*d* correspond to the piezo-resistive groups **6***a*, **6***b* of the first and second sensing units **7***a*, **7***b* in the embodiment of FIG. **2**. As better illustrated in FIG. **11**, the cap layer **902** is smaller than the sensor body layer **904** and substrate layer **906** such that the electrical pads **904***c* on the surface of the body layer are exposed to allow for electrical connection to the sensor **900**. This is better illustrated in FIG. **12**, which will now be discussed in more detail.

[0088] FIG. **12** is a perspective view of the multi-axial sensor **900** of FIGS. **10** and **11** showing the cap layer **902**, sensor body layer **904** and substrate layer **906** properly aligned and positioned on top of one another to form the assembled multi-axial sensor **900**. FIG. **12** illustrates the cap layer **902** the sensor body layer **904** and substrate layer **906** being larger than the cap layer **902** so that the electrical pads **904***c* on the surface of the body layer are exposed to provide the electrical pads **904***c* for electrical connection to the sensor **900**. The FIGS. **9-12** are simplified illustrations of the multi-axial sensor **900** and are provided to illustrate the assembly or construction of the sensor through the multiple layers **902-906** including the components of the sensor. Many of the details of the components of the sensor **900** formed in these layers **902-906** that are described in detail with reference to the embodiments of FIGS. **1**A, **1**B, **2** and **5-8** are not illustrated in FIGS. **9-12** to simplify these figures. The operation of these components is the same as that previously provided with reference to the embodiments of FIGS. **1**A, **1**B, **2** and **5-8** and is accordingly not again provided with reference to FIGS. **9-12**.

[0089] Multi-axial sensors according to embodiments of the present disclosure include no membrane or deflecting part as a main feature of the functionality of the sensor. Instead, multi-axial sensors according to embodiments of the present disclosure include three solid bodies (e.g., the cap layer **902**, sensor body layer **904** and substrate layer **906** of FIGS. **9-12**) joined together by means of rigid connections. For example, as discussed above in relation to the operation of the embodiments of FIGS. **1**A, **1**B and **2**, due to the fact that the cap **8** is anchored to the sensor body **2** through the first coupling region **16**, the relative expansion of the cap **8** on the sensor body **2** caused by a multi-axial applied force F (see arrow **40** in FIG. **4**) induces a planar stress distribution at the surface **2***a* of the sensor body **2**, and therefore on the piezoresistive units **19***a*-**19***d*. The piezoresistive units **19***a-d* are implemented on the surface **2***a* of the middle sensor layer (sensor body **2**), and excavations (recesses **14** and **10**) on the bottom (substrate **12**) and top (cap **8**) layers are covering a sensitive part of the sensor to provide a mechanical filtering to: 1) remove a vertical component of the force F over the piezoresistive units **19***a*-**19***d*); and 2) provide a desirable planar stress distribution in the region where each group of the piezoresistive units **19***a*-**19***d* (see FIG. **2**) are located.

[0090] In operation of multi-axial force sensors according to embodiments of the present disclosure, such as shown in FIGS. **1**A, **1**B, **2** and FIGS. **9-12**, in response to a normal force Fz applied on a surface of the cap **8** or cap layer **902**, an in-plane stress distribution (i.e., a stress distribution in the XY-plane in the embodiments of FIGS. **1**A, **1**B, **2** and FIGS. **9-12**) is induced within the sensitive regions in the XY-plane that will be sensed by all groups of piezoresistive sensing units (units **7***a*, **7***b* in FIG. **2**) depending on the pattern of the applied load provided by the normal force Fz. Instead, if a shear force in the XY-plane is applied to the surface of the cap **8** (FIG. **1**A, **1**B) that is considered as an out of plane force component with respect to the sensor middle layer or sensor body **2** (in FIGS. **1**A, **1**B, **2**), there will be a similar effect as above for at least two groups of piezoresistive units **19***a*-**19***d* (FIG. **2**) depending on the direction of the shear force. In addition, there will be also a local rotation within the middle layer (sensor body **2** of FIGS. **1**A, **1**B, **2**) around the axis perpendicular to the direction of the applied shear force, which allows the two other groups of resistors to be insensitive to the applied load.

[0091] Embodiments of multi-axial force sensors according to the present disclosure are particularly advantageous in relation to wafer level packaging technologies, such as fan-in and fan-out wafer level chip scale packages (WLCSP) and other suitable wafer level packages. In these wafer level packaging technologies, the sensor itself is also forms a part of the package, as will be appreciated by those skilled in the art. These types of wafer level packages can performed at the wafer level, which makes the manufacturing process even faster and less expensive. Such packages are scalable as well as the sensor itself. In addition, one of the protection layers such as cap **8** could be designed to include application specific integrate circuitry (ASIC) for signal conditioning and acquisition of signals generated by the multi-axial force sensor. The connection from the sensor to the ASIC could be done by "through-silicon via" technology in such an embodiment. Through wafer level packaging the multi-axial force sensor does not require any additional or extra complex packaging for protection or application usage of the sensor.

[0092] The various embodiments described above can be combined to provide further embodiments. These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

1. A microelectromechanical transducer, comprising:

a semiconductor body having a first surface and a second surface opposite to one another and parallel to a horizontal plane;

a plurality of trenches extending in the semiconductor body from the first surface towards the second surface including a first pair of trenches having on said horizontal plane a respective main direction of extension along a first axis, and a second pair of trenches having on said horizontal plane a respective main direction of extension along a second axis different from, and forming an angle with, the first axis;

a first piezoresistive sensor and a second piezoresistive sensor extending at the first surface of the semiconductor body and respectively arranged between said first and second pair of trenches, wherein the first piezoresistive sensor, the second piezoresistive sensor and the plurality of trenches form an active region; and

a first structural body mechanically coupled to the first surface of the semiconductor body to form a first sealed cavity which encloses the active region.

2. The microelectromechanical transducer according to claim **1**, wherein said second axis is orthogonal to the first axis.

3. The microelectromechanical transducer according to claim **1**, wherein:

the first pair of trenches includes two trenches which are aligned along respective main directions of extension which are coincident to one another, the first piezoresistive sensor being aligned along the coincident main directions of extension of the first pair of trenches; and

the second pair of trenches includes two trenches which are aligned along respective main directions of extension which are coincident to one another, the second piezoresistive sensor being aligned along the coincident main directions of extension of the second pair of trenches.

4. The microelectromechanical transducer according to claim **1**, wherein each of the first and the second pair of trenches includes two trenches which are aligned along respective main directions of extension which are parallel to, and distinct from, one another.

5. The microelectromechanical transducer according to claim **1**, further comprising:

a third piezoresistive sensor and a fourth piezoresistive sensor;

wherein the plurality of trenches includes a third pair of trenches substantially parallel to one another and to the first pair of trenches, and a fourth pair of trenches substantially parallel to one another and to the second pair of trenches; and

wherein the third piezoresistive sensor and the fourth piezoresistive sensor are respectively arranged between said third and fourth pair of trenches.

6. The microelectromechanical transducer according to claim **5**, wherein:

the third pair of trenches includes two trenches which are aligned along respective main directions of extension which are coincident to one another, the third piezoresistive sensor being aligned along the coincident main directions of extension of the third pair of trenches, and

the fourth pair of trenches includes two trenches which are aligned along respective main directions of extension which are coincident to one another, the fourth piezoresistive sensor being aligned along the coincident main directions of extension of the fourth pair of trenches.

7. The microelectromechanical transducer according to claim **5**, wherein each of the third and the fourth pair of trenches include two trenches which are aligned along respective main directions of extension which are parallel to, and distinct from, one another.

8. The microelectromechanical transducer according to claim **5**, wherein:

the first and the third piezoresistive sensors are symmetric with respect to a first axis of symmetry parallel to the first axis and passing through a centroid of the first sealed cavity, so that positive force components applied along the second axis induce compressive planar stress to the first piezoresistive sensor and tensile planar stress to the third piezoresistive sensor, whereas negative force components applied along the second axis induce tensile planar stress to the first piezoresistive sensor and compressive planar stress to the third piezoresistive sensor;

the second and the fourth piezoresistive sensors are symmetric with respect to a second axis of symmetry parallel to the second axis and passing through the centroid of the first sealed cavity, so that positive force components applied along the first axis induce compressive planar stress to the second piezoresistive sensor and tensile planar stress to the fourth piezoresistive sensor, whereas negative force components applied along the first axis induce tensile planar stress to the second piezoresistive sensor and compressive planar stress to the fourth piezoresistive sensor.

9. The microelectromechanical transducer according to claim **5**, wherein:

the first and the third piezoresistive sensors are symmetric with respect to a first axis of symmetry orthogonal to the first axis and passing through a centroid of the first sealed cavity, so that positive force components applied along the first axis induce tensile planar stress to the first piezoresistive sensor and compressive planar stress to the third piezoresistive sensor, whereas negative force components applied along the first axis induce compressive planar stress to the first piezoresistive sensor and tensile planar stress to the third piezoresistive sensor;

the second and the fourth piezoresistive sensors are symmetric with respect to a second axis of symmetry orthogonal to the second axis and passing through the centroid of the first sealed cavity, so that positive force components applied along the second axis induce tensile planar stress to the second piezoresistive sensor and compressive planar stress to the fourth piezoresistive sensor, whereas negative force components applied along the second axis induce compressive planar stress to the second piezoresistive sensor and tensile planar stress to the fourth piezoresistive sensor.

10. The microelectromechanical transducer according to claim **5**, wherein:

the first and the third piezoresistive sensors are symmetric with respect to a first axis of symmetry parallel to the first axis and passing through a centroid of the first sealed cavity, so that positive force components applied along the second axis induce tensile planar stress to the third piezoresistive sensor and compressive planar stress to the first piezoresistive sensor, whereas negative force components applied along the second axis induce tensile planar stress to the first piezoresistive sensor and compressive planar stress to the third piezoresistive sensor;

the second and the fourth piezoresistive sensors are symmetric with respect to a second axis of symmetry parallel to the second axis and passing through the centroid of the first sealed cavity, so that positive force components applied along the first axis induce tensile planar stress to the fourth piezoresistive sensor and compressive planar stress to the second piezoresistive sensor, whereas negative force components applied along the first axis induce tensile planar stress to the second piezoresistive sensor and compressive planar stress to the fourth piezoresistive sensor.

11. The microelectromechanical transducer according to claim **1**, wherein each of the piezoresistive sensors includes one of a single piezoresistive element, at least two piezoresistive elements, and four piezoresistive elements connected to form a Wheatstone bridge.

12. The microelectromechanical transducer according to claim **1**, further comprising a first coupling region between the semiconductor body and the first structural body, the first coupling region surrounding the active region and delimiting the first sealed cavity.

13. The microelectromechanical transducer according to claim **1**, wherein the first sealed cavity comprises a first recess in the first structural body, the first recess facing the semiconductor body and surrounding the active region.

14. The microelectromechanical transducer according to claim **1**, wherein the trenches are confined within the semiconductor body.

15. The microelectromechanical transducer according to claim **1**, wherein the trenches extend from the first surface to the second surface through the whole thickness of the semiconductor body, the microelectromechanical transducer, further comprising:

a second structural body mechanically coupled to the second surface of the semiconductor body; and

a second sealed cavity between the semiconductor body and the second structural body.

16. A method of manufacturing a microelectromechanical transducer, the method comprising:

forming a plurality of trenches in a semiconductor body including,

forming a first pair of trenches having a respective main direction of extension along a first axis parallel to an horizontal plane, and

forming a second pair of trenches having a respective main direction of extension along a second axis different from, and forming an angle with, the first axis and parallel to the horizontal plane;

forming a first piezoresistive sensor and a second piezoresistive sensor at the first surface of the semiconductor body respectively between said first and second pair of trenches, the second piezoresistive sensor and the plurality of trenches forming an active region of the microelectromechanical transducer; and

mechanically coupling a first structural body to the first surface of the semiconductor body to form a first sealed cavity enclosing the active region.

17. The method according to claim **16**, wherein said second axis is orthogonal to the first axis.

18. The method according to claim **16**, wherein forming each of the first and second pairs of trenches comprises forming for each of the first and the second pair of trenches two trenches are aligned along respective main directions of extension that are parallel to and distinct from each another.

19. The method according to claim **16**, wherein forming the first pair of trenches includes forming two trenches aligned along first and second main directions of extension, the first and second main directions of extension being coincident with one another, and wherein forming the first piezoresistive sensor includes forming the first piezoresistive sensor aligned along the coincident first and second main directions of extension of the first pair of trenches.

20. The method according to claim **18**, wherein forming the second pair of trenches includes forming two trenches are aligned along first and second main directions of extension, the first and second main directions of extension being coincident with one another, and wherein forming the second piezoresistive sensor includes forming the second piezoresistive sensor aligned along the coincident first and second main directions of extension of the second pair of trenches.

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