

DESCRIPTION

SENSOR DEVICE AND PRODUCTION METHOD THEREFOR

TECHNICAL FIELD

The present invention relates to a sensor device such as an acceleration
5 sensor and a gyro sensor, and the production method.

BACKGROUND ART

In recent years, wafer level packaging technique has attracted lots of
attention as an appropriate manufacturing technique for compact sensor
devices such as an acceleration sensor and a gyro sensor.

10 For example, Japanese Patent Early Publication No. 2005-251898 discloses
a manufacturing technique for a wafer level package structure **200**, as shown in
FIGS. 25A and 25B. That is, a sensor wafer **210** and a package wafer **220** are
arranged in a face-to-face relation to each other, as shown in FIG. 25A. The
sensor wafer **210** has a MEMS (Micro Electro Mechanical System) element **211**
15 and a metal wiring (outgoing electrode) **217** electrically connected to a sensing
portion (not shown) of the MEMS element **211**. The package wafer **220** has a
through-hole wiring **224** electrically connected with the metal wiring **217** and a
concave portion **221** providing a space for airtightly sealing the MEMS element
211. Then, by forming a wafer level bonding between the sensor wafer **210** and
20 the package wafer **220**, as shown in FIG. 25B, the wafer level package structure
200 is obtained. Finally, plural sensor devices are separated from the wafer
level package structure **200**.

On a surface facing the package wafer **220** of the sensor wafer **210**, a metal
layer **218** is formed to surround the MEMS element **211** of the sensor body and
25 the metal wiring **217** electrically connected to the MEMS element **211**. On the
other hand, a metal layer **228** surrounding the concave portion **221** is formed
on a surface facing the sensor wafer **210** of the package wafer **220**. In addition,
a wiring layer **219** electrically connected to the metal wiring **217** is formed at an
inner side of the metal layer **218** on the sensor wafer **210**, and a wiring layer
30 **229** electrically connected to the through-hole wiring **224** is formed at an inner

side of the metal layer **228** on the package wafer **220**. In the above-described wafer level package structure **200**, the metal layer **218** of the sensor wafer **210** is bonded to the metal layer **228** of the package wafer **220** through a soldering portion **238** such as AuSn, and the wiring layer **219** of the sensor wafer **210** is
5 bonded to the wiring layer **229** of the package wafer **220** through a soldering portion **239**.

As the MEMS element **211**, acceleration sensors and gyro sensors are well known. As the acceleration sensors, there are piezoresistive element type and capacitance-type acceleration sensors. The piezoresistance-type acceleration
10 sensor is capable of detecting acceleration according to a change in resistance value resulting from a strain of a piezoresistive element as a gauge resistance caused when the acceleration is applied. The capacitance type acceleration sensor is capable of detecting acceleration according to a change in electric capacitance between stationary and movable electrodes when the acceleration is
15 applied. In the piezoresistance-type acceleration sensor, there are cantilever type and double-supported beam type acceleration sensors. The cantilever type acceleration sensor is formed with a rectangular frame portion, a weight portion disposed inside of the frame portion, and a flexible beam portion connected at its one end to the weight portion such that the weight portion is
20 movable relative to the frame portion. On the other hand, the double-supported beam type acceleration sensor is formed with a frame portion, a weight portion disposed inside of the frame portion, and a pair of flexible beam portions extending in opposite directions from the weight portion and configured to support the weight portion to be movable relative to the frame
25 portion. In recent years, acceleration sensors for detecting acceleration with respect to each of three directions orthogonal to each other have been also proposed in, for example, Japanese Patent Early Publication No. 2004-109114 and No. 2004-233072. The acceleration sensors has a frame portion, a weight portion disposed inside of the frame portion, and four flexible beam portions
30 extending in four directions and configured to support the weight portion so as

to be movable relative to the frame portion.

In the above-described wafer level package structure **200**, however, a prescribed amount of solder is supplied to the metal layer **228** and the wiring layer **229** by a solder shooting method to bond between the metal layers (**218**, **228**) and between the wiring layers (**219**, **229**). Then, a reflow soldering process is performed to a layered structure of the sensor wafer **210** and the package wafer **220**. Therefore, when using the piezoresistance-type acceleration sensor body as the MEMS element **211**, there is a problem that variations in sensor characteristics occur because residual stress at the vicinity of the bonding interface has an influence on the flexible beam portion(s). It is estimated that such an influence of the residual stress increases as the sensor device is downsized.

SUMMARY OF THE INVENTION

Therefore, in consideration of the above problems, a primary concern of the present invention is to provide a sensor device with small variations in sensor characteristics, which is formed by bonding a sensor substrate having a compact sensor element such as acceleration sensor and a gyro sensor to a package substrate without almost causing residual stress at the bonding portion.

That is, the sensor device of the present invention comprises:
 a sensor substrate comprising a frame having an opening, a movable portion movably held in the opening, and a detecting portion configured to output an electric signal according to a positional displacement of the movable portion;
 a first package substrate bonded to one of opposite surfaces of the sensor substrate;

a second package substrate bonded to the other surface of the sensor substrate;

wherein the frame has a first surface-activated region formed on a surface facing the first package substrate over an entire circumference thereof so as to surround the movable portion, and a second surface-activated region formed on a surface facing the second package substrate over an entire circumference

thereof so as to surround the movable portion,

the bonding between the sensor substrate and the first package substrate is a solid-phase direct bonding without diffusion between the first surface-activated region and a surface-activated region formed on the first package substrate, and

the bonding between the sensor substrate and the second package substrate is a solid-phase direct bonding without diffusion between the second surface-activated region and a surface-activated region formed on the second package substrate.

According to the present invention, since each of the first and second package substrates is bonded to the sensor substrate by the solid-phase direct bonding without diffusion, it is possible to avoid a problem that variations in sensor characteristics occur due to residual stress at the bonding portion in the case of using a heat treatment such as reflow soldering as the bonding method.

In addition, one surface of the sensor substrate is bonded to the first package substrate over the entire circumference of the frame, and the other surface of the sensor substrate is bonded to the second package substrate over the entire circumference of the frame, it becomes possible to seal an interior of the sensor device from the outside in an airtight manner. For example, when an acceleration sensor is formed on the sensor substrate, an inert-gas atmosphere can be realized at the vicinity of the movable portion in the sensor device. Alternatively, when a gyro sensor is formed on the sensor substrate, a reduced atmosphere of high degree of vacuum can be realized at the vicinity of the movable portion in the sensor device.

To obtain the solid-phase direct bonding with good bonding strength, it is preferred that the first surface-activated region, the second surface-activated region, the surface-activated region of the first package substrate, and the surface-activated region of the second package substrate are any one of a plasma-treated surface, an ion-beam irradiated surface, and an atomic-beam irradiated surface. It is also preferred that at least one of the bonding between

the first surface-activated region and the surface-activated region on the first package substrate and the bonding between the second surface-activated region and the surface-activated region on the second package substrate is any one of the solid-phase direct bonding between Si and Si, the solid-phase direct bonding
5 between Si and SiO₂, and the solid-phase direct bonding between SiO₂ and SiO₂. Alternatively, at least one of the bonding between the first surface-activated region and the surface-activated region on the first package substrate and the bonding between the second surface-activated region and the surface-activated region on the second package substrate is preferably any one of the solid-phase
10 direct bonding between Au and Au, the solid-phase direct bonding between Cu and Cu, and the solid-phase direct bonding between Al and Al.

To achieve an improvement in airtightness of the sensor device, and increase the bonding reliability, it is preferred that at least one of the first surface-activated region and the second surface-activated region comprises a
15 ring-like outer surface-activated region formed over the entire circumference of the frame so as to surround the movable portion, and a ring-like inner surface-activated region formed at an inner side of the outer surface-activated region over the entire circumference of the frame so as to surround the movable portion. In this case, to further improve the reliability of airtightness, it is
20 particularly preferred that an auxiliary sealing portion for connecting between the outer surface-activated region and the inner surface-activated region is formed at plural locations spaced from each other by a predetermined distance in the circumferential direction of the frame.

From the viewpoint of improving the production yield, and obtaining good
25 bonding strength, it is particularly preferred that each of the first surface-activated region of the sensor substrate and the surface-activated region of the first package substrate is an activated surface of an Au film having a thickness of 500 nm or less.

In addition, when the sensor substrate has an integrated circuit operable in
30 collaboration with the detecting portion, and the integrated circuit is electrically

connected to a through-hole wiring formed in the first package substrate, the integrated circuit is preferably disposed adjacent to the opening of the frame, and more preferably disposed so as to surround the opening of the frame. Since a sensing portion disposed in the opening of the frame is located away
5 from the bonding portion between the first package substrate and the sensor substrate through the integrated circuit, it is possible to further reduce an influence of the bonding portion on the sensing portion, and therefore more effectively prevent the variations in sensor characteristics.

As a preferred embodiment of the present invention, when an acceleration
10 sensor is formed on the sensor substrate, it is preferred that the movable portion comprises a weight and a beam portion extending between the frame and the weight, and the detecting portion comprises at least one piezoresistive element formed on the beam portion. In addition, when a gyro sensor is formed on the sensor substrate, it is preferred that the movable portion comprises a
15 first mass body vibrated by a vibrating means, and a second mass body coupled to the first mass body, and the detecting portion is configured to convert a positional displacement of the second mass body caused when a rotational force is added during the vibration of the first mass body into an electrical signal.

In addition, it is preferred that the sensor substrate is formed by use of an
20 SOI substrate having a silicon layer on a silicon substrate through an insulating layer. In particular, when the sensor substrate has an integrated circuit operable in collaboration with the detecting portion, a further reduction in thickness of the sensor device can be achieved by forming the piezoresistive element and the integrated circuit on the silicon layer of the SOI substrate.

In addition, when the sensor substrate has a conductive layer formed at a
25 position closer to the movable portion than the first surface-activated region, and electrically connected to the detecting portion, the first package substrate has a through-hole wiring, and a wiring layer electrically connected to the through-hole wiring, the bonding between the first package substrate and the
30 sensor substrate further comprises a solid-phase direct bonding without

diffusion between an activated surface of the conductive layer and an activated surface of the wiring layer. In this case, it is possible to simultaneously obtain airtight sealing of the interior of the sensor device and an electrical connection between the first package substrate and the sensor substrate. If necessary, the same solid-phase direct bonding capable of simultaneously forming the airtight sealing and the electrical connection can be used to bond the second package substrate to the sensor substrate.

A further concern of the present invention is to provide a production method for the sensor device capable of avoiding the problem resulting from residual stress at the bonding portion such as variations in sensor characteristics. That is, the production method of the present invention comprises the steps of:

providing a sensor substrate, which comprises a frame having an opening, a movable portion movably held in the opening, and a detection portion configured to output an electric signal according to a positional displacement of the movable portion, a first package substrate bonded to one of opposite surfaces of the sensor substrate, and a second package substrate bonded to the other surface of the sensor substrate;

forming a first surface-activated region on a surface of the frame facing the first package substrate over an entire circumference of the frame so as to surround the movable portion;

forming a second surface-activated region on a surface of the frame facing the second package substrate over an entire circumference of the frame so as to surround the movable portion;

forming a surface-activated region on each of the first package substrate and the second package substrate; and

forming a direct bonding between the first surface-activated region and the surface-activated region of the first package substrate, and a direct bonding between the second surface-activated region and the surface-activated region of the second package substrate at room temperature.

According to the production method of the present invention, since the

solid-phase direct bonding between the sensor substrate and each of the first and second package substrates is formed at room temperatures, it is possible to reliably prevent variations in sensor characteristics resulting from the residual stress at the bonding portion.

5 To obtain the solid-phase direct bonding with good bonding strength, it is preferred that the first surface-activated region, the second surface-activated region, the surface-activated regions of the first package substrate and the second package substrate are formed by use of any one of an atomic beam, an ion beam and a plasma of an inert gas.

10 In addition, it is preferred that the steps of forming the first surface-activated region and the second surface-activated region, the step of forming the surface-activated regions of the first package substrate and the second package substrate, and the direct bonding step are performed in a same chamber, and an interior of the chamber is controlled into a desired atmosphere
15 prior to the direct bonding step. In this case, a desired atmosphere can be set in the sensor device according to the kind of sensor. For example, when an acceleration sensor is formed on the sensor substrate, the atmosphere adjustment is performed prior to the direct bonding step by introducing an inert gas into the chamber, so that the inert-gas atmosphere can be obtained in
20 sensor device after the direct bonding step. Alternatively, when a gyro sensor is formed on the sensor substrate, the atmosphere adjustment is performed prior to the direct bonding step to obtain a reduced atmosphere of a higher degree of vacuum, which is different from the atmosphere used for the steps of forming the surface-activated regions. As a result, the interior of the sensor device can
25 be maintained in the reduced atmosphere after the direct bonding step.

When the sensor substrate has an integrated circuit operable in collaboration with the detecting portion, an outgoing wiring layer connected at its one end to a pad of the integrated circuit, a first metal layer for providing the first surface-activated region, and a second metal layer connected to the other
30 end of the outgoing wiring layer, and used to connect with a through-hole wiring,

and the first package substrate has the through-hole wiring, a bonding metal layer formed at a position facing the first metal layer by a same material as the first metal layer, and a wiring metal layer formed at an end portion facing the sensor substrate of the through-hole wiring by a same material as the second metal layer, it is preferred that a direct bonding between activated surfaces of the first metal layer and the bonding metal layer and a direct bonding between activated surfaces of the second metal layer and the wiring metal layer are simultaneously formed at room temperature. Furthermore, it is preferred that the outgoing wiring layer, the first metal layer and the second metal layer are formed by a process comprising the steps of forming a lower metal layer as an etching stopper layer, forming an upper metal layer on the lower metal layer by use of a metal material different from the lower metal layer, and etching only the upper metal layer at regions corresponding to the first metal layer and the second metal layer until the lower metal layer is exposed. In this case, since the first and second metal layers having excellent surface flatness are formed to be flush with each other, a good bonding state can be stably obtained with an improvement in production efficiency of the sensor device.

To obtain good bonding strength by the room-temperature bonding, it is needed that the first surface-activated region and the surface-activated region of the first package substrate just contact each other. To meet this need, it is preferred that the first surface-activated region is formed by a process comprising the steps of forming a multilayer insulating film on the frame of the sensor substrate, forming a flat surface of the multilayer insulating film by etching back a part of the multilayer insulating film, forming a metal layer on the flat surface, and irradiating an atomic beam, an ion beam or a plasma of an inert gas to a surface of the metal layer. The multilayer insulating film is preferably composed of a first insulating film of a silicon oxide film formed on the frame, a second insulating film of a silicon nitride film formed on the first insulating film, a third insulating film of at least one interlayer insulating film formed on the second insulating film, and a fourth insulating film of a

passivation film formed on the third insulating film. In this case, the flat surface is preferably formed by performing etching back by using the insulating film other than the fourth insulating layer as an etching stopper layer. Excellent surface flatness of the undercoat insulating film formed by the etching back is reflected to the metal layer formed on the undercoat insulating film. Therefore, it is possible to obtain the metal layer suitable for the room-temperature direct bonding. As a further preferred embodiment for the formation of the flat surface, the etching back is performed by using the silicon nitride film of the second insulating film as the etching stopper layer. Alternatively, the flat surface may be formed by a process comprising a first etching back step using the silicon nitride film of the second insulating film as the etching stopper layer, and a second etching back step performed after the first etching back step by use of the silicon oxide film of the first insulating film as the etching stopper layer.

In addition when the sensor substrate has an integrated circuit operable in collaboration with the detecting portion, and a conductive layer formed at a position closer to the movable portion than the first surface-activated region, and electrically connected to the integrated circuit, and the first package substrate has a through-hole wiring, and a wiring layer electrically connected to the through-hole wiring, it is preferred that a direct bonding between the first surface-activated region and the surface-activated region of the first package substrate and a direct bonding between activated surfaces of the conductive layer and the wiring layer are simultaneously formed at room temperature. In this case, it is possible to simultaneously form the mechanical bonding between the first package substrate and the sensor substrate, and the electrical connection between the conductive layer and the wiring layer.

BRIEF EXPLANATION OF THE DRAWINGS

FIGS. 1A and 1B are respectively schematic plan and side views of a wafer level package structure according to a first embodiment;

FIGS. 2A and 2B are respectively schematic plan and side views of a sensor

device obtained from the wafer level package structure;

FIG. 3A is a top view of a sensor substrate, and FIG. 3B is a cross-sectional view taken along the line B-A' in FIG. 3A;

FIG. 4 is a bottom view of the sensor substrate;

5 FIG. 5 is a circuit diagram of the sensor substrate;

FIG. 6A is a top view of a first package substrate, and FIG. 6B is a cross-sectional view taken along the line A-A' in FIG. 6A;

FIG. 7 is a bottom view of the first package substrate;

FIGS. 8A and 8B are respectively top and cross-sectional views of a second
10 package substrate;

FIG. 9 is a schematic enlarged cross-sectional view of a bonding portion between the sensor substrate and the first package substrate;

FIG. 10A is a top view of the sensor substrate according to a modification of the present embodiment, and FIG. 10B is a cross-sectional view taken along the line
15 B-A' in FIG. 10A;

FIG. 11A is a top view of the first package substrate according to a modification of the present embodiment, and FIG. 11B is a cross-sectional view taken along the line A-A' in FIG. 11A;

FIG. 12 is a schematic enlarged cross-sectional view of a bonding portion
20 between the sensor substrate of FIG. 10A and the first package substrate of FIG. 11A;

FIG. 13A is a cross-sectional view showing a surface activation step, FIG. 13B is a cross-sectional view showing an atmosphere adjustment step, and FIG. 13C is a cross-sectional view showing a room-temperature bonding step;

25 FIGS. 14A and 14B are respectively schematic plan and side views of a wafer level package structure according to a second embodiment, and FIG. 14C is a schematic cross-sectional view of a sensor device in the wafer level package structure;

FIG. 15A is a top view of a sensor substrate, and FIG. 15B is a cross-sectional
30 view taken along the line A-A' in FIG. 15A;

FIGS. 16A to 16C are cross-sectional views showing embodiments of outgoing wirings each electrically connecting between a pad and a second metal layer;

FIGS. 17A to 17F are schematic cross-sectional views of a method of producing a sensor device according to a second embodiment;

5 FIG. 18A is a top view of a first package substrate, and FIG. 18B is a cross-sectional view taken along the line A-A' in FIG. 18A;

FIGS. 19A and 19B are respectively top and cross-sectional views of a second package substrate;

10 FIG. 20 is a schematic cross-sectional view of a gyro sensor device according to a third embodiment;

FIG. 21 is a schematic plan view of a sensor substrate according to the third embodiment;

FIG. 22 is an enlarged view of a relevant portion of the sensor substrate;

15 FIG. 23 is a schematic plan view of a first package substrate according to the third embodiment;

FIG. 24 is a schematic bottom view of the first package substrate; and

FIGS. 25A and 25B are explanatory views of a method of producing a conventional sensor device.

BEST MODE FOR CARRYING OUT THE INVENTION

20 Referring to the attached drawings, the sensor device of the present invention and the production method are explained below in details.

(First Embodiment)

In the present embodiment, as shown in FIGS. 1A, 1B and FIGS. 2A and 2B, it is explained about a case where a sensor device is produced by fabricating a wafer level package structure **100** comprising a semiconductor wafer **10**, in
 25 which a plurality of acceleration sensor units are integrally formed, a first package wafer **20** bonded to one of opposite surfaces of the semiconductor wafer **10**, and a second package wafer **30** bonded to the other surface of the semiconductor wafer **10**, and then dicing the wafer level package structure **100**
 30 into a size of the sensor device. Therefore, in the sensor device of the present

embodiment, a portion corresponding to the semiconductor wafer **10** is defined as a sensor substrate **1**. A portion corresponding to the first package wafer **20** is defined as a first package substrate **2**. A portion corresponding to the second package wafer **30** is defined as a second package substrate **3**.

5 The present embodiment of producing sensor devices from the wafer level package structure **100** has an advantage that a plurality of compact sensor devices can be obtained in a lump sum. However, the sensor device of the present invention is not limited to this production method. For example, each of the sensor devices may be individually produced by preparing a sensor
10 substrate having a single sensor element and a pair of first and second package substrates, and direct bonding the sensor substrate to each of the first and second package substrates at room (normal) temperature, as described later.

In the present embodiment, an SOI wafer used as the semiconductor wafer **10** is composed of a support substrate **10a** made of a silicon substrate, an
15 insulating layer (embedded oxide film) **10b** such as a silicon oxide film formed on the support substrate **10a**, and an n-type silicon layer (active layer) **10c** formed on the insulating layer **10b**. Each of the acceleration sensor units is formed by processing this SOI wafer. Each of the first package wafer **20** and the second package wafer **30** is formed by processing a silicon wafer. In the
20 present embodiment, a thickness of the support substrate **10a** of the SOI substrate is in a range of 300 μm to 500 μm , a thickness of the insulating layer **10b** is in a range of 0.3 μm to 1.5 μm , and a thickness of the silicon layer **10c** is in a range of 4 μm to 10 μm . In addition, a surface of the silicon layer **10c** that is a general surface of the SOI wafer corresponds to a (100) surface. A
25 thickness of the silicon wafer for the first package wafer **20** is in a range of 200 μm to 300 μm , and a thickness of the silicon wafer for the second package wafer **30** is in a range of 100 μm to 300 μm . These thickness values are illustrative only, and therefore the present invention is not limited to them.

FIGS. 3A and 3B are respectively top and cross-sectional views of one
30 acceleration sensor unit (corresponding to an area "A" in FIG. 1A) formed in the

sensor substrate **1**. In addition, FIG. 4 is a bottom view of the acceleration sensor unit. Each of the acceleration sensor units has a frame portion **11** (for example, a rectangular frame portion) having an inner opening, a weight portion **12** disposed inside of the frame portion **11**, and four flexible portions **13** each formed in a strip-like shape and having flexibility. The weight portion **12** is supported at the top-surface side (FIG. 3A) of the sensor unit by the flexible portions **13** to be movable relative to the frame portion **11** in a swinging manner. In other words, the weight portion **12** is movably supported in the inner opening of the frame portion **11** in a swinging manner by the four flexible portions **13** extending from four sides of the weight portions toward the frame portion **11**. The frame portion **11** is formed by use of the support substrate **10a**, the insulating layer **10b** and the silicon layer **10c** of the above-described SOI substrate. On the other hand, as shown in FIG. 3B, the flexible portions **13** are formed by use of the silicon layer **10c** of the SOI substrate. Therefore, the flexible portion **13** has a sufficiently smaller thickness than the frame portion **11**.

The weight portion **12** has a core section **12a** having a rectangular solid shape, which is supported to the frame portion **11** through the four flexible portions **13**, and four leaf sections **12b**, each having a rectangular solid shape, which are integrally coupled to four corners of the core section **12a** at the top-surface side of the sensor substrate **1**. That is, when viewing from the above of the sensor substrate **1**, each of the leaf sections **12b** is disposed in a space surrounded by the frame portion **11**, the core section **12a**, and two flexible portions **13** extending in directions orthogonal to each other. The numeral **14** designates a slit formed between each of the leaf sections **12b** and the frame portion **13**. A distance between adjacent leaf portions **12b** through the flexible portion **13** is larger than the width dimension of the flexible portion **13**. The core section **12a** is formed by the support substrate **10a**, the insulating layer **10b** and the silicon layer **10c** of the above-described SOI wafer. On the other hand, each of the leaf sections **12b** is formed by the support

substrate **10a** of the SOI wafer. At the top-surface side of the sensor substrate **1**, the top surface of each of the leaf sections **12b** is provided at a lower position than the top surface of the core section **12a**, i.e., at a side closer to the bottom of the sensor substrate **1** (FIG. 4). The frame portion **11**, the weight portion **12** and the flexible portions **13** of the sensor substrate **1** are preferably formed by using conventional lithography and etching technologies.

By the way, as shown at a lower right portion of each of FIGS. 3A, 3B and 4, when a horizontal direction of the frame portion **11** corresponds to an “**x**” axis, a horizontal direction orthogonal to the “**x**” axis corresponds to a “**y**” axis, and a thickness direction of the sensor substrate **1** corresponds to a “**z**” axis, the weight portion **12** is supported to the frame portion **11** by a pair of the flexible portions **13** extending in the “**x**” axis direction at both sides of the core section **12a**, and another pair of the flexible portions **13** extending in the “**y**” axis direction at both sides of the core section **12a**. The rectangular coordinate system defining the above-described “**x**”, “**y**” and “**z**” axes has an origin, which corresponds to a center position of the top surface of the weight portion **12** formed by the silicon layer **10c** of the sensor substrate **1**.

On the flexible portion **13** extending from the core section **12a** of the weight portion **12** in a positive direction of the “**x**” axis, i.e., the flexible portion **13** positioned at the right side of FIG. 3A, a pair of piezoresistive elements (**Rx2**, **Rx4**) are formed near the core section **12a**, and a piezoresistive element **Rz2** is formed near the frame portion **11**. On the other hand, on the flexible portion **13** extending from the core section **12a** of the weight portion **12** in a negative direction of the “**x**” axis, i.e., the flexible portion **13** positioned at the left side of FIG. 3A, a pair of piezoresistive elements (**Rx1**, **Rx3**) are formed near the core section **12a**, and a piezoresistive element **Rz3** is formed near the frame portion **11**. In this regard, the four piezoresistive elements (**Rx1**, **Rx2**, **Rx3**, **Rx4**) formed near the core section **12a** are used to detect acceleration in the “**x**” axis direction. Each of the piezoresistive elements (**Rx1**, **Rx2**, **Rx3**, **Rx4**) is formed in an elongate rectangular shape as a planar shape, and disposed such that the

elongate direction of the piezoresistive element is substantially the same as the longitudinal direction of the flexible portion **13**. In addition, these piezoresistive elements are connected by wirings (diffusion layer wirings and metal wirings **17** formed on the sensor substrate **1**) to obtain a bridge circuit **Bx** shown at a left side of FIG. 5. The piezoresistive elements (**Rx1**, **Rx2**, **Rx3**, **Rx4**) are formed at stress concentration regions of the flexible portions **13** where stress concentration occurs when the acceleration is applied in the “x” axis direction.

On the flexible portion **13** extending from the core section **12a** of the weight portion **12** in a positive direction of the “y” axis, i.e., the flexible portion **13** positioned at the upper side of FIG. 3A, a pair of piezoresistive elements (**Ry1**, **Ry3**) are formed near the core section **12a**, and a piezoresistive element **Rz1** is formed near the frame portion **11**. On the other hand, on the flexible portion **13** extending from the core section **12a** of the weight portion **12** in a negative direction of the “y” axis, i.e., the flexible portion **13** positioned at the lower side of FIG. 3A, a pair of piezoresistive elements (**Ry2**, **Ry4**) are formed near the core section **12a**, and a piezoresistive element **Rz4** is formed near the frame portion **11**. In this regard, the four piezoresistive elements (**Ry1**, **Ry2**, **Ry3**, **Ry4**) formed near the core section **12a** are used to detect acceleration in the “y” axis direction. Each of the piezoresistive elements (**Ry1**, **Ry2**, **Ry3**, **Ry4**) is formed in an elongate rectangular shape as a planar shape, and disposed such that the elongate direction of the piezoresistive element is substantially the same as the longitudinal direction of the flexible portion **13**. In addition, these piezoresistive elements are connected by wirings (diffusion layer wirings and metal wirings **17** formed on the sensor substrate **1**) to obtain a bridge circuit **By** shown at a center of FIG. 5. The piezoresistive elements (**Ry1**, **Ry2**, **Ry3**, **Ry4**) are formed at stress concentration regions of the flexible portions **13** where stress concentration occurs when the acceleration is applied in the “y” axis direction.

In addition, the piezoresistive elements (**Rz1**, **Rz2**, **Rz3**, **Rz4**) formed near

the frame portion **11** are used to detect acceleration in the “**z**” axis direction, and connected by wirings (diffusion layer wirings and metal wirings **17** formed on the sensor substrate **1**) to obtain a bridge circuit **Bz** shown at a right side of FIG. 5. The piezoresistive elements (**Rz1**, **Rz4**) are disposed on the pair of the flexible portions **13** such that that the elongate direction of the piezoresistive element is substantially the same as the longitudinal direction of the flexible portion **13**, and the piezoresistive elements (**Rz2**, **Rz3**) are disposed on another pair of the flexible portions **13** such that that the elongate direction of the piezoresistive element is substantially the same as the width (lateral) direction of the flexible portion **13**.

FIG. 3A shows only a part of the metal wirings **17** on the sensor substrate **1** in the vicinity of a second metal layer **19** described later. In addition, the diffusion layer wirings are not shown in FIG. 3A.

The piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**) and the diffusion layer wirings are formed by doping a p-type impurity into predetermined formation sites of the silicon layer **10c** at an appropriate concentration. On the other hand, the metal wirings **17** can be obtained by forming a metal film (e.g., Al film, Al alloy film or the like) on the insulating film **16** by means of sputtering or vapor deposition, and then patterning the metal film by using conventional lithography and etching technologies. The metal wirings **17** can be electrically connected to the diffusion layer wirings through contact holes formed in the insulating film **16**.

As shown in FIGS. 6A, 6B and 7, the first package substrate **2** is formed at a surface facing the sensor substrate **1** with a concave portion **21** for providing a space for positional displacement of the movable portion comprised of the weight portion **12** and the flexible portions **13** of the sensor substrate **1**, and a plurality of through holes **22** (e.g., eight through holes) formed in the thickness direction around the concave portion **21**. The outer peripheral shape of each of the sensor substrate **1** and the first package substrate **2** is a rectangular shape, and the first package substrate **2** is formed to have the same outside dimension

as the sensor substrate **1**.

The first package substrate **2** has an insulating film **23** formed by a heat insulating film (silicon oxide film) on the opposite surfaces in the thickness direction as well as the inner surfaces of the through holes **22**. Therefore, a part of the insulating film **23** lies between a through-hole wiring **24** and the inner surface of each of the through holes **22**. In this embodiment, eight through-hole wirings **24** are formed to be spaced from each other in the circumferential direction of the first package substrate **2**. As a material for the through-hole wirings **24**, for example, copper can be used. Alternatively, nickel may be used.

In addition, it is preferred that the through-hole wiring **24** formed in the first package substrate **2** has a tapered shape such that an area of an end portion facing the sensor substrate **1** is larger than the area of the other end portion. When the through-hole wiring is formed by performing electroplating in the tapered through hole formed in the first package substrate, a plating solution is supplied from the end portion having the larger opening area, so that a wiring formation metal precipitates from the end portion having the small opening area toward the other end portion having the large opening area. Thereby, air bubbles generated in the through hole can be easily exhausted to the outside, as compared with the case where the through hole has a constant opening area. In addition, since the plating solution is easy to put in the through hole, it is possible to prevent a reduction in metal ion concentration in the through hole, and increase the metal precipitation rate. As a result, there is an advantage that the through-hole wiring **24** having a uniform thickness can be efficiently formed. A plurality of electrodes **25** for external connection are formed on a (top) surface of the first package substrate **2** at an opposite side of the surface facing the sensor substrate **1** so as to be electrically connected with the through-hole wirings **24**. The electrode **25** of the present embodiment has a rectangular outer peripheral shape.

As shown in FIGS. 8A and 8B, the second package substrate **3** is formed at

a surface facing the sensor substrate **1** with a concave portion **31** having a predetermined depth (e.g., 5 μm to 10 μm) for providing a space for positional displacement of the weight portion **12**. The concave portion **31** can be formed by using conventional lithography and etching technologies. Each of the
 5 sensor substrate **1** and the second package substrate **3** has a rectangular outer peripheral shape. The second package substrate **3** is formed to have the same outside dimension as the sensor substrate **1**.

When the thickness of a portion of the support substrate **10a** used to form the core section **12a** and the weights **12b** of the weight portion **12** is determined
 10 to be smaller than the thickness of another portion of the support substrate **10a** used to form the frame portion **11** by a dimension corresponding to an allowable positional displacement amount of the weight portion **12** in the thickness direction of the sensor substrate **1**, a clearance for enabling the positional displacement of the weight portion **12** can be obtained between the weight
 15 portion **12** and the second package substrate **3** without the formation of the concave portion **31** in the second package substrate **3**.

Next, a bonding portion between the sensor substrate **1** and the first package substrate **2** is explained. On the frame portion **11** of each of the acceleration sensor units, a first metal layer **18** is formed at a side facing the
 20 first package substrate **2** over the entire circumference of the frame portion so as to surround the movable portion comprised of the weight portion **12** and the flexible portions **13**. The bonding portion between the sensor substrate **1** and the first package substrate **2** is formed, as shown in FIG. 9, by a solid-phase direct bonding without diffusion between an activated surface of the first metal
 25 layer **18** of each of the acceleration sensor units and an activated surface of a frame-like metal layer **28** formed on a corresponding region of the first package substrate **2**. This solid-phase direct bonding can be obtained by pressing the activated surfaces to each other at room temperature.

In addition, the first package substrate **2** has a plurality of wiring layers **29**,
 30 which are formed at an inner side of the frame-like metal layer **28** and around

the concave portion **21**, and electrically connected to the through-hole wirings **24**. For example, the number of the wiring layers **29** formed in the present embodiment is eight. Each of the wiring layers **29** is connected at an end portion of its longitudinal direction to the through-hole wiring **24**. The wiring layer **29** is positioned at a side closer to the weight portion **12** than the first metal layer **18** of the sensor substrate **1**, and also electrically connected to a second metal layer **19** formed on the frame portion **11**. The connection between the second metal layer **19** and the wiring layer **29** is positioned at an outer side of the metal wiring **17** on the sensor substrate **1**.

On the surface facing the first package substrate **2** of the sensor substrate **1**, an insulating film **16** is formed, which is comprised of a laminate film of a silicon oxide film and a silicon nitride film on the silicon layer **10c**. The first metal layer **18**, the second metal layers **19** and the metal wirings **17** are formed on the insulating film **16**.

The first metal layer **18** and the metal layer **28** are formed by use of the same metal material. For example, Au, Cu or Al is preferably used as the metal material. It is particularly preferred to use Au. The metal material used in the present embodiment is Au. To achieve an improvement in adhesion between the first metal layer **18** of Au and the insulating film **16**, a Ti film is formed as an intermediate layer therebetween. In other words, the first metal film **18** is comprised of a laminate film of the Ti film formed on the insulating film **16** and the Au film formed on the Ti film.

Similarly, the second metal layer **19** and the wiring layer **29** are formed by use of the same metal material. For example, Au, Cu or Al is preferably used as the metal material. It is particularly preferred to use Au. The metal material used in the present embodiment is Au. To achieve an improvement in adhesion between the second metal layer **19** of Au and the insulating film **16**, a Ti film is formed as an intermediate layer therebetween. In other words, the second metal film **19** is comprised of a laminate film of the Ti film formed on the insulating film **16** and the Au film formed on the Ti film.

With respect to each of the first metal layer **18** and the second metal layer **19**, a thickness of the Ti film can be preferably set in a range of 15 to 50 nm. In the present embodiment, a thickness of the Au film is set to 500 nm, and a thickness of the metal wiring **17** is set to 1 μm . These thickness values are illustrative only, and the present invention is not limited to them. In the case of using the Au film, it is preferred that the thickness is not larger than 500 nm from the viewpoint of improving yields in the bonding process. The Au film may be formed by use of a gold material containing an impurity other than pure gold. In the present embodiment, the Ti film is formed as the adhesive layer for improving the adhesion between the Au film and the insulating film **16**. In place of the Ti film, Cr, Nb, Zr, TiN, TaN or the like may be used as the material for the adhesive layer.

As described above, when the first metal layer **18** and the second metal layer **19** are formed by use of the same metal material, it is effective to achieve a reduction in production cost because those metal layers having substantially the same thickness can be formed simultaneously. That is, since the first metal layer **18** and the second metal layer **19** are formed to be flush with each other on the sensor substrate **1**, and the metal layer **28** and the wiring layer **29** are formed to be flush with each other on the first package substrate **2**, it becomes possible to apply a uniform pressure to the bonding interface between the sensor substrate **1** and the first package substrate **2**. Consequently, the solid-phase direct bonding between the first metal layer **18** and the metal layer **28** and the solid-phase direct bonding between the second metal layer **19** and the wiring layer **29** can be obtained with stable quality.

In addition, as shown in FIGS. 10A and 10B, the first metal layer **18** may be composed of a ring-like outer metal layer **18a** formed over the entire circumference of the frame portion **11** so as to surround the weight portion **12**, and a ring-like inner metal layer **18b** formed at an inner side of the outer metal layer **18a** over the entire circumference of the frame portion **11** so as to surround the weight portion **12**. In this case, as shown in FIGS. 11A and 11B,

it is also preferred that the metal layer **28** of the first package substrate **2** is composed of a ring-like outer metal layer **28a** and a ring-like inner metal layer **28b** disposed at an inner side of the outer metal layer **28a**, which are formed in a face-to-face relation with the first metal layer **18**. Alternatively, the metal layer **28** of the first package substrate **2** may be formed by a single metal layer, which has a width dimension determined so as to straddle between the outer metal layer **18a** and the inner metal layer **18b**. Thus, when forming double bonding between the first metal layer **18** and the metal layer **28**, as shown in FIG. 12, it is possible to further improve the effect of airtightly sealing the interior (i.e., the movable portion) of the acceleration sensor unit. In FIG. 12, a connecting portion **19b** with the metal wiring **17** is located in the concave **21** of the first package substrate **2**, and the second metal layer **19** is electrically connected to this connecting portion **19b**.

In FIG. 10A, the numeral **15** designates an auxiliary sealing layer extending between the outer metal layer **18a** and the inner metal layer **18b**. The auxiliary sealing layer **15** is provided at plural locations spaced from each other in the circumferential direction of the frame portion **11** by a predetermined distance. In addition, as shown in FIG. 11A, auxiliary sealing layers **26** are formed on the first package substrate **2** at positions corresponding to the auxiliary sealing layers **15** of the sensor substrate **1**. Therefore, when the first package substrate **2** is bonded to the sensor substrate **1**, the solid-phase direct bonding between activated surfaces of the auxiliary sealing layers (**15**, **26**) is also obtained. Moreover, the following effect is expected by the formation of the auxiliary sealing layers (**15**, **26**). For example, when a foreign substance exists on the outer metal layer **28a**, the airtightness between the outer metal layers (**18a**, **28a**) may deteriorate. Alternatively, when another foreign substance exists on the inner metal layer **28b**, the airtightness between the inner metal layers (**18b**, **28b**) may deteriorate. In these cases, it is expected to be difficult to airtightly seal the interior of the sensor device. However, when forming the bonding between the auxiliary sealing layers (**15**, **26**), a plurality of airtight

spaces can be obtained between the outer metal layer **18a** and the inner metal layer **18b**. That is, when a region where a reduction in airtightness of the bonding between the outer metal layers (**18a**, **28a**) occurs due to the foreign substance is located away from the region where a reduction in airtightness of the bonding between the inner metal layers (**18b**, **28b**) occurs due to another foreign substance, these regions can be spatially shielded from each other by the bonding between the auxiliary sealing layers (**15**, **26**). In brief, the airtightness brought by the bonding between the outer metal layers (**18a**, **28a**) and the bonding between the inner metal layers (**18b**, **28b**) can be further reliably improved by the bonding between the auxiliary sealing layers (**15**, **26**).

In the present embodiment, as described above, the first metal layer **18** is formed on the surface facing the first package substrate **2** over the entire circumference of the frame portion **11** so as to surround the weight portion **12**, and the metal layer **28** is formed at the corresponding region on the first package substrate **2**. Alternatively, it is preferred that a Si layer or a SiO₂ layer is formed in place of the first metal layer **18**, and a Si layer or a SiO₂ layer is formed in place of the metal layer **28**. In brief, the bonding between the sensor substrate **1** and the first package substrate **2** may be formed by any one of a solid-phase direct bonding between Si and Si, a solid-phase direct bonding between Si and SiO₂, and a solid-phase direct bonding between SiO₂ and SiO₂.

To form the solid-phase direct bonding without diffusion between the sensor substrate **1** and the first package substrate **2**, activated surfaces of the first metal layer **18** and the metal layer **28** are previously formed prior to the bonding step. In the present embodiment, these activated surfaces are obtained by irradiating an atomic beam, an ion beam or a plasma of argon in vacuum to clean up and activate the surfaces of the first metal layer **18** and the metal layer **28**. Similarly, the activated surfaces can be formed on the second metal layer **19** and the wiring layer **29**. Subsequently, the room-temperature bonding method described above is performed. That is, the direct bonding between the first metal layer **18** and the metal layer **28** and the direct bonding between the

second metal layer **19** and the wiring layer **29** are simultaneously formed by applying an appropriate load at room temperature.

Next, the bonding portion between the sensor substrate **1** and the second package substrate **3** is explained. The frame portion **11** of each of the acceleration sensor units has a surface activated region formed on the surface facing the second package substrate **3** over the entire circumference of the frame portion **11** by a surface activation treatment. The bonding portion between the sensor substrate **1** and the second package substrate **3** is formed by the solid-phase direct bonding without diffusion between the surface activated region of each of the acceleration sensor units and a surface activated region formed on the corresponding surface of the second package substrate **3** by the surface activation treatment. This solid-phase direct bonding can be obtained by pressing the surface activated regions to each other at room temperature. Therefore, the bonding interface in this case is formed by the solid-phase direct bonding between Si and Si. Alternatively, a SiO₂ layer may be formed on one of the sensor substrate **1** and the second package substrate **3** to obtain the solid-phase direct bonding between Si and SiO₂. In addition, the SiO₂ layer may be formed on both of the sensor substrate **1** and the second package substrate **3** to obtain the solid-phase direct bonding between SiO₂ and SiO₂. Furthermore, it is also preferred to use the solid-phase direct bonding between surface activated regions of a metal material such as the direct bonding between Au and Au described above. Thus, if necessary, the solid-phase direct bonding can be formed between the sensor substrate **1** and the first package substrate **3**, as in the case of forming the solid-phase direct bonding between the sensor substrate **1** and the first package substrate **2**.

To manufacture the wafer level package structure **100**, it is desired that the second package substrate **3** is directly bonded to the sensor substrate **1**, and then the first package substrate **2** is directly bonded to the sensor substrate **1** from the viewpoint of effectively applying the pressure to the bonding interface.

Referring to FIGS. 13A to 13C, the bonding step between the sensor

substrate **1** and each of the first package substrate **2** and the second package substrate **3** is concretely explained below.

First, as shown in FIG. 13A, the sensor substrate **1**, the first package substrate **2** and the second package substrate **3** are placed in a chamber **CH**, and the air in the chamber is exhausted to be not greater than a predetermined degree of vacuum (e.g., 1×10^{-5} Pa). Subsequently, under a reduced atmosphere, surfaces of the sensor substrate **1**, the first package substrate **2** and the second package substrate **3** are cleaned up by means of sputter etching, and then a surface activation treatment is performed. That is, the surface activation treatment is performed to the surfaces of the first and second metal layers (**18**, **19**) of the sensor substrate **1**, the surface of the frame portion **11** to be bonded to the second package substrate **3**, the metal layers (**28**, **29**) of the first package substrate **2**, and the surface of the second package substrate **3** to be bonded to the sensor substrate. As the surface activation treatment, an argon ion beam is irradiated to the surfaces to be treated for a predetermined time period (e.g., 300 seconds). During the surface activation treatment, the internal pressure of the chamber is maintained at a lower degree of vacuum (e.g., approximately 1×10^{-2} Pa) than the above-described degree of vacuum. In place of the argon ion beam, an atomic beam or a plasma of argon may be used. The gas used for the surface activation treatment is not limited to argon. Alternatively, an inert gas such as nitrogen and helium may be used.

After the surface activation treatment, an atmosphere adjusting step is performed to adjust the interior of the chamber to a desired atmosphere for the bonding step between the sensor substrate **1** and each of the first and second package substrates (**2**, **3**), as shown in FIG. 13B. By this step, the interior (i.e., the movable portion) of each of the acceleration sensor units can be maintained in the desired atmosphere after the bonding step. For example, in the present embodiment where the acceleration sensor units are formed, the interior of the chamber is controlled to an inert-gas atmosphere such as argon at atmospheric pressure to improve frequency characteristics and impact resistance by

damping effects. Such atmosphere control can be carried out by opening and closing a gas introduction valve **V1** and a gas exhaust valve **V2** of the chamber. To prevent that contamination of the activated surfaces is caused by contact with the outside air, it is particularly preferred that the atmosphere adjusting
 5 step and the bonding step are continuously performed in the chamber without exposure to the outside.

After the interior of the chamber is controlled to the desired atmosphere, the direct bonding between the activated surfaces (Au-Au surfaces) of the first metal layer **18** and the metal layer **28** of the first package substrate **2**, the direct
 10 bonding between the activated surfaces (Au-Au solid-phase bonding) of the second metal layer **19** and the wiring layer **29** of the first package substrate **2**, and the direct bonding between the activated surfaces (Si-Si solid-phase bonding) of the frame portion **11** of the sensor substrate **1** and the second package substrate **3** are formed at room temperature by applying an
 15 appropriate load (e.g., 300 N), as shown in FIG. 13C. Thus, the solid-phase direct bonding having substantially no residual stress at the bonding interface can be obtained under the condition that the interior of the sensor unit is maintained in the desired atmosphere.

Since the wafer level package structure **100** of the present embodiment has
 20 the direct bonding between the sensor substrate **1** and the first package substrate **2** and the direct bonding between the sensor substrate **1** and the second package substrate **3**, which are formed according to a low-temperature process such as the room-temperature bonding method, there is an advantage that the piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**) become
 25 hard to receive the influence of thermal stress, as compared with the case of performing the bonding step with a heat treatment such as reflow soldering. In addition, it is possible to reduce the process temperature, and achieve a simplification of the manufacturing process.

In addition, when the sensor substrate **1** is formed by use of the SOI wafer,
 30 and each of the first and second package substrates (**2**, **3**) is formed by use of

the Si wafer, it is possible to reduce stress occurring in the flexible portions **13** due to a difference in linear expansion coefficient therebetween, and the influence of the stress resulting from the difference in linear expansion coefficient on output signals of the above-described bridge circuits (**Bx**, **By**, **Bz**).

5 As a result, variations in sensor characteristics can be minimized. Each of the substrates may be formed by a semiconductor material other than silicon.

When dicing the thus obtained wafer level package structure **100** into a size of the acceleration sensor unit formed on the sensor substrate **1**, the sensor substrate **1** and the first and second package substrates (**2**, **3**) can be
10 simultaneously cut to have the same outside dimension. Therefore, it is possible to efficiently obtain compact chip size packages.

An operation of the acceleration sensor device obtained from the wafer level package structure of the present embodiment is briefly explained below.

Under the condition that no acceleration is applied to the sensor substrate **1**,
15 when acceleration is applied to the sensor substrate **1** in the positive direction of the “**x**” axis, a positional displacement of the weight portion **12** relative to the frame portion **11** occurs due to an inertia force of the weight portion **12** acting in the negative direction of the “**x**” axis. As a result, the pair of the flexible portions **13** where the longitudinal direction corresponds to the “**x**” axis
20 direction elastically deforms, so that resistance values of the piezoresistive elements (**Rx1** to **Rx4**) on the flexible portions **13** change. In this case, the piezoresistive elements (**Rx1**, **Rx3**) receive a tensile stress, and the piezoresistive elements (**Rx2**, **Rx4**) receive a compression stress. In general, when the piezoresistive element receives the tensile stress, the resistance value
25 (resistivity) increases, and when the piezoresistive element receives the compression stress, the resistance value (resistivity) decreases. Therefore, in this case, the resistance values of the piezoresistive elements (**Rx1**, **Rx3**) increase, and the resistance values of the piezoresistive elements (**Rx2**, **Rx4**) decrease. When a constant DC voltage is applied from an external power
30 source to between a pair of input terminals (**VDD**, **GND**) shown in FIG. 5, a

potential difference between output terminals (**X1**, **X2**) of the bridge circuit **Bx** shown at the left side in FIG. 5 changes depending on a magnitude of the acceleration in the “**x**” axis direction.

Similarly, when acceleration is applied to the sensor substrate **1** in the “**y**” axis direction, a potential difference between output terminals (**Y1**, **Y2**) of the bridge circuit **By** shown at a center in FIG. 5 changes depending on a magnitude of the acceleration in the “**y**” axis direction. In addition, when acceleration is applied to the sensor substrate **1** in the “**z**” axis direction, a potential difference between output terminals (**Z1**, **Z2**) of the bridge circuit **Bz** shown at the right side in FIG. 5 changes depending on a magnitude of the acceleration in the “**z**” axis direction. Therefore, the sensor substrate **1** is capable of detecting the acceleration applied to the sensor substrate **1** with respect to each of the “**x**” axis direction, the “**y**” axis direction and the “**z**” axis direction by detecting a change in output voltage of each of the bridge circuits (**Bx**, **By**, **Bz**). In the present embodiment, the movable portion is composed of the weight portion **12** and the flexible portions **13**, and the sensing portion is formed by the piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**), which are gauge resistances on the sensor substrate **1**.

By the way, as shown in FIG. 5, the sensor substrate **1** has the two input terminals (**VDD**, **GND**) shared by the three bridge circuits (**Bx**, **By**, **Bz**), the two output terminals (**X1**, **X2**) of the bridge circuit **Bx**, the two output terminals (**Y1**, **Y2**) of the bridge circuit **By**, and the two output terminals (**Z1**, **Z2**) of the bridge circuit **Bz**. These input terminals (**VDD**, **GND**) and output terminals (**X1**, **X2**, **Y1**, **Y2**, **Z1**, **Z2**) are formed on the surface facing the first package substrate **2** by the second metal layers **19**, and electrically connected to the through-hole wirings **24** formed in the first package substrate **2**. That is, in the present embodiment, the second metal layers **19** are formed at eight locations on the sensor substrate **1**, and eight through-hole wiring **24** are formed in the first package substrate **2**. Each of the second metal layers **19** formed at the eight locations is configured in a rectangular outer peripheral shape (a square outer

peripheral shape in the present embodiment). In addition, the second metal layers **19** are arranged away from each other in the circumferential direction of the frame portion **11**. In the present embodiment, a pair of the second metal layers **19** is disposed at each of four sides of the frame portion **11** having the rectangular shape.

(Second Embodiment)

As shown in FIGS. 14A to 14C, a wafer level package structure of the present embodiment is substantially the same as that of the first embodiment except that the sensor substrate **1** has an IC region **E2** other than an acceleration sensor unit, and the IC region **E2** comprises an integrated circuit (i.e., CMOS IC) using CMOS and operable in collaboration with the piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**) of gauge resistances (i.e., a sensing portion). The integrated circuit is formed by integrating a signal processing circuit configured to execute signal processing such as amplification, offset adjustment and temperature compensation to output signals of the bridge circuits (**Bx**, **By**, **Bz**) explained in the first embodiment, and an EEPROM for storing data used in the signal processing circuit. Therefore, in the following explanation, the same components as those in the first embodiment are denoted by the same reference numerals, and the duplicate explanation will be omitted.

As shown in FIGS. 15A and 15B, the sensor substrate **1** of the present embodiment is formed with a sensor region **E1** comprising a part of the frame portion **11** explained in the first embodiment, the weight portion **12**, the flexible portions **13**, and the piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**), the IC region **E2** having the integrated circuit described above, and a bonding region **E3** having the first metal layer **18** explained in the first embodiment. In a plan view, a layout of those regions (**E1**, **E2**, **E3**) is designed such that the sensor region **E1** is positioned at a substantially center portion of the sensor substrate **1**, the IC region **E2** is formed around the sensor region **E1**, and the bonding region **E3** is formed around the IC region **E2**. The frame

portion **11** of the sensor substrate **1** of the present embodiment has a larger outside dimension than that of the first embodiment. In other words, since the sensor substrate **1** has an increased width dimension of the frame portion **11**, the integrate circuit can be mounted on the frame portion **11**. In addition, a
 5 concave portion **21** of the first package substrate **2** is formed to be larger than that of the first embodiment such that the sensor region **E1** and the IC region **E2** are accommodated in the concave portion. A multilayer structure portion **41** of the IC region **E2** described later is disposed in the concave portion **21**.

The semiconductor wafer **10** is formed by use of an SOI wafer, as in the case
 10 of the first embodiment. The IC region **E2** is preferably formed by using a multilayer wiring technique to achieve a reduction in occupied area of the IC region **E2** on the sensor substrate **1**. At the IC region **E2** of the sensor substrate **1**, an insulating film **16** is formed by a laminated film of a first insulating film of a silicon oxide film on the silicon layer **10c** and a second
 15 insulating film of a silicon nitride film on the first insulating film, and the multilayer structure portion **41** is formed on the insulating film **16**. The multilayer structure portion **41** comprises a third insulating film of at least one interlayer insulating film (silicon oxide film) and a fourth insulating film of a passivation film (a laminated film of a silicon oxide film and a silicon nitride film)
 20 on the third insulating film. By removing appropriate portions of the passivation film, a plurality of pads **42** can be exposed. Therefore, in the present embodiment, a surface protection layer **40** is composed of the insulating film **16** (the first and second insulating films) and the multilayer structure portion **41** (the third and fourth insulating films). On the other hand, at the
 25 bonding region **E3**, the second metal layer **19** is formed at plural locations on the insulating film **16**. The second metal layers **19** are electrically connected to the pads **42** through outgoing wirings **43**. As a result, the pad **42** of the IC region **E2** can be electrically connected to the wiring metal layer **29** formed at one end of the through-hole wiring **24** of the first package substrate **2** through
 30 the outgoing wiring **43** and the second metal layer **19**. The pad **42** is

electrically connected to the sensing portion through the signal processing circuit, or electrically connected to the sensing portion not through the signal processing circuit.

In the sensor substrate **1** of the present embodiment, as shown in FIG. 15B, the outgoing wiring **43** and the second metal layer **19** are made of a same material, and they are continuously formed. Alternatively, as shown in FIG. 16A, the outgoing wiring **43** may be formed independently from the second metal layer **19**. In this case, the outgoing wiring **43** is preferably formed by a laminated film of an Au film and a Ti film for adhesion improvement.

By the way, when the surface protection layer **40** is formed on the general surface of the SOI substrate **10**, a step portion appears between a first region where the pad **42** of the IC region **E2** is formed and a second region where the second metal layer **19** and the first metal layer **18** are formed. Due to this step portion, it is needed to form the outgoing wiring **42** for electrically connecting between the pad **42** of the IC region **E2** and the second metal layer **19** along a side surface of the surface protection layer **40**. In the case of FIG. 16A, the thickness of the outgoing wiring **43** can be independently determined from the thickness of the first metal layer **18** and the second metal layer **19**. For example, the thickness "**A**" of the outgoing wiring **42** is set to be larger than the thickness "**B**" of the first metal layer **18** and the second metal layer **19**.

In addition, as shown in FIG. 16B, it is preferred that the outgoing wiring **43** and the second metal layer **19** are integrally formed in a continuous manner, and the thickness of the outgoing wiring **43** is set to be larger than the thickness of the first metal layer **18** and the second metal layer **19**. In this case, a film formation is performed such that the outgoing wiring **43**, the first metal layer **18** and the second metal layer **19** are simultaneously formed to have a thickness (**T1**) for the outgoing wiring **43**. Subsequently, a thickness adjustment is performed such that only the first metal layer **18** and the second metal layer **19** are etched to have a desired thickness (**T2** < **T1**). As a result, it is possible to reduce the probability that disconnection of the outgoing wiring **43** occurs at

the step portion of the surface protection layer **40**.

In the film formation stage for the outgoing wiring **43**, the first metal layer **18** and the second metal layer **19**, a lower metal layer having the thickness **T2** (e.g., a laminated film of a Ti film and an Au film on the Ti film) is firstly formed, and then an upper metal layer having a thickness corresponding to a difference between the thickness **T1** and the thickness **T2** (e.g., a laminated film of a Ti film and an Au film on the Ti film) is formed on the lower metal layer. In the thickness adjustment stage, the upper metal layer is etched at the regions corresponding to the first and second metal layers (**18**, **19**) by using the lower metal layer as an etching stopper layer. Thus, the first and second metal layers (**18**, **19**) having the thickness **T2** can be obtained. In this case, there are advantages that the thickness of the first and second metal layers (**18**, **19**) can be easily controlled, and an improvement in surface flatness of the first and second metal layers (**18**, **19**) can be achieved. As a result, it is possible to improve the production yield of the sensor device.

As shown in FIG. 16C, it is also preferred that the outgoing wiring **43** has a two-layer structure of a lower wiring layer **43a** and an upper wiring layer **43b**, and the upper wiring layer **43b** and the second metal layer **19** are integrally formed in a continuous manner. For example, the lower and upper wiring layers (**43a**, **43b**) may be formed by a laminated film of a Ti film and an Au film on the Ti film. In this case, the outgoing wiring **43** can be obtained by a process comprising the steps of forming the lower wiring layer **43a** on the surface protection layer **40**, and forming the upper wiring layer **43b** on the lower wiring layer **43a**. In the step of forming the upper wiring layer **43b**, the first and second metal layers (**18**, **19**) are simultaneously formed. The thickness of the outgoing wiring **43** is determined to be equal to a total thickness of the lower and upper wiring layers (**43a**, **43b**). Consequently, it is possible to increase the yields in the bonding step between the sensor substrate **1** and the first package substrate **2**. Furthermore, an improvement in reliability of electrical connection between the pad **42** of the IC region **E2** and the second metal layer

19 can be achieved by preventing disconnection of the outgoing wiring **43**.

Alternatively, instead of the upper wiring layer **43b**, the lower wiring layer **43a** may be integrally formed in a continuous manner with the second metal layer **19**. In this case, the first and second metal layers (**18**, **19**) are simultaneously formed in the step of forming the lower wiring layer **43a**. Subsequently, the upper wiring layer **43b** is formed on only a region corresponding to the outgoing wiring **43**. The thickness of the outgoing wiring **43** is determined by the total thickness of the lower and upper wiring layers (**43a**, **43b**).

Next, referring to FIGS. 17A to 17F, a production method of the sensor substrate **1** of the present embodiment is explained below. Each of FIGS. 17A to 17F corresponds to a cross section taken along the line A-A' in FIG. 15A. In addition, the structure of FIG. 16A is used as the outgoing wiring **43**.

First, diffusion layer wirings for the bridge circuits (**Bx**, **By**, **Bz**), the piezoresistive elements (**Rx1** to **Rx4**, **Ry1** to **Ry4**, **Rz1** to **Rz4**), and the IC region **E2** are formed on the general surface (a surface side of the silicon layer **10c**) of the SOI substrate **10** by using a CMOS process technique, so that a structure shown in FIG. 17A is obtained. In a stage where a step of exposing the pads **42** of the IC region **E2** has been finished, the multilayer structure portion **41** described above extends over the entire surface of the insulating film **16**. No metal wiring is formed at regions of the multilayer structure portion **41** corresponding to the sensor region **E1** and the bonding region **E3**. In the present embodiment, the surface protection layer **40** is comprised of the insulating film **16** and the multilayer structure portion **41**, as described above. In this stage, the surface protection layer **40** does not have the above-described step portion yet.

After finishing the step of exposing the pads **42**, a patterned resist layer is formed on the general surface of the SOI substrate **10** so as to expose regions of the surface protection layer **40** corresponding to the sensor region **E1** and the bonding region **E3**. By using this resist layer as an etching mask, a planarizing

process is performed. That is, a planarized surface of the bonding region **E3** is formed by etching back the region of the surface protection layer **40** corresponding to the bonding region **E3**. Then, the resist layer is removed, so that a structure shown in FIG. 17B is obtained. When the etching back step is performed by means of wet etching, the second insulating film of a silicon nitride film of the insulating film **16** is used as an etching stopper layer. As a result of the planarizing process, the above-described step portion of the surface protection layer **40** appears.

Subsequently, a wiring formation step for forming the outgoing wiring **43** on the general surface of the SOI substrate **10** is performed, and the first metal layer **18** and the second metal layer **19** are formed on the bonding region **E3**. Conventional thin-film deposition technique such as sputtering, and lithography and etching techniques are preferably used for the formation of the outgoing wiring and these metal layers. Next, a patterned resist layer is formed on the insulating film **16** so as to cover regions corresponding to the frame portion **11**, the core section **12a** of the weight portion **12**, the flexible portions **13**, the IC region **E2** and the bonding region **E3**, and expose the other regions. Subsequently, a first patterning process is performed. That is, by using this resist layer as an etching mask, the exposed regions of the insulating film **16** are etched to perform patterning of the insulating film **16**. The etching is further continued to have an etching depth reaching the insulating layer **10b** from the general surface side of the SOI substrate **10**. Then, by removing the resist layer, a structure shown in FIG. 17C is obtained. In this first patterning process, the insulating layer **10b** is used as an etching stopper layer. As a result of the first patterning process, the silicon layer **10c** of the SOI substrate **10** remains at the regions corresponding to the frame portion **11**, the core section **12a**, the flexible portions **13**, the IC region **E2** and the bonding region **E3**. As the etching method suitable for the first patterning process, for example, it is preferred to perform dry etching by use of an inductively-coupled plasma (ICP) type dry etching apparatus. The etching condition is set such

that the insulating layer **10b** functions as the etching stopper layer.

After the first patterning process is finished, and the resist layer is removed, a patterned resist layer is formed on a silicon oxide film **10d**, which is formed on the support substrate **10a** at the bottom surface side of the SOI substrate **10**, so as to cover regions corresponding to the frame portion **11**, the core section **12a**, the leaf portions **12b**, the IC region **E2** and the bonding region **E3**, and expose the other regions. Subsequently, a second patterning process is performed. That is, by using this resist layer as an etching mask, the exposed regions of the silicon oxide film **10d** are etched to perform patterning of the silicon oxide film **10d**. After the resist layer is removed, dry etching is performed in a substantially vertical direction by using the silicon oxide film **10d** as an etching mask to have an etching depth reaching the insulating layer **10b** from the bottom surface side of the SOI substrate **10**. By this second patterning process, a structure shown in FIG. 17D is obtained. In this patterning process, the insulating layer **10b** is used as an etching stopper layer. After the second patterning process, the support substrate **10a** of the SOI substrate **10** remains at the regions corresponding to the frame portion **11**, the core section **12a**, the leaf portions **12b**, the IC region **E2** and the bonding region **E3**. As an etching apparatus suitable for the second patterning process, for example, it is preferred to use an inductively-coupled plasma (ICP) type dry etching apparatus. The etching condition is set such that the insulating layer **10b** functions as the etching stopper layer.

After the second patterning process, a separation process is performed. That is, the frame portion **11**, the flexible portions **13** and the weight portion **12** are formed by removing undesired portions by means of wet etching, while leaving the regions corresponding to the frame portion **11**, the core section **12a**, the IC region **E2** and the bonding region **E3** of the insulating film **10b**. As a result, a structure shown in FIG. 17E is obtained. In this separation process, the silicon oxide film **10d** on the bottom surface of the SOI substrate **10** is also etched and removed.

A structure shown in FIG. 17F is obtained by room-temperature bonding each of the first package substrate **2** shown in FIGS. 18A and 18B and the second package substrate **3** shown in FIGS. 19A and 19B to the sensor substrate **1** formed according to the above procedures. That is, by performing

5 the room-temperature bonding between activated surfaces (Au-Au surfaces) of the first metal layer **18** of the sensor substrate **1** and the metal layer **28** of the first package substrate **2** and the room-temperature bonding between activated surfaces (Au-Au solid-phase bonding) of the second metal layer **19** and the wiring layer **29** of the first package substrate **2**, the sensor substrate **1** is

10 integrated with the first package substrate **2**. On the other hand, by performing the room-temperature bonding between activated surfaces (Si-Si solid-phase bonding) of the frame portion **11** of the sensor substrate **1** and the second package substrate **3**, the sensor substrate **1** is integrated with the second package substrate **3**.

15 By the way, in the present embodiment, a wafer level package structure **100** (FIG.14A) having a plurality acceleration sensors is manufactured by performing the series of steps shown in FIGS. 17A to 17F to the sensor substrate **1** and the package substrates (**2**, **3**) in a wafer level. Then, a cutting (dicing) process is performed by cutting the thus obtained wafer level package

20 structure **100** into the acceleration sensor size. In this case, the outside dimension of each of the first and second package substrates (**2**, **3**) can be accurately matched at a time with the outside dimension of the sensor substrate **1**. Therefore, this production method is particularly suitable to produce compact sensor devices in large quantities. Prior to the dicing process, it is

25 preferred to carry out an inspection stage for checking electrical characteristics of the sensing portion and the circuit portion of the sensor device. As compared with the case of checking the electrical characteristics after the sensor devices are individually separated from the wafer level package structure, it is possible to remarkably save efforts and time for the inspection stage.

30 According to the above-described production method, since the region of the

surface protection layer **40** corresponding to the bonding region **E3** is planarized by means of etching back, and then the first metal layer **18** and the second metal layer **19** used for the bonding with the first package substrate **2** are formed on the planarized surface of the bonding region **E3**, it is possible to improve the surface flatness of the first and second metal layers (**18**, **19**). Therefore, good solid-phase direct bonding can be obtained between the first metal layer **18** and the metal layer **28** of the first package substrate **2** and between the second metal layer **19** and the wiring layer **29** of the first package substrate **2**. As a result, an improvement in production yield can be achieved.

In addition, according to the above-described production method, since the etching back step is performed by using the second insulating film of the silicon nitride film of the insulating layer **16** as the etching stopper layer, the first and second metal layers (**18**, **19**) can be formed on the insulting film **16** with a comparable flatness to the general surface of the SOI substrate **10**. As a result, it is possible to achieve an improvement in surface flatness of the first and second metal layers (**18**, **19**). The insulating film used as the etching stopper layer in the planarizing process is not limited to the second insulating film. The insulating film other than the fourth insulating film of the multilayer structure portion **41** may be used. The insulating film used as the etching stopper layer can be determined according to the height level needed for the bonding region **E3**.

Alternatively, after etching is performed by using the second insulating film as the etching stopper layer, a further etching may be performed by using the first insulating film as the etching stopper layer. In this case, an undercoat insulating layer for the first metal layer **18** and the second metal layer **19** can be provided by the first insulating layer with excellent surface flatness. The silicon oxide film used as the first insulating layer is preferably formed by a thermal oxidation method or a LPCVD (Low Pressure Chemical Vapor Deposition) method.

In the sensor device of the present embodiment, since an IC chip having the

integrated circuit operable in collaboration with gauge resistances is built in the frame portion, it is possible to downsize the sensor device and achieve a reduction in production cost, as compared with conventional sensor modules. Furthermore, a reduction in wiring length between the gauge resistances and the integrated circuit brings about an improvement in sensor characteristics.

(Third Embodiment)

In each of the above embodiments, the piezoresistance-type acceleration sensor was used as the sensor unit. The technical concept of the present invention is also available to the other sensor unit such as a capacitance type acceleration sensor or a gyro sensor. The present embodiment is characterized by forming a gyro sensor unit on a sensor substrate in place of the acceleration sensor unit. The other configurations of the present embodiment are substantially the same as those of the first embodiment. Therefore, a bonding portion between the sensor substrate **101** and each of the first and second package substrates (**102**, **103**) can be formed according to the same manner as the first embodiment.

A wafer level package structure of the present embodiment has a structure comprising a semiconductor wafer with a plurality of gyro sensor units, a first package wafer bonded to one of opposite surfaces of the semiconductor wafer, and a second package wafer bonded to the other surface of the semiconductor wafer. In the following explanation, a region for forming each of the gyro sensor units of the semiconductor wafer is defined as the sensor substrate **101**. In addition, a region facing each of the sensor substrates **101** of the first package wafer is defined as the first package substrate **102**. Similarly, a region facing each of the sensor substrates **101** of the second package wafer is defined as the second package substrate **103**.

In the present embodiment, the sensor substrate **101** is formed by use of a silicon substrate having a resistivity of $0.2 \Omega \cdot \text{cm}$. Each of the first and second package substrates (**102**, **103**) is formed by use of a silicon substrate having a resistivity of $20 \Omega \cdot \text{cm}$. These resistivity values are illustrative only, and

therefore the present invention is not limited to them.

As shown in FIG. 20, the gyro sensor unit is mainly formed with a movable portion comprising a first mass body **111**, which can be vibrated by vibrating means, and a second mass body **112** coupled to the first mass body **111**, and a
 5 detecting portion configured to convert a positional displacement of the second mass body **112**, which is caused when a rotational force is applied during the vibration of the first mass body **111**, into an electrical signal.

That is, the first mass body **111** and the second mass body **112**, each of which has substantially a rectangular outer peripheral shape in plan view, are
 10 arranged in parallel along a surface of the sensor substrate **101**. In addition, the sensor substrate **101** has a frame portion **110** (e.g., a rectangular frame portion in the present embodiment) extending around the first and second mass bodies (**111**, **112**). In the present embodiment, an orthogonal coordinate system is defined, as shown at a lower right portion in each of FIGS. 20 to 24.
 15 That is, a direction of arranging the first and second mass bodies (**111**, **112**) corresponds to the "y" axis direction, and a direction orthogonal to the "y" axis direction in a plane extending along the surface of the sensor substrate **101** corresponds to the "x" axis direction. In addition, a direction orthogonal to the "x" axis direction and the "y" axis direction (i.e., a thickness direction of the
 20 sensor substrate **101**) corresponds to the "z" axis direction.

As shown in FIG. 21, the first mass body **111** and the second mass body **112** of the sensor substrate **101** are integrally coupled to each other through a pair of drive springs **113** extending in the "x" axis direction. That is, the sensor substrate **101** has a slit groove **114a** having a length slightly shorter than the
 25 entire length of the second mass body **112** in the "x" axis direction, and two slit grooves **114b** arranged in a straight line along the "x" axis direction and at the lateral side of the first mass body **111**. Each of the slit grooves **114b** has an opening at its one end. Each of the drive springs **113** is formed between the slit groove **114a** and each of the slit grooves **114b**. An end portion of each of the
 30 drive springs **113** continuously extends between an end portion of the slit

groove **114a** and a lateral edge of the second mass body **112**, and the other end portion of the drive spring **113** continuously extends to the first mass body **111** through a region between the slit grooves **114b**. The drive spring **113** is a torsion spring having a torsional deformation capability, and enable a positional displacement of the first mass body **111** relative to the second mass body **112** about the drive spring **113**. That is, the drive springs **113** enables a translational movement in the “**z**” axis direction of the first mass body **111** relative to the second mass body **112** as well as a rotational movement about the “**x**” axis of the first mass body **111** relative to the second mass body **112**. In addition, since the sensor substrate **101** uses the torsion spring as the drive spring **113**, it is not necessary to reduce a dimension of the drive spring **113** in the thickness direction of the sensor substrate **101**. Therefore, the drive springs **113** can be easily manufactured.

The numeral **115** designates a detection spring extending in the “**y**” axis direction, and continuously connected at its one end to an edge portion in the “**x**” axis direction of the second mass body **112** of the sensor substrate **101**. The opposite end portion of one of the detection springs **115** is continuously connected to that of the other detection spring **115** through a coupling member **116** extending in the “**x**” axis direction. That is, a substantially “**C**” shaped member is formed in plan view by the pair of the detection springs **115** and the coupling member **116**. In this regard, the coupling member **116** is designed to have a sufficiently higher rigidity than the drive springs **113** and the detection springs **115**. The numeral **117** designates a fixation portion projecting from an intermediate portion in the longitudinal direction of the coupling member **116**. The fixation portion **117** is fixed to a predetermined position of the second package substrate **103**. The first and second mass bodies (**111**, **112**) are separated from the detection springs **115** and the coupling member **116** by a slit groove **114c** formed in a substantially “**C**” shape. The one end of the slit groove **114b** is communicated with the slit groove **114c**. Each of the detection springs **115** has a bending deformability in the “**x**” axis direction. Therefore,

the detection springs **115** enable a positional displacement of the first and second mass bodies (**111**, **112**) relative to the fixation portion **117** in the “**x**” axis direction.

By the way, the sensor substrate **101** has four apertures **118** penetrating
5 the second mass body **112** in the thickness direction, and a stationary part **120**
disposed in each of the apertures **118**. The stationary part **120** has an
electrode portion **121** disposed in the vicinity of each end in the “**x**” axis
direction of the second mass body **112**, and a comb bone portion **122** extending
from the electrode portion **121** in the “**x**” axis direction. The electrode portion
10 **121** and the comb bone portion **122** are configured in a substantially “**L**” shape.
The electrode portion **121** and the comb bone portion **122** are bonded to the
second package substrate **103**. That is, the stationary part **120** is fixed at a
predetermined position. An inner surface of the aperture **118** extends along an
outer peripheral surface of the stationary part **120** through a clearance. A pair
15 of the electrode portions **121** is disposed at both ends in the “**x**” axis direction of
the second mass body **112**. As shown in FIG. 22, a plurality of stationary comb
teeth **123** arranged along the “**x**” axis direction are formed at both sides in the
width direction of the comb bone portion **122**. On the other hand, a plurality of
movable comb teeth **124** are formed in the aperture **118** at a side facing the
20 comb bone portion **122** of the second mass body **112**, and arranged along the
“**x**” axis direction such that each of the movable comb teeth **124** is in a
face-to-face relation with each of the stationary comb teeth **123**, as shown in
FIG. 22. Each of the movable comb teeth **124** is located away from a
corresponding stationary comb tooth **123** by a distance. When the second
25 mass body **112** is displaced in the “**x**” axis direction, a change in distance
between the stationary comb teeth **123** and the movable comb teeth **124** occurs,
so that a change in electric capacitance caused by the change in distance is
detected. That is, a detection means for detecting the positional displacement
of the second mass body **112** is composed of the stationary comb teeth **123** and
30 the movable comb teeth **124**.

The sensor substrate **101** is coupled to the second package substrate **103** by bonding the frame portion **110**, the fixation portion **117**, and the stationary parts **120** to the second package substrate **103**. In other words, the second package substrate **103** is used as a support substrate for supporting the sensor substrate **101**. On the other hand, since the first and second mass bodies (**111**, **112**) are formed to be displaceable in the "z" axis direction, the bottom surfaces facing the second package substrate **103** of the first and second mass bodies (**111**, **112**) are backed away from the second package substrate **103**, as shown in FIG. 20. That is, the thickness of each of the first and second mass bodies (**111**, **112**) in the thickness direction of the sensor substrate **101** is determined to be smaller than the thickness of the frame portion **110**. Thus, a clearance is ensured between the second package substrate **103** and each of the first and second mass bodies (**111**, **112**). In the present embodiment, a gap length between the first mass body **111** and the second package substrate **103** is set to 10 μm . This value is illustrative only, and therefore the present invention is not limited to it.

In addition, the sensor substrate **101** has a pair of ground portions **119** formed on the frame portion **110** at the vicinity of the fixation portion **117** such that the fixation portion **117** is located between the ground portions **119**. The numeral **127** designates an electrode portion electrically connected to an electrode **125** described later, and formed near one of the ground portions **119**. The ground portions **119** and the electrode portion **127** are bonded to the second package substrate **103**. At the upper-surface side, a second metal layer **128** is formed on the fixation portion **117**, the electrode portions **121**, one of the ground portions **119** and the electrode portion **127**. In this regard, one fixation portion **117**, four electrode portions **121**, one ground portion **119** and one electrode portion **127** are separately arranged from each other at the upper-surface side of the second package substrate **103**. In a state where the first package substrate **102** is not bonded to the frame portion **110**, they are electrically insulated from each other. In addition, at the upper-surface side of

the sensor substrate **101**, the frame portion **110** has a first metal layer **126** formed over the entire circumference thereof. Each of the first and second metal layers (**126**, **128**) is formed by a laminated film of a Ti film and an Au film. In brief, since the first and second metal layers (**126**, **128**) are made of the same metal material, it is possible to simultaneously obtain these metal layers with the same thickness. In each of the first and second metal layers (**126**, **128**), the Ti film preferably has a thickness of 15 to 50 nm, and the Au film preferably has a thickness of 500 nm. These thickness values are illustrative only, and therefore the present invention is not limited to them. As a material for forming the Au film, an Au material containing an impurity may be used in place of pure gold.

As shown in FIGS. 23 and 24, the first package substrate **102** has a concave portion **129** configured to provide a space for positional displacements of the first and second mass bodies (**111**, **112**) at the side facing the sensor substrate **101**, i.e., in the bottom surface of the first package substrate **102** shown in FIG. 20. In addition, the first package substrate **102** has a plurality of through holes **132** penetrating in the thickness direction. A heat insulating film **133** (a silicon oxide film) is formed on both opposite surfaces in the thickness direction of the first package substrate **102** and inner surfaces of the through holes **132**. Therefore, the heat insulating film **133** lies between a through-hole wiring **134** and the inner surface of the through hole **132**. In the present embodiment, copper is used as a material for the through-hole wiring **134**. Alternatively, nickel or the like may be used in place of copper.

The first package substrate **102** has the above-described electrode **125** (FIGS. 20 and 24) formed at a region facing the first mass body **111** on the bottom surface of the concave portion **129** through the insulating film **133**. The electrode **125** is formed by a laminated film of a Ti film and an Au film. In the present embodiment, a gap length between the first mass body **111** and the electrode **125** is set to 10 μm . This value is illustrative only, and therefore the present invention is not limited to it.

In addition, the first package substrate **102** has a plurality of metal layers **138** formed on the surface facing the sensor substrate **101**, and electrically connected to the through-hole wirings **134**. The first package substrate **102** also has a (rectangular) frame-like metal layer **136** formed over the entire circumference thereof on the surface facing the sensor substrate **101**. In this regard, the metal layers **138** are bonded to the second metal layers **128** of the sensor substrate **101** to make an electrical connection therebetween. The metal layer **136** is bonded to the first metal layer **126** of the sensor substrate **101**. Each of the metal layer **136** and the metal layer **138** is formed by a laminated film of a Ti film on the insulating film **133** and an Au film on the Ti film. In brief, since the metal layer **136** and the metal layer **138** are made of the same metal material, it is possible to simultaneously obtain these films with the same thickness. In each of the metal layer **136** and the metal layer **138**, the Ti film preferably has a thickness of 15 to 50 nm, and the Au film preferably has a thickness of 500 nm. These thickness values are illustrative only, and therefore the present embodiment is not limited to them. As a material for the Au film, an Au-based material containing an impurity may be used in place of pure gold. In addition, in the present embodiment, the Ti film is formed as an adhesive layer for improving the adhesion between the Au film and the insulating film **133**. In place of the Ti, Cr, Nb, Zr, TiN, TaN or the like may be used as the material for the adhesive layer.

The first package substrate **102** has a plurality of electrodes **135** for external connection formed on an opposite surface of the surface facing the sensor substrate **101**. These electrodes **135** are electrically connected to the through-hole wirings **134**. Each of the electrodes **135** is configured in a rectangular outer peripheral shape, and formed by a laminated film of a Ti film and an Au film.

On the other hand, the second package substrate **103** has heat insulating films (**141**, **142**) such as a silicon oxide film formed on both opposite surfaces in the thickness direction thereof.

As described in the first embodiment, the sensor substrate **101** is bonded to the first package substrate **102** by solid-phase direct bonding between the first metal layer **126** and the metal layer **136**. That is, the first package substrate **102** is sealingly bonded to the entire circumference of the frame portion **110** of the sensor substrate **101**. In addition, the second metal layer **128** is electrically connected to the metal layer **138** by solid-phase direct bonding. An interior of the gyro sensor unit is airtightly sealed from the outside by these solid-phase direct bondings. In addition, the second metal layer **128** of the sensor substrate **101** is electrically connected to the electrode **135** through the metal layer **138** and the through-hole wiring **134**. The second package substrate **102** has a wiring portion **125a** (FIG. 24) extending from the electrode **125** to a peripheral portion of the concave portion **129**, which is continuously formed with the metal layer **138** bonded to the second metal layer **128** on the electrode portion **127** of the sensor substrate **101**.

To form the bonding portion between the sensor substrate **101** and each of the first and second package substrates (**102**, **103**), a room-temperature bonding method for forming the direct bonding at low temperature is used to reduce residual stress in the sensor substrate **101**. In the room-temperature bonding method, the surfaces to be bonded are cleaned up and activated by irradiating an ion beam, an atomic beam or plasma of argon in vacuum, and then the activated surfaces are directly bonded to each other at room temperature in vacuum. In the present embodiment, according to the room-temperature bonding method described above, the direct bonding between the first metal layer **126** and the metal layer **136** and the direct bonding between the second metal layer **128** and the metal layer **138** are simultaneously obtained by applying an appropriate load to the bonding interface at room temperature in vacuum. In addition, the frame portion **110** of the sensor substrate **101** is directly bonded in an airtight manner to the peripheral portion of the second package substrate **103** at room temperature in vacuum by the room-temperature bonding method.

The room-temperature bonding method of the present embodiment is explained below. Duplicate explanations about the same steps as the first embodiment are omitted.

After micromachining is appropriately performed to the sensor substrate **101**, and the sensor substrate **102** is bonded to the second package substrate **103** at room temperature, an etching step for separating a portion used as the movable portion of the sensor substrate **101** from the other portion and a metal layer formation step for forming the first and second metal layers (**126**, **128**) are performed. In the present embodiment, the sensor substrate **101** is bonded to the second package substrate **103** by the room-temperature bonding between Si and SiO₂. Subsequently, the sensor substrate **101** integrated with the second package substrate **103** and the first package substrate **102** are placed in the chamber, and the chamber is vacuum exhausted to a predetermined degree of vacuum (e.g., 1×10^{-5} Pa). Then, a surface activation treatment is performed. That is, the surfaces to be bonded to each other of the sensor substrate **101** and the first package substrate **102** are cleaned up and activated by means of sputter etching in vacuum. The degree of vacuum in the chamber during the surface activation treatment is approximately 1×10^{-2} Pa, which is a lower degree of vacuum, as compared with the predetermined degree of vacuum in the chamber before the surface activation treatment.

After the surface activation treatment, an atmosphere adjusting step is performed to adjust the interior atmosphere of the chamber, in which the sensor substrate **101** and the second package substrate **103** are placed, to a designed atmosphere determined according to gyro sensor characteristics. In this regard, the gyro sensor of the present embodiment is designed in a predetermined degree of vacuum (a high vacuum of 1×10^{-4} Pa or less), in order to increase a mechanical Q value (mechanical quality coefficient Q_m) indicative of a mechanical vibration level in the vicinity of the resonance frequency, and achieve an improvement in sensitivity. In the atmosphere adjustment step of the present embodiment, after the surface activation treatment is finished, the

interior atmosphere of the chamber is adjusted to the designed atmosphere by performing vacuum pumping until the degree of vacuum in the chamber reaches a predetermined degree of vacuum.

After the atmosphere adjusting step is finished, the sensor substrate **101** is
5 bonded to the first package substrate **102** at room temperature under the atmosphere controlled in the atmosphere adjusting step. At the step of bonding between the sensor substrate **101** and the first package substrate **102**, the room-temperature bonding between the first metal layer **126** and the metal layer **136**, and the room-temperature bonding between the second metal layer
10 **128** and the metal layer **138** are simultaneously obtained by applying an appropriate load (e.g., 300 N). In the present embodiment, the bonding between the sensor substrate **101** and the first package substrate **102** is provided by the room-temperature bonding between Au and Au.

It is preferred that the surface activation treatment, the atmosphere
15 adjusting step and the bonding step are sequentially performed in the same chamber. The surfaces to be bonded to each other of the sensor substrate **101** and the first package substrate **102** are cleaned up and activated by the surface activation treatment. Then, those activated surfaces are bonded to each other, without exposure to the outside air, at room temperature in an airtight manner
20 under a designed atmosphere determined according to desired sensor characteristics. Thereby, good bonding strength can be obtained therebetween. In the atmosphere adjusting step, since the chamber is vacuum exhausted to a predetermined degree of vacuum after the surface activation treatment to adjust the interior atmosphere to the designed atmosphere, it is possible to obtain a
25 high mechanical Q value (mechanical quality coefficient Q_m) indicative of a mechanical vibration level in the vicinity of the resonance frequency of the gyro sensor as the sensor element, and therefore achieve an improvement in sensitivity.

As described above, the wafer level package structure of the present
30 embodiment has the direct bonding between the sensor substrate **101** and the

first package substrate **102**, and the direct bonding between the sensor substrate **101** and the second package substrate **103**, which are formed according to the low-temperature process such as the room-temperature bonding method. Therefore, it is possible to prevent the influence of thermal stress, as compared with the case of bonding the sensor substrate **101** with each of the first and second package substrates (**102**, **103**) by a heat treatment such as reflow soldering. As a result, there is an advantage that variations in sensor characteristics can be reduced. In addition, since the sensor substrate **101** is bonded to the second package substrate **103** through the insulating film **141**, it is possible to prevent a reduction in resistance to electric noise. Furthermore, since the substrates are made of silicon wafers, and the insulating film **141** is formed by a silicon oxide film, the sensor substrate **101** can be easily bonded to each of the package substrates (**102**, **103**) at room temperature, and variations in sensor characteristics can be reduced.

In the present embodiment, the second package substrate **103** is bonded to the sensor substrate **101** through the insulating film **141** formed on the surface facing the sensor substrate **101** of the second package substrate **103**. In brief, they are preferably bonded to each other through an insulating film formed on at least one of the surface facing the sensor substrate **101** of the second package substrate **103** and the surface facing the second package substrate **103** of the sensor substrate **101**.

In addition, by cutting (dicing) the wafer level package structure having the gyro sensor units integrally formed therewith into a size of the gyro sensor unit, it is possible to easily and efficiently obtain compact gyro sensor devices.

Therefore, it is suitable for mass production.

An operation of the thus obtained gyro sensor is briefly explained below.

The gyro sensor of the present embodiment detects a positional displacement of the second mass body **112** when an angular velocity is applied to the gyro sensor by an external force under the condition that a predetermined vibration is given to the first mass body **111**. In this regard, a vibrating voltage

having a sine waveform or a rectangular waveform is applied between the electrode **125** and the first mass body **111** to vibrate the first mass body **111**. For example, an AC voltage is used as the vibrating voltage, but polarity inversion is not essential. The first mass body **111** is electrically connected to the fixation portion **117** through the drive springs **113**, the second mass body **112**, the detection springs **115** and the coupling member **116**. The second metal layer **128** is formed on this fixation portion **117**. In addition, the electrode **125** is electrically connected to the second metal layer **128** on the electrode portion **127**. Therefore, when the vibrating voltage is applied between the second metal layers **128** on the fixation portion **117** and the electrode portion **127**, the first mass body **111** can vibrate in the “**z**” axis direction due to an electrostatic force between the first mass body **111** and the electrode **125**. When the frequency of the vibrating voltage is equal to a resonance frequency determined according to weights of the first and second mass bodies (**111**, **112**), and spring constants of the drive spring **113** and the detection spring **115**, a large amplitude can be obtained by a relatively small driving force.

In a state where the first mass body **111** is being vibrated, when an angular velocity is applied to the gyro sensor about the “**y**” axis, a Coriolis force occurs in the “**x**” axis direction, so that the second mass body **112** (with the first mass body **111**) is displaced in the “**x**” axis direction relative to the stationary part **120**. When the movable comb teeth **124** are displaced relative to the stationary comb teeth **123**, a change in distance between the movable comb teeth **124** and the stationary comb teeth **123** occurs, so that the electric capacitance therebetween changes. This change in electric capacitance can be taken out from the second metal layers **128** connected to the four stationary parts **120**. Thus, it can be regarded that the above-described gyro sensor is provided with four variable capacitance capacitors. Therefore, the positional displacement of the second mass body **112** can be detected by measuring the electric capacitance of each of the variable capacitance capacitors, or the total

capacitance of the variable capacitance capacitors connected in parallel. Since the vibration of the first mass body **111** is previously determined, the Coriolis force can be calculated by detecting the positional displacement of the second mass body **112**. In the present embodiment, the movable portion disposed
5 inside of the frame portion **110** is composed of the first mass body **111**, the drive springs **113**, the second mass body **112**, the detection springs **115** and the coupling member **116**, and the sensing portion is composed of the stationary comb teeth **123** and the movable comb teeth **124** formed on the second mass body **112**. In brief, a part of the sensing portion is formed in the movable
10 portion disposed inside of the frame portion **110**.

In this regard, the displacement of the movable comb teeth **124** is proportional to (the weight of the first mass body **111**) / (the weight of the first mass body **111** + the weight of the second mass body **112**). Therefore, as the weight of the first mass body **111** becomes larger than the weight of the second
15 mass body **112**, the displacement of the movable comb teeth **124** increases. As a result, an improvement in sensitivity is achieved. In the present embodiment, from this reason, the thickness dimension of the first mass body **111** is determined to be larger than the thickness dimension of the second mass body **112**.

20 INDUSTRIAL APPLICABILITY

As described above, according to the present invention, since the directly bonding between the surface-activated region formed on the sensor substrate and the surface-activated region formed on each of the package substrates is formed at room temperature, it is possible to avoid inconveniences such as
25 variations in sensor characteristics resulting from residual stress at the bonding portion. In addition, the interior of the sensor device can be airtightly sealed by the solid-phase direct bonding without diffusion between the surface-activated regions. Therefore, an appropriate atmosphere can be realized in the sensor device according to the kind of sensor such as an acceleration sensor and a gyro
30 sensor. The present invention having the above advantages is expected to be

used in a wide variety of applications requiring a compact sensor device with stable sensor characteristics.

CLAIMS:

1. A sensor device comprising:

a sensor substrate comprising a frame having an opening, a movable portion
5 movably held in said opening, and a detecting portion configured to output an electric signal according to a positional displacement of said movable portion;

a first package substrate bonded to one of opposite surfaces of said sensor substrate;

10 a second package substrate bonded to the other surface of said sensor substrate;

wherein said frame has a first surface-activated region formed on a surface facing the first package substrate over an entire circumference thereof so as to surround said movable portion, and a second surface-activated region formed on a surface facing the second package substrate over an entire circumference
15 thereof so as to surround said movable portion,

the bonding between said sensor substrate and the first package substrate is a solid-phase direct bonding without diffusion between said first surface-activated region and a surface-activated region formed on the first package substrate, and

20 the bonding between said sensor substrate and the second package substrate is a solid-phase direct bonding without diffusion between said second surface-activated region and a surface-activated region formed on the second package substrate.

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2. The sensor device as set forth in claim 1, wherein said first surface-activated region, said second surface-activated region, the surface-activated region of the first package substrate, and the surface-activated region of the second package substrate are any one of a plasma-treated surface, an ion-beam irradiated
30 surface, and an atomic-beam irradiated surface.

3. The sensor device as set forth in claim 1, wherein at least one of the bonding between said first surface-activated region and the surface-activated region on the first package substrate and the bonding between said second surface-activated region and the surface-activated region on the second package substrate is any one of the solid-phase direct bonding between Si and Si, the solid-phase direct bonding between Si and SiO₂, and the solid-phase direct bonding between SiO₂ and SiO₂.

10

4. The sensor device as set forth in claim 1, wherein at least one of the bonding between said first surface-activated region and the surface-activated region on the first package substrate and the bonding between said second surface-activated region and the surface-activated region on the second package substrate is any one of the solid-phase direct bonding between Au and Au, the solid-phase direct bonding between Cu and Cu, and the solid-phase direct bonding between Al and Al.

20

5. The sensor device as set forth in claim 1, wherein at least one of said first surface-activated region and said second surface-activated region comprises a ring-like outer surface-activated region formed in over the entire circumference of said frame so as to surround said movable portion, and a ring-like inner surface-activated region formed at an inner side of said outer surface-activated region over the entire circumference of said frame so as to surround said movable portion.

30 6. The sensor device as set forth in claim 5, further comprising an auxiliary

sealing region for connecting between said outer surface-activated region and said inner surface-activated region, and wherein said auxiliary sealing region is formed at plural locations spaced from each other by a predetermined distance in the circumferential direction of said frame.

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7. The sensor device as set forth in claim 1, wherein each of said first surface-activated region of said sensor substrate and the surface-activated region of the first package substrate is an activated surface of an Au film having a thickness of 500 nm or less.

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8. The sensor device as set forth in claim 1, wherein said sensor substrate has an integrated circuit operable in collaboration with said detecting portion, and said integrated circuit is disposed adjacent to said opening of said frame, and electrically connected to a through-hole wiring formed in the first package substrate.

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9. The sensor device as set forth in claim 8, wherein said integrated circuit is disposed so as to surround said opening of said frame.

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10. The sensor device as set forth in claim 8, wherein said through-hole wiring is formed in a tapered shape in the first package substrate such that an end portion facing said sensor substrate has a larger area than the other end portion.

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11. The sensor device as set forth in claim 1, wherein an acceleration sensor is

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mounted on said sensor substrate,

said movable portion comprises a weight and a beam portion extending between said frame and said weight, and

said detecting portion comprises at least one piezoresistive element formed
5 on said beam portion.

12. The sensor device as set forth in claim 11, wherein said sensor substrate is formed by use of an SOI substrate having a silicon layer on a silicon substrate
10 through an insulating layer.

13. The sensor device as set forth in claim 12, wherein said sensor substrate has an integrated circuit operable in collaboration with said detecting portion, and
15 said piezoresistive element and said integrated circuit are formed on the silicon layer of said SOI substrate.

14. The sensor device as set forth in claim 1, wherein a gyro sensor is mounted
20 on said sensor substrate,

said movable portion comprises a first mass body vibrated by a vibrating means, and a second mass body coupled to the first mass body, and

said detecting portion is configured to convert a positional displacement of the second mass body caused when a rotational force is added during the
25 vibration of the first mass body into an electrical signal.

15. The sensor device as set forth in claim 1, wherein said sensor substrate has a conductive layer formed at a position closer to said movable portion than said
30 first surface-activated region, and electrically connected to said detecting

portion,

the first package substrate has a through-hole wiring, and a wiring layer electrically connected to said through-hole wiring, and

the bonding between the first package substrate and said sensor substrate
 5 further comprises a solid-phase direct bonding without diffusion between an activated surface of said conductive layer and an activated surface of said wiring layer.

- 10 16. A method of producing a sensor device comprising the steps of:
 providing a sensor substrate, which comprises a frame having an opening, a movable portion movably held in said opening, and a detection portion configured to output an electric signal according to a positional displacement of said movable portion, a first package substrate bonded to one of opposite
 15 surfaces of said sensor substrate, and a second package substrate bonded to the other surface of said sensor substrate;
 forming a first surface-activated region on a surface of said frame facing the first package substrate over an entire circumference of said frame so as to surround said movable portion;
 20 forming a second surface-activated region on a surface of said frame facing the second package substrate over an entire circumference of said frame so as to surround said movable portion;
 forming a surface-activated region on each of the first package substrate and the second package substrate; and
 25 forming a direct bonding between said first surface-activated region and said surface-activated region of the first package substrate, and a direct bonding between said second surface-activated region and said surface-activated region of the second package substrate at room temperature.

17. The method as set forth in claim 16, wherein said first surface-activated region, said second surface-activated region, the surface-activated regions of the first package substrate and the second package substrate are formed by use of any one of an atomic beam, an ion beam and a plasma of an inert gas.

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18. The method as set forth in claim 16, wherein the steps of forming said first surface-activated region and said second surface-activated region, the step of forming the surface-activated region of each of the first package substrate and the second package substrate, and the direct bonding step are performed in a same chamber, and an interior of said chamber is controlled into a desired atmosphere prior to the direct bonding step.

19. The method as set forth in claim 16, wherein said sensor substrate comprises an integrated circuit operable in collaboration with said detecting portion, an outgoing wiring layer connected at its one end to a pad of said integrated circuit, a first metal layer for providing said first surface-activated region, and a second metal layer connected to the other end of said outgoing wiring layer, and used to connect with a through-hole wiring,

the first package substrate comprises said through-hole wiring, a bonding metal layer formed at a position facing said first metal layer by a same material as said first metal layer, and a wiring metal layer formed at an end portion facing said sensor substrate of said through-hole wiring by a same material as said second metal layer, and

a direct bonding between activated surfaces of said first metal layer and said bonding metal layer and a direct bonding between activated surfaces of said second metal layer and said wiring metal layer are simultaneously formed at room temperature.

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20. The method as set forth in claim 19, wherein said outgoing wiring layer, said first metal layer and said second metal layer are formed by a process comprising the steps of:

- 5 forming a lower metal layer as an etching stopper layer;
forming an upper metal layer on said lower metal layer by use of a metal material different from said lower metal layer; and
etching only said upper metal layer at regions corresponding to said first metal layer and said second metal layer until said lower metal layer is exposed.

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21. The method as set forth in claim 16, wherein said first surface-activated region is formed by a process comprising the steps of:

- forming a multilayer insulating film on said frame of said sensor substrate;
15 forming a flat surface of said multilayer insulating film by etching back a part of said multilayer insulating film;
forming a metal layer on the flat surface; and
irradiating an atomic beam, an ion beam or a plasma of an inert gas to a surface of said metal layer.

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22. The method as set forth in claim 21, wherein said multilayer insulating film comprises a first insulating film of a silicon oxide film formed on said frame, a second insulating film of a silicon nitride film formed on said first insulating film,
25 a third insulating film of at least one interlayer insulating film formed on said second insulating film, and a fourth insulating film of a passivation film formed on said third insulating film, and

the flat surface is formed by performing etching back with use of the insulating film other than said fourth insulating film as an etching stopper
30 layer.

23. The method as set forth in claim 22, wherein the etching back is performed by use of the silicon nitride film of said second insulating film as the etching stopper layer.

24. The method as set forth in claim 22, wherein the flat surface is formed by a process comprising:
a first etching back step using the silicon nitride film of said second insulating film as the etching stopper layer; and
a second etching back step performed after the first etching back step by use of the silicon oxide film of said first insulating film as the etching stopper layer.

25. The method as set forth in claim 16, wherein said sensor substrate comprises an integrated circuit operable in collaboration with said detecting portion, and a conductive layer formed at a position closer to said movable portion than said first surface-activated region, and electrically connected to said integrated circuit,

the first package substrate has a through-hole wiring, and a wiring layer electrically connected to said through-hole wiring, and

a direct bonding between said first surface-activated region and the surface-activated region of the first package substrate and a direct bonding between activated surfaces of said conductive layer and said wiring layer are simultaneously formed at room temperature.