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(71) Applicant: WISCONSIN ALUMNI RESEARCH FOUNDATION [US/US]; 614 N. Walnut Street, P.O. Box 7365, Madison, WI 53707-7365 (US).

(72) Inventor: GIANCHANDANI, Yogesh, B.; 430 Cherry Hill Drive, Madison, WI 53717 (US).

(74) Agents: ENGSTROM, Harry, C. et al.; Foley & Lardner, 150 East Gilman Street, P.O. Box 1497, Madison, WI 53701-1497 (US).

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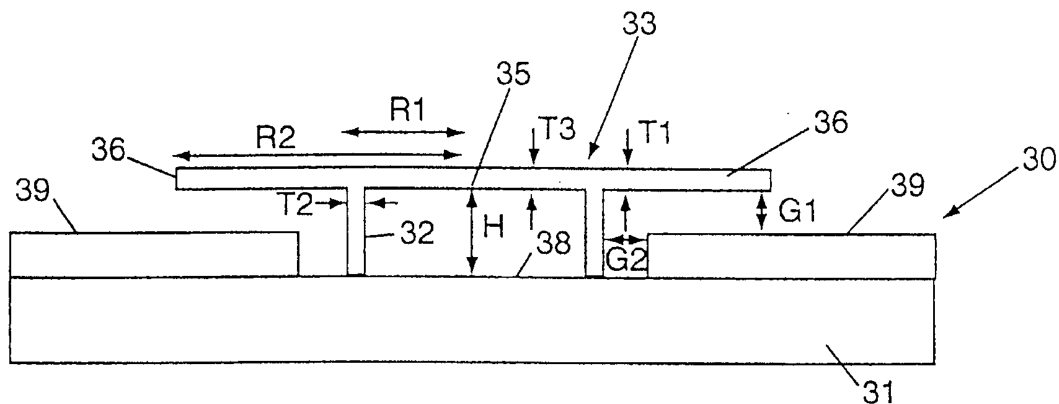

(57) Abstract

A micromachined pressure sensor is formed with a minimum number of masking and processing steps. The structure measures changes in pressure by deflection of structures having capacitive plates external to a sealed cavity so that electrical leads can be readily connected to the plates formed on the structures. The pressure sensor includes a substrate, a base secured to the substrate and a diaphragm secured to the base to define a sealed cavity. A skirt may extend outwardly from the base above the substrate to form one of the plates of the capacitor with another plate formed on the base. Changes in ambient pressure deflect the skirt toward or away from the electrode on the substrate, changing the effective capacitance between the electrodes. Electrical connections may be made to the electrode on the skirt and the electrode on the substrate utilizing electrical connectors which are external to the base and thus external to the sealed cavity.

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SEALED CAPACITIVE PRESSURE SENSORS

FIELD OF THE INVENTION

This invention pertains generally to the field of pressure sensors and
5 particularly to micromachined pressure sensors.

BACKGROUND OF THE INVENTION

Conventional pressure sensors have typically been large, discrete devices formed using a large diaphragm, usually of metal, as the pressure barrier. To minimize the fabrication cost and the size of components, and to reduce the size
10 of the pressure sensor structure to a size comparable to that of integrated circuits to which the sensors are interfaced, significant efforts have been made to produce micromachined pressure sensors on silicon substrates. For example, pressure sensors have been formed by selective etching of a silicon substrate until the etch is terminated by a highly doped layer to form a thin membrane, and by thereafter
15 bonding another member over the membrane to define a cavity, and by forming polysilicon membranes on the surface of a single crystal silicon substrate.

The diaphragm of a pressure sensor deflects in response to the differential pressure across it in a manner which is related to the differential pressure. The deflection of the diaphragm can be measured in various ways,
20 including the use of piezoresistive elements formed on the diaphragm which change in resistance as a function of the strain in the diaphragm, and by capacitive sensing in which a surface of the diaphragm forms one of the plates of a capacitor and the

other plate is formed on the substrate beneath the diaphragm. While capacitive sensing in this manner has advantages over piezoresistive sensing and is commonly used, both for conventional large, discrete pressure sensors and for micromachined sensors, microfabrication of such devices is typically complicated. In particular, where the bottom plate or electrode of the capacitor is sealed in a cavity under the diaphragm, transferring a signal from the plate to the exterior of the cavity, where the signal can be transmitted to interface electronics, presents a formidable manufacturing challenge. In general, several additional microfabrication steps are required to successfully extend a lead from the sealed cavity to the exterior, with the overall process becoming quite complicated, requiring as many as ten masking steps. See, e.g., A.V. Chavan and K.D. Wise, "A Batch-Processed Vacuum-Sealed Capacitive Pressure Sensor," Proc. Int'l. Conf. On Solid-State Sensors and Actuators, Chicago, Illinois, June 1997, pp. 1449-1452; A.V. Chavan and K.D. Wise, "A Multi-Lead Vacuum-Sealed Capacitive Pressure Sensor," Proc. Solid-State Sensor and Actuator Workshop, Hilton Head Island, S.C., June 1998, pp. 212-215. Some approaches accomplish hermetic sealing of the sensor cavity with techniques that are not generally compatible with lithography-based batch-fabrication techniques. Y. Wang and M. Esashi, "A Novel Electrostatic Servo Capacitive Vacuum Sensor," Proc. Int'l. Conf. On Solid-State Sensors and Actuators, Chicago, Illinois, June, 1997, pp. 1457-1460.

SUMMARY OF THE INVENTION

A micromachined pressure sensor in accordance with the invention can be formed utilizing a minimum number of masking and processing steps while avoiding the need to extend an electrical lead through a wall of the sealed cavity of the pressure sensor. Changes in pressure result in deflection of structures having capacitive plates formed thereon which are external to the sealed cavity, so that electrical leads can be readily connected to the plates formed on such structures. The capacitive pressure sensors can be formed in a manner which is compatible with conventional lithographic processing of silicon substrates as carried out in standard integrated circuit production, allowing such pressure sensors to be

interfaced with integrated circuits. The deformable structures of the sensor may be formed of conventional materials used in microelectronic processing, such as crystalline silicon, in an efficient and economical production process.

A pressure sensor in accordance with the invention includes a substrate, a base secured to the substrate and a diaphragm secured to the base to define a sealed cavity between the base, substrate and diaphragm. A first electrode is formed on at least one of the diaphragm or base to deflect therewith and a second electrode is formed adjacent thereto. An electrode formed, for example, on the substrate may comprise the second electrode and form one of the plates of a capacitor. A skirt extending outwardly from the base above the substrate may form the first electrode as the other plate of the capacitor, with at least one of the diaphragm or the base deforming and deflecting with changes in ambient pressure to deflect the skirt toward or away from the other electrode to change the effective capacitance therebetween in a manner which is related to the changes in pressure.

The base may be formed as a hollow cylinder and the diaphragm and skirt may be formed integrally together as a flat, circular plate which is secured to the top of the base (e.g., by being integrally formed therewith) to provide a sealed cavity under the diaphragm and with the skirt extending outwardly from the periphery of the base over an electrode formed on the substrate. The skirt itself may form one of the plates of the variable capacitor by, for example, being formed of heavily doped and electrically conductive silicon, with the other electrode plate of the capacitor deposited as a metal film on the substrate under the skirt. Alternatively, two separate electrodes forming the plates of the capacitor may be formed underneath the skirt and being coupled to each other through the skirt so that deflections of the skirt change the relative capacitance between the two separated plates. The skirt may also be formed to extend from the base at positions intermediate the top and bottom of the base rather than extending from the diaphragm, and may be formed to have various modified cantilever structures which position a section of the skirt more closely adjacent to the underlying capacitor plate on the substrate while maintaining the full height of the base. The base may also be formed with alternative structures in multiple parts with the skirt extending between

the deformable base structures, and the skirt itself may be integrally formed as a wall of the base with the skirt deflecting in response to changes in pressure within the sealed cavity to change the relative position of the sidewall of the base, functioning as the skirt, with respect to an adjacent electrode plate. Because the
5 skirt may be formed to deflect away from the adjacent electrode with increasing ambient pressure, the pressure sensors of the present invention are well suited to feedback control in which a voltage is applied across the plates of the capacitor at an appropriate level to deflect the skirt back toward a reference position.

Further objects, features and advantages of the invention will be
10 apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Fig. 1 is a simplified cross-sectional view of a pressure sensor in
15 accordance with the invention.

Fig. 2 is a cross-sectional view of the pressure sensor of Fig. 1 shown partially deflected.

Fig. 3 is a cross-sectional view of the pressure sensor of Fig. 1 shown with the diaphragm deflected to touch-down.

20 Fig. 4 is a graph illustrating computed deflection versus pressure for an exemplary pressure sensor as in Fig. 1.

Fig. 5 is a graph illustrating pressure versus capacitance for the exemplary pressure sensor in accordance with Fig. 4.

Fig. 6 is a graph of computed deflection versus pressure for another
25 exemplary pressure sensor of the invention.

Fig. 7 is a graph of computed capacitance versus pressure for a pressure sensor as in Fig. 6.

Fig. 8 is a graph of computed deflection versus pressure for a further exemplary pressure sensor in accordance with the invention.

Fig. 9 is a graph of computed capacitance versus pressure for the pressure sensor as in Fig. 8.

Fig. 10 is a simplified cross-sectional view illustrating a first step in the fabrication of a pressure sensor as shown in Fig. 1.

5 Fig. 11 is a simplified cross-sectional view showing a diffusion step in the formation of a pressure sensor as in Fig. 1.

Fig. 12 is an illustrative cross-sectional view of a glass substrate to be used in the formation of pressure sensor as in Fig. 1.

Fig. 13 is a simplified cross-sectional view illustrating the assembly 10 of the pressure sensor as in Fig. 1.

Fig. 14 is a simplified perspective view illustrating a structure for an electrical connection to the deformable silicon diaphragm of the pressure sensor.

Fig. 15 is a perspective view of an alternative structure for an electrical connection to the deformable diaphragm of the pressure sensor.

15 Fig. 16 is a perspective view of an alternative arrangement for capacitive coupling to the deformable diaphragm.

Fig. 17 is a simplified cross-sectional view illustrating an alternative structure with the diaphragm of the pressure sensor mounted over a depression in the substrate.

20 Fig. 18 is an alternative structure with the pressure sensor mounted within a depression in the substrate.

Fig. 19 is a simplified cross-sectional view of a pressure sensor with a thickly plated external electrode.

Fig. 20 is a simplified cross-sectional view of a pressure sensor 25 formed in a depression on a silicon-on-insulator substrate.

Figs. 21-28 are simplified cross-sectional views of further configurations of the pressure sensor in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

With reference to the drawings, a simplified cross-sectional view of a 30 microfabricated pressure sensor in accordance with the invention is shown in cross-

section generally at 30 in Fig. 1. The pressure sensor 30 is formed on a structural substrate 31, e.g., glass, to which is attached a deformable sensor structure comprising a base section 32 (which may be but is not necessarily cylindrical) and a flat deformable diaphragm 33. The diaphragm 33 has a central section 35 and an
5 outwardly extending peripheral skirt section 36. The central portion 35 of the diaphragm together with the cylindrical walls of the base 32 and a surface 38 of the substrate 31 define a sealed cavity, which may be evacuated or set at a reference pressure. An electrode ring 39, e.g., of a conductive metal such as platinum, gold, aluminum, etc., is formed on the substrate 31 under the extending skirt 36. The
10 electrode 39 forms one of the plates of a capacitor, a second or stationary electrode, with the other plate defining a first or deflecting electrode formed by the extending skirt 36 spaced above and adjacent to the electrode 39. For example, the skirt 36 may be coated with an electrically conductive material or the skirt itself may be formed of a material, such as single crystal silicon, which is doped to be electrically
15 conductive.

As illustrated in Fig. 2, an increase in ambient pressure causes a downward deflection of the center portion 35 of the diaphragm 33, bringing the center of the diaphragm closer to the substrate surface 38. This deflection, in turn, raises the skirt 36 away from the plates 39. If the pressure increases enough, the
20 central portion 35 of the diaphragm 33 will touch down to the surface 38 as illustrated in Fig. 3. However, because of the manner of the construction of the sensor, further increases in pressure continue to result in changes in the deflection of the skirt or flap sections 36 away from the plate 39, allowing the pressure sensor to continue to detect pressure changes even at such "over-pressure" conditions.
25 It is a particular advantage of the pressure sensor structure of the present invention that the skirt, with its associated electrode, can deflect away from the adjacent electrode (e.g., as formed on the substrate) with increases in pressure. In conventional capacitive pressure sensor designs, the diaphragm with its associated electrode is drawn closer to the underlying electrode on the substrate as
30 the ambient pressure increases. Consequently, it is generally not possible to control the position of the diaphragm by applying a voltage between the electrodes on the

substrate and diaphragm, since such a voltage would tend to draw the diaphragm toward the substrate. In contrast, applying a voltage between the skirt 36 and the underlying electrode 39 tends to draw the skirt toward the substrate, which can thus oppose the upward deflection of the skirt as ambient pressure increases. This
5 feature allows feedback control of the position of the skirt toward a reference position, and the level of the voltage applied between the plates to maintain the reference position may be used as a signal indicative of the ambient pressure.

To illustrate the properties of the pressure transducer in accordance with the invention, the following dimensions and displacements, which are
10 illustrated with respect to Figs. 1 and 2, may be defined:

T1 = Thickness of skirt or flap 36;
T2 = Thickness of sidewalls;
T3 = Thickness of central cap 35 on sealed cavity;
R1 = Radius of sealed cavity;
15 R2 = Radius of diaphragm;
H = Height of sealed cavity;
G1 = Nominal gap between skirt 36 and electrode 39;
G2 = Clearance between electrode 39 and sidewalls of base 32;
D1 = Deflection at center of diaphragm (downward is negative,
20 upward positive);
D2 = Deflection at support where diaphragm 33 is attached to base 32; and
D3 = Deflection at peripheral rim of skirt 36.

25 The following examples illustrate the performance of a pressure sensor as in Fig. 1. In each example, the parameters T1=T2=T3=5μm; H=30μm; G1=5μm; G2=0; Young's modulus = 160 GPa; residual stress = 20 MPa tensile; and Poisson's ratio = 0.2.

For the first example, in which R1 = 300μm and R2 = 424μm, Fig.
30 4 illustrates the calculated deflection versus pressure and Fig. 5 illustrates calculated capacitance versus pressure. As shown therein, the deflection of the center of the diaphragm terminates as the diaphragm reaches bottom but the displacement of the extending skirt, and thereby the relative capacitance between the plates of the sensor capacitor, continues to change beyond the point of touch down. Fig. 6 illustrates
35 computed deflection versus pressure and Fig. 7 illustrates computed capacitance versus pressure for a second pressure sensor in which R1 = 500μm and R2 =

707μm. Fig. 8 illustrates computed deflection versus pressure and Fig. 9 illustrates computer capacitance versus pressure for a third example in which R1 = 500μm and R2 = 1000μm. Again, for each of these examples, it is seen that the capacitance changes with applied pressure in a substantially linear manner up to
5 touch-down, but also continues to change in response to additional pressure in a repeatable (if nonlinear) manner after touch-down of the diaphragm to the underlying substrate surface.

The sealed cavity pressure sensor of the invention can be produced utilizing standard semiconductor processing techniques with fewer masking and
10 etching steps than are required for other sealed cavity micromachined capacitive pressure transducers. Suitable processing techniques are described in the article by Yogesh B. Gianchandani and Khalil Najafi, "A Bulk Silicon Dissolved Wafer Process for Micromechanical Devices," J. of Micromechanical Systems, Vol. 1, No. 2, June, 1992, pp. 77-85. A processing sequence for producing the pressure
15 transducer 30 of Figs. 1-3 is illustrated with respect to the views of Figs. 10-13, in which only three masking steps are required. The first step, as illustrated in Fig. 10, involves the lithographic masking of a single crystal semiconductor (e.g., silicon) substrate 45 and etching using reactive ion etching, or any other suitable method, to etch away the substrate in areas 46 adjacent to the structure and to leave
20 a central cavity 47 which is surrounded by a relatively thin walled cylindrical structure 48 which will constitute the base of the pressure sensor. The next step, as illustrated in Fig. 11, is the masking of the regions of the substrate 45 to define areas 50 on either side of the cylinder 48 and a boron diffusion step in which boron diffuses entirely through the upright cylinder 48 and to a selected depth into the
25 substrate 45 in the regions 50 which surround the cylindrical structure 48. It is understood that the views of Figs. 10 and 11 are illustrative cross-sectional views, and that the regions 50 constitute a region (which may be circular or other configuration) surrounding the cylindrical structure 48. In a next step, as illustrated in Fig. 12, a structural substrate such as a glass wafer substrate 31 has metal
30 electrodes 54 and 39 inlaid thereon. The electrodes 54 and 39 are separated by an open surface area 55 of the glass structural substrate 31 which electrically insulates

the electrodes 39 and 54 from each other. The structure shown in Fig. 13 is immersed in an enchant which etches away the undoped portions of the silicon substrate 45 to leave the diaphragm 33 defined by the heavily boron doped portion of the substrate. The regions 50 are free to now define the extending skirt sections 36 of the diaphragm and the central portion 35. The freed part is anodically bonded to the structural substrate 31, as illustrated in Fig. 13, preferably before or alternatively after etching away of the semiconductor substrate 45, with the electrode 54 in contact with and extending partially, but not entirely, underneath the cylindrical wall 32 of the base. The electrode 54 is thus in electrical contact with the base 32, and thus with the diaphragm 33 because the base and diaphragm are heavily doped and therefore are good electrical conductors. The electrode 39 forms a plate of the capacitor with the extending skirt portions 36 of the diaphragm. Although the semiconductor structure is shown in cross-section only in Fig. 13, it is understood that the electrode 39 would be formed in a pattern surrounding the base 32 at the electrode 54 (where the electrode 39 terminates so that it remains spaced from and electrically isolated from the electrode 54).

Other ways for making contact to the diaphragm or otherwise providing coupling without requiring connections through the walls of the sealed cavity are illustrated in Figs. 14-16. As shown in Fig. 14, connection may be made to the diaphragm 33 by a protruding post of heavily doped silicon 60 which extends up from contact to an electrode 54 to contact with the diaphragm 33. A notch may be formed in the skirt 36 around the post 60 to allow the skirt to flex freely. In the structure shown in Fig. 15, a free-standing post of heavily doped silicon 62 extends upwardly from contact to an electrode 54, with silicon wires 63 extending from the post 62 to the edge of the diaphragm 33. In Fig. 16, a first half electrode 39 and a second half electrode 54 are formed on the substrate 31, with the base 32 and diaphragm 33 being electrically isolated from both of the electrodes 39 and 54. The electrodes 39 and 54 are capacitively coupled together through the diaphragm 33, which thus forms an intermediate conductive sheet in the capacitor defined between these two electrodes.

One way to increase the effective capacitance, and thus the sensitivity, of the pressure sensor is to reduce the spacing between the deformable diaphragm and the electrode 39. Structures in accordance with the invention which may be utilized to reduce electrode spacing while maintaining the relative dimensions of the structure, particularly the sealed cavity, are illustrated in Figs. 17-20. With reference to Fig. 17, the substrate 31 is formed with a well or depression 65 therein which is encircled by the base 32 bonded to the surface of the substrate 31. The height of the cylindrical walls 32 can thus be made shorter while maintaining the same maximum downward deflection of the diaphragm 35. In Fig. 18, a large depression 66 is formed in the substrate 31 which has a large flat bottom 67 that is wide enough to receive the entire base 32, and the base is bonded to the bottom surface 67 of the depression. In this manner, the total height of the cylindrical base 32 may be maintained while nonetheless reducing the spacing between the electrode 39 and the outwardly extending skirt 36. As shown in Fig. 19, the spacing between the electrode 39 and the extending skirt 36 may also be reduced by forming a very thick electrode 39 (e.g., by electroplating onto the substrate) to a desired height which results in the reduced spacing between the electrode and the skirt. As shown in Fig. 20, other substrates 31 may be used, including a silicon-on-insulator substrate which includes a base layer of crystalline silicon 68, an insulating layer of silicon dioxide 69, and a surface layer 68' of silicon grown on the oxide layer 69. A depression 65 is formed by etching into the surface silicon layer 68' until it reaches the surface 65 of the oxide layer 69. The base 32 is then bonded on to the exposed surface 65 of the oxide, with a resulting reduced spacing between the electrode 39 and the extending skirt 36 of the diaphragm.

Various other structures may be formed in accordance with the invention in addition to the cylindrical base topped by a flat diaphragm structure of Figs. 1-3. Examples of such structures are illustrated in Figs. 21-28. In the structure of Fig. 21, a cylindrical base 70 is closed at its top by a diaphragm panel 71 and has skirts 72 forming the first electrode extending outwardly from the cylindrical base 70 at an intermediate position more closely spaced to the second

electrode 39 on the substrate. In the structure of Fig. 22, a cylindrical base 75 is sealed at its top by a diaphragm 76 that has a downwardly extending portion 77 and an outwardly extending portion 78 which defines a skirt forming a first electrode spaced closely adjacent to the second electrode 39. In both of the structures of Fig. 21 and Fig. 22, flexing of the diaphragm and the cylindrical sidewalls with changes in pressure will cause deflection of the extending skirts 72 and 78 to result in changes in capacitance.

In the structure of Fig. 23, a sealed interior cylindrical can structure 80, formed of a base with a diaphragm panel sealed thereto similar to the structure of Fig. 21, is surrounded by a closely spaced outer cylindrical structure 81 which has openings 82 in the top wall thereof. As the walls of the inner cylindrical can 80 that define the first electrode extend outwardly or draw inwardly with changes in ambient pressure, the capacitance between the closely adjacent surfaces of the inner cylinder 80 and the outer cylinder 81 (forming the second electrode) changes. In the structure of Fig. 24, two sealed cavity structures 85 and 86 formed of a base sealed by a diaphragm panel are mounted closely adjacent to each other on the surface of the substrate 31 separated by a small spacing distance 87. As the walls of the structures 85 and 86, which form the first and second electrodes, expand or contract with pressure, the closely adjacent walls in these two structures will deflect toward or away from each other, changing the capacitance between the structures.

In the structure of Fig. 25, a base 90 is secured to the substrate 31 and has upwardly extending cylindrical sidewalls 91 and outwardly extending skirt sections 92 forming a first electrode which are spaced above the second electrode 39. A sealed cavity in this case is formed by securing a further diaphragm structure 93 to the top of the skirt sections 92. As the diaphragm 93 is, for example, pushed downwardly by increasing pressure, the skirts 92 will be drawn upwardly away from the electrode 39, thereby changing the capacitance between these structures. The structure of Fig. 25 is adapted for production by a surface micromachining process using typical micromachined materials, e.g., polysilicon.

In the structure of Fig. 26, two sealed, spaced cavity structures 97 and 98, formed of a base sealed by a diaphragm, are mounted to the substrate 31

above a single second electrode 39 and have a bridge skirt section 99 between them forming the first electrode, which is suspended above the second electrode, and which may be perforated with openings 100. The structures 97 and 98 may be a single semi-annular cavity to ensure that the pressures in the two sides of the cavities are the same. As the walls of the sealed cavity structures 97 and 98 expand outwardly or contract inwardly with changes in pressure, the thin bridge skirt 99 between them will bulge upwardly or downwardly to change the effective capacitance with respect to the electrode 35.

In the structure of Fig. 27, a cylindrical base 105 is bonded to the surface of the substrate 31 and has outwardly extending skirts 106. Instead of a flat diaphragm, the diaphragm is formed with a conical form 107. As the surfaces of the conical section 107 are pushed inwardly with increasing pressure, the skirt portions 106 forming the first electrode are rotated upwardly away from the second electrode 39 to change the capacitance, and vice versa with a decrease in external pressure.

In the structure of Fig. 28, a hemispherical base 110 defining a continuous base and diaphragm structure is bonded to the substrate 31 to form a sealed cavity 111. A skirt 113 forming the first electrode extends out from the base 110 over the second electrode 39 in close proximity thereto. As the domed structure 110 deflects inwardly under increasing pressure, the skirt section 113 is rotated away from the electrode 39, and vice versa with a decrease in pressure.

It is understood that the invention is not confined to the particular construction and arrangement of parts set forth herein for illustration, but embraces such modified forms thereof as come within the scope of the following claims.

CLAIMS

What is claimed is:

1 1. A micromachined pressure sensor comprising:
2 (a) a substrate;
3 (b) a base secured to the substrate;
4 (c) a diaphragm secured to the base to define a cavity between the
5 base, substrate and diaphragm;
6 (d) a skirt extending from the base above the substrate with at
7 least one of the diaphragm or the base deforming and deflecting with changes in
8 ambient pressure to deflect the skirt; and
9 (e) adjacent electrodes, one of the electrodes formed to deflect
10 with the skirt to change the effective capacitance between the electrodes in a manner
11 which is related to changes in pressure.

1 2. The micromachined pressure sensor of Claim 1 wherein the
2 diaphragm and skirt are integrally formed together.

1 3. The micromachined pressure sensor of Claim 1 wherein the
2 base is formed as a hollow cylinder and the diaphragm and skirt are formed
3 integrally together as a flat circular plate which is secured to a top of the base.

1 4. The micromachined pressure sensor of Claim 3 wherein the
2 integrally formed diaphragm and skirt are integrally formed with the base.

1 5. The micromachined pressure sensor of Claim 1 wherein the
2 electrode that deflects with the skirt is defined in the skirt and the other electrode is
3 a plate formed on the substrate under the skirt.

1 6. The micromachined pressure sensor of Claim 5 wherein the
2 electrode formed in the skirt is formed of heavily doped and electrically conductive
3 silicon.

1 7. The micromachined pressure sensor of Claim 6 wherein the
2 other electrode plate of the capacitor is deposited as a metal film on the substrate
3 under the skirt.

1 8. The micromachined pressure sensor of Claim 1 wherein the
2 electrodes of the capacitor are formed underneath the skirt and are coupled to each
3 other through the skirt so that deflections of the skirt change the relative capacitance
4 between the two separated plates.

1 9. The micromachined pressure sensor of Claim 1 wherein the
2 skirt is formed to extend from the base at positions intermediate a top and bottom of
3 the base.

1 10. The micromachined pressure sensor of Claim 1 wherein the
2 base, diaphragm and skirt are formed of silicon.

1 11. The micromachined pressure sensor of Claim 1 including an
2 electrical connection extending from the substrate to the electrode formed to deflect
3 with the skirt at positions exterior to the base.

1 12. A micromachined pressure sensor comprising:
2 (a) a substrate;
3 (b) a base formed as a hollow cylinder secured to the substrate;
4 (c) a diaphragm secured to the base above the substrate to define
5 a cavity between the base, substrate and diaphragm;
6 (d) a skirt extending outwardly from the base above the substrate
7 with at least one of the diaphragm or the base deforming and deflecting with
8 changes in ambient pressure to deflect the skirt; and
9 (e) a first electrode formed on the skirt to deflect with the skirt
10 and an adjacent second electrode on the substrate such that deflection of the skirt
11 with changes in pressure changes the effective capacitance between the electrodes.

1 13. The micromachined pressure sensor of Claim 12 wherein the
2 diaphragm and skirt are integrally formed together.

1 14. The micromachined pressure sensor of Claim 12 wherein the
2 diaphragm and skirt are formed integrally together as a flat circular plate which is
3 secured to a top of the base.

1 15. The micromachined pressure sensor of Claim 14 wherein the
2 integrally formed diaphragm and skirt are integrally formed with the base.

1 16. The micromachined pressure sensor of Claim 12 wherein the
2 first electrode is formed in the skirt of heavily doped and electrically conductive
3 silicon.

1 17. The micromachined pressure sensor of Claim 16 wherein the
2 second electrode of the capacitor is deposited as a metal film on the substrate under
3 the skirt.

1 18. The micromachined pressure sensor of Claim 12 wherein the
2 skirt is formed to extend outwardly from the base at positions intermediate a top and
3 bottom of the base.

1 19. The micromachined pressure sensor of Claim 12 wherein the
2 base, diaphragm and skirt are formed of silicon.

1 20. The micromachined pressure sensor of Claim 12 including an
2 electrical connection extending from the substrate to the first electrode at positions
3 exterior to the base.

1 21. A micromachined pressure sensor comprising:
2 (a) a substrate;
3 (b) a base secured to the substrate;
4 (c) a diaphragm secured to the base to define a cavity between the
5 base, substrate and diaphragm, at least one of the diaphragm or base deforming and
6 deflecting with changes in ambient pressure;
7 (d) a first electrode formed on at least one of the diaphragm or
8 the base to deflect therewith, and a second electrode mounted adjacent thereto to

9 form a capacitor with the first electrode such that the effective capacitance between
10 the electrodes changes as the first electrode is deflected in a manner which is related
11 to changes in pressure.

1 22. The micromachined pressure sensor of Claim 21 wherein the
2 base is formed as a hollow cylinder and the diaphragm is secured to the top of the
3 base, and wherein the second electrode is formed as an exterior outer cylindrical
4 structure having an inner surface adjacent to the outer surface of the cylindrical base
5 such that the capacitance between the adjacent surfaces of the inner cylindrical base
6 and the outer cylindrical structure of the second electrode changes with changes in
7 ambient pressure.

1 23. The micromachined pressure sensor of Claim 21 wherein the
2 base is a first base comprising a hollow structure secured to the substrate and sealed
3 with the diaphragm, and wherein the second electrode comprises a second hollow
4 base structure secured to the substrate and closed with a diaphragm and mounted
5 adjacent to the first base with closely spaced walls that define the first and second
6 electrodes, such that changes in ambient pressure deform and deflect the walls of
7 the first and second bases such that the effective capacitance between electrodes
8 formed on the walls of the bases is related to changes in pressure.

1 24. The micromachined pressure sensor of Claim 21 including a
2 skirt extending from the base over the second electrode to deflect with deformations
3 and deflections of walls of the base, the first electrode formed on the skirt to deflect
4 therewith to change the effective capacitance between the first and second
5 electrodes.

1 25. The micromachined pressure sensor of Claim 24 wherein the
2 base includes a base structure secured to the substrate and closed by a diaphragm to
3 define a sealed cavity with the skirt extending as a bridge structure connected
4 thereto to deform with changes in the ambient pressure within the sealed cavity.

1 26. The micromachined pressure sensor of Claim 21 wherein the
2 second electrode is formed as a skirt extending outwardly from the base above the
3 substrate with the first electrode formed to deflect with the skirt to change the
4 effective capacitance between the first and second electrodes in a manner which is
5 related to changes in pressure.

1 27. The micromachined pressure sensor of Claim 26 wherein the
2 diaphragm and skirt are integrally formed together.

1 28. The micromachined pressure sensor of Claim 26 wherein the
2 base is formed as a hollow cylinder and the diaphragm and skirt are formed
3 integrally together as a flat circular plate which is secured to a top of the base and
4 wherein the integrally formed diaphragm and skirt are integrally formed with the
5 base.

1 29. The micromachined pressure of Claim 28 wherein the first
2 electrode is formed in the skirt of heavily doped and electrically conductive silicon.

1 30. The micromachined pressure sensor of Claim 29 wherein the
2 second electrode of the capacitor is a plate deposited as a metal film on the substrate
3 under the skirt.

1 31. The micromachined pressure sensor of Claim 26 wherein the
2 skirt is formed to extend from the base at positions intermediate a top and bottom of
3 the base.

1 32. The micromachined pressure sensor of Claim 21 wherein the
2 base and diaphragm are formed of silicon.

1 33. A method of forming a micromachined pressure sensor
2 comprising:
3 (a) lithographically masking a semiconductor substrate and
4 etching away the semiconductor substrate to leave a central cavity which is
5 surrounded by a relatively thin walled base structure;

6 (b) masking regions of the semiconductor substrate on the sides
7 of the base structure and diffusing a dopant into the base structure to a selected
8 depth and into the substrate in a region around the base structure which extends
9 outwardly therefrom;
10 (c) bonding the base structure to a structural substrate to form a
11 cavity defined by the structural substrate, the base structure and the diaphragm;
12 (d) etching away the undoped portions of the semiconductor
13 substrate to leave a diaphragm with an outwardly extending skirt defined by the
14 heavily doped portions of the semiconductor substrate and integrally attached to the
15 base structure.

1 34. The method of Claim 33 further including before bonding the
2 cylindrical base structure to the structural substrate the steps of forming an electrode
3 on the structural substrate in positions adjacent to the base structure which will be
4 under the outwardly extending skirt.

1 35. The method of Claim 33 wherein the structural substrate is
2 formed of glass and the step of bonding the base structure to the structural substrate
3 is carried out by anodically bonding.

1 36. The method of Claim 33 wherein the regions which surround
2 the base structure in the semiconductor substrate are diffused with a dopant in a
3 circular pattern to define a circular skirt which extends outwardly from the base
4 structure.

1 37. The method of Claim 33 wherein the semiconductor substrate
2 is single crystal silicon.

1 38. The method of Claim 37 wherein the dopant is boron.

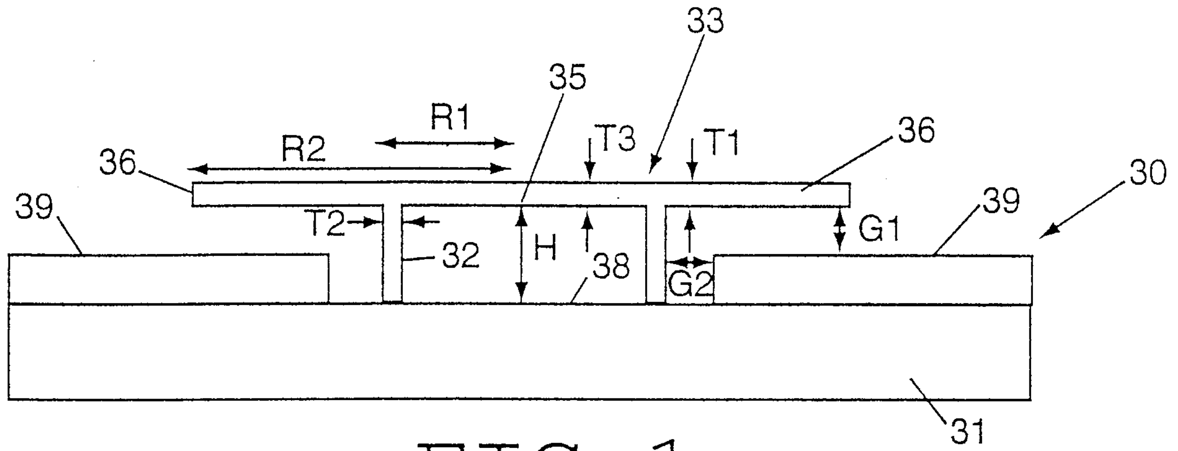


FIG.1

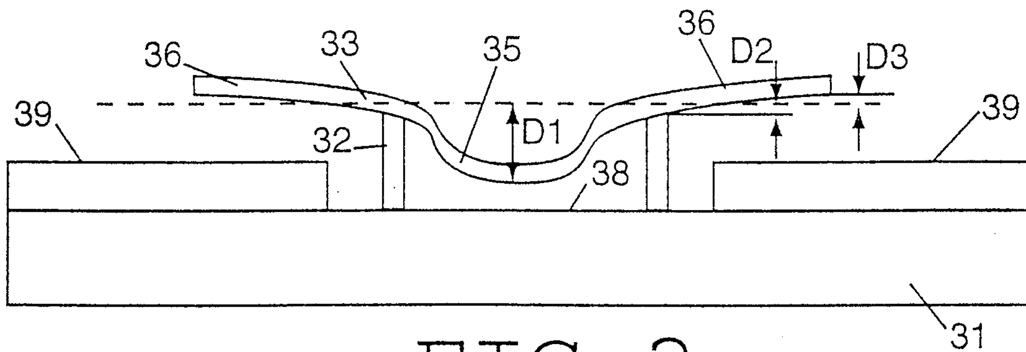


FIG.2

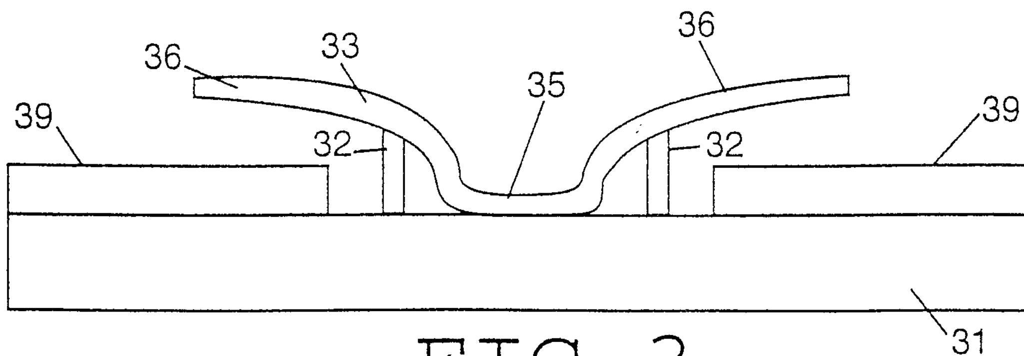
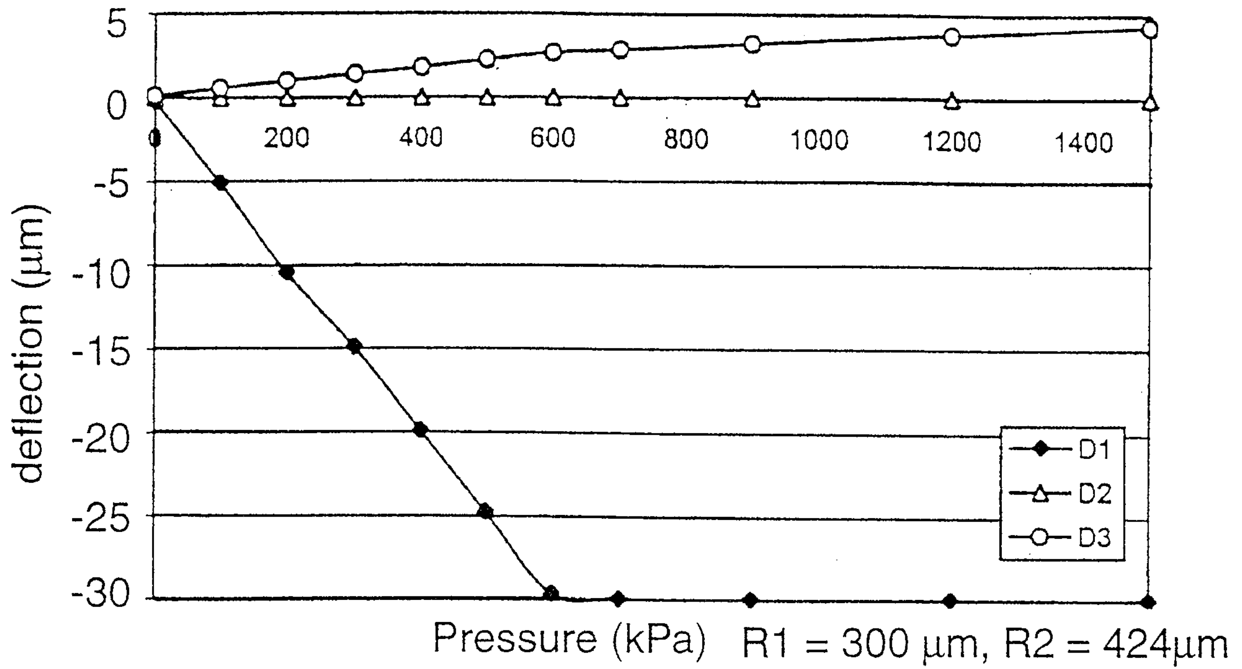


FIG.3



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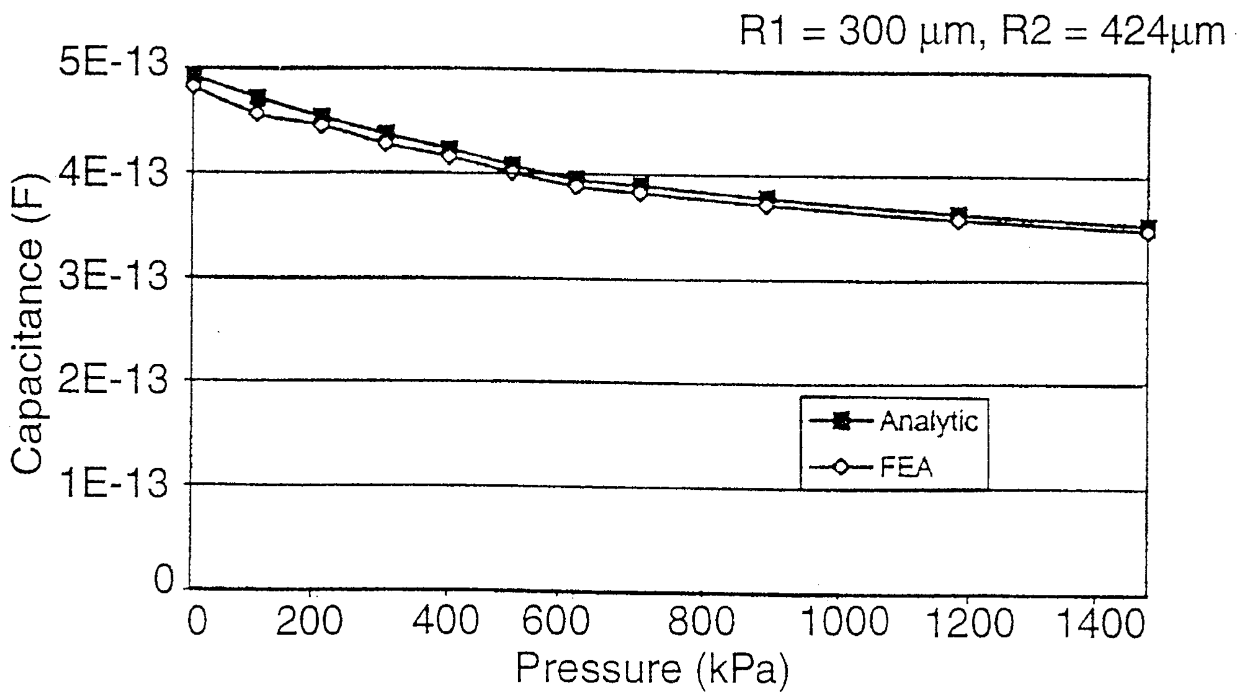

FIG.5

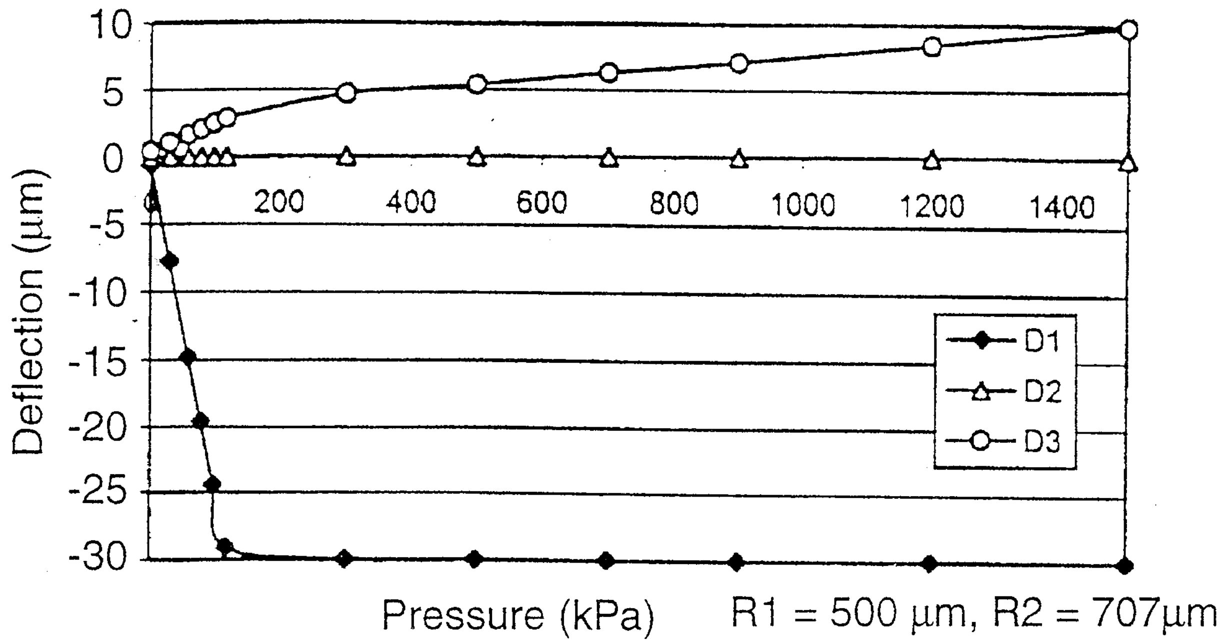

FIG.6

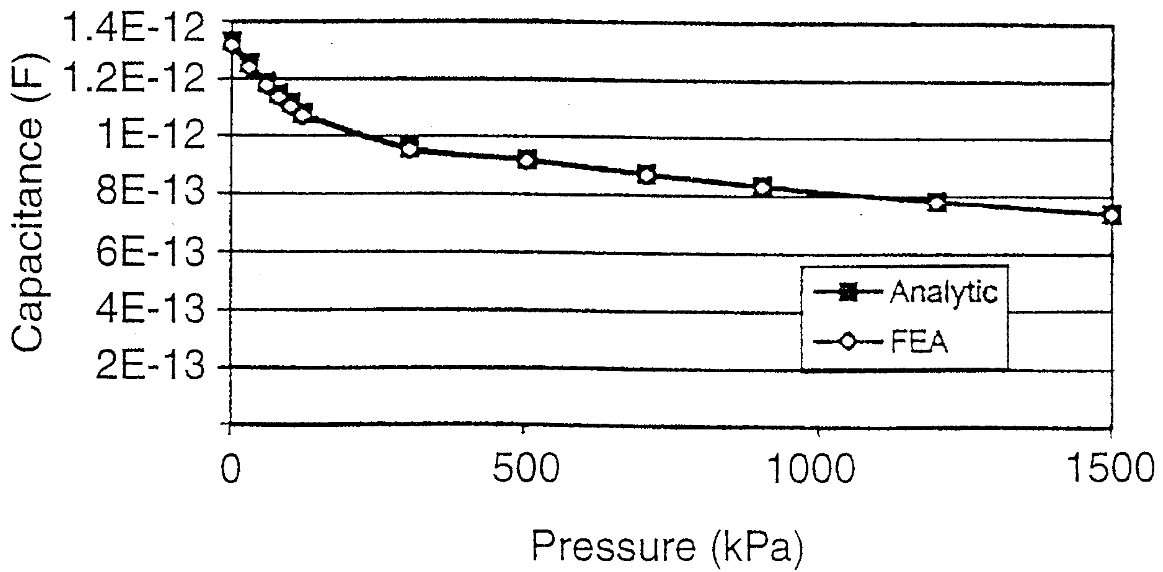

FIG.7

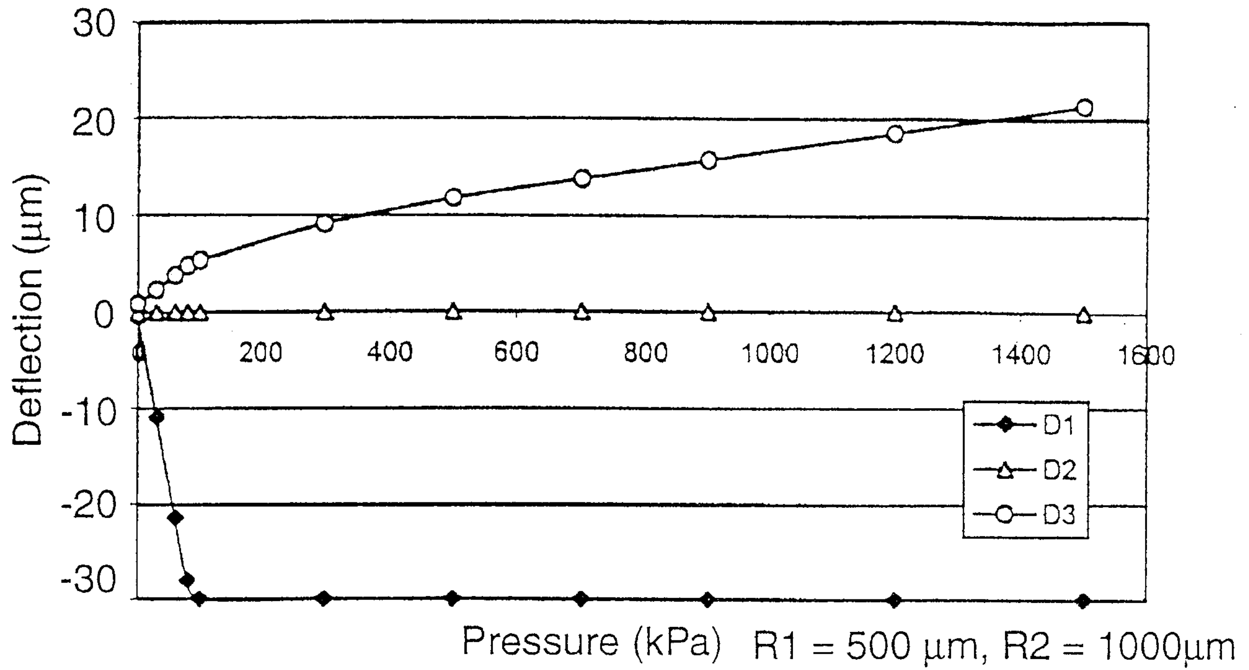

FIG. 8

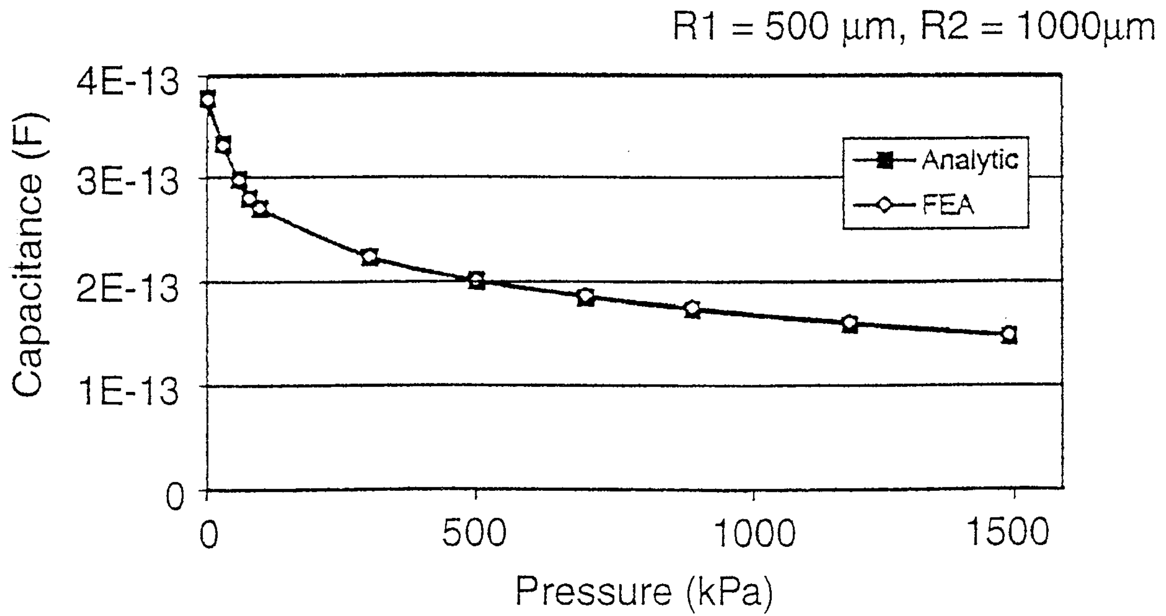

FIG. 9

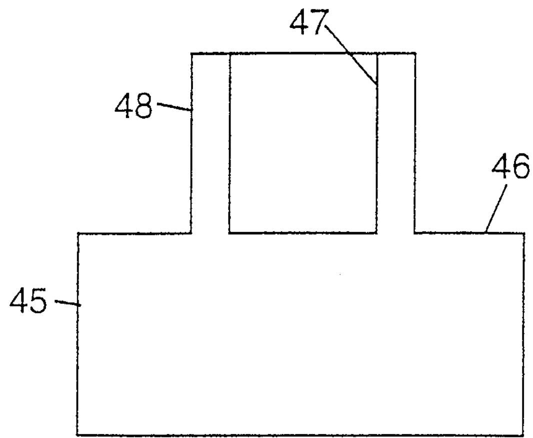

FIG.10

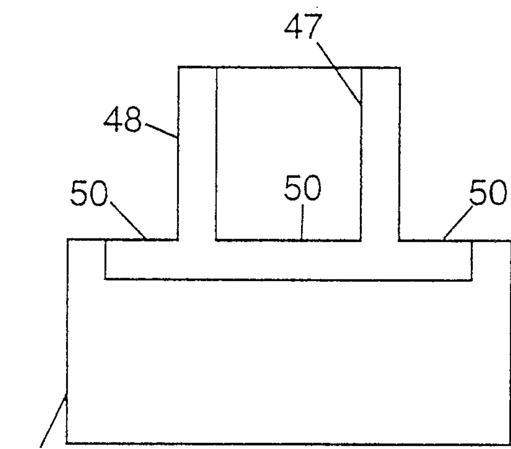

FIG.11

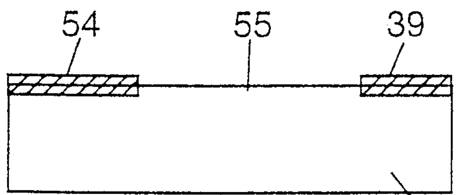

FIG.12

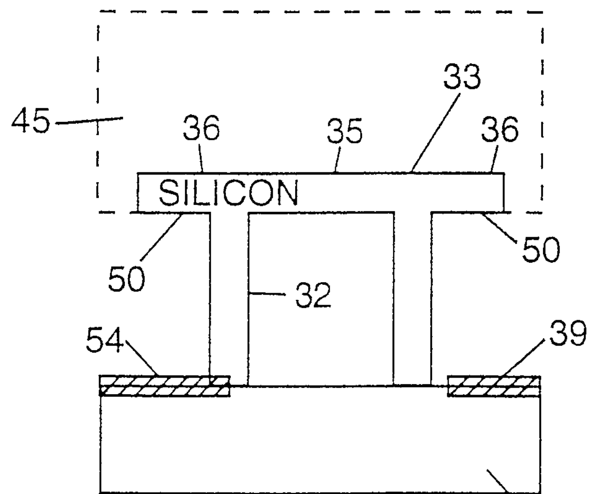

FIG.13

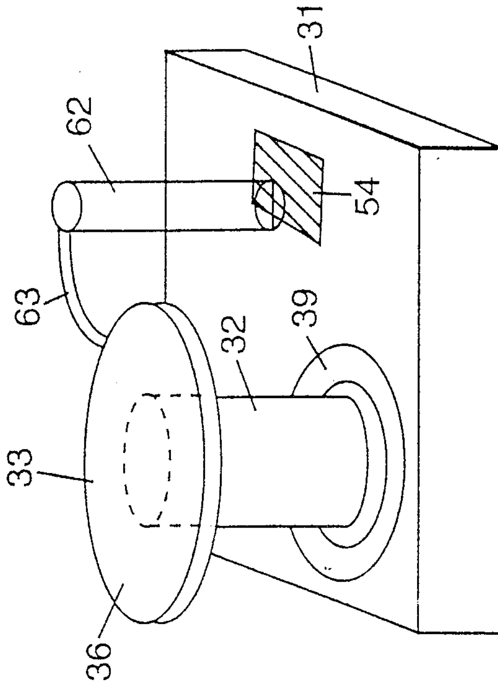

FIG.15

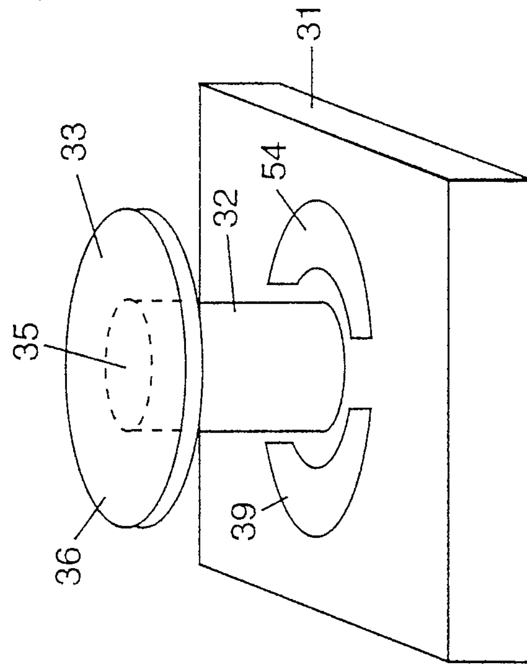

FIG.16

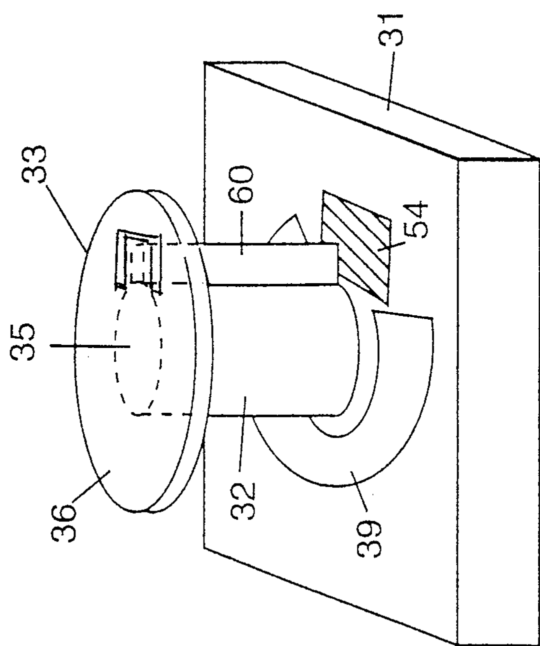

FIG.14

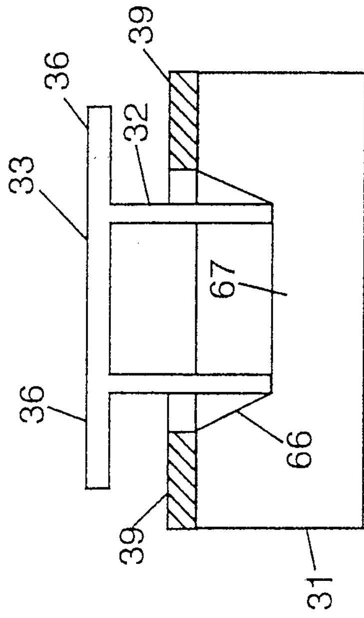

FIG.18

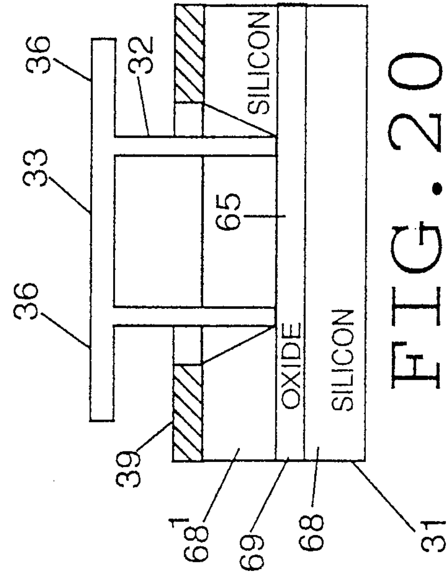

FIG.20

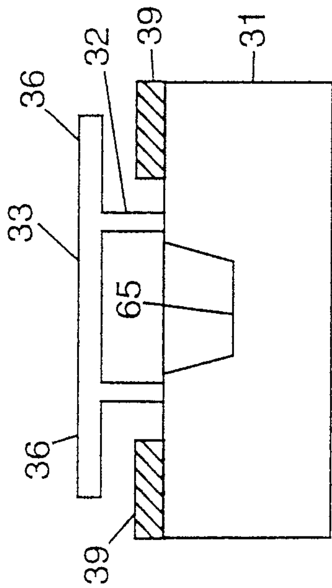

FIG.17

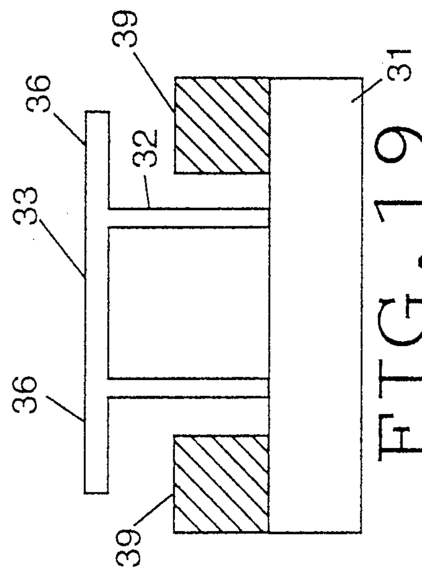

FIG.19

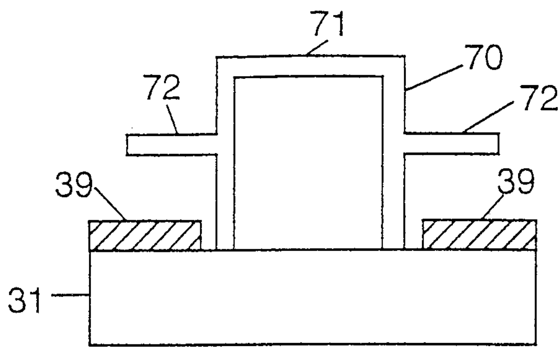

FIG.21

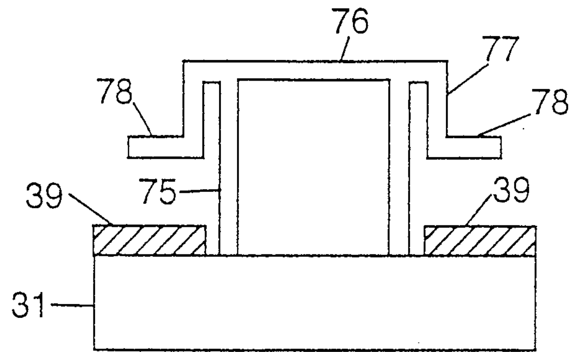

FIG.22

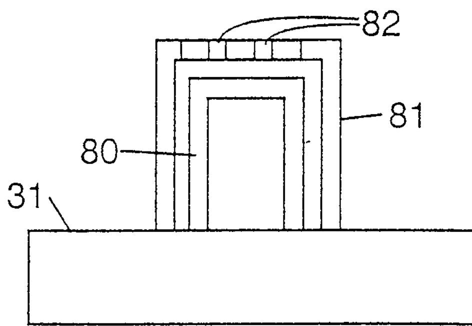

FIG.23

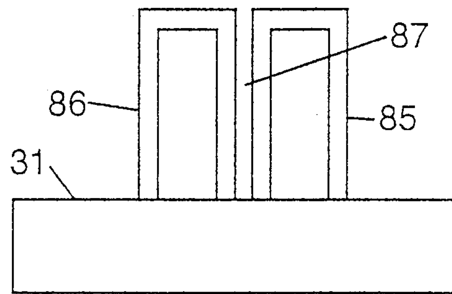

FIG.24

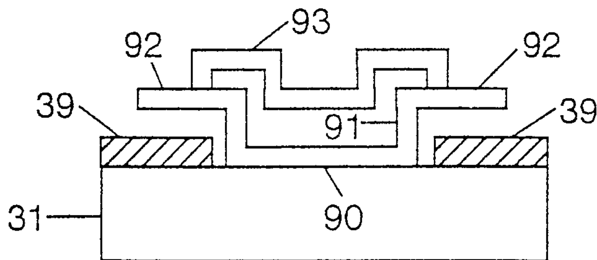

FIG.25

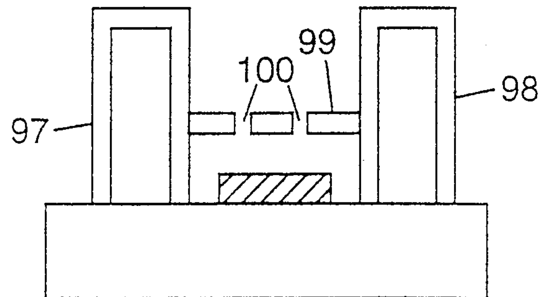

FIG.26

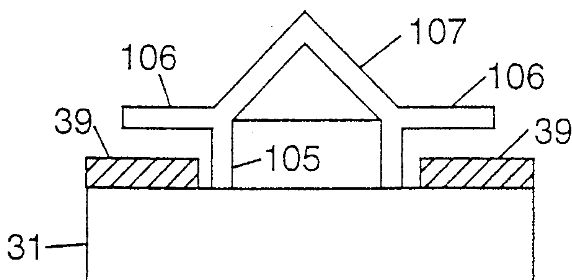

FIG.27

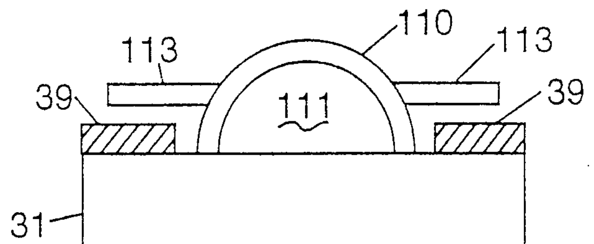

FIG.28

INTERNATIONAL SEARCH REPORT

International Application No
F.../US 99/18702

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01L9/12 G01L1/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	DE 197 40 244 A (K. BETHE) 26 February 1998 (1998-02-26) the whole document	1,2,5, 21,24-27 12,33
A	DE 195 13 921 A (SIEMENS AG) 24 October 1996 (1996-10-24) the whole document	1,12,21, 33
A	DE 41 06 288 A (ROBERT BOSCH GMBH) 3 September 1992 (1992-09-03) the whole document	1,12,21, 33

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 November 1999	26/11/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Van Assche, P

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 99/18702

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 19740244 A	26-02-1998	NONE	
DE 19513921 A	24-10-1996	WO 9632627 A	17-10-1996
		EP 0820581 A	28-01-1998
		JP 11503523 T	26-03-1999
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