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Nunn

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[54] **MINIATURE ABSOLUTE PRESSURE TRANSDUCER ASSEMBLY AND METHOD**

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[52] **U.S. Cl.** .... **338/42;** 73/88.5 SD; 338/2; 338/36

[51] **Int. Cl.**^{2} **H01C 13/00**

[58] **Field of Search** .... 338/2–5, 36, 338/42; 73/88.5 SD, 88.5 R, 398 AR; 29/626, 628

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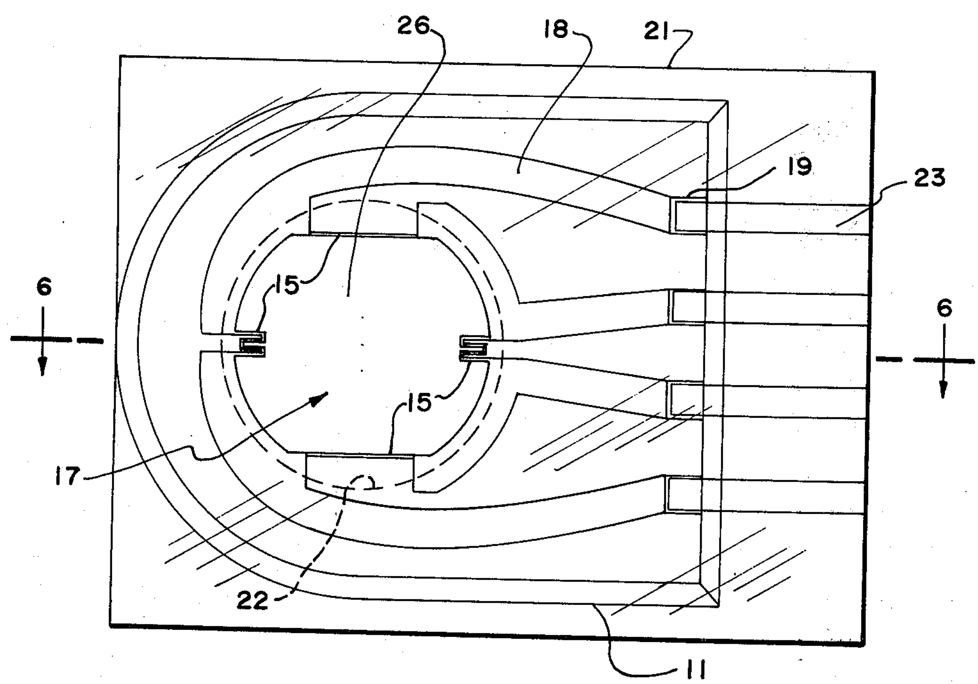
[57] **ABSTRACT**

A transducer assembly for measuring absolute pressure utilizing a glass substrate and a thin silicon diaphragm upon which is diffused a piezoresistive bridge circuit. Bridge circuit components are properly oriented and connected to bonding pads formed on the silicon. The glass substrate has a circular well formed therein having a diameter at least as large as the diameter of the diaphragm. Conducting leads are deposited on the glass substrate in a pattern matching that of the bonding pads on the silicon. The silicon is bonded to the glass substrate with the silicon diaphragm overlying the well in the glass and the bonding pads overlying the conducting leads deposited on the glass. The bond provides a hermetic seal around the well, trapping a prdetermined pressure therein which serves as a reference pressure. Ambient pressure variations cause stress variation in the diaphragm, resulting in unbalance of the bridge which can be sensed with associated circuits to give an indication of the ambient pressure.

5 Claims, 6 Drawing Figures



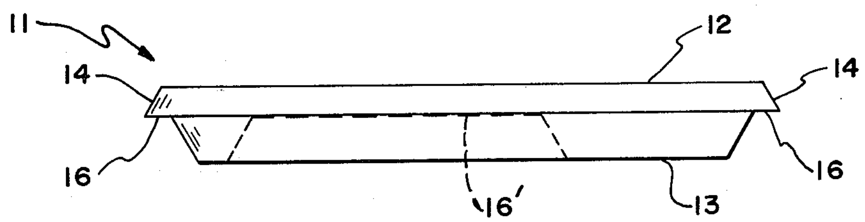


FIG.-1

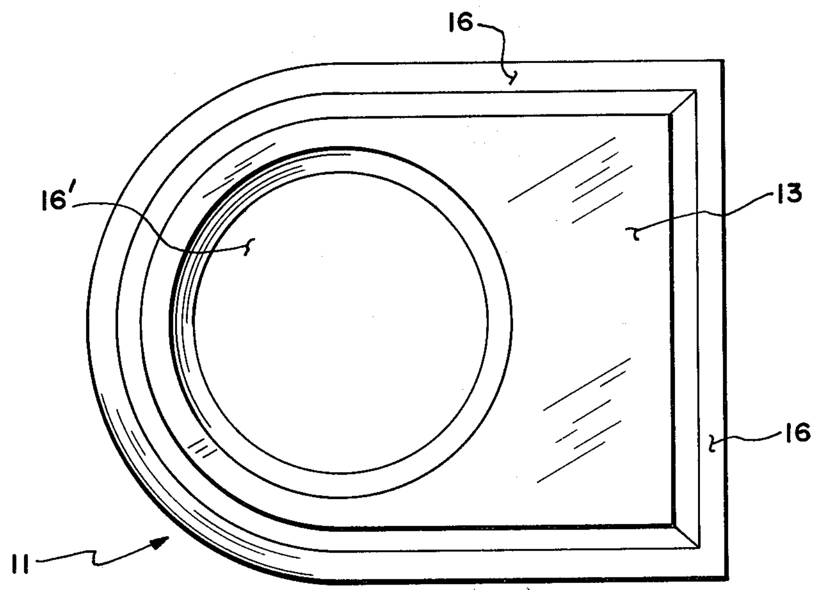


FIG.-2

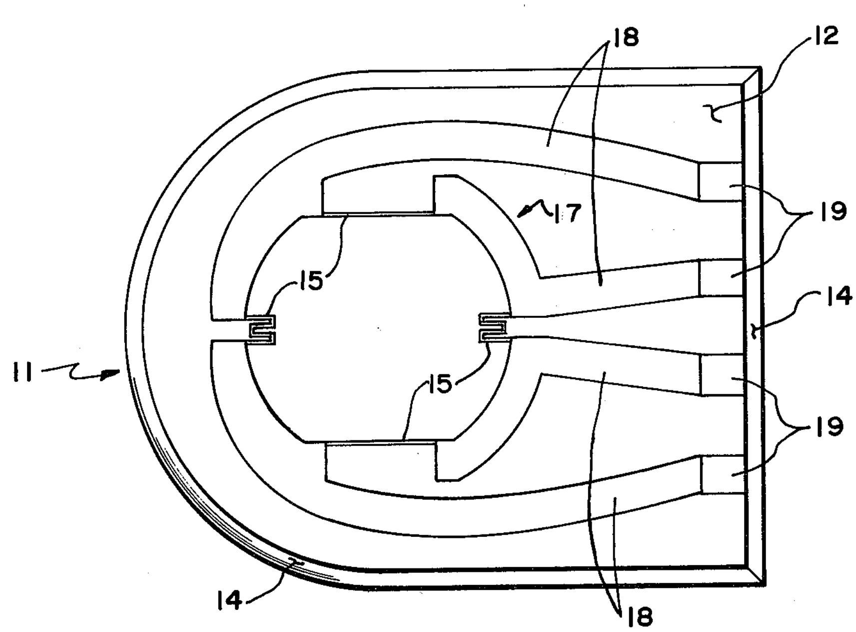


FIG.-3

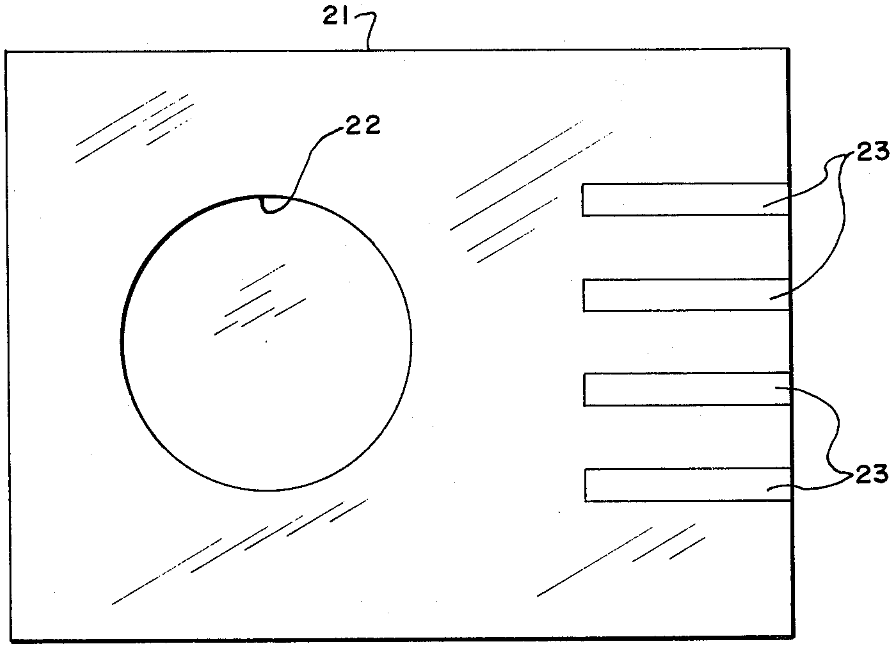


FIG.—4

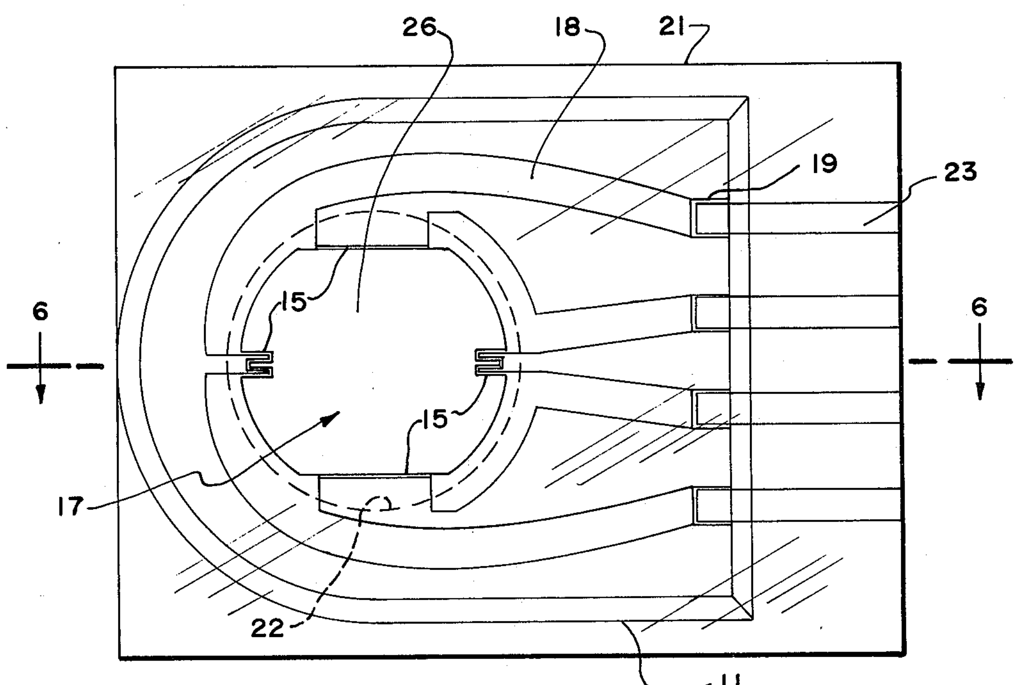


FIG.—5

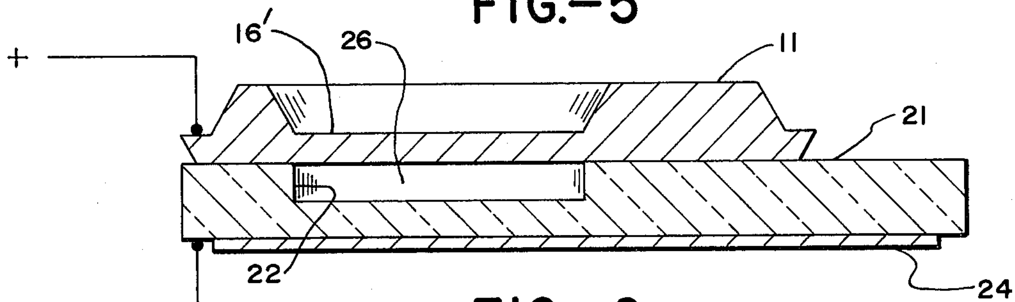


FIG.—6

MINIATURE ABSOLUTE PRESSURE TRANSDUCER ASSEMBLY AND METHOD

BACKGROUND OF THE INVENTION

This invention relates generally to a transducer assembly for measuring absolute pressure and more particularly to a miniature pressure transducer assembly and method using a diaphragm as a stress magnifying device which acts as one wall of a sealed pressure chamber.

Pressure transducers using hermetically sealed bellows or diaphragms are well known as means for indicating ambient pressure when associated with mechanical structure for monitoring diaphragm or bellows motion resulting from ambient pressure change. These transducers are relatively large due to the use of conventional welding processes which place a lower limit on the size of the parts to be welded together. Silicon strain sensitive resistive devices have been individually bonded to members stressed by pressure applied for providing resistance characteristics related to the pressure.

The need to obtain reliable pressure measurements in biological systems have been increasingly felt because of rapid advances in the biomedical field. The cardiovascular system, the cerebro-spinal system, the gastrointestinal system, and the bladder are but a few of the places in the human body where pressure readings are often required. Detailed pressure recordings from the cardiovascular system are the most important, since, in combination with an ECG, they provide accurate diagnosis of the condition of the heart.

At present, the most common techniques for measuring intra-arterial blood pressure utilizes a flexible stainless steel guide wire about 1 mm in diameter which is inserted into the artery. This guide wire is pushed to the location where pressure is to be measured, while its progress is monitored using a fluoroscope. A hollow catheter which envelopes the guide wire is then inserted and pushed to follow the guide wire to the desired location. After next removing the guide wire and filling the catheter with a suitable fluid, the in vivo pressure can be measured by placing a pressure transducer at the end of the liquid-filled catheter, outside the biological system. This method has inherent limitations due to the long path that the pressure wave has to travel to reach the pressure sensor. The recorded pressure wave is a function of the propagation characteristics of the hollow catheter and can depart appreciably from the true in vivo pressure.

Ideally, to avoid this propagation distortion, a pressure sensor could be inserted into the catheter to replace the guide wire; however, due to the scarcity of pressure sensors with an outer diameter equal to or less than that of conventional guide wires, this method is rarely followed.

A need exists for pressure transducers having self-contained reference pressure and very small physical size, which may be obtained through the use of semiconductor materials and integrated circuit processes for providing greater efficiency in the use of available volumes for a pressure transducer.

SUMMARY AND OBJECTS OF THE INVENTION

An absolute pressure transducer has a semiconductor diaphragm which is bonded to an insulator substrate overlying a well formed in the substrate. A hermetically sealed chamber is formed with the diaphragm serving as one wall of the chamber. A bridge circuit is provided on the diaphragm which is electrically connected to externally accessible conducting leads on the substrate. A predetermined reference pressure is trapped in the chamber during bonding, and the stress, imposed in the diaphragm by ambient pressure as indicated by the state of the bridge balance is indicative of the ambient pressure.

In general, it is an object of the present invention to provide an absolute pressure transducer assembly using assembly structure and methods affording extremely small physical size.

Another object of the present invention is to provide an absolute pressure transducer assembly providing external connections which do not impose physical stress on the pressure sensitive member.

Another object of the present invention is to provide an absolute pressure transducer assembly which may have any desired reference pressure.

Another object of the present invention is to provide an absolute pressure transducer assembly using simple easily controlled steps in the fabrication of the component parts, and in which the number of component parts are maintained at a minimum.

Another object of the present invention is to provide an absolute pressure transducer which is miniaturized using integrated circuit techniques.

Additional objects and features of the invention will appear from the following description in which the preferred embodiment has been set forth in detail in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side elevational view of a semiconductor diaphragm assembly having a predetermined diaphragm thickness.

FIG. 2 is a bottom plan view of the semiconductor diaphragm assembly of FIG. 1.

FIG. 3 is a top plan view showing an integrated bridge circuit formed on the semiconductor diaphragm assembly of FIG. 1.

FIG. 4 is a plan view of an insulator substrate.

FIG. 5 is an assembly plan view of an absolute pressure transducer assembly.

FIG. 6 is a sectional view along the line 6—6 of FIG. 5.

BRIEF DESCRIPTION OF THE PREFERRED EMBODIMENT

A practical structure for a miniature pressure transducer which could be used for converting blood pressure of a biological system into an electrical signal is obtained by combining a silicon diaphragm, which serves as a stress magnifying device, with diffused piezoresistors for sensing the pressure-induced stresses in the diaphragm. The piezoresistive effect is observable at low stress levels and is the result of the change in carrier mobility with stress. Combined with the advanced state of silicon processing technology developed for making integratec circuits, this effect makes silicon a desirable material for miniature pressure transducers.

FIGS. 1, 2 and 3 show one form of a semiconductor diaphragm fabricated using the method disclosed in co-pending patent application entitled "Method for Forming Regions of Predetermined Thickness in Silicon", Ser. No. 227,027 filed Feb. 17, 1972. As disclosed therein a silicon integrated circuit pressure transducer or silicon diaphragm assembly **11** is formed by using a silicon wafer having faces **12** and **13** as shown in FIG. **1.** Faces **12** and **13** are oriented in the (**100**) crystallographic plane.

An anisotropic etching technique is used for the formation of the diaphragms. This technique makes possible a novel thickness monitoring scheme which acts also as a chip separation etch. Sensors with diaphragm diameters of 0.5 mm and thicknesses of only 5 μm, surrounded by a 0.15 mm wide ring of thick silicon, have been batch fabricated using this technique. An intrinsic sensitivity of 14 μvolt per volt supply per mmHg has been achieved.

In the method for forming the silicon diaphragm assembly **11** a slot is formed in an etch resistant layer applied to face **12.** The slot has a predetermined width and when the silicon body is exposed to the anisotropic etchant the etch proceeds through the slot in the etch resistant layer until a "V" shaped groove is formed. The sides of the "V" shaped groove correspond to the (**111**) crystallographic plane. When the "V" groove is completed no (**100**) crystallographic surface is left exposed to the anisotropic etchant, and the etching effectively stops from the side of the silicon body having face **12.** Thus, the slot width determines the final depth of the "V" groove. The slot width is approximately the square root of **2** times the depth of the groove. By appropriately selecting the slot width, the depth of the "V" groove is selected. One side of the "V" groove is seen at **14** in FIG. **1** and the surface **14** corresponds to the (**111**) crystallographic plane as mentioned above.

Continuing the method disclosed in the referenced application an etch resistant layer is also applied to the face **13** of the silicon diaphram assembly **11.** Portions of the etch resistant layer are removed by any conventional process, such as photolithography, exposing face **13** in areas **16** and **16'**. When the silicon body is placed in an anisotropic etchant etching continues from face **13** toward the bottom of the "V" groove, one side of which is formed by surface **14.** A visual indication of the interception of the "V" groove bottom by the etchant proceeding from face **13** is provided when the silicon body separates from the surrounding portions of the silicon wafer following which the etch is quenched. The thickness of the silicon from areas **16** and **16'** to face **12** is therefore at the predetermined thickness represented by the height of the "V" groove.

The remaining silicon material below surface **13** which was protected by the etch resistant layer provides a reinforcing area surrounding the area **16'** which in this embodiment is circular in shape. The reinforcing area **13** thus provides structural support for circular area **16'** and defines the boundaries of circular area **16'**. Circular area **16'** will hereinafter be referred to as diaphragm **16'**.

Diaphragm **16'** is an essential part of the pressure transducer. The stress magnification properties of a clamped circular diaphragm are proportional to the square of the ratio of the diaphragm radius to its thickness. Diaphragm thickness of about 5μm, are required for obtaining reasonable sensivities with pressure sensors having diaphragm diameters of about 0.5 mm. The supporting rim **13** of thick silicon is then necessary to facilitate the handling and mounting of these structures.

The pressure-induced stresses on diaphragm **16'** are sensed by four properly-oriented piezoresistors **15** interconnected to form a bridge circuit **17.** Two diametrically opposite resistors **15** in the bridge **17** have the same sign of piezoresistivity, which is opposite to that of the remaining two resistors. After analyzing the stress patterns of the diaphragm and the orientation dependence of the piezoresistivity, the change in bridge unbalance due to an applied pressure can be maximized.

The piezoresistive bridge circuit shown generally at **17** is formed on surface **12** opposite area **16'** as seen in FIGS. **3** and **5.** The starting material used for the fabrication of the silicon diaphragm assembly **11** is n-type, 50 to 75 μm thick, (**100**) -oriented silicon wafers. Generally the starting material has one side of the wafer polished and both sides covered with silicon dioxide.

The first processing step involves the stripping of the original oxide of the wafers and regrowing it at a temperature of 1100°C. to a thickness of 7000°A. This oxide is used as a mask for the resistor and substrate contact diffusions and also as a mask during the diaphragm etching step.

To facilitate the photolithography of related patterns on the front and back side of the wafer, alignment marks are photoengraved on both sides of the wafer using a special jig, and succeeding masks are then aligned with respect to these marks. The alignment marks are aligned with flats on the wafer derived by cleaving the wafer along the [**110**] crystallographic directions.

To make the fabrication as compatible as possible with standard bipolar integrated circuit processing, the p-resistors **15** are diffused according to a standard base diffusion schedule, resulting in a sheet resistivity of close to 100 ohms per square. This schedule yields resistors **15** with a high piezoresistive coefficient and should also make possible the incorporation of on-chip signal processing at a later state in sensor development. Conducting paths **18** (doped P+) are formed using a standard emitter diffusion schedule.

After opening the contact holes and removing the photoresist, chromium is then evaporated over the entire wafer to a thickness of approximately 50A. A layer of gold approximately 1500A thick is then evaporated on top of the chromium layer. Again using photolithography, the gold and chromium layers are selectively etched away leaving the contact or bonding pads **19.** The wafers are now ready for the diaphragm etching step previously described.

Referring to FIG. **4** an insulating substrate **21** is shown having formed therein a well **22** with a diameter equal to or larger than the diameter of diaphragm **16'**. Also formed on the surface of insulating substrate **21,** on the same surface as that in which well **22** is formed, are a plurality of conducting leads **23** having a spacing matching the pattern of the bonding pads **19** on diaphragm assembly **11.**

One method of obtaining the finished insulating substrate **21** involves deposit by evaporation of a thin layer of chromium, approximately 50 angstroms, onto a glass substrate **21.** A top layer of gold is evaporated directly onto the chromium. A photolithography is then performed for removing a small circle of the chromium gold layer corresponding in size to the diameter of well **22.** The exposed glass substrate is then etched to a depth of approximately 100 μm. A subsequent photolithography removes all of the remaining chromium-gold layer except that providing the conducting leads **23.**

Surface **12** on silicon diaphragm assembly **11** is then placed adjacent to the surface on the insulating substrate 21 upon which the conducting leads 23 are formed. Diaphragm assembly 11 is oriented so that the center of diaphragm 16′ overlies the center of well 22, and the bonding pads 19 each overlie a portion of one of the spaced conducting leads 23. FIG. 6 shows the diaphragm assembly 11 and the insulator substrate 21 in position as described above.

The final step is the bonding of the silicon diaphragm assembly 11 containing the integrated circuit to the insulator substrate 21. Diaphragm assembly 11 may be bonded to the insulator substrate 21 using an anodic bonding process. The insulator substrate 21 is a glass material and is referred to as a glass cap in this embodiment. The insulating subatrate 21 may be a thin silicon wafer with glass sputtered onto one surface so that the anodic bonding process may be utilized. The bonding process involves placing the surface of glass cap 21, in which well 22 is formed, in intimate layer contact with surface 12 of silicon diaphragm assembly 11 while properly oriented as shown in FIG. 6. The diaphragm assembly 11 and glass cap 21 are heated to about 300°C. by a heater 24. This temperature is well below the softening point of the glass cap 21 and the melting point of the silicon diaphragm assembly 11. The heated glass cap 21 is slightly conductive. An electrical potential of several hundred volts, sufficient to cause a low density current to flow, is applied across the diaphragm assembly 11 and the glass cap 21 with the silicon diaphragm assembly 11 attached to the anode or positive side of the potential source. An anodically grown bond forming a hermetic seal is created between the diaphragm assembly 11 and the glass cap 21. The method of bonding disclosed in U.S. Pat. No. 3,397,278 has been used for obtaining the bond and seal between diaphragm 11 and glass cap 21. The gold pads 19 connected to the integrated circuit 17 are also bonded to the conducting paths 23 on glass cap 21 during the process in the fashion of a thermocompression bond. No external force is exerted on diaphragm 11 and glass 21 to urge them together to effect the bond. The electrical potential provides an attracting force creating high pressure at the surface interface.

A finished assembly is shown in FIG. 5, which is a view looking through the glass insulating substrate 21. A hermetically sealed chamber 26 is formed defined by the silicon diaphragm 16′ and the well 22 in substrate 21. Pressure may be adjusted in chamber 26 during the sealing process to provide any desired reference pressure therein. In this fashion a versatile absolute pressure transducer is provided having any desired predetermined pressure reference. External attachment of leads is easily accomplished by connection to the accessible areas of conducting leads 23 on substrate 21. This protects the delicate silicon diaphragm assembly 11 from breakage during external lead attachment.

The method for forming an absolute pressure transducer includes etching a well 22 in a glass substrate 21 and forming conducting leads 23 on the surface containing the well 22. The method also includes forming a thin silicon diaphragm assembly 11 with a piezoresistive bridge circuit 17 formed thereon including conducting paths 18 and bonding pads 19. Diaphragm assembly 11 is placed overlying the well 22 and bonded in place with the bonding pads 19 in electrical contact with conducting paths 23. Hermetic sealing is obtained in the bonding process which may be anodic bonding. Adjusting a desired reference pressure in a hermetically sealed chamber 26 is obtained during the bonding step in the method.

An extremely small absolute pressure transducer assembly is provided which in one embodiment utilized a glass substrate of sufficient thickness to accept a 100μm deep well, and which had a length of 2mm and a width of 1.5mm. The silicon diaphragm assembly 11 was formed of a silicon chip having a thickness of from 50 to 100μm and the etching process produced a diaphragm thickness as low as 5μm.

The piezoresistor-bridge 17 when excited with a voltage provides an unbalance voltage which is a function of applied pressure on the diaphragm 16′. Silicon diaphragm assemblies having a 0.5 mm disphragm diameter have been made. The diaphragm thickness was 7μm. A pressure transducer having 0.5mm diaphragm diameter and 7μm diaphragm thickness has provided pressure sensivity of 14μ volts per volt supply per mm Hg. Higher sensitivities are gained with either thinner diaphragms or larger diameter diaphragms.

The high sensitivity realized permits pressure variations as small as 1 mmHg to be resolved with the 0.5mm diameter. Even with these thin diaphragms, the pressure sensitivities of all sensors relized from a processing run are usually within 15 percent of the average value, with the variations attributed to small differences in diaphragm thickness from sensor to sensor. No changes in sensitivity due to repeated diaphragm flexing have been observed.

From the pressure sensitivity and the known values of diaphragm diameter and thickness, the piezoresistive coeficient of the diffused p-type resistors for known value of sheet resistivity may be calculated. Substituting the known values into the following equation:

$$\frac{V_{out}}{V_{supply}} = \frac{1}{2}\left\{\left(\frac{\Delta R}{R}\right)_r - \left(\frac{\Delta R}{R}\right)_t\right\}$$

and equating it with the measured sensitivities, we find the value of $\pi_{44} = 75 \times 10^{-12}$ cm^{2}dyne^{-1}. This value of π_{44} is in agreement with the published value for the resistivity used.

The frequency response to these transducers is more than adequate for biomedical applications. Although detailed frequency measurements have not been made above 10 kHz, the first calculated diaphragm resonance is at about 60 kHz for the 1.2mm diaphragm and is considerably higher for the smaller sensor.

These sensors, after being mounted on the tip of a small catheter, may be inserted into the biological system through the inner bore of a larger catheter which was formerly occupied by a guide wire. The sensor disclosed herein, having its own contained reference pressure cavity, does not require a clear passage to ambient pressure to make in vivo measurements.

I claim:

1. An absolute pressure transducer comprising a semiconductor diaphragm, an integral reinforcing area surrounding and defining the boundaries of said diaphragm, means forming a bridge circuit on said diaphragm, said last named means having electrical characteristics related to stress in said diaphragm, conducting pads formed on said reinforcing area in a predetermined pattern, conducting paths connected between said means forming a bridge circuit and said conducting pads, an insulator substrate having a well formed

therein with a diametral dimension at least as great as said diaphragm diametral dimension, and conducting leads formed on said insulator substrate spaced thereon to match said predetermined pattern of conducting pads, said substrate and reinforcing area being bonded together with the center of said diaphragm substantially overlying the center of said well for providing a hermetically sealed chamber therebetween, whereby said means forming a bridge circuit is enclosed in said hermetically sealed chamber for protection from ambient environments, said predetermined pattern of conducting pads substantially overlying and electrically conducting portions of said conducting leads, whereby pressure trapped in said sealed chamber provides a reference pressure and stress may be imposed in said diaphragm by ambient pressure.

2. An absolute pressure transducer as in claim **1** wherein said diaphragm is a thin silicon member, said means forming a bridge circuit is a piezoresistive integrated circuit bridge formed thereon, and said conducting paths are P+ diffusion areas.

3. An absolute pressure transducer as in claim **1** wherein said insulator substrate is glass and said conducting leads are electrically conductive strips deposited on the side of said glass in which said well is formed.

4. An absolute pressure transducer as in claim **1** wherein said insulator substrate has a larger area than said reinforcing area and said conducting leads extend beyond the area overlain by said reinforcing area, whereby said conducting paths are accessible for making connection to said means forming a bridge.

5. A transducer for absolute pressure measurement comprising a semiconductor integrated circuit pressure transducer having a diaphragm section with a piezoresistive bridge circuit formed thereon, an insulator substrate having a well formed therein, conducting leads deposited on said insulator substrate having externally accessible portions, said semiconductor integrated circuit pressure transducer being bonded to said insulator substrate with said diaphragm section overlying said well thereby forming a hermetically sealed chamber therebetween, said piezoresistive bridge circuit being enclosed in said sealed chamber for protection from ambient environment and being in electrical contact with said conductive leads on said insulating substrate, whereby said piezoresistive bridge circuit may be unbalanced by stress imposed in said diaphragm by pressure differential across said diaphragm.

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