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Thoma et al.

[11] **3,814,998**

[45] **June 4, 1974**

[54] **PRESSURE SENSITIVE CAPACITANCE SENSING ELEMENT**

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[73] Assignee: **Johnson Service Company,** Milwaukee, Wis.

[22] Filed: **May 18, 1973**

[21] Appl. No.: **361,813**

[52] **U.S. Cl.** ..... **317/246,** 73/398 C

[51] **Int. Cl.** **H01g 7/00**

[58] **Field of Search** ..... 317/246, 249 R, 258, 261; 73/398 C

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Primary Examiner—E. A. Goldberg

Attorney, Agent, or Firm—Andrus, Sceales, Starke & Sawall

[57] **ABSTRACT**

A diaphragm element includes thin outer conducting layers integrally bonded to the opposite sides of a core layer of silicone or other dielectric which is a resilient, flexible material, to form a single, integral, resilient, flexible structure.

The conducting layers are a matrix of the material of the dielectric core layer with carbon or like conductive particles embedded therein. One conducting layer is spaced peripherally from the edge of the core layer to thereby prevent electrical contact between the two conducting layers. The total unit is rigidly mounted about the peripheral edge with metallic contacts connected to the conducting layers as by a silver conducting paint applied to the outer surface of the layers. The element will thus flex to the side of the lower pressure with a change in the effective conducting area of the opposite conducting layers and a simultaneous decrease in the thickness of the dielectric inner core. Consequently, the capacitance of the unit varies as a function of the deflection and thereby in accordance with the pressure differential applied across the diaphragm element.

23 Claims, 6 Drawing Figures

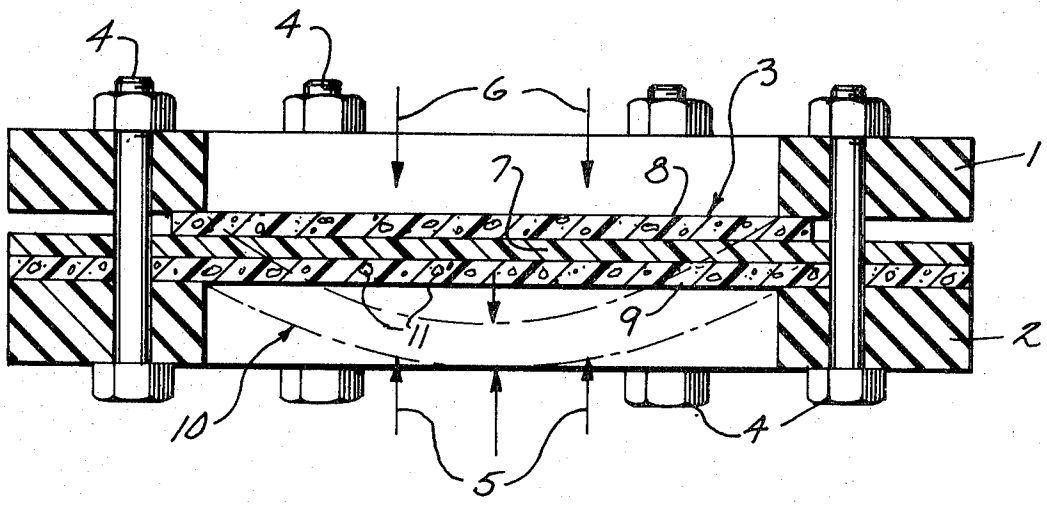


Fig. 1

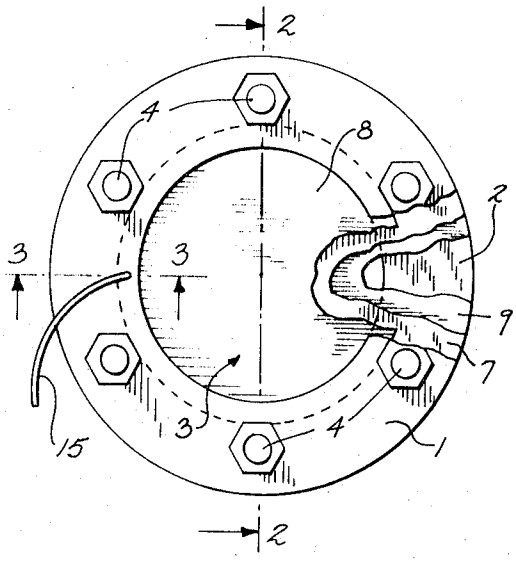


Fig. 3

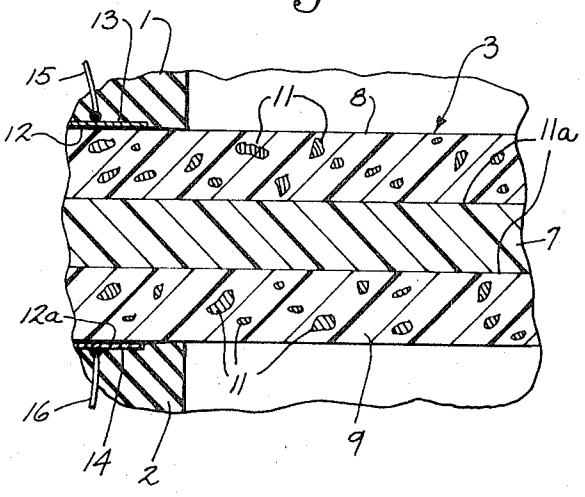


Fig. 2

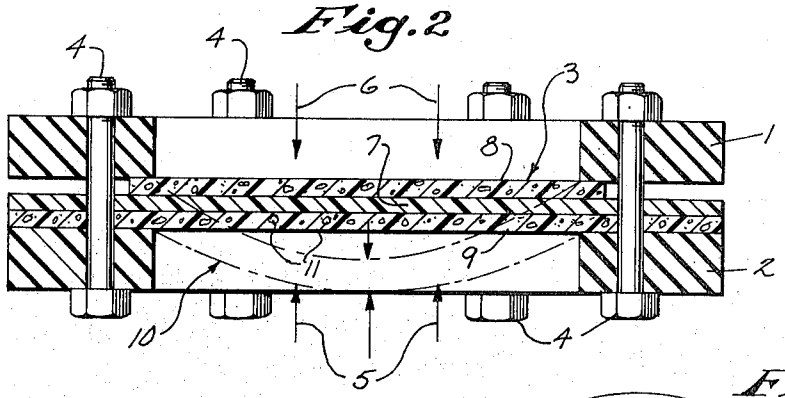


Fig. 4

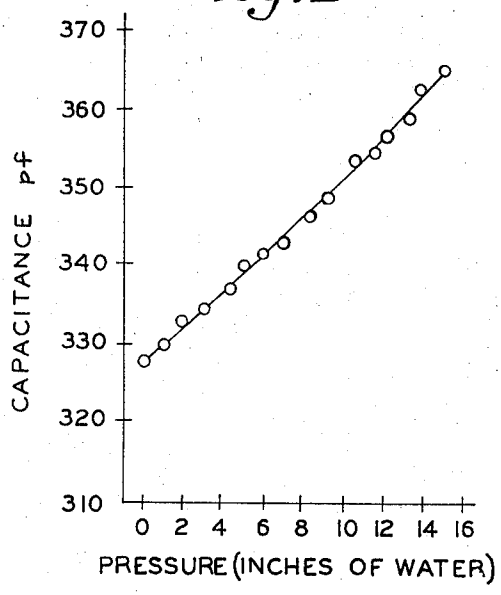


Fig. 5

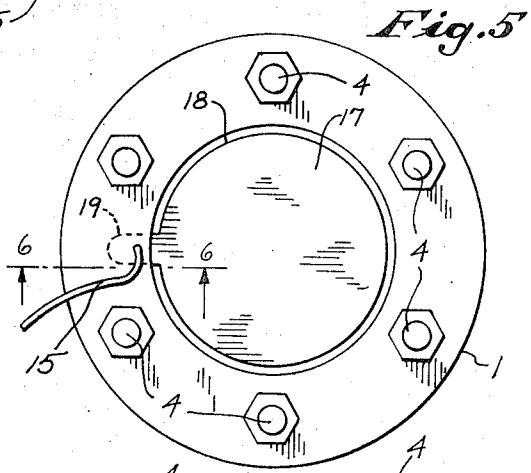
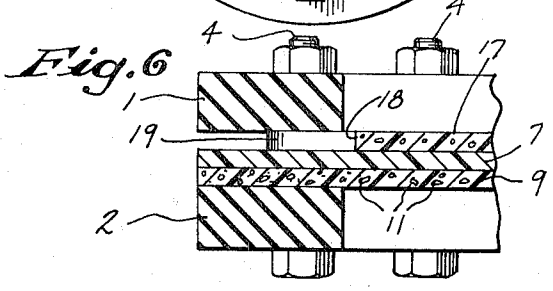


Fig. 6



PRESSURE SENSITIVE CAPACITANCE SENSING ELEMENT

BACKGROUND OF THE INVENTION

This invention relates to a novel pressure sensitive capacitance sensing element and particularly to such an element for sensing a fluid pressure condition.

In many control and/or monitoring systems pressure conditions are detected by transducing to an electrical output. Generally a pressure to electrical signal transducer employs a mechanical movement initiated by the pressure condition, with the movement effecting a corresponding change in an electrical output unit as a result of the change in a resistance, inductance, capacitance or other similar electrical characteristic.

A capacitance type pressure to electrical signal transducer is a very common form of a transducer employed in modern technology. Generally, they take either one of two forms. In one form, a fixed or stationary electrode forms a base structure for the sensing unit. A dielectric material, which may be a fluid, is supported by the stationary electrode. A conductive outer plate is movably mounted abutting the dielectric material and exposed to the pressure condition to cause flexing of the dielectric material with a corresponding change in the capacitance characteristic. In an alternative construction a conductive diaphragm is movably mounted between a pair of stationary electrode plates for movement parallel to the plates and coupled to the pressure source for corresponding positioning between the two fixed plates to thereby vary the capacitance. A fuller explanation of the broad field of pressure to electrical signal transduction and the various unit constructions including capacitance type is found in the *Handbook of Transducers for Electronic Measuring Systems* by Harry N. Norton which was published by Prentice-Hall, Inc. in 1969.

Capacitive sensing units are desirable because of the stability of their characteristic as long as the integrity of the sensing elements are maintained.

Although satisfactory pressure sensitive capacitance transducers are available, the electrode plates are relatively fragile members and present some difficulty in connection with production, particularly in a mass production process. Further, a trapped dielectric fluid is often employed between the plates. As a result of the relative moving of an element in the unit, the fluid is subject to exposure to the environment and contamination by environmental borne dust and the like. This may change the characteristic of the sensor and may, in fact, result in actual shorting of the electrode plates. Further, the fluid dielectric medium may be lost, at least in part, resulting in a distinct change in the characteristic of the sensor.

SUMMARY OF THE PRESENT INVENTION

The present invention is particularly directed to a pressure sensitive capacitance sensing unit which is readily adapted to production on a commercial basis and which provides long life with high stability in use. Generally, in accordance with the present invention the capacitance sensing unit includes an inner core and outer electrode plates having an elastic portion which is subject to elastic deformation as a result of a pressure or force differential impressed across the unit and with the capacitance directly related to the deformation.

More particularly, the capacitor sensing unit includes an inner elastic diaphragm core formed of a dielectric material with opposite conducting elastic layers firmly connected to the outer opposed surfaces of the dielectric diaphragm core. The unit is provided with laterally spaced mounting means to create a diaphragm element therebetween which will flex or bulge in accordance with a pressure differential which is applied across the diaphragm element between the mounting means. The element will thus flex to the side of lower pressure with a change in the effective conducting area of the opposite conducting layers and a simultaneous decrease in the thickness of the dielectric inner core. In accordance with known phenomena, the capacitance of a capacitor is directly proportional to the conducting plate area and inversely proportional to the thickness. Consequently, the capacitance of the unit will vary as a function of the deflection and thereby in accordance with the pressure differential applied across the diaphragm element. At zero pressure, the sensing element is in an unstressed state and the capacitance is dependent upon the basic area of the conductive layer and the thickness of the dielectric core as well as the permittivity of the dielectric core. The sensitivity in turn is dependent on the relative size of the element and the composite elastic modulus of the total diaphragm element which, in turn, is a composite of the elastic modulus of the inner core and the outer two conducting layers.

The diaphragm element of the present invention preferably includes the integral attachment of thin outer conducting layers to the opposite sides of a sheet of the dielectric core material. Thus the conducting layers are preferably deposited on the core and integrally bonded throughout the mating faces to form a single integral flexible structure. The thickness of the conducting layers as well as the elastic modulus of the conducting layers for optimum results should be less than or equal to the corresponding characteristic of the core layer.

The conducting layers may advantageously be formed of a matrix which is similar to the dielectric core layer or another material which can be integrally bonded thereto. Disposed within the conducting layers are suitable electrically conductive particles such as carbon and the like, with the amount of the particles selected to provide the desired conductivity without significantly interfering with the elastic characteristics, stability, and response to pressure change of the total unit.

The core dielectric material as well as the outer flexible conductors should have excellent resistance against plastic deformation such that the element may provide reliable and repeatable response to pressure changes. Further, one of the conducting layers is spaced peripherally from the edge of the core layer to thereby prevent electrical contact between the two conducting layers. The total unit is rigidly mounted about the peripheral edge of the element. The rigid mounting for the units preferably includes metallic contacts connected to the conducting layers by a silver conducting paint applied to the outer surface of the layers. Suitable lead wires are connected to the contacts and connected in a circuit such that the capacitance characteristic of the element provides a change in output or a detectible output with a change in pressure.

In accordance with a particular feature of the present invention, the inner core is formed of a silicone elastomer which has a dielectric constant of between 1.1 to 25 and preferably approximately 3. The elastic modulus may also vary significantly for example between 1 to 1,000,000 psi but optimum results have been found employing materials with an elastic modulus of 50 to 1,000 psi. The core layer thickness can also vary widely with a range of from 0.0001 inch to 0.1000 inch.

Applicants have found that the flexible core with the bonded outer flexible electrodes produces a highly sensitive flexible membrane or diaphragm construction which can be readily produced. Further, an integrally bonded construction essentially prevents any danger of air pocket developments or the entry of dust and other foreign material into the dielectric portion of the unit and thereby not only prevents the possibility of shorting the capacitance plates but prevents relative changes in the characteristic in the capacitor's dielectric and therefore in the capacitance characteristic.

BRIEF DESCRIPTION OF THE DRAWING

The drawing furnished herewith illustrates the best mode presently contemplated by the inventors for carrying out the subject invention in which the above advantages and features are clearly disclosed as well as others which will be readily understood from the description of such illustrated embodiment.

In the drawing:

FIG. 1 is a plan view of a pressure sensitive capacitance sensing element constructed in accordance with the present invention;

FIG. 2 is a vertical section taken generally on line 2—2 of FIG. 1;

FIG. 3 is an enlarged fragmentary section taken generally on line 3—3 of FIG. 1 illustrating a highly satisfactory construction of the elements forming the flexible portion of the sensing element;

FIG. 4 is an illustration of the sensing element's response to a pressure differential when connected in a suitable electric output circuit;

FIG. 5 is a view similar to FIG. 1 illustrating an alternative embodiment of the invention; and

FIG. 6 is a fragmentary section taken generally on line 6—6 of FIG. 5.

DESCRIPTION OF ILLUSTRATED EMBODIMENT

Referring to the drawing and particularly to FIGS. 1 and 2, a pressure sensitive capacitance sensing unit constructed in accordance with the present invention is shown including an outer annular pair of supporting rings 1 and 2 with a flexible pressure sensitive diaphragm 3 rigidly clamped therebetween. The rings 1 and 2 may be interconnected by a plurality of equicircumferentially distributed clamping screws 4 which, when drawn up, form a firm integrated structure and in particular rigidly support the flexible diaphragm 3 completely about the periphery thereof in the illustrated embodiment.

The diaphragm element thus defines a pair of distinct opposite sides or surfaces, one of which is subjected to a first or reference pressure 5 and the opposite side of which is connected to a second pressure 6 to be sensed, as diagrammatically illustrated in FIG. 2.

According to the present invention, diaphragm 3 is especially constructed as a flexible assembly which includes a central core 7 shown as a sheet-like member of a dielectric material with flexible electrode layers 8 and 9 firmly attached in abutting relation to the opposite faces of the core 7. In the embodiment of FIGS. 1 – 4 the three layer diaphragm projects laterally with all three layers being firmly held by the rings 1 and 2.

The core 7 is formed of a dielectric material and the electrodes 8 and 9 are formed of a conductive material and all three have an elastic modulus to permit the elastic movement from the rigid mounting position.

The flexible diaphragm is such, therefore, that a differential pressure arising as a result of a difference in the signal pressure 6 and the reference pressure 5 results in a corresponding movement of the diaphragm 3. As a result of the rigid holding of the periphery of the three layers and a firm interconnection between the core 7 and the conductive layers 8 and 9, the unit bulges and flexes in accordance with the differential pressure, as shown in phantom at 10 in FIG. 2. The area of a curved surface is greater than the projected flat area and the movement of the diaphragm therefore effectively increases the area of the electrode layers 8 and 9. This increase in differential pressure also results in a thinning of the multilayer diaphragm, including its core 7 which is similarly flexed, simultaneously reducing the core thickness and therefore reducing the spacing between the electrode plates.

The deflection of diaphragm 3 to the phantom line position clearly indicates the increased area of layers 8 and 9 and decreased thickness of the dielectric material 7. Both the increased area of the conducting layers 8 and 9 and the reduced thickness of the core 7 correspondingly function to vary the capacitance in the same direction and thereby have been found to provide a highly sensitive capacitance sensing element producing a reliable transduction of pressure to electrical signals.

The capacitance of a capacitor is basically given by the equation: $C = e \times A \div t$ where

C = the capacitance

e = the permittivity of the dielectric core

A = the area of the capacitor plates or electrodes

t = the thickness of the dielectric between the capacitor plates.

Consequently, the capacitance will increase with the bulging movement of the diaphragm 3, as a result of the increased area A and also as a result of the decreased thickness t and will correspondingly decrease as the capacitance diaphragm moves back to the full-line, balanced position.

The outer electrodes 8 and 9 are for optimum results integrally bonded throughout their interfaces 11*a* to the adjacent core layer 7 such that the element moves as a single integrated element. The top electrode 8 is shown formed of a smaller diameter with the periphery within the line of bolts 4. This prevents shorting of the plates. Any other suitable means can, of course, be used.

The dielectric core layer 7 is, of course, electrically insulating and formed of an elastic material which is advantageously relatively non-porous to the fluid medium to the opposite sides of the diaphragm. A silicone elastomer having a dielectric constant of about 3, an elastic modulus of about 500 psi and a resistivity of the order of 1×10^{15} microhm cm has been found to be a satisfactory material for the dielectric core. Applicants have found that the dielectric constant of the core can readily vary from a dielectric constant of 1.1 to 25. Simi-

larly, the elastic modulus of the core layer can readily vary between 1 psi and 1,000,000 psi with more typical values ranging from 50 psi to 1,000 psi. A typical resistivity of the insulating core is about 1×10^{15} microhm cm. The thickness of core layer 7 may readily vary from 0.0001 inch to 0.1000 inch. In practical applications, applicants have found a range of 0.0003 inch to 0.0200 inch to provide particularly useful results.

Although the conducting layers or electrodes may be formed of any suitable material, they are advantageously formed as a matrix with a base which is similar to the dielectric core layer material such as silicone elastomer. Highly electrically conductive particles 11 such as graphitized carbon and deoxidized carbon are dispersed through the conducting electrodes such that they define conductive plates of an elastic nature.

The conducting electrodes 8 and 9 may be constructed in any suitable manner, for example, by dispersing of graphitized carbon through a silicone elastomer, as more fully disclosed in U.S. Pat. No. 3,582,728. The one electrode layer 8 or 9 can readily be cast as a film on a clean glass plate. The dielectric core 7 is thereafter applied on the film and interconnected to the electrode by cross linking. Subsequently, the outer electrode is cast as an appropriate film over the core layer and interconnected by cross linking.

Optimum results are obtained by maintaining the elastic modulus of the conducting layers 8 and 9 at values less than or equal to that of the core layer 7 and similarly of a thickness which is less than or euqal to that of the core layer.

Further, the diaphragm 3 should, of course, be formed of a material which also has excellent resistance to plastic deformation such that the element returns to the balanced pressure position to maintain accurate and repeatable outputs with varying pressure input. If it does not, the unit will, of course, plastically deform with pressure changes and result in a variation in a subsequent response of the element to the same pressure change.

As the capacitor unit of the invention is particularly adapted to a fluid pressure medium, the conducting layers and the core layer are formed of a suitable material which is relatively non-porous to the fluid medium. If the layers are porous, the pressure would, of course, be transmitted through the unit and correspondingly reduce the sensitivity of the unit to pressure changes.

In the illustrated embodiment of the invention, the bottom conducting layer 9 is coextensive with the dielectric core layer 7. The opposite or top conducting layer 8 is spaced from the peripheral edge of the dielectric core layer 7. This ensures effective spacing between the two electrodes 8 and 9 and minimizes creation of electrical contact therebetween with the resulting shorting of the electrode plates.

Circuit connections are made to the conducting electrodes in any suitable manner. As shown in FIGS. 1 and 3, the conducting layers 8 and 9 within the clamping rings 1 and 2 may be provided with a spot coating of a silver conducting paint 12 and 12*a* to provide connection to the conductive particles 11 within the layers 8 and 9. Metallic contacts 13 and 14 within the rigid mounting elements 1 and 2 are aligned with and make contact with the silver conducting paint 12 and 12*a*. Lead wires 15 and 16, in turn, are connected to the metallic contacts and provide connection of the capacitance sensing element in any suitable system. The pressure sensing element, for example, may be connected into a leg of an alternating current bridge circuit, not shown, which is energized from a suitable alternating current source. The balanced condition, and therefore, the output, of the bridge is responsive to the capacitance of the capacitance element. The output is such that it can be readily detected and amplified by a suitable amplifier or the like to energize a suitable detection or control load.

The characteristic of a unit such as shown in FIGS. 1 and 2 is shown in FIG. 4. The characteristic of FIG. 4 is illustrative of a unit having an active conducting area in the balanced position as shown in FIG. 2 of 0.60 square inches. The dielectric core 7 was 0.0004 inch thick and the outer conducting layers 8 and 9 were of a corresponding thickness, and were formed as sheet-like layers bonded to the core as previously described with reference to U.S. Pat. No. 3,582,728.

The core layer was a silicone elastomer with a dielectric constant of 3.0. The conducting layers were similarly a silicone elastomer matrix with a conductive carbon particle uniformly dispersed therein. The test was run with atmosphere as a reference pressure and with air pressure supplied to the opposite side of the capacitance element. The circuit was energized from an alternating current source of a thousand cycles per second and readings taken at increments of 1 inch of water. As shown, the capacitance changes essentially in accordance with a straight line function between approximately 328 picofarads at zero signal pressure to 365 picofarads at 15 inches of water. The sensitivity of the unit corresponds essentially to the slope of the illustrated curve and was essentially 2.5 picofarads per inch of water.

An alternative embodiment is shown in FIGS. 5 and 6 having three bonded elements, and elements corresponding to the elements of the first embodiment are similarly numbered for simplicity and clarity of explanation. In the alternative embodiment the one electrode plate, shown as the top plate 17, is especially formed and applied to minimize the projection beneath the clamping ring 1. This minimizes the hysteresis of the element and further contributes to the stability and performance of the unit.

More particularly, in FIGS. 5 and 6, the electrode plate 17 is a circular element of a slightly smaller diameter than the inner diameter of the ring 1. The plate 17 is bonded or otherwise suitably affixed to the core with a circumferential space or gap 18 extending essentially completely about the unit. A small tab-like extension 19 is integrally formed on the edge of plate 17 and aligned with the contact 13, shown only in FIG. 3, of the ring 1 to provide connection to the electrode.

The bonded plate construction is particularly significant in the practical construction and application of the capacitive sensor. Thus, the construction provides a simple mechanism which is relatively stable and relatively rugged. Thus, the outer carbon plates tend to be somewhat sensitive to tearing and would be subject to breakage. However, the interconnected bonding to the interior dielectric provides significant support to the plates.

The capacitance sensing element of the present invention thus provides a relatively simply constructed mechanism which provides a long reliable life with repeatable outputs or output characteristics.

Various modes of carrying out the invention are contemplated as being within the scope of the following claims, particularly pointing out and distinctly claiming the subject matter which is regarded as the invention.

We claim:

1. A pressure sensitive capacitance sensing element comprising a core formed of a dielectric material, a plurality of electrically conductive electrodes interconnected with said core layer to define capacitor plates to the opposite side of such core and defining a capacitor unit, said capacitor unit being elastic and having fixed mounting means at spaced points of the capacitor unit with the unit elastically moving with respect to the said fixed mounting means and correspondingly elastically deforming the capacitor unit with an increased conductive area of the electrodes with respect to said mounting and a decreased dielectric core thickness to thereby provide a change in the capacitance of the element.

2. The sensing element of claim 1 wherein said dielectric core and said electrically conductive electrodes are flexible solid elements and the electrodes are integrally bonded throughout the interface to the dielectric core.

3. The capacitance sensing element of claim 1 wherein each of said electrodes include electrically conductive particles distributed throughout an electrically insulating material.

4. The capacitance sensing element of claim 3 wherein said particles are graphitized carbon.

5. The capacitance sensing element of claim 1 wherein each of said conductive electrodes are formed of the same material as said core and having electrically conductive particles distributed throughout the electrode.

6. The capacitance sensing element of claim 1 wherein the one conducting layer is coextensive with the dielectric core and the opposite electrode is spaced from the periphery of the core, and having a peripheral mounting means extending over at least one of the electrodes to establish said fixed mounting means of said spaced points.

7. The sensing element of claim 6 wherein said opposite electrode is further essentially completely spaced from the mounting means.

8. The sensing element of claim 7 wherein said opposite electrode has a small tab extending into the mounting means and defining a circuit connection means.

9. The capacitance sensing element of claim 1 having a peripheral mounting means extending over and being attached to both of the electrodes and defining fixed mounting at spaced points.

10. The sensing element of claim 1 wherein said dielectric core and said electrically conductive electrodes are integrally bonded throughout their interface, said core being formed of a silicone elastomer, each of said conductive electrodes being formed of a silicone elastomer and having electrically conductive particles distributed throughout the rubber to define a conductive plate.

11. The sensing element of claim 11 wherein the individual electrode thickness is no greater than the thickness of the core.

12. The capacitance sensing element of claim 2 wherein the core is a solid flexible element having a dielectric constant of essentially 1.1 to 25, an elastic modulus of essentially 1 to 1,000,000 pounds per square inch and a thickness of essentially 0.0001 inch to 0.1000 inch.

13. The capacitance sensing element of claim 13 wherein the elastic modulus and the thickness of the electrodes are not greater than the elastic modulus and the thickness of the core.

14. The capacitance sensing element of claim 12 wherein the core has a dielectric constant of three.

15. The capacitance sensing element of claim 12 wherein the core and electrodes have an elastic modulus between 50 and 1,000 pounds per square inch.

16. The capacitance sensing element of claim 12 wherein the core thickness is constant and between 0.0003 and 0.0200 inch thick.

17. A pressure sensitive capacitance sensing element comprising a sheet-like core formed of a flexible solid dielectric material, a plurality of electrically conductive and flexible solid electrodes interconnected with said core layer to define a capacitor diaphragm, a fixed mounting means connected to said electrodes and rigidly supporting of spaced portions of the diaphragm and with the diaphragm elastically moving with respect to the fixed mounting and correspondingly deforming the capacitor with an increased conductive area of the electrodes with respect to said mounting and a decreased dielectric layer thickness to thereby provide a change in the capacitance of the element in response to a differential fluid force applied to opposite sides of the diaphragm.

18. The sensing element of claim 17 wherein said dielectric core and said electrically conductive electrodes are integrally bonded throughout the interface to the dielectric core, and said mounting means extends completely about the periphery to correspondingly flexibly mount the diaphragm about the periphery.

19. The capacitance sensing element of claim 18 wherein the thickness and the elastic modulus of each of said conductive electrodes is no greater than the thickness and elastic modulus of said core.

20. The capacitance sensing element of claim 18 wherein the diaphragm core and electrodes are formed of a material which is essentially free of plastic deformation within the normal differential pressure conditions.

21. The pressure sensitive capacitance sensing element of claim 19 wherein the mounting means includes a pair of ring-like members secured in clamping relationship to the peripheral edge portion of the diaphragm, wherein at least one ring-like member is of an insulating material and contact means in each of said ring-like members firmly abutting the adjacent electrode.

22. The pressure sensitive capacitance sensing element of claim 22 wherein one of said electrodes is smaller in area than the other and wherein said ring-like member of an insulating material is positioned on the same side as said smaller electrode and is spaced therefrom except for a limited contact portion as said contact means.

23. The sensing element of claim 21 wherein said electrodes include a conducting point on the surface in alignment with said contact means.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,814,998 Dated June 4, 1974

Inventor(s) Paul E. Thoma and Jeannine O. Colla

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, line 15, cancel "0.0004" and substitute ---0.004---

Column 7, line 61, cancel "10" and substitute ---11---

Column 7, line 64, cancel "2" and substitute ---1---

Column 8, line 5, cancel "13" and substitute ---12---

Column 8, line 48, cancel "19" and substitute ---18---

Column 8, line 56, cancel "22" and substitute ---21---

Signed and sealed this 1st day of October 1974.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

FORM PO-1050 (10-69)

USCOMM-DC 60376-P69
* U.S. GOVERNMENT PRINTING OFFICE : 1969 O—366-334.

UNITED STATES PATENT OFFICE
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