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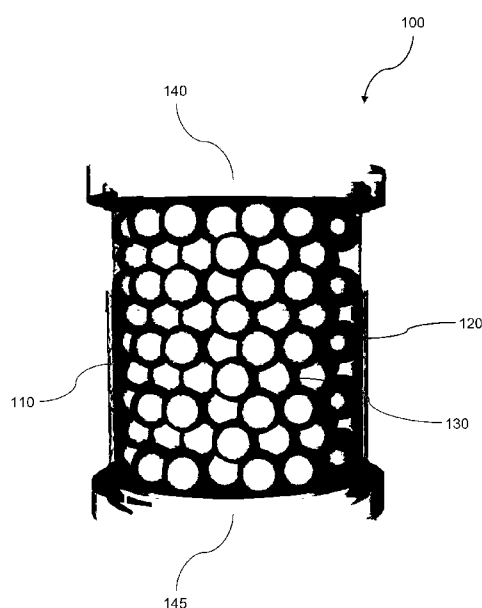


FIG. 1

(57) Abstract: A pressure sensor (100) comprises a container (110) and a plurality of granules (120) disposed within the container (110). The plurality of granules (120) has a closely-packed interrelationship defining a plurality of inter-granular contact points (130), each contact point (130) having a contact surface area. At least some of the plurality of granules (120) comprise a conductive material. The plurality of granules (120) are each deformable, under the application of pressure, to cause a variation in the contact surface areas of the inter-granular contact points (130), the variation resulting in a change in resistivity of the plurality of granules (120), and the pressure sensor (100) is configured to measure the amount of pressure applied to the plurality of granules (120) based on the change in the resistivity thereof.

A PRESSURE SENSOR

FIELD OF THE INVENTION

[0001] The present invention relates to a pressure sensor and a method of measuring pressure applied to a pressure sensor. Such a pressure sensor has applications in the fields of civil engineering, geotechnical engineering, coastal and offshore engineering, pavement engineering, agriculture, petroleum engineering, mining and geology and can be used to measure pressure in many different types of environment in which it is desired to know the loading conditions in complex field situations. The information gathered using the pressure sensor is important to the design of pavements, building foundations, pipework, tunnel construction, embankments, retaining walls, landfills, and also for use in landslide and earthquake management structures, in surveying and profiling agricultural land, and in surveying and profiling deep-situ geological formations.

[0002] The pressure sensor also has applications in the fields of robotics, wearable equipment, aerospace engineering, biomedical engineering, healthcare and sport-related applications. The information gathered using the pressure sensor is then useful to improving the design of structures, products and devices for use in those technical fields.

BACKGROUND OF THE INVENTION

[0003] Known pressure sensors incorporate a number of mechanical sensing elements to detect applied pressure. Such known pressure sensors include, for example, piezoresistors, strain gauges, percolation mechanisms, quantum tunnelling conduction mechanisms, inclinodeformometer devices and dilatometer devices.

[0004] In one example, a piezoresistor sensor typically comprises a sensing material (i.e. a diaphragm) formed on a solid semiconductor material (i.e. silicon). In general terms, the semiconductor deforms under the application of pressure, causing a change in the resistivity of the diaphragm. The change in resistivity is measured and used to determine the amount of pressure applied to the semiconductor. In another example, percolation mechanisms generally comprise an insulating matrix and conductive particles embedded in the insulating matrix. Under the application of pressure, the conduction pathways of the conductive particles re-

arrange to cause a variation in the resistivity of the particles. The resistivity change is measured and subsequently used to determine the amount of pressure applied.

[0005] A disadvantage of the known pressure sensors is that they that do not readily allow for adaptability in a wide variety of applications. In the example of the piezoresistor sensor above, the semiconductor material is typically formed of a single, rigid piece of material (i.e. silicon) of a fixed size and shape. In the example of the percolation mechanism above, the conductive particles are arranged in a fixed matrix. Such known pressure sensors are therefore difficult to customise (i.e. easily adapt to suit the surrounding environment) and are therefore limited in their ability to provide accurate in-situ (i.e. on-site) assessment of pressure.

OBJECT OF THE INVENTION

[0006] It is an object of the present invention to overcome or at least substantially ameliorate one or more of the above disadvantages.

SUMMARY OF THE INVENTION

[0007] In accordance with one aspect, the present invention provides a pressure sensor comprising:

- a container; and

- a plurality of granules disposed within the container, the plurality of granules having a closely-packed interrelationship defining a plurality of inter-granular contact points, each contact point having a contact surface area,

- wherein at least some of the plurality of granules comprise a conductive material, and

- wherein the plurality of granules are each deformable, under the application of pressure, to cause a variation in the contact surface areas of the inter-granular contact points, the variation resulting in a change in resistivity of the plurality of granules, and wherein the pressure sensor is configured to measure the amount of pressure applied to the plurality of granules based on the change in the resistivity thereof.

[0008] The pressure sensor may further comprise an electrode pair having a first electrode and a second electrode, the first and second electrodes being disposed in spaced relation with one another inside the container and forming an electrical path therebetween, the first and second

electrodes being configured to measure the change in the resistivity of the granules along the electrical path.

[0009] The electrode pair may be further configured to measure normal stress to a plane orthogonal to the electrical path between the first and second electrodes.

[0010] The pressure sensor may further comprise a plurality of electrode pairs, each electrode pair having a first electrode and a second electrode dispersed among the plurality of granules and forming an electrical path therebetween, the plurality of electrode pairs each being configured to measure the change in the resistivity of the granules along the respective electrical path.

[0011] The plurality of electrode pairs may be further configured to measure normal stress to one or more planes, each plane being orthogonal to the respective electrical path between the respective first and second electrodes of each electrode pair.

[0012] At least some of the granules of the plurality of granules may further comprise a non-conductive material.

[0013] The container may be formed of an insulating material, and/or may be made of a flexible material.

[0014] The pressure sensor may further comprise a non-conductive fluid contained within the container and disposed among the plurality of granules. Preferably, a pressure of the non-conductive fluid contained within the container can be varied. This preferred embodiment enables the measurement of stiffness of a material surrounding the pressure sensor.

[0015] The pressure sensor may further comprise a first outer layer adapted to enclose the container, the first outer layer comprising a first flexible material having a predetermined density.

[0016] The pressure sensor may further comprise a second outer layer adapted to enclose the first outer layer, the second outer layer comprising a second flexible material having a predetermined stiffness.

[0017] In accordance with another aspect, the present invention provides a method of measuring pressure applied to a pressure sensor, the pressure sensor comprising a flexible container and a plurality of granules disposed within the container, the plurality of granules having a closely-packed interrelationship defining a plurality of inter-granular contact points, each contact point having a contact surface area, wherein the plurality of granules are each deformable under the application of pressure, the method comprising:

applying pressure to the pressure sensor such that the granules deform to cause a variation in the contact surface areas of the inter-granular contact points, whereby the variation results in a change in resistivity of the granules; and

measuring the amount of pressure applied to the pressure sensor based on the change in the resistivity of the granules.

[0018] The pressure sensor may further comprise an electrode pair having a first electrode and a second electrode, the first and second electrodes being disposed in spaced relation with one another inside the flexible container and forming an electrical path therebetween, wherein measuring the amount of pressure applied to the pressure sensor comprises measuring a change in voltage along the electrical path and calculating the change in resistivity based on the change in voltage.

[0019] The pressure sensor may further comprise a plurality of electrode pairs, each electrode pair having a first electrode and a second electrode dispersed among the plurality of granules and forming an electrical path therebetween, wherein the method further comprises measuring a normal stress applied to the plurality of granules in one or more planes orthogonal to the respective electrical paths.

[0020] The pressure sensor may further comprise a non-conductive fluid within the container and the method may further comprise changing a pressure of the non-conductive fluid within the container to cause a change in volume of the container, and determining a stiffness of a material surrounding the container from the change in volume of the container and from said measurement of normal stress applied to the plurality of granules.

[0021] Preferably, the change in the pressure of the non-conductive fluid is achieved by changing the amount of the non-conductive fluid within the container. More preferably, the change in the pressure of the non-conductive fluid is achieved by injecting or extracting an

amount of non-conductive fluid into or from the container, whilst maintaining the container in a saturated state.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Preferred embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings wherein:

[0023] Fig. 1 is a side perspective view of first embodiment of a pressure sensor;

[0024] Fig. 2 is a side perspective view of a second embodiment of a pressure sensor;

[0025] Fig. 3 is a cross-sectional view of the pressure sensor shown in Fig. 2;

[0026] Fig. 4 is a cross-sectional view of the pressure sensor shown in Fig. 2 with additional outer layers; and

[0027] Fig. 5 is a perspective view of two pressure sensors connected to a power supply.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0028] Fig. 1 shows a first embodiment of a pressure sensor 100 comprising a container 110 and a plurality of granules 120 disposed within the container 110. The plurality of granules 120 are formed either entirely of conductive material, for example stainless steel or aluminium, or alternatively of a mixture of conductive and non-conductive material. Examples of suitable non-conductive materials include ceramic, rubber or polymer. The container 110 is formed of an insulating material such as rubber, polymer film or plastic film, or other suitable material to provide a barrier between the plurality of granules 120 and the external environment in which the pressure sensor 100 is to be deployed. The container 110 may be flexible or it may be at least partially rigid depending on the intended application of the pressure sensor 100, as will be explained in further detail below. In the embodiment as shown in Fig 1, the container 110 is in the shape of a cylinder. However, it will be understood that the container 110 may alternatively take the form of various other shapes, such as a sphere, cube or an irregular shape (an example of which is shown in Fig. 3), depending on the specific application.

[0029] The pressure sensor 100 may further comprise a non-conductive fluid (not shown) contained within the container 110 and disposed among the plurality of granules 120. In an embodiment, the non-conductive fluid is injected into container 110. The pressure of the non-conductive fluid inside the container 110 may be adjustable depending on the required use of the pressure sensor 100. Introducing variable fluid pressure enables the measurement of stiffness of the surrounding materials. For example, the pressure sensor 100 may be used to measure the stiffness of the external material. For that, the pressure of the non-conductive fluid inside the container 110 may be slightly varied. Then, the change of volume of the container 110 can be established through the known compressibility of the non-conductive fluid. The sensor 100 can be used to measure the change in the stress, and the stiffness of the external material can be measured in terms of the known elastic relationships of the granules 120 in the sensor.

[0030] The plurality of granules 120 have a closely-packed interrelationship within the container 110, defining a plurality of inter-granular contact points 130. Each granule of the plurality of granules 120 is deformable under the application of pressure. The total number of granules may be varied depending on the required size and use of the pressure sensor 100. It will be understood that a variation in the number of granules will also result in a variation in the number of inter-granular contact points 130. For example, by decreasing the total number of granules, the total number of inter-granular contact points 130 will also decrease. This causes an increase or a decrease in the conductivity (and conversely, a decrease or an increase in the resistivity) of the plurality of granules 120 as a whole, depending on the contact network between all the granules.

[0031] Additionally, by providing the pressure sensor 100 with larger granules, such that the number of granules decreases in a given volume, the pressure sensor 100 may also achieve an increased level of sensitivity (i.e. accuracy). This enhances the ability of the pressure sensor 100 to detect smaller changes in pressure (albeit of a narrower overall pressure range). Conversely, by providing the pressure sensor 100 with smaller granules, such that the number of granules decreases in a given volume, the pressure sensor 100 will have a lower level of sensitivity towards smaller changes in pressure. However, the pressure sensor 100 will be able to detect a wider overall range of pressure.

[0032] Each of the inter-granular contact points 130 has a contact surface area. It will be understood that the shape and size of each of the plurality of granules 120 may be varied,

depending on the required size and use of the pressure sensor 100. For example, it will be understood that increasing the size of each granule for a given pressure level will result in an increase in the size of the individual inter-granular contact surface areas of the plurality of granules 120 as a whole. This in turn increases the conductivity (and conversely, decreases the resistivity) of the plurality of granules 120 as a whole.

[0033] Additionally, by providing the pressure sensor 100 with granules that are larger in size, the pressure sensor 100 may also achieve an increased level of sensitivity (i.e. accuracy). As discussed above, the ability of the pressure sensor 100 to detect smaller changes in pressure will be enhanced. Conversely, reducing the size of each granule will result in a reduction in the size of the individual inter-granular contact surface areas of the plurality of granules 120. Whilst this will reduce the sensitivity of the pressure sensor 100, the ability of the pressure sensor 100 to detect a wider overall range of pressure will be improved. Each granule of the plurality of granules 120 may typically have a diameter ranging from about 1 mm to 20 mm. However, it is envisaged that the diameter or typical size dimension of each granule of the plurality of granules 120 may range from as small as a micrometre to as large as a metre.

[0034] In the embodiment as shown in Fig. 1, each of the plurality of granules 120 has a spherical shape, however, it is envisaged that at least some of the plurality of granules 120 may alternatively be in the shape of a cylinder, an ellipsoid, a polyhedron or an irregular shape, for example. It is also envisaged that the surface topology (e.g. roughness) of the surface of each granule may be varied depending on the sensitivity and range of measured pressure required. For example, modifying the surface area of each granule of the plurality of granules 120 will result in an increase (or decrease), depending on the surface treatment method used, in the total size of the inter-granular contact surface areas, which in turn increases (or decreases) the sensitivity of the pressure sensor 100. The plurality of granules 120, when comprised of a conductive material, may also exhibit a passivated surface oxide layer. It will be understood by a skilled person that passivating a conductive material makes it less chemically reactive. As such, the conductive material will be protected from corrosion and contamination, for example, from further potential chemical reactions with the surrounding environment whilst increasing its electrical stability.

[0035] In the embodiment as shown in Fig. 1, the pressure sensor 100 further comprises an electrode pair having a first electrode 140 and a second electrode 145. As will be appreciated by

a person skilled in the art, the first and second electrodes 140 and 145 may be formed of a metallic material such as copper, graphite, titanium or platinum, for example. The first and second electrodes 140 and 145 are disposed in spaced relation with one another inside the flexible container 110 at opposite ends thereof and form an electrical path therebetween. It will be understood that, upon introduction of a current across the electrical path, an initial resistivity and an initial stress of the plurality of granules 120 (i.e. when the pressure sensor 100 is in a resting state) is measureable by firstly determining the voltage across the electrical path between the first and second electrodes 140 and 145. The measured voltage is then used to derive the values of resistivity and stress (e.g. by using Ohm's Law and stress tensor equations). Likewise, when the pressure sensor 100 is in a deformed state (i.e. during the application of pressure to the plurality of granules 120), a final resistivity and a final stress of the plurality of granules 120 will be derivable from the measured voltage in the same manner described above.

[0036] The operation of the pressure sensor 100 will now be described.

[0037] The initial resistivity of the plurality of granules 120 is first determined from the measured voltage across the first and second electrodes 140 and 145. The plurality of granules 120 is contained between the first and second electrodes 140 and 145. Briefly, a power supply 150 (see Fig. 5) is connected to the pressure sensor 100 by way of an insulated cable 160. The power supply 150 is configured to provide an electrical current across the electrical path between the first and second electrodes 140 and 145 (i.e. through the plurality of contacting granules 120). It will be understood that such an electrical current may either be a direct current (DC) or an alternating current (AC). As described above, a measurement of the voltage across the first and second electrodes 140 and 145 will subsequently give rise to a measurement of the initial resistivity of the plurality of granules 120 as a whole. A measurement of the initial normal stress of the plurality of granules 120 acting on a plane orthogonal to the electrical path between the first and second electrodes 140 and 145 may also be inferred from the electrical current running through the electrical path.

[0038] The pressure sensor 100 is then positioned at a desired location for measurement of pressure, for example underneath a layer of soil. In this example, the weight of the soil on the pressure sensor 100 applies a pressure on the plurality of granules 120 inside the pressure sensor 100. Such application of pressure deforms (i.e. compresses) the plurality of granules 120. The deformation in the plurality of granules 120 causes a variation in the contact surface areas of the

inter-granular contact points 130. This effect is referred to in the art as contact deformation. As a result of the variation in the contact surface areas, the resistivity of the plurality of granules 120 may either increase or decrease. The final resistivity of the plurality of granules 120 is then determined in the same manner described above with respect to the initial resistivity. The change in resistivity (i.e. the difference between the final resistivity and the initial resistivity) of the plurality of granules 120 is then used to calculate the amount of pressure applied to the pressure sensor 100.

[0039] The application of pressure may also result in a variation in the relative positions of the plurality of granules 120, whereby the number of inter-granular contact points 130 either increases or decreases. This effect is referred to in the art as a system rearrangement. As a result of the variation in the number of inter-granular contact points 130, the stress in the direction along the electrical path between the first and second electrodes 140 and 145 may generally change. The final stress of the plurality of granules 120 may then be determined in the same manner described above with respect to the initial stress. The change in stress (i.e. the difference between the final stress and the initial stress) of the plurality of granules 120 may be used to calculate the normal stress on a plane orthogonal to the direction of the shortest electrical path between the first and second electrodes 140 and 145.

[0040] Whilst the pressure sensor 100 is positioned at the desired location, the stiffness of a material, e.g. the layer of soil, surrounding the pressure sensor 100 is determined by injecting or otherwise introducing a non-conductive fluid into the container 110 at a controlled initial pressure. It is envisaged that the non-conductive fluid is introduced into the container 110 until the container 110 reaches a state of full saturation. Beyond this point, a further injection of the non-conductive fluid into the container 110 will create an internal fluid pore pressure within the container 110. After reaching this state of full saturation, the pressure of the non-conductive fluid is then varied slightly whilst the container 110 remains fully saturated, e.g. by injecting or extracting a small amount of the fluid into or from the container 110 and registering a change in the internal fluid pore pressure. It will be appreciated that by injecting an amount of non-conductive fluid into the container 110, the internal fluid pore pressure within the container 110 will increase, whilst by extracting an amount of non-conductive fluid from the container 110, the internal fluid pore pressure within the container 110 will decrease. The resulting change in volume in the container 110 can be determined using the known compressibility of the non-conductive fluid. The stiffness can then be determined from the change in volume, change in

stress (as measured by the pressure sensor 100) and the known elastic relationships of the plurality of granules 120 in the pressure sensor 100, as is known in the art.

[0041] Depending on the required use of the pressure sensor 100, the container 110 may be formed of a flexible material or of a combination of rigid and flexible materials. For example, when the pressure sensor 100 is being used to measure stresses within a soil mass, the container 110 should be formed entirely of a flexible material to simulate the physical properties of the surrounding soil mass. When the pressure sensor 100 is being used to measure pressure against a relatively rigid wall (for example, a retaining wall), the container 110 should be formed of a substantially rigid material and should be mostly contained within the retaining wall. However, a portion of the container 110 (e.g. a face of the container 110) should be formed of a flexible material so as to enable compression of the plurality of granules 120 in a direction normal to the wall.

[0042] Figs. 2 to 4 show a second embodiment of a pressure sensor 200 which generally operates in the same manner as the first embodiment of the pressure sensor 100 described above, with like reference numerals being used to indicate like features. However, the pressure sensor 200 comprises a plurality of electrode pairs having a plurality of first electrodes 240a, 240b, 240c and 240d and a plurality of second electrodes 245a, 245b, 245c and 245d, respectively. The plurality of electrode pairs facilitates the measurement of stress within the pressure sensor 200 in more than one direction. Each measurable direction is along an electrical path between the respective first and second electrodes (240a and 245a, 240b and 245b, etc.) of each electrode pair. In the examples as shown in Figs. 2 to 4, there are four electrode pairs dispersed among the plurality of granules 120. It will be appreciated that the number of electrode pairs may be decreased or increased, depending on the required use of the pressure sensor 200 and the number of directional normal stresses to be determined. This embodiment enables decoupling of the individual stress components in a generally complex stress state, as compared to the single pressure value measurable by the first embodiment. For example, in practice the full stress state at a given point in space is generally defined by six independent stress components (three normal stresses and three shear stresses acting on three orthogonal planes). As will be appreciated by those skilled in the art, by measuring six normal stress components acting on six different planes, with none of which being parallel to the other, the full stress state at a given point in space could be determined.

[0043] In the example as shown in Fig. 4, the pressure sensor 200 further includes a first outer layer 250 adapted to enclose the container 110. The first outer layer has a predetermined density and may be in the form of a solid layer of material, or a fluid or particle-filled layer. The density of the first outer layer 250 may be varied by adjusting the material, size or weight of the solid layer or the fluid or particles selected for the fluid-filled layer. The pressure sensor 200 may further include a second outer layer 260 adapted to enclose the first outer layer 250. The second outer layer 260 has a predetermined stiffness and may be also be in the form of a solid layer of material, or a fluid or particle-filled layer. The stiffness of the second outer layer 260 may likewise be varied by adjusting the material, size or weight of the solid layer or the fluid or particles selected for the fluid-filled layer. Suitable materials for the first and second outer layers 250 and 260 may include rubber, polymer, plastic or sponge-like material, for example. The variability in the density and stiffness of the first and second outer layers allows the pressure sensor to simulate the physical properties of the surrounding environment. For example, the overall density of the pressure sensor 200 can be adjusted to that of the surrounding materials to counter the buoyancy force.

[0044] The power supply 150 may be connected to more than one pressure sensor. For example, with reference to Fig. 5, the power supply 150 is connected to two pressure sensors 100 by way of their respective insulated cables 160. The provision of multiple pressure sensors may allow for the measurement of pressure at a number of different points per location without requiring a separate power supply for each pressure sensor.

[0045] Various forms of the pressure sensor described above may have one or more of the following advantages. Firstly, the flexible and fluent granular construct of the pressure sensor allows for the various physical properties (e.g. size, shape, density, stiffness) of the pressure sensor to be adjustable, depending on the required use of the pressure sensor. This adjustability can be achieved for example, by varying the quantity, size, shape or surface topology of the granules; the size and type of material used to form the flexible container or the first and second outer layers; or the pressure of the non-conductive fluid in the container. In one example, the quantity, size and ratio of conductive and non-conductive materials may be used to control the sensitivity and directionality of the granules. As discussed above, decreasing the number of granules (i.e. decreasing the number of individual inter-granular contact points) or increasing the size of the granules (i.e. increasing the size of the individual inter-granular contact surface areas) will increase the sensitivity of the pressure sensor. This provides the pressure sensor with an

enhanced ability to detect smaller changes in measured pressure. Conversely, increasing the number of granules or decreasing the size of the granules will decrease the sensitivity of the pressure sensor, whilst allowing the pressure sensor to detect a wider overall range of pressure. Further, it is envisaged that by introducing non-conductive granules the mixture of granules, the number of inter-granular contact points between the conductive granules decreases, which results in an increase in the sensitivity of the pressure sensor. The pressure sensor may therefore provide increased versatility and adaptability in a wide variety of conditions.

[0046] The pressure sensor is also capable of measuring pressure and stresses in more than one direction. Such multi-directional functionality adds to the versatility and adaptability of the pressure sensor. The pressure sensor may therefore be utilised for widespread in-situ (i.e. on-site) applications, for example in complex field situation in which a number of different pressure and stress parameters must be taken into account. Depending on the required use, the pressure sensor may satisfy a variety of complex technical demands and allow for accurate in-situ assessment of pressure and stress. For example, the pressure sensor may be adapted for applications in the fields of mining, tunnelling, agriculture, slope stability, robotics, wearable equipment, civil engineering, coastal and offshore engineering, aerospace engineering, biomedical engineering, healthcare and sport-related applications.

[0047] Further, the pressure sensor is adapted to be installed and operated in a relatively non-intrusive manner, and is therefore operable with little effect on the surrounding environment (for example, in areas where the land may be fragile or unstable). This is again attributed to the versatility and adaptability of the pressure sensor, the physical properties (e.g. size, shape, density, stiffness) of which may be varied to simulate the physical properties of the surrounding environment.

[0048] In addition to being simple to install and use, the pressure sensor is also simple to fabricate. The construction of the pressure sensor does not involve complex techniques. Standard materials may be used to create the various elements of the pressure sensor. The cost to fabricate the pressure sensor is therefore relatively low. Further, the pressure sensor is configured to consume relatively low power in operation, thus reducing the operational costs of the pressure sensor.

[0049] Although the invention has been described with reference to a preferred embodiment, it will be appreciated by those skilled in the art that the invention may be embodied in many other forms.

CLAIMS

1. A pressure sensor comprising:
a container; and
a plurality of granules disposed within the container, the plurality of granules having a closely-packed interrelationship defining a plurality of inter-granular contact points, each contact point having a contact surface area,
wherein at least some of the plurality of granules comprise a conductive material, and
wherein the plurality of granules are each deformable, under the application of pressure, to cause a variation in the contact surface areas of the inter-granular contact points, the variation resulting in a change in resistivity of the plurality of granules, and wherein the pressure sensor is configured to measure the amount of pressure applied to the plurality of granules based on the change in the resistivity thereof.
2. The pressure sensor according to claim 1, further comprising an electrode pair having a first electrode and a second electrode, the first and second electrodes being disposed in spaced relation with one another inside the container and forming an electrical path therebetween, the first and second electrodes being configured to measure the change in the resistivity of the granules along the electrical path.
3. The pressure sensor according to claim 2, wherein the electrode pair is further configured to measure normal stress to a plane being orthogonal to the electrical path between the first and second electrodes.
4. The pressure sensor according to claim 1, further comprising a plurality of electrode pairs, each electrode pair having a first electrode and a second electrode dispersed among the plurality of granules and forming an electrical path therebetween, the plurality of electrode pairs each being configured to measure the change in the resistivity of the granules along the respective electrical path.
5. The pressure sensor according to claim 4, wherein the plurality of electrode pairs is further configured to measure normal stress to one or more planes, each plane being orthogonal to the respective electrical path between the respective first and second electrodes of each electrode pair.

6. The pressure sensor according to any one of the preceding claims, wherein at least some of the granules of the plurality of granules further comprise a non-conductive material.
7. The pressure sensor according to any one of the preceding claims, wherein the container is formed of an insulating material.
8. The pressure sensor according to any one of claims 1 to 7, wherein the container is made of a flexible material.
9. The pressure sensor according to any one of the preceding claims, further comprising a non-conductive fluid contained within the container and disposed among the plurality of granules.
10. The pressure sensor according to any one of the preceding claims, further comprising a first outer layer adapted to enclose the container, the first outer layer comprising a first flexible material having a predetermined density.
11. The pressure sensor according to claim 10, further comprising a second outer layer adapted to enclose the first outer layer, the second outer layer comprising a second material having a predetermined stiffness.
12. A method of measuring pressure applied to a pressure sensor, the pressure sensor comprising a container and a plurality of granules disposed within the container, the plurality of granules having a closely-packed interrelationship defining a plurality of inter-granular contact points, each contact point having a contact surface area, wherein the plurality of granules are each deformable under the application of pressure, the method comprising:
 - applying pressure to the pressure sensor such that the granules deform to cause a variation in the contact surface areas of the inter-granular contact points, whereby the variation results in a change in resistivity of the granules; and
 - measuring the amount of pressure applied to the pressure sensor based on the change in the resistivity of the granules.
13. The method according to claim 12, wherein the pressure sensor further comprises an electrode pair having a first electrode and a second electrode, the first and second electrodes being disposed in spaced relation with one another inside the flexible container and forming an

electrical path therebetween, wherein measuring the amount of pressure applied to the pressure sensor comprises measuring a change in voltage along the electrical path and calculating the change in resistivity based on the change in voltage.

14. The method according to claim 13, wherein the pressure sensor further comprises a plurality of electrode pairs, each electrode pair having a first electrode and a second electrode dispersed among the plurality of granules and forming an electrical path therebetween, wherein the method further comprises measuring a normal stress applied to the plurality of granules on one or more planes being orthogonal to the directions of the respective electrical paths.

15. The method according to claim 14, wherein the pressure sensor further comprises a non-conductive fluid contained within the container and wherein the method further comprises changing a pressure of the non-conductive fluid to cause a change in volume of the container, and determining a stiffness of a material surrounding the container from the change in volume and from the said measurement of normal stress applied to the plurality of granules.

16. The method according to claim 15, wherein the step of changing the pressure of the non-conductive fluid comprises injecting or extracting an amount of the non-conductive fluid into or from the container whilst maintaining the container in a saturated state.

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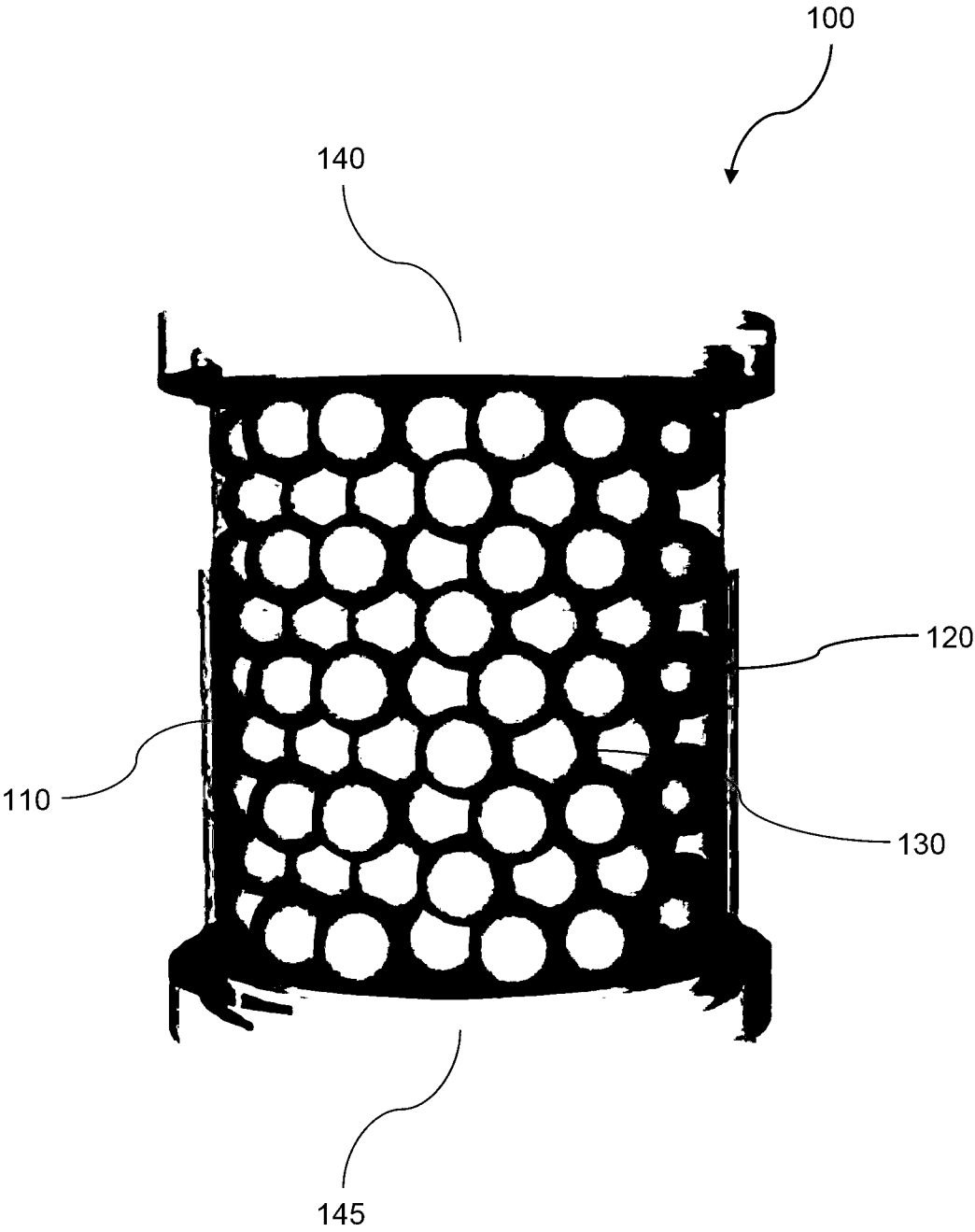


FIG. 1

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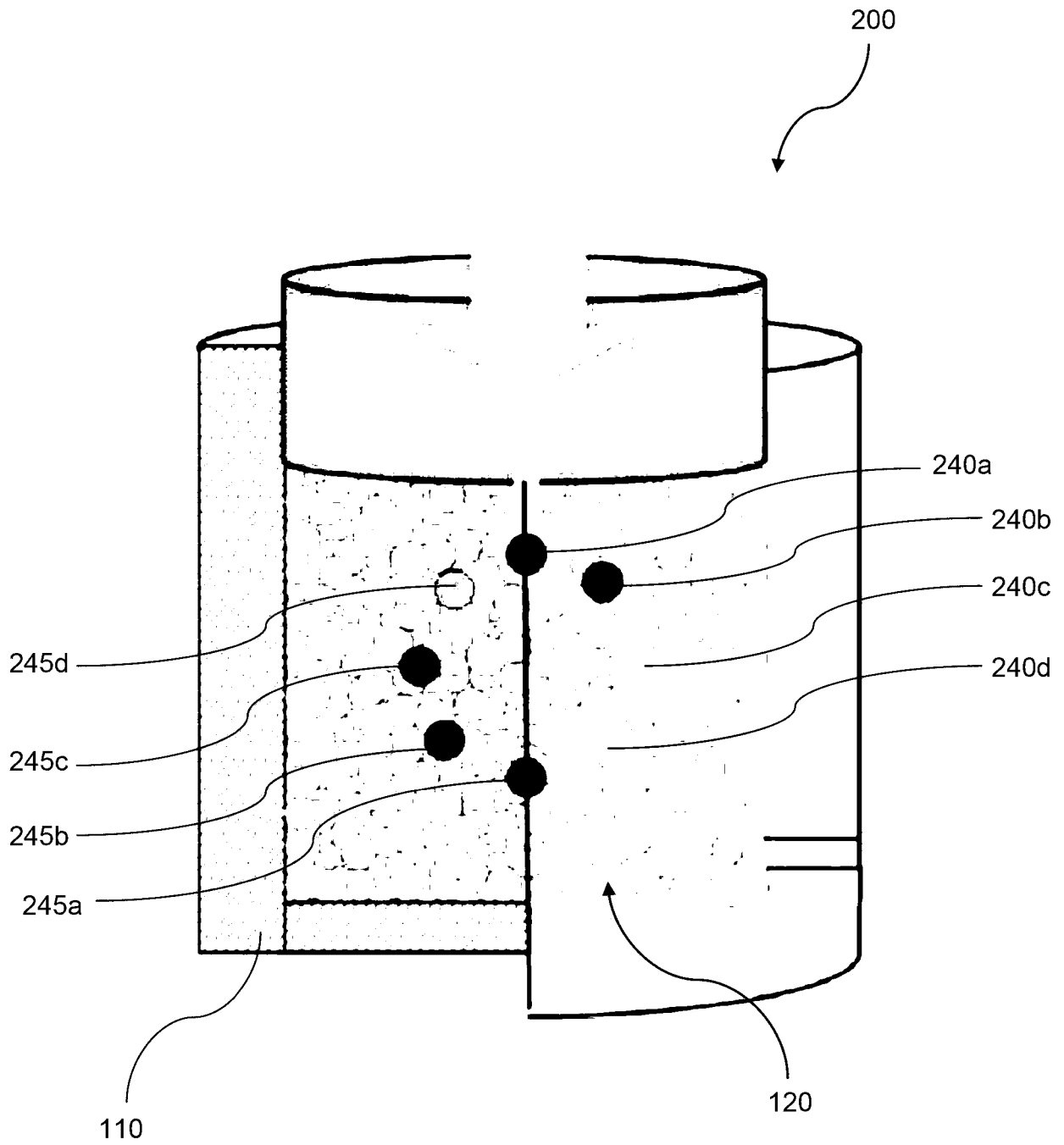


FIG. 2

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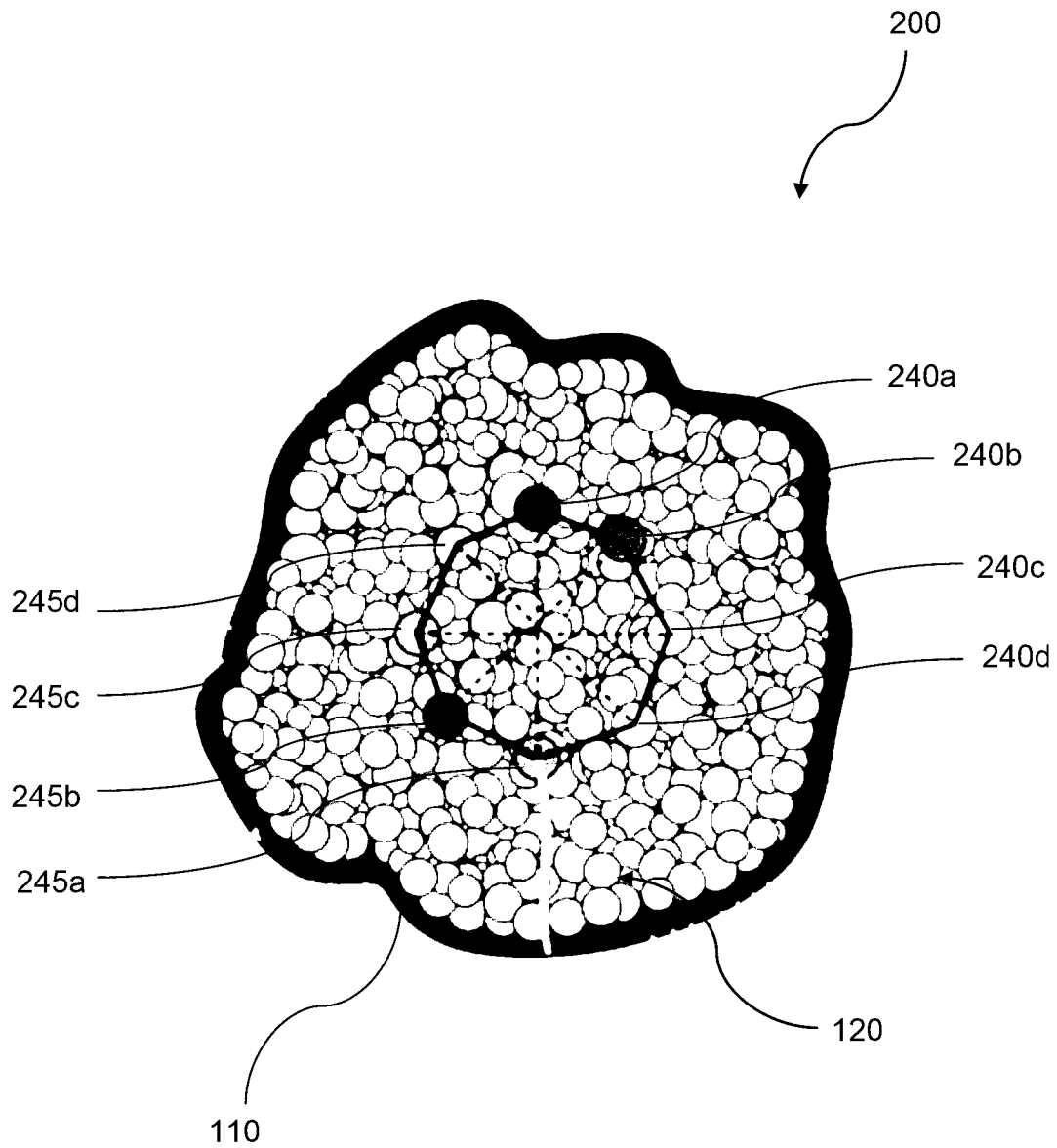


FIG. 3

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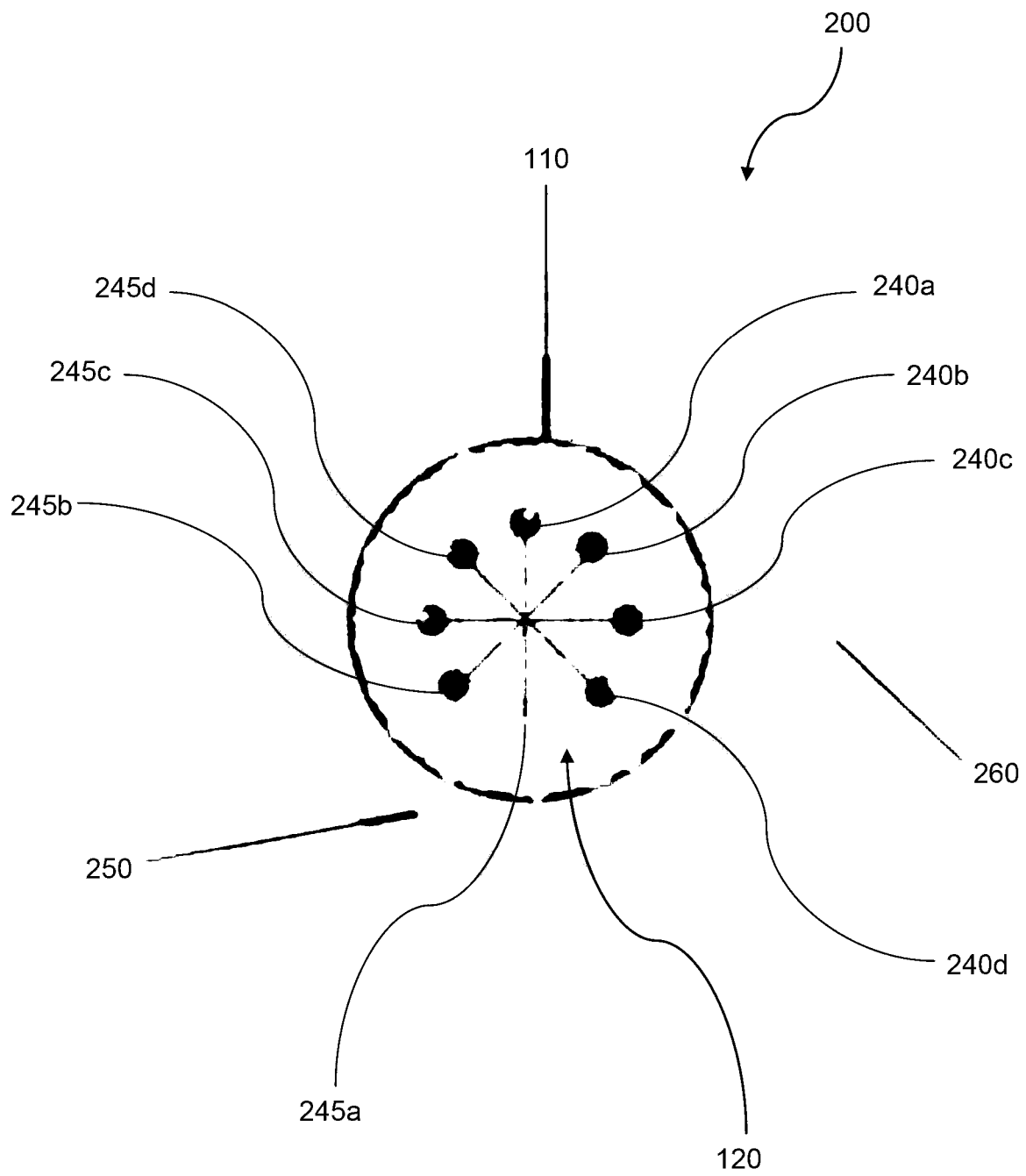


FIG. 4

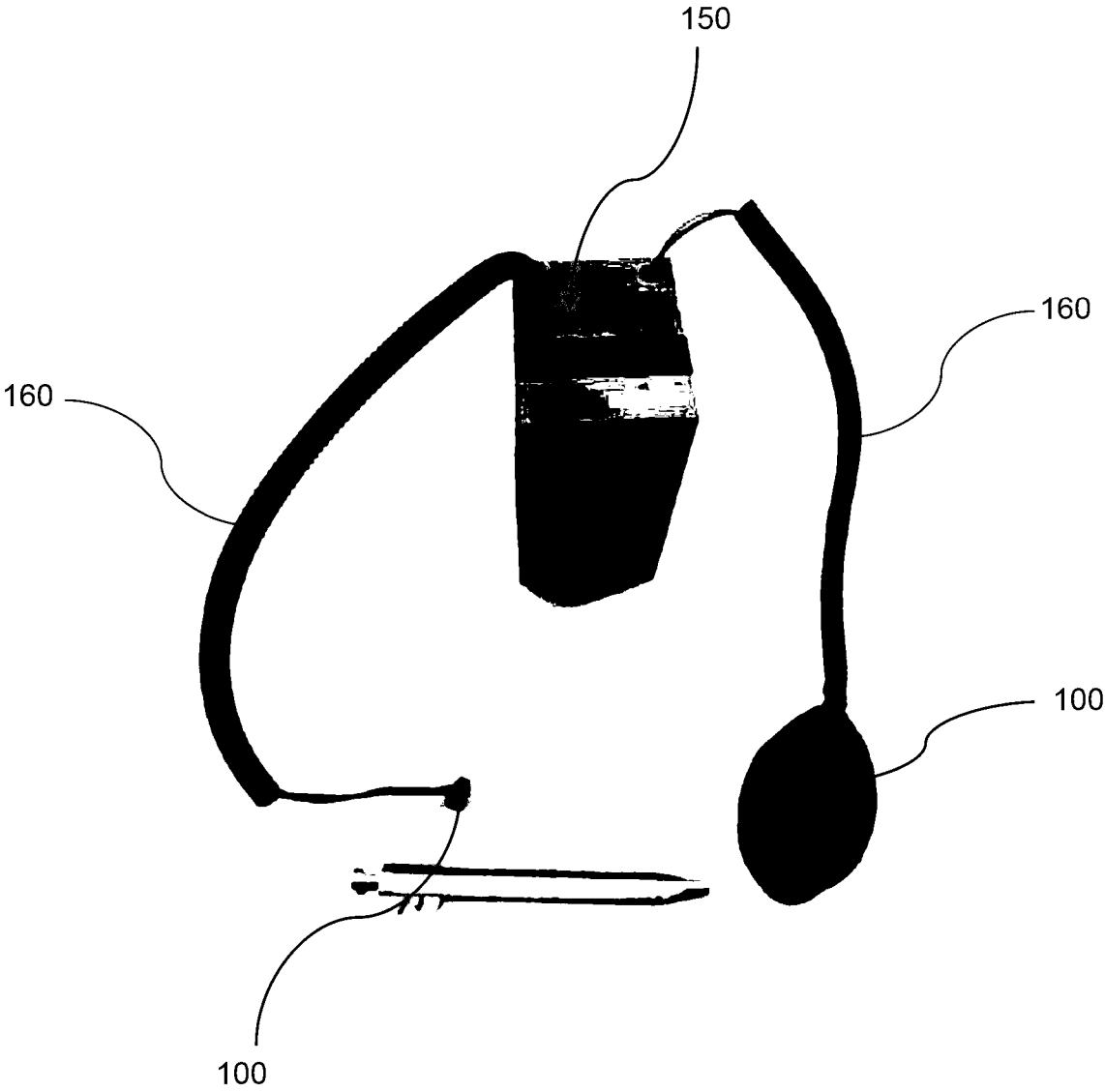


FIG. 5

INTERNATIONAL SEARCH REPORT

 International application No.
PCT/AU2017/000178

A. CLASSIFICATION OF SUBJECT MATTER

G01L 1/20 (2006.01) G01L 9/02 (2006.01)

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)

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 practicable, search terms used)

Database: PATENW (EPODOC, WPIAP and English full text databases), IPC and CPC: G01L 1/20 (and sub-marks); G01G 3/14 (and sub-marks); H01C 10/10 (and sub-marks); G01L 9/02 (and sub-marks); G01G; G01L. CPC: G01L 9/0002; G01L 9/0083. Keywords: granule, grain, sphere, particle; close, densely; packed; HCP, FCC; area; contact, touching, connecting; pressure, stress, force, weight, mass; measure, sense, detect, transducer; resistance, conductance; voltage, potential; drop, change; fluid, liquid, gas; volume, size; change, vary, increase, decrease, adjust; AND LIKE TERMS. Databases: INSPEC and MEDLINE. Search terms: pressure, stress, force, weight, mass; measure, sense, detect, transducer; granule, grain, sphere, particle; close, densely; packed; HCP, FCC; resistance, conductance; voltage, potential; drop, change; area; contact, touching, connecting; Zhai (Author), Gan (Author), Hanaor (Author), Proust (Author), Einav (Author); AND LIKE TERMS. Databases: Espacenet and Auspat. Search terms: The University of Sydney (Applicant); G01G (IPC); G01L (IPC); G01P (IPC); Chongpu Zhai (Inventor), Yixiang Gan (Inventor), Dorian Hanaor (Inventor), Gwenaelle Proust (Inventor), Itai Einav (Inventor); AND LIKE TERMS. Database: Google Scholar. Search terms: Zhai, Gan, Hanaor, Proust, Einav; AND LIKE TERMS. Applicant and Inventor names searched in internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"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
"E"	earlier application or patent but published on or after the international filing date	"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
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		
Date of the actual completion of the international search 31 October 2017		Date of mailing of the international search report 31 October 2017	
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au		Authorised officer Richard Baker AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. +61262832583	

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2017/000178
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3683307 A (PATTERSON) 08 August 1972 Abstract, column 1 lines 7 to 30, column 2 line 52 to column 3 line 38, figure 2	1-16
Form PCT/ISA/210 (fifth sheet) (July 2009)		

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2017/000178	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 3683307 A	08 August 1972	US 3683307 A	08 Aug 1972
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			