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Cheng et al.

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(54) **STRAIN SENSOR**

(56) **References Cited**

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G01B 7/16 (2006.01)

(52) **U.S. Cl.** **73/774; 73/760**

(58) **Field of Classification Search** **73/760-774, 73/777**

See application file for complete search history.

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(57) **ABSTRACT**

A strain sensor (10) for measuring strain greater than 10%, the sensor (10) comprising: an upper polydimethylsiloxane (PDMS) substrate (20) having measurement electrodes (90) extending therethrough; a lower PDMS substrate (30) bonded to a lower surface of the upper PDMS substrate (20), and an upper surface of the lower PDMS substrate (30) having a patterned portion (50); and a conductive fluid (70) contained within the patterned portion (50) in contact with the measurement electrodes (90).

18 Claims, 8 Drawing Sheets

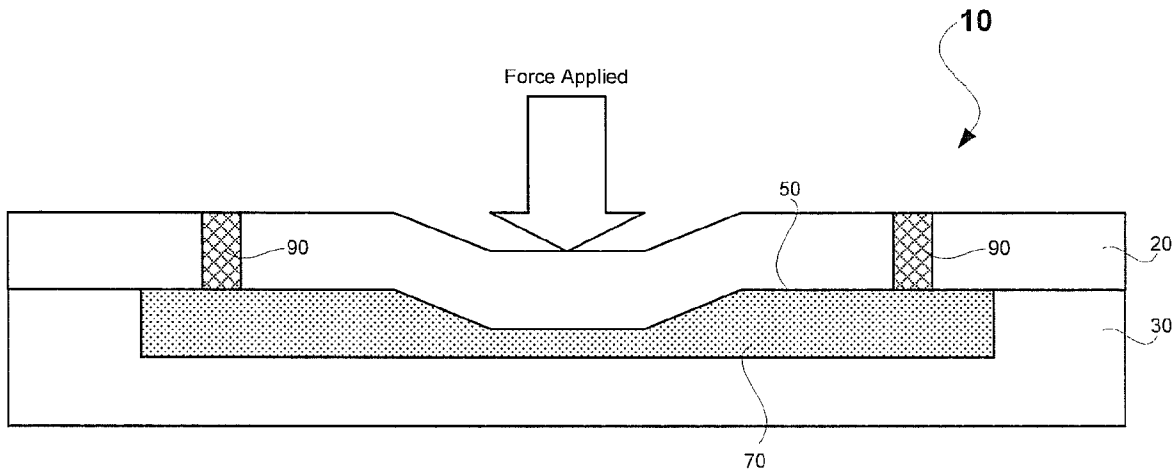


Figure 1

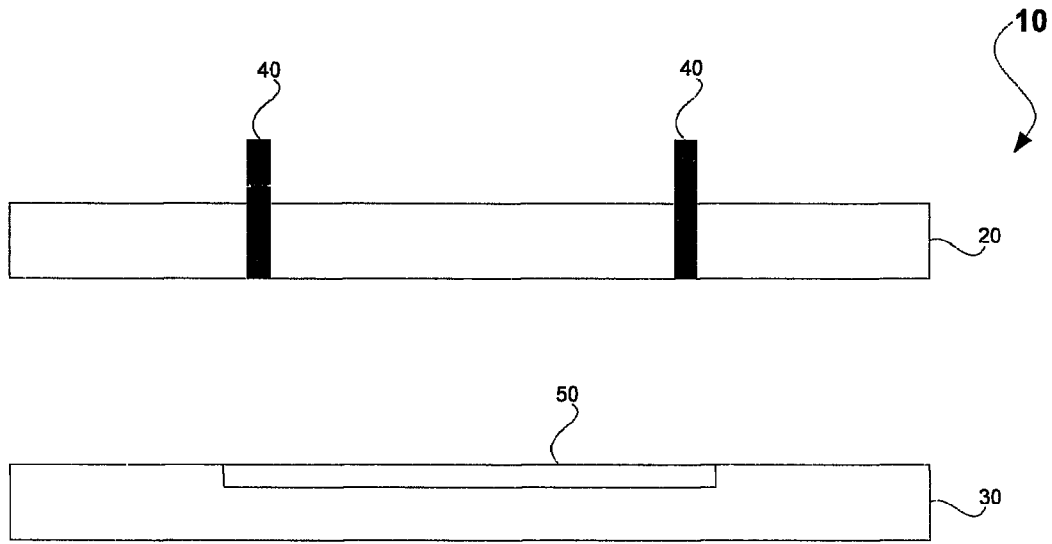


Figure 2

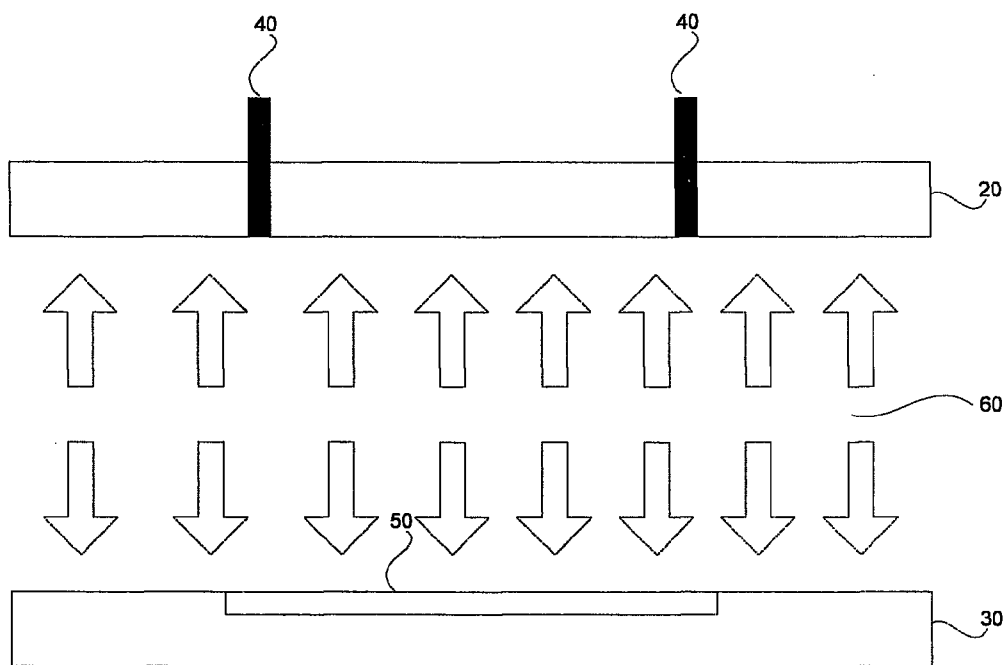


Figure 3

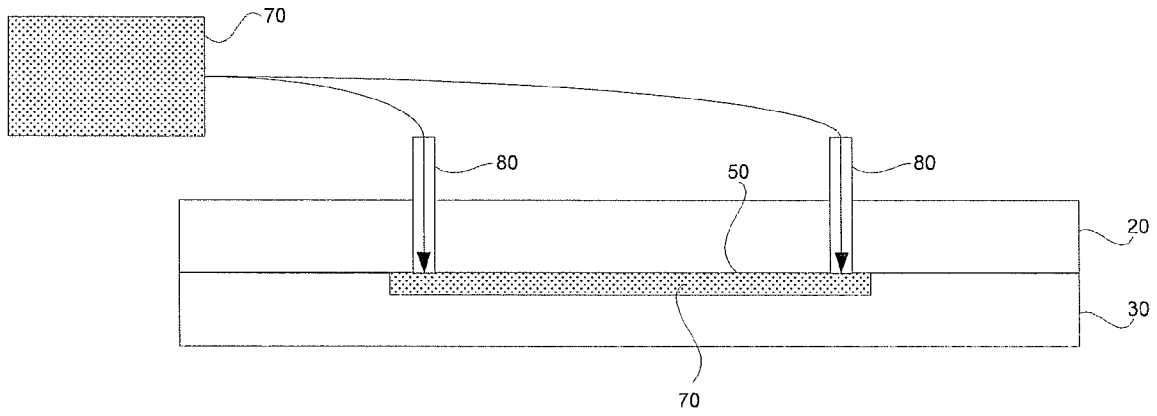


Figure 4

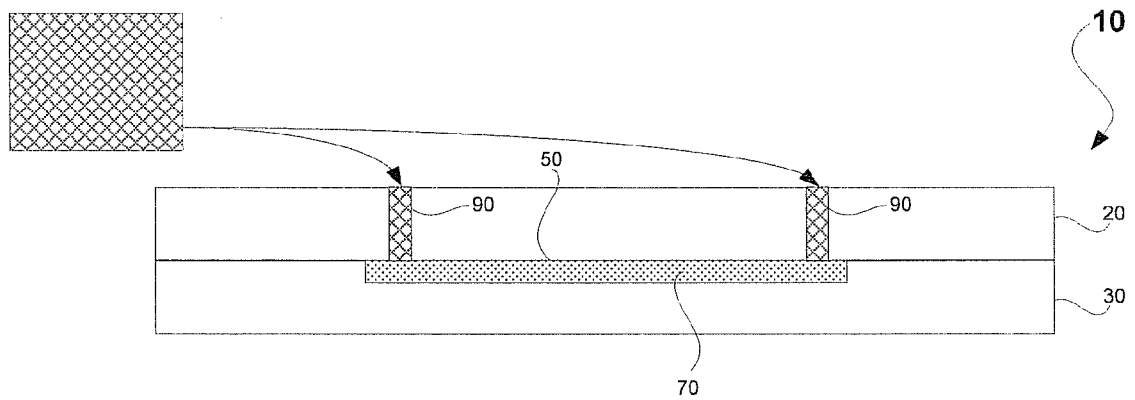


Figure 5

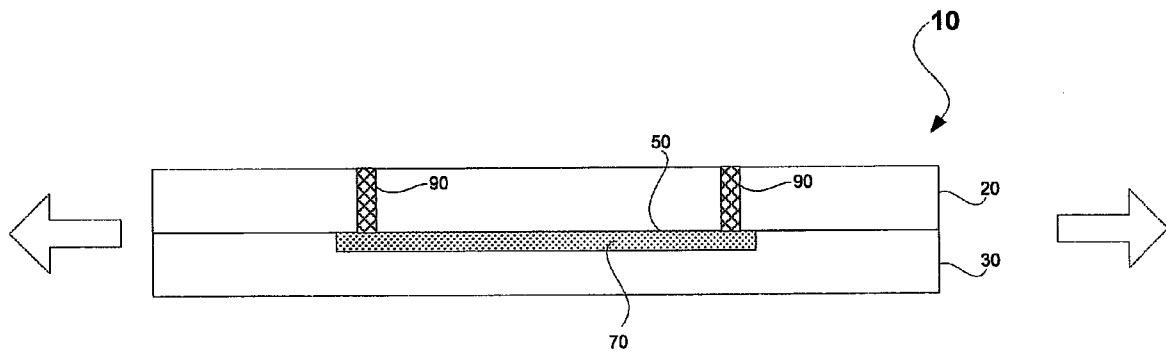


Figure 6

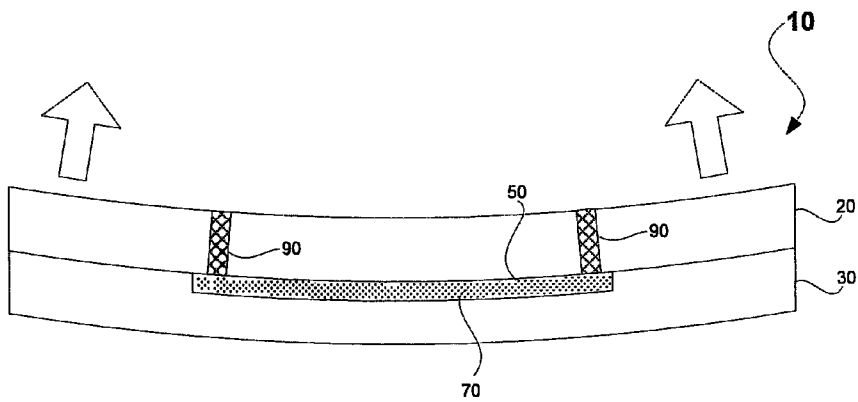


Figure 7

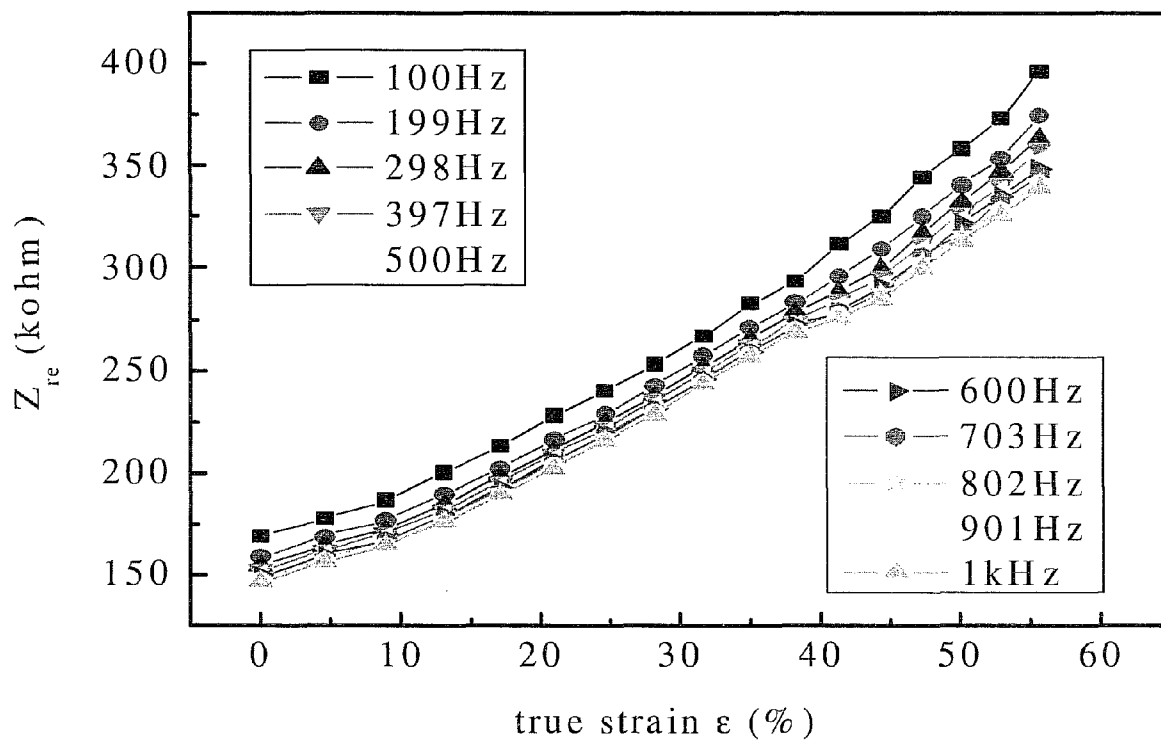


Figure 8

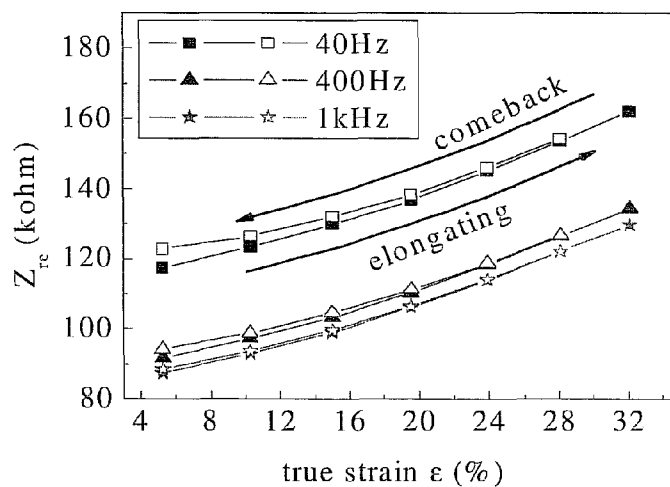


Figure 9

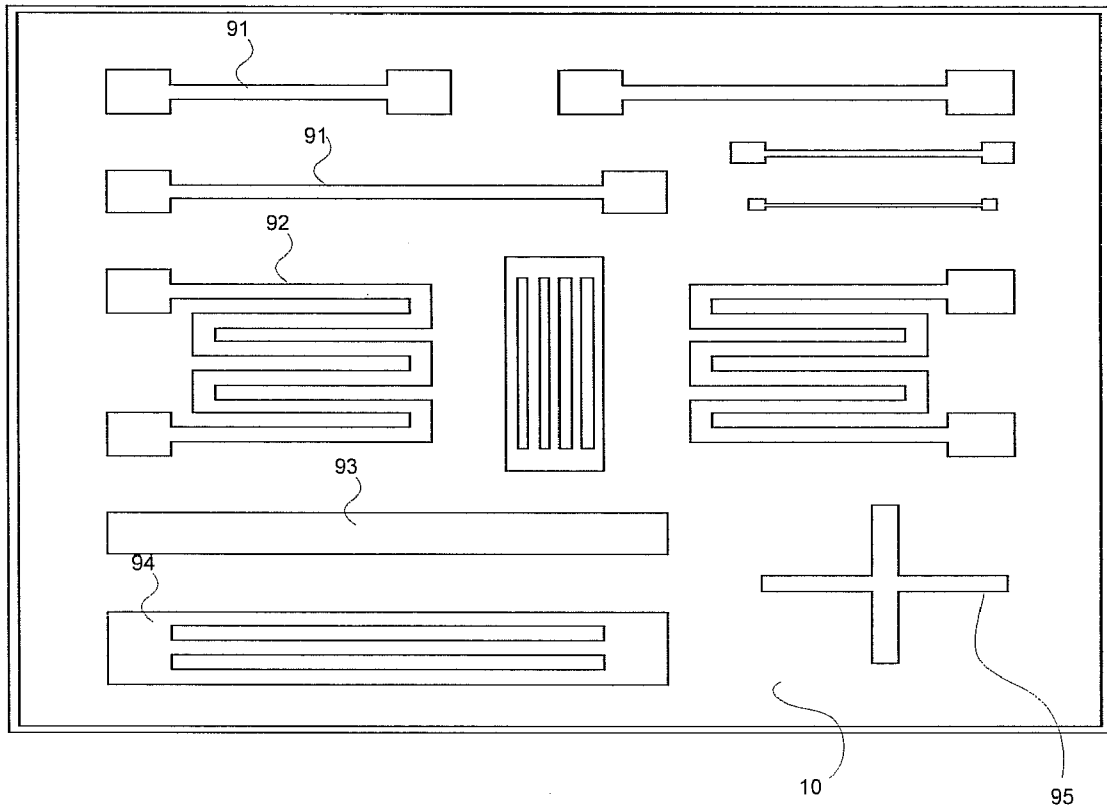


Figure 10

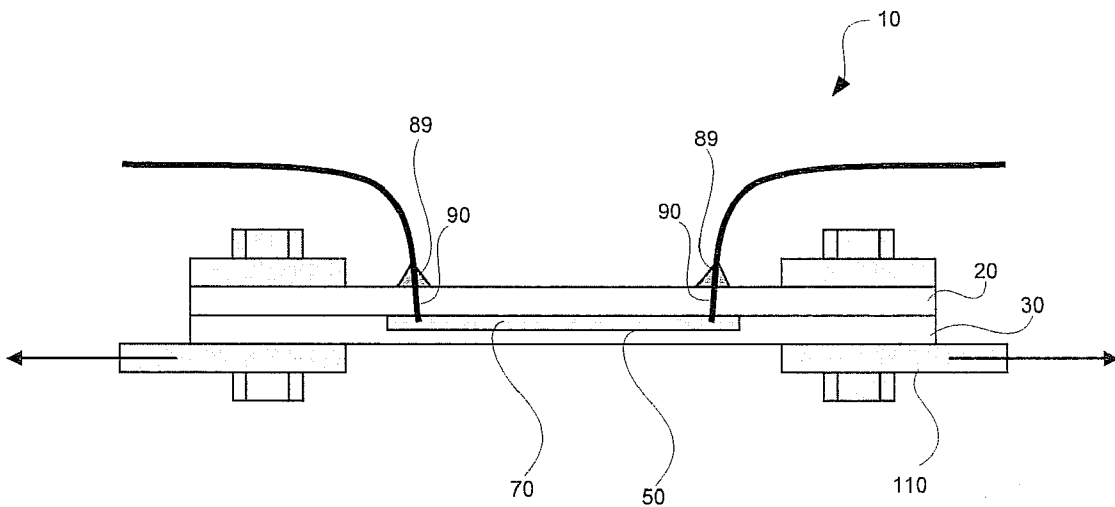


Figure 11

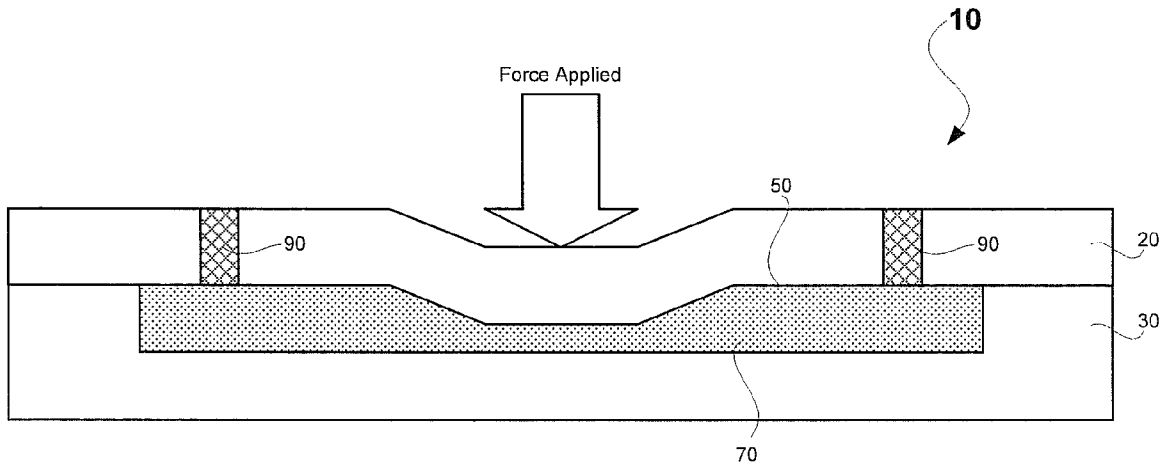


Figure 12

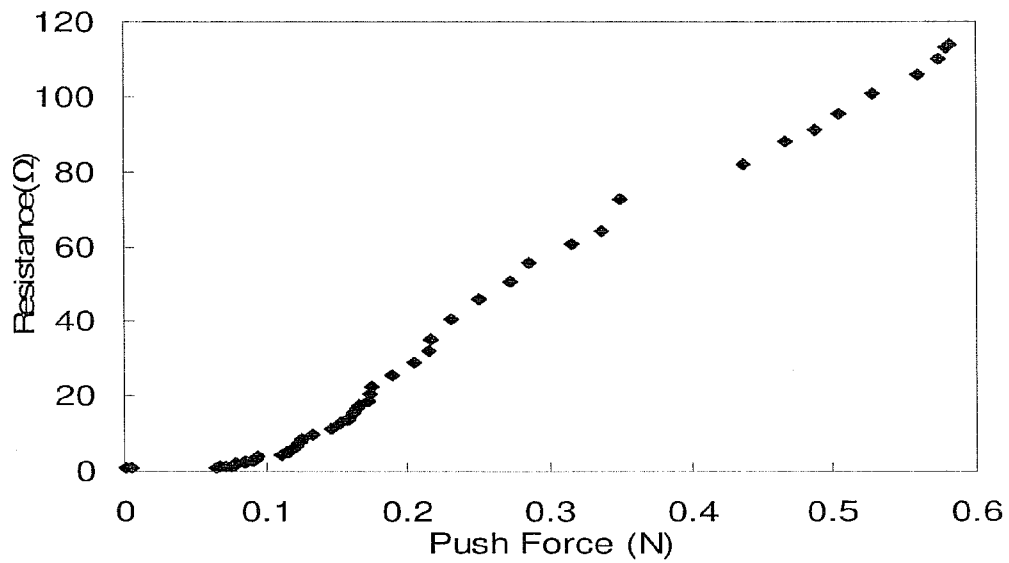


Figure 13

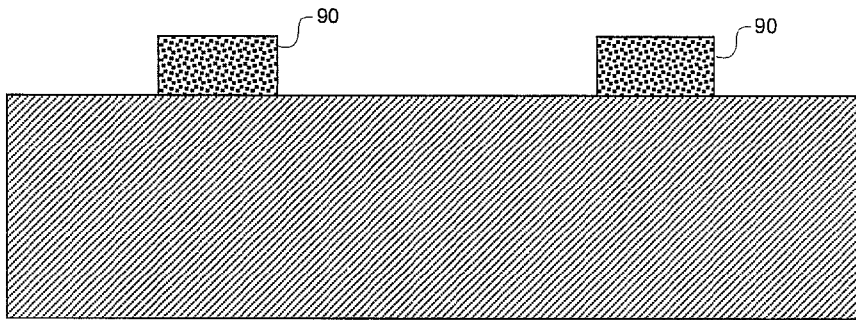


Figure 14

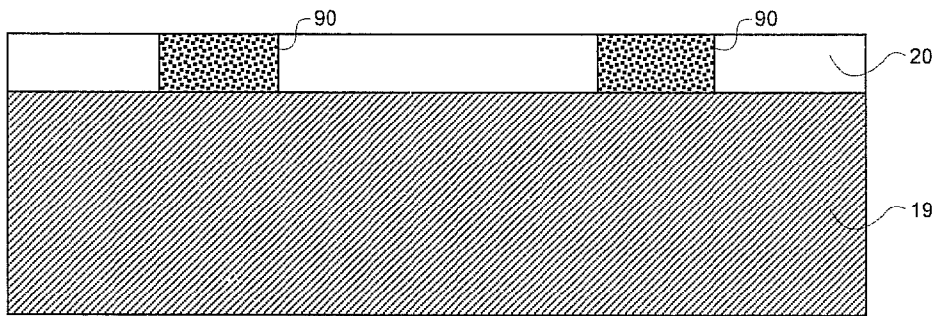


Figure 15

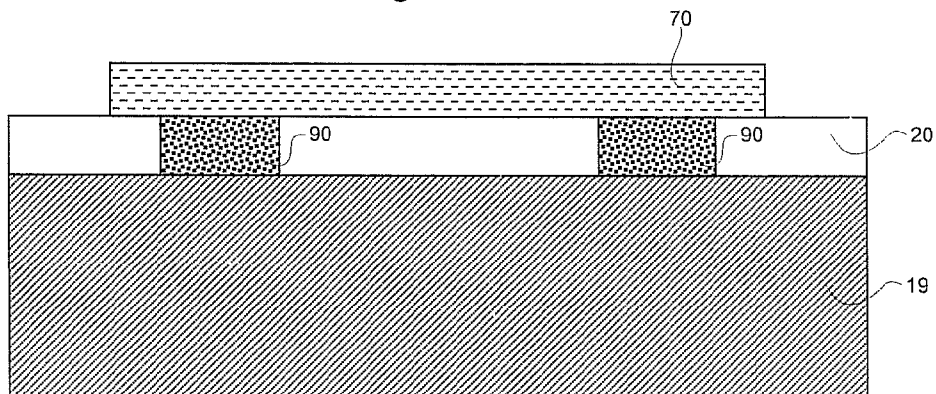


Figure 16

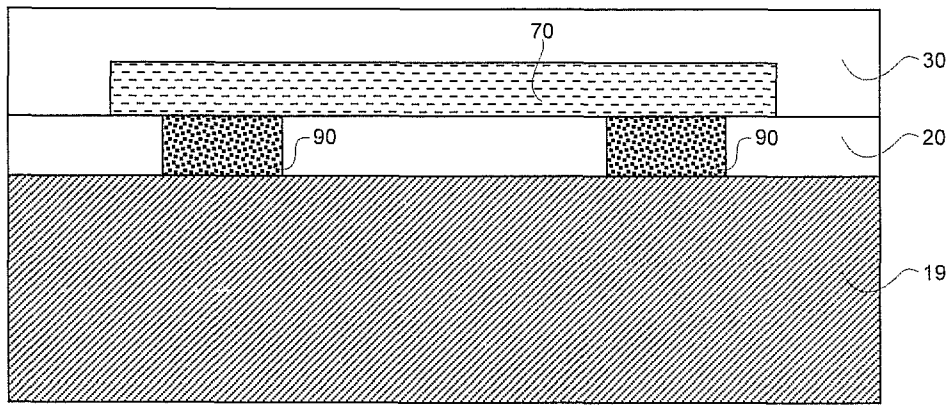


Figure 17

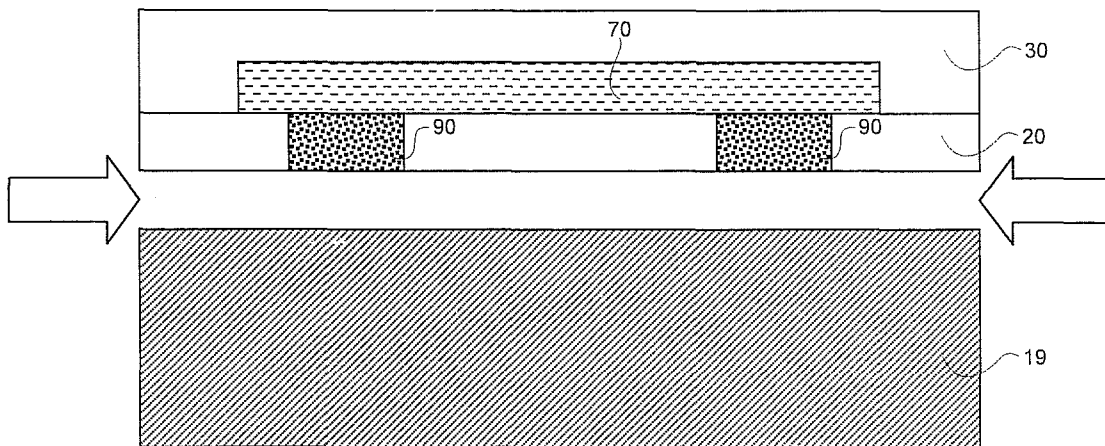
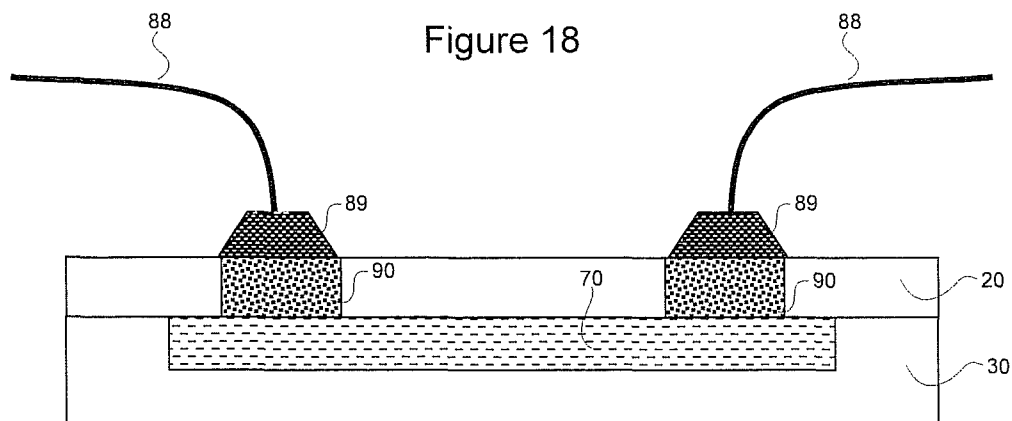


Figure 18



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STRAIN SENSOR

TECHNICAL FIELD

The invention concerns a strain sensor for measuring strain greater than 10% and a method for manufacturing the strain sensor.

BACKGROUND OF THE INVENTION

A traditional metal wire strain gauge or foil type strain gauge is limited in measuring large strain since they typically only measure strain up to around several percent. For example, platinum-8% tungsten has the strain range of about $\pm 0.3\%$. A copper-nickel alloy has the strain range of up to $\pm 5\%$.

A strain sensor made of commercial fabrics coated by a conductive polymer is able to detect a large strain deformation; however, the repeatability and reliability is limited. After frequent usage, the performance of this strain sensor reduces gradually due to the poor mechanical properties of the polymer, the aging of polymer and reduction of adhesion, especially in cyclic deformation.

A salt water based strain sensor is able to measure large strain and has no aging problem. However, the evaporation of water and the corrosion of the electrodes are significant problems encountered.

Mercury based strain sensors are able to measure large strain. However, the use of mercury is not environmentally friendly.

Accordingly, there is a desire for a strain sensor that ameliorates at least some of the problems identified with prior art strain gauges outlined above.

SUMMARY OF THE INVENTION

In a first preferred aspect, there is provided a strain sensor for measuring strain greater than 10%, the sensor comprising: an upper polydimethylsiloxane (PDMS) substrate having measurement electrodes extending therethrough; a lower PDMS substrate bonded to a lower surface of the upper PDMS substrate, and an upper surface of the lower PDMS substrate having a patterned portion; and a conductive fluid contained within the patterned portion in contact with the measurement electrodes.

The conductive fluid may be a room temperature ionic liquid for use as a piezoresistive gauge material or a eutectic alloy comprising at least gallium and indium.

The sensor may further comprise a casing made from polymers or elastomers

The casing may be made from PDMS.

The measurement electrodes may be carbon nanotubes doped PDMS

The carbon nanotubes may be multiwalled.

The measurement electrodes may be lacquered wires or carbon fibers.

The PDMS substrates may be bonded to each other after an oxygen plasma treatment is applied on the PDMS substrates.

In a second aspect, there is provided a method for manufacturing a strain sensor for measuring strain greater than 10%, the method comprising:

bonding an upper polydimethylsiloxane (PDMS) to a lower PDMS substrate;

injecting a conductive fluid via holes in the upper PDMS substrate to be contained in a patterned portion of the lower PDMS substrate; and

filling the holes in the upper PDMS substrate with measurement electrodes that are in contact with the conductive fluid.

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The conductive fluid may be a room temperature ionic liquid.

The holes may be sealed with carbon nanotube doped PDMS to form the measurement electrodes.

Lacquered wires or carbon fibers may be inserted in the holes to form the measurement electrodes.

The method may further comprise the initial step of punching the two holes through the upper PDMS substrate.

The method may further comprise the initial step of inserting two metal molds to form the holes of the upper PDMS substrate through which the conductive fluid is injected.

The method may further comprise the initial step of patterning the lower PDMS substrate using an SU-8 channel mold to form the patterned portion for containing the conductive fluid.

The method may further comprise the initial step of applying an oxygen plasma treatment to the PDMS substrates prior to bonding them together.

BRIEF DESCRIPTION OF THE DRAWINGS

An example of the invention will now be described with reference to the accompanying drawings, in which:

FIG. 1 is a side view of preparing two PDMS substrates for manufacturing a strain sensor in accordance with a preferred embodiment of the present invention;

FIG. 2 is a side view of applying an oxygen plasma treatment to the prepared PDMS substrates of FIG. 1;

FIG. 3 is a side view of injecting ionic liquid into the bonded PDMS substrates of FIG. 2;

FIG. 4 is a side view of sealing the strain sensor of FIG. 3 with a conductive polymer;

FIG. 5 is a side view of applying tensile deformation in the plane on the strain sensor of FIG. 4;

FIG. 6 is a side view of applying bending deformation on the strain sensor of FIG. 4;

FIG. 7 is a chart showing the relationship between Z_{re} and applied strain, ϵ , of the strain sensor measured at different frequencies;

FIG. 8 is a chart showing the results of a cyclic measurement test on the strain sensor;

FIG. 9 is an image of a mask for patterning a channel to contain the conductive liquid of a strain sensor according to an embodiment of the present invention;

FIG. 10 is a schematic diagram of strain sensor with carbon fiber electrodes;

FIG. 11 is a side view of applying a compressive mode across a patterned channel of the strain sensor of FIG. 4;

FIG. 12 is a chart illustrating the measurement of resistance versus push force of the strain sensor of FIG. 11;

FIG. 13 is a side view of screen printing of a conductive polymer to serve as bond pads for a strain sensor according to an embodiment of the present invention;

FIG. 14 is a side view of screen printing of a first elastomer to serve as a casing layer for the strain sensor of FIG. 13;

FIG. 15 is a side view of screen printing of a conductive liquid to serve as a sensing material for the strain sensor of FIG. 13;

FIG. 16 is a side view of spin coating of a second elastomer to serve as a casing layer for the strain sensor of FIG. 13;

FIG. 17 is a side view of peeling off the encapsulated strain sensor from the substrate to become a finished product; and

FIG. 18 is a side view of wire bonding to the bond pads using silver paste or epoxy.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to the drawings, a strain sensor **10** for measuring strain greater than 10% is provided. The sensor **10** generally comprises: two polydimethylsiloxane (PDMS) substrates **20**, **30** and a conductive fluid **70**. The two PDMS substrates include an upper polydimethylsiloxane (PDMS) substrate **20** having measurement electrodes **90** extending therethrough and a lower PDMS substrate **30** bonded to a lower surface of the upper PDMS substrate **20**. An upper surface of the lower PDMS substrate **30** has a patterned portion **50**. The conductive fluid **70** is contained within the patterned portion **50** which is in contact with the measurement electrodes **90**.

Preferably, the conductive fluid is a room temperature ionic liquid **70** because it is highly advantageous. The ionic liquid **70** is used as the piezoresistive gauge material in the strain sensor **10**. The ionic liquid **70** has excellent properties including: good electrical conductivity, "zero" vapor pressure, low viscosity coefficient, good thermal and chemical stability, and wide temperature range, etc. The liquid gauge material can measure strain over 55%. The ionic liquid based strain sensor **10** is environmentally friendly compared to a mercury based strain sensor **10** because no mercury or heavy toxic metals are required. Ionic liquid **70** almost does not volatilize over a wide temperature range therefore as compared to a salt water based strain sensor **10**, it is persistently usable with no liquid gauge material consumption. Ionic liquid **70** has a higher potential window, from 4 to 6 volts, depending on its species, and therefore has a wide working voltage range. The refraction index of ionic liquid **70** (i.e. 1.42) is close to that of the PDMS substrates **20**, **30** (i.e. 1.4), the patterned channel **50** become invisible after the injection of the ionic liquid **70** as shown in FIG. **9**. It has potential use in the research of invisible devices and optical devices.

The measurement electrodes **90** may be prepared by two modes. One uses PDMS mixed with MWCNTs (multiwalled carbon nanotubes) as flexible electrodes. The other uses traditional lacquered wires **88** or carbon fibers (see FIG. **10**). In one embodiment, CNTs doped PDMS are used in the strain sensor **10** as the measurement electrodes **90**. The mixture shows good conductivity when the percentage by weight of CNTs is over 8%. This flexible electrode **90** can seal up the conductive channel **50** very well and it combines with the PDMS substrate **20** closely under large strain. Use of such an electrode **90** solves the flaking off or sliding off problem in connecting point as compared to a metal electrode/PDMS substrate system. Furthermore, a mixture of CNT and PDMS is anticorrosive and is highly suitable for an electrode material. This flexible electrode **90** provides a broad application if its resistivity is reduced correspondingly. A carbon fiber electrode **90** combines the benefits of above two electrode materials because it has a good conductivity and is anticorrosive.

The casing of the strain sensor **10** can be made of polymers or elastomers so as to achieve a large strain. In one embodiment, the piezoresistive strain sensor **10** is used for large strain measurement in which the true strain, $\epsilon = \ln(L/L_0)$, (L_0 is the original length and L is the final length of the sensor **10**) is measured due to the large deformation. Since the casing is merely a package, aging of the package material is not a problem in the sensor **10**. If PDMS is used as the casing, it can be adjusted to different elasticity as demanded by changing the ratio of the PDMS pre-polymer to the curing agent.

A detailed microfabrication process for the strain sensor **10** is depicted in FIGS. **1** to **4**. Turning to FIG. **1**, two pieces of PDMS substrates **20**, **30** are prepared. The two pieces of PDMS substrates **20**, **30** are 500 μm thick PDMS substrates (Dow Corning Sylgard 184, 1:10 w/w ratio of curing agent to

elastomer base, hardened in an oven at 70° C. for an hour). The upper substrate **20** is smooth. Two access holes are punched through the upper substrate **20** for liquid phases and measurement electrodes **90**. The punching is performed after curing of the upper PDMS substrate **20**. Another technique to form the access holes is to insert two metal molds **40** during solidification of the upper PDMS substrate **20**. The lower substrate **30** is patterned using an SU-8 channel mold **50** to form the channel **50** for containing the conductive liquid **70**. A channel mold **50** with 50 μm thick features is fabricated using a single step photolithography with SU-8 **50** photoresist. Using optical lithography processes, the mold **50** is exposed for 60 seconds under UV light on a mask aligner. A sample of the strain sensor **10** with a single-line microchannel, $13 \times 1.5 \times 0.05 \text{ mm}^3$ is measured and the results are shown in FIG. **7**.

Referring to FIG. **2**, after the PDMS substrates **20**, **30** are prepared, oxygen plasma treatment **60** is applied to both PDMS substrates **20**, **30**.

Referring to FIG. **3**, the two PDMS substrates **20**, **30** are bonded together. The metal molds **40** are removed and two hollow metal tubes **80** are inserted. Ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate [Bmim][BF₄] **70** is injected via the hollow metal tubes **80** to the patterned portion **70** of the lower substrate **30**.

Referring to FIG. **4**, the hollow metal tubes **80** are removed. The sensor **10** is sealed with a conductive polymer (carbon nanotube doped PDMS) **90**. This fills the voids left by the punched holes or the holes formed by the hollow metal tubes **80** with carbon nanotube doped PDMS **90**. The carbon nanotube doped PDMS are the measurement electrodes **90**.

In another scenario where the strain sensor **10** using the lacquered wires **88** or carbon fibers as the measurement electrodes **90**, the microfabrication process differs by inserting two lacquered wires or carbon fibers in the voids left by the hollow metal tubes **80** and sealing the joint area with instant glue.

Referring to FIGS. **5** and **6**, force may be applied (or transferred from the object to the gauge through the interface) onto the fluidic piezoresistive strain sensor **10** at the two ends. The resistance of a confined gauge material of the strain sensor **10** changes upon an applied deformation onto the casing of the strain sensor **10**. There are two deformation modes. In FIG. **5**, there is tensile deformation in the plane. In FIG. **6**, there is bending deformation. The stress transfer mechanism may be through directly applying a tensile force at the two ends of the strain sensor **10**; or through interfacial stress transfer by attaching the sensor **10** to the surface of a deforming body.

The result of measurement is shown in FIG. **7** showing the relationship between Z_{re} and applied strain, ϵ , of the strain sensor **10** measured at different frequencies (100 Hz-1 kHz). The variation between the real part of the impedance measured (Z_{re}) against strain applied (ϵ) at different applied frequencies for the strain sensor **10** is depicted. In order to reduce the cost of fabrication for more applications, a batch encapsulation method of ionic liquid is envisaged.

During a cyclic measurement test, the strain sensor **10** exhibits a good stability and a long operational life. In order to understand the repeatability, loop measurements are made to study its hysteresis. FIG. **8** illustrates the dependence of the real part of the impedance Z_{re} on applied strain ϵ of the strain sensor **10**, the frequency is 40 Hz, 400 Hz, and 1 kHz, respectively, and the applied voltage is 500 mV. The results indicate that the return curve almost superposes with the initial elongation curve after ten times cyclic deformation, except for the tiny offset at low frequency. This offset is coming from the

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change of polarization resistance caused by ion polarization. When the frequency increases, the effect of ion polarization decreases, and the offset vanishes gradually. No hysteresis was observed under more times cyclic measurements. The good repeatability makes the strain sensor **10** more attractive for practical use.

Referring to FIG. **8**, dependence of the real part of the impedance Z_{re} on applied strain ϵ of the strain sensor **10** at different frequencies 40 Hz, 400 Hz, and 1 kHz, and the applied voltage is 500 mV. The solid symbols show the measurement results with the increase of ϵ . The hollow symbols show the results with the decrease of ϵ after ten times cycle of elongating and contracting.

Referring to FIG. **9**, is an image of a mask for patterning the channel **50** to contain the conductive liquid **70** of a strain sensor **10**. There are different shapes and sizes, including dog bone **91**, serpentine **92**, cross **95**, single line **93**, multiple lines **94**, etc. to fit for different applications. The electrodes **90** are made of PDMS mixed with MWCNTs (multiwalled carbon nanotube). Other embodiments use lacquered wires as the electrodes or carbon fibers as the electrodes. The patterned channel **50** becomes invisible which is due to the close refraction index between the ionic liquid and PDMS substrates **20**, **30**.

Referring back to FIGS. **5** and **6**, a sample of the strain sensor **10** was made using PDMS as the casing, [Bmim][BF₄] as the piezoresistive gauge material, and MWCNT doped PDMS as the electrode. However, lacquered wires (copper and 0.21 mm in diameter) or carbon fibers may be used as the electrode. The weight proportion of the electrode material used (MWCNT:PDMS) is 1:10. Referring to FIG. **10**, a sample of the strain sensor **10** having carbon fiber electrodes **90** was tested under increasing strains applied through a moving platform **110** by electrochemical impedance spectroscopy. The corresponding result is shown in FIG. **7**. An electrochemical impedance analysis is used for the measurement.

In another embodiment, a liquid metal alloy is used as the conductive liquid **70** instead of ionic liquid. Liquid metal alloy is a suitable material to replace mercury because of its low toxicity to humans and the environment. One such liquid metal alloy is Galinstan™ made by Geratherm Medical AG. Galinstan™ is a eutectic alloy of gallium (Ga), indium (In), and tin (Sn)—(Ga: 68.5%, In: 21.5%, Sn: 10%), which is liquid at room temperature and typically freezes at -19° C. (-2.2° F.). Other suitable liquid metal alloys include: Ga—In (Ga: 75.5%, In: 24.5%), Ga—In—Sn (Ga: 62.5%, In: 21.5%, Sn: 16.0%), or Ga—In—Sn—Zn (Ga: 61%, In: 25%, Sn: 13%, Zn: 1%). Due to the low toxicity and environmentally-friendly nature of its component metals, these liquid metal alloys are a non-toxic replacement for liquid mercury or NaK (sodium-potassium alloy). Composition: 68.5% Ga, 21.5% In, 10% Sn. A liquid metal alloy can be detected using a simple DC circuit, for example a Wheatstone bridge, to measure its pure resistance like measuring a metal wire. However, its resistance is very low similar to the connecting wires **88**, so a thin and long serpentine wire pattern needs to be used to increase its resistance, similar to a regular strain gauge. The conductive liquid **70** is patterned **50** so that the sensor **10** is made very small comparable to a conventional solid metal strain gauge. The pattern **50** can also be designed in different shapes for different applications, as the mask layout as depicted in FIG. **9**.

However, if ionic liquid **70** is used rather than liquid metal alloy, the resistance of the ionic liquid is much higher than liquid metal alloy so most of the voltage drop will be across the strain sensor **10** without being concerned about the serial resistance from the connecting wires **88**. It also consumes

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much lower power with much less joule heating effect due to its higher resistance. However, the impedance of the ionic liquid **70** needs to be detected using an AC circuit with oscillation frequencies since it is conducted by ions, which contains both resistance and capacitance components in its impedance. Using an AC current can also prevent the formation of electrical double layer on the interface between ionic liquid **70** and contact pads **90** when driven by a DC current.

Referring to FIGS. **11** and **12**, a diagram and a chart of a fabricated prototype of the liquid-metal-alloy strain sensor **10** having force applied on its center is depicted. The force is applied to determine the increase of its resistance. When a compressive strain is applied across the liquid-metal-alloy filled channel **50**, it will reduce the cross-sectional area of the channel **50** and therefore increase the resistance of the sensing material **70**, which is described by the following equation:

$$R = \rho \frac{L}{A}$$

where R=resistance, ρ =resistivity, L=length, A=cross-sectional area

Referring to FIGS. **13** to **18**, a mass production fabrication process is described to batch fill the conductive liquid **70** into an elastomer casing. Firstly, a conductive polymer based on carbon nanotube (CNT) or carbon black (CB) is filled with PDMS and is patterned on the substrate **19** by screen printing followed by curing to solidify the elastomer. Screen printing of the conductive polymer serves as bond pads **90** to later electrically connect the conductive liquid **70** to the bond wires **88**. The first elastomer **20** made from PDMS is screen-printed and cured on the substrate **90** leaving openings on the bond pads **90** for electrical connection. Screen printing of the first elastomer **20** serves as a casing layer to encapsulate the liquid conductor **70**. The conductive liquid (ionic liquid or liquid metal alloy) **70** is screen printed on the first elastomer casing layer **20** with connection to the bond pads **90**. Screen printing of the conductive liquid, for example, ionic liquid or liquid metal alloy **70**, serves as the strain sensing material. A second elastomer **30** made from PDMS is spin-coated to cover the liquid conductor **70**. This fully encapsulates the strain sensing material **70** and serves as a casing layer. The encapsulated strain sensor **10** is peeled off the substrate **19** to become a finished product. Lastly, bond wires **88** are connected to bond pads **90** using silver paste or epoxy **89** to provide electrical connection to detection circuits.

The strain sensor **10** is useful in measuring large strain, for example, true strain of up to 55%. Stable strain measurement is achieved by using ionic fluid. The strain sensor **10** can be used in biomedical applications for the measurement of tissue deformation. Therefore, it is more competitive for practical application. Moreover, the said sensor **10** is very sensitive to applied strain or stress, it can be considered to be used as flexible switch or other contact mode devices.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the scope or spirit of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects illustrative and not restrictive.

We claim:

1. A strain sensor for measuring strain of an object greater than 10% of a length of the strain sensor, the sensor comprising:

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an upper polydimethylsiloxane (PDMS) substrate having measurement electrodes extending therethrough;
 a lower PDMS substrate bonded to a lower surface of the upper PDMS substrate, and an upper surface of the lower PDMS substrate having a patterned portion; and
 a conductive fluid contained within the patterned portion in contact with the measurement electrodes.

2. The sensor according to claim 1, wherein the conductive fluid is a room temperature ionic liquid for use as a piezoresistive gauge material or a eutectic alloy comprising at least gallium and indium.

3. The sensor according to claim 1, further comprising a casing made from polymers or elastomers.

4. The sensor according to claim 3, wherein the casing is made from PDMS.

5. The sensor according to claim 1, wherein the measurement electrodes are carbon nanotubes doped PDMS.

6. The sensor according to claim 5, wherein the carbon nanotubes are multiwalled.

7. The sensor according to claim 1, wherein the measurement electrodes are lacquered wires or carbon fibers.

8. The sensor according to claim 1, wherein the PDMS substrates are bonded to each other after an oxygen plasma treatment is applied on the PDMS substrates.

9. A method for manufacturing a strain sensor for measuring strain greater than 10% of a length of the strain sensor, the method comprising:

bonding an upper polydimethylsiloxane (PDMS) to a lower PDMS substrate;

injecting a conductive fluid via holes in the upper PDMS substrate to be contained in a patterned portion of the lower PDMS substrate; and

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filling the holes in the upper PDMS substrate with measurement electrodes that are in contact with the conductive fluid.

10. The method according to claim 9, wherein the conductive fluid is a room temperature ionic liquid.

11. The method according to claim 9, wherein the holes are sealed with carbon nanotube doped PDMS to form the measurement electrodes.

12. The method according to claim 9, wherein lacquered wires or carbon fibers are inserted in the holes to form the measurement electrodes.

13. The method according to claim 9, further comprising the initial step of punching the two holes through the upper PDMS substrate.

14. The method according to claim 9, further comprising the initial step of inserting two metal molds to form the holes of the upper PDMS substrate through which the conductive fluid is injected.

15. The method according to claim 9, further comprising the initial step of patterning the lower PDMS substrate using an SU-8 channel mold to form the patterned portion for containing the conductive fluid.

16. The method according to claim 9, further comprising the initial step of applying an oxygen plasma treatment to the PDMS substrates prior to bonding them together.

17. The sensor according to claim 1, wherein the lower PDMS substrate is patterned via an SU-8 channel mold to thereby form the patterned portion.

18. The sensor according to claim 1, wherein an oxygen plasma treatment is applied to the upper and lower PDMS substrates prior to bonding the lower PDMS substrate to the upper PDMS substrate.

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