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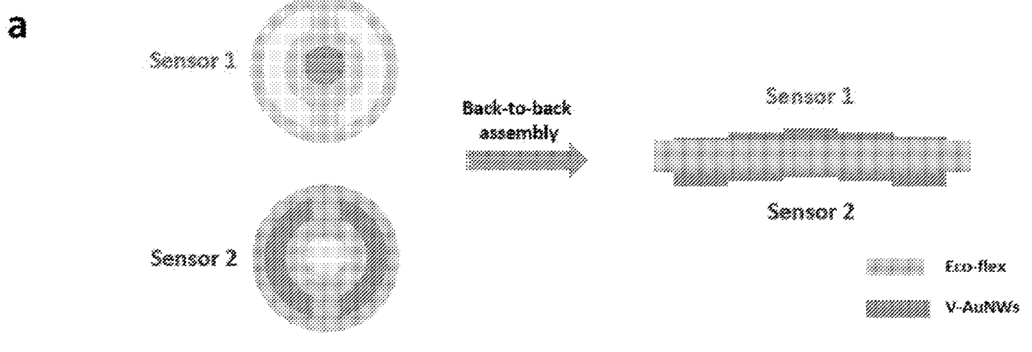
(54) **Title:** A PRESSURE SENSOR AND A PROCESS FOR PRODUCING A PRESSURE SENSOR

Figure 15



(57) **Abstract:** A pressure sensor, including a sheet-like substrate having electrically conductive nanowires projecting from opposite sides thereof, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different nanowire lengths and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the pressure sensor and corresponding pressure sensing regions of the pressure sensor where the pressure was applied.

A PRESSURE SENSOR
AND
A PROCESS FOR PRODUCING A PRESSURE SENSOR

TECHNICAL FIELD

The present invention relates to pressure sensors, and in particular to pressure sensors that can measure pressure applied to one or more regions of the sensor by an object, and identify to which regions of the sensor that pressure was applied. The sensor can be flexible to conform to non-planar surfaces, and can be used as a tactile sensor.

BACKGROUND

A unique advantage of the human skin sensory system is its specificity. As far as pressure is concerned, our skin can identify not only where an external force is applied, but also whether it is applied with a sharp object or a blunt object. To mimic this skin function, pixelated sensor arrays have been developed and connected to matrix circuitry in order to monitor pressure-induced electric, magnetic and optical signal changes. However, such arrays require numerous and complex wiring interconnects, rending them impractical for large-area pressure mapping applications (for example, to cover the entire curvilinear surface of the human body).

It is desired, therefore, to provide a pressure sensor and a process for producing a pressure sensor that alleviate one or more difficulties of the prior art, or to at least provide a useful alternative.

SUMMARY

In accordance with some embodiments of the present invention, there is provided a pressure sensor, including a sheet-like substrate having electrically conductive nanowires projecting from opposite sides thereof, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different nanowire lengths and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the pressure sensor and corresponding pressure sensing regions of the pressure sensor where the pressure was applied.

In some embodiments, the pressure sensing regions of the pressure sensor are arranged such that the corresponding pressure sensing regions of the pressure sensor identify one or more corresponding locations of the pressure sensor where the pressure was applied. The pressure sensor may be a tactile sensor.

In some embodiments, the electrically conductive nanowires are gold nanowires.

In some embodiments, the pressure sensing regions are arranged in a one-dimensional manner to identify the locations with respect to only one spatial dimension. In other embodiments, the pressure sensing regions are arranged in a two-dimensional manner to identify the locations with respect to two spatial dimensions. In some embodiments, the pressure sensing regions are generally circular, annular and/or part-annular.

In some embodiments, the first and second measurements of resistance are indicative of sharpness of an object applying the pressure to the sensor.

In some embodiments, the substrate and sensor are flexible such that the sensor can conform to curved or other non-planar surfaces of objects and remain functional.

In some embodiments, the sensor is stretchable by at least 10% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state. In some embodiments, the sensor is stretchable by at least 20%, preferably at least 30%, and more preferably at least 40% of its unstretched length. In some embodiments, the sensor is stretchable by at least 50% of its unstretched length.

In accordance with some embodiments of the present invention, there is provided a process for producing a pressure sensor, including the step of forming electrically conductive nanowires projecting from opposite sides of a sheet-like substrate, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different nanowire lengths and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the pressure sensor and corresponding pressure sensing regions of the pressure sensor where the pressure was applied.

In some embodiments, the pressure sensing regions of the pressure sensor are arranged such that the corresponding pressure sensing regions of the pressure sensor identify one or more corresponding locations of the pressure sensor where the pressure was applied. The pressure sensor may be a tactile sensor.

In some embodiments, the step of forming includes:

depositing metallic nanoparticles on opposed sides of the sheet-like substrate;

growing nanowires from the deposited nanoparticles;

selectively growing subsets of the grown nanowires by respective different amounts to form the respective pressure sensing regions with respective different lengths of nanowires and respective different electrical resistances.

In some embodiments, the step of selectively growing subsets of the grown nanowires includes repeatedly forming a corresponding patterned mask on the nanowires, and further growing a corresponding subset of the nanowires that are not covered by the corresponding patterned mask.

In some embodiments, the pressure sensing regions are arranged in a one-dimensional manner to identify the locations with respect to only one spatial dimension. In other embodiments, the pressure sensing regions are arranged in a two-dimensional manner to identify the locations with respect to two spatial dimensions. In some embodiments, the pressure sensing regions are generally circular, annular and/or part-annular.

In some embodiments, the first and second measurements of resistance are indicative of sharpness of an object applying the pressure to the sensor.

In some embodiments, the substrate and sensor are flexible such that the sensor can conform to curved or other non-planar surfaces of objects and remain functional.

In some embodiments, the sensor is stretchable by at least 10% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state.

In some embodiments, the sensor is stretchable by at least 20%, preferably at least 30%, more preferably at least 40%, and most preferably at least 50% of its unstretched length.

Also described herein is a pressure sensor, including a sheet-like substrate having electrically conductive nanowires projecting from opposite sides thereof, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different lengths of the nanowires and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the sensor and a corresponding location of the pressure applied to the sensor. The electrically conductive nanowires may be gold nanowires.

The pressure sensing regions may be arranged in a one-dimensional manner to sense pressure along only one spatial dimension. Alternatively, the pressure sensing regions may be arranged in a two-dimensional manner to sense pressure along two spatial dimensions. The pressure sensing regions may be generally annular or part-annular.

The first and second measurements of resistance may be indicative of sharpness of an object applying the pressure to the sensor.

The substrate and sensor may be flexible such that the sensor can be made to conform to curved or other non-planar surfaces of objects and remain functional.

The sensor may be stretchable by at least 10% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state.

The sensor may be stretchable by at least 20%, at least 30%, or at least 40% of its unstretched length. The sensor may be stretchable by 50% of its unstretched length.

Also described herein is a process for producing a pressure sensor, including the steps of:

depositing metallic nanoparticles on opposed sides of a sheet-like substrate;

growing nanowires from the deposited nanoparticles;

selectively growing subsets of the grown nanowires by respective different amounts to form respective pressure sensing regions with respective different lengths of nanowires and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the sensor and a corresponding location of the pressure applied to the sensor.

The step of selectively growing subsets of the grown nanowires may include repeatedly forming a corresponding patterned mask on the nanowires, and further growing a corresponding subset of the nanowires that are not covered by the corresponding patterned mask.

The pressure sensing regions may be arranged in a one-dimensional manner to sense pressure along only one spatial dimension.

The pressure sensing regions may be arranged in a two-dimensional manner to sense pressure along two spatial dimensions. The pressure sensing regions may be generally annular or part-annular.

The first and second measurements of resistance may be indicative of sharpness of an object applying the pressure to the sensor.

The substrate and sensor may be flexible such that the sensor can be made to conform to curved or other non-planar surfaces of objects and remain functional.

In some embodiments the sensor is stretchable by at least 10%, 20%, 30%, 40% or 50% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present invention are hereinafter described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 is a flow diagram of a process for producing a pressure sensor in accordance with an embodiment of the present invention;

Figure 2 is a flow diagram of a selected area growth process of the process of Figure 1;

Figure 3 includes scanning electron microscope (SEM) images showing (a) side and (c) plan views of a nanowire layer for 10 minutes of growth time, and corresponding statistical distributions of the diameters of (b) the nanowires, and (d) the gold nanoparticles at the ends of the nanowires;

Figure 4 includes (a) a schematic illustration of the fabrication of a nanowire layer in the form of a three-step staircase, (b) atomic force microscopy (AFM) images and line scans of the step boundary regions of the nanowire layer, and SEM images showing (c) a plan view of a step boundary region and (d) a cross-sectional view of the nanowire layer;

Figure 5 includes SEM images (with a 5 μm scale bar) of the step boundary regions of the nanowire film, for the steps corresponding to growth times between (a) one and two minutes, (b) two and three minutes, (c) three and four minutes, and (d) four and five minutes;

Figure 6 includes plan and cross-sectional (after FIB milling) side view SEM images of a step boundary region of the nanowire layer;

Figure 7 includes (a) a schematic illustration of an experimental configuration used to characterise the sensors’ response to pressure, and (b) to (d) graphs of the change in electrical resistance of a nanowire layer grown for three minutes, (b) as a function of the static pressure applied to the layer, (c) as a function of time during the cyclic application of different maximum pressures, and (d) is a function of cycle number during a reliability test in which a pressure of 2 kPa was dynamically applied to the layer for 5000 cycles;

Figure 8 includes (a) a graph of the sheet resistance of nanowire layers as a function of nanowire growth time, for layers as-grown on an Eco-flex substrate that was fixed onto a pre-cleaned and silanized glass slide, and after removal of the glass substrate, and plan view optical microscope images of the nanowire layers (b) to (e) as grown, and (d) to (f) after removal from the Eco-flex substrate, for growth times of (b), (f) two, (c), (g) four, (d), (h) six, and (i) eight minutes;

Figure 9 is a graph of the change in electrical resistance of nanowire layers as a function of applied pressure for different layer thicknesses corresponding to nanowire growth times of 1 to 10 minutes, with an inset showing the same data for a smaller y-axis scale;

Figure 10 includes (a) a schematic side view of a sensor having nanowire layers on opposite sides of an electrically insulating substrate, with the nanowire layers having six mutually aligned regions of complementary thicknesses, (b) graphs showing the change in electrical resistance of each nanowire layer as a function of time during the cyclic application of a pressure of 10 kPa for each of the six regions of the nanowire layers, (c), (d) graphs of the change in electrical resistance of the respective nanowire layers as a function of pressure in each of the six regions of each layer; (e) a graph of the location-specific dimensionless parameter for each of the six regions of the sensor, demonstrating its independence from the applied pressure over a pressure range from 4 to 40 kPa, and (f) a graph showing the relationship between the value of applied pressure determined by the sensor and the actual applied pressure;

Figure 11 includes (a) a schematic illustration of the stretching of the sensor of Figure 10 by 50%, (b) a graph of the location-specific dimensionless parameter for each of the six regions of the stretched sensor, demonstrating its independence from the applied pressure over a pressure range from 4 to 40 kPa, (c) graphs of the change in electrical resistance of regions I and V respectively, as a function of applied pressure, for uniaxial strains (i.e., length elongations) of 0, 10%, 30% and 50%, and (d) a bar chart of the pressure sensitivity of each of the six regions of the sensor for uniaxial strains of 0, 10%, 30% and 50%;

Figure 12 is a graph of the electrical resistance of a six-step staircase sensor as a function of uniaxial strain;

Figure 13 includes optical microscope images showing the surface morphology of a six-step staircase nanowire layer under 50% uniaxial strain at regions (a) I, (b) II, (c) IV, and (d) VI of the layer;

Figure 14 includes plan view (a) optical microscope and (b) schematic images of a nine step staircase spiral nanowire layer pattern (nanowire growth times of 1 to 9 minutes with 1 minute increments as labelled in (b), and (c) a graph of electrical current through spiral structure as a function of time for a constant voltage of 0.1 V and for an pressure of 20 kPa successively applied and removed three times to each of regions 1 to 9 of the spiral structure;

Figure 15 includes (a) schematic top and bottom plan views and a cross-sectional side view of a tactile sensor in accordance with an embodiment of the present invention, (b), (c) resistive responses of sensor 1 and sensor 2, respectively, to the cyclic application of pressures (from 0.0375 to 0.1875 N) to the sensor by cylinders with radii of 0.6, 1.3, and 2 mm, (d) a photograph of the tactile sensor attached to a human fingertip, and (e) a bar chart of a sharpness-specific parameter S_R for pressures of 0.05, 0.1 and 0.15N applied by each of the three cylinders;

Figure 16 includes (a) schematic plan views of the two patterned nanowire layer structures of Figure 15 overlaid with equivalent series resistor circuitry, (b) to (d) finite element analysis (FEA) simulation results showing the stress distribution in a 500 µm Eco-flex film subjected to a normal force of 0.15N by cylinders with radii of 0.6, 1.3 and 2 mm; and

Figure 17 includes resistive responses of (a) to (c) sensor 1 and (d) to (f) sensor 2 to pressures of 0.4, 4.8, and 7.2 kPa applied to the sensors by cylinders with radii of 0.6, 1.3, and 2 mm.

DETAILED DESCRIPTION

The embodiments of the present invention described herein include a pressure sensor and a process for producing a pressure sensor. The pressure sensor includes electrically conductive nanowires projecting from opposite sides of a sheet-like substrate.

Surprisingly, the inventors have determined that the electrical resistance of a layer of the nanowires depends on the thickness of the layer and on the instantaneous pressure applied to the layer, and that when the pressure is removed, the electrical resistance of the layer returns to its original value (*i.e.*, the resistance value before the pressure was applied). Importantly, as demonstrated below, these characteristics remain unchanged even after many cycles of pressure application and removal, allowing a layer of the nanowires to be used as a pressure sensor by measuring the electrical resistance of the layer.

As described below, the nanowires on each side of the substrate can be configured to define different pressure sensing regions of respective different thicknesses (corresponding to respective different nanowire lengths, and consequently respective different electrical resistances). The pressure sensing regions on each side of the substrate can be arranged relative to the pressure sensing regions on the other side of the substrate such that a measurement of the electrical resistance of the nanowire layer on one side of the substrate and a corresponding measurement of electrical resistance of the nanowire layer on the other (second) side of the substrate are together indicative of both the pressure (if any) applied to the sensor and also the thicknesses of the pressure sensing region(s) where that pressure was applied. In the described embodiments, the pressure sensing regions of the pressure sensor are arranged so that once the thicknesses of the pressure sensing regions have been determined, then this can be used to determine one or more corresponding locations of the pressure sensor where the pressure was applied.

In the described embodiments, this is achieved by having the different pressure sensing regions on each side of the substrate aligned or registered in a complementary manner relative to the pressure sensing regions on the other side of the substrate such that the sum of the thicknesses of each pressure sensing region and the corresponding pressure sensing region on the opposite side of the substrate is constant. However, this need not be the case in other embodiments, provided that the combination of measurements of the total resistances of the nanowire layers on either side of the substrate uniquely identifies both the applied pressure and the regions of the sensor where that pressure was applied.

As described below, each pressure sensing region includes many nanowires of a corresponding length projecting away from the sheet-like substrate in an orientation that is generally orthogonal to the substrate. Thus each side of the substrate can be considered to have a corresponding coating or layer of nanowires, with each layer having different pressure sensing regions of different coating/layer thicknesses. If the nanowires are exactly orthogonal to the substrate, then the thickness of the nanowire layer in each pressure sensing region is equal to the length of the nanowires in that region.

In the described embodiments, the configuration of the pressure sensing regions is such that the sum of the thicknesses of the nanowire layers on opposite sides of the substrate at the location of any given pressure sensing region is constant. However, this need not be the case in other embodiments.

The pressure sensing regions can be arranged in any of a wide variety of different configurations, depending on the requirements of the sensor. For example, in some embodiments the pressure sensing regions are arranged in a one-dimensional manner to identify the location of pressure applied to the sensor along only one spatial dimension. In other embodiments, the pressure sensing regions are arranged in a two-dimensional manner to sense the location of applied pressure along two spatial dimensions. In some embodiments, the pressure sensing regions are generally annular or part-annular. It will be apparent to those skilled in the art that in general the pressure sensing regions can be patterned in any desired two-dimension shape in plan view; thus other shapes and configurations will be apparent to those skilled in the art in light of this disclosure.

As described below, in some embodiments the composition of the substrate can be chosen to provide a flexible material, allowing the sensor to conform to curved or other non-planar surfaces of objects and yet remain functional as described above. Moreover, the substrate can be formed from an elastically deformable or resiliently stretchable material wherein the sensor remains functional in both stretched and unstretched states. For example, in one embodiment described below, a sensor with a stretchable substrate remains fully functional when stretched up to at least 50% of its original length. Thus, similar to human skin, for example (and in contrast to prior art sensors), such a stretchable sensor can sense and quantify pressure and the location of that pressure in both stretched and unstretched states.

Moreover, the ability of the sensors described herein to discriminate both pressure and location allows the sensors to discriminate characteristics of the shape of an object applying the pressure to the sensor, in particular its sharpness.

The sensors described herein can be produced by processes that involve depositing metallic nanoparticles on opposite sides of a sheet-like substrate, growing nanowires from the deposited nanoparticles, and selectively further growing subsets of the grown nanowires by respective different amounts to form respective pressure sensing regions with respective different lengths of nanowires and respective different electrical resistances. The pressure sensing regions on each side of the substrate can be arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the sensor and a corresponding location of the pressure applied to the sensor. In the described embodiments, this is achieved by arranging the pressure sensing regions on opposite sides of the substrate in a complementary manner such that the sum of the thicknesses of any corresponding pair of pressure sensing regions (on opposite sides of any location on the substrate) is constant, although other configurations may be used in other embodiments.

In the described embodiments, the step of selectively growing subsets of the grown nanowires includes repeatedly forming a corresponding patterned mask on the nanowires, and further growing a corresponding subset of the nanowires that are not covered by the corresponding patterned mask.

As shown in Figure 1, a process for producing a pressure sensor begins by selecting an electrically insulating substrate at step 102. In the described embodiments, the substrate is in the form of a thin sheet, although this need not be the case in other embodiments. In some embodiments, the substrate is rigid. In other embodiments, the substrate is flexible, allowing it to be shaped as desired, or conformed to an existing shape. As described below, in some embodiments the substrate is composed of a stretchable material that allows the sensor itself to be stretchable without loss of function, as demonstrated below.

At step 104, metallic nanoparticles are deposited on opposite sides of the substrate. In the described embodiments, the metallic nanoparticles are gold nanoparticles. At step 106, nanowires are grown from the deposited nanoparticles using any of a variety of suitable methods known to those skilled in the art. The result of this step is that each side of the substrate effectively has a coating or layer of nanowires. The nanowires are typically straight or linear, closely packed, and project or extend away from the sheet-like substrate in an orientation that is generally orthogonal to the substrate. Thus each of the nanowire layers visually resembles a layer of grass, for example, or the long thin stems of cultivated enokitake mushrooms, or possibly a very dense brush, as can be seen from the examples described below and shown in the Figures.

At step (or selective growth process) 108, one or more selected regions or subsets of the nanowire layers are selectively grown by an additional amount to extend the length of the nanowires in those selected regions or subsets whilst the other nanowires in each layer remain at their current length. In the described embodiments, this is achieved by patterning or masking different regions or subsets of each nanowire layer so that only the selected regions or subsets are exposed to a growth medium or solution for further growth, as shown in the flow diagram of Figure 2. However, other selected-area growth processes may be used in other embodiments.

In the selective growth process 108 of Figure 2, a masking layer composed of a mask or masking material is deposited over the entirety of each nanowire layer at step 202. At step 204, the deposited mask material is patterned to expose only one or more selected regions of each nanowire layer in which further nanowire growth is desired. As known by those skilled in the art, this patterning step 204 involves removing the masking material from the one or more selected regions, leaving the masking material to cover the remainder of each nanowire layer, thus preventing further growth. The patterning can be achieved by use of a photoresist masking material, exposing selected regions of the photoresist to light, and developing the photoresist material to remove corresponding regions of the photoresist.

Regardless of how the masking material is patterned, at step 206 the nanowires in the exposed regions are grown by a desired amount by repeating the initial nanowire growth step 106 for a corresponding period of time. If one or more additional regions of growth are required, then the process 108 loops back to repeat steps 202 to 208. Otherwise, the patterned masking material can then be removed at step 210, and the selective growth process 108 returns to step 110 of the process 100 of Figure 1.

This selective growth process 108 can be repeated any practical number of times so that the final result is that each nanowire layer has at least two (and typically at least several) different regions of different thicknesses, with the thickness of the nanowire layer in each region corresponding to the length of the nanowires in that region.

At step 110, electrical contacts are formed to the nanowire layer on each side of the substrate so that the electrical resistance of each nanowire layer can be measured (and recalling that the substrate is electrically insulating, and does not interfere with the measurements of the electrical resistance of the nanowire layer on each side of the substrate).

Each nanowire layer acts as a pressure sensor to the extent that the electrical resistance or conductivity of each region is not only dependent on the thickness of that region, but also is linearly dependent upon the pressure applied to it. Because each layer has regions of different thicknesses, a single measurement of electrical resistivity is insufficient to uniquely determine the pressure applied to the layer. However, by aligning regions of different layer thicknesses on either side of the substrate and measuring the electrical resistivities of both layers, it is possible to determine not only the applied pressure, but also the region of the sensor where that pressure was applied. Accordingly, the spatial resolution of this sensing is dependent upon the spatial dimensions of each region.

In order to use the pressure sensor, at step 112 the electrical resistance of each nanowire layer is measured, and at step 114 the two resistance measurements are used together (as described below) to determine the pressure applied to the sensor and the location of that pressure, specifically the pressure sensing region(s) where that pressure was applied to the sensor. As described herein, that information can also be used as an indication of the sharpness of the object that was used to apply the pressure to the sensor (to the spatial resolution limit of the pressure sensor corresponding to the spatial dimensions of the pressure sensing regions).

EXAMPLES

Electrically conductive thin films of nanowires were grown on Eco-flex substrates using a modified seed-mediated approach as described in He J. *et al. Forest of gold nanowires: A new type of nanocrystal growth*, *ACS Nano* **7**, 2733-2740 (2013).

Specifically, gold (III) chloride trihydrate ($HAuCl_4 \cdot 3H_2O$, 99.9%), Triisopropylsilane (99%), 4-Mercaptobenzoic acid (MBA, 90%), (3-Aminopropyl) trimethoxysilane (APTMS), sodium citrate tribasic dihydrate (99.0%), L-ascorbic acid and ethanol (analytical grade), and sodium borohydride ($NaBH_4$) were purchased from Sigma Aldrich. All solutions were prepared using deionized water (resistivity >18 $M\Omega \cdot cm^{-1}$). All chemicals were used as received, unless otherwise indicated. A conductive thread was purchased from Adafruit. PDMS substrates were made by mixing a prepolymer gel (Sylgard 184 Silicone Elastomer Base) and a cross linker (Sylgard 184 Silicone Elastomer Curing Agent) at a weight ratio of 10:1. The mixture was spin coated on a glass slide at 300 rpm for 2 minutes, and oven cured at 65 °C for 2 hours.
After curing, the resulting PDMS sheet had a thickness of 300 μm.

Synthesis of 5 nm gold nanoparticles. 0.2 ml 25 mM gold (III) chloride trihydrate and 0.147 mL 34 mM sodium citrate was added into a conical flask with 20 mL H_2O under vigorous stirring. After 1 min, 600 μL of ice-cold, fleshing prepared 0.1M $NaBH_4$ solution was added with stirring. The solution turned brown immediately. The solution was stirred for 2 min and then stored at 4 °C until needed.

Growth of vertically aligned gold nanowires. Nanowires were grown on a stretchable Eco-flex substrate. Eco-flex substrates were made by pouring Eco-flex curable silicone fluid (Smooth-On Ecoflex 00-30) onto a 3" glass slide, followed by spin coating at 500 rpm for 1 minute, and curing at room temperature for 1 hour. After solidification, the as-fabricated Eco-flex film (~200 μm in thickness, confirmed by optical microscopy) was pretreated with an air plasma for 12 minutes to improve its surface hydrophilicity. The film was then functionalized with an amino group by reacting with an APTMS solution (5 mM) for 1 h. Subsequently, the Eco-flex film was soaked in an excess citrate-stabilized Au seed (3-5 nm) solution for 2 hours to ensure the adsorption of Au seeds (by electrostatic attraction), and rinsed with water 10 times to remove any unadsorbed Au seeds. Then, the substrates with adsorbed Au seeds were floated on the surface of the growth solution (10 ml) for a growth time of 2 minutes, with the APTMS-functionalized side facing downward in the solution to uniformly grow vertical gold nanowires (hereinafter also referred to as "V-AuNWs") without forming of precipitates. The V-AuNW growth solution contained ligand MBA (550 μM), $HAuCl_4$ (6.8 mM), and L-ascorbic acid (16.4 mM). Finally, the V-AuNW film was rinsed with Ethanol 3 times, and dried naturally. As shown in Figure 3, scanning electron microscope (SEM) characterization confirmed that the as-formed gold nanowires have an enokitake-like morphology, standing normal to the supporting substrate. In this example, the diameter of the nanowire stem is 11.5±2.4 nm, and the top nanoparticle diameter is 13.2±2.8 nm.

The selective growth process 108 used in this example is illustrated in Figure 4. The initial or '1st-step' nanowire layer was partially passivated by a polyimide (PI) mask, with the remainder exposed, and the sample was immersed into the nanowire growth solution for another 2 minutes. This leads to further growth and elongation of the exposed regions of the 1st-step nanowire layers to form a 2nd-step nanowire layer region. The mask-assisted step-growth process can be repeated any practical number of times to form 3rd-step, 4th–step, … *n*th-step nanowire layer regions, although in this example only three nanowire layer regions were formed. Finally, the PI mask used in the last growth step is peeled off to provide a stepped or 'staircase'-like nanowire layer structure on the elastomer substrate. Remarkably, the stepped nanowire layers are firmly bonded to the Eco-flex substrate without any observable damage that might have occurred during the peeling off step. The strong bonding is due to chemical bonding between the amine moieties and the gold nanowires.

The stepped or 'staircase' morphology of the nanowire films is confirmed by atomic force microscopy (AFM) and scanning electron microscopy (SEM). Figure 4b includes AFM images and corresponding line scan profiles of the three-step staircase nanowire film. The step heights for the first, second and third regions were measured to be ~0.35 μm, ~0.48 μm and ~0.71 μm, respectively. The overall height of the 3rd-step to the Eco-flex substrate is estimated to be ~1.5 μm from an AFM line scan profile. The staircase morphology was further confirmed by SEM characterization (Figures 4c, 5 and 6). Figure 4d is a representative cross-sectional SEM image of one region of the stepped nanowire layer, clearly showing the enokitake-like standing nanowire morphology that was seen in each region. It is noted that, to the inventors' knowledge, such unique staircase-like structures have not been reported previously. The time-controllable nanowire lengths, in conjunction with PI masking, allows for precise fabrication of electrically conducting films with well-defined 'hierarchical' structures (i.e., each nanowire layer having regions with different thicknesses). Although the regions form a staircase -like structure in this example, it will be apparent that in general the regions of different heights can have arbitrary shapes in plan view, and need not monotonically increase in thickness in any given direction.

The conductivity of the nanowire layer decreases when a localized pressure is applied. The inventors believe that this may be due to the generation of cracks in the conductive thin film as a result of pressure induced deformation. Regardless of the exact mechanism, the resistivity/conductivity of the nanowire film is fully reversible with respect to both static and dynamic pressure up to at least 40 kPa, as shown in Figures 7(a) to (c). The nanowire layer was also subjected to a durability test of over 5,000 cycles with an applied pressure of 2 kPa, as shown in Figure 7(d), which demonstrated no substantial change in performance after this large number of cycles.

The electrical conductivities of nanowire films with different thicknesses were investigated by fabricating ten 1×1 cm^2 nanowire film samples on spun-coated Eco-flex on glass substrates as described above, but varying the growth time from 1 to 10 minutes. The 1-min growth nanowire film has a sheet resistance of 2,959±586 Ω/square. As the nanowire growth time gradually increases, the sheet resistance quickly decreases initially, but then reaches an almost steady resistance after 7 minutes of growth time, as shown in Figure 8(a). With 10 minutes' growth, a typical sheet resistance of 10.5±3.9 Ω is obtained. The sheet resistance for all 10 samples reduced further after the Eco-flex substrates were peeled from their glass supporting substrates. Typically, the electrical resistance of the freestanding and wrinkled nanowire films with growing time from 1 to 10 minutes ranged from 1,728±225 Ω to 8.4±3.7 Ω. This may be attributed to shrinkage of the Eco-flex after stress releasing from the glass substrate, which tightens the nanowire packing and causes wrinkling of the nanowires, as shown in the optical micrographs of Figure 8. Furthermore, the electrical resistivities of nanowire samples as a function of pressure for films with nanowire growth times from 1-10 minutes are shown in Figure 9. It is observed that the pressure sensitivity of the nanowire films decreases with increasing nanowire length up to a growth time of 7 minutes, after which the sensitivity does not appear to change. The reduction in sensitivity with increasing nanowire length is considered to be due to the lower base resistance of the films with longer nanowires.

As already described above, the dependence of the electrical resistivity of the nanowire layers on layer thickness and applied pressure can be exploited to produce pressure sensors that are able to measure both the applied pressure and the location of that pressure by providing nanowire layers on both sides of a substrate, with each layer having regions with different layer thicknesses, and the regions on each side of the substrate being mutually aligned to define a unique combination of nanowire layer thicknesses so that the combination of the measurements of electrical resistivity of both layers identifies the specific thicknesses of those regions on each layer, and thus the location of the applied pressure relative to the sensor.

In the following example, the most simple nanowire layer configuration is described, wherein the thickness of each nanowire layer varies in a stepwise manner with distance along only one spatial dimension. That is, the thickness of each layer varies in a stepwise manner like a conventional staircase, with the two layers being arranged in opposite orientations (equivalent to a 180° rotation around an axis orthogonal to the plane of the substrate) so that one layer becomes progressively thicker as the other layer becomes progressively thinner as a function of distance from one edge of the substrate, but the sum of those thicknesses remains constant.

As shown in Figure 10a, two nanowire sensor strips (of dimensions 30×5 mm^2 in plan view) were fabricated on Eco-flex substrates and configured in aligned but opposite orientations and with 6-step staircase morphologies (each step region having dimensions of 5×5 mm^2 in plan view) produced by successive one-minute nanowire growth periods. Due to the variation in nanowire film thickness, the conductivity of each nanowire film region changes along the longitudinal dimension in opposite direction senses for the 'front' (sensor 1) and 'back' (sensor 2) sensors, as shown in Figure 10 (b). Consequently, the overall resistance increment of the two strips subjected to a load at different steps enables accurate determination of both the applied load and its location along the sensing strip, as explained below.

Specifically, the resistance changes of sensor 1 and sensor 2 from responses at each step region (the step regions being respectively numbered from *I* to *VI*) to a constant pressure are recorded, as shown in Figures 10(c) and (d). In a calibration process, linear fits are determined for each step region, providing a set of 6 linear fits for each of sensors 1 and 2. The pressure sensitivity S for each region of each film is defined as the slope of the corresponding linear fit.

Each of the six-step staircase films can be regarded as equivalent to six resistors connected in series. When a constant pressure P is applied to the nth-step, the sensitivity of each film is defined as:

$$S_n = \frac{\Delta R_n / \sum R_n}{P} \qquad (1)$$

where $\sum R_n$ is the sum of the resistances of the step regions when no pressure is applied, and ΔR_n is the relative change in the electrical resistance of the nth-step region.

In the composite sensor with two films (or sensors, also referred to as sensor 1 and sensor 2) configured as described above, the location-specific dimensionless parameter L_n, namely the sensitivity ratio of sensors 1 and 2 (S_{n1}/S_{n2}) at step n is defined as:

$$L_n = \frac{S_{n1}}{S_{n2}} = \frac{(\Delta R_n)_1 (\sum R_n)_2}{(\Delta R_n)_2 (\sum R_n)_1} \qquad (2)$$

The relationship between the pressed location (in terms of region selected from regions I to VI) and L_n is shown in Figure 10(e), where the value of the sensitivity ratio L_n is calculated for each location based on the linear fits shown in Figures 10(c) and (d). The location specificity is well discriminated over a wide range of pressures (4-40 kPa). The pressure accuracy of sensor 1 was also demonstrated by comparing the real values of applied load and the calculated values of the load, Figure 10(f) shows that these values are nearly identical for pressures between 0 and 40 kPa.

These data demonstrate that the dual layer nanowire sensors described herein can be used to accurately measure both the pressure and the location of forces applied to the sensor.

Remarkably, the location-specific pressure sensing capability of the sensors described herein is maintained even when the sensor is deformed. For example, as shown in Figure 11(a), the sensor strip described above was subjected to a 50% uniaxial elongation, and the characteristics of the sensor in this elongated state were measured. Measurements of the sensitivity ratio of sensors 1 and 2 from location *I* to location *VI* are shown in Figure 11(b), and are clearly independent of the applied pressure. The overall resistance of the staircase film increases with increasing strain from 0% to 50%, as shown in Figure 12, possibly due to the generation of strain-induced cracks at each step region of the film, as shown in the optical micrographs of Figure 13. Larger gaps and cracks are observed in thicker step regions, leading to more conductivity losses compared to thinner step regions. Accordingly, the conductivity difference between adjacent step regions becomes smaller at greater step thicknesses. As a result, the thicker steps (for example, regions *IV, V,* and *VI* of sensor 1) are less responsive to pressure than the thinner nanowire regions (regions *I, II,* and *III* of sensor 1) with increasing strain, as shown in Figures 11(c) and (d).

Although the dual layer sensor described above has a very simple staircase configuration along one spatial dimension only, it will be apparent in light of this disclosure that the location-specific sensor can be also be configured with other and more complex topologies; for example, a spiral pattern in plan view, such as that shown in Figure 14(a).

The dual layer sensors described herein can also be used as tactile sensors that discriminate the sharpness of an object applying pressure to the sensor; for example, to determine whether the object or part of the object applying that pressure is sharp or blunt. This is achieved by determining the spatial extent of the regions of the sensor to which that pressure is applied, requiring those regions to have spatial dimensions capable of discriminating over the spatial dimensions of interest.

In one example, a dual layer sensor with complementary nanowire layer configurations including concentric circles, as shown in Figure 15(a) was produced. Firstly, two concentric circle films with three-step staircase nanowire layers were fabricated on opposite sides of a Eco-flex substrate and with complementary thickness changes, as shown in the cross-sectional side view on the right-hand side of Figure 15(a). In this example, the radii of the three circles from inside to outside are 0.8 mm, 1.5 mm and 2.2 mm, respectively. The thickness of each circular/annular region is controlled by the nanowire layer growth time, which in this example was varied by 2 minute intervals from 2 minutes to 6 minutes. Theoretically, the concentric circle configuration can be regarded as electrically equivalent to five resistors connected in series, as represented schematically in Figure 16(a). In addition, due to the low Young’s modulus of the soft Eco-flex thin film, stress concentration occurs at the edge area when the film is subjected to a uniform pressure, as shown in the simulations of Figures 16(b)-(d)). Owing to the difference in thickness of each circular or annular region between the top and bottom films, the top sensor is more responsive to a larger pressure application area because stress is mostly concentrated at the outside and thinnest annular region, while the bottom sensor is more sensitive to smaller pressure application areas where the inner and thinner circular region is activated.

To evaluate the ability of the concentric circle sensors to indicate sharpness, three cylinders with respective radii of 0.6 mm, 1.3mm and 2 mm were utilized as probes. The force-dependent resistance changes of the top and bottom films in response to the application of force by the three cylinder probes are shown in Figures 15(b) and (c). The resistance measurements of both films were able to distinguish the different probes sizes over a wide range of forces from 0.0375 N to 0.1875 N, and therefore can be used to evaluate the sharpness of objects in this regime. Note that the pressure area specificity is also demonstrated by pressure-dependent resistance changes of both sensors, as shown in Figure 17, indicating that the ability of the sensor to estimate the contact area of objects is independent of the applied force or pressure.

The sharpness detection was further demonstrated by attaching the wearable sensors onto a human fingertip integrated with Bluetooth circuitry, as shown in the photograph of Figure 15(d). Circular cone shaped objects with respective contact areas of 0.75 cm^2, 0.3 cm^2 and 0.03 cm^2 could be resolved by tapping the sensors against each of these objects. A sharpness-specific dimensionless parameter S_R, namely the sensitivity ratio of sensors 1 and 2 (S_1/S_2) pressed by a cylinder with radius R can be defined as:

$$S_R = \frac{S_1}{S_2} = \frac{(\Delta R_R)_1(\sum R_R)_2}{(\Delta R_R)_2(\sum R_R)_1} \qquad (3)$$

where $\sum R_R$ is the sum of the electrical resistances of the annular/circular regions with no applied pressure, and ΔR_R is the relative change in electrical resistance when a force is applied by a cylinder with radius R. Figure 15(e) is a bar chart of S_R values for the different cylinder radii R and applied forces of 0.05 N, 0.1 N and 0.15 N.

As described above, the nanowire layer sensors described herein are able to measure or quantify both the pressure applied to the sensors and the locations and regions on the sensors where the pressure is applied. Moreover, each pressure and location measurement is achieved using only two measurements of electrical resistance or conductivity, and generally avoids any requirement for wiring to individual regions or 'pixels'. The fabrication of nanowire layers with aligned regions of complementary layer thickness on opposite sides of a common substrate is scalable, and does not require complex and expensive equipment. Embodiments of the present invention include skin-mimicking sensors that may be integrated with soft human skin/muscles for bio-diagnostics. The described sensors can be formed using a stretchable substrate and can sense and quantify pressure and the location of that pressure relative to the sensor in stretched and unstretched states, like human skin.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

CLAIMS:

1. A pressure sensor, including a sheet-like substrate having electrically conductive nanowires projecting from opposite sides thereof, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different nanowire lengths and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the pressure sensor and corresponding pressure sensing regions of the pressure sensor where the pressure was applied.

2. The sensor of claim 1, wherein the pressure sensing regions of the pressure sensor are arranged such that the corresponding pressure sensing regions of the pressure sensor identify one or more corresponding locations of the pressure sensor where the pressure was applied.

3. The sensor of claim 1 or 2, wherein the electrically conductive nanowires are gold nanowires.

4. The sensor of any one of claims 1 to 3, wherein the pressure sensing regions are arranged in a one-dimensional manner to identify the locations with respect to only one spatial dimension.

5. The sensor of any one of claims 1 to 3, wherein the pressure sensing regions are arranged in a two-dimensional manner to identify the locations with respect to two spatial dimensions.

6. The sensor of any one of claims 1 to 5, wherein the pressure sensing regions are generally circular, annular and/or part-annular.

7. The sensor of any one of claims 1 to 6, wherein the first and second measurements of resistance are indicative of sharpness of an object applying the pressure to the sensor.

8. The sensor of any one of claims 1 to 7, wherein the substrate and sensor are flexible such that the sensor can conform to curved or other non-planar surfaces of objects and remain functional.

9. The sensor of any one of claims 1 to 8, wherein the sensor is stretchable by at least 10% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state.

10. The sensor of claim 9, wherein the sensor is stretchable by at least 20%, preferably at least 30%, and more preferably at least 40% of its unstretched length.

11. The sensor of claim 9, wherein the sensor is stretchable by at least 50% of its unstretched length.

12. A process for producing a pressure sensor, including the step of forming electrically conductive nanowires projecting from opposite sides of a sheet-like substrate, the nanowires on each of the sides of the substrate being configured to define respective pressure sensing regions with respective different nanowire lengths and respective different electrical resistances, the pressure sensing regions on each side of the substrate being arranged relative to the pressure sensing regions on the other side of the substrate such that a first measurement of electrical resistance of the nanowires projecting from a first side of the substrate and a second measurement of electrical resistance of the nanowires projecting from the other (second) side of the substrate are together indicative of a pressure applied to the pressure sensor and corresponding pressure sensing regions of the pressure sensor where the pressure was applied.

13. The process of claim 12, wherein the pressure sensing regions of the pressure sensor are arranged such that the corresponding pressure sensing regions of the pressure sensor identify one or more corresponding locations of the pressure sensor where the pressure was applied.

14. The process of claim 12 or 13, wherein the step of forming includes:
    depositing metallic nanoparticles on opposed sides of the sheet-like substrate;
    growing nanowires from the deposited nanoparticles;
    selectively growing subsets of the grown nanowires by respective different amounts to form the respective pressure sensing regions with respective different lengths of nanowires and respective different electrical resistances.

15. The process of claim 14, wherein the step of selectively growing subsets of the grown nanowires includes repeatedly forming a corresponding patterned mask on the nanowires, and further growing a corresponding subset of the nanowires that are not covered by the corresponding patterned mask.

16. The process of claim 14 or 15, wherein the pressure sensing regions are arranged in a one-dimensional manner to identify the locations with respect to only one spatial dimension.

17. The process of claim 14 or 15, wherein the pressure sensing regions are arranged in a two-dimensional manner to identify the locations with respect to two spatial dimensions.

18. The process of claim 17, wherein the pressure sensing regions are generally circular, annular and/or part-annular.

19. The process of any one of claims 12 to 18, wherein the first and second measurements of resistance are indicative of sharpness of an object applying the pressure to the sensor.

20. The process of any one of claims 12 to 18, wherein the substrate and sensor are flexible such that the sensor can conform to curved or other non-planar surfaces of objects and remain functional.

21. The process of any one of claims 12 to 20, wherein the sensor is stretchable by at least 10% of its unstretched length, and the first and second measurements of resistance remain indicative of pressure irrespective of whether the substrate is in a stretched or unstretched state.

22. The process of claim 21, wherein the sensor is stretchable by at least 20%, preferably at least 30%, more preferably at least 40%, and most preferably at least 50% of its unstretched length.

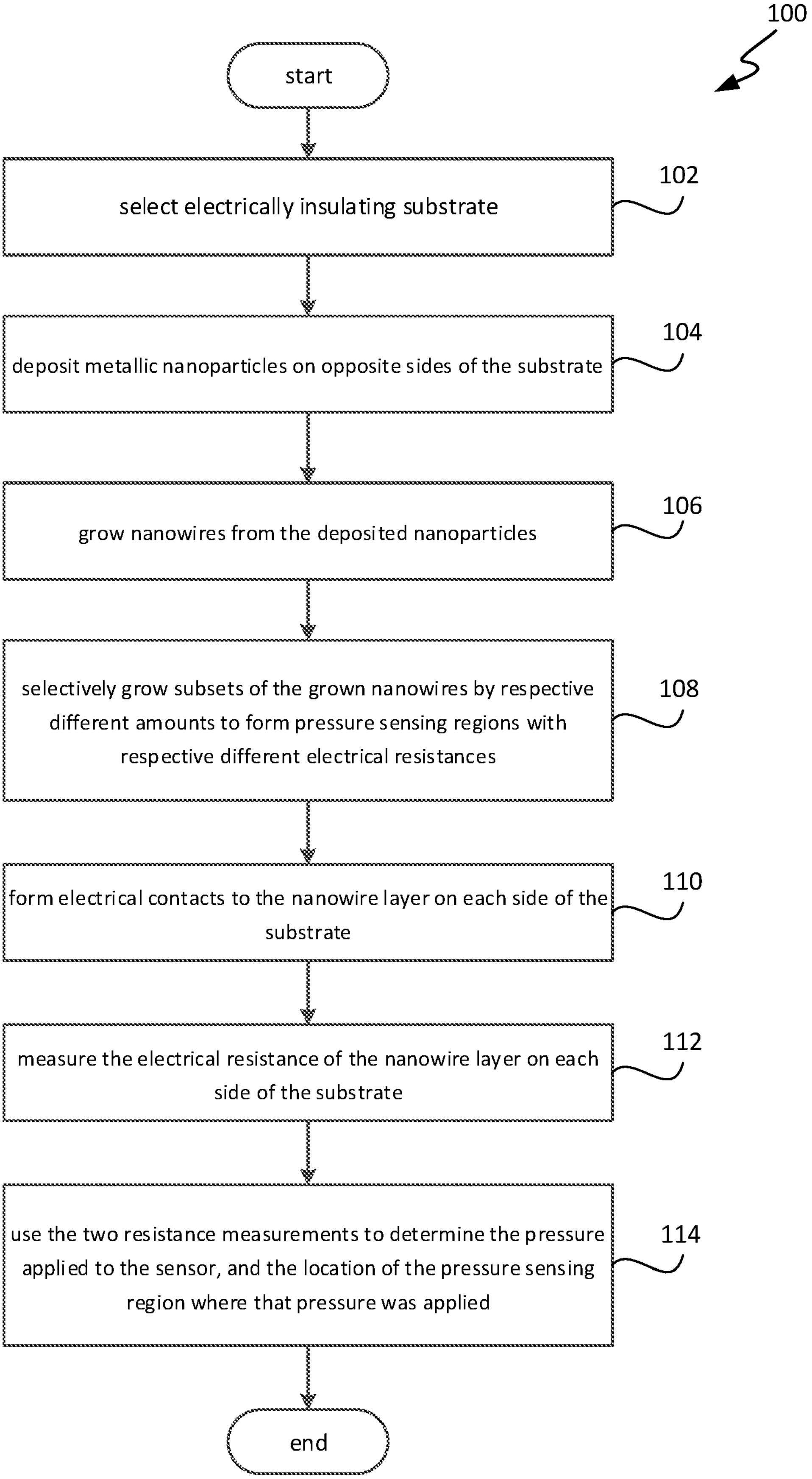

100
start
select electrically insulating substrate
102
deposit metallic nanoparticles on opposite sides of the substrate
104
grow nanowires from the deposited nanoparticles
106
selectively grow subsets of the grown nanowires by respective different amounts to form pressure sensing regions with respective different electrical resistances
108
form electrical contacts to the nanowire layer on each side of the substrate
110
measure the electrical resistance of the nanowire layer on each side of the substrate
112
use the two resistance measurements to determine the pressure applied to the sensor, and the location of the pressure sensing region where that pressure was applied
114
end

Figure 1

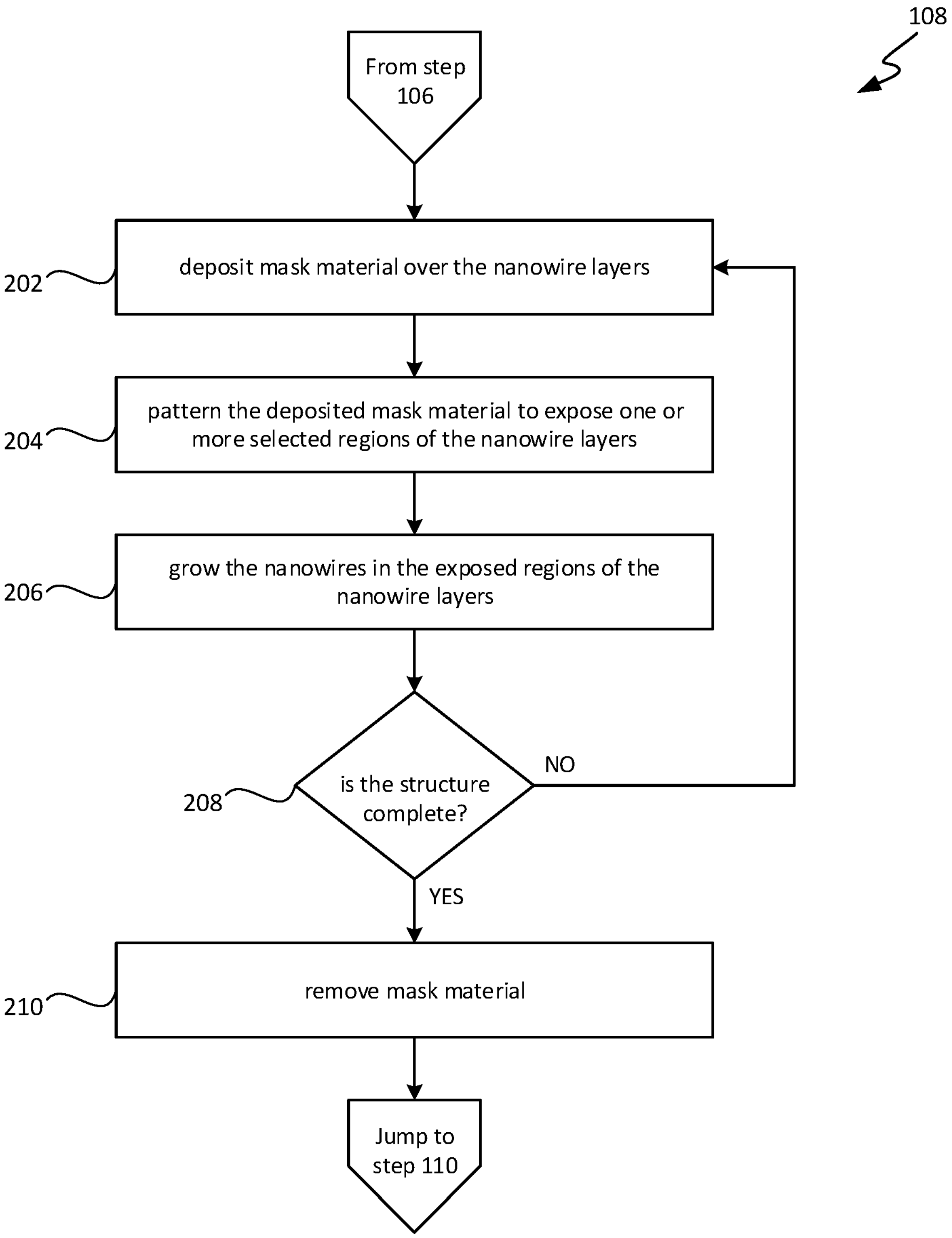

108
From step 106
202
deposit mask material over the nanowire layers
204
pattern the deposited mask material to expose one or more selected regions of the nanowire layers
206
grow the nanowires in the exposed regions of the nanowire layers
208
is the structure complete?
NO
YES
210
remove mask material
Jump to step 110

Figure 2

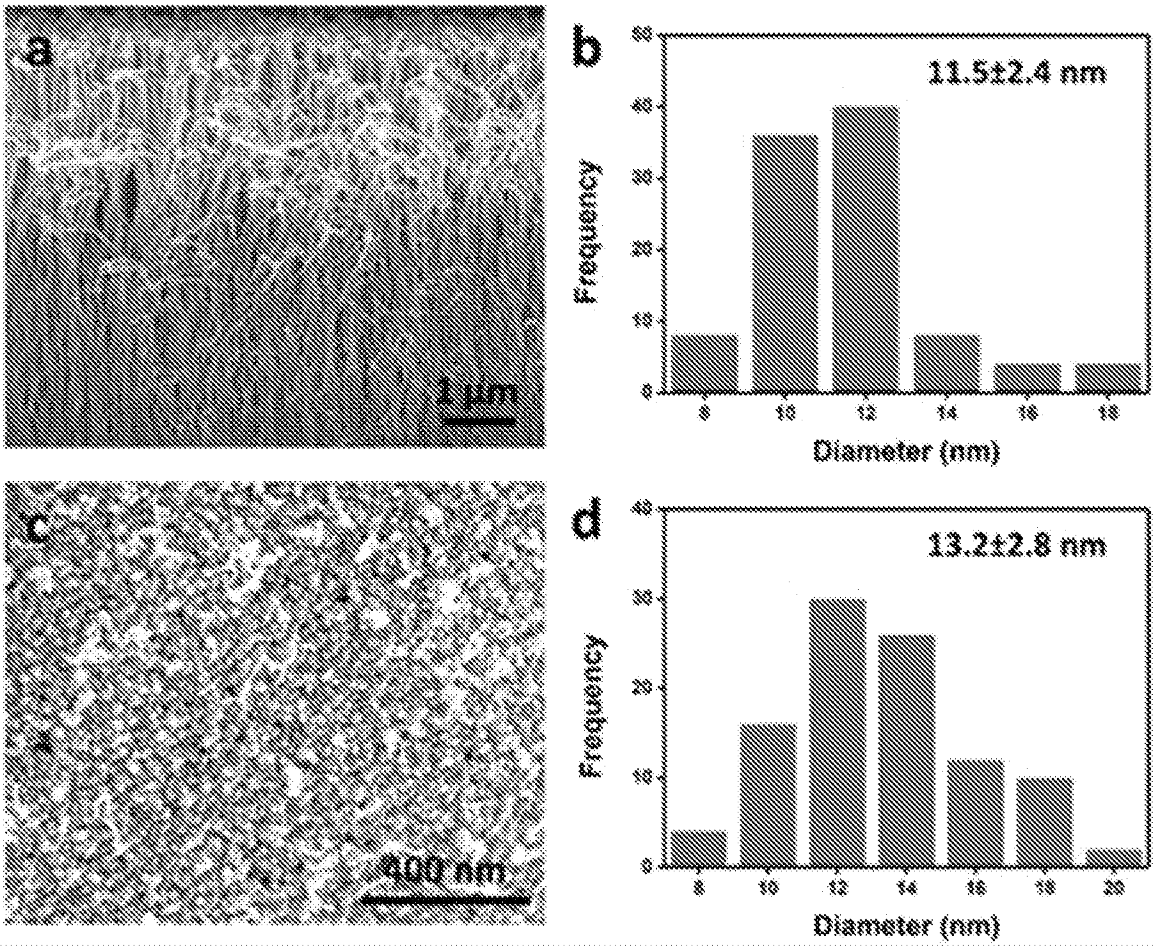

a
1 µm
b
11.5±2.4 nm
Frequency
Diameter (nm)
0
10
20
30
40
50
8
10
12
14
16
18
c
400 nm
d
13.2±2.8 nm
Frequency
Diameter (nm)
0
10
20
30
40
8
10
12
14
16
18
20

Figure 3

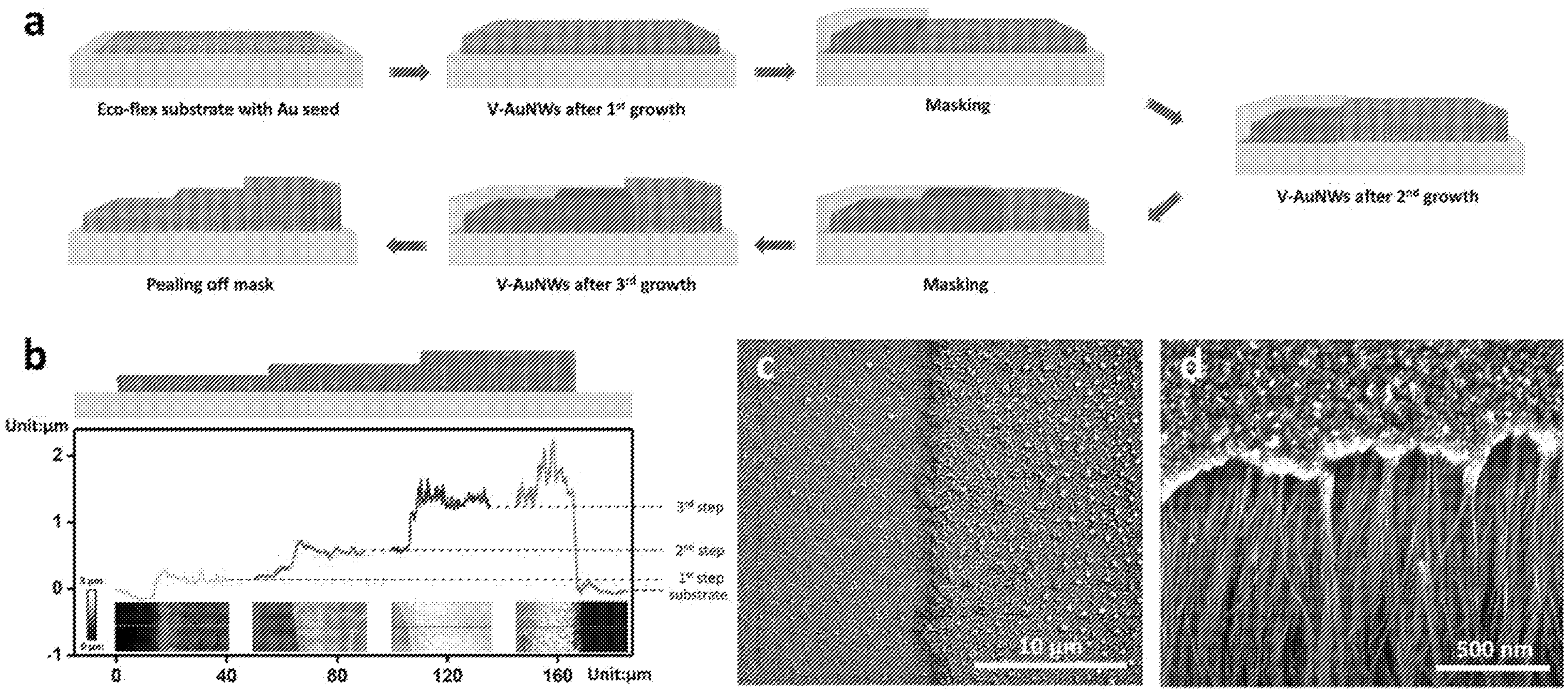

a
Eco-flex substrate with Au seed
V-AuNWs after 1st growth
Masking
V-AuNWs after 2nd growth
Masking
V-AuNWs after 3rd growth
Pealing off mask
b
Unit:μm
2
1
0
-1
0
40
80
120
160
Unit:μm
3rd step
2nd step
1st step
substrate
c
10 μm
d
500 nm

Figure 4

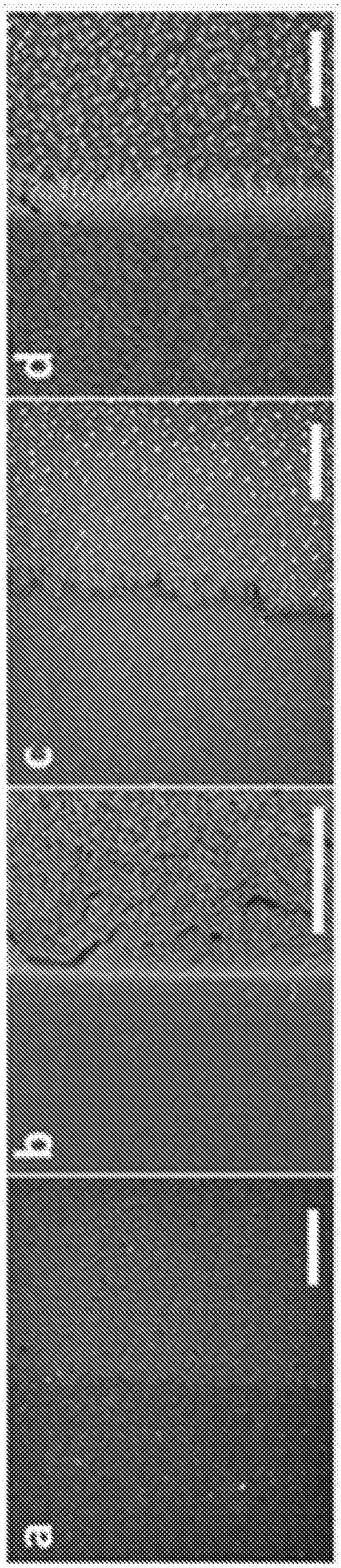


Figure 5

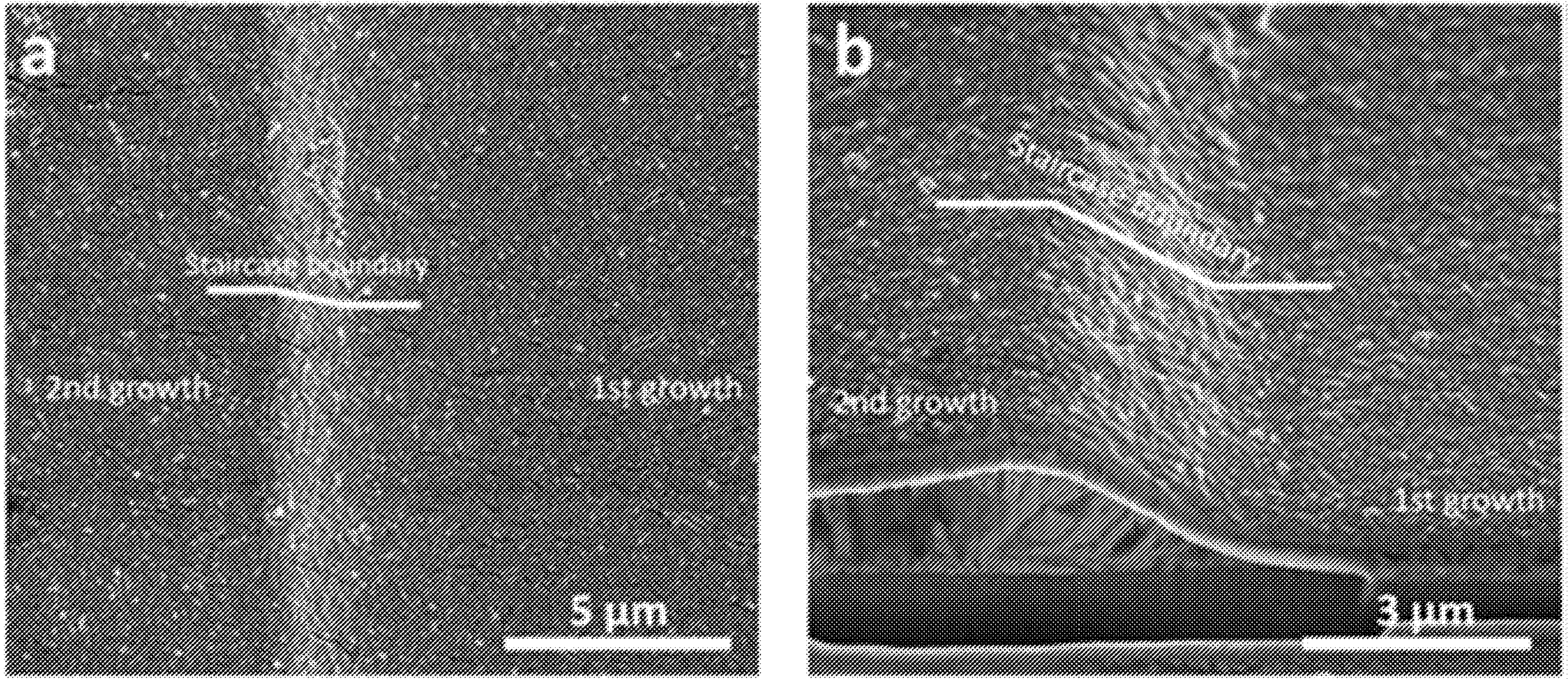

a
Staircase boundary
2nd growth
1st growth
5 µm
b
Staircase boundary
2nd growth
1st growth
3 µm

Figure 6

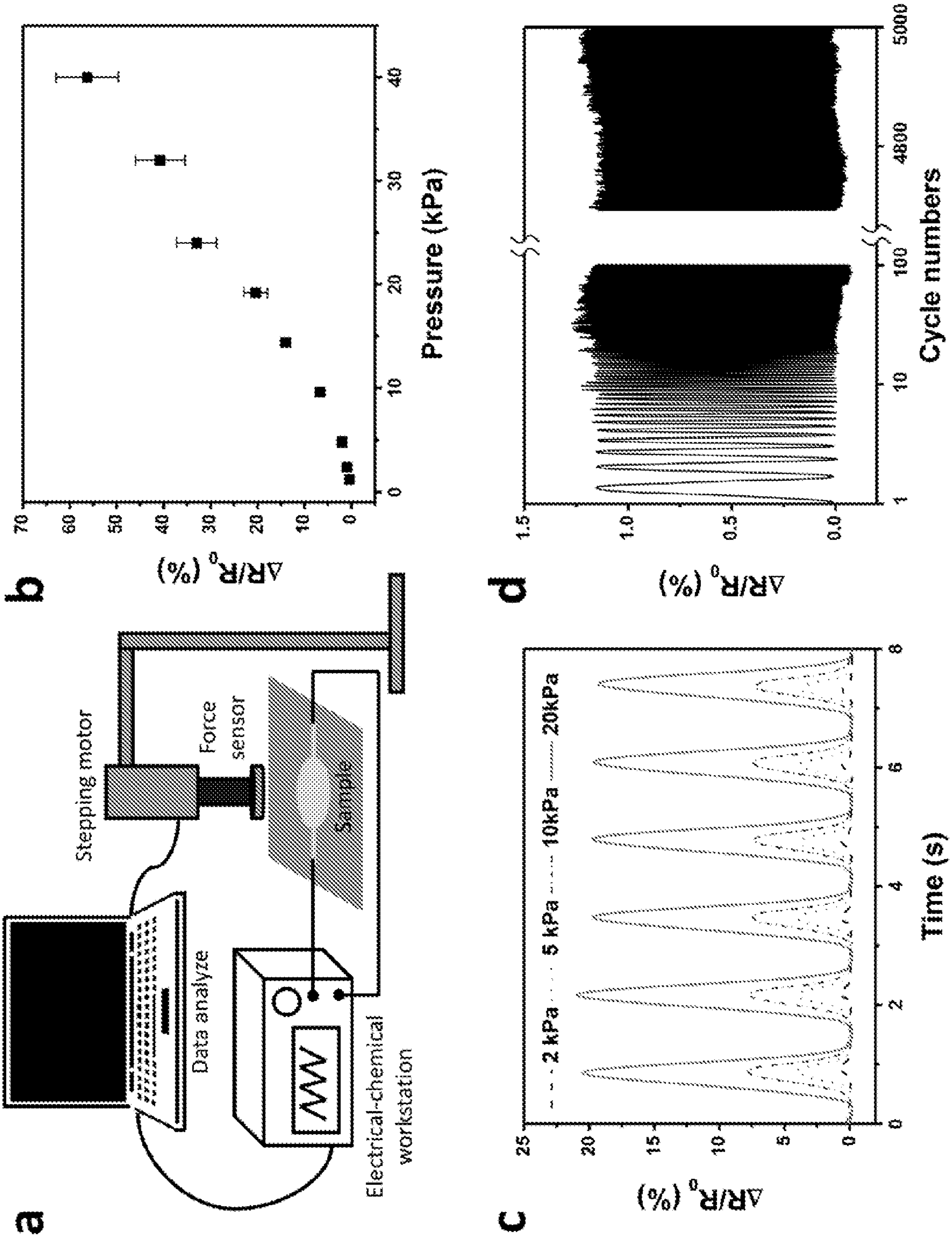

a
Data analyze
Electrical-chemical workstation
Stepping motor
Force sensor
Sample
b
ΔR/R0 (%)
0
10
20
30
40
50
60
70
Pressure (kPa)
0
10
20
30
40
c
ΔR/R0 (%)
0
5
10
15
20
25
2 kPa
5 kPa
10kPa
20kPa
Time (s)
0
2
4
6
8
d
ΔR/R0 (%)
0.0
0.5
1.0
1.5
Cycle numbers
1
10
100
4800
5000

Figure 7

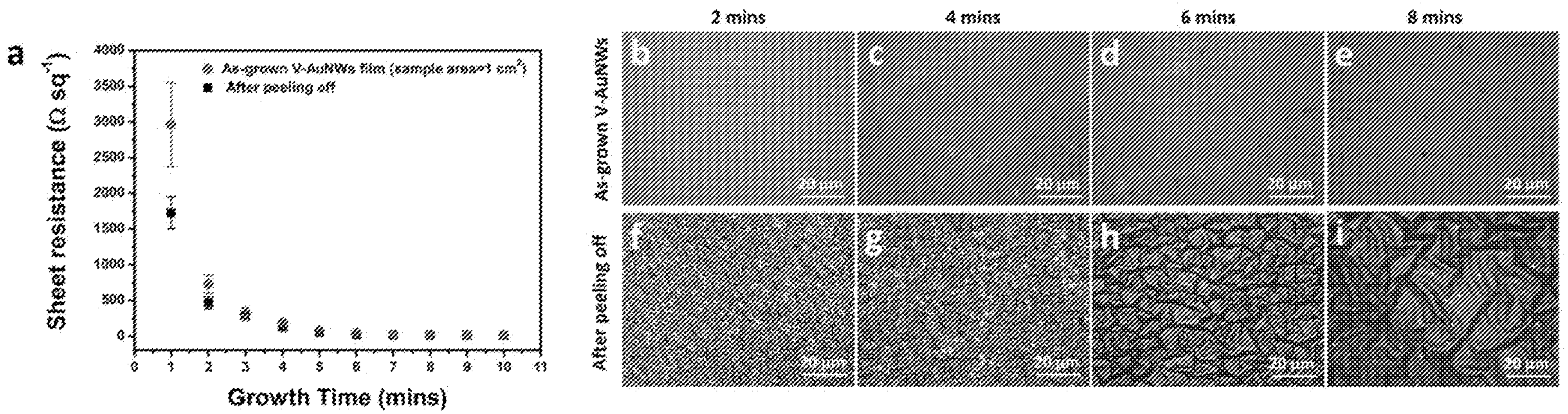

a
Sheet resistance (Ω sq⁻¹)
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
11
Growth Time (mins)
As-grown V-AuNWs film (sample area=1 cm²)
After peeling off
2 mins
4 mins
6 mins
8 mins
As-grown V-AuNWs
After peeling off
b
c
d
e
f
g
h
i
20 μm

Figure 8

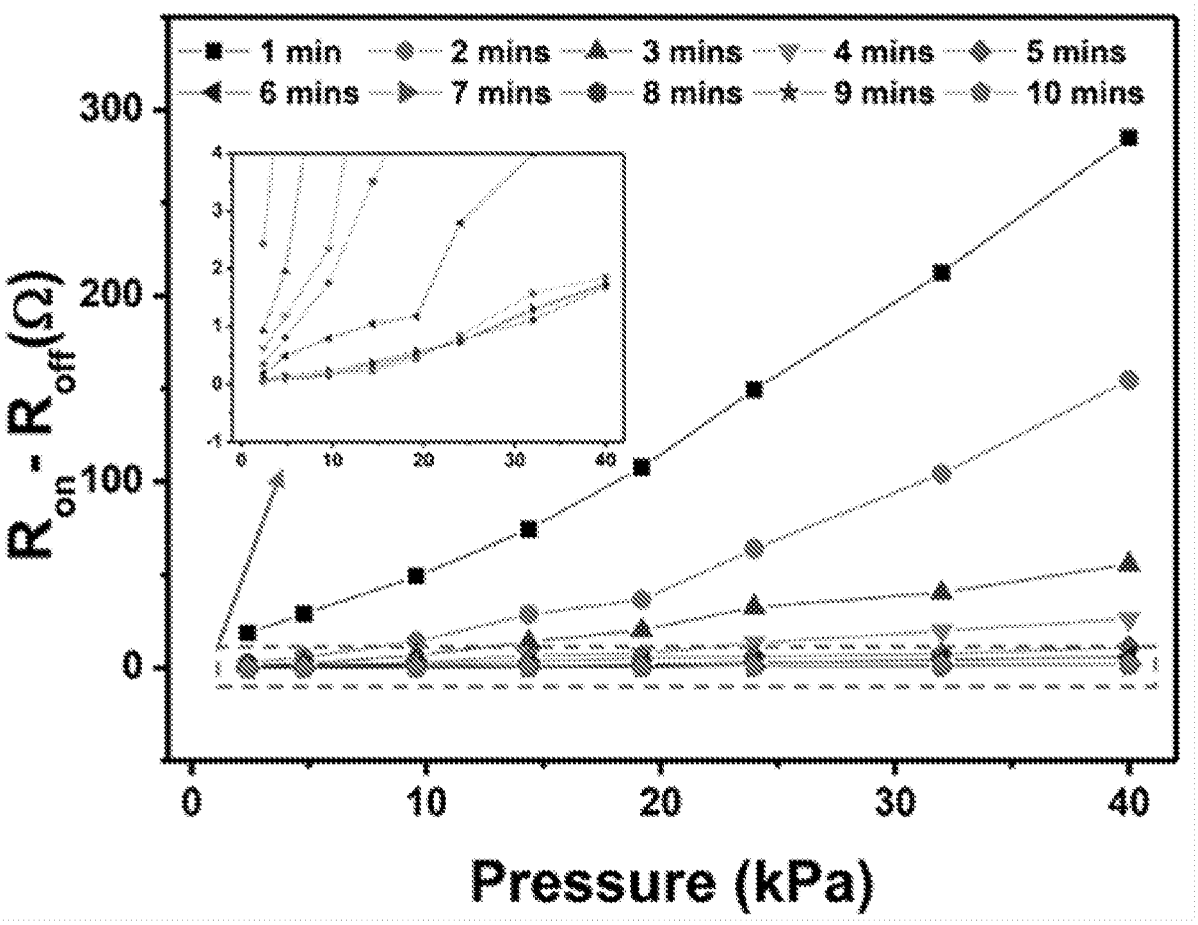

1 min
2 mins
3 mins
4 mins
5 mins
6 mins
7 mins
8 mins
9 mins
10 mins
300
200
100
0
$R_{on} - R_{off} (\Omega)$
0
10
20
30
40
Pressure (kPa)
4
3
2
1
0
-1
0
10
20
30
40

Figure 9

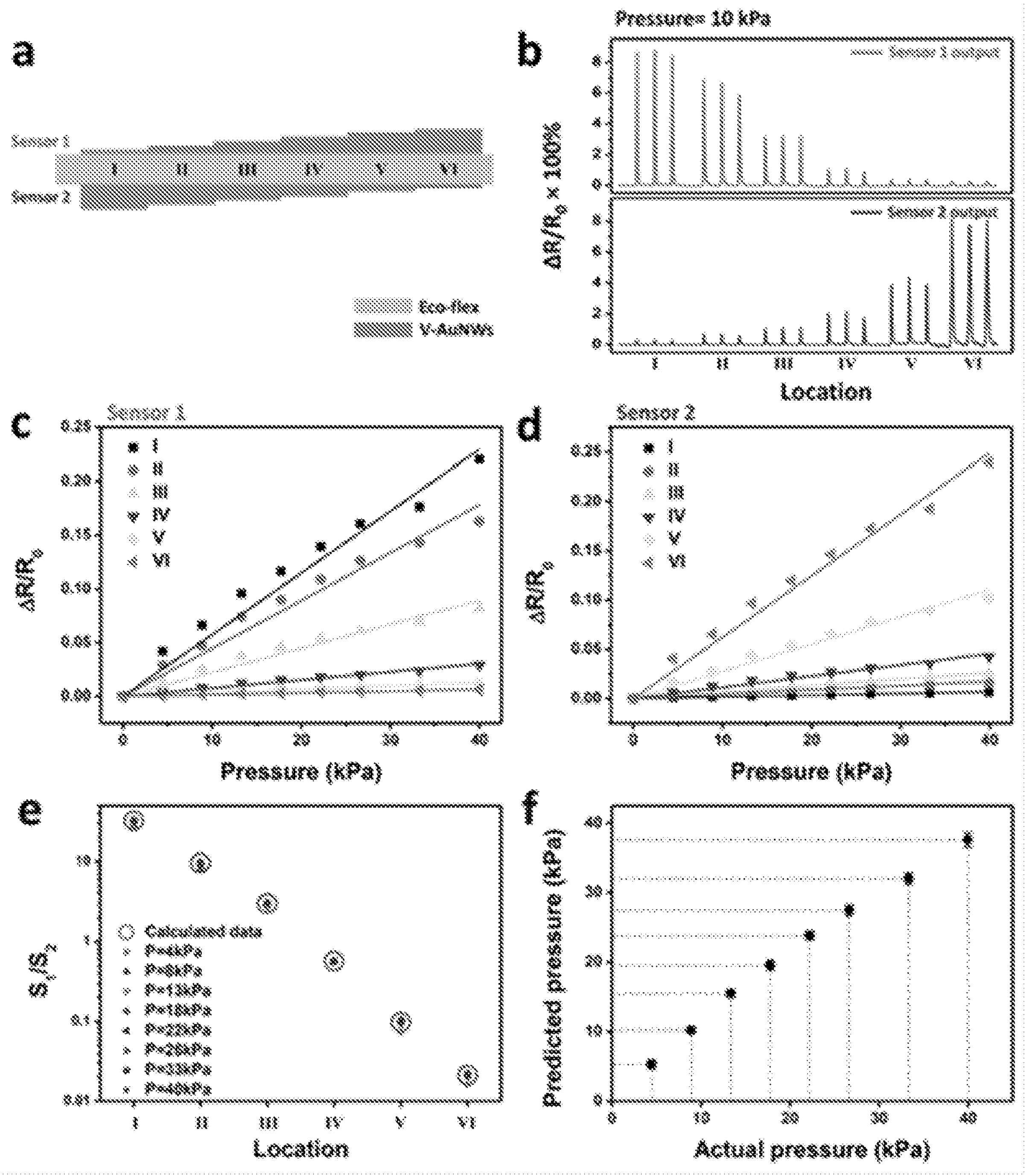

a
Sensor 1
I
II
III
IV
V
VI
Sensor 2
Eco-flex
V-AuNWs
b
Pressure= 10 kPa
Sensor 1 output
Sensor 2 output
ΔR/R0 × 100%
0
2
4
6
8
I
II
III
IV
V
VI
Location
c
Sensor 1
ΔR/R0
0.00
0.05
0.10
0.15
0.20
0.25
I
II
III
IV
V
VI
0
10
20
30
40
Pressure (kPa)
d
Sensor 2
ΔR/R0
0.00
0.05
0.10
0.15
0.20
0.25
I
II
III
IV
V
VI
0
10
20
30
40
Pressure (kPa)
e
S1/S2
0.01
0.1
1
10
Calculated data
P=4kPa
P=9kPa
P=13kPa
P=18kPa
P=22kPa
P=26kPa
P=33kPa
P=40kPa
I
II
III
IV
V
VI
Location
f
Predicted pressure (kPa)
0
10
20
30
40
0
10
20
30
40
Actual pressure (kPa)

Figure 10

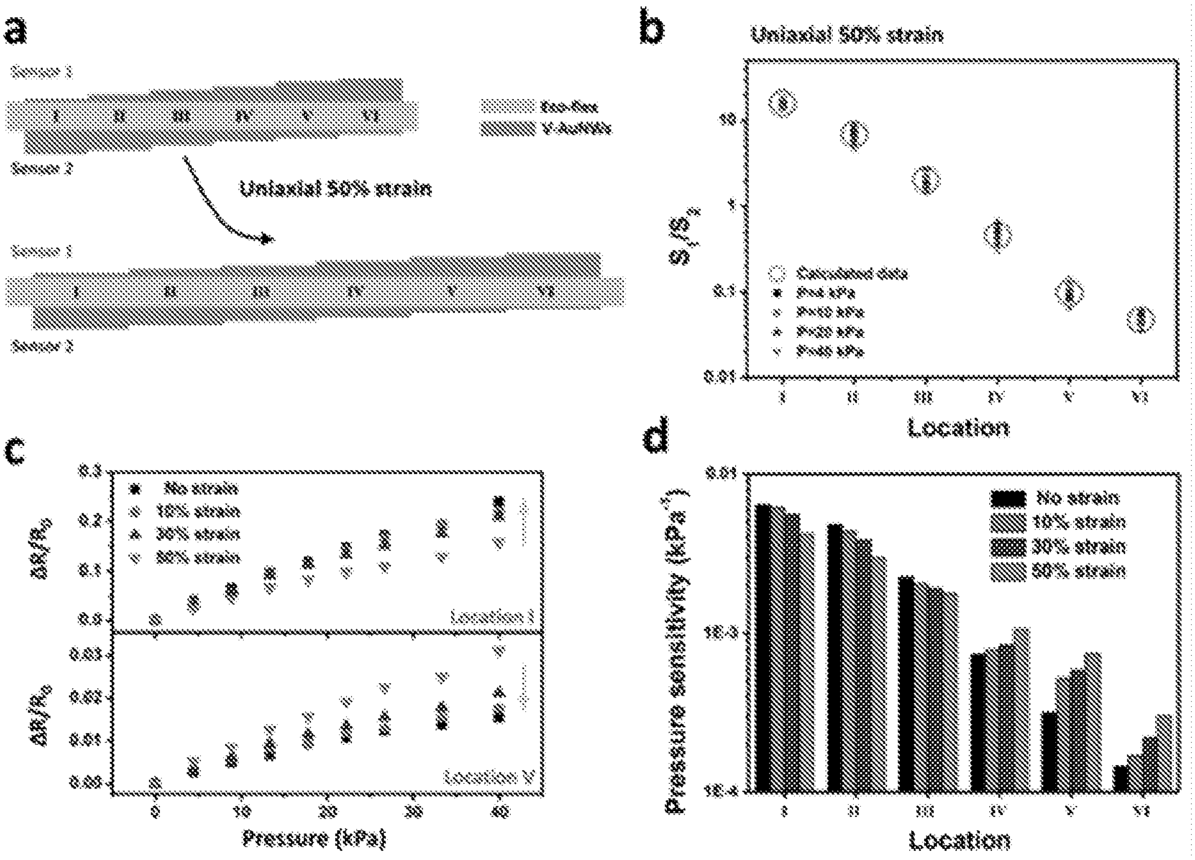

a
Sensor 1
I II III IV V VI
Sensor 2
Eco-flex
V-AuNWs
Uniaxial 50% strain
Sensor 1
I II III IV V VI
Sensor 2
b
Uniaxial 50% strain
S_i/S_{ii}
10
1
0.1
0.01
Calculated data
P=4 kPa
P=10 kPa
P=20 kPa
P=40 kPa
I II III IV V VI
Location
c
0.3
0.2
0.1
0.0
ΔR/R₀
No strain
10% strain
30% strain
50% strain
Location I
0.03
0.02
0.01
0.00
ΔR/R₀
Location V
0 10 20 30 40
Pressure (kPa)
d
0.01
1E-3
1E-4
Pressure sensitivity (kPa⁻¹)
No strain
10% strain
30% strain
50% strain
I II III IV V VI
Location

Figure 11

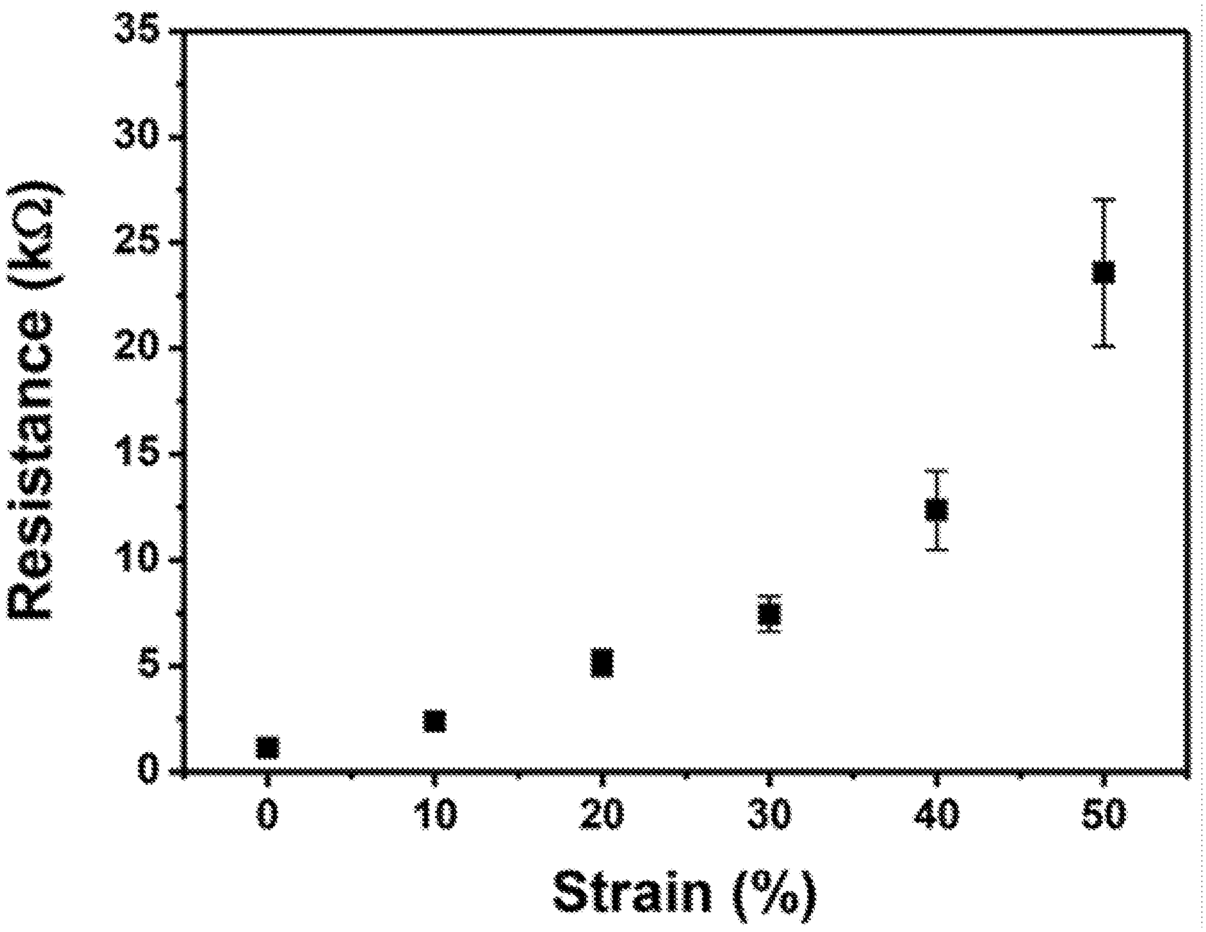


Figure 12

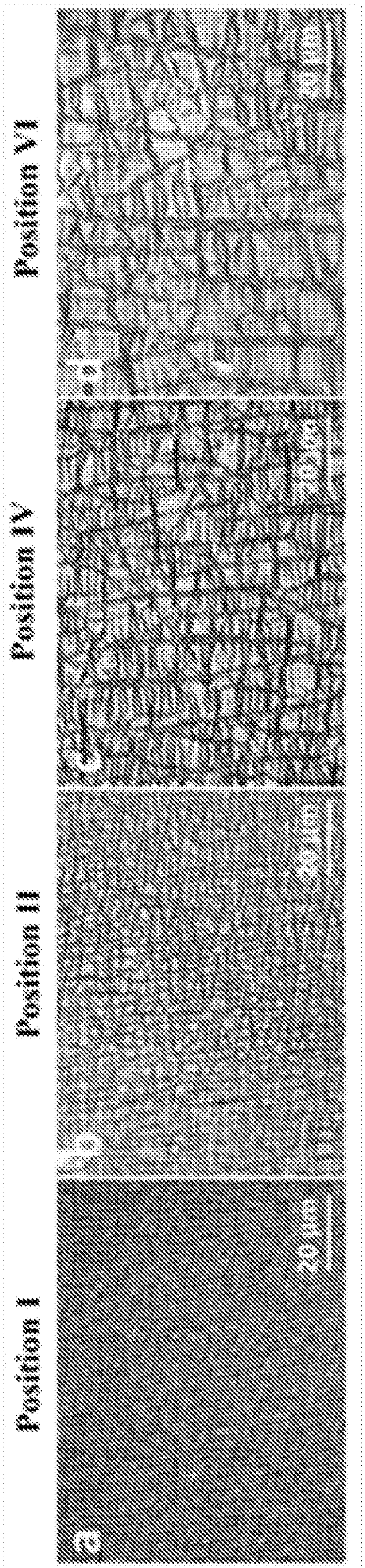

Position I
Position II
Position IV
Position VI
a
20 µm
b
20 µm
c
20 µm
d
20 µm

Figure 13

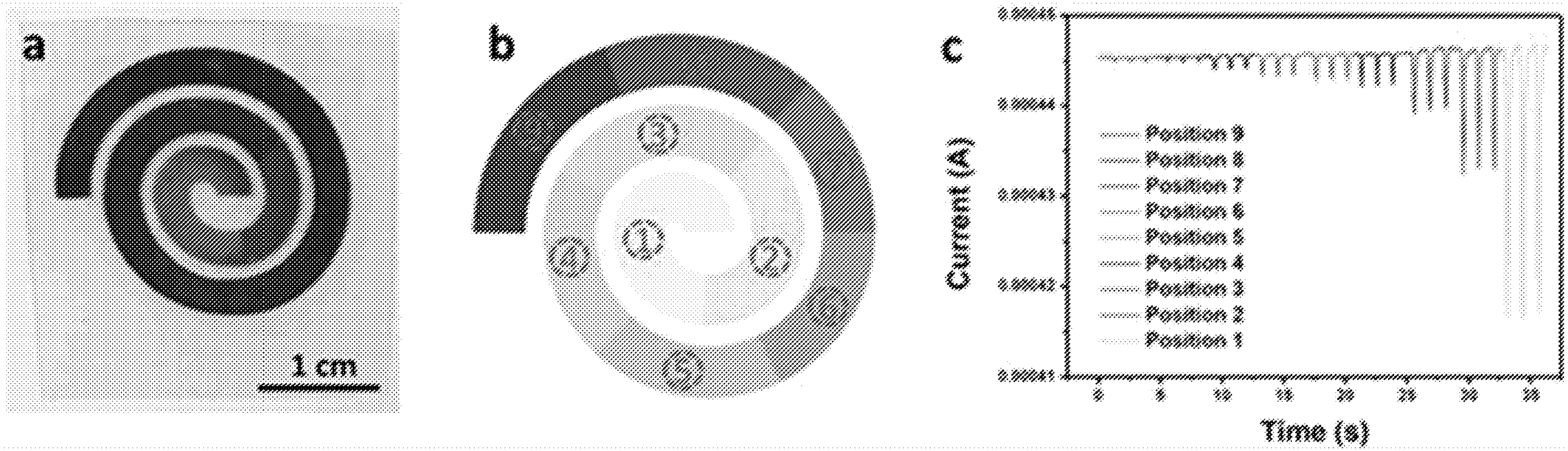

a
1 cm
b
①
②
③
④
⑤
⑥
c
Current (A)
0.00045
0.00044
0.00043
0.00042
0.00041
Position 9
Position 8
Position 7
Position 6
Position 5
Position 4
Position 3
Position 2
Position 1
0
5
10
15
20
25
30
35
Time (s)

Figure 14

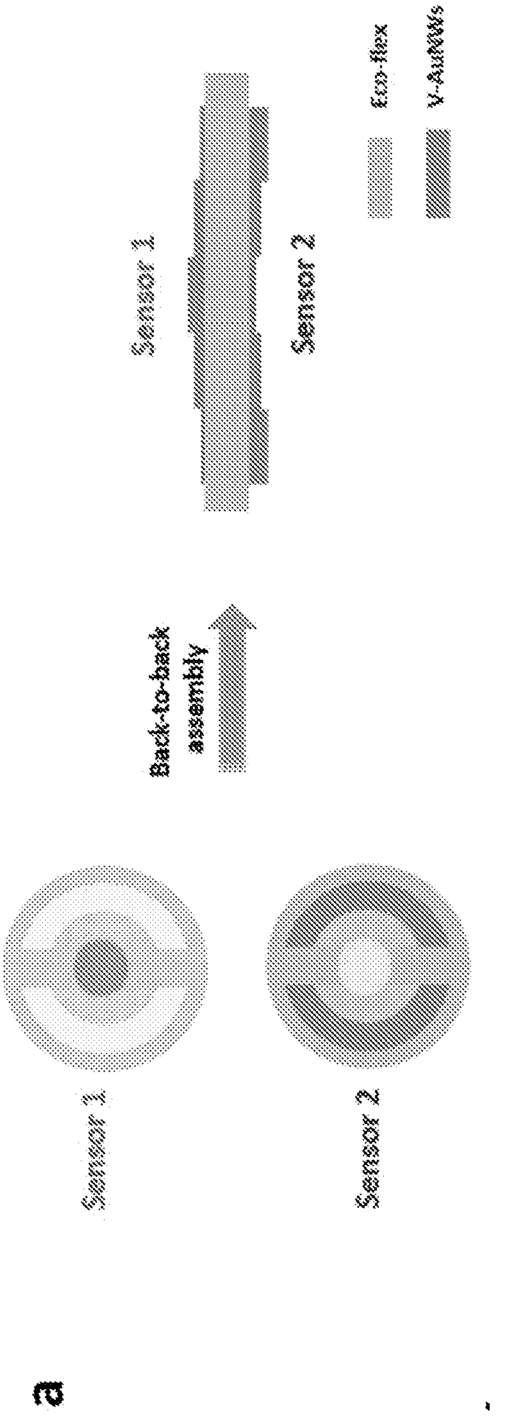

a
Sensor 1
Sensor 2
Back-to-back assembly
Sensor 1
Sensor 2
Eco-flex
V-AuNWs

Figure 15

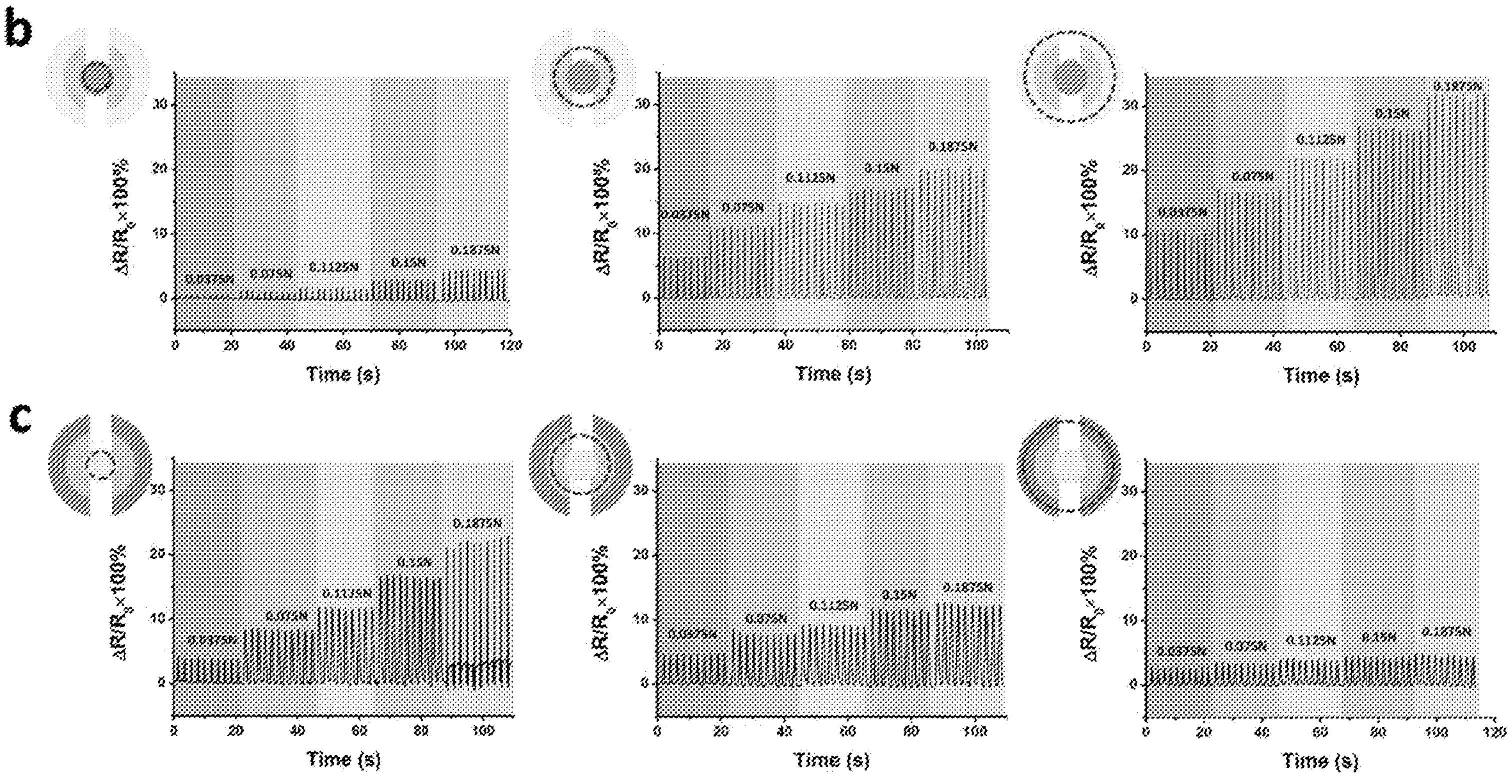

b
c
ΔR/R$_0$×100%
Time (s)
0.0375N
0.075N
0.1125N
0.15N
0.1875N
0
10
20
30
0
20
40
60
80
100
120

Figure 15

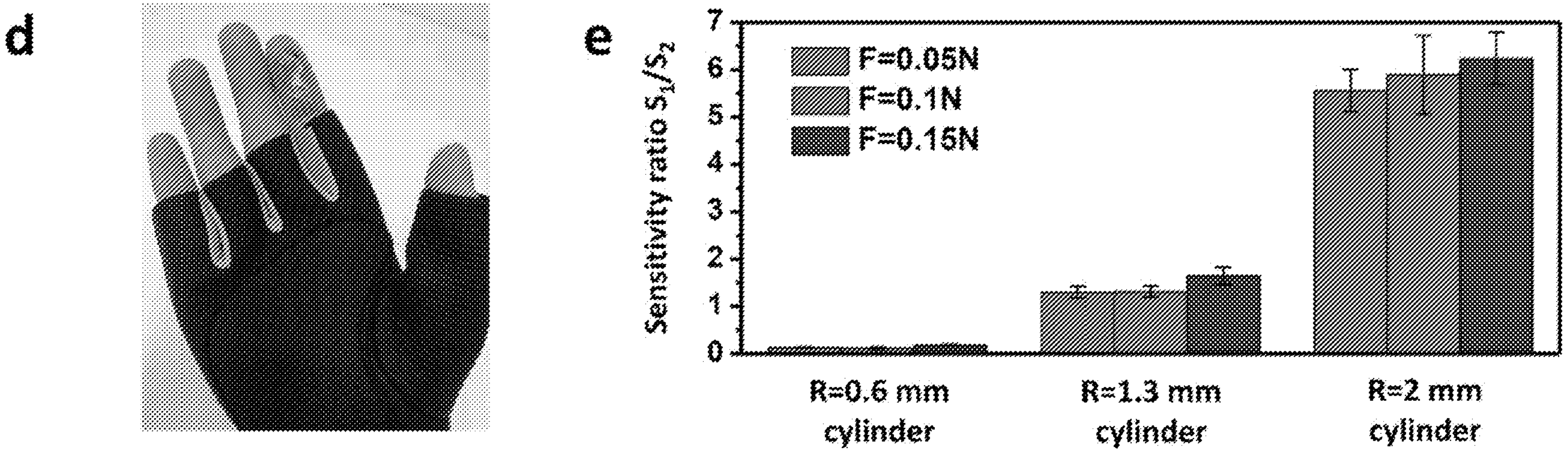

d
e
Sensitivity ratio S_1/S_2
0
1
2
3
4
5
6
7
F=0.05N
F=0.1N
F=0.15N
R=0.6 mm cylinder
R=1.3 mm cylinder
R=2 mm cylinder

Figure 15

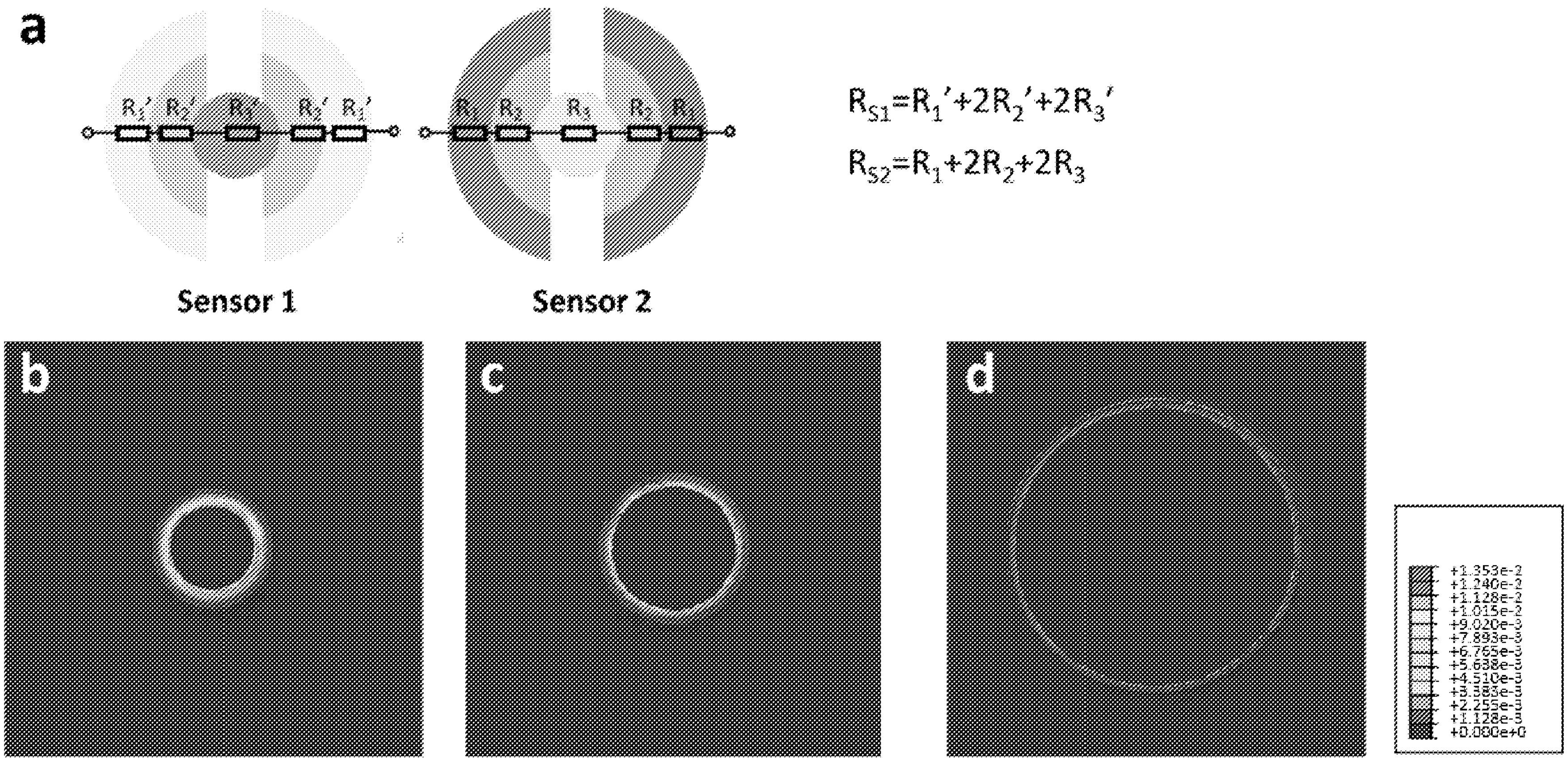

a
R1' R2' R3' R2' R1'
R1 R2 R3 R2 R1
$R_{S1}=R_1'+2R_2'+2R_3'$
$R_{S2}=R_1+2R_2+2R_3$
Sensor 1
Sensor 2
b
c
d
+1.353e-2
+1.240e-2
+1.128e-2
+1.015e-2
+9.020e-3
+7.893e-3
+6.765e-3
+5.638e-3
+4.510e-3
+3.383e-3
+2.255e-3
+1.128e-3
+0.000e+0

Figure 16

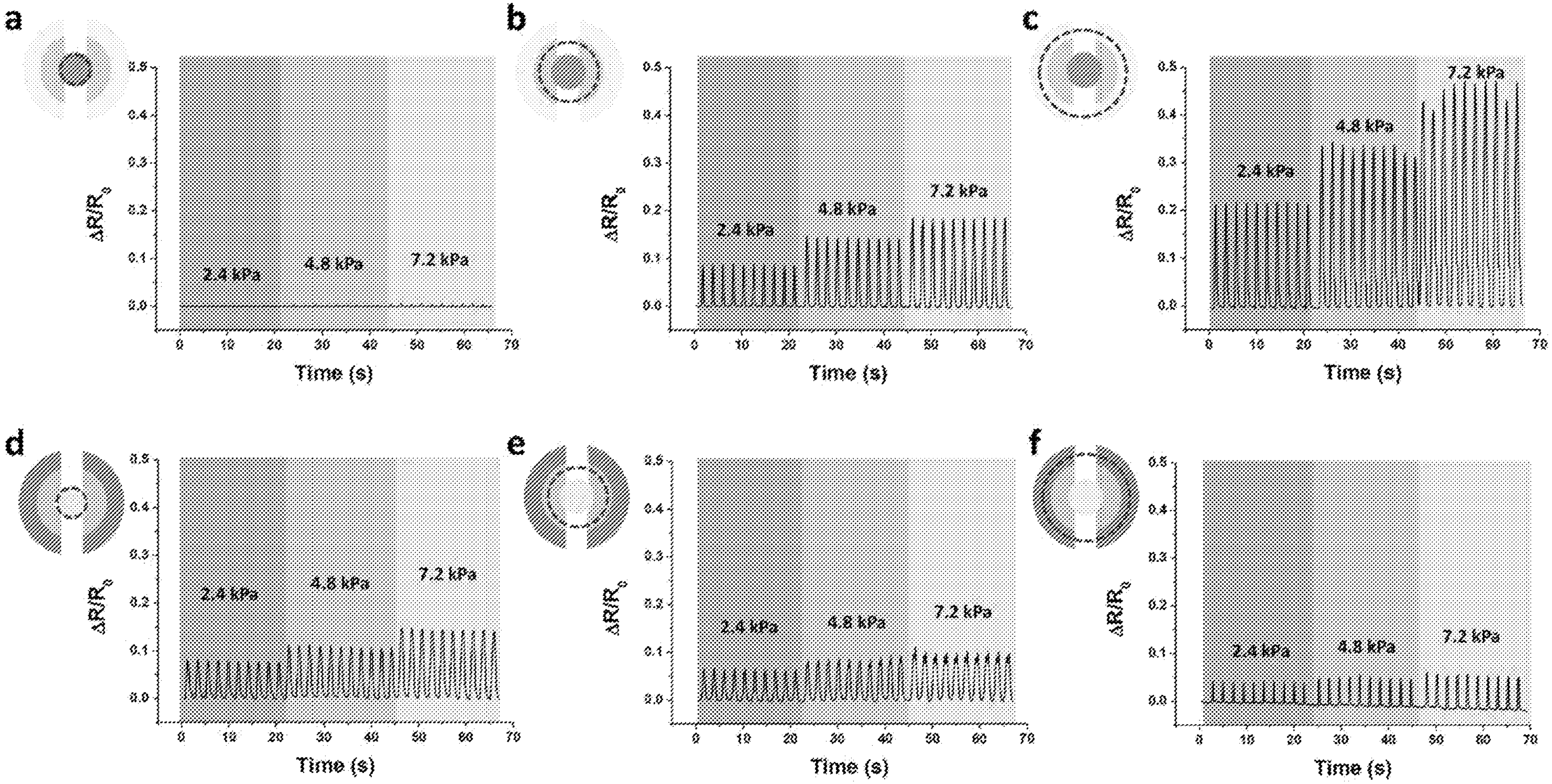

a
b
c
d
e
f
ΔR/R0
Time (s)
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50
60
70
2.4 kPa
4.8 kPa
7.2 kPa

Figure 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2019/050713

A. CLASSIFICATION OF SUBJECT MATTER

G01L 1/18 (2006.01) B82Y 15/00 (2011.01) B82Y 30/00 (2011.01) B82Y 40/00 (2011.01) A61B 5/00 (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)

Databases: PATENW = (EPODOC, WPIAP, Full text), INSPEC
Keywords: pressure, tactile, nanowire, project, perpendicular, length, pattern, region, zone, opposite, double, sensor and similar terms
IPC/CPC marks: G01L1, B81B2201/0264, A61B5/6801, B82Y30, B82Y40, B82Y15, B81B1/00
Databases: Google, Google Patents, Google Scholar, Espacenet
Keywords: nanowire, pressure, sensor, tactile, opposite side, double sided, both sides, sheet, substrate, perpendicular, orthogonal, resistance, stepped, staircase and similar terms
IPC/CPC marks in Espacenet: B82Y30/00, B82Y40/00, B82Y15/00, G01L1/205, A61B2562/00, A61B5/6801, G01L1/18
Applicant(s)/Inventor(s) name search in Google Patents, Espacenet and Auspat:
Keywords: Wenlong Cheng, Yan Wang, Lim Wei Yap, Shu Gong, MONASH and like terms
Applicant(s)/Inventor(s) name 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

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"D"	document cited by the applicant in the international application
"E"	earlier application or patent but published on or after the international filing date
"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)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed
"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"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
"&"	document member of the same patent family

Date of the actual completion of the international search 18 September 2019	Date of mailing of the international search report 18 September 2019
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustralia.gov.au	**Authorised officer** Susan Bellm AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. +61262832751

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	NOUR, E. S. et al., "A flexible anisotropic self-powered piezoelectric direction sensor based on double sided nanowires configuration", Nanotechnology. 2015, Vol. 26, 095502. DOI:10.1088/0957-4484/26/9/095502 abstract; Figure 1(a), Figure 1(b), Figure 2(a), Figure 3(a); Section 3.2, first paragraph	1-22
A	US 2017/0363489 A1 (TECHNION RESEARCH & DEVELOPMENT FOUNDATION LTD.) 21 December 2017 [0007], [0031]	1-22
A	US 9664717 B2 (CHOI J.W. et al.) 30 May 2017 abstract	1-22
A	WU, W. et al., "Taxel-Addressable Matrix of Vertical-Nanowire Piezotronic Transistors for Active and Adaptive Tactile Imaging", Science. 2013, Vol. 340, pages 952-957. DOI:10.1126/science.1234855 abstract	1-22
A	Gong, S. et al., "A wearable and highly sensitive pressure sensor with ultrathin gold nanowires", Nature Communications. 2014, 5:3132. DOI: 10.1038/ncomms4132. abstract	1-22

INTERNATIONAL SEARCH REPORT Information on patent family members	International application No. **PCT/AU2019/050713**

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 2017/0363489 A1	21 December 2017	US 2017363489 A1	21 Dec 2017
		CN 107003190 A	01 Aug 2017
		EP 3230706 A1	18 Oct 2017
		JP 2017537316 A	14 Dec 2017
		WO 2016092494 A1	16 Jun 2016
US 9664717 B2	30 May 2017	US 2015109006 A1	23 Apr 2015
		US 9664717 B2	30 May 2017
		WO 2013163549 A1	31 Oct 2013

End of Annex

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.