

TITLE OF INVENTION

Flexible Strain Sensor

TECHNICAL FIELD

[001] The disclosure relates to sensors for measuring deformation.

BACKGROUND OF THE INVENTION

[002] The Internet of Things (IoT) – embedding sensors and actuators in machines and other physical objects to connect them digitally - enabling organizations to monitor and control objects in the physical world electronically has spread rapidly across diverse segments, including manufacturing, farming, utility, environment, defense, wellness, healthcare, entertainment, and sports. Benefits include being able to manage assets better, optimize performance, and create new business models. In healthcare, IoT-enabled remote monitoring can improve patients' health with chronic illnesses while reducing healthcare costs.

[003] The myriad possibilities of connecting billions of IoT devices has spurred a surge of innovation and enthusiasm in every aspect of the IoT value chain. Flexible strain-sensitive sensors have the potential to be one of the most critical components of this value chain. As the demands for new IoT devices continue to soar, the strain-sensitive sensing market is likewise expected to expand significantly when they eventually find their way into new, still untapped applications.

[004] Flexible strain-sensitive sensors may take various forms to monitor, detect, or measure an applied force. It may take the form of a pressure sensor sensitive to a compressing force and may be measured, for example, through a decrease in the

electrical resistance due to decreased spacing between conductive particles under compressive loading. The strain-sensitive sensor may take the form of a stretch sensor sensitive to a stretching force and may be measured, for example, through an increase in the electrical resistance due to increased spacing between conductive particles under tensile strain. And lastly, the strain-sensitive sensor may also take the form of a sensor array sensitive to a combination of compressing and stretching, such as in a bending, shearing, or twisting force.

[005] Flexible strain-sensitive sensors, however, must meet several technical criteria for them to become valuable. These sensors must have an excellent physical-to-electrical signal translation, the requisite flexibility, elasticity, or compressibility at a relatively affordable cost.

[006] The two most common types of flexible strain-sensitive sensors are capacitive and resistive strain-sensitive sensors. Capacitive strain-sensitive sensors employ a parallel-plate electrode configuration with a layer of flexible dielectric between the electrodes. The capacitance for this type of sensor changes in response to an applied strain or force that decreases the thickness of the dielectric layer. Capacitive strain-sensitive sensors are highly susceptible to noise and require complex conditioning circuits, making them expensive to fabricate.

[007] Unlike capacitive strain-sensitive sensors, resistive strain-sensitive sensors need not have a parallel-plate-electrode configuration. This configuration allows for greater design flexibility and potential reduction in fabrication cost. Various resistive strain-sensitive sensing requirements are currently addressed using composite-based piezoresistive sensors that rely on the interactions between conductive particles suspended in an elastomeric matrix wherein electron transport is governed primarily by quantum tunnelling. In this type of sensor, the

conductivity of the material depends on the type of dielectric used and the average distance between the suspended conductive particles. Depending on the kind of strain on these sensors, the distance between particles may be reduced, as in pressure sensors, resulting in increased conductivity (reduced resistance) of the sensor. On the other hand, increasing the distance between particles, as in stretch sensors, results in the sensors' decreased conductivity (increased resistance).

[008] The piezoresistive materials in this kind of sensor are usually prepared in the form of conductive particle suspensions comprising carbon black, graphene, carbon nanotubes, metal nanoparticles, or any other suitable particles suspended in an elastomer or solvent. Depending on the conductive particles' size, shape, and concentration, the resistance of the piezoresistive material may either increase or decrease with applied pressure. For example, carbon nanotubes have a positive pressure coefficient of resistance, while carbon black particles have a negative pressure coefficient.

[009] Currently, composite-based piezoresistive sensors are used primarily in a clinical or research setting or in other venues where a trained specialist must always be available to ensure proper use. These kinds of research and medical environments may use these sensors through devices such as treadmills, measuring mats, and some in-shoe measurement devices.

[010] While these kinds of sensors can be highly sensitive, a significant limitation of composite-based piezoresistive sensors is their slow response and significant signal hysteresis due to the composite material's response time being dependent upon the viscosity of the elastomer used. Another disadvantage of this kind of sensor is that conduction can involve multiple mechanisms, such as percolation, tunneling, or displacement. This can lead to high susceptibility to noise which can

manifest in poor sensor linearity or measurement precision. Other issues remain which limits their range of applications. For example, the conductivity range of these sensors tends to be narrow. While it may be possible to widen their conductivity range, they require custom-designed particles that allow high percolation within the composite. The uniform dispersion of the particles in the composite, which is essential to sensor performance, mechanical property issues, and fabrication reproducibility also remains a challenge.

[011] Also, a significant challenge in fabricating sensors using composite materials as the piezoresistive element is establishing a uniform and stable dispersion of the filler within the bulk elastomer. This type of sensors also suffers from physical and chemical degradation of the elastomer matrix leading to signal creep and a short lifetime of the resulting sensor. These requirements can add to the cost of sensor fabrication and limit scalability.

[012] The use of conductive materials in sensors, such as graphite, having sufficient affinity to the surface of flexible elastomers have been previously disclosed. These sensors are typically fabricated by first depositing graphite particles on the surface of a thin film comprising natural rubber followed by the deposition of an insulating layer composed of liquid natural rubber. The opposite ends of the sensor are attached permanently to a solid substrate and lead wires (electrodes) are connected to the sensor via a conductor such as conductive paint. Although this type of sensor offers responsiveness and measurement reproducibility under a wide range of strain, they show a nonlinear response to stretching. The sensor nonlinearity is believed to be due to the non-uniform strain distribution between the middle part of the sensor and its terminals. Further, the sensors showed an inadequate response to strains below 100%.

[013] In contrast to prior art composite-based and contact resistance-based sensors, the sensors described herein take advantage of specific unique properties of discrete piezoresistive particles that make them advantageous for use in sensors. Little attention has been given to the unique, innate properties of discrete piezoresistive particles, such as graphite, for use in flexible strain sensors.

BRIEF SUMMARY OF THE INVENTION

[014] This disclosure describes flexible strain-sensitive sensors and methods for their use for monitoring, detecting, or measuring. The sensor or sensor assembly is designed to conform to a surface that allows deformation of the surface to be measured with sufficient sensitivity and accuracy. The flexible strain-sensitive sensors measure stretch, pressure, or a combination of both, such as bending. The surface may be substantially flat or curved. One or more surface deformations may be monitored, detected, and measured, which include at least one of stretching, flexing, bending, shrinkage, or compression, or any of their combinations.

[015] It has been observed from prior art that pressure sensors exhibit increasing conductivity with increasing pressure. In contrast, stretch sensors show decreasing conductivity with increasing stretch. In comparison to other conductive materials, graphite shows excellent affinity to elastomer surfaces. The use of graphite facilitates surface modification and provides high graphite-on-elastomer sensor conductivity. The present disclosure provides various sensor configurations that address the operational limitations of graphite-on-elastomer sensors from prior art.

[016] The approach described in this disclosure takes advantage of graphite's innate piezoresistivity. The conductivity of graphite increases with directly applied

external pressure. This behavior, observed when using graphite particles as a piezoresistive element, introduces unwanted effects such as the sensor's nonlinearity. For example, at relatively short stretching distances, a transverse compression's contribution to increasing the piezoresistive element's conductivity overshadows the conductivity decrease due to increasing particle separation. This effect may manifest as apparent low sensitivity. Thus, the various sensor configurations described in this disclosure allows minimizing or preventing graphite compression during stretching, which results in enhanced sensor sensitivity and response linearity. The solution optimizes the sensor conductivity partly because the piezoresistive elements such as graphite particles are not suspended within an elastomer composite.

[017] As to be discussed in various examples provided in this disclosure, the impact of transverse compression when the elastomer stretches may be reduced by introducing at least two types of physical spacers. One kind of spacer, applicable in planar sensor configuration, is an inert granular substance with an average grain size at least an order of magnitude larger than that of the graphite particles. This spacer can serve at least partly as a scaffolding to prevent or minimize transverse compression across the region between the two elastomer layers. In another example, a hollow, elastomer layer in the form of a sealed tube is used, wherein a thin layer of graphite is deposited on the tube's inner wall, rather than filing the tube with graphite. The tube's resistance to compressive forces provides a means to prevent contact between the opposite sides of the tube wall.

[018] In one example, the sensor comprises at least one elastomer layer, at least one elastomer support matrix, a piezoresistive element, a spacer element, and at

least one pair of electrodes. The piezoresistive element and the spacer element can be deposited on at least one elastomer layer. The spacer element is preferably larger than the piezoresistive element, for example, at least about one order of magnitude larger than the piezoresistive element. The spacer element may comprise a plurality of stationary, nonconductive elements located at certain intervals within the sensor or mixed with the piezoresistive elements. In one example, the spacer elements are distributed at fixed locations in the sensor. The spacer element allows contact to be minimized among at least some of the piezoresistive element, such as when a force is exerted on the sensor.

[019] It is preferred that the elastomer layer comprises an elastomer that is an elastomeric adhesive. The elastomer layer may comprise a textured surface, which may be created by, for example, molding, etching, or using a granular material. The elastomer layer can have a substantially planar configuration, but other elastomer layer configurations may be used, such as one with a tubular shape. The sensor may comprise a second elastomer layer, which may be coated with a layer comprising a piezoresistive element. In another example, the sensor is one of a plurality of sensors that form a sensor assembly. The sensor may also comprise an elastomer support matrix which further comprises a flexible, stretchable material and a flexible, substantially non-stretchable material.

[020] In an example of preparing a stretch sensor, an elastomer is added to a supporting matrix to form a composite elastomer layer. Next, a certain amount of piezoresistive element, which may be mixed with the spacer elements, is deposited on a surface of the composite elastomer layer. Two or more electrodes are then connected electrically to the piezoresistive element. A substrate serves to seal in the piezoresistive element and the spacer elements within the sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[021] FIG. 1 is a schematic diagram showing examples of sensor configurations that exhibit nonlinear output.

[022] FIG. 2 is a schematic diagram that shows an example of a flexible pressure sensor configuration.

[023] FIG. 3 is a schematic diagram illustrating an example of a fabrication method of a piezoresistive graphite-based sensor with a texturized elastomer layer.

[024] FIG. 4 is a schematic diagram illustrating an example of an alternative method of flexible pressure sensor fabrication using a granular substance to form a textured elastomer surface.

[025] FIG. 5 is a schematic diagram illustrating another example of a fabrication method of a sensor with a textured elastomer surface.

[026] FIG. 6 is a schematic diagram illustrating still another example of a fabrication method of a sensor with electrodes bonded at the opposite ends of two substrate layers that flank the electrodes.

[027] FIG. 7 is a schematic diagram illustrating another example of a method for fabricating a pressure sensor.

[028] FIG. 8 shows a plot that compares the measured conductance as a function of pressure for two sensors with one and two piezoresistive layers, respectively.

[029] FIG. 9 is a schematic diagram showing an example of a stretch sensor fabrication method.

[030] FIG. 10 is a schematic diagram that illustrates another example of a stretch sensor fabrication method.

[031] FIG. 11 is a schematic diagram illustrating an example of a multiple sensor assembly.

[032] FIG. 12 is a schematic diagram illustrating another example of a multi-sensor assembly.

DETAILED DESCRIPTION OF THE INVENTION

[033] The following terms will be used throughout the specification:

[034] The term "piezoresistive element" is used herein to refer to a single unit or plurality of piezoresistive element. The term "piezoresistive element" is also used herein to refer to the type of piezoresistive material that includes but are not limited to graphene nanoparticles, carbon black, fullerene, carbon nanoparticles, graphene oxide particles, functionalized carbon-based nanomaterials, graphite particles or a combination thereof.

[035] The term "strain sensor" is used herein to refer to either a pressure sensor or stretch sensor.

[036] The term "transverse compression" or "transverse compressive force" is used herein to refer to the compressive force generated when a sensor stretches and spontaneously contracts in directions transverse to the direction of stretching.

[037] The term "substrate" generally refers to an outermost layer of the sensor, which may comprise an elastomer or other suitable materials having sufficient mechanical strength and elasticity required in typical flexible sensors. The substrate may also comprise an elastic or flexible mesh-type structure embedded with an elastomer. The substrate typically serves as an additional support layer (in cases where a first support layer is present) to, for example, enhance the

sensor's durability, as well as protect the sensor's internal components from environmental elements.

[038] The detailed description provided below in connection with the appended drawings is intended as a description of the present examples and is not intended to represent the only forms in which the present examples are constructed or utilized. The description sets forth the functions and the sequence of operations for constructing and operating the provided examples. However, the same or equivalent functions and sequences may be accomplished by other examples.

[039] The change in conductivity with applied pressure is realized through a 3D-texturized elastomer surface in contact resistance-based sensors. With increasing applied pressure, the elastomer surface undergoes deformation, which increases the surface area of the interface between the texturized elastomer and the planar electrode. When the textured elastomer surface is further modified by, for example, depositing a conductive material on the textured elastomer surface, the increasing contact interface surface area with applied pressure results in lower contact resistance between the conductive material particles on the elastomer surface and the planar electrode. The sensor sensitivity can be tuned using elastomer with different elasticities.

[040] The various examples of flexible stretch sensors described in this disclosure are based on the piezoresistive particles', such as graphite's, electro-conductive property above their percolation threshold. When not subjected to compression, the resistivity of a graphite layer is directly proportional to the strain exerted on the graphite particles. To assess the sensor performance, the sensor is subjected to controlled changes in either the magnitude of the pulling force or strain the sensor experiences. An applied strain or pulling force magnitude can be

incremental or decremental, with the changes in the applied force or strain calculated based on a known pulling force or strain value.

[041] The fabrication of the various flexible pressure sensors covered in this disclosure is compatible with existing manufacturing processes. Typically, the fabrication involves depositing a liquid elastomer using known techniques, including but not limited to injecting, soaking, swiping, spraying, or screen-printing. A support layer or matrix can be introduced either before or after the deposition of the mixture.

[042] If higher pressure sensitivity over certain pressure ranges is needed, additional texturization can be performed on the piezoresistive particle--on-elastomer pressure sensor by depositing on a patterned mold with the desired granularity, pattern, or degree of roughness. The use of a textured surface provides beneficial additive effects from the pressure-dependent contact resistance between the 3D texturized surface of the graphite-modified elastomer surface and the planar electrode and the graphite's innate piezo-resistance.

[043] Alternatively, the elastomer mixture can be deposited as a thin layer on a smooth elastomer surface. A textured surface can then be formed via subsequent deposition of granular or crystalline material. The thickness of the elastomeric film is preferably less than or similar to the granular or crystalline material's grain size to avoid encapsulating the granular material particle. Once cured, the patterned mold or granular material used for forming the textured surface can be removed.

[044] . Aside from using adhesives for bonding the sensor layers, other coupling or fastening techniques such as sewing, threaded fastening, or vacuum sealing may also be used to seal the sensor. Next, piezoresistive particles are deposited on the exposed part of the textured elastomer layer, for example, by pneumatic, for

example spray-coating, or vigorous agitation of the exposed elastomer layer or via other dry surface-modification processes. The piezoresistive particles may spontaneously attach electrostatically or undergo self-assembly on the exposed portion of the textured elastomer layer. The various layers are then aligned and bonded together.

[045] The sensor's pressure sensitivity is no longer limited by elastomer elasticity. Furthermore, the graphite's innate piezoresistivity results in multiple orders of magnitude increase in the sensor's pressure sensitivity. Further, the high affinity of graphite to the elastomer surface allows for easy surface modification, which simplifies sensor fabrication while preserving the graphite's exceptional conductive and piezoresistive properties.

[046] Preferably, the piezoresistive particles of the second layer adhere spontaneously and self-assembles on the elastomer surface of the first layer. In this ideal scenario, the resistance of the sensing layer would be the only variable of concern during the operation of the sensor. This is due to the contact area between the piezoresistive particles and electrodes increasing with applied pressure. However, for sensitive low-noise applications of the flexible sensor, the threshold of observable applied pressure may be considerably low, and an instability may be observed as noise due to contact resistance.

[047] If the piezoresistive element does not have sufficient affinity with or tendency to self-assemble on a chosen elastomer layer, a pre-compression step is preferably performed during the sensor fabrication. This step increases the total contact area between the piezoresistive layer and the electrode. Pre-compression may be performed in several ways. One such method involves reducing the physical distance between the sensor's two outer layers that encompass the

piezoresistive layer, for example the mesh-elastomer matrix layer on one side and the substrate comprising electrodes on the other, as an additional step during sensor fabrication.

[048] The choice of elastomeric material used for the first layer is essential in determining the flexibility, durability, and comfortability of the sensor and its application, such as with a wearable medical device. Any material used as an elastomer or an elastomer substitute must be flexible and able to contain the piezoresistive particles.

[049] The elastomer may comprise at least one of polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene-propylene rubber, neoprene, cork, natural rubber, silicone, and thermoplastic elastomeric gel and any other elastic material. The elastomer may also be substituted wholly or partially with synthetic or natural latex, agar, a combination of water and starch, or any other suitable elastic material. The elastomer may further be comprised of a thermoplastic elastomer, thermoset resin such as an acrylic elastomer, resole resin, or elastomer-modified epoxy, polyolefins such as polyethylene, polypropylene, copolymers such as ethylene-propylene, polyesters such as polyethylene terephthalate, polyamide resin such as nylon; vinyl chloride polymer, polycarbonate resin, and other engineering thermoplastic such as ABS class or any composites using these resins, elastomers, or polymers. The elastomer may include additives or materials that enhance the elastomer's rigidity or elasticity, such as fiberglass, metal, elastomeric fibers, polymeric fibers, graphite fibers, carbon fibers, boron fibers,

nano-composite additives such as carbon nanotubes and any other suitable fibers or materials.

[050] The application of a durable mesh within the elastomer layer is a simple way to improve its durability. The choice of supporting mesh may also minimize the dampening of force. A supporting non-stretchable mesh may reduce the shearing or parallel displacement of the force exerted on the sensor.

[051] A piezoresistive-coated elastomer layer may comprise a different type of elastomer from the elastomer layer used as a support layer/substrate that provides mechanical support for the adjacent piezoresistive-coated elastomer layer or the electrodes. The use of two different types of elastomers for the support elastomer layer and the piezoresistive-coated elastomer layer may be used, for example, in cases where the desired sensor elasticity lies somewhere between those of the two different elastomers to be used in the sensor. The use of different types of elastomers in a sensor may be advantageous when one desires to adjust or modulate the sensor elasticity and in cases where neither of the two elastomers used provides the requisite or desired sensor elasticity (and thus, sensor elasticity). For specific applications or sensor configurations, the elastomer layer is the preferred outermost sensor layer, while in other sensor configurations, a mesh-elastomer support layer is more advantageous as an outermost layer.

[052] The support matrix, mesh, or support layer may comprise at least one but are not limited to nylon, wool, elastane, or cellulose fiber. The substrate layer may comprise polycarbonate, polyvinylchloride, acrylics, for example Styrene-acrylonitrile copolymers, acrylonitrile styrene acrylate, polymethyl-methacrylate, polyethylene terephthalate, and glycol-modified polyethylene terephthalate, and

optionally fiber reinforcement such as carbon, glass, aramid fibers, or any other suitable material.

[053] The sensor comprises electrodes that may be printed, drawn, coated, grown, deposited, stitched, or glued using a conductive adhesive unto opposite ends of the sensor assembly to ensure stable sensor contact-resistance. The electrodes may also comprise one or more printed or printable electrodes, nanoparticles, nanosheets, nanotubes, graphene sheets, conductive wires, flakes, metal alloys, metal particles, conductive adhesives such as isotropic and anisotropic conductive adhesives, and conductive tapes. The electrode may be a stretchable electrode made of electrically conductive material, conductive ink or inks, or electrically conductive fabric or fiber such as polyamide or polyester coated with a metal layer. The sensor electrodes may comprise aluminum, carbon, silver, gold, stainless steel, conductive threads and fibers, and other conductive materials.

[054] Once the piezoresistive particles and spacer elements have been deposited on the composite elastomer-stretchable mesh layer, electrode terminals are affixed at two opposite ends of a second composite elastomer-mesh layer by, for example, fastening, stitching, or gluing the terminals to one side or surface of the second elastomer-mesh layer. Afterwards, any exposed terminals may be encapsulated with an elastomer to complete the sensor assembly. In certain sensor configurations or applications, combinations of different electrode types may be used.

[055] However, other applications requiring higher elasticity or stretchability may be beyond the physical limitations of polymeric substrates. For such applications, 3-dimensional electrodes may be used such as thin metallic wires, conductive elastomers, conductive threads, or other similar conductors. Good physical

contact between the electrodes and the piezoresistive element can be maintained even when the electrodes undergo deformation, such as in the case of interlaced looping, even at the most compressed state of the sensor.

[056] A mediating conductor may be applied as a bridge between the piezoresistive particles and the electrode. It is preferred that the mediating conductor is a conductive adhesive. The conductive adhesive provides conditions for graphite to form a fixed layer at its surface as a fixed contact area to transfer charge towards the electrodes.

[057] FIG. 1 is a schematic diagram showing examples of configurations of sensors **100**, **101**, **102** that give rise to a nonlinear sensitivity or response to an applied force. Each of these three sensors **100**, **101**, **102** comprises a piezoresistive element **103**, an elastomer layer **104**, a support substrate **105**, and an electrode **106**. For example, if one or more sensor components have a non-uniform thickness or varying elasticity, any applied force on the sensor surface is likely to be distributed unevenly across any of the sensors **100**, **102**, **102**.

[058] In this case, the piezoresistive element **103**, such as graphite particles, would be subjected to a force or pressure of varying magnitudes across the sensors **100**, **101**, **102**, and those piezoresistive elements **103** subjected to higher pressures than the other piezoresistive elements **103** or other portions of the piezoresistive layer would bear most of the load **100**. If the sensing area is thinner than the rest of the sensor **101**, the sensor to have reduced sensitivity to low pressures. If a spacer is placed between the elastomer layer and the planar electrode's supporting layer **102**, physical contact between the graphite and electrodes may initially be minimal and thus produce low initial readings. But the sensor's conductivity can rise dramatically as the contact area between the

elastomer layer and the planar electrode increases. This pressure sensor configuration can be used for many applications such as for a switch. The generated signal for this sensor configuration arises from a combination of contact resistance and graphite-based piezoresistive effects.

[059] FIG. 2 is a schematic diagram that shows an example of a flexible pressure sensor configuration **200**, wherein an elastomer **201** forms the top layer having a matching geometry as that of the supporting matrix **202** below it. Beneath the supporting matrix **202** is the piezoresistive layer **203**, which is flanked by adhering, coupling, or fastening means **204**, for example conductive tape, on the opposite ends of the piezoresistive layer **203**. The sensor **200** also includes a lower layer comprising a substrate **205** through which electrodes **206** are affixed. The substrate **205** is fastened to the supporting matrix **202**, and the electrodes **206** to the piezoresistive layer **203**, through the adhering, coupling, or fastening means **204**. Contact resistance between the electrodes **206** and the piezoresistive layer **203** is minimized using the adhering, coupling, or fastening means **204**.

[060] FIG. 3 is a schematic diagram illustrating an example of a fabrication method of a graphite-based sensor with a texturized elastomer layer, the graphite serving as a piezoresistive element. In step (a), a liquid form of an elastomer layer **300** is initially deposited on a patterned mold **301** to produce a textured surface having a desired surface roughness. Suitable examples of a pattern mold include coated abrasive sheet, etched silicon, glass, or other materials that are non-reactive to the elastomer layer **300**. In step ((b)), a supporting mesh layer **302** is deposited on the textured elastomer layer **300**, after which the textured elastomer layer **300** is allowed to cure and harden. In step (c), the composite layer comprising the cured textured elastomer layer **300** and support elements **302** is removed from the

patterned mold 301, and structural supports **303** are attached to the textured surface of the elastomer layer **300**. In step (d), piezoresistive particles **304** are deposited on the remaining exposed parts of the textured surface of the textured elastomer layer **300** and structural supports **302**. Finally, in step (e), a substrate **305** comprising electrodes **306** is connected to the structural supports **303**, which completes the flexible pressure sensor **307** fabrication.

[061] FIG. 4 is a schematic diagram illustrating an example of an alternative method of flexible pressure sensor fabrication. In this example, a granular substance **400** may be used instead of a patterned mold to form a textured elastomer surface **401** in step (b). In this method, the granular substance is **400** deposited on top of an uncured elastomer **300** deposited on top of a substrate **302**. As shown, a pair of adhering, coupling, or fastening means **303** such as an insulating adhesive, are then applied in step (c) to the opposite ends of the textured elastomer layer **401** surface followed by deposition of the piezoresistive layer **304** in step (d). In step (e), a conductive bridge layer **402** may or may not be attached to each electrode that form part of the substrate layer **305**. Lastly, the textured elastomer layer **401** surface is attached in step (f) to the substrate layer **305**.

[062] FIG. 5 is a schematic diagram illustrating an example of a sensor like that shown in FIG. 4. But unlike the textured elastomer layer **401** in FIG. 4, the textured elastomer layer in this example is an adhesive-type textured elastomer layer **500**. Using an adhesive-type textured elastomer layer **500** simplifies the fabrication process, and the thickness of the sensor can also be reduced since the adhesive-type textured elastomer layer **500** does not require a separate adhering, coupling, or fastening means for attaching the adhesive-type textured elastomer layer **500**

to the substrate layer **305** comprising a pair of electrodes **306**. As in FIG. 4, a piezoresistive layer **304** may be deposited on the textured surface of the adhesive-type textured elastomer layer **500**. The textured surface of the adhesive-type textured elastomer layer **500** may be formed using, for example, a patterned mold or a granular substance.

[063] FIG. 6 is a schematic diagram illustrating still another example of a sensor. In this example, the sensor **600** comprises electrodes **601** bonded to the opposite ends of two composite layers that flank the electrodes **601**. Unlike the electrodes **306** in FIG. 5, the electrodes **601** are sensor components installed separately from the other sensor components, rather than being, for example, part of the substrate layer **305** shown in FIG. 5. Each of the two composite layers in FIG. 6 comprises a textured elastomer layer **602**, which face each other in the region spanning the two electrodes **601**. In addition to the substrate layer **604**, each of the two composite layers may comprise an elastomer layer **603**, separate from the textured elastomer layer **602**. Alternatively, both textured elastomer layer **602** and the elastomer layer **603** of each composite layer may comprise a single elastomer layer with a textured surface. A piezoresistive layer may be deposited on the textured surface of each of the two textured elastomer layers **602**, or piezoresistive particles may be deposited on the textured surface along with spacer elements. In this example, the textured elastomer layer **602** may be a separate layer from the elastomer layer **603**. The sensor illustrated in FIG. 6 is particularly advantageous for applications requiring low noise and high sensor sensitivity, such as for sensing a gradually increasing pressure due to, for example, a swelling portion of a lump.

[064] FIG. 7 is a schematic diagram illustrating an example of fabricating a strain sensor **700** such as a pressure sensor. Similar to the sensor shown in FIG. 6, the sensor in this example also comprises two separate piezoresistive layers. But unlike in FIG. 6, only one of the elastomer layers coated with a piezoresistive layer comprises a textured surface. The other elastomer layer **702** has relatively planar surfaces. A first composite layer is prepared by depositing a piezoresistive layer **701** on a relatively planar elastomer layer **702**. A substrate layer **703** is provided as a support layer adjacent to the elastomer layer **702**. A second composite layer is then prepared by forming a textured elastomer layer **705** and depositing a piezoresistive layer **704** on the textured surface of the elastomer layer **705**. A support layer **706** is also provided adjacent to the textured elastomer layer **705**. Next, electrodes **707** are attached to opposite ends of the textured elastomer layer **705**. Finally, the first composite layer is connected to the second composite layer via electrodes **707**, which completes the pressure sensor. The sensor configuration in FIG. 7 is advantageous for use in applications requiring greater sensitivity than those that only comprise a single piezoresistive layer.

[065] The fabricated flexible pressure sensor is stable under mechanical deformation and can be used for various wearable applications such as medical diagnostics, wellness, and health-monitoring, as well as for recreational, athletic, safety, or industrial applications. The flexible pressure sensor can also be easily and seamlessly integrated with, for example, articles of clothing, footwear, and other applications.

[066] In one example of sensor application, a plurality of pressure sensors forming a sensor assembly is integrated into a glove with accompanying electronic circuits and data logging and processing software to detect any pressure exerted by a user.

Electrical resistance values corresponding to detected pressure changes from the glove can be collected and converted into their corresponding pressure values using a pressure-versus-electrical-signal equation. The data logging and processing software may be programmed to send audiovisual alerts or notifications when the measured pressure exceeds a predefined threshold value, which may signal a possible punch or action executed using the glove.

[067] Another example of an application of the flexible pressure sensor is the detection of the pressure exerted by an elastic bandage. The flexible pressure sensor may be embedded into the elastic bandage and connected to electronic modules or circuits with data logging and processing capabilities. The data logging and processing software can be programmed to send audiovisual cues to preselected alert or notification recipients when the pressure exerted by the elastic bandage exceeds a predefined pressure threshold.

[068] The pressure sensor's flexibility does not preclude it from being used in other non-wearable applications in which non-flexible sensors may be used. For example, the pressure sensor and the accompanying electronics may be used as an active layer of a pressure mat to detect the pressure exerted on a bed, a chair, a ball, and other objects. As with other applications of the flexible sensor, the pressure mat may be used for medical, health, security, industrial, wellness, and recreational purposes.

[069] In another example, the sensor and accompanying electronic circuit may be integrated into a tissue-holder to monitor and measure the resulting pressure decrease as the quantity of available tissue roll decreases. The sensor's accompanying electronic circuit can send an audio alert, mobile message, or other notification methods to inform a recipient that the tissue roll needs replacing. The

sensor can also be configured as part of a sensor array for various applications that require the monitoring of a relatively wide area or surface for monitoring, measuring or detection. The pressure sensing array may also be used for monitoring, measuring, and detecting the pressure exerted on car seats, chairs and beds in homes, eldercare facilities and hospitals or when calibrating or measuring the pressure exerted by certain devices in an industrial setting.

[070] In its use as a stretch sensor, multiple layers and components are used to encapsulate the piezoresistive material inside the sensor. The various layers and components of the stretch sensor may comprise an elastomer, a flexible non-stretchable mesh, a flexible stretchable mesh, a piezoresistive material and a spacer material. The elastomer in the stretch sensor may also be in the form of a thin elastic tube such as prefabricated elastomeric tubing materials. The elastic tubing may or may not comprise a supporting mesh. Due to graphite's affinity to the elastomer surface, it may be deposited pneumatically and selectively on the inner wall of the tubing. The air gap inside of the tubing acts as the spacer in the case of planar stretch sensors. The outward transverse tension present in the tubing walls also reduces the susceptibility of the sensor to external transverse pressures. Stretch sensors may also be arranged in a parallel or serial manner and expressed as an array.

[071] Suitable elastomers include but are not limited to polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene propylene rubber, neoprene, cork, natural rubber, silicone, and thermoplastic elastomeric gel. The elastomer may also be substituted wholly or partially with synthetic or natural latex, agar, or a combination of water

and starch. The flexible, non-stretchable mesh minimize stretching at or near the sensor's terminals, which helps reduce contact resistance variations. The flexible, non-stretchable mesh or support layer may comprise at least one of nylon, wool, or cellulose fiber. The flexible, non-stretchable mesh also provides mechanical support to the elastomer layer. The flexible stretchable mesh may comprise an elastic woven fabric such as elastane. The flexible stretchable mesh provides additional mechanical support especially during a stretched state.

[072] An elastomer-mesh layer may be prepared by depositing a liquid elastomer into a mesh. The elastomer, which may comprise an elastomer mixture, may be deposited in various ways such as by swiping, spraying, screen-printing.

[073] After the elastomer added into the mesh has been allowed sufficient time to set, the liquid elastomer is deposited on the elastomer-mesh layer, which serves as a supporting matrix for the added elastomer layer. Conductive particles and nonconductive spacer elements are then deposited on the liquid elastomer. When graphite particles are used as the piezoresistive element, nonconductive and chemically inert elements are added as spacers between the graphite particles with a certain spacer-to-graphite particle volume ratio. The spacers minimize contact between graphite particles when transverse compressive forces are generated when the sensor undergoes stretching, which could cause significant sensor reading errors.

[074] The sensor's conductive elements are typically mixed with nonconductive and chemically inert elements with an average grain size or more than that of the conductive elements. The conductive and nonconductive elements are preferably deposited on an elastomer layer before the elastomer has undergone substantial curing. An example of a suitable sensor conductive element is graphite particles.

Inert spacer elements may comprise but are not limited glass, silica gel, sand, salt, or any of their combinations.

[075] The nonconductive and chemically inert spacer elements are preferably immobilized on the elastomer-stretchable mesh layer. This makes the sensor perform more reliably and consistently and allow the nonconductive elements to function reliably as spacers.

[076] When immobilizing the spacer elements on an elastomer layer, a thin film of elastomer in liquid form may be deposited on a cured layer of a similar elastomer or an elastomer with a composite mesh. On top of the liquid film, a blend of conducting particles and nonconductive spacer materials are spray-coated on the liquid thin film. Alternatively, the spacer materials may be scattered on top of the liquid film followed by the deposition of the conductive particles. The cured elastomer or composite elastomer-mesh layer is pre-patterned with indentations that are approximately the same size as half of the average grain size of the nonconductive spacer. Multiple nonconductive spacers particles are then deposited on the pre-patterned elastomer until all, or most indentations are filled with the nonconductive spacer. The conducting particles are then deposited on top.

[077] FIG. 8 is a schematic diagram that shows an example of a fabrication method of a stretch sensor **800**. The flexible sensor **800** can detect and measure a strain such as a pulling or stretching force exerted on the sensor **800**. When the sensor **800** undergoes stretching, it generates an electrical signal that varies proportionally with the magnitude of elongation of the sensor **800**. The sensor **800** converts the strain incident on it to an electrical signal through the conductive particles such as graphite that form part of the sensor **800**. In step (a), a first composite mesh layer is prepared by attaching a non-stretchable, flexible mesh **801** to opposite ends of a

stretchable, flexible mesh **802**. The flexible mesh layer **801**, **802** provides a deposition surface for the sensor's piezoresistive elements and mechanical support for the other sensor layers and encapsulate the piezoresistive elements. In step (b), an elastomer layer **803** is deposited on the composite mesh layer followed in step (c) by deposition of conducting particles **804** and spacers **805** on the elastomer layer **803**. In step (d), the electrodes **806** are bonded on the opposite ends of the elastomer layer **803**. In step (e), the stretch sensor **800** is completed by adhering, coupling, or fastening a second composite elastomer-mesh layer as prepared in step (b) on the other ends of the electrodes **806** to seal in the conductive particles **804** and spacer elements **805** and protect them from the environment.

[078] The elastomer includes, but is not limited to, polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene propylene rubber, neoprene, cork, natural rubber, silicone, and thermoplastic elastomeric gel. The elastomer may also be substituted wholly or partially with synthetic or natural latex, agar, or a combination of water and starch. The stretchable mesh may comprise elastic fabric, such as but not limited to, elastane, nylon, and natural fibers.

[079] Here, the stretchable mesh typically encapsulates and protects the sensor's conductive and nonconductive materials from environmental elements and prevents the degradation of the sensor's performance. The stretchable mesh also serves as a mechanical scaffolding for the elastomer layer and helps with the elastomer shape retention during sensor assembly and enhances elastomer durability. The stretchable mesh helps retain the elastomer elasticity over a more

extended period even when the elastomer is repeatedly subjected to external pressure.

[080] Having multiple layers and components decreases the sensor's flexibility or elasticity. In that case, when the sensor is subjected to uneven strain, such as in twisting or bending actions, the sensor may become permanently deformed and its accuracy compromised. A single sensor may be replaced by an array or matrix of sensing points to minimize this effect. The array of sensing points may be expressed as multiple sensors proximally linked by glue, stitch, fasteners, or other flexible constraints. A sensing point may not necessarily be linked directly to another sensing point and an intermediary material may be placed in between. The proximal links may also be a shared electrode of the sensing points, such as a conductive thread. A combination of stretch and pressure sensors may also be arranged as an array to measure the combination of forces acting on the device.

[081] FIG. 9 is a schematic diagram that illustrates a fabrication method for a stretch sensor **900**. The process described in FIG. 9 is preferably used when the stretch sensor **900** is tubular such as that shown in FIG. 9. As shown in the first step in FIG. 9, a support matrix **901** is prepared by attaching two pieces of a flexible, non-stretchable mesh **902** to opposite ends of a flexible, stretchable mesh **903**. An elastomer layer **904** is then deposited on the inner wall of the support matrix **901**. Next, an electrode **905** is bonded to one end of each composite elastomer-support layer, which seals that end of the tubular sensor **900**. piezoresistive elements **906** are then deposited on the elastomer layer **904** using a suitable process such as pneumatic deposition. In this example, the tube's inner walls and air serve as spacer elements. Finally, the other end of the tube is sealed with a second electrode **907**, which completes the stretch sensor fabrication.

[082] FIG. 10 is a schematic diagram illustrating an example of a multiple sensor assembly **1000**. Multiple sensors can enhance the reliability of measurements, especially when dealing with non-uniform strain over an area or surface being monitored. In this example, an elastomer **1001** is deposited on a support layer **1002** comprising an elastic sheet or a mesh layer comprising a mesh such as elastane or spandex. The elastomer used for the elastomer layer **1001** and the support layer **1002** may be the same or similar, for example different grades of silicone. A thin intermediate adhesion layer comprising a mixture of two materials may be deposited between the two elastomer layers. A piezoresistive material **1003**, such as graphite particles, is deposited on the support layer **1002** after which a substrate **1004** comprising electrodes is attached to the support layer **1002**. The sensor configuration illustrated in this example offers the advantage of being suitable for either stretch or pressure sensing, a soft elastic sheet elastomer being advantages for stretch sensors, and the less elastic or more rigid elastomer sheet for pressure sensing. A stretch sensor and a pressure may also be combined to create a flex sensor.

[083] FIG. 11 is a schematic diagram illustrating another example of a multi-sensor assembly **1100**. Here, the composite elastomer-support mesh layer **1101** comprises piezoresistive elements **1103** surrounded by a non-conductive material **1102** which may or may not be the same as the elastomer-support mesh layer **1101**. Electrodes **1104** are embedded in the composite elastomer-support mesh layer **1101**, wherein a pair of electrodes **1104** are attached to each piezoresistive element **1103**. This multi-sensor configuration offers an advantage of greater sensor flexibility and higher sensor sensitivity to strain, thus making them suitable in applications in which the monitored area covers a

relatively large surface area, or the strain occurs to varying extents in different locations of the monitored surface at the same or different times.

[084] In one example, a plurality of stretch sensors is attached to a balloon and connected to a data processing system with data logging and processing software to detect changes in balloon circumference. A sensor array used for a series of such measurements from the same sensor positions is more reliable than the current practice of using a measuring tape. Electrical resistance measured by, for example, an ohmmeter connected to the sensor may be collected and used to calculate a balloon circumference based on the equation of each corresponding sensor. The data logging and processing software may be set to transmit an audiovisual cue that indicates the balloon inflation.

[085] An example of a stretch sensor application is by integrating, for example, stitching or gluing a sensor unto an elbow pad to detect, monitor, or measure, for example, the extent of bending for an elbow. Threshold values corresponding to the elbow dimensions increase, for example along the x and y axes, are initially set. The sensor can be programmed such that when it detects a strain leading to elbow stretching beyond the predefined threshold stretching values, the sensor sends a visual, audio, or audiovisual notification or alerts to one or more preselected notification recipients, for example, athlete, coach, patient, attending physician, or physical therapist, connected to a mobile device or central server where data collected by the stretch sensor is stored for subsequent or immediate processing, analysis, diagnosis, or consultation. The notifications may be sent to a device such as the recipient's mobile phone, laptop, desktop computers, PDA, and any other digital devices.

[086] The sensor, whether for pressure, stretch, or its combination, typically includes a wired or wireless interface for communicating with external devices such as a smartwatch, cell phone, laptop, IoT devices, tablets, PDA, cloud servers, for example for analyzing or transmitting data, sending notifications, or receiving instructions. Examples of suitable communications interface include USB, Firewire, ANT, Bluetooth, NFC, Wi-Fi. The sensors may communicate with the external devices wirelessly through one or more antennas.

[087] The sensor may also include one or more ports configured to communicate data collected by the sensors to an external source in one or more known manners. The port is preferably a universal communication port configured for communicating data in a universally readable format. The port includes an interface for connecting to an electronic module or device. The interface may take the form of electrical contacts. The port is adapted for connection to various electronic modules, such as memory, for example, a flash drive. The port may include electronic contacts as an interface for connecting to an electronic module or device, USB port, Firewire port, Wi-Fi, Bluetooth, near-field communication, RFID, Bluetooth Low Energy, Zigbee, or an IR or any other wireless interface.

[088] Communication between the sensors and electronic modules or devices may be accomplished through one or more transmitters, receivers, or transceivers. The sensor's data may be stored in memory and made available, for example, for transmission by the transmission/reception system to some remote user(s), location(s), or system(s).

CLAIMS

1. A method of fabricating a flexible strain-sensitive pressure sensor, including the steps of:
 - a) depositing an elastomer material in liquid form on a patterned mold;
 - b) depositing a supporting mesh on the elastomer material;
 - c) curing the elastomer material to thereby form a textured elastomer layer having a textured surface and a support mesh layer;
 - d) depositing a graphite-based piezoresistive layer over the textured surface of the textured elastomer layer; and
 - e) overlaying a substrate layer supporting one or more electrodes therein.
2. A method according to claim 1, further including the step of attaching one or more structural supports on the textured surface.
3. A method according to claim 2, further including the step of also depositing the graphite-based piezoresistive layer on the structural support(s).
4. A method according to any one of the preceding claims, wherein the patterned mold includes at least one of a coated abrasive sheet, etched silicon, glass or other textured material that is non-reactive to the elastomer.
5. A method according to any one of the preceding claims, wherein the piezoresistive layer includes graphene nanoparticles, graphite particles or a combination thereof.

6. A method according to any one of the preceding claims, wherein the elastomer layer includes polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene-propylene rubber, neoprene, cork, natural rubber, silicone, thermoplastic elastomeric gel, or a combination thereof.

7. A method of fabricating a flexible strain-sensitive stretch sensor, including the steps of:

- a) preparing a first composite mesh layer by attaching a non-stretchable, flexible mesh material to opposing ends of a stretchable mesh material;
- b) depositing elastomer material over the first composite mesh layer to form an elastomer layer thereon;
- c) preparing a second composite mesh layer by attaching a non-stretchable, flexible mesh material to opposing ends of a stretchable mesh material;
- d) depositing elastomer material over the second composite mesh layer to form an elastomer layer thereon;
- e) depositing graphite conductive particles and spacer elements over the first elastomer layer;
- f) securing electrodes at opposite ends of the first elastomer layer; and
- g) securing the second composite elastomer-mesh layer over the first composite mesh layer to thereby retain in place the graphite conductive particles and spacer elements therebetween.

8. A method according to claim 7, wherein the elastomer layer includes polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene-propylene rubber, neoprene, cork, natural rubber, silicone, thermoplastic elastomeric gel, or a combination thereof.

9. A flexible strain-sensitive stretch sensor fabricated using a method according to claim 7 or 8.

10. A method of fabricating a flexible strain-sensitive stretch sensor, including the steps of:

- a) preparing a support matrix by attaching a non-stretchable, flexible mesh material to opposing ends of a tubular stretchable mesh material;
- b) depositing elastomer material on an inner wall of the support matrix;
- c) securing a first electrode to the elastomer layer at one end of the support matrix to thereby seal the one end of the support matrix;
- d) depositing graphite conductive elements over the elastomer layer; and
- e) securing electrodes at opposite ends of the first elastomer layer; and
- f) securing a second electrode to an opposing end of the support matrix to thereby seal the opposing end of the support matrix to thereby retain the graphite conductive elements therein.

11. A method according to claim 10, wherein the elastomer layer includes polydimethylsiloxane, polyurethane, polyethylene, poly (ethylene-vinyl acetate), polyvinyl chloride, polyborodimethylsiloxane, polystyrene, acrylonitrile-butadiene-styrene, styrene-butadiene-styrene, ethylene-propylene rubber, neoprene, cork, natural rubber, silicone, thermoplastic elastomeric gel, or a combination thereof.

12. A flexible strain-sensitive stretch sensor fabricated using a method according to claim 10 or 11.

13. A method of fabricating a multi-sensor assembly including a plurality of flexible strain-sensitive pressure sensors, including the steps of:

- a) depositing an elastomer material on an elastic support layer;
- b) depositing a graphite-based piezoresistive layer over different spaced apart areas on the support layer; and
- c) attaching a substrate layer supporting a plurality of electrodes to the support layer

such that a plurality of the flexible strain-sensitive pressure sensors are provided within the multi-sensor assembly.

14. A method according to claim 13, wherein the piezoresistive layer includes graphene nanoparticles, graphite particles or a combination thereof.

15. A method according to claim 13 or 14, wherein the support layer is an elastane or spandex mesh.

16. A method according to claim 13 or 14, wherein the elastomer layer and support layer is formed from the same elastomer.

17. A method according to any one of claims 13 to 16, further including depositing an intermediate adhesion layer between the elastomer layer and support layer.

18. A multi-sensor assembly fabricated using a method according to any one of claims 13 to 17.