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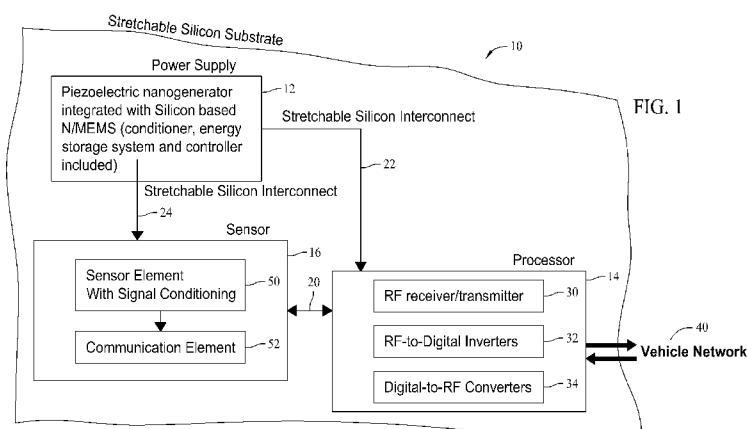
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(54) Title: SENSOR NETWORK INCORPORATING STRETCHABLE SILICON



(57) Abstract: A sensor network is described which includes a stretchable silicon substrate, and a plurality of nodes fabricated on the stretchable silicon substrate. The nodes include at least one of an energy harvesting and storage element, a communication device, a sensing device, and a processor. The nodes are interconnected via interconnecting conductors formed in the substrate.

SENSOR NETWORK INCORPORATING STRETCHABLE
SILICON

BACKGROUND

The field of the disclosure relates generally to sensor networks, and more specifically, to methods and systems relating to sensor networks that incorporate stretchable silicon.

Existing solutions for monitoring, for example, the structural health of large areas, include interconnecting networks of sensors based on electrically conductive wires and optically conductive fibers. While fiber optic communications enables low power devices in certain communications systems, it does not enable addressing of an array of sensors without the complexity of interconnections among network nodes. Other considerations include 5 manufacturability, mechanical connection of input/output signals, scalability, cost and reliability of wiring/fiber-optic harnesses, power busses, and data busses.

BRIEF DESCRIPTION

10 In one embodiment, a sensor network is provided that includes a stretchable silicon substrate and a plurality of nodes fabricated on the stretchable silicon substrate. The nodes include at least one each of an energy harvesting and storage element, a communication device, a sensing device, and a processor. The nodes are interconnected via interconnecting conductors.

15 In another embodiment, a method for fabricating a network is provided. The method includes stretching a silicon medium over a desired area, processing the stretched silicon medium to generate a number of nodes thereon, and utilizing conductive paths within the stretchable medium to redundantly interconnect the generated nodes to form the network.

20 In still another embodiment, a network for monitoring a structure is provided. The network includes a stretchable silicon substrate, a plurality of sensors fabricated on the stretchable silicon substrate, at least one communication device fabricated on the stretchable silicon substrate, and at least one energy harvesting and storage element fabricated on the stretchable silicon substrate. The stretchable silicon substrate includes a plurality of conductive paths therein that interconnect the plurality of sensors, the at least one communication device, and the at least one energy harvesting and storage element. The network is configured for

attachment across a structure, dispersing the sensors. Data from the sensors is communicated to an external device via the at least one communication device.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a system block diagram illustrating a sensor network fabricated using stretchable silicon in an advantageous embodiment.

5 Figure 2 is a diagram illustrating a sensor network in another advantageous embodiment, that includes stretchable silicon interconnecting energy harvesting and storage elements, wireless and wired communication devices, micro-sensors, and network management processors.

Figure 3 is a flowchart illustrating a method for fabricating a sensor network using stretchable silicon in another advantageous embodiment.

DETAILED DESCRIPTION

10 Figure 1 is a block diagram of a sensor network 10 that is based on stretchable silicon. In the illustrated embodiment, three nodes have been fabricated on a stretchable silicon substrate. The three nodes include a power supply node 12, a processor node 14, and a sensor node 16. The nodes are interconnected via interconnecting conductors 20, 22, and 24 formed in the stretchable silicon substrate.

15 In one embodiment, the power supply node 12 may be an energy harvesting and storage element. For example, power supply node may be a piezo-electric generator that is integrated with silicon-based Nano/Micro-Electromechanical Systems (N/MEMS) In this embodiment, the combination is able to generate and store electrical power. The power supply node 12 may provide such power to both the processor node 14 and the sensor node 16. In other 20 embodiments, a plurality of power supply nodes 12 may be distributed across the stretchable silicon substrate providing power to nodes hosting such processing, sensing, or communication functions.

25 The processor node 14 includes a processing function and may include an RF receiver and transmitter 30 for communicating with portions of the sensor node 16 that are capable of communicating wireless methods. The processor node 14 may further include processing capabilities for communicating via a digital vehicle network interface 40, for example. The

embodiment of Figure 1 may include an RF-to digital inverter 32 and a digital-to-RF converter 34 facilitating communications between the vehicle network 40 and the sensor node 16 via the RF receiver/transmitter 30. The processor node 14 may be configured to manage and monitor the behavior of sensor network 10, including power generation and consumption, data 5 acquisition, and communications both within the sensor network 10 and with external devices such as vehicle network 40.

The sensor node 16, may have a wireless operating capability, though alternative embodiments are operable through wired operating capabilities. In both configurations, the sensor node 16 includes a sensor element 50 and a communication element 52. The sensor element 50 may include integrally formed signal conditioning circuitry or signal conditioning circuitry may be physically separated from the sensor element. 10

The sensor node 16 as shown in Figure 1 is configured for wireless operation, similar to the processor node 14 described above. However, embodiments are contemplated where the stretchable silicon medium is utilized as a communications interconnect between the sensor node 15 16 and the processor node 14, as shown by the stretchable silicon interconnect 20. Stretchable silicon interconnect 22 is utilized in the illustrated embodiment to provide the power to the processor node 14 from the power supply node 12, while the stretchable silicon interconnect 24 is utilized in the illustrated embodiment to provide the power to the sensor node 14 from the power supply node 12.

20 Figure 2 is an illustration of a sensor network 100 fabricated using stretchable silicon 105. In the illustrated embodiment, the network 100 includes a plurality of components that have been fabricated on the stretchable silicon 105. The components include, for example, energy harvesting and storage elements 110, communication devices 120, sensors 130, and network management processors 140. The communications devices 120 may include both 25 wireless and wired devices. As described herein, the plurality of components are integrated on a medium of stretchable silicon 105, which provides multiple conductive paths 160 (interconnects) formed therein which provide, for example, conduction of electrical power from the energy harvesting and storage elements 110 to the communication devices 120, sensors 130, and network management processors 140.

The conductive paths 160 also provide for at least some of the communications between the above listed components. As described further herein, and in one embodiment, the stretchable silicon 105 forms a portion of an autonomous network of wireless sensors. A high reliability results due to the redundancy built into the network 100 with stretchable silicon 5 interconnects 160. As such, the network 100 may utilize use alternative paths between the various network components to achieve reliable communications between the sensors 130 and the existing vehicle communication network. As the illustrated network 100 has its own power source, energy harvesting and storage elements 110, the addition of such a network does not tax vehicle power systems.

10 The stretchable silicon medium 105 is an excellent enabler because every node formed thereon can be converted into a component that provides a desired function. Examples include a processor function and miniature sensor nodes. In one embodiment, the nodes have a size of about 200 micrometers. In one embodiment, the stretchable silicon medium 105 is processed from a foundry-processed, monolithic silicon die, of a size between one centimeter and twenty 15 centimeters and stretched over a larger area. The process results in a plurality of robust conductors that run between the various nodes that are fabricated on the medium 105.

Network 100 resolves at least some of the prior problems that have been associated with weight and supportability of energy storage devices, complexity of interconnections among network nodes, manufacturability, mechanical connection of input/output signals, and scalability. 20 More specifically, a system incorporating network 100 enables networked sensor coverage of large areas with multiple applications. One such application involves monitoring structural health of a structure where a plurality of the above mentioned sensors provide data to a processing element which can be queried by an external system. Other applications include the monitoring of air flow over aerodynamic surfaces utilizing applicable sensors fabricated on 25 medium 105 and the monitoring of ice accretion and other hazardous conditions that may be encountered with the use of an aerospace structure.

Turning now to the individual components of network 100, energy harvesting and storage elements 110 provide power to the other elements of network 100. In one embodiment, a nano-piezoelectric generator effect is utilized within element 110 to convert mechanical stress into 30 electrical current or voltage for powering the other components of network 100, including any sensors that may be fabricated on the medium 105. In one specific embodiment, zinc oxide

(ZnO) nanowires are utilized in network 100. These ZnO nanowires are grown using chemical synthesis on a substrate with any curvature and materials nature. These ZnO nanowire generators produce power on the order of milliwatts in an area that is about one square millimeter.

5 A power output associated with such energy harvesting and storage elements 110 proportionally increases as the nanowire substrate area is expanded. Also, these devices are easily integrated with stretchable silicon based nano/micro electronics devices to develop robust Nano/Micro-Electro-Mechanical Systems (N/MEMS). In certain embodiments, the energy harvesting nodes of elements 110 incorporate capacitance-based or other energy storage components to meet the energy demands of the network 100.

10 In regard to the communication devices 120, at least one embodiment incorporates wireless transceiver nodes allowing data to be transmitted to and from the network 100. Such embodiments are referred to as single chip transceivers based on silicon systems. One embodiment incorporates the stretchable silicon in the fabrication of transceiver integrated 15 circuits including the development of RF and baseband components of wireless transceivers on a single die. Wireless transceiver nodes can be directly connected to external devices.

20 Silicon offers a high level of integration and a low cost which is desirable for large scale manufacture, and also has the potential of reducing the power consumption. Lower power consumption allows for cheaper packaging materials such as plastic which greatly reduces the cost of a chip. For integrated solutions using silicon, bipolar and CMOS are the most popular process technologies. Bipolar technologies offer high speed and are most commonly used in analog applications. CMOS has a lower limit frequency but offers a high level of integration which is attractive for digital applications.

25 The sensor nodes 130 form a network constructed with silicon based devices. In various embodiments, the sensor nodes 130 may include sensors for structural health monitoring, temperature sensors, pressure sensors, vibration sensors, ice accretion sensors, dynamic air flow separation sensors, and other sensor types. In one embodiment, the sensor nodes 130 include signal conditioning circuitry, providing an interface between the sensor nodes 130 and the communications devices 120 and/or an interface between the sensor nodes and network 30 management processors 140. Network management processors 140 may monitor the network for

active sensor nodes 130 and determine if they belong to the network. The power required by the communications device 120, sensor nodes 130 and the network management processors 140 is supplied, in various embodiments, by the energy harvesting and storage elements 110 described above.

5 Figure 3 is a flowchart 200 further illustrating a method for fabricating a sensor network such as those described herein incorporating stretchable silicon. The method illustrated in the flowchart 200 includes stretching 202 a silicon medium over a desired area, processing 204 the stretched silicon medium to generate a number of nodes thereon, and utilizing 206 conductors within the stretchable medium to redundantly interconnect the generated nodes to form the
10 network.

15 As further described herein, processing 204 the stretched silicon medium may include generating one or more of an energy harvesting and storage element, a communication device, a sensing device, and a processor, while utilizing 206 conductors within the stretchable medium may include routing power from energy harvesting and storage elements to the various communication devices, sensing devices, and processors.

20 Processing 204 the stretched silicon medium, in one embodiment, includes generating at least one communications device with a wireless communications capability. In another embodiment, processing 204 the stretched silicon medium includes generating at least one processor capable of communicating with an external network. As further described herein, the method described by flowchart 200 is useful for multiple applications, and therefore, processing 204 the stretched silicon medium may include, but is not limited to, generating sensors for structural health monitoring and management, generating ice accretion sensors, and generating sensors configured for sensing dynamic flow separation of the air surrounding the sensor.

25 Various embodiments described herein may be used for structural health monitoring and management, for example, of aircraft and other vehicles. In such applications, the stretchable silicon substrate is capable of being stretched out, for example, up to 100 times its original size. In the structural health application, such a substrate may be attached across a relevant portion of the structure. In the configuration, sensors are able to sense changes in the environment, provide data to network processors such as network management processors 140 which in turn utilize
30 communications devices 120 to communicate the sensor data to an external system. Examples of

applications outside of structural health monitoring include dynamic flow separation of the surrounding air, and the monitoring of ice accretion on structures.

The autonomous network of wireless sensors described herein accommodates the rigorous configuration control demands of aerospace applications and enhances sensor designs 5 and construction methods suitable for installation in hostile environments. A wide range of temperature sensors, pressure sensors and flow sensors for harsh and demanding environments can be utilized in aircraft and aero engines where unique applications are desired. Also, the described network has the capability of incorporating advanced data systems architectures that are necessary to communicate, store and process massive amounts of health management data 10 from large numbers of diverse sensors.

In one example, network 100 can be configured to perform as a portion of an Integrated Vehicle Health Management (IVHM) system that will provide real-time knowledge of structural, propulsion, thermal protection and other critical systems for optimal vehicle management and mission control. In such systems, on-board, real-time sensing systems are a critical component 15 of a vehicle health management system. To provide such capability, network 100 includes sensors that have an ability to withstand harsh aerospace operating environments, while also having minimal size, weight, and power requirements.

This written description uses examples to disclose various embodiments, including the best mode, and also to enable any person skilled in the art to practice those embodiments, 20 including making and using any devices or systems and performing any incorporated methods. The patentable scope is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of 25 the claims.

WHAT IS CLAIMED IS:

1. A sensor network comprising:

a stretchable silicon substrate; and

5 a plurality of nodes fabricated on said stretchable silicon substrate, said nodes comprising at least one of an energy harvesting and storage element, a communication device, a sensing device, and a processor, said nodes interconnected via interconnecting conductors formed in said substrate.

2. A sensor network according to Claim 1 wherein said energy harvesting and storage elements are configured to provide power to said communication devices, said sensing devices, and said processor.

10 3. A sensor network according to Claim 1 wherein said energy harvesting and storage elements comprise piezo-electric devices configured to convert mechanical stress into electrical energy.

4. A sensor network according to Claim 1 wherein said stretchable silicon substrate comprises a plurality of conductors for interconnecting said nodes.

15 5. A sensor network according to Claim 1 wherein a portion of said nodes comprise a wireless communication capability.

6. A sensor network according to Claim 5 wherein the wireless communication capability comprises an RF transceiver.

20 7. A sensor network according to Claim 1 wherein at least one of said nodes comprises processing capabilities for communicating with a system external to said sensor network.

8. A sensor network according to Claim 7 wherein the communications with the external system are via a vehicle network interface.

25 9. A sensor network according to Claim 1 wherein said sensing devices comprise at least one of a sensor for structural health monitoring and management, an ice

accretion sensor, and a sensor configured for sensing dynamic flow separation of the air surrounding said sensor.

10. A sensor network according to Claim 1 wherein said stretchable silicon substrate comprises a monolithic silicon die stretched over an area.

5 11. A sensor network according to Claim 1 wherein said energy harvesting and storage elements comprise zinc oxide nanowires grown on said stretchable silicon substrate.

12. A sensor network according to Claim 1 wherein said sensing devices comprises at least one of temperature sensors, pressure sensors, and vibration sensors.

13. A method for fabricating a network comprising:

10 stretching a silicon medium over a desired area;

processing the stretched silicon medium to generate a number of nodes thereon; and

utilizing conductors within the stretchable medium to redundantly interconnect the generated nodes to form the network.

15 14. A method according to Claim 13 wherein processing the stretched silicon medium comprises generating at least one each of an energy harvesting and storage element, a communication device, a sensing device, and a processor.

20 15. A method according to Claim 14 wherein utilizing conductors within the stretchable medium comprises routing power from the energy harvesting and storage elements to the communication devices, the sensing devices, and the processors.

16. A method according to Claim 14 wherein processing the stretched silicon medium comprises generating at least one communications device with a wireless communications capability.

25 17. A method according to Claim 14 wherein processing the stretched silicon medium comprises generating at least one processor capable of communicating with an external network.

18. A method according to Claim 13 wherein processing the stretched silicon medium comprises generating at least one of a sensor for structural health monitoring and management, an ice accretion sensor, and a sensor configured for sensing dynamic flow separation of the air surrounding the sensor.

5 19. A network for monitoring a structure, said network comprising:

a stretchable silicon substrate;

a plurality of sensors fabricated on said stretchable silicon substrate;

at least one communication device fabricated on said stretchable silicon substrate;

and

10 at least one energy harvesting and storage element fabricated on said stretchable silicon substrate, said stretchable silicon substrate comprising a plurality of conductive paths therein that interconnect said plurality of sensors, said at least one communication device, and said at least one energy harvesting and storage element, said network configured for attachment across a structure dispersing said sensors, data from said sensors communicated to an external 15 device via said at least one communication device.

20. A network for monitoring a structure according to Claim 19 further comprising at least one processor interconnected with said at least one energy harvesting and storage element, said at least one communication device, and said plurality of sensors, said at least one processor operable to communicate with a system external to said network.

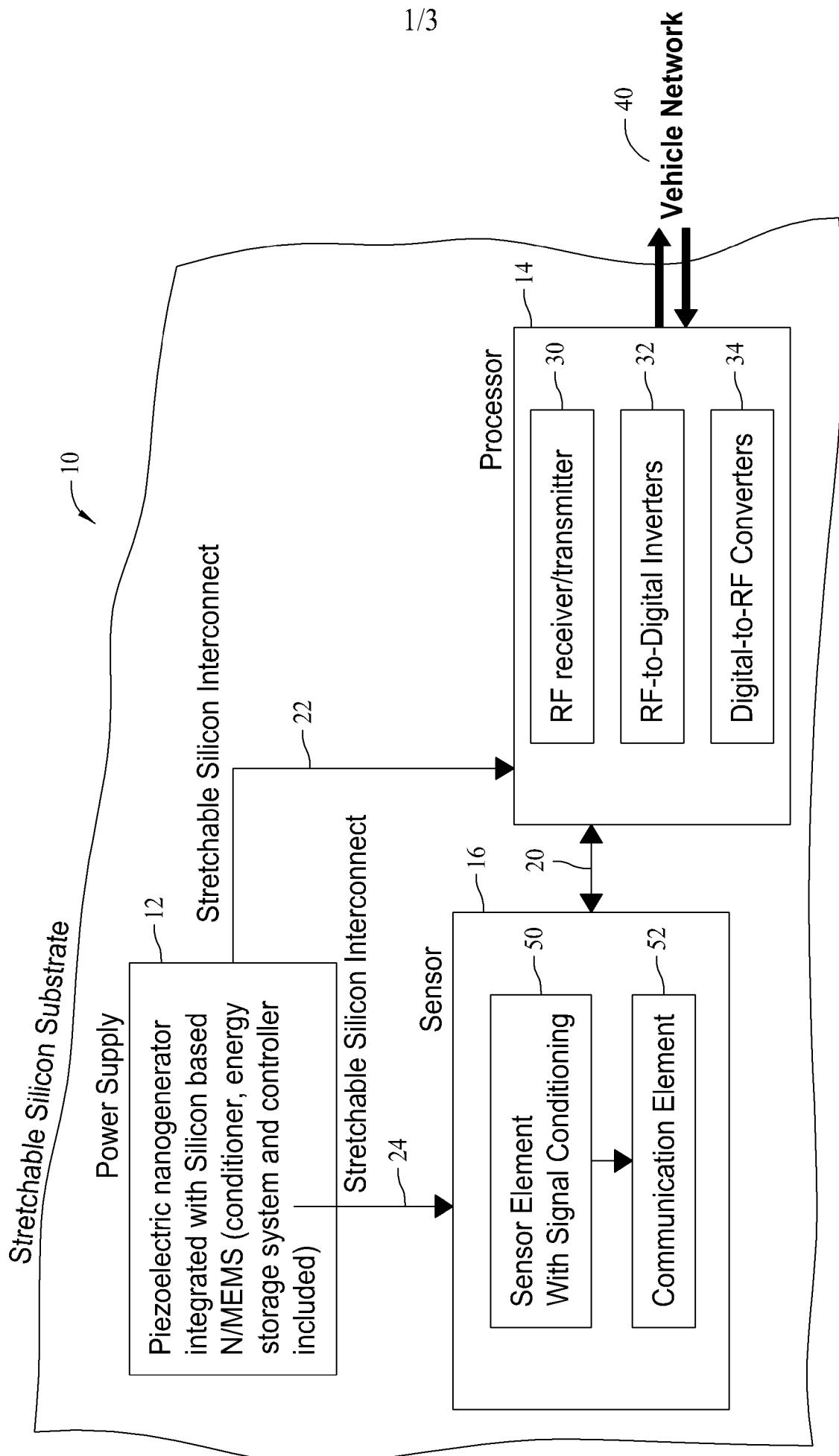


FIG. 1

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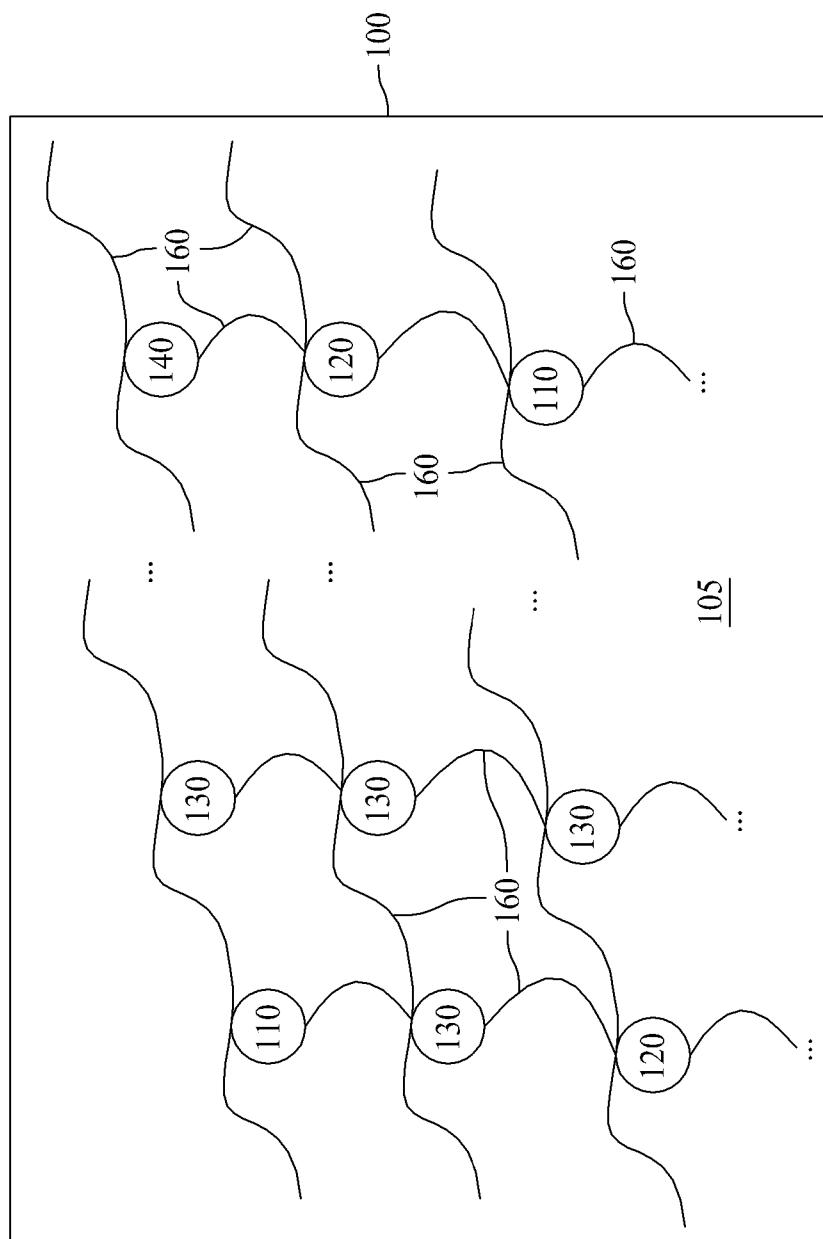


FIG. 2

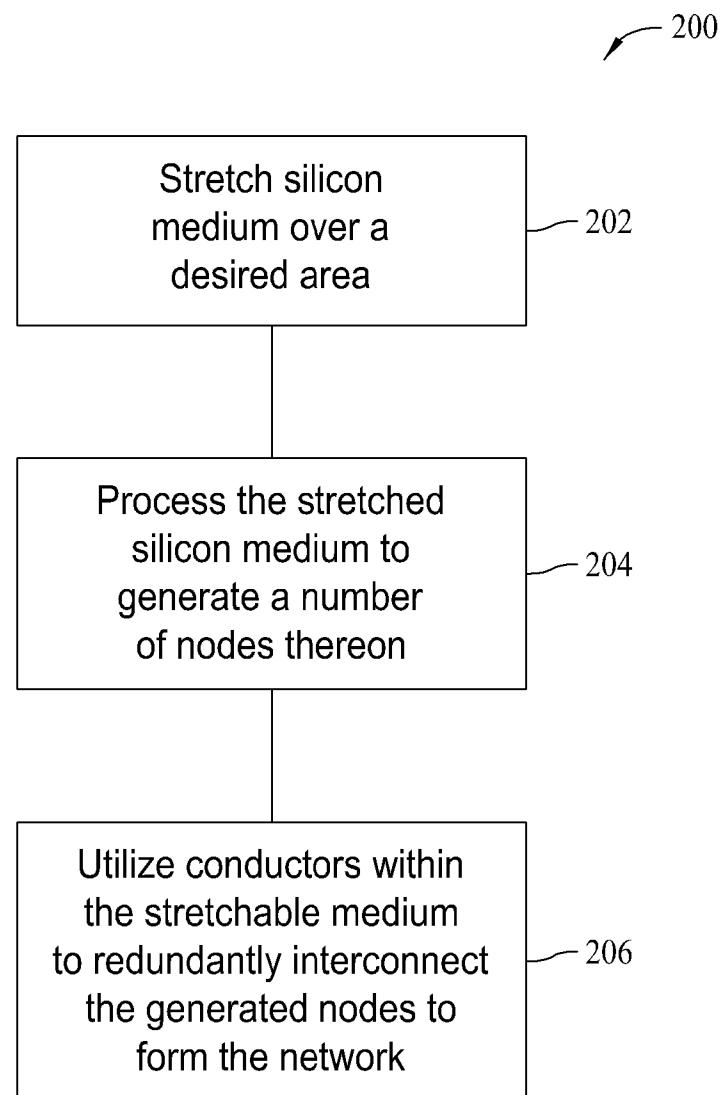


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2010/020301

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01M5/00

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)
G01M

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 practical, search terms used)

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/064125 A1 (PEUMANS PETER [US] ET AL) 13 March 2008 (2008-03-13) paragraph [0019] - paragraph [0059]; figures 1-4 ----- HUANG K ET AL: "Stretchable silicon sensor networks for structural health monitoring" PROCEEDINGS OF THE SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING USA LNKD- DOI:10.1117/12.660083, vol. 6174, 16 March 2006 (2006-03-16), pages 617412-1-617412-10, XP002576705 ISSN: 0277-786X the whole document ----- -/-	1-20
X		1-20

Further documents are listed in the continuation of Box C.

See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No PCT/US2010/020301

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>SOSIN S ET AL: "Mesh interconnects for silicone embedded stretchable silicon electronics" 10TH ELECTRONICS PACKAGING TECHNOLOGY CONFERENCE (EPTC 2008) IEEE PISCATAWAY, NJ, USA LNKD- DOI:10.1109/EPTC.2008.4763439, 2008, pages 230-235, XP002576706 ISBN: 978-1-4244-2117-6 the whole document</p> <p>-----</p> <p>ZOUMPOULIDIS T ET AL: "Process technology of high-aspect-ratio silicon beams for stretchable silicon electronics" 10TH ELECTRONICS PACKAGING TECHNOLOGY CONFERENCE (EPTC 2008) IEEE PISCATAWAY, NJ, USA LNKD- DOI:10.1109/EPTC.2008.4763461, 2008, pages 361-366, XP002576707 ISBN: 978-1-4244-2117-6 the whole document</p> <p>-----</p>	1-20
X	<p>-----</p>	1-20
A	<p>WO 2008/156606 A2 (PELKUS ADRIAN [US]) 24 December 2008 (2008-12-24) paragraph [0016] – paragraph [0024]; figures 1-3</p> <p>-----</p>	1-20
A	<p>US 2007/125176 A1 (LIU YUE [US]) 7 June 2007 (2007-06-07) paragraph [0019] – paragraph [0032]; figures 1-4</p> <p>-----</p>	1-20
A	<p>CHIBA S ET AL: "Innovative power generators for energy harvesting using electroactive polymer artificial muscles" PROCEEDINGS OF THE SPIE – THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING SPIE – THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING USA LNKD- DOI:10.1117/12.778345, vol. 6927, 27 March 2008 (2008-03-27), pages 692715-1-692715-9, XP002576708 ISSN: 0277-786X the whole document</p> <p>-----</p>	1-20
A	<p>US 2007/114422 A1 (BERTCAN ERTUGRUL [US] ET AL) 24 May 2007 (2007-05-24) paragraph [0029] – paragraph [0063]; figures 1-11</p> <p>-----</p>	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2010/020301

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008064125	A1 13-03-2008	NONE	
WO 2008156606	A2 24-12-2008	NONE	
US 2007125176	A1 07-06-2007	NONE	
US 2007114422	A1 24-05-2007	NONE	