US 20250258052A1

(19) **United States**
(12) **Patent Application Publication**
Bibl et al.

(10) **Pub. No.: US 2025/0258052 A1**
(43) **Pub. Date: Aug. 14, 2025**

(54) **DEFORMABLE SENSOR ARRAYS**

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(21) Appl. No.: **19/171,044**

(22) Filed: **Apr. 4, 2025**

Related U.S. Application Data

(63) Continuation-in-part of application No. 18/775,951, filed on Jul. 17, 2024.

(60) Provisional application No. 63/553,095, filed on Feb. 13, 2024.

Publication Classification

(51) **Int. Cl.**

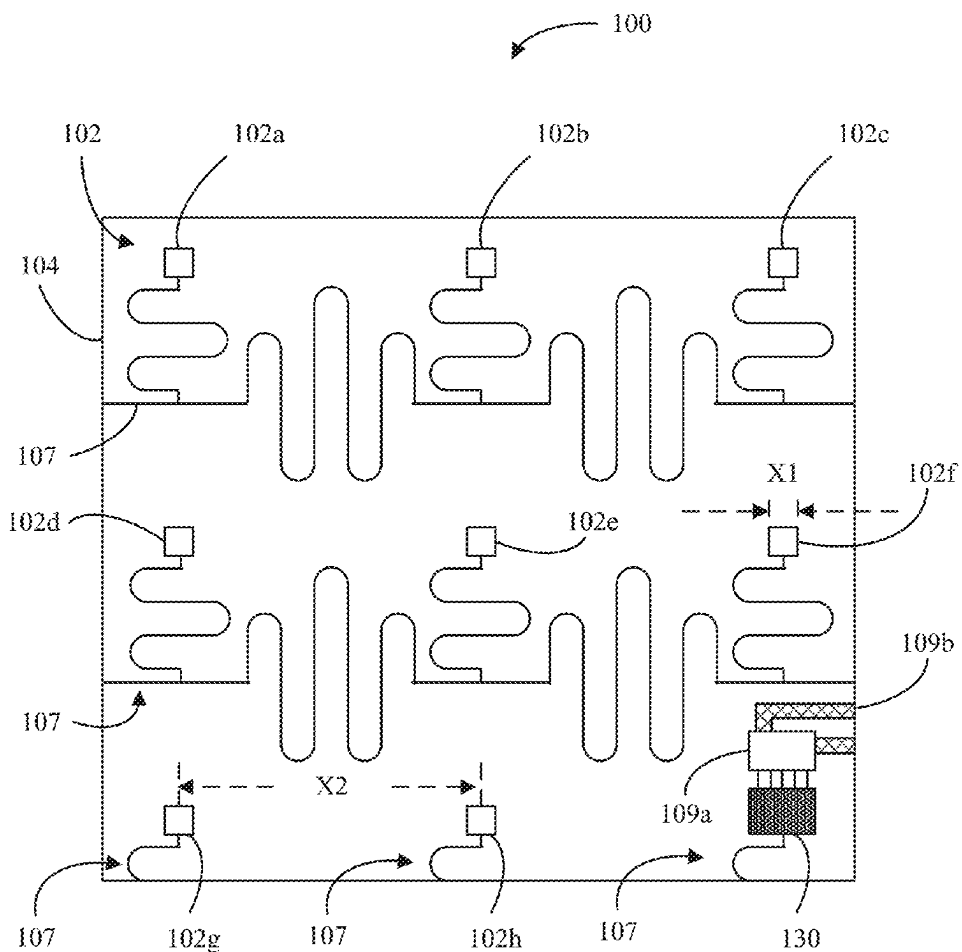
G01L 5/102	(2020.01)
G06F 3/01	(2006.01)
H01L 23/00	(2006.01)
H01L 23/498	(2006.01)
H01L 23/538	(2006.01)
H01L 25/065	(2023.01)

(52) **U.S. Cl.**

CPC ***G01L 5/102*** (2013.01); ***H01L 23/49827*** (2013.01); ***H01L 23/5386*** (2013.01); ***H01L 23/5387*** (2013.01); ***H01L 25/0657*** (2013.01); *G06F 3/014* (2013.01); *H01L 24/16* (2013.01); *H01L 2224/16146* (2013.01); *H01L 2224/16227* (2013.01); *H01L 2224/16238* (2013.01); *H01L 2924/1424* (2013.01); *H01L 2924/14253* (2013.01)

(57) **ABSTRACT**

A sensor array may include a plurality of sensors coupled with a flexible substrate. Each sensor may include a sensor die that generates an analog signal based on sensing, and a converter die that performs analog-to-digital conversion (ADC) of the analog signal to generate a digital output. The flexible substrate may include electrical interconnect to transmit digital outputs from sensors of the plurality of sensors. The flexible substrate may include strain relief cutouts between the sensors to enable deformation of the sensor array. Other aspects are also described and claimed.



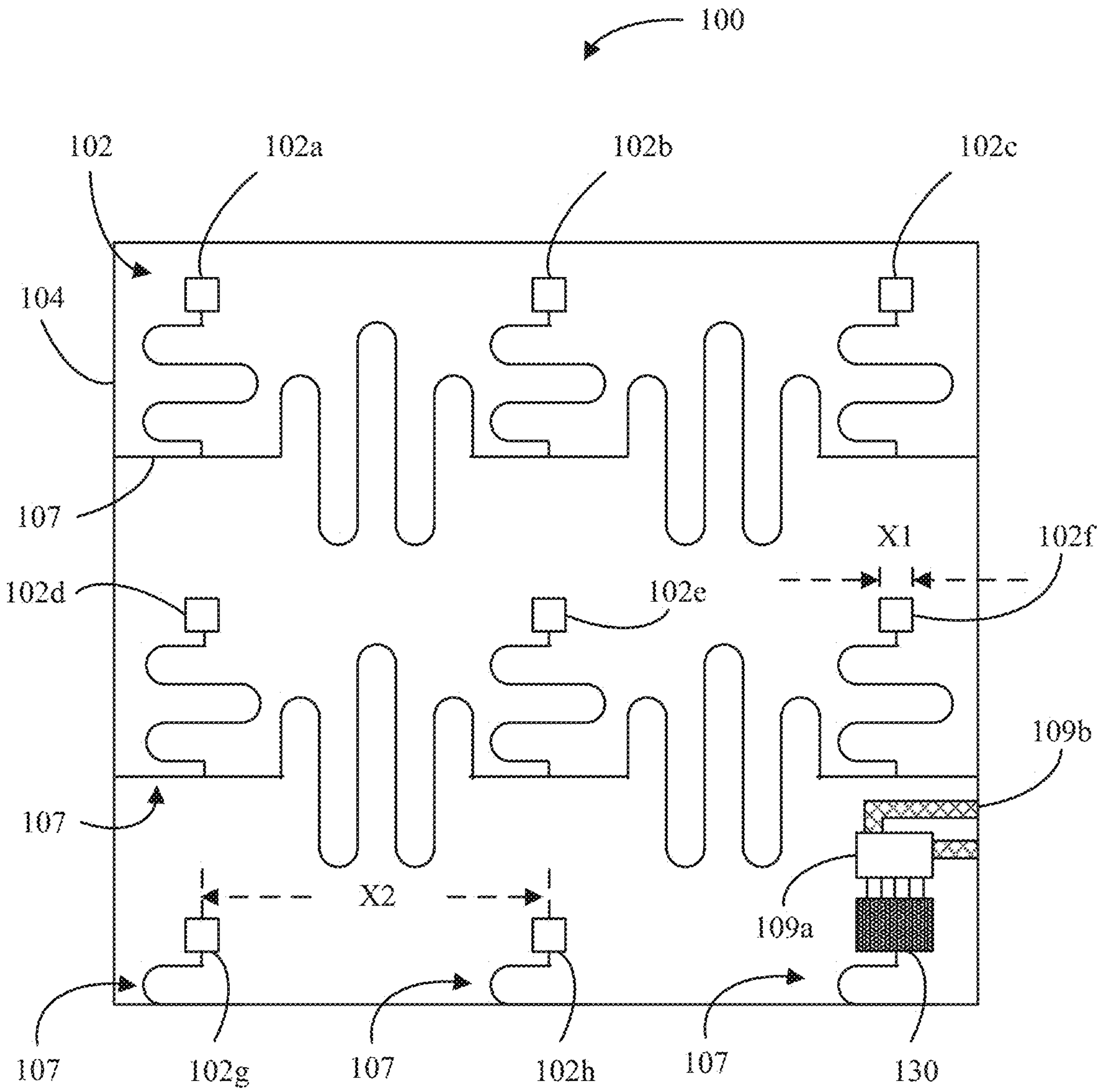
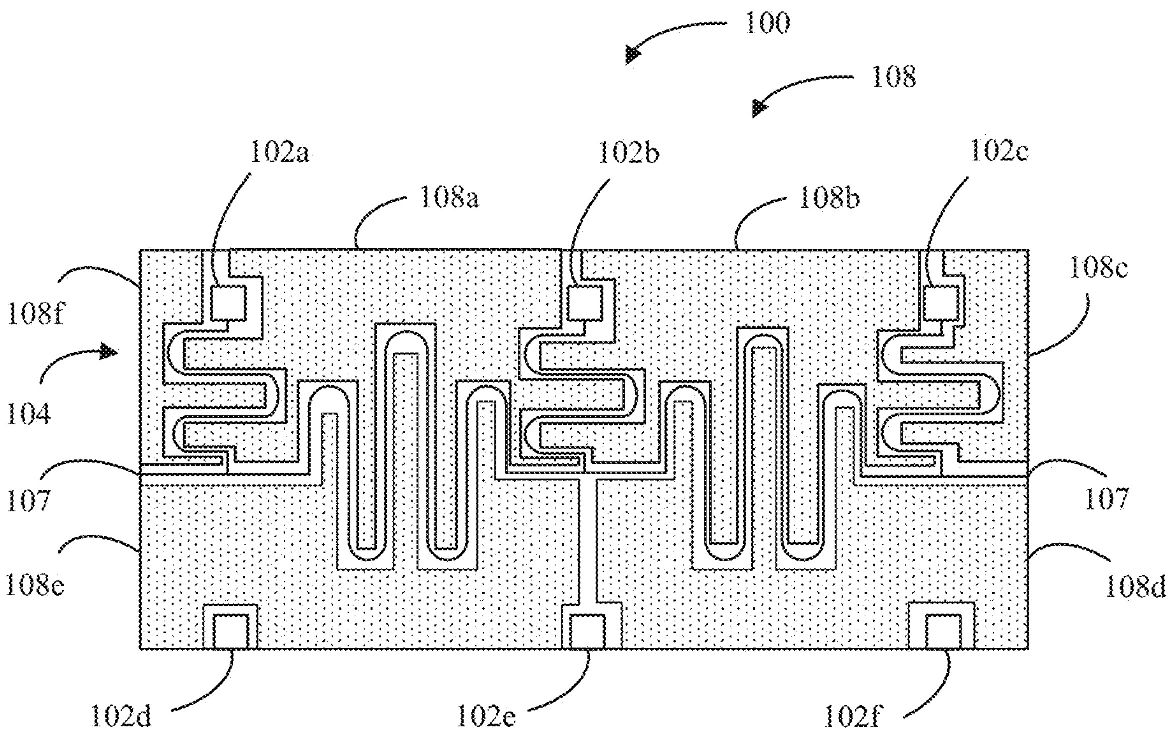

100
102
102a
102b
102c
104
107
X1
102f
102d
102e
109b
107
X2
109a
107
102g
107
102h
107
130

FIG. 1A



100
108
102a
108a
102b
108b
102c
108c
108f
104
107
107
108e
108d
102d
102e
102f

FIG. 1B

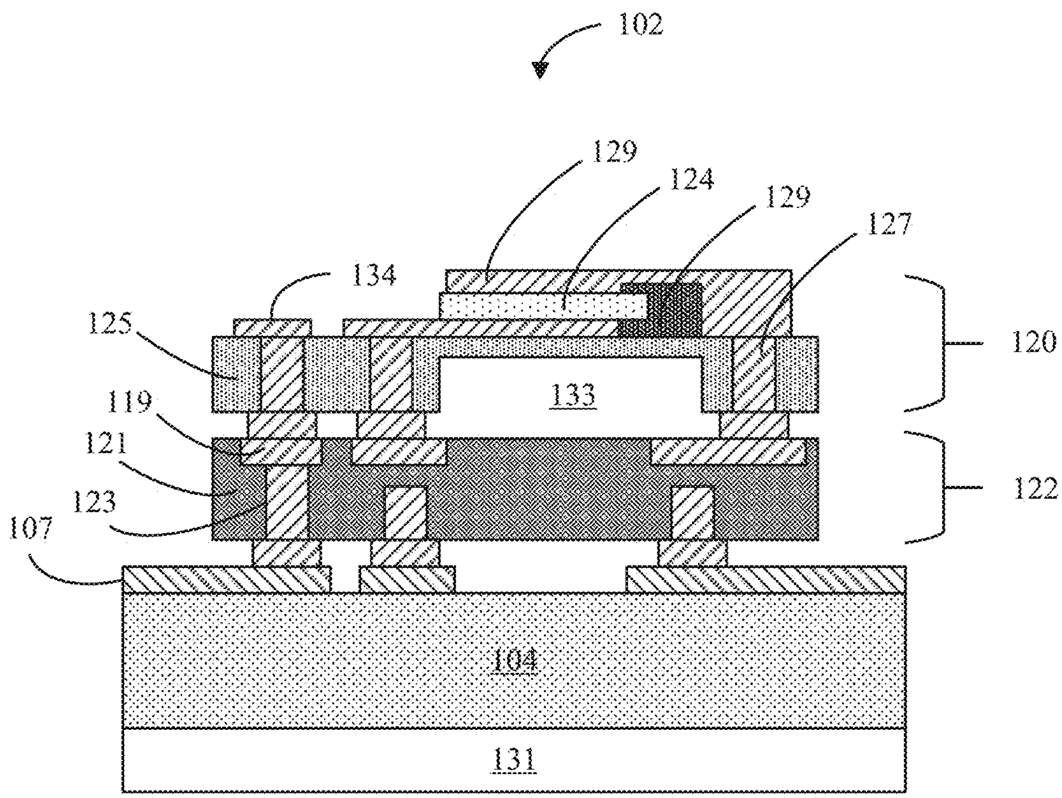


FIG. 2

CROSS-SECTION A_A

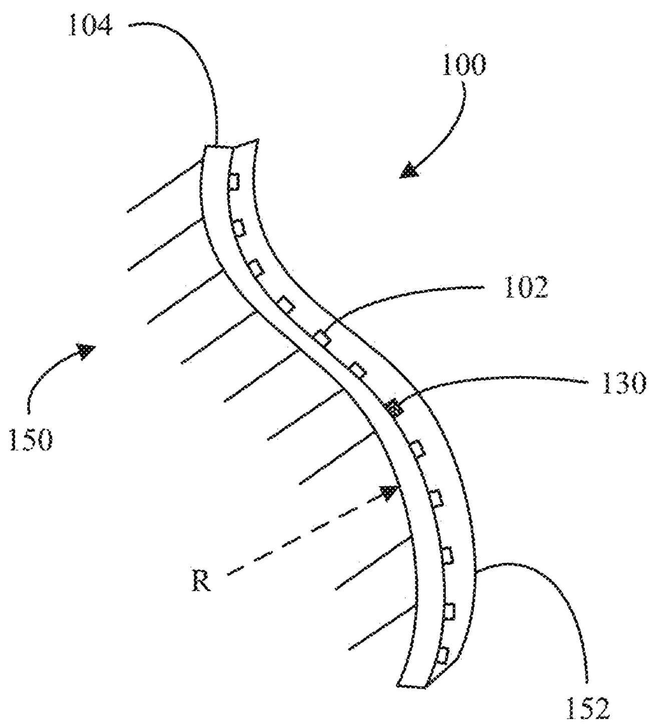


FIG. 3

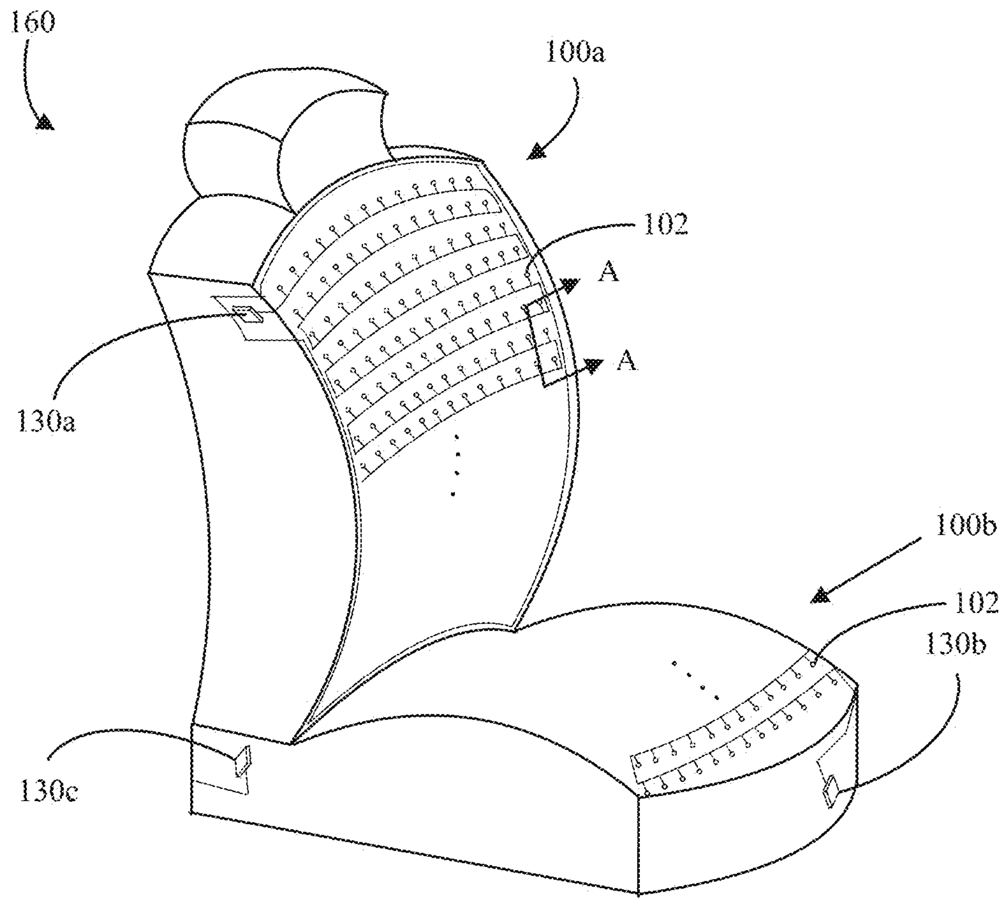


FIG. 4

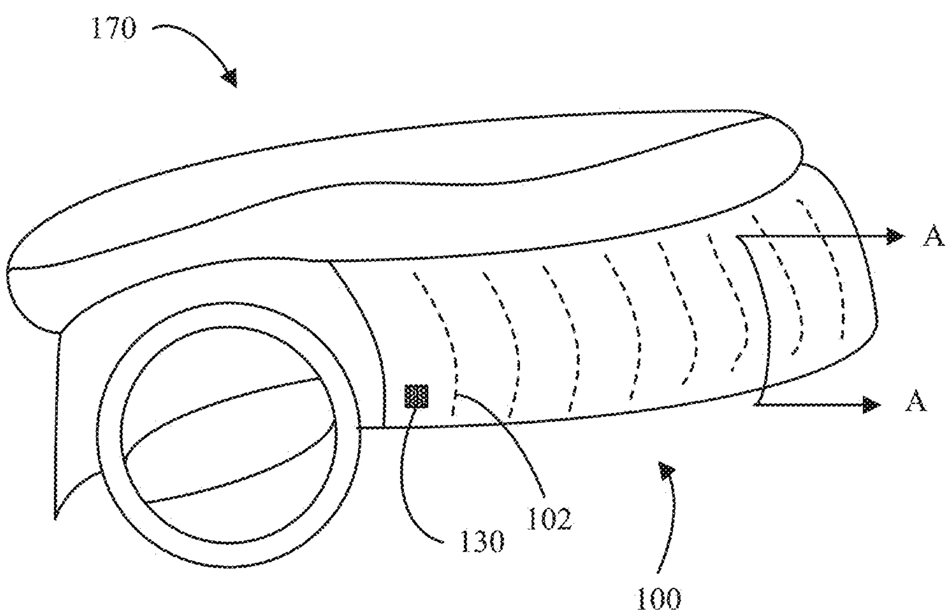


FIG. 5

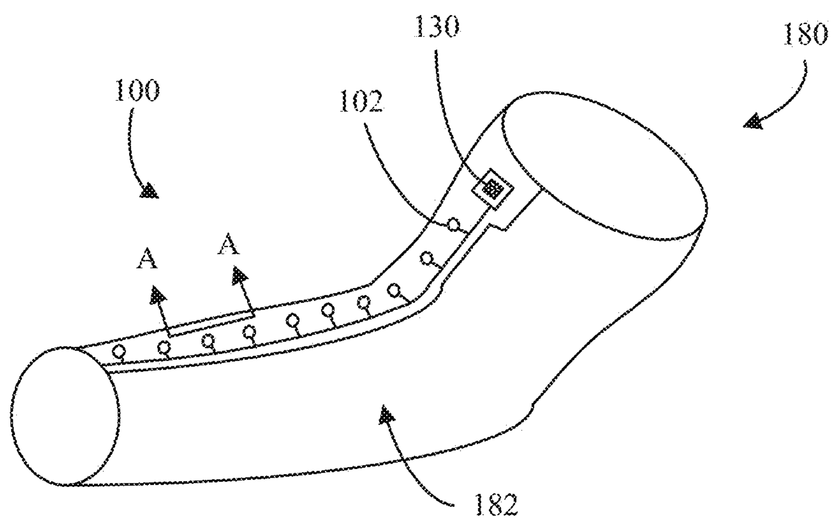


FIG. 6A

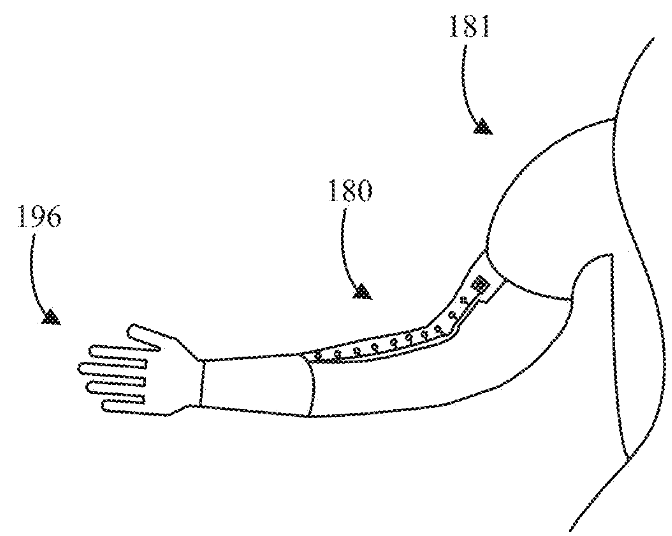


FIG. 6B

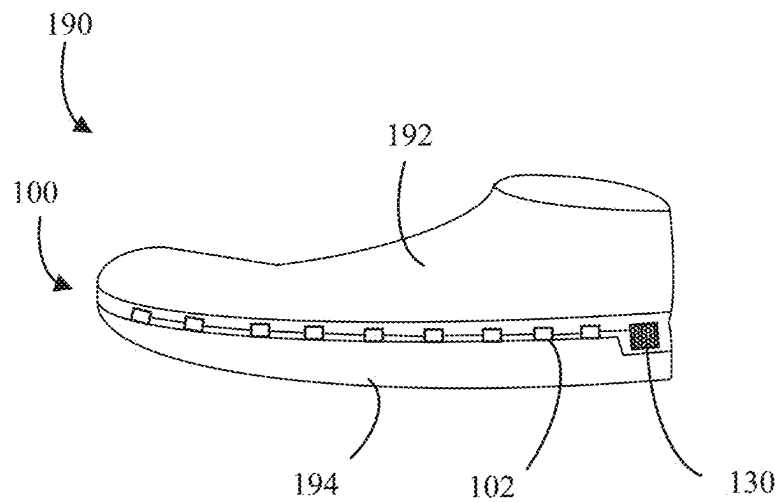


FIG. 7A

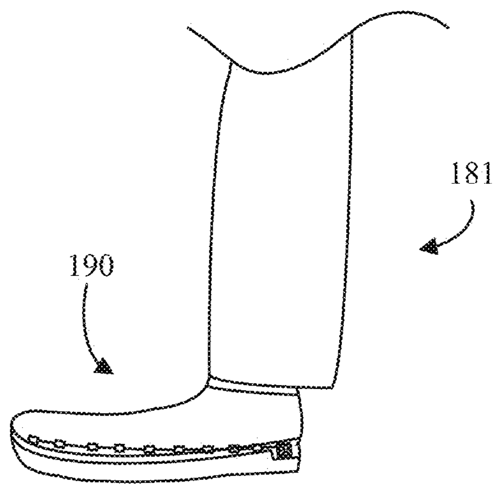


FIG. 7B

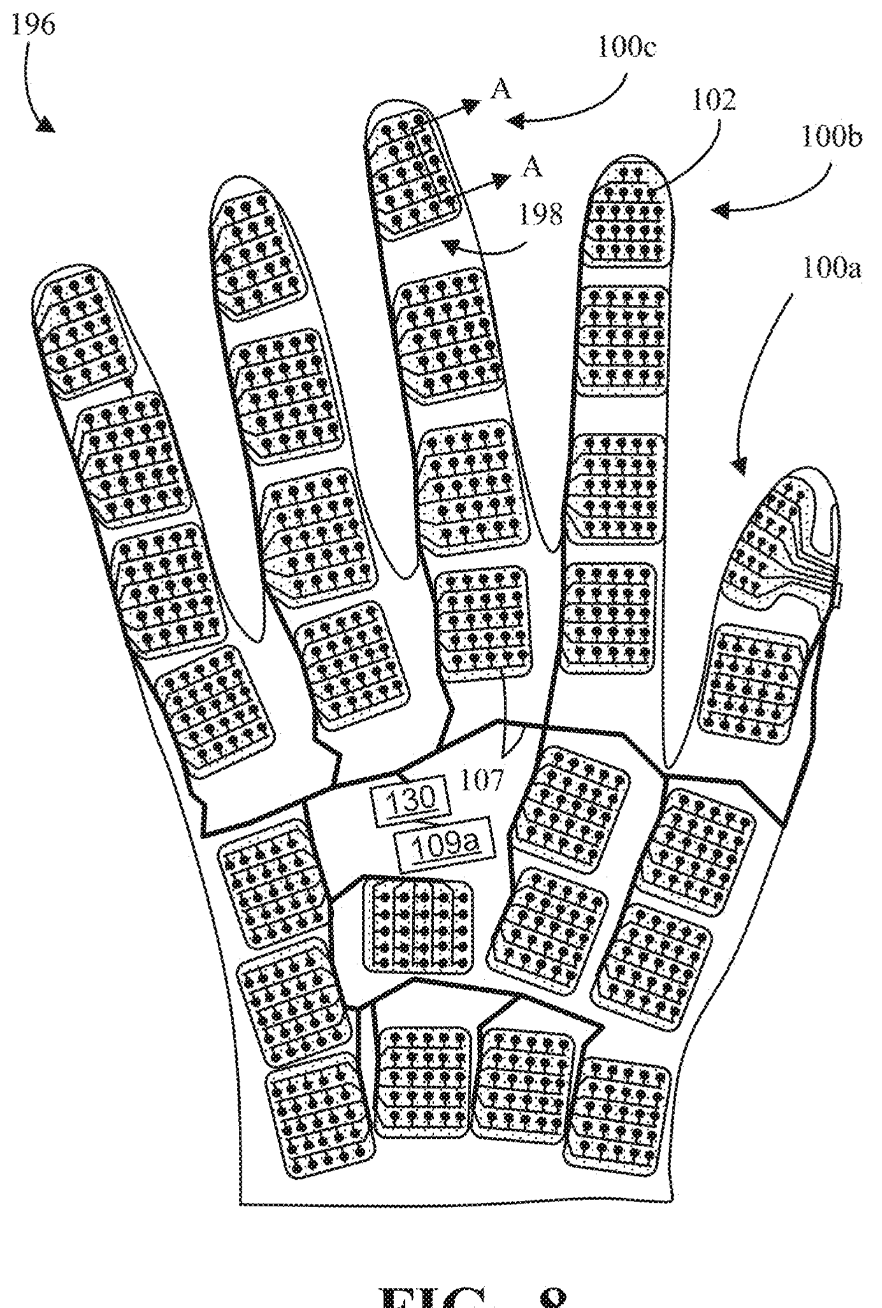


FIG. 8

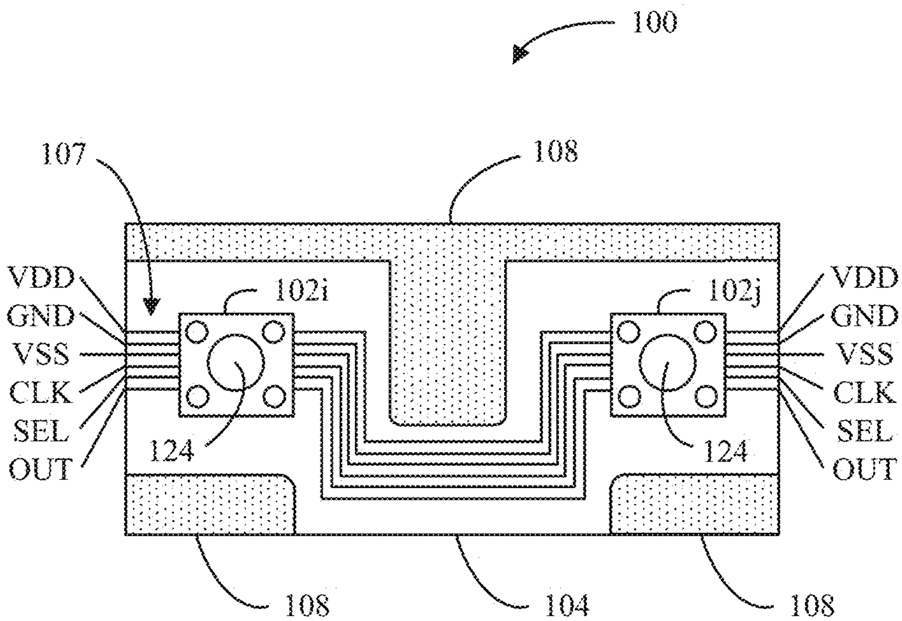

100
107
108
VDD
GND
VSS
CLK
SEL
OUT
102i
102j
124
124
VDD
GND
VSS
CLK
SEL
OUT
108
104
108

FIG. 9

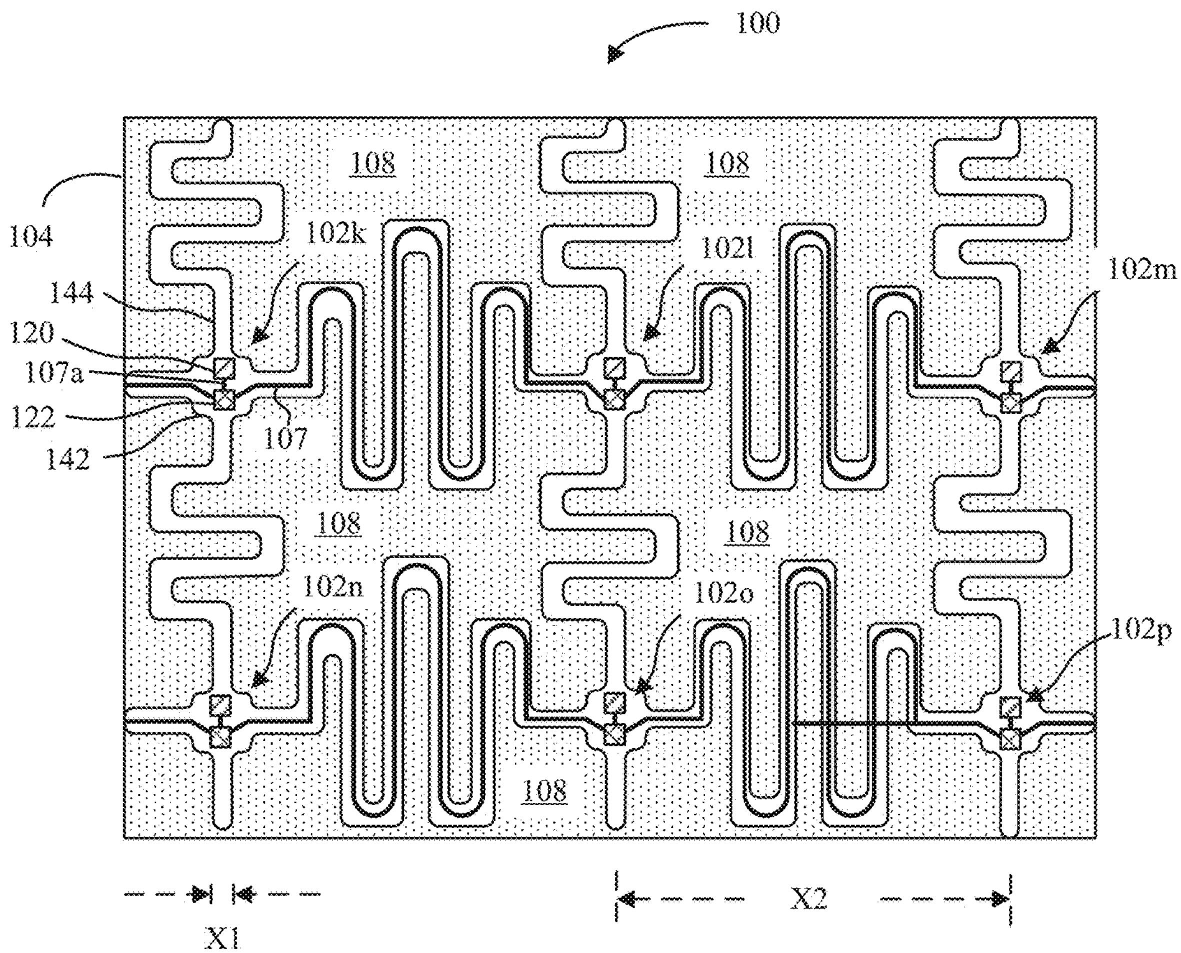

100
104
108
108
102k
102l
102m
144
120
107a
122
142
107
108
108
102n
102o
102p
108
X1
X2

FIG. 10A

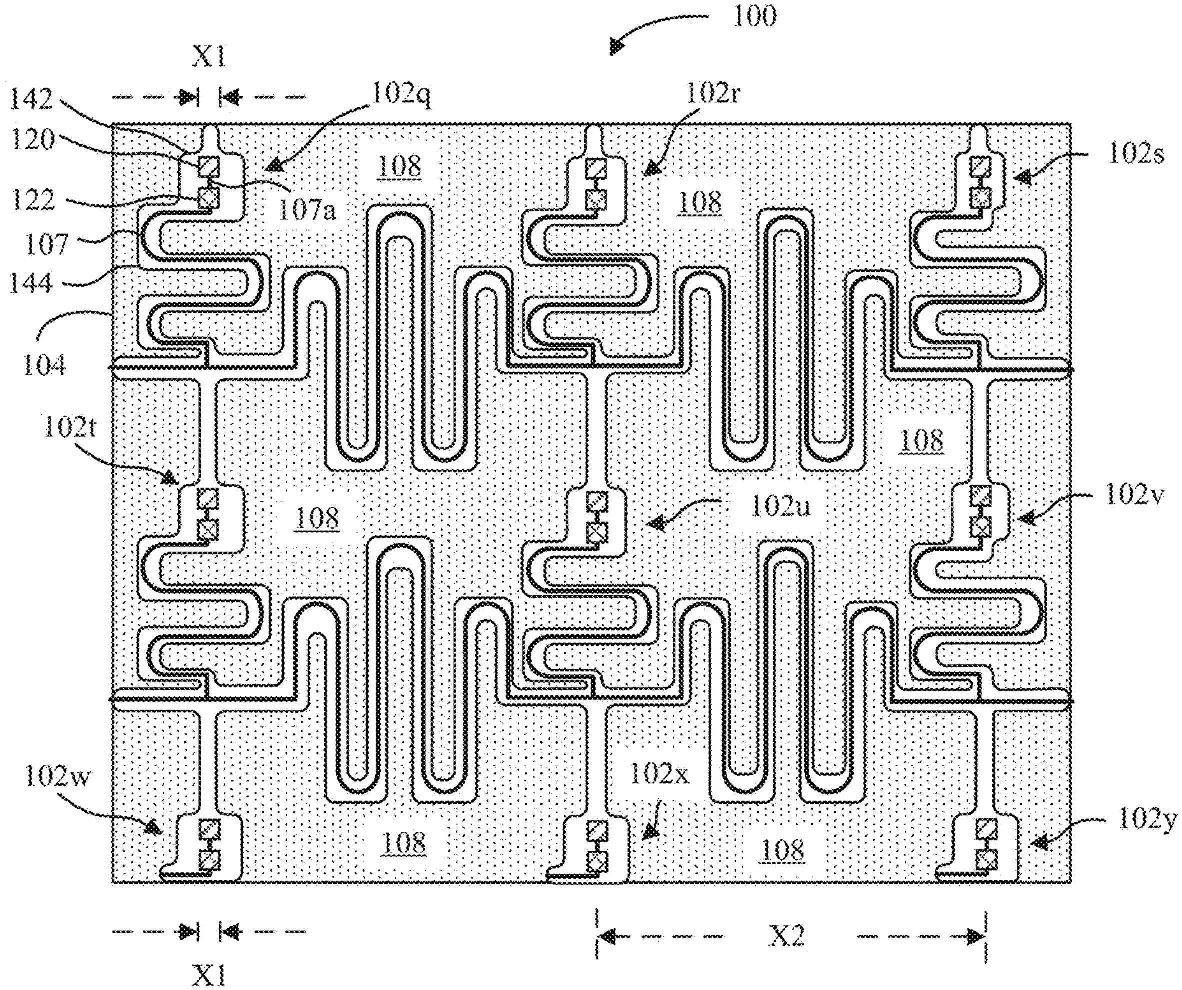

100
X1
142
120
122
107
144
104
102q
107a
108
102r
108
102s
108
102t
108
102u
102v
102w
108
102x
108
102y
X1
X2

FIG. 10B

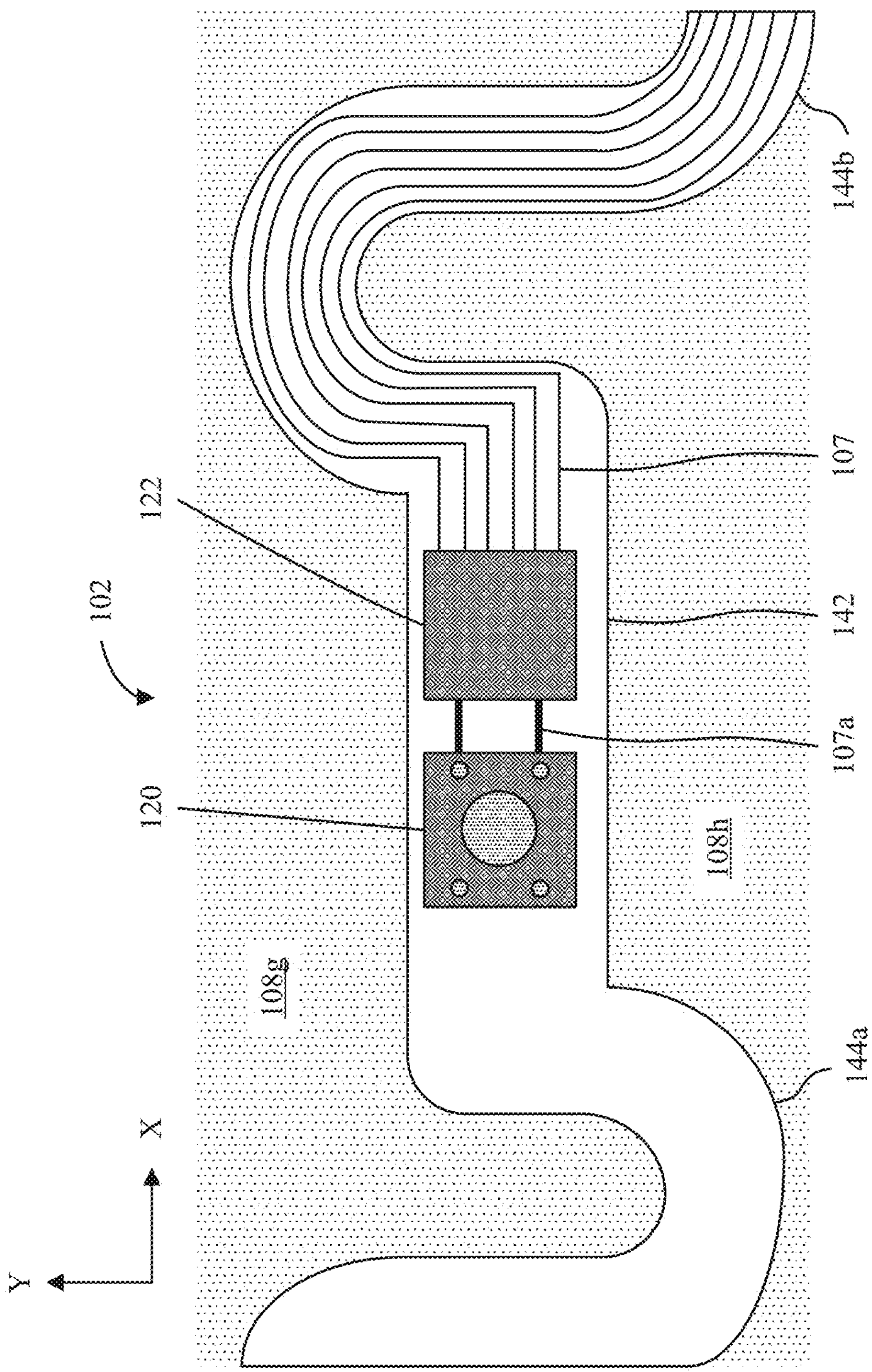
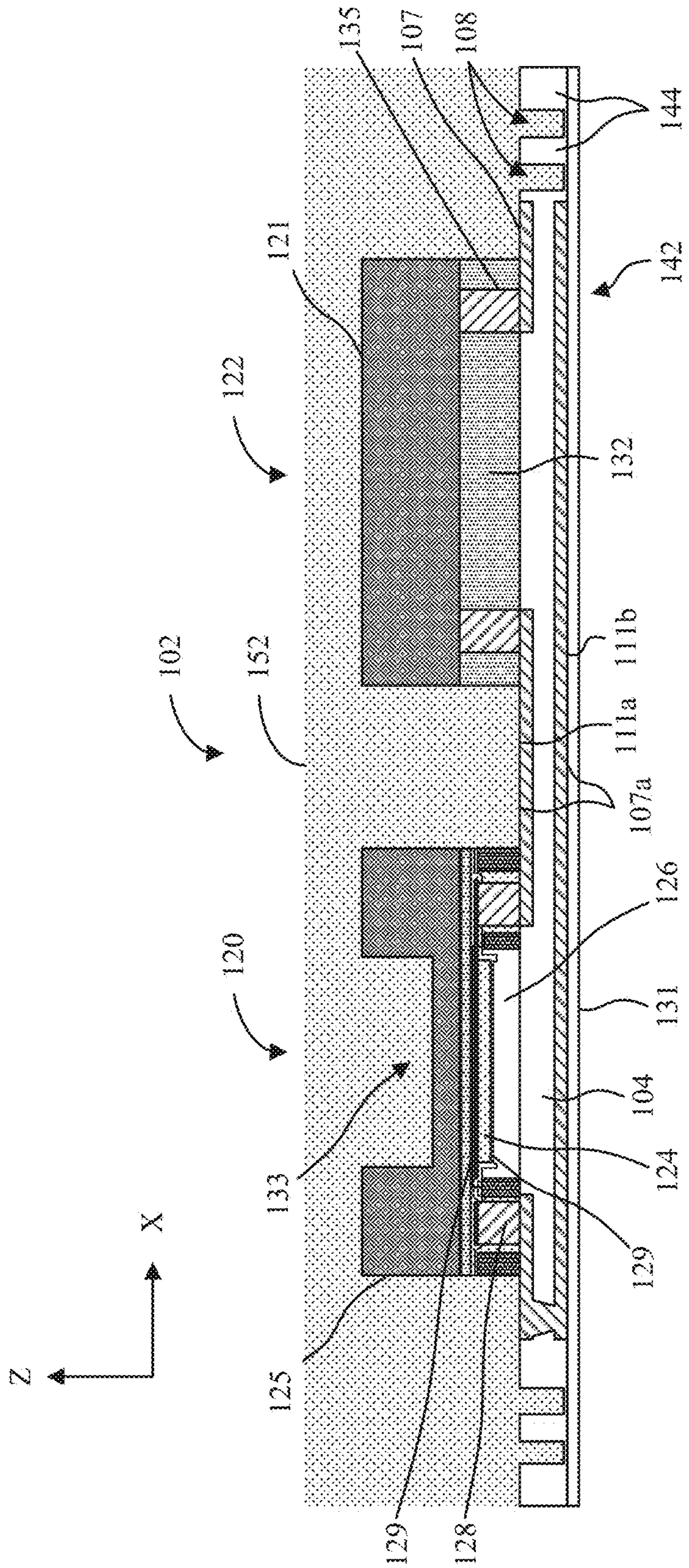


FIG. 11



135
107
108
144
121
122
142
132
102
152
111b
111a
107a
126
120
131
104
133
124
129
X
Z
125
129
128

FIG. 12

DEFORMABLE SENSOR ARRAYS

RELATED APPLICATIONS

[0001] This patent application is a continuation in part of co-pending U.S. patent application Ser. No. 18/775,951, filed Jul. 17, 2024, which claims the benefit of priority of U.S. Provisional Application No. 63/553,095, filed Feb. 13, 2024, both of which are incorporated herein by reference in their entirety.

BACKGROUND

Field

[0002] This disclosure relates generally to sensor arrays and, more specifically, to deformable sensor arrays. Other aspects are also described.

Background Information

[0003] A sensor array may refer to a group of sensors used for collecting information about an environment. Sensors of a sensor array may be arranged in a certain geometric configuration or pattern. Sensor arrays may enable collecting information over a greater area than a single sensor, and in two or three dimensions of the environment.

[0004] In operation, a sensor of a sensor array can generate an output signal indicating detection of a physical phenomenon. For example, a piezoelectric sensor can utilize the piezoelectric effect and/or the pyroelectric effect to detect changes in pressure, acceleration, temperature, strain, or force by converting such detections to electrical charge. In another example, a capacitive sensor can utilize capacitive sensing to detect an object in proximity that may be conductive or may have a dielectric constant that is different from air.

SUMMARY

[0005] Implementations of this disclosure include a sensing system comprising a deformable sensor array having a plurality of sensors and a flexible substrate. Each sensor of the plurality of sensors may include a sensor die to generate an analog signal and a converter die to perform analog-to-digital conversion (ADC) of the analog signal to generate a digital output. The flexible substrate may be coupled with the deformable sensor array on an upper surface and with an article on a lower surface. For example, the article may be an object (which could also have tight curves and/or a complex shape), such as a glove, sleeve, shoe, seat, dashboard, etc. The flexible substrate may include electrical interconnect coupling sensors of the plurality of sensors, and strain relief cutouts between sensors of the plurality of sensors and between the electrical interconnect. The flexible substrate and the strain relief cutouts may enable deformation of the plurality of sensors with the article.

[0006] Some implementations may include a large area (e.g., one square foot or more), multimodal, distributed, deformable sensor array that may be affixed to a complex three-dimensional surface via a flexible substrate, for collecting information about an environment. The sensors may be spread over a large area, such as one square foot or more. The sensor array may be comprised of microfabricated sensor dies bonded to or co-fabricated with local analog-to-digital converter dies to enable digital data to be collected from data bus lines. The digital data can traverse greater distances (e.g., hundreds to thousands of millimeters) without signal degradation, as opposed to analog data which may be attenuated or noisy over such distances. The sensor array may include micro-fabricated sensors (e.g., micro sensors, or sensing pixels) that may have area dimensions in a range, for example, of 100 to 1000 micrometers (μm), and in some cases, 100 μm to 300 μm. This may facilitate large open areas for strain relief cutouts between sensors. The sensors may be spread over the large area at a pitch, for example, >1 mm, and in some cases, >5 mm, or >10 mm, in both X and Y directions (e.g., in a grid pattern). This may enable flexible trace designs of electrical interconnect, coupled with the sensors and a controller, to follow a meandering pattern, such as a serpentine, zigzag, or other shape, to accommodate large deformations of the substrate. Aspects described herein may include local digital conversion of analog sensor signals, and/or large open areas surrounding the sensors, which enable uniaxial or biaxial stretchability, bendability, and foldability of the sensor array (and flexible substrate) affixed to an article. Other aspects are also described and claimed.

[0007] The above summary does not include an exhaustive list of all aspects of the present disclosure. It is contemplated that the disclosure includes all systems and methods that can be practiced from all suitable combinations of the various aspects summarized above, as well as those disclosed in the Detailed Description below and particularly pointed out in the Claims section. Such combinations may have particular advantages not specifically recited in the above summary.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Several aspects of the disclosure herein are illustrated by way of example and not by way of limitation in the figures of the accompanying drawings in which like references indicate similar elements. It should be noted that references to "an" or "one" aspect in this disclosure are not necessarily to the same aspect, and they mean at least one. Also, in the interest of conciseness and reducing the total number of figures, a given figure may be used to illustrate the features of more than one aspect of the disclosure, and not all elements in the figure may be required for a given aspect.

[0009] FIG. **1**A is an example of a deformable sensor array.

[0010] FIG. **1**B is an example of strain relief cutouts in a deformable sensor array.

[0011] FIG. **2** is a cross-section of an example of a sensor of a deformable sensor array.

[0012] FIG. **3** is a cross-section of an example of a deformable sensor array affixed to an article.

[0013] FIG. **4** is an example of a deformable sensor array integrated with a seat.

[0014] FIG. **5** is an example of a deformable sensor array integrated with a dashboard.

[0015] FIG. **6**A is an example of a deformable sensor array integrated with a sleeve.

[0016] FIG. **6**B is an example of a user wearing a deformable sensor array as a sleeve.

[0017] FIG. **7**A is an example of a deformable sensor array integrated with a shoe.

[0018] FIG. **7**B is an example of a user wearing a deformable sensor array as a shoe.

[0019] FIG. **8** is an example of a deformable sensor array integrated with a sensing glove.

[0020] FIG. 9 is an example of a close-up top view of a deformable sensor array.

[0021] FIG. 10A is an example of a deformable sensor array connected in a daisy chain.

[0022] FIG. 10B is a second example of a deformable sensor array with specified inputs/outputs.

[0023] FIG. 11 is an example of a close-up top view of a deformable sensor array.

[0024] FIG. 12 is a cross-section of an example of a sensor of a deformable sensor array.

DETAILED DESCRIPTION

[0025] Large area sensor arrays may be limited by the large, rigid sensors of which they are comprised. These sensors may limit the minimum bending radius of curvature and elongation of the substrate. Large area sensor arrays may also be limited by a sensor fill factor (or sensor density) which limits the overall area available for routing electrical interconnects to and from each of the sensors. They may also be limited by the long wires and connections over which small analog signals, produced by the sensors, may be subject to noise, interference, attenuation, and other signal integrity issues. As a result, applications of sensor arrays are typically limited to environments that do not involve tight curves, complex shapes, and/or high signal-to-noise ratio (SNR).

[0026] Implementations of this disclosure address problems such as these by utilizing large area, stretchable, bendable, foldable sensor arrays coupled with flexible substrates (e.g., flexible circuits or backplanes). A microfabricated sensor die (e.g., having a piezoelectric, capacitive, piezoresistive, or temperature sensing area) may be co-located with and connected to an amplifier and/or an ADC of a converter die at each sensor. This may enable digital outputs to be transmitted over greater distances with greater noise-immunity as compared to analog outputs. In this way, digitized sensor signals can be routed over greater distances (e.g., hundreds to thousands of millimeters) in the sensor array, which might otherwise be impractical for low-level analog signals due to noise, attenuation, and/or other signal integrity issues.

[0027] The sensors described herein may each include a sensor die coupled with a converter die. The sensor die may include a sensing area. The sensor die can include circuitry to couple with the sensing area and the converter die.

[0028] As described herein, for each sensor, amplification and ADC of analog signals may be performed in a microfabricated integrated circuit (IC) converter die. The converter die may have a smaller size and footprint, such as lateral dimensions that may be in a range of 100 to 1000 μm, and in some cases, in a range of 100 to 300 μm, per side and a thickness in a range of 10 to 100 μm, and in some cases, in a range of 10 μm to 30 μm (e.g., a micro IC). The converter die may include through vias, such as through silicon vias (TSVs), for connecting to the sensor die. The converter die may be coupled with a flexible substrate by conventional pick-and-place mounting methods, such as flip-chip solder bonding. The smaller footprint of the sensor (via the converter die) may enable a reduced radius of curvature directly under and adjacent to the sensor. The converter die may be coupled with electrical interconnect of the sensor array. The electrical interconnect may include, for example, power, ground, data (e.g., a digital output), clock (e.g., readout synchronization), control (e.g., a configuration input), and/or enable (e.g., a readout trigger). In some cases, the electrical interconnect may implement a serial bus.

[0029] The microfabricated sensor die may provide an analog signal representing, for example, normal force, shear force, temperature, or proximity. The sensor die may include a sensing area, for sensing the normal force, shear force, temperature, or proximity. The sensor die may have a smaller size and footprint, such as lateral dimensions in a range of 100 to 1000 μm, and in some cases, in a range of 100 to 300 μm, per side and a thickness in a range of 10 to 100 μm, and in some cases, in a range of 10 to 30 μm (e.g., a micro sensor). Electrical connections of the sensor die may correspond to electrical connections of the converter die, and each sensor die may be coupled with, bonded to, or fabricated with a corresponding converter die (e.g., the sensor die may be in direct electric contact with the converter die). In this way, the converter die may provide power and ground to the sensor die and may amplify and convert analog signals from the sensor die, at the location of the sensor.

[0030] In some implementations, the sensor die may be arranged side by side with the converter die (laterally adjacent to one another) on a hub platform or island of the flexible substrate. Strain relief cutouts laterally adjacent to the sensor die and the converter die on multiple sides may define flexible arms or bridges. By arranging the sensor on the on a hub platform, an open area around the sensor may enable mechanical strain reliefs (e.g., cutouts) and meandering patterns of circuit routing (e.g., electrical interconnect). This, in turn, may enable high uniaxial or biaxial stretchability, bendability, foldability, and conformality of the flexible substrate to enable deformation of the sensor array, so that the sensor array can be laminated to complex three-dimensional surfaces of an article to form a sensing system.

[0031] In some implementations, the sensor die may be stacked relative to the converter die. By stacking the sensor die relative to the converter die, an even greater open area around the sensor may enable mechanical strain reliefs (e.g., cutouts) and meandering patterns of circuit routing (e.g., electrical interconnect). This, in turn, may enable high uniaxial or biaxial stretchability, bendability, foldability, and conformality of the flexible substrate to enable deformation of the sensor array, so that the sensor array can be laminated to complex three-dimensional surfaces of an article to form a sensing system.

[0032] In some implementations, the deformable sensor array may be integrated with a seat (e.g., an automotive seat, massage chair, or upholstered seat). The sensor array can then sense information, such as the presence of persons or objects, to provide a closed-loop control of a system, such as applied pressures and/or temperatures of the seat. In some implementations, the sensor array may be integrated with active compression garments to provide a closed-loop control of applied pressure in the active compression garment. The sensor array can sense information to provide a closed-loop control of applied pressures to mitigate, for example, lymphedema, deep vein thrombosis, or varicose veins. In some implementations, the sensor array may be integrated with footwear or compression garments to provide feedback for manual adjustments of the footwear or compression garments, such as to alleviate pressure “hotspots.” In some implementations, the sensor array may be integrated with athletic equipment (e.g., golf grips, shoe insoles) to provide measurements of applied pressure on the equipment, for example, to improve athletic performance. In some implementations, the sensor array may be integrated with large area tactile input surfaces with software-reconfigurable buttons, switches, and/or dials, such as a curved vehicle dashboard, on which control elements can be configured by a user or through over-the-air software updates. In some implementations, the sensor array may be integrated with a mattress (e.g., a hospital bed) to provide pressure mapping, such as to alleviate bed sores. In some implementations, the sensor array may be coupled with a haptic actuator to provide a tactile signal to the user to help locate and interact with the control elements.

[0033] FIG. **1**A is an example of a deformable sensor array **100** including a plurality of sensors **102** and a flexible substrate **104** (e.g., polyimide). The plurality of sensors **102** may include, for example, sensors **102***a* to **102***h*, arranged in a grid. The sensors **102** may be micro sensors spread over a large area, such as one square foot or more. Each sensor **102** may include a sensor die to generate an analog signal and a converter die to perform amplification and ADC of the analog signal to generate a digital output. The sensor die and the converter die may be stacked relative to one another as described herein. In some cases, the sensor array **100** may provide multimodal sensing by having different sensors **102** to sense combinations of normal forces, shear forces, temperatures, and/or proximities (e.g., sensor **102***a* sensing a normal force, sensor **102***b* sensing a shear force, sensor **102***c* sensing a temperature, sensor **102***d* sensing a proximity, and so forth). The plurality of sensors **102** may be coupled with the flexible substrate **104** which, in turn, may be coupled with or affixed to an article to be used by a user such as via lamination and/or an adhesive.

[0034] The sensor array **100** may include, for example, 1,000 sensors, 10,000 sensors, or more, integrated with the article. In some cases, the article may have a plurality of sensor arrays **100**, and each sensor array **100** may be utilized based on its location on the article. For example, each sensor **102** of the array may have smaller lateral dimensions (X1), such as, in a range of 100 to 1000 μm, and in some cases, 100 μm to 300 μm. This may facilitate large open areas for strain relief cutouts **108** between sensors **102** (discussed with respect to FIG. **1**B). The sensors of the array may also be spread over a larger area with a pitch (X2) (larger as compared to the smaller lateral dimensions (X1), for example, X2>1 mm, and in some cases, >5 mm, or >10 mm, in both X and Y directions (e.g., in a grid pattern).

[0035] The flexible substrate **104** may include electrical interconnect **107** (e.g., metal routing, such as copper traces) coupled with the sensors **102**. The electrical interconnect **107** may include a common set of signal wires or connections for controlling digital readout of the sensors **102**. For example, the electrical interconnect **107** may include connections such as V_{DD} (power), V_{SS} (ground), clock, select (e.g., digital input to trigger a readout of a sensor **102**), and/or a digital output (e.g., 8 bits, 12 bits, or more, representing sensing performed by the sensor at a given time). The electrical interconnect **107** may include connections to implement a digital bus for communicating with the plurality of sensors **102**. In some cases, the electrical interconnect **107** may implement a serial bus, such as an inter-integrated circuit (I^2C) bus, SPI bus, differential signaling bus, or system management (SM) bus. The electrical interconnect **107** may have a meandering pattern of circuit routing between the sensors **102**, and a controller **130** coupled with the sensors **102**.

[0036] With additional reference to FIG. **1**B, the flexible substrate **104** may include a plurality of strain relief cutouts **108** between the sensors **102** and between the electrical interconnect **107** in X and Y directions, such as strain relief cutouts **108***a* to **108***f*. For example, the flexible substrate **104** may include strain relief cutout **108***a* between sensors **102***a* and **102***b*, and between legs of a serpentine routing of the electrical interconnect **107** of those sensors. The strain relief cutouts **108** may enable high uniaxial or biaxial stretchability, bendability, foldability, and conformality of the sensor array **100**. Thus, the flexible substrate **104** forms a serpentine pattern defined by the strain relief cutouts **108**, defining flexible arms or bridges.

[0037] Further, the strain relief cutouts **108** may be between sensors **102** in different directions. For example, strain relief cutout **108***a* may be between sensors **102***a* and **102***b* in a first direction (horizontally, along an X-axis in the X direction) and between sensors **102***a* and **102***d* in a second direction (vertically, along a Y-axis in the Y direction). As a result, the sensor array **100** may enable a reduced radius of curvature that, in turn, enables coupling with tight contours of an article, such as a wearable device (e.g., a glove, sleeve, or shoe) or other system providing localized control (e.g., a seat or dashboard).

[0038] Referring again to FIG. **1**A, the controller **130** may perform a fast digital readout of the sensors **102**. For example, the controller **130** can cause a pulse to be sent to a digital input of a first sensor, e.g., sensor **102***a*, to trigger a measurement from that sensor. After that measurement is performed, and data from the sensor is transmitted back to the controller **130**, the first sensor can then trigger a second sensor to perform a measurement and transmit data, e.g., sensor **102***b*, and so forth. For example, the sensor array **100** may include a daisy chain connection of sensors **102** providing serial readout. In some cases, the controller **130** can selectively trigger one or more sensors **102** via a serial bus interface, such as by utilizing a clock and bi-directional digital data. As a result, the controller **130** can selectively cause digital inputs to be transmitted to sensors **102**, then read digital outputs from the sensors **102**, to perform the readout and receive the measurements.

[0039] With additional reference to FIG. **2**, each sensor **102** may include a sensor die **120** coupled with a converter die **122** (e.g., each a microfabricated IC). In various configurations, the sensor die **120** could perform force, temperature, or proximity sensing. The sensor die **120** may include a microfabricated sensing area **124** for sensing a normal force, shear force, temperature, and/or proximity. In some implementations, the sensing area **124** may comprise a piezoelectric, piezoresistive, capacitive, or other sensing structure. The sensor die **120** may implement circuitry coupled with the sensing area **124** on a first side and with the converter die **122** on a second side. For example, the sensor die **120** could implement circuitry to connect the sensing area **124** to the converter die **122**. The sensor die **120** may generate an analog output based on sensing (e.g., a force corresponding to the article touching a user or object), and the sensor die **120** can transmit the analog output to the converter die **122**. A cavity **133** may be formed in the base substrate **125** of the sensor die **120** to enable flex of the sensor die **120** with an application of force directed to the sensing area **124**. This may further improve sensitivity and/or deformability.

[0040] In the exemplary implementation illustrated, the sensor die **120** can include a base substrate **125**. Where the circuitry is included, the base substrate **125** may be silicon or a III-V semiconductor, for example, with the circuitry and back-end-of-the-line (BEOL) routing **134** formed using customary techniques. As shown, the BEOL routing **134** can include landing pads, for example, for external connection, as well as routing for connection with the sensing area **124** and through vias **127**. As shown, a plurality of through vias **127** can extend through the base substrate **125** of the sensor die **120** to provide vertical interconnection to the converter die **122**. In a particular implementation, the through vias **127** can be TSVs where the base substrate **125** is silicon. A plurality of leads **129** may be further connected with the sensing area **124**, and electrically connected with the working circuitry of the sensor die **120** and/or the through vias **127**.

[0041] The sensor die **120** may provide an analog signal indicating a measurement from sensing, such as a measurement of a normal force, shear force, temperature, or proximity of an object, detected via the sensing area **124**. The sensor die **120** may be a micro sensor, having lateral dimensions, for example, in a range of 100 to 1000 μm, and in some cases, 100 to 300 μm, per side, and a thickness in a range of 10 to 100 μm, and in some cases, 10 to 30 μm. Bottom side electrical connections of the sensor die **120** may be connected to (e.g., bonded to) corresponding electrical connections on a top side of the converter die **122**, for example, with solder bumps, metal-metal bonds, or other suitable electrically conductive bonding material. The sensor die **120** may be bonded to or fabricated with the converter die **122** (e.g., in direct electric contact) with the sensing area **124** exposed on a top of the sensor **102**. In this way, the converter die **122** may provide power and ground to the sensor die **120** and may amplify and convert analog signals from the sensor die **120** at the exact location of the sensor **102** in the sensor array **100**.

[0042] Bonding between the sensor die **120** and the converter die **122** could be performed, for example, at the die level with a pick-and-place process, or at the wafer level followed by singulation. Stacking the sensor die **120** on the converter die **122** for a given sensor **102** can facilitate integration of a greater number of sensors **102** per unit area in the sensing system. Additionally, this may enable more available area for strain relief cutouts **108** to allow greater deformability of the article **150**.

[0043] The converter die **122** may include circuitry to perform amplification and ADC of the analog output, from the sensor die **120**, to generate a digital output that is a representation of the analog output. For example, the converter die **122** could implement a charge amplifier to amplify voltages and/or currents, generated by the sensor die **120**, for the ADC. The digital output could comprise 8 bits, 12 bits, or more, representing the analog sensing.

[0044] In the exemplary implementation illustrated, the converter die **122** can include a base substrate **121**. Where the circuitry is included, the base substrate **121** may be silicon or a III-V semiconductor, for example, with the circuitry and BEOL **119** formed using customary techniques. As shown through vias **123** can extend through the base substrate **121** of the converter die **122** to provide vertical interconnection between the sensor die **120** and electrical interconnects **107** (e.g., copper wiring) over the flexible substrate **104**. This can optionally be supported by a substrate **131** (e.g., glass, polymer) that can be adhered to the article **150** on a bottom side. In a particular implementation, the through vias **123** can be TSVs where the base substrate **121** is silicon.

[0045] The converter die **122** could be a MOSFET or CMOS IC comprised of single-crystalline silicon. Like the sensor die **120**, the converter die **122** may have lateral dimensions, for example, in a range of 100 to 1000 μm, and in some cases, 100 to 300 μm, per side, and a thickness in a range of 10 to 100 μm, and in some cases, 10 to 30 μm.

[0046] In some implementations, the converter die **122** may be coupled with the flexible substrate **104** by conventional pick-and-place mounting methods (e.g., flip-chip solder bonding). The sensor die **120** and the converter die **122** may be micro-fabricated separately from the flexible substrate **104** and subsequently assembled to the flexible substrate **104** (which may be coupled with the article **150**). In some implementations, each sensor array **100** may be coupled with its own flexible substrate **104**.

[0047] The smaller footprint of the sensor die **120** and the converter die **122** may enable a smaller radius of curvature directly under and adjacent to the sensor **102**. The converter die **122** may be coupled with electrical interconnect **107** (e.g., copper wiring) of the sensor array **100** that may, in turn, be coupled with other components of the sensing system (e.g., other sensors **102** and/or the controller **130**).

[0048] Referring again to FIG. **1**A, the controller **130** (e.g., another IC in the sensing system, such as an application-specific integrated circuit (ASIC), microcontroller, or field-programmable gate array (FPGA)) may be connected to the plurality of sensors **102**. The controller **130** may also connect to a communications device **109***a* which, in some cases, may include an antenna **109***b* to enable wireless communications with another system. The antenna **109***b* could be a microstrip antenna coupled with the flexible substrate **104**, along with the communications device **109***a* and the controller **130**. In some implementations, the communications device **109***a* may enable wired communications with the other system, without an antenna.

[0049] In operation, the controller **130** can cause one or more sensors **102** to each transmit a digital output. A digital output from a sensor **102** may indicate sensing performed by that sensor **102** at a given time in response to receiving the digital input (e.g., a trigger to cause a readout), and might also contain stored readings. In some cases, the controller **130** can directly cause transmission of a digital output from a sensor **102**, such as by sending a digital input to the sensor **102**. In other cases, the controller **130** can indirectly cause transmission of a digital output from a sensor **102**, such as by causing a local controller to send a digital input to the sensor **102**, and/or by causing one sensor **102** to send a digital input to trigger another sensor **102** (e.g., sensors connected in a daisy chain).

[0050] The communications device **109***a* may enable transmission of a collection of digital outputs from sensors **102** to another system. The communications device **109***a* may utilize wired or wireless connections, such as universal serial bus (USB), low-voltage differential signaling (LVDS), serial peripheral interface (SPI), Bluetooth, or Ethernet, to transmit the digital data. For example, the controller **130** can receive digital outputs from the sensors **102** based on triggering those sensors, then utilize the communications device **109***a* to transmit a compressed digital bitstream encoding the digital outputs to another system, such as a host computer or server, via the antenna **109***b*. As a result, the controller **130** can selectively perform readout of sensors **102** of the sensor array **100** to obtain sensing information with high temporal resolution while the sensor array is deforming or is deformed with the article.

[0051] In some implementations, a sensing system may include a plurality of sensor arrays **100**. Each sensor array **100** may be coupled with its own flexible substrate **104**. For example, the controller **130** of each sensor array **100** could be a local controller connected to a global controller in the sensing system.

[0052] FIG. **3** is an example of a cross-section of a sensor array **100**. The plurality of sensors **102**, coupled with the flexible substrate **104**, may be shaped to conform to contours of an article **150** to which the sensor array **100** is applied or affixed. The article **150** may have tight curves and/or a complex shape, such as a glove, sleeve, shoe, seat, dashboard, etc. For example, the sensor array **100** could be shaped to conform to contours of an active compression garment to provide a closed-loop control (e.g., via the controller **130**) of applied pressure in the active compression garment, such as to mitigate lymphedema, deep vein thrombosis, or varicose veins. In another example, the sensor array **100** may be shaped to conform to contours of footwear or compression garments to provide feedback (e.g., via the controller **130**) for manual adjustments of the footwear or compression garments, such as to alleviate pressure "hot-spots." In another example, the sensor array **100** may be shaped to conform to contours of athletic equipment (e.g., golf grips, shoe insoles) to provide measurements of applied pressures (e.g., via the controller **130**) on the equipment, for example, to improve performance of an athlete.

[0053] The flexible substrate **104** may be adhered to the contours of the article **150**, such as by lamination and/or adhesive. Further, the sensors **102** may be encapsulated in an encapsulation layer **152** (e.g., silicone) to protect the sensor array **100** from environmental conditions while sensing. The smaller footprint of the sensors **102** may enable a reduced radius of curvature (shown as "R" in FIG. **3**) directly under and adjacent to the sensors **102** to enable the stretching, bending, folding, and conforming of the sensor array **100**.

[0054] FIG. **4** is an example of a sensing system including a plurality of sensor arrays integrated with an article, such as a seat **160** (e.g., the article **150**, shown in cross-section A-A of FIG. **3**). For example, the seat **160** could be an automotive seat, massage chair, or other furnishing. The plurality of sensor arrays may include sensor arrays **100***a* and **100***b* integrated with, or affixed to, different portions of the seat **160**. For example, the flexible substrates **104** of the sensor arrays may each be coupled with upholstery of different portions of the seat **160**, such as sensor array **100***a* coupled with a back portion, and sensor array **100***b* coupled with a seat portion. The plurality of sensors **102**, coupled with the flexible substrates **104** of the different sensor arrays, may stretch, bend, and fold to follow contours of the seat **160** and may be deformable with persons and objects in the seat **160**. The sensor arrays can sense information, such as whether an occupant or object is in the seat **160** and/or a weight of the occupant or object. Local controllers of the sensor arrays, such as local controllers **130***a* and **130***b*, can communicate with a global controller of the sensing system, such as global controller **130***c*. The global controller **130***c* can receive sensing input and utilize closed-loop control, for example, to regulate one or more aspects of a system, such as pressures and/or temperatures applied by the seat **160**, based on the sensed conditions indicated by the sensor arrays.

[0055] FIG. **5** is an example of a sensing system including a sensor array **100** integrated with an article, such as a dashboard **170** (e.g., the article **150**, shown in cross-section A-A of FIG. **3**) of an automobile or vehicle. The dashboard **170** may represent a large, curved, contoured area (e.g., a square foot or more) with complex three-dimensional surfaces. The sensor array **100** may provide tactile input surfaces for a user, and in some cases, may include software-reconfigurable buttons, switches, and/or dials. The sensor array **100** can sense information from the user and provide closed-loop control (via the controller **130**) to configure and control elements of the dashboard **170**, for example by reconfiguring buttons for a driving mode vs. a parked mode.

[0056] FIG. **6**A is an example of a sensing system including a sensor array **100** integrated with an article, such as a sleeve **180** (e.g., the article **150**, shown in cross-section A-A of FIG. **3**). The sleeve **180** may be worn, for example, to provide compression to an arm (or leg) of a user **181** (or worn on a robotic arm or leg) as shown in FIG. **6**B. For example, the flexible substrate **104** may be coupled with an elastic textile surface **182** of the sleeve **180**. The plurality of sensors **102**, coupled with the flexible substrate **104**, may stretch, bend, and fold to follow contours of the sleeve **180**, and may be deformable with motion of the user's arm or leg or a robotic arm or leg. For example, the sensor array **100** can sense information of the wearer of the sleeve **180** and provide a closed-loop control (via the controller **130**) of pressures applied by the sleeve **180** to the wearer.

[0057] FIG. **7**A is an example of a sensing system including a sensor array **100** integrated with an article, such as a shoe **190** (e.g., an athletic shoe). The shoe **190** may be worn on a foot of the user **181** (or worn on a robotic foot) as shown in FIG. **7**B. For example, the shoe **190** could be the article **150**, shown in cross-section A-A of FIG. **3**. The sensor array **100** may be integrated, or affixed, between an upper portion **192** of the shoe **190** and a lower portion or sole **194** of the shoe **190**. For example, the encapsulation layer **152** shown in FIG. **3** may be coupled with the upper portion **192**, and the flexible substrate **104** may be coupled with the lower portion or sole **194**, with the sensor array **100** in between (e.g., configured as a midsole in this example). The plurality of sensors **102**, coupled with the flexible substrate **104** and the encapsulation layer **152**, may stretch, bend, and fold to follow contours of the shoe **190** and may be deformable with motion of the user or robotic device (e.g., stepping or jumping).

[0058] FIG. **8** is an example of a sensing system including a plurality of sensor arrays **100** integrated with an article (e.g., the article **150**, shown in cross-section A-A of FIG. **3**). For example, the article may be a sensing glove **196** worn on a hand of a user or a robotic hand, e.g., the user **181** of FIG. **6**B. The sensor arrays **100** may be woven or adhered to an exterior surface **198** of the sensing glove **196**. The sensor arrays **100** may be integrated with different portions of the sensing glove **196**, such as fingers, thumbs, and/or palm locations on a palmar side of the glove. For example, a first sensor array **100***a* may correspond to a first group of sensors **102** (e.g., 10 sensors, 100 sensors, or more) arranged on a thumb or thumb tip, a second sensor array **100***b* may correspond to a second group of sensors **102** (e.g., another 10 sensors, 100 sensors, or more) arranged on a first finger or fingertip, a third sensor array **100***c* may correspond to a third group of sensors **102** (e.g., another 10 sensors, 100 sensors, or more) arranged on a third finger or fingertip, and so forth. Sensor arrays **100** may also be arranged between joints of fingers/thumbs and/or contours of the palm.

[0059] A plurality of flexible substrates **104** may be coupled with the exterior surface **198** (e.g., a textile surface) for each sensor array **100**. The sensor arrays **100**, coupled with the flexible substrates **104**, may stretch, bend, and fold to follow contours of the sensing glove **196** and may be deformable with motion of the user or robotic hand. For example, the sensor arrays **100** can sense information of the wearer of the sensing glove **196**. FIG. **9** is an example of a close-up top view of a sensor array **100**, including electrical connections between sensors **102***i* and **102***j*, via electrical interconnect **107**, shown by way of example. The sensors **102** may be connected in series (e.g., a daisy chain) or in parallel via one or more signals of the electrical interconnect **107**, such as a select line ("SEL") or digital input. The number of electrical signals connected to the sensors **102** can be reduced by the sensors **102** sharing a same basic, common set of signal wires, such as power 1 ("V_{DD}," a high voltages supply), ground ("GND"), clock ("CLK"), a select line ("SEL"), a digital output ("OUT"), and/or power 2 ("V_{SS}," a low voltage supply). The controller **130** can utilize the select line to send a digital input to the sensors **102** and utilize the digital output to receive outputs from the sensors **102**. In some cases, the electrical interconnect **107** may implement a serial bus, such as an I^2C bus, a SPI bus, or an SM bus. The controller **130** can utilize the clock to synchronize the outputs from the sensors **102** during the readout. In some cases, additional signals may be used for further control and/or synchronization of the read out.

[0060] As discussed above with respect to FIG. **1**B, the flexible substrate **104** may include strain relief cutouts **108** between the sensors **102** and the electrical interconnect **107**. For example, the flexible substrate **104** may include strain relief cutouts **108** between sensors **102***i* and **102***j* and their electrical connections. The strain relief cutouts **108** may be a physical absence of material in the flexible substrate **104**, or a softer material, to accommodate flex, fold, and strain of the article when worn by a user or a robotic device.

[0061] In some implementations, the sensor die **120** may be arranged side by side with the converter die **122** on a hub platform of the flexible substrate **104**. The strain relief cutouts **108** may be laterally adjacent to the sensor die **120** and the converter die **122** on multiple sides in an X-Y plane, defining flexible arms or bridges coupled with hub platforms. FIG. **10**A illustrates a deformable sensor array **100** including a plurality of sensors **102** and a flexible substrate **104** (e.g., polyimide). The plurality of sensors **102** may include, for example, sensors **102***k* to **102***p* arranged in a grid. The sensors **102** may be micro sensors spread over a large area, such as one square foot or more. The sensor die **120** and the converter die **122** may be arranged side by side with one another on a hub platform **142** or island of the flexible substrate **104**. Further, the strain relief cutouts **108** may be laterally adjacent to the sensor die **120** and the converter die **122** on multiple sides (e.g., opposing sides) in the X-Y plane, defining the flexible arms **144** or bridges. In some cases, the sensor array **100** may provide multimodal sensing by utilizing different sensors **102** to sense combinations of normal forces, shear forces, temperatures, and/or proximities (e.g., a sensor **102***k* sensing a normal force, a sensor **102***l* sensing a shear force, a sensor **102***m* sensing a temperature, and sensor **102***n* sensing a proximity, and so forth). The plurality of sensors **102** may be coupled with the flexible substrate **104** which, in turn, may be coupled with or affixed to the article **150** to be used by a user, such as via lamination and/or an adhesive.

[0062] The sensor array **100** may include, for example, 1,000 sensors, 10,000 sensors, or more, integrated with the article. Each die of each sensor **102** may have smaller lateral dimensions (X1), such as, in a range of 100 to 1000 μm, and in some cases, 100 μm to 300 μm. This may facilitate large open areas for strain relief cutouts **108** between sensors **102**. The sensors of the array may also be spread over a larger area with a pitch (X2) (larger as compared to the smaller lateral dimensions (X1), for example, X2>1 mm, and in some cases, >5 mm, or >10 mm, in both X and Y directions (e.g., in a grid pattern).

[0063] The flexible substrate **104** may include electrical interconnect **107** (e.g., digital interconnect, such as metal routing implemented by copper traces) coupled with the sensors **102**. As described above with respect to FIGS. **1**A, **1**B and **9**, the electrical interconnect **107** may include a common set of signal wires or connections for controlling digital readout of the sensors **102**. For example, the electrical interconnect **107** may include connections such as V_{DD} (power), V_{SS} (ground), clock, select (e.g., digital input to trigger a readout of a sensor **102**), and/or a digital output (e.g., 8 bits, 12 bits, or more, representing sensing performed by the sensor at a given time). The electrical interconnect **107** may include connections to implement a digital bus for communicating with the plurality of sensors **102**. In some cases, the electrical interconnect **107** may implement a serial bus, such as an I^2C bus, SPI bus, differential signaling bus, or SM bus. The electrical interconnect **107** may have a meandering pattern of circuit routing between the sensors **102** and the controller **130**.

[0064] In the sensor array **100** illustrated in FIG. **10**A, the electrical interconnect **107** includes both inputs and outputs from each sensor **102** (e.g., the converter die **122**) in a daisy chain fashion, similar to FIGS. **1**A and **1**B. This may enable the electrical interconnect **107** density to be reduced. In another implementation, such as the sensor array **100** illustrated in FIG. **10**B, the number of connections to each sensor **102** (e.g., to the converter die **122**) can be reduced with each sensor **102** including a specified input/output coupled with the electrical interconnect **107** (e.g., a tapped connection).

[0065] The flexible substrate **104** may include a plurality of strain relief cutouts **108** between the sensors **102** and between the electrical interconnect **107** in X and Y directions. For example, the flexible substrate **104** may include a strain relief cutout **108** between sensors **102***q* and **102***r*, and between legs of a serpentine routing of the electrical interconnect **107** of those sensors. The strain relief cutouts **108** may enable high uniaxial or biaxial stretchability, bendability, foldability, and conformality of the sensor array **100**. Thus, the flexible substrate **104** forms a serpentine pattern defined by the strain relief cutouts **108**, defining the flexible arms **144**.

[0066] Further, the strain relief cutouts **108** may be present between sensors **102** in different directions. For example, a strain relief cutout **108** may be between sensors **102***q* and **102***r* in a first direction (horizontally, along an X-axis in the

X direction) and between sensors **102***q* and **102***t* in a second direction (vertically, along a Y-axis in the Y direction).

[0067] FIG. **11** illustrates a close-up top view of a sensor array **100**, corresponding to FIG. **10**B (e.g., each sensor **102** including specified inputs and outputs for a tapped connection), shown by way of example. The close-up top view illustrates a sensor **102** including a sensor die **120** to generate an analog signal and a converter die **122** to perform amplification and ADC of the analog signal to generate a digital output. The sensor die **120** and the converter die **122** are arranged side by side with one another on a hub platform **142** of the flexible substrate **104** with strain relief cutouts **108***g* and **108***h* laterally adjacent to the sensor die **120** and the converter die **122** on opposing sides of the dies and the hub platform **142** in a first direction (e.g., Y-axis). This may also define flexible arms **144***a* and **144***b*, based on the formed serpentine patterns, coupled with the hub platform **142** on opposing sides in a second direction (e.g., X-axis). As a result, the sensor array **100** may enable a reduced radius of curvature that, in turn, enables coupling with tight contours of an article, such as a wearable device (e.g., a glove, sleeve, or shoe) or other system providing localized control (e.g., a seat or dashboard). The controller **130** may perform a fast digital readout of the sensors **102**, including as described above with respect to FIGS. **1**A and **1**B.

[0068] With additional reference to FIG. **12**, each sensor **102** may include a sensor die **120** electrically coupled with a converter die **122** via analog interconnect **107***a* (e.g., metal routing, such as copper traces for analog outputs, carrying the analog signal derived from sensing). Each die may be a microfabricated IC. The sensor die **120** and the converter die **122** may each be coupled with the flexible substrate **104**, laterally adjacent to one another in the X-Y plane. Top sides of the sensor die **120** and the converter die **122** (and their surrounding edges) may be encapsulated in the encapsulation layer **152**. In various configurations, the sensor die **120** could perform force, temperature, or proximity sensing. The sensor die **120** may include the sensing area **124** for sensing a normal force, shear force, temperature, and/or proximity based on its configuration.

[0069] The sensor die **120** may implement circuitry in the base substrate **125**. A central bottom side of the base substrate **125** may be coupled with the sensing area **124**. In the exemplary implementation illustrated, the base substrate **125** may be silicon or a III-V semiconductor formed using customary techniques. In some implementations, the circuitry in the base substrate **125** may include analog front end (AFE) circuitry to amplify and filter the analog signal derived from sensing via the sensing area **124** (e.g., the sensor die **120** may transmit an analog signal that is a filtered and amplified analog signal to the converter die **122** via analog interconnect **107***a*). In some implementations, the circuitry in the base substrate **125** may transmit the analog signal via analog interconnect **107***a*, based on the sensing, and circuitry of the converter die **122** may include AFE circuitry to amplify and filter the analog signal (e.g., the sensor die **120** may transmit an analog signal via analog interconnect **107***a*, to be filtered and amplified by the converter die **122** receiving the analog signal). A plurality of leads **129** may be further connected with the sensing area **124** and electrically connected with the circuitry of the base substrate **125**.

[0070] The base substrate **125** may be supported by the flexible substrate **104**. For example, a peripheral bottom side of the base substrate **125** may be coupled (bonded to) the flexible substrate **104** via thermo-compression bonds **128** or landing pads. Specifically, the bonds **128** may be connected to a first interconnect **111***a* of the analog interconnect **107***a*, metal deposited on a top side of the flexible substrate **104**, providing an analog signal of the sensing, and a second interconnect **111***b* of the analog interconnect **107***a*, metal deposited on a bottom side of the flexible substrate **104**, which may provide an analog shield signal. Thus, the flexible substrate **104** may provide a two layer chip-on-flex or backplane configuration. Further, the flexible substrate **104** can optionally be supported by a substrate **131** (e.g., glass, polymer) that can be adhered to the article **150** on a bottom side.

[0071] The sensor die **120** may generate an analog output based on sensing, such as a force corresponding to the article touching a user or object when configured as a force sensor. The sensor die **120** can transmit the analog output to the converter die **122** via the analog interconnect **107***a*. The analog interconnect **107***a* may be wider than the electrical interconnect **107** and may be routed on a surface of the flexible substrate **104** for improved signal integrity, layout, and/or routing. A cavity **133** may be formed in a top side of the base substrate **125** exposing a top side of the sensing area **124** (e.g., a piezoelectric membrane). Further, a gap **126** (e.g., an air gap) may be formed on a bottom side of the sensing area **124**, between the sensing area **124** and the flexible substrate **104**. The cavity **133** and/or the gap **126** may enable access to and flex of the sensor die **120** with an application of force directed to the sensing area **124**, which may further improve sensor sensitivity and/or sensor array deformability in three dimensions.

[0072] The sensor die **120** may provide an analog signal indicating a measurement from sensing, such as a measurement of a normal force, shear force, temperature, or proximity of an object, detected via the sensing area **124**. The sensor die **120** may be a micro sensor, having lateral dimensions, for example, in a range of 100 to 1000 μm, and in some cases, 100 to 300 μm, per side, and a thickness in a range of 10 to 100 μm, and in some cases, 10 to 30 μm. Bottom side electrical connections of the sensor die **120** (e.g., the bonds **128**) may be coupled to (e.g., bonded to) the flexible substrate **104** by conventional pick-and-place mounting methods (e.g., flip-chip solder bonding).

[0073] The converter die **122** may amplify and convert analog signals received from the sensor die **120**, via the analog interconnect **107***a*, at the exact location of the sensor **102** in the sensor array **100**. In some cases, the converter die **122** may provide power and ground to the sensor die **120** via the analog interconnect **107**. Specifically, the converter die **122** may include circuitry to perform amplification and ADC of the analog output, received from the sensor die **120** via the analog interconnect **107***a*, to generate a digital output via the electrical interconnect **107**. The digital output may be a digital representation of the analog output. For example, the converter die **122** could implement a charge amplifier to amplify voltages and/or currents, generated by the sensor die **120**, for the ADC. The digital output from the ADC could comprise 8 bits, 12 bits, or more, representing the analog sensing.

[0074] In the exemplary implementation illustrated, the converter die **122** can include a base substrate **121**. The base substrate **121** may be silicon or a III-V semiconductor formed using customary techniques. The base substrate **121**

may include circuitry implementing amplification and ADC of analog signals from the sensor die **120**. In some implementations, the circuitry in the base substrate **121** may include AFE circuitry to amplify and filter the analog signal received from the sensor die **120** via analog interconnect **107***a*. In some implementations, the analog signal received from the sensor die **120** via analog interconnect **107***a* may already be filtered and amplified via the sensor die **120** (e.g., the sensor die **120** may include the AFE). A top side of the converter die **122** is encapsulated in the encapsulation layer **152**. A peripheral bottom side of the converter die **122** may include thermo-compression bonds **135** or landing pads for connecting to the electrical interconnect **107** and the analog interconnect **107***a* over the flexible substrate **104**. Thus, the converter die **122** may be connected with the sensor die **120**, via the analog interconnect **107***a*, and with another sensor **102** (and the controller **130**) via the electrical interconnect **107**. Further, the base substrate **121** may be supported by an underfill **132** between the converter die **122** and the flexible substrate **104**. The flexible substrate **104** can optionally be supported by a substrate **131** (e.g., glass, polymer) that can be adhered to the article **150** on a bottom side.

[0075] The converter die **122** could be a MOSFET or CMOS IC comprised of single-crystalline silicon. Like the sensor die **120**, the converter die **122** may be a micro sensor having lateral dimensions, for example, in a range of 100 to 1000 μm, and in some cases, 100 to 300 μm, per side, and a thickness in a range of 10 to 100 μm, and in some cases, 10 to 30 μm. The sensor die **120** and the converter die **122** may be separated by a pitch of 1 mm or less. Bottom side electrical connections of the converter die **122** (e.g., the bonds **135**) may be coupled to (e.g., bonded to) the flexible substrate **104** by conventional pick-and-place mounting methods (e.g., flip-chip solder bonding). The sensor die **120** and the converter die **122** may be micro-fabricated separately from the flexible substrate **104** and subsequently assembled to the flexible substrate **104** (which may be coupled with the article **150**). In some cases, each sensor array **100** may be coupled with its own flexible substrate **104**.

[0076] The smaller footprint of the sensor die **120** and the converter die **122** may enable a smaller radius of curvature directly under and adjacent to the sensor **102**. The converter die **122** may be coupled with electrical interconnect **107** of the sensor array **100** that may, in turn, be coupled with other components of the sensing system (e.g., other sensors **102**, the controller **130**, and/or other sensor arrays).

[0077] As used herein, the term "circuitry" refers to an arrangement of electronic components (e.g., transistors, resistors, capacitors, and/or inductors) that is structured to implement one or more functions. For example, a circuit may include one or more transistors interconnected to form logic gates that collectively implement a logical function.

[0078] In utilizing the various aspects of the implementations, it would become apparent to one skilled in the art that combinations or variations of the above implementations are possible for utilizing deformable sensor arrays. Although the implementations have been described in language specific to structural features and/or methodological acts, it is to be understood that the appended claims are not necessarily limited to the specific features or acts described. The specific features and acts disclosed are instead to be understood as implementations of the claims useful for illustration.

What is claimed is:

1. A sensor array, comprising:

a plurality of sensors, each sensor including 1) a sensor die that generates an analog signal based on sensing, and 2) a converter die that performs analog-to-digital conversion (ADC) of the analog signal to generate a digital output; and

a flexible substrate coupled with the plurality of sensors, the flexible substrate including electrical interconnect to transmit digital outputs from sensors of the plurality of sensors, wherein the flexible substrate includes strain relief cutouts between the sensors to enable deformation of the sensor array.

2. The sensor array of claim **1**, wherein the flexible substrate forms a serpentine pattern defined by the strain relief cutouts.

3. The sensor array of claim **1**, wherein the strain relief cutouts are laterally adjacent to sensors on multiple sides.

4. The sensor array of claim **1**, wherein the sensor die and the converter die are coupled with the flexible substrate laterally adjacent to one another.

5. The sensor array of claim **1**, wherein the flexible substrate includes an analog interconnect to transmit the analog signal from the sensor die to the converter die.

6. The sensor array of claim **1**, wherein the electrical interconnect comprises a digital bus for communicating with the plurality of sensors.

7. The sensor array of claim **1**, wherein the sensor die includes analog front end (AFE) circuitry to amplify and filter the analog signal transmitted to the converter die.

8. The sensor array of claim **1**, wherein the converter die includes AFE circuitry to amplify and filter the analog signal received from the sensor die.

9. The sensor array of claim **1**, wherein the sensor die includes a cavity on a top side and is bonded to the flexible substrate on a bottom side.

10. The sensor array of claim **9**, wherein the sensor die includes a gap between the bottom side and the flexible substrate.

11. The sensor array of claim **9**, wherein top sides of the sensor die and the converter die are encapsulated in an encapsulation layer.

12. The sensor array of claim **1**, wherein the sensor die and the converter die each have a lateral dimension that is less than 1000 μm, and wherein the sensor die and the converter die are separated by a pitch of 1 mm or less.

13. The sensor array of claim **1**, wherein the converter die is connected with another sensor via the electrical interconnect.

14. A sensing system, comprising:

an article to be used by a user;

a flexible substrate coupled with the article;

a plurality of sensors, each sensor including 1) a sensor die that generates an analog signal based on sensing, and 2) a converter die that performs ADC of the analog signal to generate a digital output; and

a flexible substrate coupled with the plurality of sensors, the flexible substrate including electrical interconnect to transmit digital outputs from sensors of the plurality of sensors, wherein the flexible substrate includes strain relief cutouts between the sensors to enable deformation of the plurality of sensors with contours of the article.

15. The sensing system of claim **14**, further comprising:
a controller in communication with the plurality of sensors, wherein the controller provides closed-loop control based on a sensed condition indicated by the plurality of sensors.

16. The sensing system of claim **14**, further comprising:
a global controller in communication with a first local controller coupled with the plurality of sensors and the flexible substrate and a second local controller coupled with a second plurality of sensors and a second flexible substrate.

17. The sensing system of claim **14**, wherein the article is a seat and the flexible substrate is coupled with upholstery of the seat.

18. The sensing system of claim **14**, wherein the article is a dashboard and the flexible substrate is coupled with a curved contour of the dashboard.

19. The sensing system of claim **14**, wherein the article is a compression sleeve and the flexible substrate is coupled with an elastic textile surface of the compression sleeve.

20. The sensing system of claim **14**, wherein the article is a shoe and the flexible substrate is arranged between an upper portion and a sole of the shoe.

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