

AN ULTRA-LOW COST, WIDE RANGE, CROSS-TALK FREE, NEAR HUMAN  
SKIN SENSITIVITY FINGERTIP TACTILE SENSOR

**Cross-Reference to Related Application**

- 5 [0001] This application claims the benefit of priority of Singapore Patent Application No. 10202204103R, filed 20 April 2022, the content of it being hereby incorporated by reference in its entirety for all purposes.

**Technical Field**

- 10 [0002] The present disclosure relates to a flexible pressure sensor and a method of forming the flexible pressure sensor. The present disclosure also relates to a device comprising the flexible pressure sensor.

**Background**

- 15 [0003] Flexible tactile pressure sensors traditionally have vast potential for applications, such as in intelligent prosthetics, humanoid and industrial robot grippers, augmented/virtual reality, and wearable electronics. Based on the underlying sensing principle, they can be classified as resistive, capacitive, inductive, piezoelectric, and optical types.

- 20 [0004] Resistive type tactile pressure sensors may be the most popular amongst all because of their relatively straightforward design and ease of measuring the sensor output signals. Traditional strategies to fabricate resistive type flexible tactile pressure sensors may include fabricating microchannels in soft materials filled with a conductive liquid metal, dispersing micron or submicron conductive particles in soft materials, and  
25 sensor arrays fabricated from conductive yarns, conductive textiles, and conductive polymers sandwiching a sensing element.

- [0005] However, aforesaid fabrication methods may be complex, time consuming, and expensive. The fabrication methods may be complex because the fabrication may require multiple steps with each step requiring a specialized manufacturing process,  
30 such as molding soft materials, multiple curing steps between subsequent processes, depositing or dispersing conductive materials, or manually stitching the conductive yarns on soft materials. In addition, in-process manufacturing time and inter-process

waiting time render these fabrication techniques time-consuming. High material cost, such as the cost of liquid metal and expensive cleanrooms, makes the final cost of these tactile pressure sensors economically undesirable.

[0006] Currently available or reported sensors tend to suffer from slow response time (typically more than 30 ms), narrow pressure measurement range (up to 10 kPa), and high hysteresis. For example, most reported resistive tactile pressure sensors may have a high sensitivity at low pressures (less than 10 kPa), allowing for ultra-sensitive detection. However, at high pressures (greater than 10 kPa), the sensitivity declines dramatically making such reported sensors unsuitable for practical applications. Object manipulation, for example, produces pressures of more than 10 kPa and hence fast responding sensors with human-like sensitivity in a wide range are particularly required for practical purposes.

[0007] Simultaneously detecting pressure at multiple points within a sensor also tends to be an important feature of tactile sensors. Array type sensors containing multiple sensing nodes may have been developed for detecting pressure at multiple locations. However, these sensors tend to suffer from cross-talk between adjacent sensing nodes, which affects the prediction accuracy of the location of applied pressure and hence cross-talk free tactile sensors are particularly required for precisely predicting the location of applied pressure.

[0008] There is thus a need to provide for a solution that addresses one or more of the limitations mentioned above.

### **Summary**

[0009] In a first aspect, there is provided a flexible pressure sensor comprising:  
a first flexible layer;  
a second flexible layer;  
one or more pressure sensitive layers;  
wherein each of the first flexible layer and the second flexible layer comprises electrodes spaced apart at a distance sufficient to minimize cross-talk,  
wherein the first flexible layer and the second flexible layer are arranged to have the electrodes of the first flexible layer correspond in position with the electrodes of the second flexible layer;

and wherein the one or more pressure sensitive layers are configured between the first flexible layer and the second flexible layer, and in contact with the electrodes of both the first flexible layer and the second flexible layer.

[0010] In another aspect, there is provided a device comprising the flexible pressure sensor described in various embodiments of the first aspect.

[0011] In another aspect, there is provided a method of forming the flexible pressure sensor described in various embodiments of the first aspect, the method comprising:

forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon;

providing the one or more pressure sensitive layers to be configured between the first flexible layer and the second flexible layer, and in contact with the electrodes of both the first flexible layer and the second flexible layer; and

arranging the first flexible layer and the second flexible layer to have the electrodes of the first flexible layer correspond in position with the electrodes of the second flexible layer.

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### **Brief Description of the Drawings**

[0012] The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the present disclosure. In the following description, various embodiments of the present disclosure are described with reference to the following drawings, in which:

[0013] FIG. 1A shows the fabrication of the outermost (e.g. top) and innermost (e.g. bottom) layer of a fingertip sensor of the present disclosure. Any materials suitable for forming silver nanoparticles can be used as the silver nanoparticles precursor as shown in FIG. 1A. Apart from silver nanoparticles, other types of conductive inks can be used. The organic stabilizer is any organic molecule that can prevent agglomeration of the silver nanoparticles and silver nanoparticles precursor.

[0014] FIG. 1B shows an Optomec aerosol jet 3D (three dimensional) printing setup.

[0015] FIG. 1C shows a circuit diagram of the sensor connections of a sensor of the present disclosure.

[0016] FIG. 1D shows plots of variation of power consumed with continuously increasing pressure at different voltages (left to right: 5 V to 3 V).

[0017] FIG. 2A shows the layers in the fingertip sensor of the present disclosure, which is a flexible tactile pressure sensor. The top image is a perspective view of the flexible tactile pressure sensor and the bottom image is the side view. The polyimide layers are denoted by 1a, 1b. The silver electrodes are denoted 2a, 2b. The pressure sensitive films are denoted 3a, 3b. In the top image, the silver electrodes 2a are not shown. The top layer 1a and the bottom layer 1b contain an array of conductive electrodes (e.g. silver electrodes 2a and 2b), respectively. These electrodes are 3D printed on them. The array of electrodes 2b on the bottom layer 1b correspond (e.g. in position) to the array of electrodes 2a on the top layer 1a and vice versa. These electrodes can be 3D printed from conductive nanoparticle inks such as gold (Au), silver (Ag), Copper (Cu), etc. In certain non-limiting examples, Ag nanoparticle ink was used. Optomec aerosol jet printer was used to print the Ag electrodes and interconnects. Ag nanoparticle ink of 40% weight loading (UTDAg40TE, UT Dots Inc.) was used for this. Ag nanoparticle size in range of 30 nm to 50 nm was used. The viscosity and the surface tension of the ink are  $10 \pm 2$  mPas and  $35 \pm 3$  mN m<sup>-1</sup> respectively. The electrodes were printed on polyimide sheets of thickness 75  $\mu$ m. The patterning of the silver ink for the fabrication of the electrodes (electrically conducting) is done through the generation of toolpath for the print nozzle using AutoCAD's plugin (Virtual Masking Tool). The electrodes are printed with a single print pass and its film thickness is approximately 0.1  $\mu$ m to 0.3  $\mu$ m. The sensing element 3 may consist of a number of layers of pressure sensitive material such as 3a, 3b and so on. In certain non-limiting examples, a 1-layer configuration, a 2-layer configuration, and a 3-layer configuration of pressure sensitive materials, were constructed.

[0018] FIG. 2B compares the structure of the multi-point touch-sensitive fingertip sensor of the present disclosure to human skin. The polyimide layers are denoted by 1a, 1b. The sensing element is denoted 3.

[0019] FIG. 2C shows a top view of a 3  $\times$  3 fingertip sensor (i.e. tactile pressure sensor) of the present disclosure with nine sensing nodes. Distance between each sensing node is 2 mm and size (i.e. area) of each sensing node is 2  $\times$  2 mm<sup>2</sup>. In other words, the electrically conductive electrodes and interconnects are 3D printed in a 3 X 3 array configuration. Each electrode represents a sensing node on the flexible tactile pressure sensor. The overall size of the tactile pressure sensor is 10 x 10 mm<sup>2</sup>. A total of 9 sensing

nodes are present on the tactile pressure sensor. Each node is individually sensitive to an externally applied pressure. This is advantageous in detecting applied pressure in situations when pressure is applied at multiple locations on the sensor. Thus, the sensor in this non-limiting example demonstrates the sensitivity to multi-point pressure. The shortest distance between two points on the fingertip that results in the perception of two different stimuli may be referred to as the threshold for discrimination. In normal humans, this threshold for discrimination may be 2 mm to 3 mm at the fingertip. As shown in FIG. 2C, the electrodes in the array are located at a distance of 2 mm from adjacent electrodes in the same row and same column. This facile yet advantageous approach renders the tactile pressure sensor cross-talk free.

[0020] FIG. 3 shows the properties of a multi-point touch-sensitive fingertip sensor of the present disclosure.

[0021] FIG. 4A shows relative change in sensor output currents with linearly increasing pressure from 10 kPa to 600 kPa at 5 V.

[0022] FIG. 4B shows relative change in sensor output currents with linearly increasing pressure from 10 kPa to 600 kPa at 4 V (using the same sensor of FIG. 4A).

[0023] FIG. 4C shows relative change in sensor output currents with linearly increasing pressure from 10 kPa to 600 kPa at 3 V (using the same sensor of FIG. 4A).

[0024] FIG. 4D shows the sensor hysteresis at 5 V (using the same sensor of FIG. 4A).

[0025] FIG. 4E shows the sensor hysteresis at 4 V (using the same sensor of FIG. 4A).

[0026] FIG. 4F shows the sensor hysteresis at 5 V (using the same sensor of FIG. 4A).

[0027] FIG. 5 shows relative change in sensor output currents with linearly increasing pressure from 0 kPa to 50 kPa at 5 V (using the same sensor of FIG. 4A).

[0028] FIG. 6 is a table indicating sensitivity and hysteresis results from one non-limiting example of a sensor of the present disclosure.

[0029] FIG. 7A shows the response time of a sensor of the present disclosure.

[0030] FIG. 7B is a plot of the change in resistance recorded by a sensing node of a tactile pressure sensor (i.e. same sensor of FIG. 7A) under a loading and unloading cycle for single piezoresistive layer tactile sensor at 5 V.

[0031] FIG. 7C shows the relaxation time of the sensor of FIG. 7A.

[0032] FIG. 7D is a plot of the sensor repeatability test results for the sensor of FIG. 7A, which has a single piezoresistive layer.

[0033] FIG. 7E is a plot of the results of consistent performance experiment for various sensors of FIG. 7A constructed with different number of layers.

[0034] FIG. 7F is a plot of the sensor performance of FIG. 7A (for a single piezoresistive layer) at different temperatures.

5 [0035] FIG. 8 shows the sequence of images obtained from the visualization interface showing no cross-talk between adjacent sensing nodes.

[0036] FIG. 9A depicts the deep learning CNN classification network. The CNN receives a series of 400 x 400 pixel images as input. Four 2D convolution layers were used. The number of filters and filter size in each layer were gradually increased. The first layer is set with of 16 filters of size 1 X 1. 32 filters of size 2 X 2, 64 filters of size 3 X 3, and 128 filters of size 4 X 4 are used in the second, third, and fourth convolution 2D layers, respectively. Rectified linear unit (ReLU) was chosen as the activation function in each convolution layer. Each convolution layer is followed by a 1 X 1 Maxpooling layer of stride 2 to decrease the number of parameters the network needs to learn. A fully connected layer with output dimension equal to the number of classes is present after downsampling by the Maxpooling layer. Finally, the output of the fully connected layer is normalized using a softmax function. The CCN architecture was used to conduct two sorts of tests. The first test is to discriminate between the fingers depending on which fingertip sensor is touched on the glove. The second test involves determining if the object on the fingertips is sharp or blunt. All tests were run on Matlab 2021b.

[0037] FIG. 9B shows an example set of the pressure map images generated by a sensor of the present disclosure, wherein the pressure maps correspond to index touched, middle touched, ring touched, little touched, index and thumb touched, middle and thumb touched, ring and thumb touched, little and thumb touched, thumb touched, and all fingers touched. Notable differences were observed mainly in the location of taxels activated by touching the fingertip sensors with different objects. A dataset of 4,730 images of these pressure maps was created (430 images in each class). The network was trained using 70% of the pressure maps in the dataset. The network was tested using the remaining 30% of the pressure map images in the dataset.

[0038] FIG. 9C is a confusion chart of fingertip discrimination, which shows the test verification results of test dataset. The classification network had a flawless accuracy

of 100 percent and could consistently predict which of the fingertip sensors had been touched.

[0039] FIG. 9D shows the pressure maps generated by a sensor of the present disclosure, wherein the pressure maps correspond to blunt object on both fingertips, blunt object on index, blunt object on thumb, sharp object on both fingertips, sharp object on index, and sharp object on thumb. FIG. 9D shows an example set of these pressure map images. Observable differences were seen in the pressure maps of each case. Approximately, 4 taxels were activated each time when touched by a blunt object. The intensity of these activated taxels varied depending on the orientation of the blunt object and the amount of pressure applied to the sensing nodes on the fingertip sensor. For sharp objects, one taxel was activated. A dataset of 560 pressure map images was created. Again, 70% of this dataset was used for training, with the remaining 30% used for testing. The same network model as illustrated in FIG. 9A was employed. A classification accuracy of 95.9 % was achieved. The confusion chart of the actual object on the fingertip and the predicted object on the fingertip for this test is shown in FIG. 9E.

[0040] FIG. 9E shows the confusion chart for sharp and blunt objects discrimination.

[0041] FIG. 10A depicts the deep learning classification network used for discriminating direction of touch in this research. A pretrained network ResNet-18 was used for feature extraction. The dimension of the extracted feature with ResNet-18 was 512. The extracted features were then fed into Long Short-Term Memory (LSTM) layer to classify the sequence of feature vector representing a video. LSTM layer with 1500 hidden units with a dropout layer afterwards was used. The dropout layer prevents the network from being over-tuned on the training data. Finally, a fully connected layer with output size corresponding 12 classes, a softmax layer and a classification layer is present. A classification accuracy of 97.8 % was achieved in this test. The confusion chart for this test with actual direction of touch and predicted direction on the fingertips is shown in FIG. 10C.

[0042] FIG. 10B shows an example set of sequence of images of pressure maps generated from a multi-point fingertip sensor of the present disclosure for clockwise direction of touch. To discriminate between the direction of touch, 6 types of movements on the fingertip sensors of index finger and thumb using the tip of a pen (top to bottom, bottom to top, left to right, right to left, clockwise circular motion and

anti-clockwise circular motion) were performed. Approximately, 1.5 minutes long videos displaying pressure maps for each type of motion were created. Each video corresponds to a class. A sequence of images obtained from the video for clockwise motion of the pen tip on the fingertip sensor is shown in FIG. 10B.

5 [0043] FIG. 10C is a confusion chart of recognizing direction of touch.

[0044] FIG. 11 shows the pressure maps generated by a smart glove (incorporating a sensor of the present disclosure) from (a) grabbing a soda can, (b) grabbing a banana, (c) grabbing an orange, (d) grabbing a pen, (e) grabbing a scissor, and (f) grabbing a tape roll. Application of the smart glove to generate pressure maps demonstrates for the  
10 sensor's capability for operation with common objects that are handled by humans in daily life. The set of objects chosen for this test has a diverse mechanical configuration. The pressure maps generated were explored while handling six objects of different shapes, sizes, and hardness (i.e. a soda can, a banana, an orange, a pen, a scissor, and a tape roll). From the pressure maps generated by the smart glove during interaction with  
15 these objects, it was observed that each of these objects generated completely different pressure maps depending on the shape, material, and mechanical configuration. For example, pen and scissors both were held in prismatic grasp between the thumb and index finger. However, the pressure maps for both these objects were completely different. This is mainly because of the difference in the shape of these objects. It was  
20 also observed that when grabbing the same object multiple times different pressure maps were generated. These differences in pressure maps while holding the same object can be attributed to different orientations and positions of the object in grip.

### **Detailed Description**

25 [0045] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the present disclosure may be practised.

[0046] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments.  
30 Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as

described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0047] The present disclosure describes for a flexible pressure sensor. The flexible pressure sensor is interchangeably herein referred to as a flexible tactile pressure sensor, tactile pressure sensor, tactile sensor, multi-point touch-sensitive fingertip tactile sensor, multi-point touch fingertip sensor, flexible fingertip tactile sensor, fingertip pressure sensor, fingertip sensor, resistive pressure sensor, and three-layered microstructure flexible tactile sensor. For brevity, the flexible pressure sensor may be referred to as the pressure sensor, present sensor, or sensor. The term “flexible pressure sensor” herein means that the present sensor can be subject to various contortions (e.g. twisting, bending, stretching, compressing) without having its pressure sensing capabilities/performance compromised and without being damage.

[0048] The present sensor is structurally configured comparable to a human skin structure. For example, the micro-structured sensor layers in the pressure sensor may be analogous to the epidermis, dermis and hypodermis of human skin.

[0049] Advantageously, the present sensor demonstrates not only a much faster response time (e.g. 4 ms or less) than that of the human skin and reported pressure sensors, but also a level of sensitivity better than sensitivity of human skin without requiring complex or complicated components. As the components used to construct the present sensor and the construct of present sensor are neither overly complex nor complicated, the present sensor can be kept thin (e.g. even lesser than 1 mm, 0.5 mm, etc.) and fabricated economically (each sensor may cost less than SGD 1.50) with a facile approach, i.e. each of the present sensor is an ultralow cost sensor. Moreover, the present sensor has tunable sensitivity and hysteresis, and is operable over a wider pressure range (e.g. up to 600 kPa) as compared to reported sensors and over a wider temperature range of -45°C to 60°C (i.e. the sensor is thermally stable). The performance of the sensor is highly repeatable (i.e. high repeatability).

[0050] The present disclosure also describes for a method of forming the present sensor. The method is a considerably fast fabrication process, as certain components can be printed (e.g. 3D printing) directly on the various layers. For example, electrically conductive electrodes and interconnects need not be soldered on, but can be printed (e.g. 3D printed) directly on a substrate to form the present sensor. Even with such a

relatively straightforward method, the present sensor does not suffer from cross-talk. That is to say, the individual sensing nodes, especially nodes adjacent to each other, are free from cross-talk. As the present sensor is compact (can fit within a human fingertip), it can be easily incorporated into various devices for various applications.

5 [0051] Details of various embodiments of the present sensor and method of forming the sensor, and advantages associated with the various embodiments are now described below. Where the embodiments and advantages are already described in the examples section further hereinbelow, they shall not be iterated for brevity.

[0052] The present disclosure relates to a flexible pressure sensor. The flexible pressure  
10 sensor comprises a first flexible layer, a second flexible layer, and one or more pressure sensitive layers. The first flexible layer is herein interchangeably referred to as a substrate. The second flexible layer is also herein interchangeably referred to as a substrate. The first flexible layer and second flexible layer are herein each referred to as substrate, as they are the components on which electrodes are formed.

15 [0053] In various embodiments, each of the first flexible layer and the second flexible layer comprises or consists of electrodes formed thereon. Each of the electrodes is electrically conductive. Each of the electrodes is a pressure sensing node, as the applied pressure can be sensed specifically at the locations where the electrodes are located. For example, if the pressure is applied between two sensing nodes, or in a region of the  
20 sensor where an electrode is absent, then the applied pressure may not be sensed accurately or may not be sensed at all. The pressure identification at a location depends on three components, i.e. the electrodes of the first flexible layer, the electrodes of the second flexible layer, and the pressure resistive layer(s) between the electrodes. The corresponding electrodes of the first and second flexible layers serve as a conductive  
25 path, which aids in conduction of current through the pressure sensitive layer(s) at points which the electrodes correspond.

[0054] In various embodiments, the electrodes are spaced apart at a distance sufficient to minimize cross-talk. Said differently, the electrodes are spaced apart at a distance so as to have no interference arising from adjacent electrodes and hence the present sensor  
30 is absent of cross-talk.

[0055] In various embodiments, the first flexible layer and the second flexible layer are arranged to have the electrodes of the first flexible layer correspond in position with the

electrodes of the second flexible layer. The electrodes of the first flexible layer can be aligned in position with electrodes of the second flexible layer, for example, the first flexible layer can be arranged over the second flexible layer such that each electrode of each flexible layer are vertically aligned over each other.

5 [0056] In various embodiments, the one or more pressure sensitive layers are configured between the first flexible layer and the second flexible layer. In various embodiments, the one or more pressure sensitive layers are in contact with the electrodes of both the first flexible layer and the second flexible layer. For example, the one or more pressure sensitive layers can be sandwiched between and in contact with  
10 both the first flexible layer and the second flexible layer absent of any air gap between the first flexible layer and the second flexible layer. In other words, there is no air gap between the first flexible layer and the one or more pressure sensitive layers, and also no air gap between the second flexible layer and the one or more pressure sensitive layer.

15 [0057] In various embodiments, the first flexible layer and the second flexible layer may comprise polyimide, silicone, a thermoplastic elastomer, an insulating material, or a printable resin. Non-limiting examples of the thermoplastic elastomer include polyurethane (PU) and ethylene-vinyl acetate (EVA). The printable resin can be any resin that is printable. For example, the resin may be composed of or may comprise a  
20 polymer.

[0058] In various embodiments, the one or more pressure sensitive layers are resistive in nature such that electrical resistance of a pressure sensitive layer may change when it is subjected to mechanical stress or strain (e.g. application of a pressure). The change in resistance can be measured and used to identify or measure the mechanical stress or  
25 strain applied to the material. In various embodiments, the one or more pressure sensitive layers can be piezoresistive. Due to aforesaid resistive property, each of the one or more pressure sensitive layers can be herein referred to as a resistive layer or piezoresistive layer.

[0059] In various embodiments, the one or more pressure sensitive layers may comprise  
30 a polymeric material incorporated with carbon black, carbon fiber, activated carbon, carbon nanotube, or graphene. The one or more pressure sensitive layers may comprise

a carbon polymer composite. The polymer material confers electrical resistance while the carbon-based material (e.g. carbon black) confers electrical conductivity.

[0060] In various embodiments, the one or more pressure sensitive layers may comprise a thickness of at least 0.1 mm. In various embodiments, the one or more pressure sensitive layers may be thinner than 0.1 mm.

[0061] In various embodiments, the electrodes of each of the first flexible layer and the second flexible layer may be arranged in an array electrically connected by interconnects.

[0062] In various embodiments, the electrodes and the interconnects may comprise or may consist of electrically conductive nanoparticles. In various embodiments, the conductive nanoparticles may comprise or may consist of gold, silver, copper, or any combination thereof. The conductive nanoparticles can comprise other electrically conductive materials.

[0063] In certain non-limiting embodiments, each of the electrodes may have a thickness (i.e. vertical height) in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.2  $\mu\text{m}$ , 0.2  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , etc. In certain non-limiting embodiments, the interconnects may have a thickness (i.e. vertical height) in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.2  $\mu\text{m}$ , 0.2  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , etc. In certain non-limiting embodiments, each of the electrodes may have a thickness (i.e. vertical height) in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.2  $\mu\text{m}$ , 0.2  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , etc., and the interconnects may have a thickness (i.e. vertical height) in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , 0.1  $\mu\text{m}$  to 0.2  $\mu\text{m}$ , 0.2  $\mu\text{m}$  to 0.3  $\mu\text{m}$ , etc. In certain non-limiting embodiments, each of the electrodes and the interconnects may have the same thickness. Such thicknesses are advantageous for better flexibility and renders lower stress when the sensor is contorted (e.g. folded and/or bent), in turn increasing the reliability of any printed circuits (e.g. the electrodes and interconnects) of the sensor. The thickness of the electrodes and interconnect can be configured based on the number of passes made during printing (e.g. 3D printing of the electrodes and interconnects).

[0064] In various embodiments, the distance between adjacent electrodes of each of the first flexible layer and the second flexible layer may be in a range of 2 mm to 3 mm, 2.5 mm to 3 mm, 2 mm to 2.5 mm. Said differently, the distance between adjacent electrodes on each of the first flexible layer may be in a range of 2 mm to 3 mm, 2.5

mm to 3 mm, 2 mm to 2.5 mm, and the distance between adjacent electrodes on each of the second flexible layer may be in a range of 2 mm to 3 mm, 2.5 mm to 3 mm, 2 mm to 2.5 mm.

[0065] In various embodiments, the flexible pressure sensor may further comprise a module operably coupled to the flexible pressure sensor. In various embodiments, the module is trainable to discriminate a point of contact. In various embodiments, the module is trainable to discriminate a direction of the contact (i.e. the direction of pressure applied). In various embodiments, the module is trainable to discriminate the type of object that is contacted, e.g. if an object is sharp or blunt. In various embodiments, the module aids in generating a pressure map on a user interface for identifying the point of the contact, the direction of the contact, and the type of object contacted (e.g. if the object is sharp or blunt).

[0066] In various embodiments, the flexible pressure sensor is operable in a range of 0 kPa to 600 kPa, 5 kPa to 600 kPa, 10 kPa to 600 kPa, etc.

[0067] The present disclosure also relates to a device comprising the flexible pressure sensor described in various embodiments of the first aspect. Embodiments and advantages described for the present sensor of the first aspect can be analogously valid for the present device subsequently described herein, and vice versa. Where the various embodiments and advantages have already been described above and in the examples section further hereinbelow, they shall not be iterated for brevity. The device can be, as non-limiting examples, a glove, a heart-monitoring device, a smart watch, etc.

[0068] The present disclosure further relates to a method of forming the flexible pressure sensor described in various embodiments of the first aspect. Embodiments and advantages described for the pressure sensor of the first aspect can be analogously valid for the present method subsequently described herein, and vice versa. Where the various embodiments and advantages have already been described above and in the examples section further hereinbelow, they shall not be iterated for brevity.

[0069] In various embodiments, the method comprises forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon, providing the one or more pressure sensitive layers to be configured between the first flexible layer and the second flexible layer, and in contact with the electrodes of both the first flexible layer and the second flexible layer, and arranging the first flexible layer and the

second flexible layer to have the electrodes of the first flexible layer correspond in position with the electrodes of the second flexible layer.

[0070] In various embodiments, forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon may comprise printing the electrodes on each of the first flexible layer and the second flexible layer. The printing can be 3D printing, inkjet printing and/or aerosol jet printing.

[0071] In various embodiments, the method may further comprise cleaning of the first flexible layer and the second flexible layer, prior to printing the electrodes. The cleaning may include contacting (e.g. wiping) the first flexible layer and the second flexible layer with an alcohol (e.g. ethanol). The cleaning may include sonicating the first flexible layer and the second flexible layer in distilled water (e.g. to rinse off the alcohol and/or any undesired debris). Air drying the first flexible layer and the second flexible layer may be carried out prior to the printing and after the cleaning.

[0072] In various embodiments, forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon may comprise mixing conductive nanoparticles in an aqueous medium (e.g. water) to form a nanoparticle ink. Other components, such as solvent, surfactant, and organic stabilizer may be mixed therein. In various embodiments, the nanoparticle ink may comprise the conductive nanoparticles in a concentration range of 20 wt% to 60 wt%, 30 wt% to 50 wt%, 40 wt% to 50 wt%, 30 wt% to 40 wt%, etc.

[0073] In various embodiments, wherein forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon may comprise printing the electrodes to be spaced apart at a distance sufficient to minimize cross-talk. In various embodiments, as mentioned above, the distance between adjacent electrodes of each of the first flexible layer and the second flexible layer may be in a range of 2 mm to 3 mm, 2.5 mm to 3 mm, 2 mm to 2.5 mm.

[0074] In various embodiments, forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon may comprise printing interconnects to have the electrodes of each of the first flexible layer and the second flexible layer electrically connected.

[0075] In various embodiments, the method may further comprise sintering the electrodes at a temperature in a range of 100°C to 300°C, 150°C to 250°C, 200°C to 250°C, 150°C to 200°C, etc.

[0076] The word “substantially” does not exclude “completely” e.g. a composition which is “substantially free” from Y may be completely free from Y. Where necessary, the word “substantially” may be omitted from the definition of the present disclosure.

[0077] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0078] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance.

[0079] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0080] Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

### Examples

[0081] The present disclosure relates to a pressure sensor, a device comprising the pressure sensor, and a method of forming the pressure sensor. The pressure sensor can be a resistive type pressure sensor (i.e. a resistive pressure sensor), as the pressure sensor involves resistive pressure sensing layers for sensing pressure.

[0082] Advantageously, the present sensor offers faster response time and relaxation time, a wider range of pressure measurement, tunable sensitivity (comparable to or near human skin sensitivity), tunable hysteresis, is cross-talk free, and thermally stable (e.g. up to 60°C), compared to reported sensors. Also, advantageously, the method of forming the present sensor is simpler and faster compared to methods for forming reported sensors.

[0083] The present sensor, a device comprising the present sensor, and method of forming the present sensor, are described in further details, by way of non-limiting examples, as set forth below.

**[0084] Example 1: Introductory Discussion**

[0085] The human fingertip is a master of sensing. There are over 10000 mechanoreceptors in human fingertips allowing us to feel things such as individual hairs, object shapes, and textures. Tactile perception is mainly based on the information received from this variety of mechanoreceptors. It enables a human brain to process the sensations we feel whenever we interact with objects in the environment. It is a system that has evolved for millions of years for its survival and has been used to help make life easier for humans.

[0086] In recent years, researchers have been looking for ways by which they can replicate the sensing capability of human skin on different materials which are not biological to fabricate tactile sensors operably comparable to a human skin. Such tactile sensors are meant to be comparable in structure and functions to those of human skin. These tactile sensors are widely used in applications such as wearable devices, healthcare monitoring, soft robots, humanoids, rehabilitation devices, and augmented and virtual reality. The present sensor possesses and matches such capability.

[0087] The advent of the Internet of actions (IoA) is accelerating the mechanosensory revolution. This is because mechanosensation tends to be believed as the core of it. Over the last few years, various types of mechanical tactile sensors may have been fabricated to emulate the functions of mechanoreceptors found in human skin. Based on the underlying sensing principle, they can be classified as mentioned above in the background section of the present disclosure. Resistive type mechanical tactile sensors, in particular, have some advantages, including low cost, good durability, and a simple structure. However, limitations of these sensors include small pressure measurement range, slow response time, and high hysteresis. For example, the majority of reported resistive tactile pressure sensors tend to suffer from a decline in sensitivity dramatically at high pressures of more than 10 kPa, which is undesirable for applications such as object manipulation as pressures produced are more than 10 kPa. The slow response time of these sensors (typically more than 30 ms) is also an issue for practical use. Maintaining high sensitivity more than or comparable to human skin in a wide pressure range with a fast response time is required, which the sensor of the present disclosure is capable of.

[0088] Another critical issue that needs to be addressed with traditional skin-inspired sensors is how to achieve multi-point sensing capability, which is the simultaneous detection of touch at multiple different locations within a sensor. This necessitates a higher density of sensing nodes on the sensor. However, increasing the density of sensing nodes beyond a certain limit has drawbacks. First, it increases the number of interconnecting wires. These interconnecting wires restrict the motion of the robotic artifact because they can get entangled during motion. Second, it corrupts the sensor output signals because of cross-talk between the neighboring interconnects. Array-type tactile sensor designs may solve the problem of interconnecting wires to some extent but cross-talk between the sensing nodes tends to remain an issue with the majority of reported tactile sensors. A solution to this is to consider the density of sensing nodes and carefully planning the spatial distribution of these sensing nodes on the sensor.

[0089] The fabrication of high-density sensing nodes on flexible substrates may often pose challenges and limitations such as the need for tooling, material compatibility issue, and high fabrication cost. For instance, silicon wafer technology with high fabrication resolution only works with a rigid silicon substrate, whereas the vapor deposition technique usually requires a mask for each electrode design which is very costly for the customization of sensor electrodes. Additive manufacturing or 3D printing of electronics, on the other hand, overcomes these issues and allows for greater design and fabrication flexibility. Inkjet printing and aerosol jet printing are some of the commonly used 3D electronic printing techniques that are used for the fabrication of sensors, circuits, and electrical components. Aerosol jet printing, in particular, has been shown to be capable of achieving high-resolution printing, which may be used for the fabrication of high-density sensing nodes of the tactile sensor.

[0090] As the number of sensing nodes on the sensor increases, a large amount of data may be generated from each sensing node. With each sensing node generating different levels of analog/digital sensor signals, handling sensor data and making sense of this sensor information becomes difficult. Machine learning (ML) has emerged as a versatile tool for dealing with large amounts of data and deriving meaning from sensor signals. Recently, several ML approaches for analyzing and predicting from sensor information seems to have been reported such as ridge regression for predicting the location of indentations on a fingertip sensor, convolutional neural networks (CNN) for

identifying touch locations by learning from deformations on a sensor array, three layered CNN for recognizing shape, size, and material of objects, ResNet-18 based CNN architecture for identifying 26 objects and creating tactile signatures of human grasp, support vector machine (SVM) for reading Braille letters,  $k$ -nearest neighbors (kNN) to estimate twist and bend angles in sensors, and SVM, random forest, and kNN for recognizing cloth material by learning textures.

[0091] In the present disclosure, the fabrication of an ultra-low-cost (less than SGD 1.50), ultra-thin (0.25 mm to 0.45 mm), multi-point touch-sensitive, cross-talk free, fast responding, (response time of 4 ms), and a wide range (5 kPa to 600 kPa) flexible fingertip tactile sensor, is described. The multi-point touch-sensitive fingertip tactile sensors can be assembled with 3D printed silver (Ag) nanoparticle electrodes on polyimide (PI) sheets and piezoresistive sensing films (i.e. the one or more pressure sensitive layers). The effect of the number of layers of piezoresistive sensing films on the sensing range, sensitivity, and hysteresis of the tactile sensor is demonstrated so as to provide an understanding of the performance of the sensors. To eliminate cross-talk between the sensing nodes, a facile approach was adopted in which the spatial distribution of the sensing nodes is configured based on the threshold for discrimination between two different stimuli on human skin. The flexible fingertip sensors were integrated into a commercial glove to render a smart glove. In total, there can be 45 pressure sensing nodes on the smart glove (nine on each fingertip). The fingertip sensor information is combined with deep learning to predict sharp and blunt objects and the direction of touch. Finally, the real-time usage of the smart glove is demonstrated. The smart glove is used to grab different objects handled by humans in daily life. The pressure maps generated are displayed on a user interface.

25 **[0092] Example 2A: Materials for Fabrication of Sensor**

[0093] The materials for fabricating a sensor of the present disclosure is described in the present example. The sensor fabricated can be a multi-point touch-sensitive fingertip sensor.

[0094] Optomec aerosol jet printer (see FIG. 1B) was used to print the Ag electrodes and interconnects. Ag nanoparticle ink of 30% to 50% (e.g. 40%) weight loading (UTDAg40TE, UT Dots Inc.) was used for this. Ag nanoparticle size in the range of 30 nm and 50 nm were used. The viscosity and the surface tension of the ink were  $10 \pm 2$

mPa s and  $35 \pm 3 \text{ mN m}^{-1}$ , respectively. The electrodes were printed on PI sheets of thickness 75  $\mu\text{m}$ . The patterning of the silver ink for the fabrication of the conducting electrodes was done through the generation of a toolpath for the print nozzle using AutoCAD's plugin (Virtual Masking Tool). The conductive electrodes were printed with a two print pass and their film thickness was about 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ . The resistive pressure sensing layers (Velostat) of thickness 0.1 mm were used. The temperature limits of the sensing layers were  $-45^{\circ}\text{C}$  to  $65^{\circ}\text{C}$ . The volume resistivity and surface resistivity of the pressure sensing layer was less than 500  $\Omega\text{cm}$  and 31  $\text{k}\Omega \text{ sqcm}^{-1}$ , respectively. There were nine sensing nodes in each multi-point fingertip sensor. Size of each sensing node was  $2 \times 2 \text{ mm}^2$ . The overall thickness of the fingertip sensor with one resistive layer, two resistive layers, and three resistive layers were 0.25 mm, 0.35 mm, and 0.45 mm, respectively. The interconnects were connected to wires using copper-nickel (Cu-Ni) tapes.

**[0095] Example 2B: Characterization and Statistical Analysis**

[0096] Data from the sensor was collected using an Arduino microcontroller at a baud rate of 115 200. A BST PSD30 constant voltage dc power source was used to supply the input voltage for all measurements. A lab-made setup with a load cell of 10 kg load capacity was used for all force and pressure measurements. To generate pressure maps two 74HC595 shift registers and two 74HC4051 analog multiplexers were used. The circuit diagram of the fingertip sensor connection is shown in FIG. 1C.

[0097] The data of the pressure map was visualized in processing 4.0 beta 5 software. All the deep learning networks were implemented using Matlab 2021b software. The dataset for the fingertip discrimination experiment consisted of 4730 pressure map images. The dataset for recognizing sharp and blunt objects consisted of 560 pressure map images. The dataset was divided into two parts in each case. 70% of the dataset was used for training and the remaining 30% was used for testing. A CNN classification network was used to predict the class of the test data in these experiments. The dataset for identifying the direction of touch on the multi-point touch-sensitive fingertip sensor consisted of  $\approx 1.5$  min long videos corresponding to each class. A pretrained ResNet-18 network architecture along with LSTM was used for predicting the direction of touch. An initial learning rate of 0.0001 was set for all deep learning methods. Adaptive moment estimation (ADAM) solver is used in all the deep learning methods.

**[0098] Example 2C: Fabrication of Sensor**

[0099] FIG. 1A shows the procedure to print the electrodes and interconnect pattern on the polyimide (PI) sheet. The procedure involves three main steps: (i) PI substrate cleaning, (ii) aerosol jet printing of silver electrodes and interconnect, and (iii) laser sintering of the printed electrodes and interconnect. A 75  $\mu\text{m}$  thick PI substrate is thoroughly cleaned to remove any undesirable organic substances and dust from its surface. To clean the surface of PI substrate, the surface is first wiped with ethanol. It is then sonicated in distilled water bath for 15 minutes to rinse off the contaminated ethanol from the surface. Finally, it is air-dried before printing. The cleaned substrate is then ready for printing the pattern of electrodes and interconnects. Aerosol jet printing of silver (Ag) nanoparticle ink is used to print the pattern on PI substrate. Ag nanoparticle ink of 40% weight loading (UTDAg40TE, UT Dots Inc.) was used for this.

[00100] Ag nanoparticle size range in between 30 and 50 nm. The Ag nanoparticle ink was deposited at room temperature using Optomec Aerosol Jet 5x system's ultrasonic atomizer. The Optomec Aerosol Jet 3D printing setup is shown in FIG. 1B. The thickness of the pattern printed on the PI substrate is 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ . Finally, the printed pattern is sintered at 100°C to 300°C (e.g. 150°C to 250°C, 200°C) for 2 hours.

[00101] The sensor layers are finally stacked as shown in FIG. 2A. Pressure sensitive resistive (e.g. piezoresistive) layers are stacked on the innermost PI layer containing the Ag nanoparticles printed pattern. Each resistive layer has a thickness of 0.1 mm. Multiple layers of resistive layers can be stacked on the PI substrate. The sensitivity and hysteresis of the sensing nodes on the fingertip sensor varies with the number of resistive (e.g. piezoresistive) layers used. Finally, the outermost PI layer containing the Ag nanoparticles printed pattern of electrodes and interconnect is carefully placed and aligned with the electrodes of the innermost layer. The whole sensor is laminated together to maintain structural integrity. The terms “outermost” and “innermost” are used herein as the layers are structurally compared to the outermost and innermost layers of the human skin (see FIG. 2B).

[00102] The overall fabrication time of each fingertip sensor is about 2 hour and 10 mins. This includes 2 minutes print time of Ag electrodes and interconnects on PI sheets, 2 hours for sintering, and 8 minutes for assembling the layers and making wire connections. It should be noted that multiple fingertip sensors can be sintered

simultaneously. Thus, these fingertip sensors can be fabricated in a very small time making them suitable for mass production.

**[00103] Example 2D: Sensor Structure**

**[00104]** Skin is often referred to as the largest organ in the human body. It is composed of three layers: epidermis, dermis, and hypodermis. The purpose of the epidermis is to protect the underlying dermis from pathogens by physical barriers. The dermis has sensory receptors such as mechanoreceptors and nociceptors that provide information regarding contact with objects or environment and pain, respectively. The dermis contains microscopic nerve endings that are sensitive to touch. These nerves send signals to the brain, which interprets them as touches on the skin. The shortest distance between two points on the fingertip that results in the perception of two different stimuli is called the threshold for discrimination. In normal humans, this threshold for discrimination is 2 mm to 3 mm at the fingertip. The hypodermis is the innermost layer of skin, which provides structural support and protection for the body in all parts of the body. In development of a pressure sensor that is operably comparable to a human skin, the present disclosure describes for a three-layered microstructure flexible tactile sensor consisting of piezoresistive sensing films sandwiched between 3D printed Ag nanoparticle electrodes on PI sheets, similar to a dermis sandwiched between epidermis and hypodermis.

**[00105]** FIG. 2B shows the analogy between the different layers of the fingertip sensor of the present disclosure and those of human skin. The sensor comprises of a flexible top layer 1a to protect the sensor analogous to epidermis, a flexible bottom layer 1b to support the sensor analogous to hypodermis, and a sensing layer 3 analogous to dermis. The top and bottom layer can be any flexible material such as silicone, 3D printed soft resin, polyimide (PI), etc. For the sole purpose of demonstration and not to intend to limit the materials, the material of top and bottom layer in the present example are polyimide. The sensing layer 3 can be any pressure sensitive material. As can be seen, a three-layered fingertip sensor is constructed, which has two PI layers sandwiching the pressure sensitive layers. The top-most PI layer provides protection to the sensing element from damage and the innermost PI layer provides support to the sensor. The PI layers contain aerosol jet-printed sensor electrodes and interconnect patterns. The sensor electrodes are printed in a  $3 \times 3$  array configuration (see FIG. 2C). Each printed

electrode is positioned at a distance of 2 mm from its neighboring electrodes in the same row and same column of the array. Thus much like human skin the threshold for discrimination on the fingertip sensor is 2 mm. A total of nine pressure sensing nodes are present on each fingertip sensor. The area of each pressure sensing node in the present sensor is  $2 \times 2 \text{ mm}^2$  and the overall size of each fingertip sensor is  $10 \times 10 \text{ mm}^2$ . FIG. 3 shows the properties of the present fingertip tactile sensors. The sensors were finally assembled on a commercial glove. Overall the sensing glove has 45 sensing nodes (nine on the fingertip of each finger).

[00106] As described hereinabove, the fabrication of electrodes on the flexible PI layer may provide several advantages such as flexibility, faster processing (2 mins in various examples of the present disclosure), and automated process. The ink described for 3D printing can have adjustable viscosity, surface tension, and electrical conductivity. It can also have adjustable nanoparticle size and percentage weight composition. The nanoparticle ink can also comprise of any conductive nanoparticle such as Au, Ag, Cu etc. or a combination thereof. The sensor thickness (e.g. see FIG. 2A) can be adjusted by choosing the thickness of the top layer 1a, bottom layer 1b, 3D printed electrode layers 2a and 2b, and sensing layer 3. In certain non-limiting examples, each of the PI layers comprising the top and bottom layers have a thickness of 75  $\mu\text{m}$ . Individual sensing layers can have a thickness of 0.1 mm. The film thickness of 3D printed electrodes can be in the range of 0.1  $\mu\text{m}$  to 0.3  $\mu\text{m}$ . The overall thickness of fingertip sensor with 1 sensing layer, 2 sensing layers, and 3 sensing layers can be 0.25 mm, 0.35 mm, and 0.45 mm, respectively.

**[00107] Example 3A: Discussion of Characterization Results – Sensitivity and Hysteresis**

[00108] To quantitatively evaluate the performance of these tactile pressure sensors, its electrical characteristics were investigated. Tactile sensors with one to three layers of sensing films were used in this study. FIG. 4A to 4C show relative change in sensor output currents ( $\Delta I/I_0$ ) measured against increasing pressure from 5 kPa to 600 kPa at constant voltages 5, 4, and 3 V, respectively. The plots show that the response of these tactile sensors are almost linear. This indicates that the tactile pressure sensor of the present disclosure can reliably measure a wide range of pressure from 5 kPa to 600 kPa.

[00109] On further investigation at low pressures (5 kPa to 50 kPa), it was found that the tactile sensors with single layer of tactile sensing film did not respond to pressures applied in the range from 5 to 10 kPa (see FIG. 5), whereas those with two and three layers of sensing films responded for pressures  $\geq 5$  kPa. This indicates that the tactile pressure sensors with two and three layers of sensing films can sense an impressively wide range of pressure from 5 to 600 kPa. This sensing range is wider than those of reported pressure sensors.

[00110] The sensitivity of the tactile pressure sensor are advantageously tunable depending on the supply voltage and the number of sensing layers used in sensor structure. The sensitivity of a pressure sensor ( $S$ ) is defined as:

$$[00111] S = \delta(\Delta I/I_o) / \delta p$$

[00112] where  $p$  is the applied pressure and  $\Delta I$  and  $I_o$  is the change in sensor output current with applied pressure and sensor output current when no pressure is applied, respectively.

[00113] The results show that the sensitivity of the sensor increases with increasing supply voltage. This is because the pressure sensing films in our sensors are made of carbon black (CB) impregnated in the polymeric material. In CB impregnated polymers, with increasing supply voltage, up to 5 V, more and more current paths are formed. Indicating that the resistance in the pressure sensing film decline at a faster rate. Thus sensitivity increases with increasing supply voltage. However, as the number of piezoresistive layers in the sensor increases, the sensitivity decreases. This could be because, despite the sensing layers are in contact, there are fewer continuous current paths established between two adjoining sensing layers. This increases the resistance between the adjacent layers, lowering sensitivity.

[00114] In one example (see FIG. 6), the sensor sensitivity is highest when the number of piezoresistive layer is one and the supply voltage is 5 V. The highest sensitivity of tactile pressure sensor is  $1.35 \text{ kPa}^{-1}$ . This is better than the sensitivity of human skin ( $18$  to  $78 \text{ MPa}^{-1}$ ) and better than the sensitivity of reported sensors.

[00115] The effect of voltage and the number of piezoresistive layers on the hysteresis of the sensor were quantified. Hysteresis ( $H$ ) can be defined as the maximum difference between sensor output with increasing and decreasing loads. It is caused by the natural

reluctance of piezoresistive material to return to its original shape or form after being mechanically deformed.

[00116] FIG. 4D to 4F show sensor hysteresis curves at constant voltages 5, 4, and 3 V, respectively. To take hysteresis into account the pressure on the sensing nodes of the sensor was gradually increased from 0 to 600 kPa. The load was then diminished gradually from 600 to 0 kPa. The loading and unloading curves form a hysteresis loop. The area under the loading curve and unloading curve was calculated using Riemann sums. Finally, the hysteresis of each sensor is expressed in percentage as the ratio of area difference between the loading and unloading curves (area of the hysteresis loop) by the area of the unloading curve given as:

$$[00117] H = (\Delta A / A_{ul}) \times 100\%$$

[00118] where  $\Delta A = A_{ul} - A_l$  is the area of the hysteresis loop,  $A_l$  is the area under the loading curve, and  $A_{ul}$  is the area under the unloading curve. A summarized result of this experiment is presented in FIG. 6. With an increasing number of piezoresistive layers in the present sensor structure, the hysteresis increased. This is because as the number of piezoresistive sensing layers increases, so does the creep effect and thus hysteresis. The sensor exhibits highest hysteresis when the number of sensing layers is three. It exhibits lowest hysteresis (9.22%) when the number of piezoresistive layers in the sensor structure is one and the supply voltage is 3 V, albeit improvement is already observed with just one layer. These results can be a guideline for configuring a suitable sensor structure and supply voltage. Thus pressure sensors with different sensor characteristics can be obtained according to the configuration taught in the present disclosure and there is versatility for configuring the sensor to one which suits best for an application.

[00119] **Example 3B: Discussion of Characterization Results – Response Time, Repeatability of Sensing Nodes, Effect of Temperature and Cross-talk**

[00120] The response time and repeatability of the sensing nodes of the fingertip sensor of the present disclosure are investigated.

[00121] In one example, the results of the response time of a sensing node on the fingertip sensor using a single piezoresistive layer at 5 V are shown in FIG. 7B. The fingertip pressure sensor exhibited a very rapid response time and relaxation time when a stepwise pressure was applied. The change in resistance of the sensing node ascended

rapidly within an ultra-fast response time of  $\approx 4$  ms when loaded and then stayed stable (see FIG. 7A). This is faster than the response time of human skin (30 ms to 50 ms). The change in resistance decreased promptly on removing the load in a very short time of  $\approx 6$  ms (see FIG. 7C). The response time and relaxation time of the present sensors are much faster than those reported. FIG. 7D shows the results of the repeatability test performed on a sensing node of a single-piezoresistive layer fingertip sensor of the present disclosure at 5 V. The experiment included quick loading/unloading pressures of 100 kPa twice, followed by 200 kPa twice, 300 kPa twice, and so on up to 600 kPa. The results show that the present pressure sensor presents a quick and stable response with great repeatability. Investigations were also conducted to understand if the electromechanical performances of the sensors were consistent. The electromechanical responses of various sensors were compared, i.e. (i) a single layer of pressure sensing films at 5 V, (ii) two layers of pressure sensing films at 5 V, and (iii) three layers of pressure sensing films at 5 V. The results of these experiments are shown in FIG. 7E. The sensor electromechanical responses during loading were found to be consistent, with a slight deviation during unloading. This deviation during unloading is observed due to the viscoelastic nature of the sensing element. FIG. 7F shows the effect of variation in temperature (30 to 60°C) on the sensing performance of the present single piezoresistive layer fingertip sensor at 5 V. It was found that the sensor performance remained stable up to 60 °C. The cross-talk between the sensing nodes was also investigated. To accomplish this, a visualization interface for the sensor pressure map. Each taxel on the interface represented a sensing node of the fingertip sensor. The individual nodes of the sensor array were touched by the tip of a sharp object in quick succession. It was found that every time a sensor node was touched only one taxel on the interface was activated. This is because whenever a sensor node is touched, the current of only that sensing node increased dramatically and the adjacent nodes remained insensitive to applied pressure. FIG. 8 shows the results of this test in real-time and it can be seen that none of the adjacent taxels were activated. The results show that there is no cross-talk between the adjacent sensing nodes.

**[00122] Example 3C: Discussion of Characterization Results – Implementation on a Glove (Perception of Object and Direction of Touch)**

[00123] The flexible tactile pressure sensors of the present disclosure were integrated on the fingertips of a glove. Experiments were conducted to distinguish between sharp and blunt objects, direction of applied pressure, and to generate the pressure maps of some common objects that humans handle in daily life.

5 [00124] The sense of touch allows humans to figure out the shape, size, weight, and texture of an object without seeing or smelling it. This is how we tell what something feels like by touching it with our hands. The sense of touch not only gives the sensations of what objects feel like but also allows decisions to be made about whether or not something is right. For example, sharp objects are potentially harmful to humans. Even  
10 when blindfolded, humans may still distinguish between sharp and blunt objects by touching the objects. This demonstrates that humans can use differences in tactile sensations to determine whether something is sharp or blunt. To be able to do that with the present fingertip pressure sensors, deep learning techniques were paired with the sensor information. Deep learning was incorporated with the present sensor to create a  
15 perception that aims to mimic the human-like ability to distinguish between sharp and blunt objects.

[00125] The classification network of deep learning CNN is shown in FIG. 9A. The input of the CNN is a set of images with dimension  $400 \times 400$ . Four convolution 2D layers were used. In each layer, the number of filters and filter size was increased  
20 progressively. The first layer was set with 16 filters of size  $1 \times 1$ . The second, third, and fourth convolution 2D layers were set with 32 filters of size  $2 \times 2$ , 64 filters of size  $3 \times 3$ , and 128 filters of size  $4 \times 4$ , respectively. In each convolution layer, rectified linear unit (ReLU) was chosen as the activation function. To reduce the number of parameters the network needs to learn, each convolution layer is followed by a  $1 \times 1$  Maxpooling  
25 layer of stride two. After down-sampling by the Maxpooling layer, a fully connected layer with an output dimension equal to the number of classes is present. Finally, a softmax function is used to normalize the output of the fully connected layer. Two types of tests were performed using the CCN architecture mentioned above. The first test was to discriminate between the fingers depending on which fingertip sensor was touched  
30 on the glove. The second test was to discriminate between the type of object on the fingertips that is, sharp or blunt object. All these tests were performed on Matlab 2021b.

[00126] To discriminate between which of the fingertip sensors is touched, each fingertip sensor on the glove was touched by multiple objects several times to generate pressure maps. The pressure maps were obtained using processing software. FIG. 9B shows an example set of these pressure map images. Notable differences were observed  
5 mainly in the location of taxels activated by touching the fingertip sensors with different objects. A dataset was prepared containing 4730 images of these pressure maps (430 images in each class). 70% of the pressure maps in the dataset were used to train the network. The remaining 30% of the pressure map images in the dataset were used to test the network. FIG. 9C shows the test verification results of test dataset. Our  
10 classification network reached a perfect 100% accuracy and was able to predict reliably which of the fingertip sensors was touched.

[00127] The experiment to discriminate between sharp and blunt objects was performed on index and thumb fingertip sensors. To discriminate between blunt and sharp objects, the fingertip sensors were first contacted with a blunt object multiple  
15 times at different locations to get pressure map images corresponding to blunt objects on both fingertips, a blunt object on the index, and a blunt object on the thumb. Similarly, the fingertip sensors were contacted with a sharp object to obtain pressure map images corresponding to a sharp object on both fingertips, a sharp object on the index, and a sharp object on the thumb.

[00128] FIG. 9D shows an example set of these pressure map images. Observable differences were seen in the pressure maps of each case. Approximately, four taxels were activated each time when touched by a blunt object. These activated taxels had different intensities depending on the orientation of the blunt object and the amount of pressure experienced by sensing nodes on the fingertip sensor. For sharp objects, one  
25 taxel was activated each time. A dataset containing 560 images of the pressure maps was prepared. Again 70% of this dataset was used for training and the remaining 30% was used for testing. The same network model as described earlier was used. Classification accuracy of 95.9% was achieved. FIG. 9E shows the confusion chart of the actual object on the fingertip and the predicted object on the fingertip for this test.

[00129] To discriminate between the direction of touch, six types of movements were performed on the fingertip sensors of the index finger and thumb using the tip of a pen (top to bottom, bottom to top, left to right, right to left, clockwise circular motion, and  
30

anti-clockwise circular motion). Approximately, 1.5 min long videos displaying pressure maps for each type of motion were created. Each video corresponds to a class. A sequence of images obtained from the video for the clockwise motion of the pen tip on the fingertip sensor is shown in FIG. 10B. FIG. 10A shows the deep learning classification network used for discriminating the direction of touch in this investigation. A pretrained network ResNet-18 was used for feature extraction. The dimension of the extracted feature with ResNet-18 was 512. The extracted features were then fed into long short-term memory (LSTM) layer to classify the sequence of feature vectors representing a video. LSTM layer with 1500 hidden units with a dropout layer afterward was used. The dropout layer prevents the network from being over-tuned on the training data. Finally, a fully connected layer with an output size corresponding to 12 classes, a softmax layer, and a classification layer is present. Classification accuracy of 97.8% was achieved in this test. The confusion chart for this test with the actual direction of touch and predicted direction on the fingertips is shown in FIG. 10C.

[00130] Furthermore, the smart glove was used to generate pressure maps for common objects that are handled by humans in daily life. The set of objects chosen for this test had a diverse mechanical configuration. The pressure maps generated were explored while handling six objects of different shapes, sizes, and hardness (a soda can, a banana, an orange, a pen, a scissor and a tape roll). An example set of pressure maps generated by the smart glove during interaction with these objects is shown in FIG. 11. It was observed that each of these objects generated completely different pressure maps depending on the shape, material, and mechanical configuration. For example, the pen and scissors both were held in a prismatic grasp between the thumb and index finger. However, the pressure maps for both these objects were completely different. This is mainly because of the difference in the shape of these objects. It was also observed that when grabbing the same object multiple times different pressure maps were generated. These differences in pressure maps while holding the same object can be attributed to different orientations and positions of the object in grip.

#### [00131] **Example 4: Summary and Applications**

[00132] In summary, ultralow cost piezoresistive type fingertip tactile pressure sensors were developed. The sensors exhibit capability to measure a wide range of pressure (5 kPa to 600 kPa with two and three layers of piezoresistive sensing films and 10 kPa to

600 kPa with a single layer of piezoresistive film in the sensor structure) with no degradation in performance up to 60°C. Thus, it can be used to measure pressure for practical purposes such as object manipulation. The present sensor is multi-point touch-sensitive and exhibits a cross-talk free performance. As demonstrated in the present disclosure, the sensor sensitivity and hysteresis can be tuned by varying the number of piezoresistive sensing films and supply voltages. Depending on the sensor structure and applied voltage, the sensors exhibit sensitivities ranging from 1.35 kPa<sup>-1</sup> to 0.11 kPa<sup>-1</sup>. A low hysteresis of 9.22% was observed at 3 V with one layer of piezoresistive film in the sensor structure. The response time (about 4 ms or less) of the sensor is much faster than that of the human skin. The fingertip sensors were integrated into a commercial glove. Combined with deep learning methods the smart glove recognized sharp and blunt objects and the direction of pressure applied at the fingertip. It was also used to generate pressure maps of objects with different mechanical configurations. The pressure maps were displayed on the user interface in real-time. Considering the unique properties of the present fingertip sensors integrated with the glove, it has vast potential for applications such as intelligent prosthetics, humanoid robotics, and AR/VR. Also, for a long time, energy consumption in sensors has been a critical area of study. The sensors described in the present disclosure currently consume up to 30 mW of power when operated at 5 V, up to 12 mW at 4 V, and up to 6 mW at 3 V (FIG. 1D).

[00133] The flexible tactile sensor described herein this disclosure can have multiple commercial applications such as in prosthetics and rehabilitation, humanoid and industrial robotics, augmented and virtual reality, and health monitoring. In particular, it can be used on bionic hands which receive tactile sensory signals from objects and convert them into electrical signals to control computerised limbs. The flexible tactile sensor can be used to enhance the sense of touch on prosthetic limbs and rehabilitation devices or even to provide 3D information about objects which would not otherwise be possible to perceive by other senses. It can be used to enable those with limited dexterity or mobility to perform tasks that would otherwise require a great deal of attention and manual dexterity such as handling sharp objects like scissors, knife, etc. In the domain of soft robotics, the tactile pressure sensor provides force feedback to the user interface while exploring complex objects, For example, among other applications, a robotic arm could be used for aiding mobility impaired people by providing them with tactile

feedback on object surfaces. It can also be used in many industries where it is important to have feedback on 3D orientation of an object during use. This technology can also be applied on a prosthesis to provide tactile sensation to the user. For example, especially when it is interacting with sensitive objects such as glass or food, it would be useful for the user if she/he had some kind of feedback from touching those things.

5 [00134] The flexible tactile sensor disclosed can be used as an effective interface for manipulating objects in humanoid robots and industrial robots. It can provide robots ability have a better perception of the environment without losing precision or accuracy. It can be used on the robot's gripper or fingers and hands to provide naturalistic interaction with a user in human robot interaction. It can be used by robots to control small devices or interface with other sensors in a robot's body.

10 [00135] The latest development in virtual reality is the introduction of flexible gloves which provide haptic feedback to users rather than visual feedback. The flexible pressure sensors on the fingertips of the gloves can be used to capture the movements of the user's fingers and feed this information to a machine that can reconstruct the finger's exact position in virtual reality. It can be used to provide haptic feedback to people interacting with virtual objects such as digital games and video games. The advantage of using tactile feedback is that it makes interaction with virtual objects more realistic. This can be done with visual feedback as well but tactile feedback feels more natural. The flexible tactile sensor disclosed herein can be linked with actuator such as piezoelectric actuators to provide force feedback to the user in a virtual environment. For instance, when a user touches a virtual wall, haptic feedback creates an impression of friction. In the future, such gloves could enhance many aspects of life. One example is the ability to communicate with others in virtual reality.

20 [00136] In health monitoring the sensor can be used to monitor involuntary muscle movements such as measuring heart rate. For instance, with embedded microprocessors the sensor can be used in smart watches to monitor heart rate of the patients. It can also be embedded in footwear for monitoring human body motion. For instance, it can be embedded in footwear to distinguish between running and walking and identify number of steps covered.

30 [00137] While the present disclosure has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art

that various changes in form and detail may be made therein without departing from the spirit and scope of the present disclosure as defined by the appended claims. The scope of the present disclosure is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore  
5 intended to be embraced.

**CLAIMS**

1. A flexible pressure sensor comprising:
  - a first flexible layer;
  - a second flexible layer;
  - one or more pressure sensitive layers;
  - wherein each of the first flexible layer and the second flexible layer comprises electrodes spaced apart at a distance sufficient to minimize cross-talk,
  - wherein the first flexible layer and the second flexible layer are arranged to have the electrodes of the first flexible layer correspond in position with the electrodes of the second flexible layer;
  - and wherein the one or more pressure sensitive layers are configured between the first flexible layer and the second flexible layer, and in contact with the electrodes of both the first flexible layer and the second flexible layer.
2. The flexible pressure sensor of claim 1, wherein the first flexible layer and the second flexible layer comprise polyimide, silicone, a thermoplastic elastomer, an insulating material, or a printable resin.
3. The flexible pressure sensor of claim 1 or 2, wherein the one or more pressure sensitive layers are piezoresistive.
4. The flexible pressure sensor of any one of claims 1 to 3, wherein the one or more pressure sensitive layers comprise a polymeric material incorporated with carbon black, carbon fiber, activated carbon, carbon nanotube, or graphene.
5. The flexible pressure sensor of any one of claims 1 to 4, wherein the electrodes of each of the first flexible layer and the second flexible layer are arranged in an array electrically connected by interconnects.

6. The flexible pressure sensor of claim 5, wherein the electrodes and the interconnects comprise electrically conductive nanoparticles.
7. The flexible pressure sensor of claim 5 or 6,  
wherein each of the electrodes has a thickness in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ ;  
and/or  
wherein the interconnects have a thickness in a range of 0.1  $\mu\text{m}$  to 1  $\mu\text{m}$ .
8. The flexible pressure sensor of any one of claims 1 to 7, wherein the distance between adjacent electrodes of each of the first flexible layer and the second flexible layer is in a range of 2 mm to 3 mm.
9. The flexible pressure sensor of any one of claims 1 to 8, further comprising a processing module operably coupled to the flexible pressure sensor, wherein the module:
  - (i) is trainable to discriminate:
    - a point of contact,
    - a direction of the contact, and
    - if an object is sharp or blunt,
  - and
  - (ii) aids in generating a pressure map on a user interface for identifying the point of the contact, the direction of the contact, and if the object is sharp or blunt.
10. The flexible pressure sensor of any one of claims 1 to 9, wherein the flexible pressure sensor is operable in a range of 0 to 600 kPa.
11. A device comprising the flexible pressure sensor of any one of claims 1 to 10.

12. A method of forming the flexible pressure sensor of any one of claims 1 to 10, the method comprising:

forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon;

providing the one or more pressure sensitive layers to be configured between the first flexible layer and the second flexible layer, and in contact with the electrodes of both the first flexible layer and the second flexible layer; and

arranging the first flexible layer and the second flexible layer to have the electrodes of the first flexible layer correspond in position with the electrodes of the second flexible layer.

13. The method of claim 12, wherein forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon comprises printing the electrodes on each of the first flexible layer and the second flexible layer.

14. The method of claim 13, further comprising cleaning of the first flexible layer and the second flexible layer, prior to printing the electrodes.

15. The method of any one of claims 12 to 14, wherein forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon comprises mixing conductive nanoparticles in an aqueous medium to form a nanoparticle ink.

16. The method of claim 15, wherein the nanoparticle ink comprises the conductive nanoparticles in a concentration range of 20 wt% to 60 wt%.

17. The method of any one of claims 12 to 16, wherein forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon comprises printing the electrodes to be spaced apart at a distance sufficient to minimize cross-talk, wherein the distance between adjacent electrodes of each of the first flexible layer and the second flexible layer is in a range of 2 mm to 3 mm.

18. The method of any one of claims 12 to 17, wherein forming the first flexible layer and the second flexible layer both comprising electrodes patterned thereon comprises printing interconnects to have the electrodes of each of the first flexible layer and the second flexible layer electrically connected.

19. The method of any one of claims 12 to 18, further comprising sintering the electrodes at a temperature in a range of 100°C to 300°C.