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Woven Structure for Flexible Capacitive Pressure Sensors

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Abstract

Flexible and stretchable capacitive pressure sensors have been developed in recent years due to their potential applications in health monitoring, robot skins, body activity measurements and so on. In order to enhance sensor sensitivity, researchers have changed structure of the dielectric of parallel plate capacitive sensor . Here we enhance the sensor sensitivities by changing electrode composition and explore the use of a woven electrode structure sensor with silver coated nylon yarn and Ecoflex™. The woven structure enhanced sensitivity 2.3 times relative to a simple cross-grid geometry (sensitivity was 0.003 kPa^{-1}). Furthermore, it is also observed that the sensor with the woven electrode also had better repeatability and showed less creep than a device using carbon black electrodes. The woven structure of the electrodes enabled the device to be compliant, despite the presence of the stiff nylon fibres – thereby enabling good sensitivity without the creep seen in softer electrodes.

INTRODUCTION

Capacitive pressure sensors have long been recognized to be an effective component for interaction with electronic devices. The growing interest in the development of flexible wearable electronics has prompted the interest in flexible sensors. Flexible and wearable capacitive pressure sensors can be used for robotics skins, patient diagnostics, body activity measurements and health monitoring [1-3].

Capacitive sensors are composed of two electrodes separated by a dielectric. In the simplest parallel plate case, the capacitance is given by $C = \varepsilon A/d$, where the parameters are dielectric permittivity (ε), electrode area (A), and dielectric thickness (d). When a capacitive pressure sensor is compressed, e.g. by touch, electrodes are pushed closer together. The reduction in dielectric thickness increases the capacitance. The area is also increased during compression, also increasing capacitance.

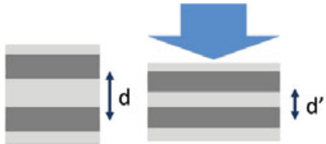

Figure 1. Capacitive sensor working principle

Application of a compressive stress lead to a thinner and wider structure of higher capacitance. In figure 1, electrodes are in dark grey, while the dielectric is light grey.

The electrode materials used in the literature include conducting polymers (e.g. PEDOT), hydrogel, Ag nanowire, carbon nanotube and carbon black based composites [1-3,5-10,12]. In order to enhance sensitivities, soft materials are used for the dielectric layer. One candidate dielectric is Ecoflex™ since it is of low modulus, so compressive and expands in area substantially when it is compressed [4].

A number of researchers are trying to change the structure of dielectric material to make sensors even softer – for example by making the materials microporous or by structuring the dielectric material to form pyramids or other shapes [2,3,10-12]. Kwon et al. have developed a capacitive pressure sensor in which micro porous Ecoflex™ was used as the dielectric. By using a structured dielectric, sensor sensitivity was 4.8 times higher than that of solid dielectric sensor in the 30-130 kPa pressure range. [2]

One of the simplest ways of developing capacitors is to create a sandwich of dielectric between two electrodes. This is the sensor architecture we explore in this work. Multiple sensors can be formed by having a collection of electrode pairs on a dielectric. However, this requires twice as many electrical connections as sensors. Here we create an array by having a set of parallel strips of electrodes on top, and a perpendicular set of parallel strip electrodes on the bottom, all separated by a deformable dielectric. This forms what is commonly known as a cross -grid array, with each crossing point forming a capacitive sensing region. The number of electrical connections is greatly reduced in this way, saving space and electrical components. This cross-grid, described in previous papers [6,12], is compared to a woven pattern. We also explore using conductive yarn as electrodes, in place of less conductive but more stretchable carbon black filled rubber. We compared the sensitivity and repeatability with non-interlaced silver-coated nylon and carbon black based electrodes in this study.

FABRICATION

Four sensor types were fabricated. In all cases there is a dielectric layer that separates two sets of electrodes. The electrodes are arranged orthogonally to each other, as shown in figure 2. The first sensor is simply composed of Ecoflex™ and a carbon black containing Ecoflex™ grid of electrodes, as shown in figure 2(a). On the top layer are electrodes going left to right across the device. These sit above a dielectric layer, which in turn is above a layer with parallel electrodes arranged orthogonally to those on top. The second sensor type replaces the carbon black electrodes with parallel silver-coated Nylon threads (figure 2(b)). In the third implementation, the nylon electrodes are woven from the top surface down to the bottom and back again (figure. 2(c)). The electrodes widths were 2.5 mm and the grid spacings were 9.5 mm for all these sensors. The fourth implementation consists of Ecoflex™ coated yarn, that is woven, as shown in figure. 2(d).

Fabrication of orthogonal sensors with carbon black

Ecoflex™ 00-30 was used in this and other sensor types as 1mm thick encapsulation layers (top and bottom) and as a 1.5 mm thick dielectric. Ecoflex™ was poured into a mould whose area was 55 mm x 120 mm and cured at 60℃ for 30 minutes. To make the capacitive electrodes, carbon black and Ecoflex™ were mixed together. The mixture was patterned on either side of the Ecoflex™ dielectric layer using a mask made of a 120 μm thick plastic sheet. The electrode width was 2.5 mm and it was patterned with 9.5 mm spacing. The conductive composite was also cured at 60 ℃ for 30 minutes. The substrate layers and the dielectric layer were bonded together using Ecoflex™, as shown in (figure 2(a)).

Fabrication of orthogonal sensors with silver coated Nylon yarn

A 3D printed mould whose area was 55 mm x 55 mm and it had slots that are 2.5 mm x 55 mm x 0.5 mm, as shown in figure 2(e), for insertion of the silver coated Nylon yarn (0.54 mm diameter, 0.47 Ω/cm, V Technical Textiles Inc., New York, U.S.A) was prepared. Ecoflex™ was poured into the mould and cured at 60 ℃ for 30 minutes. After curing it, silver coated Nylon yarn was laid into spaces and each space could include five yarns, as depicted in figure 2(e). The electrodes with five yarns were 2.5 mm wide on a 9.5 mm pitch. After yarns were laid into the spaces, Ecoflex™ was poured in slowly until the yarn was covered fully, and then cured in the oven at 60 ℃ for 30 minutes. The 1.5 mm thick Ecoflex™ dielectric layer was sandwiched by electrodes, with the top and bottom electrodes arranged orthogonally to each other (figure 2(b)).

Fabrication of woven structure sensor with silver coated Nylon yarn

A mould for a patterned dielectric was 3D printed. It has 40 square poles inside (dimension 2.5 mm x 0.5 mm x 1.5 mm) (figure 2 (f)). After pouring Ecoflex™ and curing it, the resulting dielectric layer has 40 holes. The silver coated Nylon yarns were passed through these holes as shown in figure 2 (f). Five yarns were sewn into each hole in the warp and weft directions, by hand. The electrodes were 2.5 mm wide with 9.5 mm spacing. At the end, 1 mm thick Ecoflex™ layers were cured in another mould and bonded on the top and bottom of the dielectric layers. These were then cured at 60 ℃ for 30 minutes. (figure 2(c)).

Fabrication of woven fabric sensor with silver coated Nylon yarn

Five silver coated Nylon yarns were twisted together manually, dip coated with Ecoflex™ and cured at room temperature for 60 mins. This procedure was repeated twice. A woven fabric was formed with the coated nylon replacing cotton yarns every 4th strand, in both the warp (0^{o}) and weft (90^{o}) directions. The fabric is shown in (figure

2(d)). A hand-made loom was used for weaving. The yarn density was 3.5 ends/cm and 5 picks/cm. The conductive yarn spacing was 1.25 cm in warp and 0.95 cm in weft.

CHARACTERIZATION OF SENSOR RESPONSE

In order to characterize sensor performance, a Bose Electro-force dynamic mechanical analyser (DMA 3100) was used. The Bose DMA was used to apply controlled forces using an artificial 'finger' that was 3D printed. The indenting surface of the 'finger' was 12 mm x 12 mm. (figure 2(g)). A 4 x 4 readout circuit was connected to the sensor to read capacitance [11].

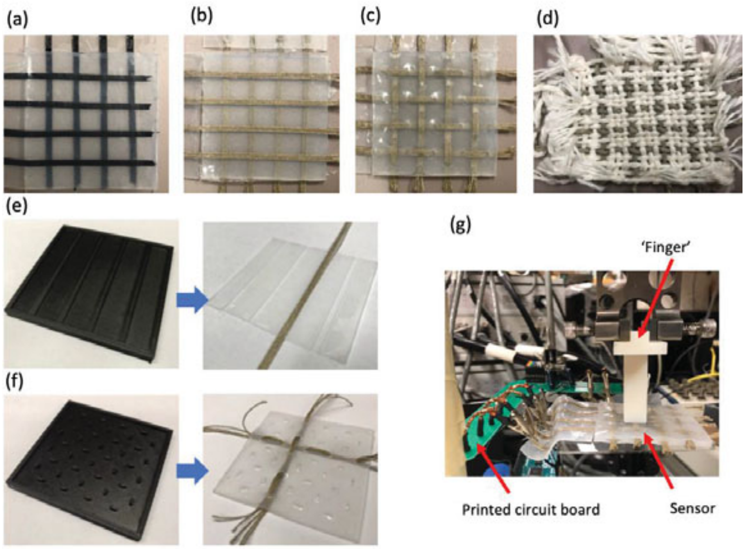

Figure 2. (a) Orthogonal Carbon Black sensor (CB), (b) Orthogonal Silver coated Nylon yarn (Ag yarn) sensor (c) Woven Ag yarn sensor (d) Woven fabric sensor, with white cotton threads and Ag yarn. (e) A 3D printed mould for the Orthogonal Ag yarn electrode and the resulting Ecoflex™ with Ag yarns inserted into one of the channels. (f) A 3D printed mould for the dielectric layer, with square pins that result in holes in the Ecoflex™ layer. Ag threads are then sewn through the holes, as seen on the right, (g) Compression testing of the sensor, including the printed circuit board, and the 3D printed 'finger'.

RESULTS AND DISCUSSION

Measurements of capacitance response to increasing pressure

Figure 3 (a) shows relative capacitance changes ($\Delta C/Co$) in response to 'finger' touches, applied by indentation using the apparatus shown in figure 2(g). A programmed pressure stimulus was applied with increasing levels of pressure from 10 to

100 kPa, returning to the 'zero' level after each stimulus. Cross-sectional images of the deformation induced by the 'finger' are shown in figure 3 (b) for the Orthogonal Ag yarn case (top) and the Woven Ag yarn (bottom). In all experiments a 'zero' pressure of 4 kPa is applied to ensure good contact. The results are obtained from element 2,2 in the arrays. Co is defined as the average of capacitance value obtained during the 20 seconds prior to the application of force to the sample. Co was 1.20 pF for the Orthogonal CB, 1.29 pF for the Orthogonal Ag yarn and 1.40 pF for the Woven Ag yarn. The woven sensor capacitance is likely higher due to the geometry of the woven electrodes, which bend around each other, as seen in figure 3(b). For all sensors there is a step-like rise in capacitance when pressure is applied, with the amplitude increasing as pressure goes up. There is some viscoelastic response, with the change in capacitance showing a rise or a fall and then stabilization following the step changes in force. There is also some creep, which is particularly evident in the carbon black sample, where unloaded capacitance continually rises over the course of the experiment. The highest sensitivity is obtained from the Woven Ag yarn sensor.

Electrode Material effect

Replacing the carbon black with Ag yarn using the same orthogonal electrode geometry leads to a drop in sensitivity but also a drop in creep. Sensitivities are calculated by using the formula $S = \Delta C/Co/P$ (% kPa^{-1}). At 100 kPa, sensitivities are 0.32 % kPa^{-1} and 0.12 % kPa^{-1} for Orthogonal CB and Orthogonal Ag yarn, respectively - with the carbon black version being a factor of 2.6 times higher. An important aspect of the response is that the capacitance of the CB sensor after a pressure stimulus does not return to the initial value upon releasing the stress. This is presumably due to the viscoelastic nature of the elastomer and the CB composite. The final capacitance value of the CB sensor was 8 % higher than the initial rest state, however the difference was only 2 % for the Orthogonal Ag yarn sensor. If the creep is taken into account, the sensitivity of the CB sensor is 0.24 % kPa^{-1}, and 0.11 % kPa^{-1} for the Orthogonal Ag yarn sensor – still a factor of 2.2 different. The Ag yarn is a stiff material that is unlikely to show low creep. It also will prevent much of the lateral movement in the dielectric, perpendicular to the applied pressure. Reduction in this lateral creep reduces the change in capacitance that would otherwise occur as the electrode area expands. As a result, it is not surprising that the Orthogonal Ag yarn sensor shows both lower sensitivity but also lower creep than the Orthogonal CB sensors. Interestingly, the woven yarn shows low creep and sensitivity that is only slightly reduced compared to the carbon black. This is now discussed.

Architecture effect

The woven sensor has a distinct electrode architecture that changes both the electrical and mechanical responses of the material. Sensitivity of the Woven sensor (0.30 % kPa^{-1}) is 2.3 times greater than that of the Orthogonal sensor. The sensitivity is only slightly lower than that of the CB sensor – presumably because the undulating nature of the yarn electrode enables both vertical and lateral deformations of the sensor. The final capacitance at zero load of the woven Ag yarn sensor was 1.5 % higher than the initial value, similar to the Orthogonal Ag yarn case, but much lower than in the carbon black case.

As seen in figure 3(a), all the sensors demonstrate phenomena which capacitances were not returned to the initial value and when pressure was increased and decreased rapidly, capacitances didn't immediately reach their steady state values. At 100 kPa, where the effect is largest, a relative change in capacitance of 0.9 % is observed in the CB sensor over the 30 seconds that the pressure is maintained. These phenomena are likely due to viscoelasticity of the Ecoflex^{TM}, as previously observed [11]. Specifically, the orthogonal CB sensor shows larger creep, which makes sense since the entire sensor, including the electrode, is made of soft elastomer. The stiff nylon fibres presumably act to limit these effects. Figure 3 (c) shows the repeatability of sensors and a comparison of change in capacitance of each sensor due to same stimulus. 100 kPa was applied for ten cycles. This shows that sensors produce a reproduceable response for multiple pressure cycles of loading and unloading. It is observed that the capacitance value is mostly recovered upon release of the pressure for both the Ag yarn sensors, whereas creep is significant for the CB sensor. figure 3 (d) illustrates the response when different programmed levels of pressures are applied to the Woven Ag yarn. It is observed that there is a relatively small history effect in the Woven Ag yarn. Figure 3(c) shows that this creep effect is mostly stabilized after the first cycle.

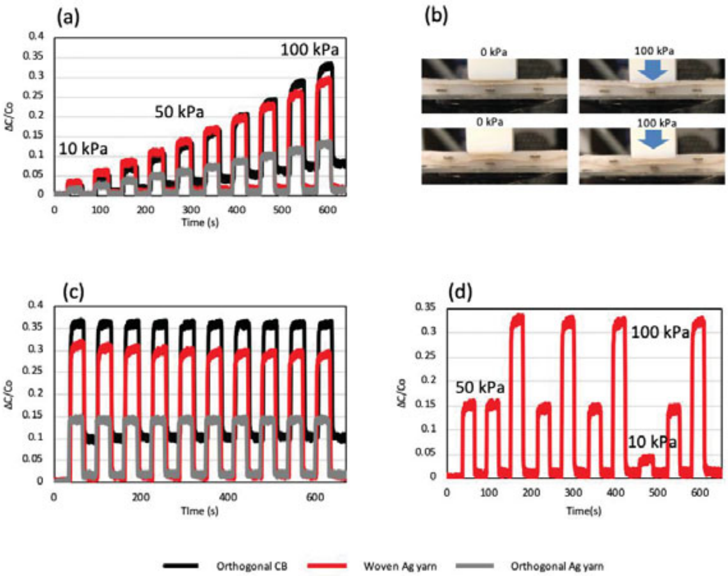

Figure 3. (a) Relative change in capacitance, comparing results among orthogonal CB, Ag yarn and Woven Ag yarn sensors response to increasing pressures up to 100 kPa, (b) Cross-section of Orthogonal and Woven Ag yarn before (0 kPa) and during (100 kPa) indentation, (c) Response to 10 step loads of 100 kPa and (d) Relative change in capacitance of the woven sensor in response to steps in pressure of varying amplitudes.

Strain stress measurements

The stress-strain characteristics of the sensors are shown in figure 4 (a) over five cycles. The sensor thicknesses were 2.81 mm for Orthogonal CB sensor, 3.07 mm for Orthogonal Ag yarn sensor and 3.57 mm for Woven Ag yarn sensor. The variation of thickness is considered due to be primarily due to the thickness of the layer of Ecoflex^{TM} that is encapsulating electrode. The thickness of dielectric and the width of the electrodes are held constant. Comparisons between devices are made based on relative changes in capacitance to normalize for any differences in geometry. Every sensor shows a hysteresis like behaviour. After a single loading and unloading cycle, the values of strain were 17.7 % for the Orthogonal CB, 8.6% for the Woven Ag yarn and 6.6% for the Orthogonal Ag yarn. These responses show the viscoelastic nature of the Ecoflex^{TM} elastomer material. The strain over the first cycle explains the offset in the capacitance value that is seen in figure 4(b) upon releasing the stress. The hysteresis like behaviour for a solid Ecoflex^{TM} dielectric and also a dielectric with air cavities is discussed in detail by Sarwar et. al. [12]. Interestingly, the creep seen in the stress-strain curves is much larger, percentage wise, than the offset seen in the capacitance, as seen in figure 4(b) shows the relationships between strain and capacitance change ratio. There is an offset of about 10 % in the capacitance after the first cycle for the carbon black electrode. This is presumably because the capacitance, Co, also includes fringing capacitances and parasitic capacitances away from the cross-over region, as discussed by Sarwar et al [12] ΔC/Co is linear with strain, with some viscoelastic effect, as seen from the first cycle offset and the 'hysteresis'.

Comparing the elastic moduli from the slopes of the plots in figure 4(a), it is observed that Orthogonal CB sensor is softer than Orthogonal Ag yarn sensor, and the Woven Ag yarn sensor is more compliant than the Orthogonal Ag yarn sensor. This order corresponds to and explains the relative sensitivities of the sensors, as seen from the slopes in figure 4(b). In the case of the Orthogonal CB sensor, the electrodes are deforming along with the dielectric. In the Orthogonal Ag yarn sensor case, threads are not stretchable, reducing strain and creep in the dielectric and in the electrodes. In spite of having Ag yarn as electrodes, the woven capacitor is relatively compliant. It is likely deformed more than the Orthogonal Ag yarn because the woven structure is also relatively compliant. This compliance and the deformation of the woven structure can be seen by examining the cross-sections of the two when under compression (figure 3(b)). The woven sensor is softer than an orthogonal sensor, enabling more change in thickness and area.

So far, we have shown that the woven sensor shows nearly the same sensitivity as the sensor with the carbon black electrodes. A key advantage of the woven geometry is its lower creep. Another advantage is that the silver yarn offers lower resistance 2.3 x10^4 S/m for the silver yarn vs. 2 S/m for carbon black containing Ecoflex^{TM}. The higher conductivity should enable faster measurement of capacitance since resistance effects are lower. The smaller RC charging time enable capacitance to be measured faster.

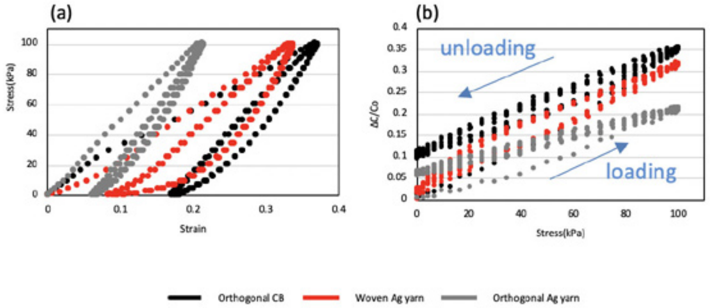

Figure 4 (a) Stress-strain curves (first and second cycles) run at a rate of 3.3 kPa/s and (b) Capacitance change during the stress-strain tests from the three film sensors.

Woven fabric sensor

We briefly explore making the sensor completely woven. Fig. 5 shows the change in capacitance, ΔC (pF) of woven fabric sensor of figure 1(d) when a pressure stimulus is applied to two different locations where the electrodes intersect (also known as taxels). Each Ecoflex^{TM} coated yarn thickness was 1.49 mm. (thickness without Ecoflex^{TM} was 1.16 mm) Upon applying and releasing the final load of 100 kPa, the steady state capacitance was 2 % greater than the steady state capacitance value at the beginning. This is an almost same deviation compared to the Ag yarn sensor. The results in Fig. 5 demonstrate that the woven sensor is repeatable over several presses. The slight difference in the ΔC values of the two taxels is likely because the coated yarn and non-conductive yarn was not thin enough to make this fabric smooth - which means that the pressure may not be uniformly applied under the indenter. Nevertheless, the results are within 10 % of each other. The advantages of fabric over film are breathability, potential to make if highly bendable and conformability thus more comfortable to wear and easier to handle and processing into broad spectrum of products.

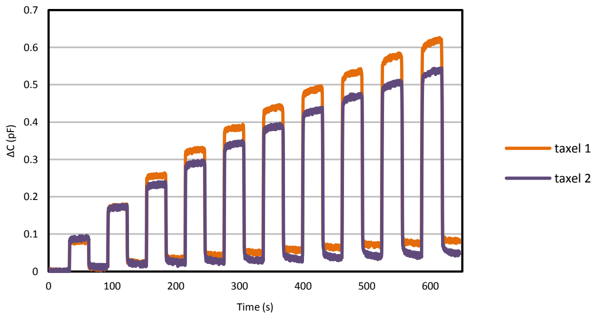

Figure. 5 Change in capacitance of woven fabric response to increasing pressure up to 100 kPa

CONCLUSION

In summary, we have developed a woven structure sensor with Ecoflex^{TM} elastomer as the dielectric and silver coated nylon yarn as the electrodes. It is found that the woven structure enhances the sensitivity compared to an orthogonal structure with Ag yarn. The woven silver yarn electrode pattern provides a 2.3 times higher sensitivity than that of the orthogonal sensor. A sensor made using orthogonal carbon black electrodes shows slightly higher sensitivity than the woven silver yarn sensor, but also showed large creep. The main advantage of the woven elastomer geometry is the reduced electrode creep, compared to carbon black, providing higher stability in sensing, combined with the enhanced compliance of the woven structure, allowing sensitivity to be maintained.

ACKNOLEDGEMENTS

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