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Wearable capacitive pressure sensor using interdigitated capacitor printed on fabric

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Abstract

This paper presented a systematic approach to electro-textile pressure sensors dependent on interdigitated capacitors (IDCs) printed on fabric. In this study, we proposed a highly sensitive, broad-range pressure sensor based on the combination of porous Ecoflex, carbon nanotubes (CNTs), and interdigitated electrodes. Firstly, characterizations of the interdigitated capacitor using silver ink on Cotton and Polyester fabric were completed by precision LCR meter across the frequency range from 1 to 300 kHz. The effect of the fabric on the performance of sensor sensitivity was included. Secondly, estimating and optimizing the volume fraction of CNTs and air gaps on the properties of composites are included. The presence of volume fraction CNTs enhanced the bond strength of composites and improved sensor deformability. The robustness of the presented sensor was demonstrated by testing under high pressure at 400 kPa for more than 20,000 cycles. Thirdly, the combination of CNTs and porous dielectric achieved a broad detection range (400 kPa) with a sensitivity range from 0.035 (at 400 kPa) to 0.15 KPa^{-1} (at 50 kPa). Finally, the Cotton and Polyester substrate comparison demonstrates that selecting a suitable dielectric substrate affects sensor sensitivity and signal output.

Keywords: Capacitive pressure sensor, Electro-textile, Wearable sensor, Wearable electronics , Fabric sensor

Introduction

Nowadays, wearable sensors, particularly textile sensors, have become an exciting issue and attracted significant interest from researchers. Among these sensors, the exceptional properties of pressure sensors make them a promising component in the next generation of flexible electronics. They have been made for commercial purposes along with scientific fields such as healthcare monitors, aeronautics, robotics, etc. (Castano & Flatau, 2014; Huang et al., 2019; Seyedin et al., 2019). In addition, they can be attached to the skin or on clothing to monitor physiological signals or external pressure under continuous working conditions without disrupting or limiting the individual's day-to-day activities. Many efforts have been studied to develop flexible pressure sensors. There are numerous approaches for measuring pressure using piezocapacitive, piezoelectric, triboelectric, and piezoresistive effects. Among them, capacitive pressure sensors depending on a parallel plate capacitor are widely used due to the advantages of lower power consumption, faster response times, and a simple structure. In theory, the capacitance of a parallel plate capacitor is given by the Formula (1):

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \tag{1}$$

where ε_r represents the dielectric constant of the material, ε_0 vacuum permittivity is, A is the effective area of upper and lower plates, and d is the thickness or spacing between two electrodes. By changing ε_r, A, and d, the capacitive sensors can be divided into three types: variable dielectric, variable area (Guo et al., 2019; Wan et al., 2017), and variable spacing distance (Mahata et al., 2020; Ruth et al., 2020). In this approach, thickness or dielectric layer changes under external force, simultaneously leading to variation in the capacitance of the sensor. Due to dependence on parameters A and d in Formula (1), changing the area or thickness affects the pressure sensitivity ("One-Rupee Ultrasensitive Wearable Flexible Low-Pressure Sensor | ACS Omega" n.d.). Therefore, the sensitivity that this method can achieve is typically very low (Zang et al., 2015). Most methodologies on flexible sensors have been focused on improving the sensitivity and flexibility of capacitive pressure sensors. Those depend on the dielectric layer's deformability ("Flexible Capacitive Pressure Sensor Enhanced by Tilted Micropillar Arrays | ACS Applied Materials & Interfaces" n.d.; Ruth & Bao, 2020; Wang et al., 2020; Xiong et al., 2020) or increase in effective area and thickness ("One-Rupee Ultrasensitive Wearable Flexible Low-Pressure Sensor | ACS Omega" n.d.). However, these methods have a slow recovery time, high cost, and complicated fabrication to make the microstructure. In addition, the high density of porosity in the dielectric layer may create noise and affect the stability and durability of sensors.

In this work, we proposed designing and implementing the textile pressure sensor based on calculating interdigital capacitance. We focused on only the modification of the dielectric layer to improve sensitivity. This method uses only one electrode, so the sensor is not affected by the distance of the dielectric layer but instead detects a variable capacitance from changing the relative permittivity of the porous polymer layer under compression. The electrode was fabricated using silver paste printed on cotton fabric, which resembles the comb with multiple interdigitated fingers. The efforts to increase the sensitivity in this paper were grouped into two major studies: the dielectric change of the elastic layer and the generation of microparticles inside the dielectric layer. Finally, the experiment results showed that the proposed sensors could be advantageous in size, sensitivity, cost, durability, and power consumption, which will have many potential applications in the next generation of wearable electronics.

The rest of the paper was separated into the following sections. Firstly, the experiment introduces novel pressure techniques based on changing the relative permittivity. Secondly, "fabrication" illustrates the fabrication process of the proposed capacitive pressure sensor. Next, "measurement results and discussion," where the comparison of characteristics between Polyester and Cotton substrates, including effects of sensitivity, cost, and durability. Finally, conclusions were drawn in the last section.

Experimental

Conductive tracks and principle of the transducer

The interdigitated capacitor uses lumped circuit elements known as a multi-finger periodic structure. Unlike the parallel plate capacitor, the interdigitated capacitor requires only one-sided to detect variations of material under test (MUT). This design has a higher quality factor than a parallel capacitor (Aparicio & Hajimiri, 2002). The interdigitated sensor has the same principle of operation as two parallel plate capacitors. In this structure, the capacitance occurs across between narrow gaps of fingers. When the gaps decrease, the capacitance increases accordingly. The shape of the sensor is described by the parameters shown in Fig. 1.

Typically, we chose the dimension of the gaps among fingers (G), and spaces at the end of fingers are the same. The capacitor design with eight fingers shown in Fig. 1 has the following parameters in Table 1. Due to the potential for high conductive and low cost, the structure of the presented sensor uses silver ink as a conductive material. This technique can achieve high geometrical precision with a resolution lower than 100 um. The characteristics and curing conditions of DM-SIP-2001 silver past applied in this study are shown in Table 2.

When the MUT (material under test) is applied onto the interdigital capacitor electrodes, the capacitor across the finger electrodes will change due to the frequency and

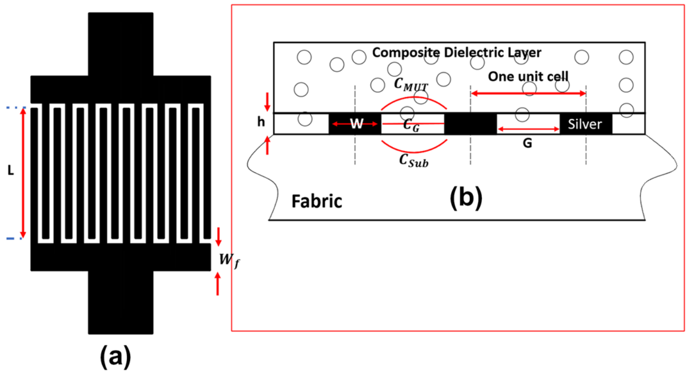


Fig. 1 **a** Top view and **b** cross-section view of the integrated capacitor

Table 1 Characteristics of silver ink printed on fabric

Type	Property
Curing conditions (°C, min)	120, 15
Density (g/cm^3)	2.1
Sheet resistance (mΩ/□/mil)	< 29 @120 °C

Table 2 Final structural dimensions of the proposed sensor

Parameter	Dimension
Finger width (W)	0.57 (mm)
Gap between fingers (G)	0.71 (mm)
Length of the overlapped region (L)	15 (mm)
Width of feedline (W_f)	2.85 (mm)

dielectric variations. Finally, the presented sensor transforms dielectric changes of MUT into pressure. The capacitance change for the interdigital microstrip structure is determined by summing up the unit cell capacitance (Fig. 1b). Each unit cell is calculated as formula (2) (Ong & Grimes, 2000):

$$C_{Cell} = C_{MUT} + C_{Sub} + C_G \tag{2}$$

$$C_{MUT} + C_{Sub} = \varepsilon_0 \frac{(\varepsilon_{\text{MUT}} + \varepsilon_{\text{Sub}})K(\sqrt{1-\delta^2})}{2K(\delta)} \tag{3}$$

$$C_G = \varepsilon_0 \varepsilon_{\text{MUT}} \frac{\text{h}}{\text{a}} \tag{4}$$

$$\delta = \frac{\text{h}}{\text{a}} \tag{5}$$

where $\varepsilon_0 = 8.85x10^{-12}F/m$ is the relative permittivity of free space, C_{Sub} is the capacitance of substrate, and ε_{MUT} is the relative permittivity of the MUT. C_{MUT} is the capacitance of material under test (MUT). C_G is the capacitance between electrodes. K(x) is the elliptic integrals of the first kind, h is the thickness of the metal layer, and a is the dimension one unit cell. The Formula (3) shows that $(\varepsilon_{\text{MUT}} + \varepsilon_{\text{Sub}})$ represents the capacitance changes in the sensor. This capacitance is far more significant than capacitance between electrodes (C_G), so the effect of C_G is not considered. In formula (3), capacitance increases correspond to increasing dielectric MUT and substrate featured by a gain equal to $(\varepsilon_{\text{MUT}} + \varepsilon_{\text{Sub}})$. In this series component, ε_{MUT} is assumed to be changed under pressure, whereas ε_{Sub} is considered constant. To evaluate the dielectric substrate's effect, we used two kinds of fabric: a low dielectric, whereas the other is high. Moreover, it is known that in terms of loss tangent, Polyester is the best loss tangent, while Cotton fabric is the worst (Cerovic et al., 2009), so both kinds of fabric are good choices for comparisons. Note that because the sensing capacitor depends on the change permittivity of MUT ($\Delta\varepsilon$), various in capacitance ΔC can be understood by calculating (6):

$$\Delta C = \Delta\varepsilon C_0 \tag{6}$$

where C_0 is baseline capacitance or initial capacitance. Capacitance values of interdigitated electrodes are typically low around several femtofarads. In addition, parasitic capacitances are unwanted elements that can affect signal-to-noise in the readout circuitry system. Therefore, from (6), a higher baseline capacitance is needed for more changes in capacitance variance. However, the sensitivity of capacitive pressure sensors is calculated by $S = \frac{\frac{\Delta C}{C_0}}{P} W$ here P represents the applied pressure. Therefore, increasing the sensor's initial capacitance leads to a decrease in the sensitivity, respectively. This discussion will be gone further in the next section. Before that, it is necessary to define that the main challenge to transfer dielectric changes into pressure comes from $\Delta\varepsilon$. The higher $\Delta\varepsilon$, the more sensitivity can be achieved. In this paper, we used two methodologies to develop the deformability of the dielectric layer.

The first method is based on percolation theory using CNTs (carbon nanotubes) as filler load to improve polymer properties. In this method, two main issues should be considered since they affect the selection of suitable particles. The first is the interfacial interaction between CNTs or reinforcement and polymer, known as the percolation path. And the second is the proper distribution and dispersion of CNTs inside the polymer, known as concentrations. The reason for choosing CNTs comes from the aspect ratio between the length and diameter of CNTs. The CNTs have a much larger aspect ratio than 1. On the other hand, the spherical particles have an aspect ratio of approximately 1. The aspect ratio of CNTs is a great advantage for lower critical volumes since the percolation threshold reduces with an expanding aspect ratio of the filler (Bauhofer & Kovacs, 2009). In the next section, we will describe the relationship between concentrations and the percolation path of CNTs composites more clearly. According to the percolation theory, the relationship between relative permittivity (ε) and the volume fraction of the composite filler can be explained by the following power law (Shang et al., 2021; Wang et al., 2015):

$$\varepsilon \alpha \varepsilon_p (f_c - f_{CNTs})^{-t} \text{for} f_{CNTs} < f_c \tag{7}$$

where ε is the dielectric permittivity of mixer composites, ε_p is the relative permittivity of polymer, f_c is the percolation threshold or critical volume, f_{CNTs} is the volume fraction of filler, and t is the dielectric critical exponent.

In addition, to increase sensitivity, we studied the combination of the composite with the microporous. As explained in some earlier works, the capacitance changes when the dielectric of elastomeric changes (Kwon et al., 2016; Yoon et al., 2017). As a result, under pressure, the thickness change in the microporous dielectric layer leads to higher permittivity than none porous one. Then the variations in the effective relative permittivity of microporous (ε_{e}) under external pressure can be determined as follow (Atalay et al., 2018):

$$\varepsilon_{\mathrm{e}} = \varepsilon_{\mathrm{air}} V_{\mathrm{air}} + \varepsilon_{\mathrm{mixer}} V_{\mathrm{mixer}} \tag{8}$$

where $\varepsilon_{\mathrm{air}} = 1$, and $\varepsilon_{\mathrm{mixer}}$ is dielectric mixer of the porous CNTs/polymer. Then V_{air} and V_{mixer} represent the volume fraction of air and composite mixer. Under pressure, the volume air gaps steadily reduce, increasing the relative permittivity of the mixer. In our case, when the air gap reduces to zero, we boost the capacitance change by increasing the ratio dispersion of CNTs inside the elastomeric layer. Note that increasing the number of CNTs inside the polymer leads to changes in the relative permittivity and elastomeric properties. Therefore, choosing a suitable dielectric elastomer is essential to enhancing sensitivity, especially under high pressure. Due to excellent flexibility, elasticity, and stability, the Ecoflex (Smooth-on Inc., Macungie, PA, USA) with hardness at shore 00–30 is suitable for this study.

Fabrication

A screen printing process was used to fabricate electrodes of the presented sensor. The structure of the proposed sensor is shown in Fig. 2, which consists of the fabric playing as the substrate layer, Ag electrodes, and pressure-sensing layer. Two kinds of fabric are

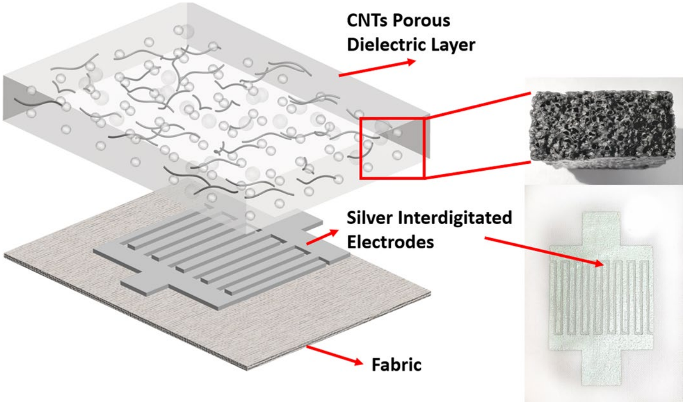


Fig. 2 Schematic diagram of the fabricated pressure sensor. *CNTs* Carbon nanotubes

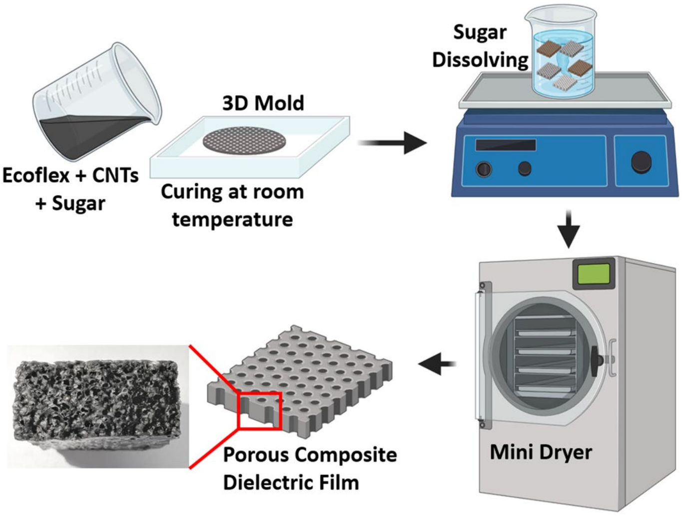


Fig. 3 A fabrication process of the Porous Composite Dielectric Layer

used as the sensor substrate: 100% polyester (nonwoven, 0.3 mm in thickness) and 100% cotton (woven, 0.22 mm in thickness).

The microporous dielectric layer or the pressure-sensing layer was fabricated by the process shown schematically in Fig. 3. The Ecoflex solution was obtained by mixing a base (called Part A) and cured agent (called Part B) with a volume weight ratio of 1:1. After this process, single-wall carbon nanotubes (CNTs) (TUBALL, diameter smaller than 2 nm, produced by OCSiAl) were applied to disperse in the Ecoflex solution. The stirring at 120 rpm for 15 min helps segregate the CNTs bundles and evenly distribute the carbon fibers in the composite. After that, granulated brown sugar was added to the solution and stirred again. The different dielectric films were obtained by changing the volume weight ratio of CNTs and Sugar distributed in the Ecoflex, as shown in Table 3.

The mixer was cured at room temperature (30 °C) for 3 h. In order to form the shape of dielectric films, we used a 3D mold with a length, width, and height of 2, 2, and 0.7 cm, respectively. After the curing time, the mixer was removed from the 3D mold and then dissolved the sugar in boiler water with magnetic stirring at 200 rpm two times, last at

Table 3 Dielectric films with different weight ratios of CNTs inside the Ecoflex polymer

Samples	Volume of Ecoflex (g)	Volume of CNTs (g)	Volume of sugar in the mixture (g)	Percentage of sugar in the Ecoflex (%)	Percentage of CNTs in the Ecoflex (%)
CNTs + Ecoflex	1	$2.5x10^{-3}$	0	0	0.25
CNTs + Ecoflex + Sugar	1	$2.5x10^{-3}$	1	100	0.25
Ecoflex + Sugar	1	0	1	100	0

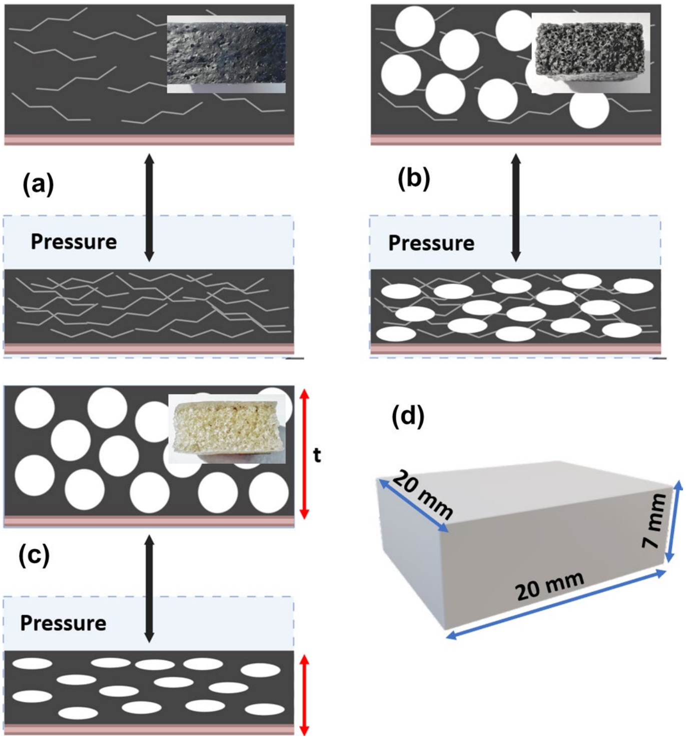


Fig. 4 Schematic illustrations of the capacitive pressure sensor **a** CNTs + Ecoflex; **b** CNTs + Sugar + Ecoflex; **c** Sugar + Ecoflex; **d** 3D view of the dielectric film

least 24 h. One of the reasons for using "weight concentration" is to deal with calculating represent of the amount of sugar in composite in the dissolved process. After the dissolving process, the weight of the composite was reduced by half. Finally, the dielectric films were dried to remove moisture in a conventional mini dryer for 2 h at 100^0 C. In Fig. 4, we can see how the structure of composites interacts with and without appearing porous. As can be seen in Fig. 5, the porous dielectric film shows high mechanical elasticity and flexibility under compression and release. The obtained capacitors are highly flexible, allowing smaller than 20 degrees of bending angle (Fig. 5b).

Results and Discussion

It is known that due to high aspect ratios and long-range Va der Waals interactions, SWCNTs tend to form ropes or bundles with a highly complicated structure, as shown in Fig. 6a. Therefore, CNTs were spread inside the polymer in the form of bundles, as

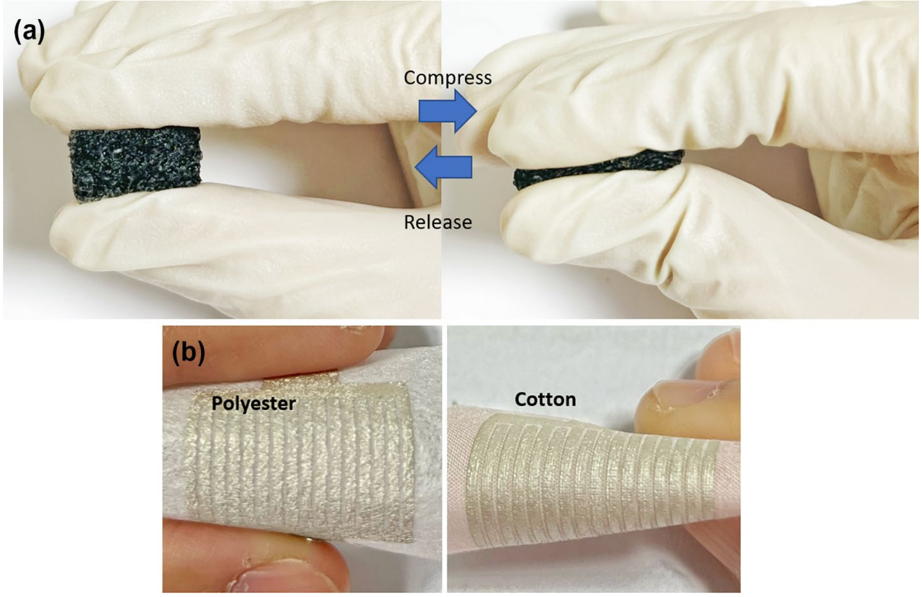


Fig. 5 **a** High flexibility of the dielectric layer; **b** High flexibility of the silver layer

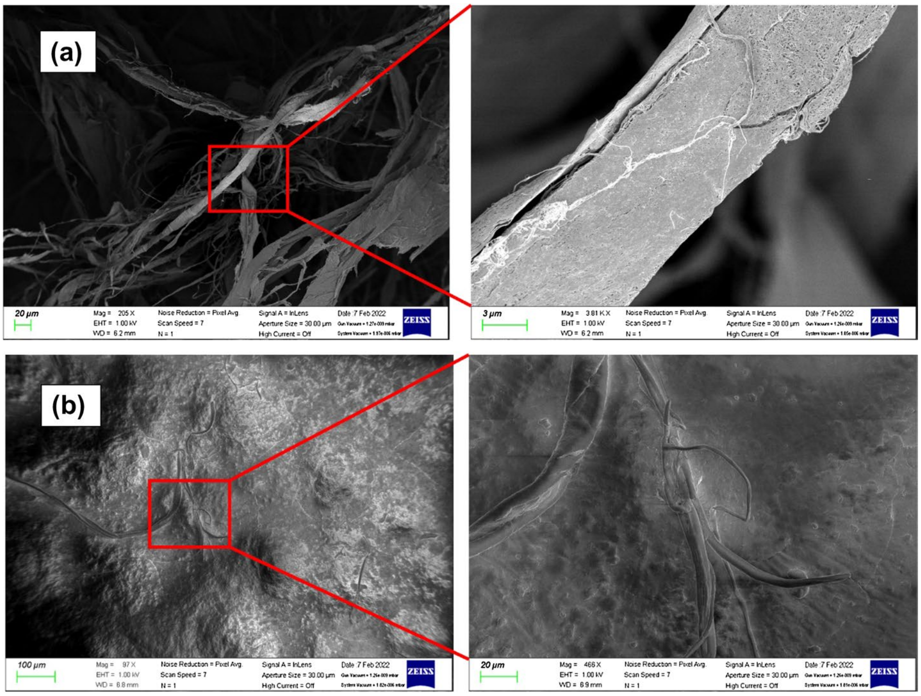


Fig. 6 SEM images of **a** the CNTs; **b** the CNTs Composite Dielectric Layer (CNTs + Ecoflex)

can be seen in Fig. 6b, leading to developing bond strength and enhancing the durability of the polymer. In this study, The robustness of the presented sensor was demonstrated by testing under high pressure for more than 20,000 cycles. In addition, nanotube bundles tended to form a continuous cross-network under pressure, increasing the volume of CNTs dispersed in the composite due to shortening inter-filler distances, as shown

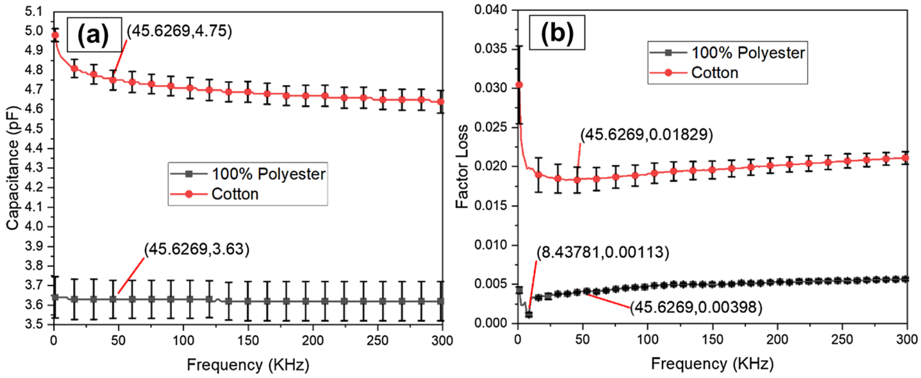


Fig. 7 Frequency dispersion of **a** capacitance; **b** loss tangent

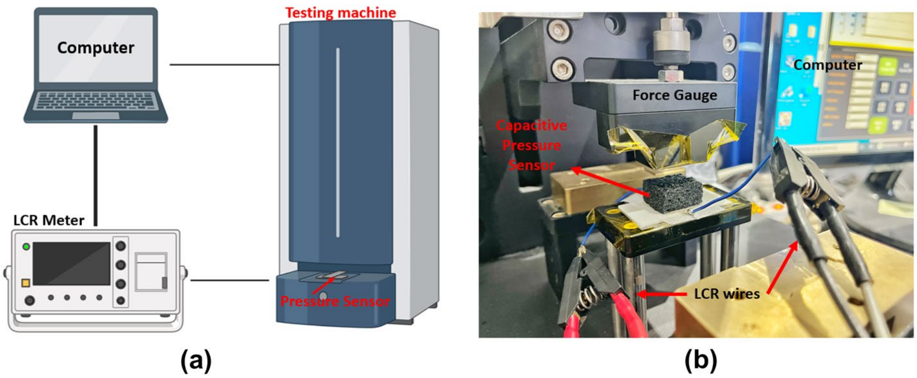
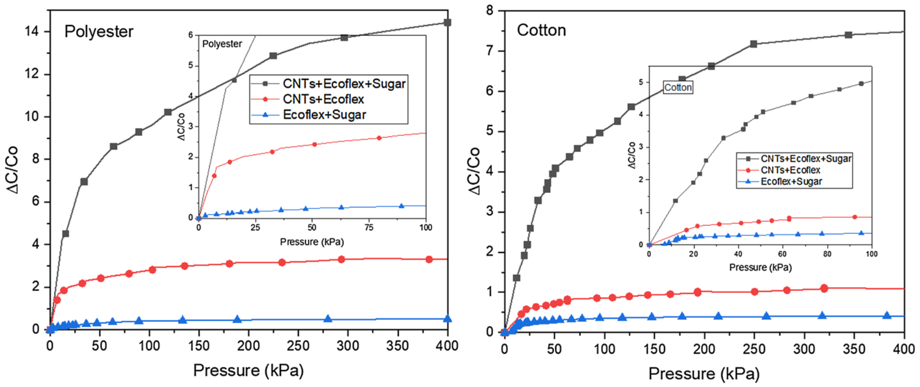


Fig. 8 **a** Schematic of the universal testing machine; **b** Measurement setup for presented pressure sensor with Porous Composite Dielectric Film

in Fig. 4a. From formula (7), the dielectric permittivity increases with an increase in the filler volume fraction; here is CNTs. So the volume fraction plays one of the essential factors of composite. During the preparation process in the laboratory, we choose to due with the weight concentration (wt%) because it is much easier when converting mass fraction to volume fraction. Moreover, due to the high aspect ratio of CNTs, a considerable enhancement in the composite can be achieved with a small volume concentration of filler. The lower the CNTs contents, the more cost is saved; so in this study, using CNTs volumes as low as 0.25% CNTs could be observed.

In order to study the effect of frequency, we tested the capacitance and dielectric loss of silver interdigitated electrodes on both polyester and cotton substrates by using Precision LCR Meter E4980AL. The measurements under 1 kHz are not stable; therefore, Figs. 8 and 9 show results over a frequency from 1 to 300 kHz. From formula (3), the higher permittivity ε_{Sub}, the higher capacitance. Therefore, as can be seen in Fig. 7a, the capacitance value of Cotton fabric is more elevated than Polyester one. Moreover, from Fig. 7b, we can see the dielectric loss of the materials ranges from 0.00113 to 0.02, so it is not negligible in electro-textiles. In order to optimize the dielectric loss, we choose the frequency at the lowest dielectric loss point. Note that even the lowest dielectric loss of Polyester at 8.43 kHz is much lower than the Cotton one; however, it changed



(a) **(b)**

Fig. 9 **a** Pressure-response curves of capacitive pressure sensors with Polyester fabric; **b** Pressure-response curves of capacitive pressure sensors with cotton fabric

dramatically for both fabrics around 8.43 kHz point. So in order to evaluate the effect of non-conductive fabric on sensor sensitivity, in this study, we selected the lowest dielectric loss of cotton fabric at 45 kHz for all measurements.

The schematic diagram for evaluating the performance of the presented sensor is seen in Fig. 8a. The pressure was applied using a Keysight LCR meter (E4980AL) and a force gauge Universal Testing Machine (Dacell Co., Seoul, Korea). They were all connected to a computer to collect the data (Fig. 8b).

Figure 9 shows the pressure-response of different proposed dielectric films on Cotton (Fig. 9a) and Polyester (Fig. 9b) fabric. Experiment results show that for both Figures, the porous CNTs dielectric film has the highest pressure-sensing performance from 0 to 400 kPa, while the porous dielectric film is the lowest. In order to demonstrate this phenomenon, we recall the Formula (8). Under pressure, the porous composite with lower dielectric due to the volume fraction air gap will be replaced by the higher dielectric constant of the non-porous one, consequently increasing the effective dielectric constant of the porous composite.

Moreover, it should be considered that the difference in sensitivity between Cotton and Polyester is significant when using the same kind of dielectric film. As we mentioned in formula (6), the large baseline capacitance is necessary for more change in capacitance variance, making detecting the signal output much more manageable. However, the Formula of sensitivity shows a different way. In our experiment, the baseline capacitance of porous CNTs on the Polyester is around 7 pF, and the Cotton is 13 pF. Even under compression, the capacitance of Cotton fabric is higher than Polyester, the variations in subtraction ΔC and division $\frac{\Delta C}{C_0}$ lead to reducing sensitivity by half. That is why the sensitivity of the sensor printed on Polyester fabric is higher than that of the Cotton one. Note that no porous CNTs sample's baseline capacitance or initial capacitance is more elevated than a porous one. Hence, the sensitivity of no porous CNTs pieces printed on Polyester is three times higher than that of Cotton. In addition, when the initial capacitance of the sensor is too low, like in the porous Ecoflex (Ecoflex + sugar) samples, the variation of sensitivity is not significant on both fabrics.

The pressure response time of the presented sensor was investigated in Fig. 10a. Two different pressures were applied at low and high compressions, 47 kPa and 400 kPa, respectively, which are higher sensitivities than some previously reported pressure sensors (Table 4). The results show that the samples under low pressure were more highly stable and reversible than under high pressure. However, all pieces illustrated a rapid recovery time lower than 0.2 s. In this study, The robustness of the presented sensor was demonstrated by testing under high pressure for more than 20,000 cycles (shown in Fig. 10b). After the first 1000 cycles, the sensor remains stable. As can be seen, the performance of the presented sensor was stable after 20,000 cycles.

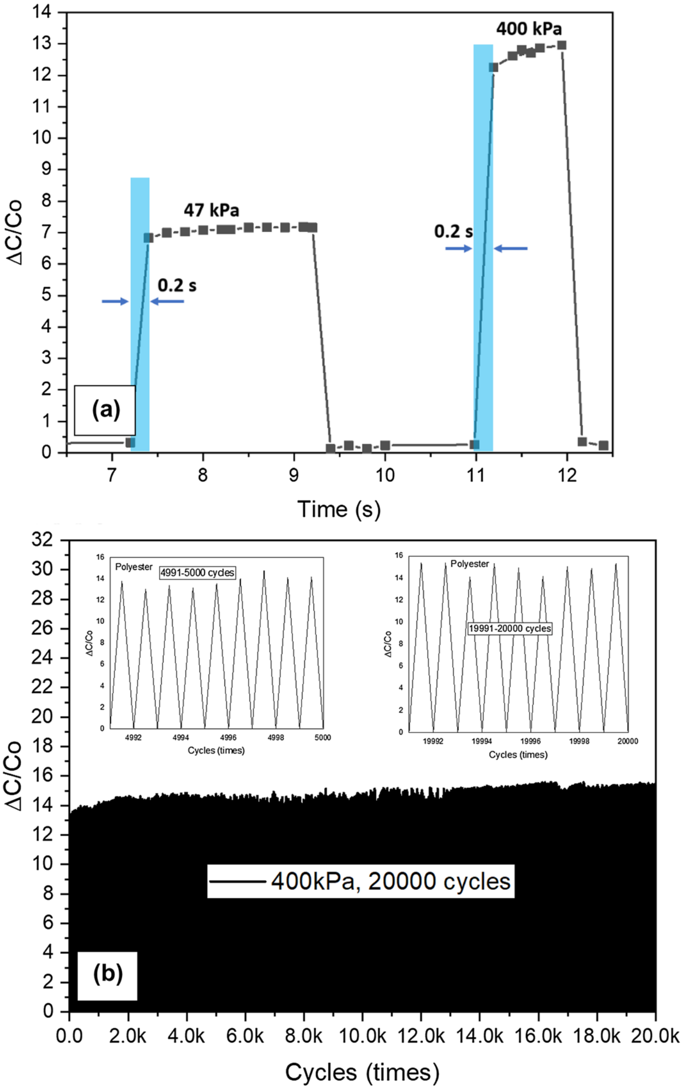


Fig. 10 **a** Pressure-response time of capacitive pressure sensors at 47 kPa and 400 kPa; **b** Capacitance response of pressure sensor during 20,000 loading and unloading cycles at an applied pressure of 400 kPa

Table 4 Comparison of the proposed sensor with reported pressure

References	Principle	Sensitivity kPa^{-1}	Pressure point (kPa)
This work	Capacitive	0.15 0.03	50 400
Lei et al. (2017)	Capacitive	0.17	1
Atalay et al. (2018)	Capacitive	0.0121	100
Kou et al. (2018)	Capacitive	0.0078–0.24	1–100
Hwang et al. (2021)	Capacitive	0.18	5
Feng et al. (2020)	Resistive	7.62 0.14	50 200
Chen et al. (2018)	Resistive	5.67	0.42

Conclusions

We presented a novel approach to electro-textile pressure sensors using interdigitated capacitors (IDCs) fabricated a flexible substrate. The presented sensor can accomplish a highly sensitive, broad range (400 kPa) with a sensitivity range from 0.035 (at 400 kPa) to 0.15 KPa^{-1} (at 50 kPa). The dielectric layer can achieve outstanding durability due to the combination of highly resilient characteristics of Ecoflex and CNTs. Furthermore, the proposed sensor exhibited fast response and recovery time with a wide detection range of more than 400 kPa. Moreover, the effect of dielectric substrate on the performance of sensor sensitivity plays a key role in insensitivity and detection of signal output. Therefore, selecting a suitable dielectric substrate for practical application should be considered.

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Author contributions
As a corresponding author, Kim Jooyong was responsible for the whole structure construction and drafted the manuscript. At the same time, Truong TranThuyNga was responsible for experiment design, data collection, data processing, and modeling. Kim Ji-Seon and Eunji Yeun were responsible for data cleaning and choosing materials. Finally, all authors read and approved the final manuscript.

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Availability of data and materials
Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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