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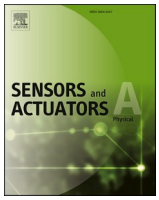
Sensors & Actuators: A. Physical 392 (2025) 116734

Contents lists available at ScienceDirect

Sensors and Actuators: A. Physical

journal homepage: www.journals.elsevier.com/sensors-and-actuators-a-physical



Highly sensitive PDMS-Ag nanoflakes porous pressure sensors prepared by templating and molding approaches for wearable applications

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ARTICLE INFO

Keywords:
PDMS foam
Silver nanowires
Wearable pressure sensor
Piezocapacitance
Templating method

ABSTRACT

The rise of information technologies has led to the need for collecting vast amounts of multidisciplinary data related to human habits, social interactions, and physical activities. This demand has intensified the challenge of integrating rigid electronics with the flexibility of human tissue. Wearable sensors have emerged as a solution to detect several biometric signals from human body. Among these applications, pressure sensing is particularly crucial. In this work, we present a flexible, sandwich-structured pressure sensor based on a porous PDMS sponge. Two distinct fabrication methods were investigated with a critical analysis of their advantages and limitations. A templating technique using a common sugar cube as a sacrificial mold, and a molding method where a sugar-PDMS slurry was shaped using a predefined mold. While the templating approach offers simplicity and accessibility, the molding method provides greater control over geometry and customization. All fabricated sensors demonstrated excellent piezocapacitive performance under mechanical compression, characterized by minimal hysteresis during cyclic loading—an essential feature for consistent and reliable sensing. To boost sensitivity, silver nanoflakes were incorporated into the polymer matrix, resulting in a 65 % increase in pressure sensitivity, achieving up to 0.047 kPa^{-1} , one of the highest value reached by PDMS-based foam sensors, and lowering the detection threshold to just 0.6 g (40 Pa). The successful implementation of these sensors in wearable formats underscores their potential as lightweight, scalable, and cost-effective platforms for continuous biometric monitoring in real-world applications.

1. Introduction

The recent development of Information Technologies requires to collect a large amount of multidisciplinary data derived from humans' habits, social life and physical activities. Consequently, the need for new ways to interface rigid electronic devices with soft and flexible human tissues has drastically grown. Nowadays, wearable sensors and devices constitute the link between the two realms. Wearable devices have such a pervasive and widespread range of applications thanks to the ability to be suitable for a lot of different scenarios and to detect and monitor a full range of signals, from heart rate to anxiety. Among them, pressure is a crucial physical quantity to be sensed in real-time health monitoring [1–4].

A variety of feasible transduction mechanisms of pressure and, in general, of mechanical stimuli have been explored so far, such as piezoresistivity [5–8], piezocapacity [9,10], piezoelectricity [11,12] and triboelectricity [13,14]. Capacitive pressure sensors have attracted more interest compared to other types of sensors such as resistive, piezoelectric and triboelectric, thanks to their simple structure, low fabrication cost, low power consumption, high sensitivity, good dynamic response performance and strong adaptability to harsh conditions such as high temperature, radiation and strong vibration [15,16]. For capacitive pressure sensor a highly deformable dielectric layer is the crucial component for enhancing the sensitivity [15,17]. Promising candidates for this task are the hydrogels, 3D crosslinked networks of hydrophilic polymers capable of retaining large volumes of water. They are either chemically or physically crosslinked and possess highly tunable structural and mechanical properties that can be tailored to the specific requirements of flexible pressure sensors [18]. Water evaporation is one of the main issue with hydrogels since they become dry and losses their physical properties, while the other great challenge with conductive hydrogels is to overcome the incompatibility between mechanical elasticity and high electrical conductivity [19].

Sponges made up of porous polymers are an interesting alternative to hydrogel. The porous structure lends flexibility and lightweight without the risk to lose the physical and mechanical properties over time.

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https://doi.org/10.1016/j.sna.2025.116734
Received 5 March 2025; Received in revised form 9 May 2025; Accepted 25 May 2025
Available online 26 May 2025

Moreover, they merge an high pressure sensitivity with a wide sensing range, because of the softness guarantee by the porous structure. Porous polymer foam has been prepared following different approaches. Most commons are based on the use of preformed templates infiltrated with uncured polymer, such as sugar cubes [20–24], but also the use of salt and sugar powder as filler to be later removed [25–27] or emulsion based on liquid templates [28–30] has been investigated, together with more exotic technique such as infiltration into natural or synthetic sponges [31–33] and microfluidic emulsion approach [34]. Porous structures have also the possibility to load huge amounts of filler to modify the dielectric or conductive properties of the sponge with the goal to increase pressure sensitivity [35,36].

In this study, we developed a high-performance piezocapacitive wearable pressure sensor utilizing a polymer sponge as a soft, compressible dielectric material. Polydimethylsiloxane (PDMS) was selected as the base polymer and rendered porous via two distinct fabrication strategies. The first method used a sugar cube templating technique, where PDMS precursor infiltrated the template by capillary action. The resulting porous sensors exhibited a pronounced piezocapacitive response under compressive stress, which was significantly enhanced by the incorporation of silver nanoflakes. These sponge-based sensors demonstrated excellent mechanical stability, high reproducibility, and negligible hysteresis, alongside an exceptionally low limit of detection (LOD), key parameters for reliable pressure sensing. To overcome limitations in shape control imposed by the cubic sugar templates, we adopted an alternative method using sugar powder. By directly mixing sugar powder with liquid PDMS and casting the mixture into molds, we fabricated flexible, mold-conforming foams. After curing and sugar removal, the resulting sensors retained precise geometries and superior mechanical flexibility. Notably, the molded PDMS foams loaded with silver nanoflakes outperformed the templated counterparts, achieving a twofold increase in pressure sensitivity (0.047 kPa^{-1}) and lowering the LOD to just 0.6 g (40 Pa), among the highest sensitivities reported for PDMS-based capacitive pressure sensors. These exceptional properties underscore the potential of our sensors for integration into next-generation wearable and flexible electronic devices.

2. Materials and methods

2.1. Templating method

Samples were prepared using bi-component PDMS (Sylgard-184 from Dow Corning), silver nanoflakes (average size 4–8 μm, Sigma Aldrich) and sugar cubes acquired from food market. The main steps to prepare a PDMS sponge sensor are sketch in Fig. 1a. PDMS base elastomer and curing agent are mixed in 5:1 or 10:1 ratio in a beaker and are manually stirred with a metallic spatula for 2 min. For composite samples, Ag flakes were added to the PDMS solution at this point. The mixture was then degassed in a container connected with a vacuum pump for 15 min to remove incorporated air bubbles. At this stage a lump of sugar is soaked by half in the blend and placed again in vacuum container for 15 min to facilitate the liquid PDMS mixture to totally fill the inner pores of the sugar cube. The process is repeated for the other half of the cube and then the sample is inserted into an oven (Memmert) at 60°C for 1 h to cure the PDMS. After curing, the cube is submerged in a beaker full of deionized water at 60°C for 30 min in order to dissolve the sugar template. The water is kept in constant agitation by a magnetic stirrer to facilitate the complete dissolution of sugar template which results in a porous PDMS (pPDMS) foam with pore sizes comparable to those of the sugar grains of the template. The as-prepared pPDMS is finally washed a couple of times with DI water and dried into the oven at 60°C.

2.2. Molding method

The uncured PDMS and the sugar powder were directly mixed to be

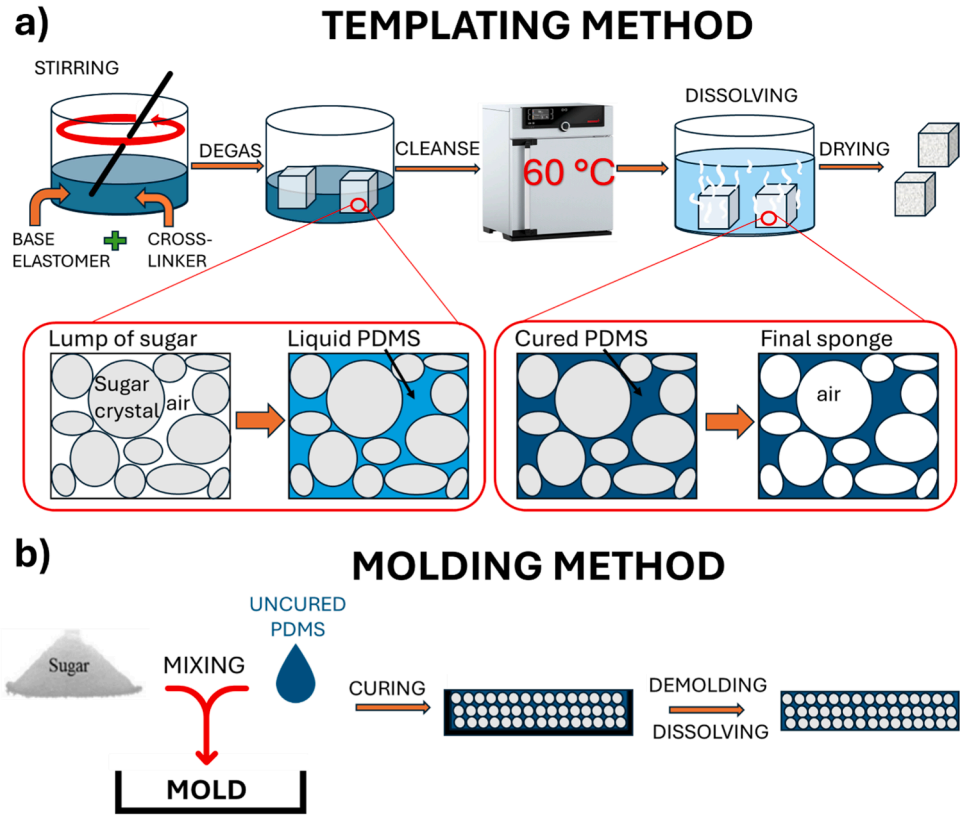

Fig. 1. a) Sketch of the templating method to obtain PDMS sponge sensor with a scheme of PDMS infiltration in the sugar cube and b) sketch of the molding method.

poured in a case. First of all, base elastomer and curing agent were mixed in 5:1 ratio and degassed. Later, commercial white sugar powder was added in a 3:1 wt ratio with respect to the uncured PDMS. For composite samples, Ag flakes were added to the blend at this point. The paste was vigorously stirred by hand for a couple of minutes to reach a sufficient degree of homogeneity and to avoid PDMS sediment. Thereafter, the mixture was poured on a mold, compacted, and cured in the oven at 60°C for 2 h. After the curing process, the sugar was washed away through a deionized water bath in a magnetic stirrer (60°C, 30 min) and the resulting molded porous foam was washed and dried. The main steps are summarized in Fig. 1b

2.3. Characterizations

The pressure sensors were assembled cutting PDMS foam in piece of 3 mm thickness and 1 cm^2 area and coupling with polyimide-copper foils as electrodes. Electromechanical performances of porous sensors were evaluated by means of compressive tests (at velocity of 10 mm min^{-1}) using a universal testing machine (FZ3- X500) while measuring electrical capacitance with a LCR meter (BK precision 894). For all the electrical measures a voltage amplitude of 500 mV and a testing frequency of 300 kHz were used. Relative capacitance variations ($\Delta C/C_0$) were computed according to the following formula:

$$\frac{\Delta C}{C_0} = \frac{C(t) - C_0}{C_0}$$

where where C is the capacitance measured at a certain time t and C_0 is its value when sample is not subjected to any load. Sensitivity (S) was evaluated using:

$$S = \frac{\frac{\Delta C}{C_0}}{p}$$

where p is the pressure applied to the sample. Limit of detection was extracted with static test performed with calibration weights.

Electron microscope characterization was performed by Field Emission Scanning Electron Microscopy (FESEM, Zeiss Supra 40).

3. Results

Polymeric PDMS foam was produced using two different approaches. The first is a casting method with sugar cubes as a template (scheme in Fig. 1a). Sugar cubes were dipped into uncured PDMS and placed in a

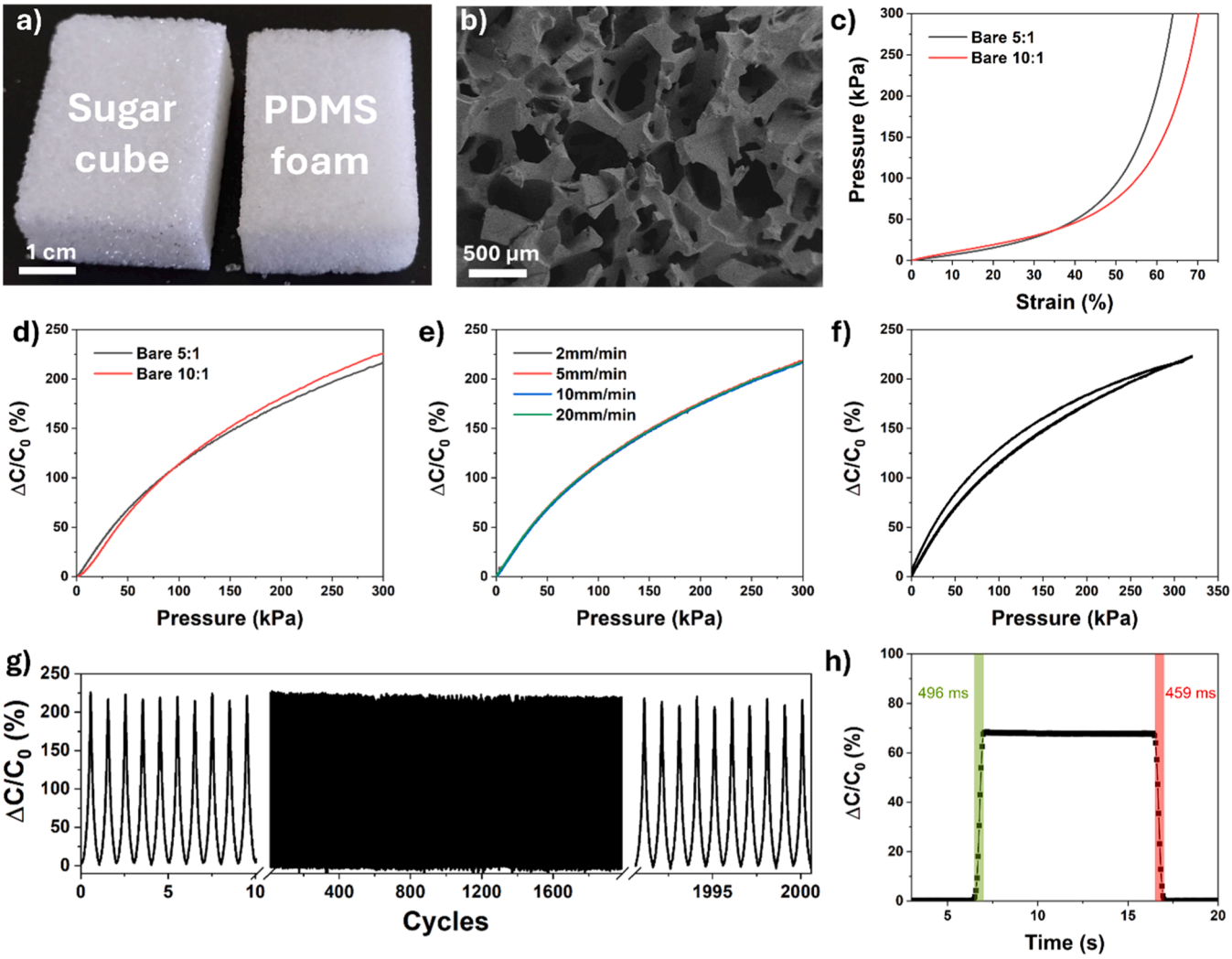

Fig. 2. a) Image of sugar cube and PDMS foam obtained by templating method. b) Scanning Electron Microscope (SEM) image of PDMS foam highlighting the porous structure of the foam. c) Compressive stress-strain and d) piezocapacitive curves of PDMS sponge prepared by templating approach with different PDMS copolymer to curing agent ratio. e) Capacitive response of Bare 5:1 PDMS foam under compressive pressure applied at different velocities. f) Piezocapacitive response of bare PDMS sponge sensor under ten cyclic compression cycles as function of pressure. g) Porous sensor response under 2000 compressive cycles at 320 kPa. h) Relative capacitance response time and recovery time of the PDMS sponge under a compressive stress of 50 kPa.

vacuum container to facilitate the polymer infiltration in the space among the sugar crystals. Uncured PDMS excess was removed from the cubes surfaces to avoid the formation of a polymeric layer on the surface which prevents the accessibility of the pore. After thermal curing, the sugar was dissolved into deionized water leaving a polymeric porous structure. The advantages of this approach lay in its simplicity and reproducibility of the process to obtain polymeric foams, while the limitation resided in the shape of the final sample which is restricted to the starting sugar cube. With the aim of decoupling the shape of the sponge from that of the cubic sugar template a second approach based on a molding method (Fig. 1b) was used. In this approach, white sugar powder and uncured PDMS were mixed together in a 3:1 ratio by weight. The blend was then poured in a mold and cured to reach polymer reticulation. The sample was then demolded and the sugar dissolved in hot water bath leaving the final foam with desired shape.

Given that the polymeric foam can act as a highly deformable dielectric under mechanical stress, the prepared samples can work as pressure sensors exhibiting piezocapacitive properties. These properties were tested using mechanical compression cycles applied with a universal testing machine coupled with electrical impedance measurement. Firstly, the polymeric foam prepared with templating approach were tested. Fig. 2a and b show that the foam shape is strictly dependent on the sugar cube template used and evidence how the PDMS is able to infiltrate in the space among sugar crystals. Foam samples were prepared using 5:1 and 10:1 ratio of PDMS copolymer to curing agent to understand the role of the different mechanical properties of the polymer (i.e. higher content of curing agent will increase the rigidity of the bulk polymer). Stress-strain curves (Fig. 2c) evidence how the mechanical properties are similar for both foams since the porous structure dominates over the mechanical properties of the polymer, especially for lower deformation values. PDMS sponge sensors showed an increase in electrical capacitance under compression (Fig. 2d), due to the reduction in thickness. Both 5:1 and 10:1 foams showed the same behavior, thus for all the following samples presented in this work a 5:1 ratio of PDMS copolymer to curing agent was chosen due to the low viscosity of the mixture before polymerization, which facilitated the infiltration process into the pores of the sugar cubes. The porous structures easily deform under mechanical compression, resulting in a notable capacitance increase even at low pressures. The relative capacitance variation curve is not linear across the entire range but tends to grow slowly under higher pressures. This trend is expected and relates to the relationship between applied stress and induced deformation as shown in Fig. 2c. The PDMS sponge exhibited significant deformation under low stress because the pores close with low mechanical resistance. As the pores close completely, the mechanical resistance increases, and higher pressure results in only slight deformation. Low applied stress values are more relevant for wearable sensing, as this pressure range is typical in human-related applications [37]. The sensor's sensitivity in the 0–50 kPa range, where our sensor exhibits a linear trend with a slope of 0.014 kPa^{-1}, a value comparable to the sensitivity reported for porous sensors prepared using the template approach, whether operating via piezoresistive or piezocapacitive mechanisms [36,38,39]. Moreover, the sensors demonstrated excellent response stability and repeatability. This behavior is evidenced by the piezocapacitive analysis under different applied compression velocities and by the cyclic characterizations. Fig. 2e shows that sensor response is independent on the velocity of applied stress since the transfer curves completely overlap. At the same time the relative capacitance variation curve under ten compressive cycles shows a very good repeatability (Fig. 2f) and overlap of different cycles with almost negligible hysteresis. Excellent stability of foam response is observed also for a higher number of cycles (Fig. 2g). This behavior is attributed to the mechanical properties of the sensor, as the porous structure of the foam reduces the viscoelastic behavior of the PDMS polymer within the investigated pressure range. Moreover, the PDMS foam shows also a fast response to the applied strain, with response time and of recovery time below 500 ms (Fig. 2h), fundamental properties for sensing applications.

To enhance the sensor's sensitivity, we explored the effect of incorporating a metallic filler into the polymer foam, which influenced both its mechanical and electrical properties. Silver nanoflake powder was added to the PDMS mixture before the sugar cube infiltration step at concentrations of 5 %, 10 %, 20 %, 40 %, 60 %, and 80 % by weight relative to the polymer. As the silver nanoflake concentration increased from 5 wt% to 80 wt%, the resulting sponges progressively darkened in color (Fig. 3a). However, the 80 wt% sample exhibited multiple structural voids due to the high viscosity of the precursor solution, which prevented effective capillary infiltration. Consequently, portions of the template remained composed solely of sugar, which were entirely removed during the template dissolution step. Due to these structural inconsistencies, the 80 wt% sample was excluded from electromechanical testing. Piezocapacitive characterizations (Fig. 3b) revealed that the relative capacitance variation increased with higher silver nanoflake content. Sensor sensitivity was evaluated across three pressure ranges (0–50 kPa, 50–150 kPa, and 150–250 kPa), where all samples displayed a linear response. Sensitivity was highest in the low-pressure range but decreased at higher pressures. This behavior corresponds to the stress-strain response of the porous foams. At low applied stress, the material undergoes significant deformation due to pore compression, whereas at higher stress levels, all pores are fully compressed, and only the polymer itself deforms. Across all pressure ranges, sensitivity increased with silver nanoflake content (Fig. 3c). The 60 wt% sensor achieved a sensitivity of 0.023 kPa^{-1} , marking a 65 % improvement over the bare PDMS sponge sensor. Previous works demonstrated that the addition of filler in porous polymeric structure improved the sensitivity in the piezocapacitive effect [40,41]. In this composite foam, increasing the filler content leads to a rise in the dielectric constant due to enhanced interfacial polarization between the conductive silver nanoflakes and the insulating PDMS matrix (or air). This increase in dielectric constant, derived from capacitive measurements using the parallel plate capacitor model, correlates directly with an improvement in pressure sensitivity. This relationship is evidenced by the overlapping trends of the two parameters shown in Fig. 3d. Cyclic testing demonstrated stable device performance with negligible hysteresis, even in composite foam sensors. In addition to sensitivity to applied stress, another key figure of merit for pressure sensors was analyzed. The limit of detection (LOD), defined as the minimum detectable weight with sufficient confidence, was determined using the sensor's response curve under extremely low applied pressures and the noise level of the electrical signal. It was calculated as three times the uncertainty of the zero pressure signal, a standard threshold used in spectroscopy to confirm resonance peaks and in biological assay statistics to validate data points (three times the standard deviation) [42–44]. While the LOD did not show a clear correlation with silver nanoflake concentration, it remained around 1 g (60 Pa) for all devices. These results highlight the potential of PDMS-decorated sponge sensors for detecting small pressures with high sensitivity.

The templating method, combined with the addition of silver fillers, successfully enabled the fabrication of highly sensitive pressure sensors. However, the main limitation of this approach lies in the geometric constraints imposed by using sugar cubes as templating structures. To overcome this restriction, a molding approach was explored for creating porous capacitive sensors, and devices fabricated using both methods were compared. Using the molding approach (Fig. 1b), foam-based sensors with various geometries were produced, both with pure PDMS and PDMS filled with silver nanoflakes. For this method, only 40 wt% and 60 wt% silver nanoflake concentrations were used, as previous characterization of templated samples indicated that foam sensitivity increase with filler content and these concentrations yielded the highest sensing response. Similar to templating approach, 80 % filler results in multiple structural voids in the final material, as the high viscosity of the precursor solution at this level prevented effective capillary infiltration. Fig. 4a presents an example of a dumbbell-shaped structure created

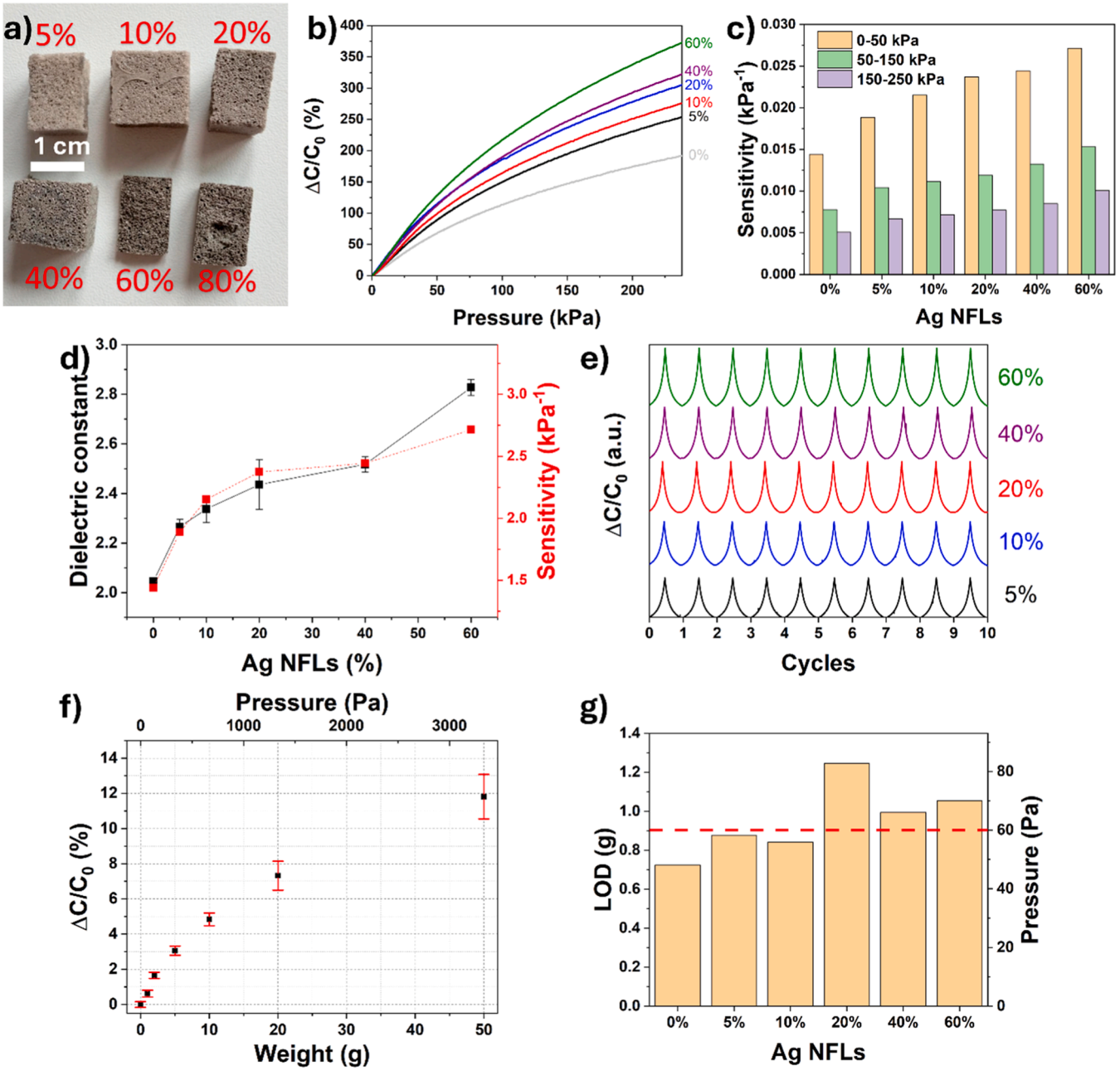

Fig. 3. a) Image of PDMS foam prepared by templating method decorated with different concentration of silver nanoflakes (NFLs). b) Piezocapacitive response under applied compressive pressure of porous sensors prepared by templating approach with different concentration of Ag nFL. c) Sensitivity in the three different analyzed pressure ranges of the different foam sensors prepared by templating approach. d) Comparison of dielectric constant and pressure sensitivity in the 0–50 kPa range of the foam sensor the foam sensors prepared by templating method with different concentration of Ag nFL. e) Piezocapacitive response of the different sponge sensors under ten cyclic compression cycles as function of time. f) Piezocapacitive response of bare PDMS foam sensor prepared by templating approach when compressed with small weight. The curve is used to compute the limit of detection of the sensors. g) Limit of detection (LOD) of the foam sensors prepared by templating method decorated with different concentration of Ag nFL. Red dot line evidence the LOD of 60 Pa.

through molding with 60 wt% Ag-NFLs content, while SEM images highlight the porous structure and the uniform dispersion of the filler within the PDMS matrix. The piezocapacitive response of the molded foams closely resembled that of the templated samples. Sensitivity increased with the addition of silver nanoflakes (Fig. 4b), and cyclic deformation tests showed no hysteresis in the electrical signal (Fig. 4c). Sensitivity was evaluated across three pressure ranges, with the molded sample reaching a maximum value of 0.047 kPa^{-1} for the 60 wt% composition in the low-pressure range. This sensitivity represents one of the higher values present in the literature for capacitive sensors using porous PDMS as dielectric layer, as evidences in the literature comparison shown in Table 1.

A final comparison between the two fabrication approaches was conducted using both bare PDMS samples and composite foams containing 60 wt% silver nanoflakes. By analyzing the piezocapacitive curves and sensitivity (Fig. 5a–b), it was observed that the bare PDMS foams exhibited similar responses and sensitivities, regardless of whether they were produced via templating or molding. However, for composite foams, the molding approach led to a significant improvement in sensitivity, yielding nearly double the response compared to the templating method. This enhancement is attributed to the presence of larger pores in the molded foam structures, resulting from the

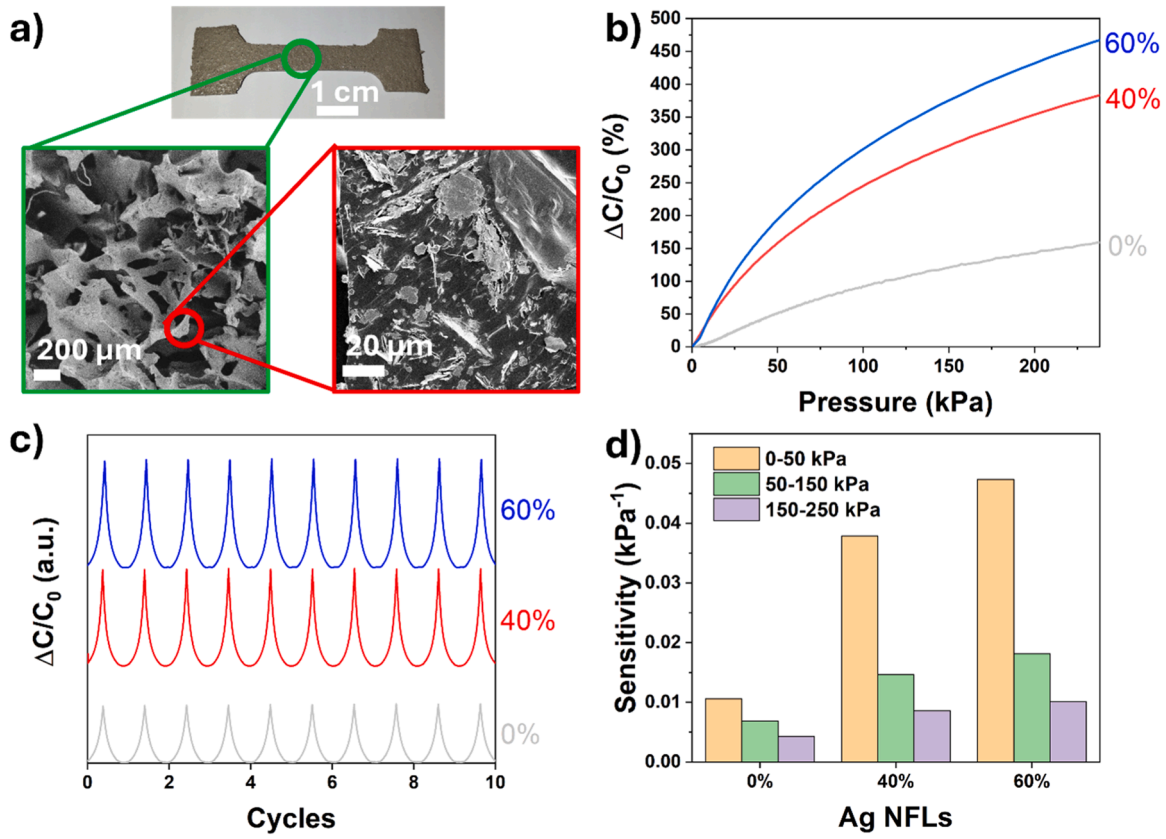

Fig. 4. a) Image of a dumbbell PDMS foam prepared with molding method with 60 % concentration of silver nanoflakes (nFL). SEM image shows the homogeneous dispersion of Ag nFL in the PDMS matrix. b) Piezocapacitive response under applied compressive pressure of porous sensors prepared by molding approach with different concentration of Ag nFL. c) Piezocapacitive response of the different sponge sensors prepared by molding technique under ten cyclic compression cycles as function of time. d) Sensitivity in the three different analyzed pressure ranges of the different foam sensors prepared by molding approach.

Table 1
Comparisons of different capacitive pressure sensors using porous PDMS as the dielectric layer.

Dielectric Material	Foam fabrication method	Electrode	Sensitivity	Pressure range	References
Porous PDMS/Ag nanoflakes	Molding with sugar powder	PI-Cu	0.0473 kPa^{-1}	0–50 kPa	This work
			0.0182 kPa^{-1}	50–150 kPa	
			0.0102 kPa^{-1}	150–250 kPa	
Porous PDMS/Ag nanoflakes	Sugar cube template	PI-Cu	0.023 kPa^{-1}	0–50 kPa	This work
			0.0154 kPa^{-1}	50–150 kPa	
			0.01 kPa^{-1}	150–250 kPa	
Porous PDMS	CO_2 liberation	Ag-TPU	0.0107 kPa^{-1}	0–20 kPa	[46]
			8.4 MPa^{-1}	20–200 kPa	
			3.2 MPa^{-1}	200–1000 kPa	
Porous PDMS	Emulsion	Al and Cu	0.18 kPa^{-1}	0–400 kPa	[15]
Porous PDMS	Leaf and sugar template	MWCNT/PEDOT: PSS	1.12 MPa^{-1}	0–300 kPa	[47]
			0.36 MPa^{-1}	300–800 kPa	
Porous PDMS/BaTiO3	Emulsion	PEDOT: PSS/AgNWs	5.7 MPa^{-1}	0–90 kPa	[48]
Porous PDMS	Ammonium bicarbonate template	PEDOT: PSS/AgNWs	5.5 MPa^{-1}	0–170 kPa	[25]
Porous PDMS	Sugar cube template	MWNT/PEDOT:PSS	1.2 MPa^{-1}	0–300 kPa	[20]
			0.86 MPa^{-1}	300–800 kPa	
			0.36 MPa^{-1}	800–1200 kPa	
Porous PDMS	Molding with sugar powder	ITO	0.01097 kPa^{-1}	10–100 kPa	[49]

aggregation of sugar crystals during processing, as well as the lower uniformity in sugar dispersion compared to the consistent structure provided by sugar cubes in the templating method. To validate this hypothesis, a morphological analysis was conducted on 60 wt% Ag-NFLs templated and molded foams using electron microscopy to assess pore size distribution. The average pore size in the templated sample was found to be 415 ± 124 µm, whereas the molded foam exhibited a larger average pore size of 658 ± 176 µm. Both foams showed significant variability in pore size, primarily due to the non-uniform dimensions of the initial sugar crystals and the complex geometry of the pores, which complicates visual analysis. Nonetheless, the consistently larger pore size observed in the molded samples is likely responsible for the higher pressure sensitivity exhibited by this foam sensor. Under equivalent compressive loading conditions, foam-based sensors with larger pore diameters undergo greater compressive strain relative to those with smaller pores, due to their intrinsically lower Young's modulus. This increased mechanical deformation yields a more substantial reduction in the dielectric layer thickness, thereby resulting in a more pronounced

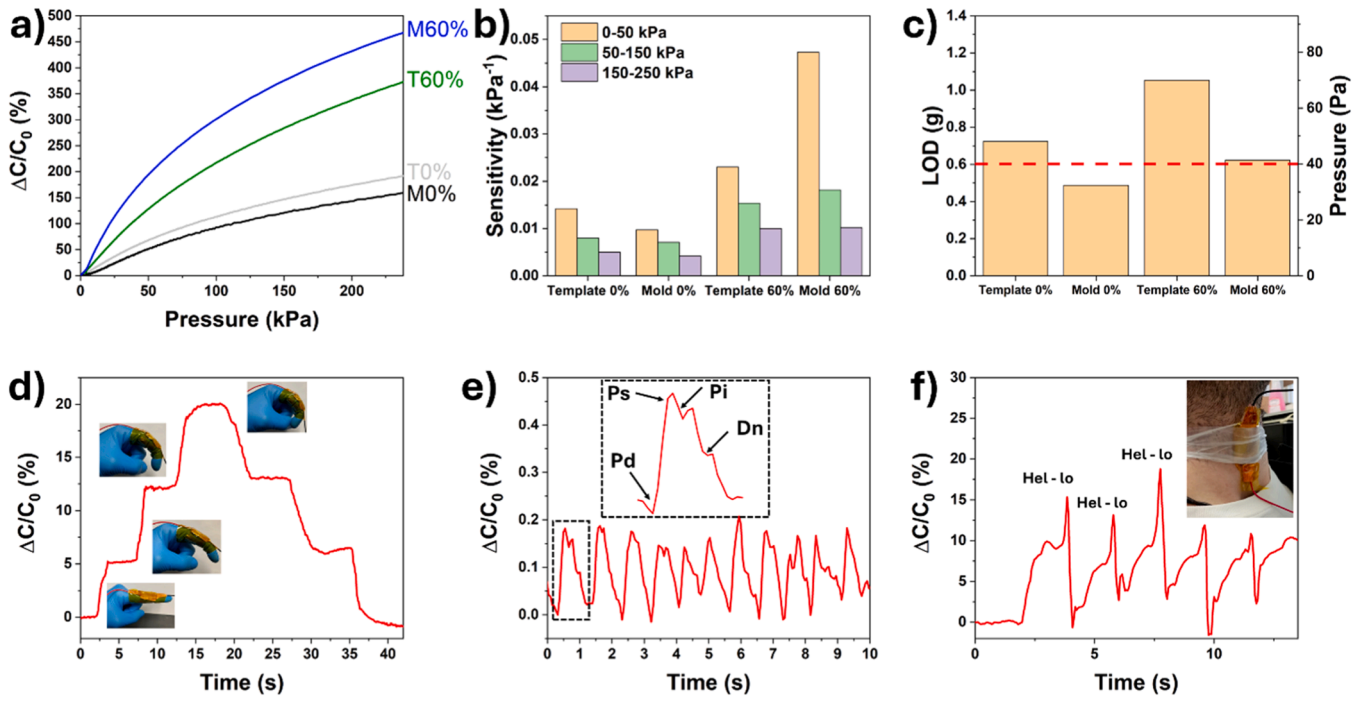

Fig. 5. a) Piezocapacitive response under compressive pressure of bare foams and with 60 % of silver nanoflakes content prepared with templating (T) and molding (M) methods. b) Sensitivity in the three different analyzed pressure ranges and c) limit of detection (LOD) of the different foam sensors. Red dot line evidence the LOD of 40 Pa. d) Relative capacitance variation of the T_60 % foam sensor while increasing and then decreasing finger bending angles. e) Heart pulse wave sensed from the wrist and its main features evidenced in the inset (Pd = diastolic pressure, Ps = systolic pressure, Pi = inflection point, Dn=dicrotic notch) f) Monitoring of vocal cords vibrations when "hello" is repeatedly pronounced.

increase in capacitance. These improvements were also reflected in the limit of detection (LOD), which was lower for the molded samples, reaching a value of 0.6 g, corresponding to 40 Pa (Fig. 5c).

The potential application of the prepared foams as wearable sensors was demonstrated by assembling a 60 wt% Ag-NFLs molded foam device with polyimide-copper foil electrodes in a sandwich configuration. The device was mounted on different parts of the body to assess its ability to detect various biometric signals. When placed on a finger, the sensor effectively monitored different bending angles, producing a stable signal over time with good repeatability, as indicated by the consistent response to identical bending angles (Fig. 5d). More notably, the sensor also demonstrated the ability to detect biometric signals characterized by subtle motions. When attached to the wrist of an adult male, it successfully measured the peripheral pulse wave, showcasing its potential for real-time health monitoring. As illustrated in Fig. 5e, the sensor accurately captured the pulse wave's shape, with characteristic points matching those reported in previous studies [45], confirming its capability to track heart rate. Additionally, when positioned on the throat, the sensor detected the minute vibrations of the vocal cords during speech. The capacitive signal patterns remained consistent when the same word (e.g., "hello") was pronounced, with each syllable corresponding to a distinct signal peak (Fig. 5f). These findings suggest that the tactile sensor could serve as an alternative to microphones for speech recognition, particularly in noisy environments where traditional audio-based methods are unreliable.

4. Conclusion

In summary, a piezocapacitive wearable pressure sensor made from a soft, flexible polymer sponge was developed and studied. The PDMS sponge, enhanced with silver nanoflakes, was fabricated using two different approaches, a templating method, which involved capillary infiltration of the precursor solution into sugar cubes, and a molding method, where a slurry of sugar and uncured PDMS was cast into shape. While the templating approach offers simplicity, it is constrained by the geometry of the template. This limitation is overcome by the molding method, which also provides greater sensitivity to applied pressure. The resulting sensors exhibit a piezocapacitive response, with compressive pressure sensitivity in the 0–50 kPa range, reaching up to 0.0473 kPa^{-1} for molded foam with a 60 wt% concentration of silver nanoflakes. Additionally, the sensors achieve an impressive limit of detection (LOD) of 0.6 g (40 Pa). When tested as wearable devices, these sensors demonstrated their potential for lightweight, easily manufacturable applications capable of monitoring biometric signals in real-time.

CRediT authorship contribution statement

Giorgio Mogli: Writing – original draft, Investigation, Formal analysis, Data curation. **Stefano Stassi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Data curation, Conceptualization. **Matteo Costantini:** Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Ministero dell'Università e della Ricerca (MUR), through PRIN 2022 - PASSO Prot. 20222TKNRJ grant, the National Plan for Complementary Investments to the NRRP, project "D3–4Health - Digital Driven Diagnostics, prognostics and therapeutics for sustainable Health care" (project code:PNC0000001) and within the Agritech National Research Center which received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E

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Data availability

Data will be made available on request.

References

[1] K.-H. Kim, S.K. Hong, N.-S. Jang, S.-H. Ha, H.W. Lee, J.-M. Kim, Wearable resistive pressure sensor based on highly flexible carbon composite conductors with irregular surface morphology, ACS Appl. Mater. Interfaces 9 (2017) 17499–17507.

[2] G. Mogli, I. Roppolo, A. Chiappone, S. Stassi, Multi-responsive 3D printable organohydrogel for the fabrication of durable and low-hysteresis flexible sensors, Appl. Mater. Today 44 (2025) 102675.

[3] Q. Zhong, Y. Mao, B. Zhou, W. Hu, All-textile 3D triboelectric nanogenerator derived from bidirectional cross-weaving binary-yarns for bio-motion energy harvesting and sensing, Chem. Eng. J. 504 (2025) 158871.

[4] L. Liu, Y. Li, M. Xu, R. Tao, Q. Zhong, X. Yang, et al., Hybrid tribo/piezoelectric nanogenerator textile derived from 3D interlocked parallel-arranged yarns for bio-motion energy harvesting and tactile sensing, Chem. Eng. J. 474 (2023) 145866.

[5] J. Chen, T. Song, X. Wang, Y. Zhou, T. Wang, X. Zhang, et al., Ultrasensitive and wide-range MXene/PDMS piezoresistive sensors inspired by rose petals, Nano Energy 131 (2024) 110285.

[6] W. Ye, L. Meng, J. Xi, H. Bian, Z. Xu, H. Xiao, et al., Superelastic carbon aerogels with anisotropic and hierarchically-enhanced cellular structure for wearable piezoresistive sensors, J. Colloid Interface Sci. 666 (2024) 529–539.

[7] S. Stassi, G. Canavese, V. Cauda, S.L. Marasso, C.F. Pirri, Evaluation of different conductive nanostructured particles as filler in smart piezoresistive composites, Nanoscale Res. Lett. 7 (2012).

[8] M. Xu, Y. Mao, W. Hu, All-hydrogel yarn-based supercapacitor wrapped with multifunctional cotton fiber for energy storage and sensing, Nano Energy 130 (2024) 110142.

[9] B. Wu, W. Wu, R. Ma, H. Chen, Y. Zhao, Y. Li, et al., High-sensitivity and wide-range flexible ionic piezocapacitive pressure sensors with porous hemisphere array electrodes, Sensors 24 (2024).

[10] H. Zhou, Z. Wang, W. Zhao, X. Tong, X. Jin, X. Zhang, et al., Robust and sensitive pressure/strain sensors from solution processable composite hydrogels enhanced by hollow-structured conducting polymers, Chem. Eng. J. 403 (2021) 126307.

[11] S. Chen, J. Li, B. Zhang, L. Huang, K. Chen, W. Fan, et al., Fluorine polyimide nanofibrous composites with outstanding piezoelectric property for human motion monitoring, Chem. Eng. J. 502 (2024) 157320.

[12] W. Fan, R. Lei, H. Dou, Z. Wu, L. Lu, S. Wang, et al., Sweat permeable and ultrahigh strength 3D PVDF piezoelectric nanoyarn fabric strain sensor, Nat. Commun. 15 (2024) 3509.

[13] B. Guo, S. He, L. Li, S. Chen, Z. Guo, M. Yao, et al., Anisotropic conductive eutectogels for strain sensing and triboelectric nanogeneration in extreme environments, J. Colloid Interface Sci. 679 (2025) 906–917.

[14] A. Chiappone, I. Roppolo, E. Scavino, G. Mogli, C.F. Pirri, S. Stassi, Three-dimensional printing of triboelectric nanogenerators by digital light processing technique for mechanical energy harvesting, ACS Appl. Mater. Interfaces 15 (2023) 53974–53983.

[15] J. Hwang, Y. Kim, H. Yang, J.H. Oh, Fabrication of hierarchically porous structured PDMS composites and their application as a flexible capacitive pressure sensor, Compos. Part B: Eng. 211 (2021) 108607.

[16] S. Li, K. Dong, R. Li, X. Huang, T. Chen, X. Xiao, Capacitive pressure sensor inlaid a porous dielectric layer of superelastic polydimethylsiloxane in conductive fabrics for detection of human motions, Sens. Actuators A: Phys. 312 (2020) 112106.

[17] S. Stassi, A. Sacco, G. Canavese, Impedance spectroscopy analysis of the tunnelling conduction mechanism in piezoresistive composites, J. Phys. D: Appl. Phys. 47 (2014).

[18] G. Mogli, A. Chiappone, A. Sacco, C.F. Pirri, S. Stassi, Ultrasensitive piezoresistive and piezocapacitive cellulose-based ionic hydrogels for wearable multifunctional sensing, ACS Appl. Electron. Mater. 5 (2023) 205–215.

[19] G. Mogli, M. Reina, A. Chiappone, A. Lamberti, C.F. Pirri, I. Roppolo, et al., Self-powered integrated tactile sensing system based on ultrastretchable, self-healing and 3D printable ionic conductive hydrogel, Adv. Funct. Mater. 34 (2024) 2307133.

[20] S.W. Park, P.S. Das, J.Y. Park, Development of wearable and flexible insole type capacitive pressure sensor for continuous gait signal analysis, Org. Electron 53 (2018) 213–220.

[21] R. Iglio, S. Mariani, V. Robbiano, L. Strambini, G. Barillaro, Flexible polydimethylsiloxane foams decorated with multiwalled carbon nanotubes enable unprecedented detection of ultralow strain and pressure coupled with a large working range, ACS Appl. Mater. Interfaces 10 (2018) 13877–13885.

[22] X. Zhao, F. Meng, Y. Peng, Flexible and highly pressure-sensitive ternary composites-wrapped polydimethylsiloxane sponge based on synergy of multi-dimensional components, Compos. Part B: Eng. 229 (2022) 109466.

[23] Y. Song, H. Chen, Z. Su, X. Chen, L. Miao, J. Zhang, et al., Highly compressible integrated supercapacitor–piezoresistance-sensor system with CNT–PDMS sponge for health monitoring, Small 13 (2017) 1702091.

[24] L.-W. Lo, J. Zhao, H. Wan, Y. Wang, S. Chakrabartty, C. Wang, A soft sponge sensor for multimodal sensing and distinguishing of pressure, strain, and temperature, ACS Appl. Mater. Interfaces 14 (2022) 9570–9578.

[25] X. Karagiorgis, G. Khandelwal, A. Beniwal, R. Chirila, P.J. Skabara, R. Dahiya, Polydimethylsiloxane foam-based fully 3D printed soft pressure sensors, Adv. Intell. Syst. 6 (2024) 2300367.

[26] Y. Zhao, J. Zhou, C. Jiang, T. Xu, K. Li, D. Zhang, et al., Highly sensitive and flexible capacitive pressure sensors combined with porous structure and hole array using sacrificial templates and laser ablation, Polymers 16 (2024).

[27] Y. Zhang, S. Yang, Y. Liu, T. Gu, F. Liu, Dual network structures of PDMS-based composite foam via anchoring liquid metal nanoparticles for improved thermal conductivity and electromagnetic interference shielding performances, J. Mater. Chem. A 12 (2024) 27527–27539.

[28] L. Yang, C. Jiang, J. Yan, Y. Shen, Y. Chen, L. Xu, et al., Structuring the reduced graphene oxide/polyHIPE foam for piezoresistive sensing via emulsion-templated polymerization, Compos. Part A: Appl. Sci. Manuf. 134 (2020) 105898.

[29] M. Pruvost, W.J. Smit, C. Monteux, P. Poulin, A. Colin, Polymeric foams for flexible and highly sensitive low-pressure capacitive sensors, npj Flex. Electron. 3 (2019) 7.

[30] F. Nie, Y.-L. Gu, L. Zhao, L.-T. Li, F.-X. Shen, J. Song, et al., Construction of conductive polymer coatings onto flexible PDMS foam composites with exceptional mechanical robustness for sensitive strain sensing applications, Adv. Sens. Res. 3 (2024) 2300140.

[31] X. Dong, Y. Wei, S. Chen, Y. Lin, L. Liu, J. Li, A linear and large-range pressure sensor based on a graphene/silver nanowires nanobiocomposites network and a hierarchical structural sponge, Compos Sci. Technol. 155 (2018) 108–116.

[32] X. Yin, T.P. Vinod, R. Jelinek, A flexible high-sensitivity piezoresistive sensor comprising a Au nanoribbon-coated polymer sponge, J. Mater. Chem. C 3 (2015) 9247–9252.

[33] S. Lan, Y. Mao, B. Zhou, W. Hu, PEDOT-molecular bridging foam-hydrogel based wearable triboelectric nanogenerator for energy harvesting and sensing, Nano Energy 134 (2025) 110572.

[34] J. Oh, J.-O. Kim, Y. Kim, H.B. Choi, J.C. Yang, S. Lee, et al., Highly uniform and low hysteresis piezoresistive pressure sensors based on chemical grafting of polypyrrole on elastomer template with uniform pore size, Small 15 (2019) 1901744.

[35] S.Y. Liu, J.G. Lu, H.P.D. Shieh, Influence of permittivity on the sensitivity of porous elastomer-based capacitive pressure sensors, IEEE Sens J. 18 (2018) 1870–1876.

[36] X. Tan, J. Zheng, A novel porous PDMS-AgNWs-PDMS (PAP)-sponge-based capacitive pressure sensor, Polymers 14 (2022) 1495.

[37] B. Sha, X. Lü, L. Jiang, High sensitivity and wide range biomimetic tactile-pressure sensor based on 2D graphene film and 3D graphene foam, Micromachines 13 (2022) 1150.

[38] S.-J. Park, J. Kim, M. Chu, M. Khine, Flexible piezoresistive pressure sensor using wrinkled carbon nanotube thin films for human physiological signals, Adv. Mater. Technol. 3 (2018) 1700158.

[39] J. Oh, J.-O. Kim, Y. Kim, H.B. Choi, J.C. Yang, S. Lee, et al., Highly Uniform and Low Hysteresis Piezoresistive Pressure Sensors Based on Chemical Grafting of Polypyrrole on Elastomer Template with Uniform Pore Size, 15(2019) 1901744.

[40] J. Choi, D. Kwon, K. Kim, J. Park, D.D. Orbe, J. Gu, et al., Synergetic effect of porous elastomer and percolation of carbon nanotube filler toward high performance capacitive pressure sensors, ACS Appl. Mater. Interfaces 12 (2020) 1698–1706.

[41] K.-H. Ha, W. Zhang, H. Jang, S. Kang, L. Wang, P. Tan, et al., Highly sensitive capacitive pressure sensors over a wide pressure range enabled by the hybrid responses of a highly porous nanocomposite, Adv. Mater. 33 (2021) 2103320.

[42] V. Thomsen, D. Schatzlein, D. Mercuro, Limits of detection in spectroscopy, Spectroscopy (Santa Monica) 18 (2003) 112–114.

[43] C. Ricciardi, K. Santoro, S. Stassi, C. Lamberti, M.G. Giuffrida, M. Arlorio, et al., Microcantilever resonator arrays for immunodetection of B-lactoglobulin milk allergen, Sens. Actuators B: Chem. 254 (2018) 613–617.

[44] S. Stassi, G. De Laurentis, D. Chakraborty, K. Bejtka, A. Chiodoni, J.E. Sader, et al., Large-scale parallelization of nanomechanical mass spectrometry with weakly-coupled resonators, Nat. Commun. 10 (2019).

[45] A.P. Avolio, M. Butlin, A. Walsh, Arterial blood pressure measurement and pulse wave analysis—their role in enhancing cardiovascular assessment, Physiol. Meas. 31 (2010) R1.

[46] S. Masihi, M. Panahi, D. Maddipatla, A.J. Hanson, A.K. Bose, S. Hajian, et al., Highly sensitive porous PDMS-based capacitive pressure sensors fabricated on fabric platform for wearable applications, ACS Sens. 6 (2021) 938–949.

[47] T. Zhao, T. Li, L. Chen, L. Yuan, X. Li, J. Zhang, Highly sensitive flexible piezoresistive pressure sensor developed using biomimetically textured porous materials, ACS Appl. Mater. Interfaces 11 (2019) 29466–29473.

[48] X. Karagiorgis, M. Ntagios, P.J. Skabara, R. Dahiya, Elastomeric foam-based soft capacitive pressure sensors using direct ink writing, IEEE J. Flex. Electron. 2 (2023) 175–182.

[49] J.I. Yoon, K.S. Choi, S.P. Chang, A novel means of fabricating microporous structures for the dielectric layers of capacitive pressure sensor, Micro Eng. 179 (2017) 60–66.

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