proceedings

MDPI

Proceedings

Porous Polymer Based Flexible Pressure Sensors for Medical Applications †

Sylvie Bilent, Thi Hong Nhung Dinh, Emile Martincic and Pierre-Yves Joubert *

Centre for Nanoscience and Nanotechnology, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91120 Palaiseau, France; Sylvie.bilent@u-psud.fr (S.B.); thi-hong-nhung.dinh@u-psud.fr (T.H.N.D.); emile.martincic@u-psud.fr (E.M.)

* Correspondence: pierre-yves.joubert@u-psud.fr; Tel.: +33-(0)1-69-15-41-02

† Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 4 December 2018

Abstract: This paper focuses on the use of microporous PDMS foams as a highly deformable film to improve the sensitivity of flexible capacitive pressure sensor dedicated to wearable use. A fabrication process allowing the mechanical properties of foams to be adjusted is proposed together with a non-linear behavioral model used to objectively estimate the sensor performances in terms of sensitivity and measurement range. Sensors fabricated and characterized in this study show that the sensitivity and the measurement range can be adjusted from 0.14%/kPa up to 13.07%/kPa, and from 594 kPa to 183 kPa, respectively, while the PDMS film porosity ranges from 0% up to 85%.

Keywords: polymer-based flexible pressure sensors; microporous PDMS foam; electromechanical characterizations; sensor behavioral modelling

1. Introduction

Flexible pressure sensors raise strong interest in non-invasive health monitoring applications [1]. Indeed, they allow wearable devices to be developed and find numerous applications such as plantar pressure monitoring [2] or bandage compression control in the therapy of chronic venous disorders [3]. Among the existing pressure sensing technologies, polymer-based capacitive sensors are very popular since they allow a large variety of sensor to be designed (including 3D sensors), they are rather robust to temperatures changes, and they can be driven by low power electronics [4]. The basic principle of such sensors is to sense the deformation of the used polymer under stress, by means of the capacitance changes read out between electrodes integrated within the polymer, that moves relatively to one another when a load is applied. Among the possible polymers, PolyDiMethylSiloxane (PDMS) constitute good candidates for elaborating such sensors. Indeed, PDMS is a non-toxic material, which features dielectric properties as well as relevant mechanical properties, allowing up to 100% deformation without damage [5]. However, bulk PDMS films are hardly compressible and pressure sensors often lack sensitivity to normal pressure [5]. This is why PDMS films featuring inner microporosities draw more and more attention since they allow sensing performances to be significantly improved, thanks to a higher compressibility [6]. In this paper, we propose a methodology for fabricating PDMS foams with adjustable mechanical properties. Sensors fabricated with PDMS foams are electromechanically characterized, and a non-linear behavioral model is proposed so that a large variety of sensors can be objectively compared in terms of sensitivity and pressure range.

2. Sensor Principle

The sensors considered in this paper are elementary proof-of-concept pressure sensors composed of two 1 mm-thick square shaped brass electrodes (side length l = 15 mm) facing one another and placed at each faces of a microporous PDMS film (Figure 1). When a load is applied to the sensor, the capacitance change ΔC expressed in percentage relatively to the unloaded capacitor C_0 reads [5]:

$$\frac{\Delta C}{C_0}(\%) = 100 \times \frac{d_0 - d}{d}, \quad (1)$$

where $\Delta C = C - C_0$, C is the loaded sensor capacitance, C_0 is the load-free capacitance, d is the thickness of the PDMS foam under load, and d_0 is the thickness of the unloaded foam.

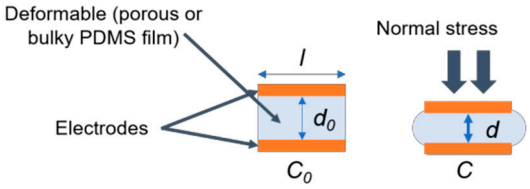


Figure 1. Principle of operation of a flexible normal pressure capacitive sensor.

3. PDMS Foam

Figure 2 shows the fabrication process of the microporous PDMS foam. PDMS is formed by mixing two components: silicon elastomer (Sylgard 184A) and curing agent (Sylgard 184B) with standard ratio 10:1. Sugar particles are added within the PDMS in volume ratios ranging from 4 to 6 (sugar) per 1 (PDMS). The preparation is poured into a 5 cm diameter Petri dish and compacted to form a block of the mixture. The mixture is cured in a stove for 2 h at 90 °C. After curing, the mixture is removed from the Petri dish and soaked in a water bath to dissolve the sugar and thereby obtain the microporous PDMS foam. Once the sugar is completely dissolved, the PDMS foam is again placed in the stove for 1 h 30 min at 75 °C to remove the excess water. Finally, the obtained PDMS foam is cut to the shape of the electrodes for electromechanical characterization.

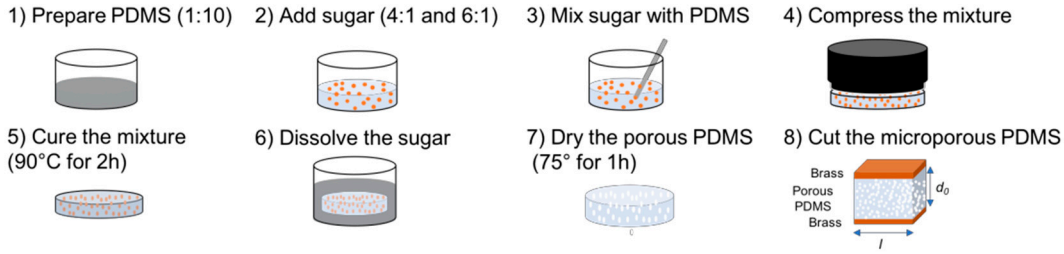


Figure 2. Fabrication process of the microporous PDMS foams.

Sugar crystals of various sizes have been distributed into three sets by means of 500 µm, 1000 µm and 2000 µm sieving grids. The size distribution of the crystal within each set was analyzed by means of a Keyence VHX-1000 optical microscope, and characterized using subsets of around one hundred crystals. The sugar crystal size distributions within the three sets (small, medium and large size) used to form 4:1 and 6:1 PDMS foams are gathered in Table 1. In addition, cross-sections of the obtained PDMS foams were observed with a Hitachi S3600N scanning electron microscope. From these observations it was concluded that the size (cross section) of the micropores within the foam are directly related to the size (cross section) of the used sugar crystals. The porosity Φ of the obtained PDMS foams is determined from the density of the foam ρ_{foam}, and the density of the bulk PDMS ρ_{bulk} (assumed to be 1109 kg/m^3), so that:

$$\Phi(\%) = 1 - \frac{\rho_{foam}}{\rho_{bulk}} \quad (2)$$

The porosities estimated for the fabricated bulk PDMS films and foams samples are gathered in Table 1. All fabricated PDMS samples (bulk films or foams) are 6 ± 0.5 mm thick.

Table 1. Variation of the relative permittivity of the microporous PDMS as function of the porosity.

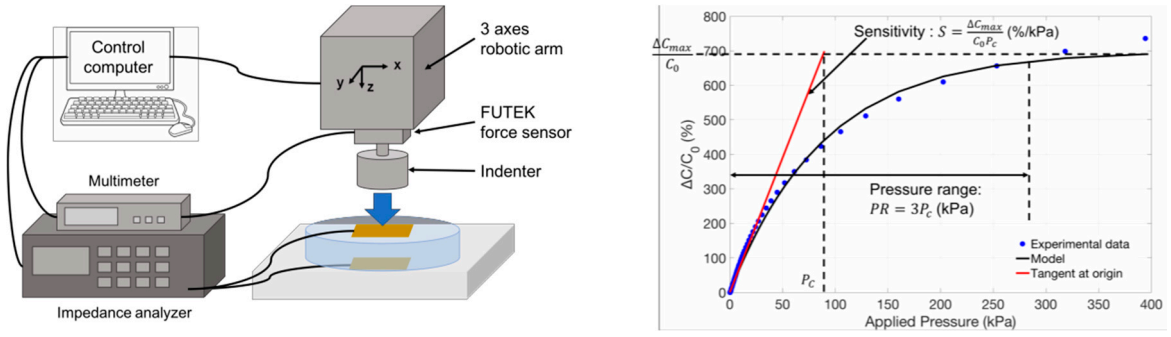
Sugar:PDMS Volume Ratio	Sugar Crystal Sizes (µm)	Φ (%)	P_C (kPa)	PR (kPa)	S (%/kPa)	Hysteresis (%)
0:1 (*bulk*)	no crystal	0	198	594	0.14	8.85
4:1 (*foam*)	470 ± 100	78.58 ± 3.11	81	243	6.50	5.60
	700 ± 230	79.76 ± 1.42	85	255	6.87	5.43
	1100 ± 330	81.22 ± 0.97	86	257	8.85	5.32
6:1 (*foam*)	470 ± 100	82.84 ± 1.28	55	165	11.62	6.43
	700 ± 230	85.18 ± 0.85	61	183	13.07	4.58

4. Sensor Electromechanical Characterization

The capacitance changes versus applied load characteristics of the fabricated sensors were obtained by means of a dedicated PC-controlled electromechanical test bench. This bench is composed of (i) an indenter applying loads to the sensor under test through an ISEL iMC-S8 robotic arm, (ii) a Futek FSH00105 110N range force sensor connected to an HP34401A multimeter measuring the applied load, and (iii) a HP4192A impedance analyzer measuring the sensor capacitance changes, at a frequency of 1 MHz (Figure 3a). A typical sensor characteristic curve is provided in Figure 3b. In order to quantify the sensor performances, we propose a first order exponential behavioral model which reads:

$$\frac{\Delta C}{C_0}(\%) = \frac{\Delta C_{\max}}{C_0}\left(1 - e^{-(P/P_C)}\right) \quad (3)$$

where P (kPa) is the applied pressure, ΔC_{max} is the maximum capacitance change and P_C is the characteristic pressure at which 63% of ΔC_{max} is reached. This model is adjusted to the experimental data and allows the sensitivity S of the sensor to be defined as the slope of the tangent to the curve at the origin, and the pressure measurement range PR to be defined as the pressure at which 95% of the ΔC_{max} is reached, i.e., $PR = 3Pc$ (Figure 3b).



(**a**) (**b**)

Figure 3. (**a**) Electromechanical test bench (**b**) Typical sensor response and first order exponential behavior model allowing sensor sensitivity (S) and pressure range (PR) to be determined.

Sensors fabricated with bulk PDMS films and 4:1 and 6:1 microporous PDMS foams were electromechanically characterized involving 3 consecutive load and release cycles operated in a 0 to 500 kPa normal pressure range. Obtained results are presented in Figure 4 and synthetized in Table 1. Figure 4a shows the sensor characteristics as a function as the sugar: PDMS ratio, and Figure 4b shows

the measured characteristics as a function of the micropore sizes. The hysteresis between load and release phases presented in Table 1 were calculated as the difference between the area under the load and release curves, expressed in percentage. The hysteresis being always lower than 10%, the sensor sensitivity and pressure ranges were estimated using the model fitted to the load and release average curve.

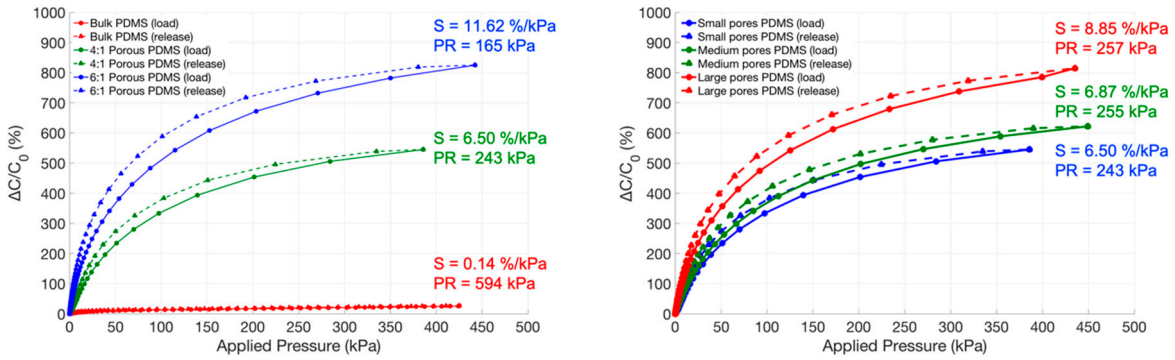


Figure 4. Variation of the sensor capacitance according to the applied pressure (**a**) Depending on the sugar:PDMS ratio; (**b**) Depending on the micropore size.

5. Conclusions

Electromechanical characterizations showed that the sensitivity of the PDMS based pressure sensors strongly increases from 0.14%/kPa up to 13%/kPa, the pressure range decreases from 594 kPa down to 183 kPa, and hysteresis decreases from 8.85% down to 4.58%, while the porosity of the involved PDMS foam increases from 0% up to over 85%. The control of the porosity in the fabrication process of porous-PDMS based sensors, associated to the proposed non-linear model opens the way to the design of high sensitivity flexible capacitive sensors tailored to applications.

Author Contributions: S.B. and T.H.N.D. participated to the fabrication process and characterization of PDMS foams, all authors contributed to the sensor characterizations and analysis and to the writing of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgments: this work was done with the C2N PIMENT facilities and partly supported by RENATECH network and the general Council of Essonne.

References

1. Trung, T.Q.; Lee, N.E. Flexible and Stretchable Physical Sensor Integrated Platforms for Wearable Human-Activity Monitoringand Personal Healthcare. *Adv. Mater.* **2016**, *28*, 4338–4372.
2. Motha, L.; Kim, J.; Kim, W.S. Instrumented rubber insole for plantar pressure sensing. *Org. Electron. Phys.Mater. Appl.* **2015**, *23*, 82–86.
3. al Khaburi, J.; Dehghani-Sanij, A.A.; Nelson, E.A.; Hutchinson, J. Effect of bandage thickness on interface pressure applied by compression bandages. *Med. Eng. Phys.* **2012**, *34*, 378–385.
4. Huang, Y.; Yuan, H.; Kan, W.; Guo, X.; Liu, C.; Liu, P. A flexible three-axial capacitive tactile sensor with multilayered dielectric for artificial skin applications. *Microsyst. Technol.* **2017**, *23*, 1847–1852.
5. Dinh, T.-H.-N.; Martincic, E.; Dufour-Gergam, E.; Joubert, P.-Y. Mechanical characterization of PDMS films for the optimization of polymer based flexible capacitive pressure microsensors. *J. Sens.* **2017**, 2017, doi:10.1155/2017/8235729.
6. Chhetry, A.; Yoon, H.; Park, J.Y. A flexible and highly sensitive capacitive pressure sensor based on conductive fibers with a microporous dielectric for wearable electronics. *J. Mater. Chem. C* **2017**, *5*, 10068–10076.