Experimental study of PDMS mechanical properties for the optimization of polymer based flexible pressure micro-sensors

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Abstract. This paper reports on the optimization of flexible PDMS-based normal pressure capacitive micro-sensors dedicated to wearable applications. The deformation under a normal force of PDMS thin films of thicknesses ranging from 40 µm to 10 mm is firstly experimentally studied. This study points out that for capacitive micro-sensors using bulky PDMS thin films as deformable dielectric material, the sensitivity to an applied normal load can be optimized thanks to an adequate choice of the so-called form ratio of the involved PDMS thin film. Indeed, for capacitive micro-sensors exhibiting 9 mm^2 electrodes, the capacitance change under a 6 N load can be adjusted from a few percent up to over 35% according to the choice of the load-free thickness of the used PDMS film. These results have been validated thanks to electromechanical characterizations carried out on two flexible PDMS based capacitive normal pressure micro-sensor samples fabricated with two different thicknesses. The obtained results open the way to the enhanced design of PDMS based pressure sensors dedicated to wearable and medical applications. Further works will extend this study to a wider range of sensor dimensions, and using numerical modelling.

1. Introduction

Thanks to progresses made in the fabrication of flexible electronics and micro-sensors, wearable physiological measurement devices are more and more developed for ambulatory and self-monitoring purposes [1]. Among them, devices using polymer based capacitive micro-sensors are very popular since they gather advantageous features, such as being sensitive to various physiological quantities as well as being easily wearable. This kind of sensors is basically constituted of metallic electrodes deposited on - or imbedded in - dielectric polymer films. Besides, among the existing polymers Polydimethylsiloxane (PDMS) is a primary reference material, hence suitable for biocompatible and wearable use [2]. Furthermore, PDMS being a dielectric material [3], it is appropriate to be used in capacitive sensing applications. Finally, PDMS films are known to be highly deformable, allowing flexible sensors to be produced. Therefore they are particularly well suited to be part of wearable capacitive force or pressure sensors. Indeed, associated to metallic electrodes, the deformation of the PDMS films under pressure induces capacitance changes between electrodes that can be read out for pressure measurement. For that reason, PDMS-based capacitive sensors are found in many medical applications involving pressure monitoring, such as tactile sensing [4], gesture or gait analysis [5]. Since PDMS films are deformable under shear and normal forces, three-axis pressure capacitive micro-sensors array can be developed with appropriate electrode design [6]. However, it has been shown that the thickness of a PDMS film as well as the surface on which the load is applied can

strongly affect its deformation properties and hence the resulting capacitance change [7,8]. Finally, PDMS thin films are known to be hardly compressible, with a Poisson coefficient close to 0.49 [9]. This is why capacitive normal pressure sensors constituted of bulky PDMS films are often reported as lacking sensitivity to normal pressure [6,10]. Hence authors have proposed structured PDMS films to enhance the sensor sensitivity to normal pressure [10]. However the fabrication processes associated to these designs are more complex and can result in higher manufacturing costs. In addition, the obtained structure makes it difficult to foresee or adjust the sensor sensitivity and measurement range. In this paper, the mechanical behavior of bulky PDMS film samples under normal pressure is experimentally investigated. This study aims at analyzing and optimizing the sensitivity of bulky flexible capacitive normal pressure sensors. In addition, PDMS-based sensor samples are fabricated and electromechanically characterized. The measured sensitivity is discussed comparatively to the previously determined mechanical properties of the used PDMS films. Finally, optimization rules for the design of enhanced capacitive normal pressure flexible micro-sensors are highlighted.

2. Sensors design

2.1. Basic principle of the sensor

For the sake of simplicity, a simple parallel plate capacitive normal pressure micro-sensor is considered in this study. The side length of the considered micro-sensor is of a few millimeters, as required e.g. for wearable plantar pressure monitoring applications. The sensor is constituted of two square-plate copper electrodes facing one another. The electrodes are separated by a deformable dielectric film made of PDMS. The sensor is deposited on a Kapton substrate, used to provide both flexibility and mechanical robustness to the fabricated device. In load-free conditions, the capacitance of such sensor is given by [11]:

$$C = \left(2.47b + 1\right)\frac{\varepsilon_0 \varepsilon_r}{d} L^2 \qquad (1)$$

where ε_0 and ε_r are the permittivity of vacuum and the relative permittivity of PDMS, respectively; d is the distance between the electrodes and L is the electrode side-length. The capacitance of the sensor is altered when pressure is applied, since the distance d between the two electrodes is changed. Reading out the capacitance change gives information about the applied pressure.

2.2. Evaluation of mechanical behavior of PDMS

In order to quantitatively estimate the mechanical properties of PDMS films under normal pressure, PDMS film samples of various thicknesses were realized. The films are of a Sylgard®184 type. They feature an oligomer/curing agent ratio of 10/1 by weight, and they are cured at 75°C during 1 hour. The fabricated film samples have thicknesses ranging from 40 μm to 9.8 mm.

During fabrication, the thickness of the film samples is controlled by the speed of spin, during the spin coating [12]. After fabrication, the film samples are mechanically characterized using a CSM Instruments micro-indentation tester. The tester is implemented with cylindrical indentation tips of radius r = 1.7 and 2.5 mm. Each film sample is positioned under the indentation tip thanks to a 3 axis motorized table featuring a 0.25 μm position resolution. The indentation tip, normal to the film surface is driven into the sample by applying a load of 6 N, while the position of the tip is measured. Therefore the set-up allows the PDMS thickness change under load to be evaluated as a function of the applied load. Based on Eq. 1, it is possible to foresee the capacitance change of a PDMS based capacitive pressure sensor, ΔC, with the given applied load, using:

$$\Delta C_{\%} = 100 \frac{\Delta d}{d - \Delta d} \qquad (2)$$

where d is the initial load-free thickness of the PDMS film and Δd is the measured PDMS thickness change under load. For PDMS film samples ranging from $d = 40$ μm to 9.8 mm, the capacitance changes expected for the two considered indentation tips are plotted in Figure 1.

One can observe that for an indentation tip of a given radius r, there exists an optimal PDMS film load-free thickness d that maximizes the capacitance change under load. In other words, the sensitivity of the designed sensor can be adjusted or optimized according to the relevant choice of the so-called form ratio ρ, defined by:

$$\rho = \frac{S}{d} \tag{3}$$

where S is the indentation surface upon which the load is applied. Based on the experiments carried out for two indentation surfaces (resulting from the two different radii), it appears (Figure 1) that the capacitance change is optimized for the same value of the form ratio $\rho_{opt} \approx 3.9$ mm $\pm 7\%$ (all curve fittings have a coefficient of determination R^2 better than 98.8 %). In order to validate these conclusions, pressure sensor samples are designed with $\rho = \rho_1$ and $\rho = \rho_2$ (Figure 1). We describe how these sensors are fabricated and mechanically characterized in what follows.
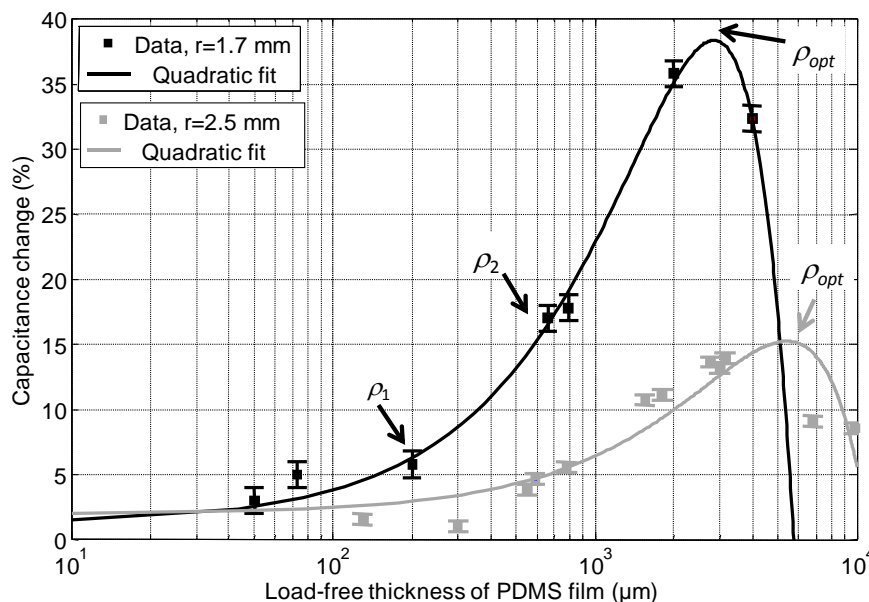

Figure 1. Estimation of sensor capacitance changes versus load free thickness of the used PDMS films, for two indentation-tip radii, and for an applied load of 6 N. Error bars are twice the standard deviation of the data estimated from 4 measurement cycles.

3. Sensor fabrication

3.1. Fabrication process

In order to fabricate PDMS based pressure sensors, it is necessary to deposit copper electrodes at each side of PDMS films. It is however difficult to do so because of the low surface energy and of the highly compliant nature of PDMS films. To bypass this drawback, the so-called "film-transfer" fabrication process [12,13] is implemented. Indeed, this fabrication process enables assemblies using heterogeneous or even incompatible materials and technologies to be considered. The film-transfer process involves 4 fabrication steps (Figure 2). In the first step, copper top electrodes are realized on a donor wafer covered by a low adhesion layer and copper bottom electrodes are fabricated on a target wafer using the micro-molding process (step 1). Then, the fabricated copper lines are covered with PDMS (step 2). It should be noted that a gap corresponding to the position of the conductor pad on the target substrate is intended for further electrical connection purposes. The third step aims at aligning and bonding the two wafers using an uncured PDMS layer as glue. Finally, after removing the donor wafer, a capacitor with a PDMS dielectric layer is obtained (step 4). The PDMS films used to fabricate the sensors are identical to the ones used for characterization purposes.
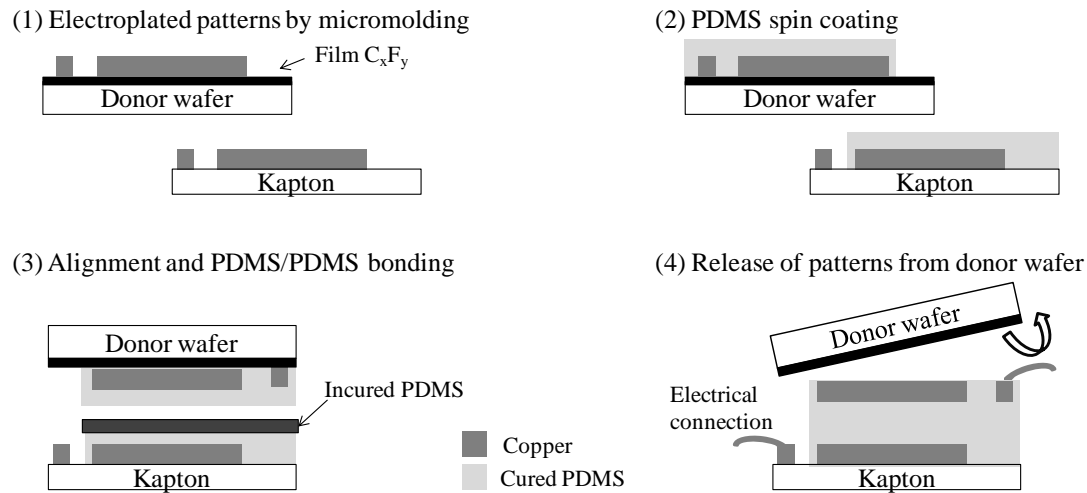
Figure 2. The four-step fabrication process of the sensors

3.2. Fabricated devices

In this work, sensor samples are fabricated on 10 cm diameter Kapton substrates. The fabrication process enables a large number of sensors together with their connection tracks to be fabricated on the same substrate with a transfer yield of 100%. In what follows, two types of sensor are considered for electromechanical characterizations. They are of same size (side-length L = 3 mm) but exhibits different PDMS film thicknesses, as presented in Table 1. The connection tracks are 100 µm wide. An example of a realized sensor is shown in Figure 3. The load-free capacitances of the fabricated sensors are measured by means of a HP1492A impedance analyzer operating at 1MHz. For the eighteen fabricated sensor samples, the measured values are close to the expected ones, which were evaluated using Eq. 1 in which ε_r is assumed to be equal to 2.68 in PDMS [3]. The observed discrepancies between experimental and expected values can be attributed to the possible inaccurate estimation of thickness d, to a possible misalignment of electrodes during fabrication, as well as to the approximations used to build the model of Eq. 1 [11]. The variability between the measured capacitances of sensors of same type can also be attributed to the slight inhomogeneity of the PDMS thickness over the whole film, which was evaluated to be less than 5% according to our thickness measurements.

Table 1. Sensor sample features and characterization results

Sensor type	d (mm)	ρ (mm)	Load-free Capacitance (pF)			ΔC max (at 6 N)
			Expected	Experiment	Discrepancy	
1	0.20	45	1.23	1.27±0.06	3.2 %	6%
2	0.66	13.6	0.49	0.48±0.02	2 %	17%

3.3. Electromechanical characterization

In addition, electromechanical characterizations were carried out on two sensor samples. In order to estimate their capacitance change under normal pressure, a dedicated electromechanical test bench was set up (Figure 3). The set-up includes an indenter tip associated to a spring loaded commercial force gauge, fixed on a PC controlled 3-axis robot arm. The load applied to the capacitive sensors is

monitored using the force gauge, and the capacitance changes are measured using the same impedance analyzer, as a function of the applied load. The capacitance changes obtained in the 0-6 N force range for sensors of type 1 and 2 are plotted in Figure 4. Each measurement point results from a set of 20 different measurements implemented during 20 load-and-release cycles.
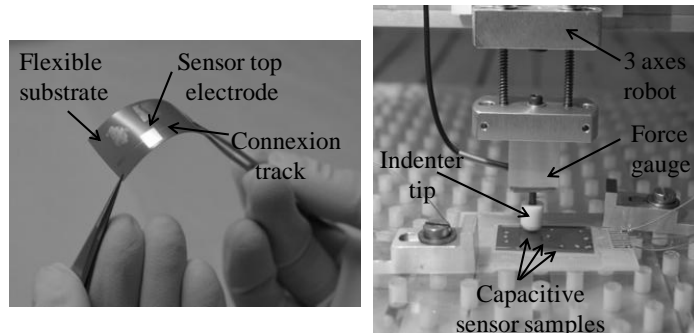

Figure 3. Capacitive pressure sensor sample and electromechanical characterization set-up.
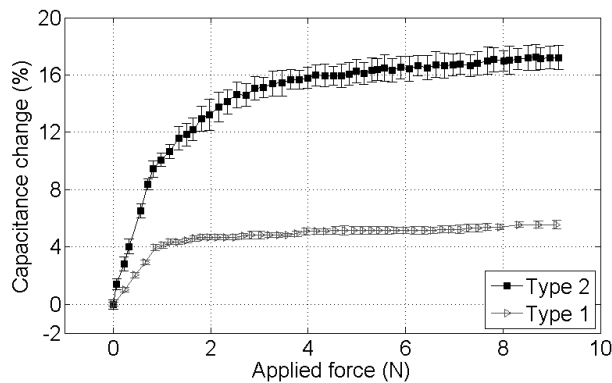

Figure 4. Capacitance changes of sensor samples of type 1 and 2 (Table 1) versus applied force. Error bars are twice the standard deviation of the data, estimated from 20 measurements.

It may be noted that the maximum capacitance change reaches less than 6 % for type 1 sensor, which is designed with a load-free PDMS thickness $d = 200\mu m$, and a form ratio $\rho_1 = 45$ mm. For the same load, the capacitance change is 17% for the type 2 sensor, which is designed with $\rho_2 = 13.6$ mm. Since ρ_2 is closer to the optimal form ratio ρ_{opt} than ρ_1, the type 2 sensor is, as expected, more sensitive than the type 1 sensor (Figure 1 and Figure 4). For these sensor dimensions, the maximum capacitance change under 6N load would have been in the order of 37% for a load-free thickness of PDMS $d = 3$mm (Figure 1). The capacitance change is then lowered if the used PDMS film is of a greater thickness. These results confirm that the sensor sensitivity to normal stress can be optimized according to the form ratio ρ of the designed sensor.

4. Conclusion
In conclusion, PDMS thin films have been fabricated and their mechanical properties under normal load have been experimentally studied. Thanks to this study it was established that the capacitance changes of micro-sensors constituted of bulky PDMS thin films and metallic electrodes can be optimized according to their form ratio. Indeed for a 3 mm side length micro-sensor, the capacitance change under a 6 N load can vary from a few percents up to more than 35%, if the load-free thickness of the film is adequately chosen. To validate these results, PDMS based normal pressure micro-sensor samples have been fabricated using a transfer of film fabrication process, and electromechanically characterized. Based on the characterization of two different sensor samples, it has been experimentally confirmed that the form ratio of the used PDMS film enables the sensitivity of the sensor to be optimized for a given side length of the sensor. These results should be validated thanks to an extended study involving a wider range of sensor dimensions, either via an experimental study or

by means of numerical computations. Nevertheless, the results presented in this study open the way to the design of enhanced flexible pressure sensors dedicated to wearable applications.

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