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Abstract

Flexible capacitive pressure sensors fabricated with nanocomposites were experimentally characterized and results compared with simulations from analytical modeling. Unlike traditional diaphragm silicon pressure sensors, the flexible nanocomposite sensors present a linear response over a large pressure range due to the changes in the volume of the dielectric that cause the pressure inside the dielectric cavity to change. Several devices with different geometries were used and the model results compare well with the experimental data. Sensitivities ranging from 2.5-20 fF/kPa were obtained and the devices dynamic response show a dual behavior, i.e., response time of the sensor during a pressure decreasing step is lower than for a pressure increasing step. This comportment is explained by the viscoelastic behavior of the PDMS-based nanocomposites used for fabrication of the capacitive sensor electrodes.

Keywords: Modeling; nanocomposites; pressure sensors; flexible sensors.

1. Introduction

Flexible pressure sensors have been proposed for several applications, including robotics [1, 2], human-machine interfaces [3, 4] and biomedical applications [5, 6]. Work on flexible pressure sensors is focusing predominantly on the fabrication technology [1-5], while some of the modeling aspects still need to be better addressed. In fact, and since the materials used for the fabrication of flexible sensors are usually characterized by a low Young's Modulus, relatively high deformations occur during operation.

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These aspects need to be properly included in the modeling both in the mechanical and fluidic domains. The work presented in this paper addresses the modeling and experimental characterization of flexible pressure sensors having a closed cavity and fabricated with nanocomposites [5]. The fabrication process is quite facile and enables the realization of flexible pressure sensors capable of large deformations (>30% strain) and low bending angles.

2. Pressure sensor model

The architecture of the pressure sensors used in this work is similar to typical configurations of capacitive pressure sensors. It is comprised of two square-plate electrodes (diaphragm) separated by a dielectric (air) of separation d_0 at pressure P_0. Fig. 1a and 1b show a schematic of the flexible pressure sensor, using two square-plate diaphragms (side length of *2a*).

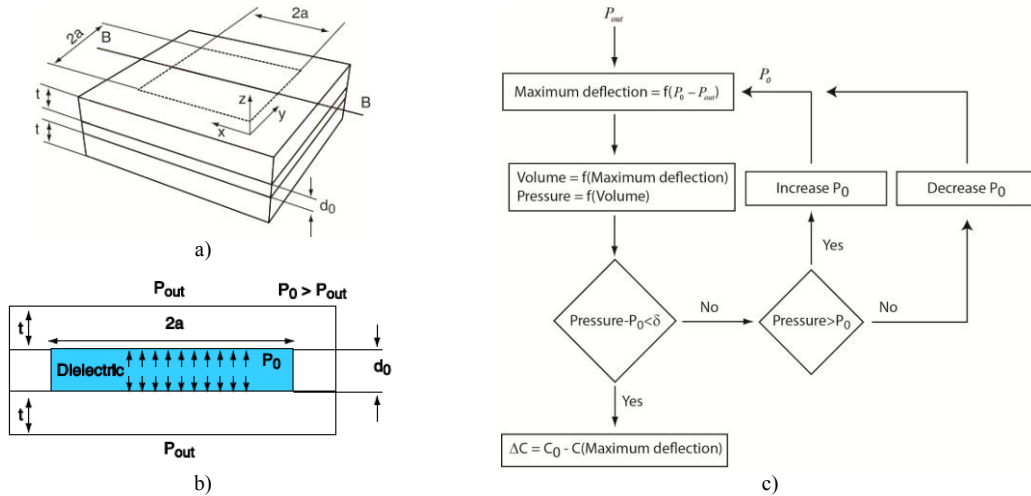

Fig. 1. Schematic of the square (side length = 2a) pressure sensor showing a) 3D view and b) section cut B-B and c) iterative algorithm to compute the capacitive changes of flexible capacitive pressure sensors.

A detailed description of the modeling approach for the electro-mechanical behavior of the pressure sensor is presented in [6]. A key feature of the nanocomposites used for fabrication of the sensors is the low Young's Modulus (~1.7MPa) [5] and, therefore, large deformations of the electrodes are expected. Since small pressure changes in the outside (P_{out}) cause large diaphragm deformations and large deformations cause volume changes of the dielectric material (air here), the pressure (P_0) inside the dielectric will change (from the ideal gas law, $P_i V_i = P_f V_f$). In order to capture this behavior the model presented in [6] was extended and an iterative model using the fluxogram presented in Fig. 1c was implemented in Matlab.

3. Sensor fabrication

The fabrication process uses vertically aligned-carbon nanotubes (A-CNTs) to build the conductive electrodes of the capacitor, embedded in a flexible substrate of polydimethylsiloxane (PDMS). A schematic of the fabrication process to obtain a single membrane is depicted in Fig. 2a. The process of embedding the A-CNTs begins with the fabrication of the mould. Poly(methyl methacrylate) (PMMA) is used as the mould material due to its good mechanical properties and low cost. The electrodes are built with forests or "carpets" of as-grown A-CNTs (1% volume fraction), grown via an atmospheric chemical vapour deposition (CVD) process [5, 6]. Next, the A-CNTs are slowly submerged in the uncured PDMS substrate to fabricate the A-CNTs/PDMS nanocomposites. The pressure sensor is composed of three thin

membranes, with the top and bottom layers defining the electrodes (each membrane has ~1% CNTs volume fraction), and the middle one defining the dielectric (see Fig. 2b). To obtain the final configuration, an uncured PDMS bonding process is used. Fig. 2c shows fabricated flexible sensors.
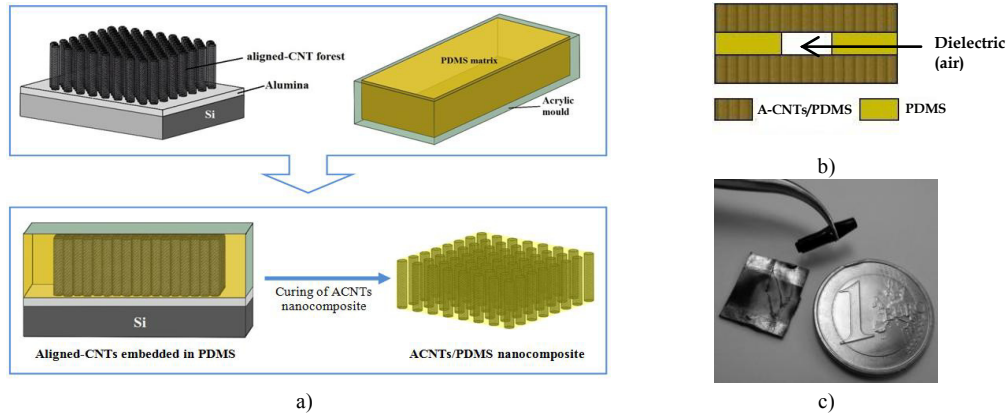

Fig. 2. Fabrication of the flexible sensors. a) Process flow for the development of a flexible A-CNTs/PDMS nanocomposite membrane, b) schematic of the pressure sensor composed of three thin membranes (top and bottom layers are A-CNTs/PDMS nanocomposites and the middle one is made of pure PDMS) and c) photograph of fabricated sensors.

4. Experimental results

Fabricated pressure sensors were placed inside a pressure chamber and a LCR meter (Philips PM6304) was used to measure the capacitive changes. A reference pressure sensor (Keller PAA 21R) was used for data comparison. LCR meter (10 fF resolution) and reference pressure sensor outputs where acquired at a sampling frequency of 1.6 Hz and data was stored in a PC for later comparison. Several sensors were tested and static responses of three devices with different diaphragm geometries and thicknesses are presented in Fig. 3.
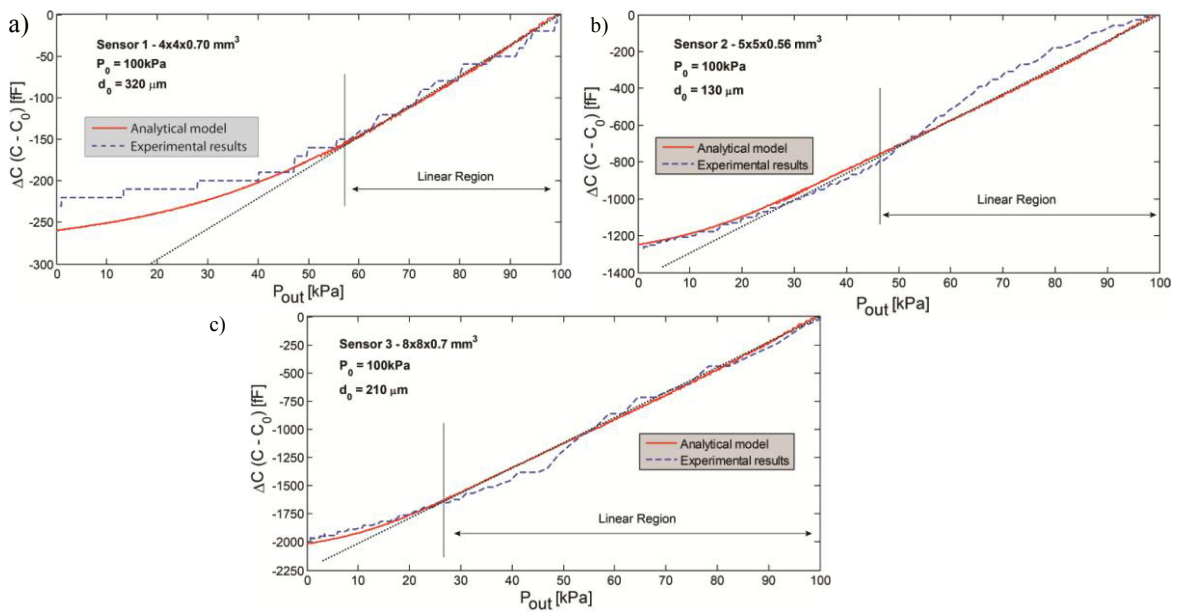

Fig. 3. Experimental results and comparison with analytical model.

Response of the sensors was also measured for both decreasing and increasing pressure steps (within the 0-100kPa range) and a sample result is presented in Fig. 4. Results show a very large time response for increasing pressure steps. In this case, the tensioned nanocomposites are returning to the rest position, and due to the viscoelastic behavior of the nanocomposites, strain takes additional time to disappear which explains the observed step curves.

5. Conclusions

The modeling and experimental characterization of flexible pressure sensors was presented in this paper. The large deformation of the flexible membranes used for sensor fabrication cause large volume changes within the dielectric cavity that need to be included in the model. Both the model and experimental results show a linear response of the capacitive sensor over a large pressure range. This behavior is not observed in traditional silicon pressure sensors (the deformations are very small in this case) and can be explored for the realization of pressure sensors with improved linear response and extended dynamic range.
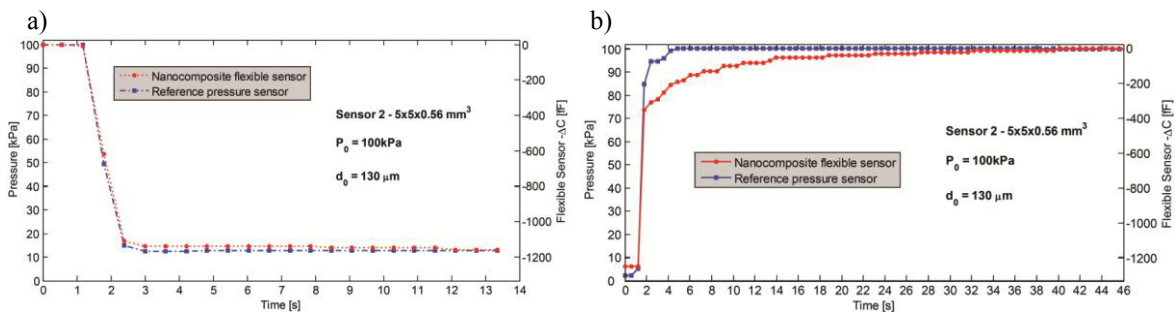
a) b)

Fig. 4. Flexible pressure sensors dynamic response.

Acknowledgements

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