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## Nanocomposite flexible pressure sensor for biomedical applications

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### Abstract

A new approach for the fabrication of flexible pressure sensors based on aligned carbon nanotubes (A-CNTs) is described in this paper. The technology is suitable for blood pressure sensors that can be attached to a stent-graft and deployed during an endovascular aneurysm repair (EVAR) procedure. Given the specifications of EVAR, the device should be foldable (extremely flexible) and characterized by a (very small) profile that integrates with the stent-graft cross section. A-CNTs embedded in a flexible substrate of polydimethylsiloxane (PDMS), a transparent, nontoxic and biocompatible silicone elastomer, are used to fabricate elements of the capacitive sensors. Fabricated prototypes validate our approach and show that CNTs/PDMS layered composites can be used to create highly flexible pressure sensors.

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*Keywords:* Flexible pressure sensor; aneurysms; carbon nanotubes; pressure sensor design, polymer nanocomposite.

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### 1. Introduction

Research on CNT-based sensors, i.e. sensors that employ CNTs as the transduction element, has been very active in the past years [1], whereas the work on nanocomposites for microsystems has been primarily focusing on materials technology, with little work reported on nanocomposites-based sensors. Due to the good electric properties, CNTs can provide the nanocomposites with electrical transduction mechanisms, like piezoresistivity and capacitive detection. MEMS-scale pressure sensors [2] are devices

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of great interest for biomedical applications mostly due to the small scale of the devices (usually planar areas below  $4 \text{ mm}^2$  [2]), low power consumption and low fabrication costs. Pressure sensors have been proposed for permanent implant through minimally invasive procedures, commonly done through catheter delivery systems. These sensors are typically silicon-based, have limited high-temperature operation, require internal power sources and have limited biocompatible packaging technologies [3]. New solutions are focusing on the development of flexible technologies for the sensor fabrication, where the pressure sensor can be delivered in folded-up compact shapes and then expanded post-delivery [4]. The work presented here addresses the development of a flexible pressure sensor for biomedical applications, focusing on the technology to fabricate the flexible sensor using polymer nanocomposites.

## 2. Development of the flexible pressure sensor: design and fabrication

A promising application for flexible pressure sensors is stent-graft placement monitoring through the measurement of the aneurysm sac pressure [3-4]. For this application the sensor needs to be fixed to the stent-graft, and therefore the sensing element should be foldable, highly flexible (allowing the attachment to the stent-graft), have a small profile, and the technology must be simple and biocompatible.

The capacitive pressure sensor presented here is based on two square-plate electrodes (diaphragm) separated by a dielectric (air) at pressure  $P_0$ . Bending of the square-plates, caused by variations in outside pressure,  $P$ , generates capacitive changes proportional to the pressure changes. The sensor fabrication process uses aligned-CNTs (to build the conductive elements) embedded in a flexible substrate of PDMS, which enables the sensor to be integrated in a stent-graft, improving existing methods to deliver the sensors within the aneurysm sac and allowing the placement of several sensors thereby improving assessment of spatial pressure variations .

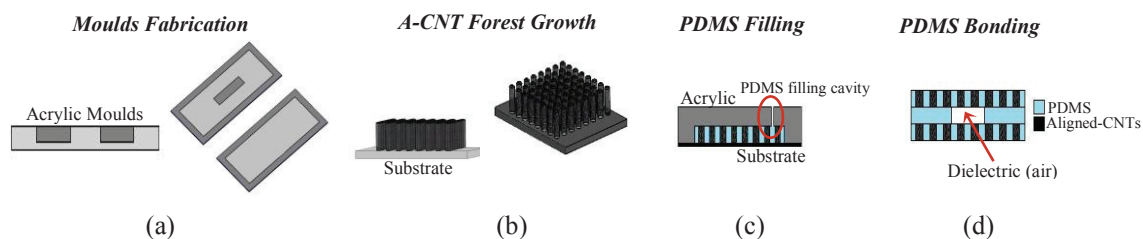


Fig. 1. Fabrication process flow for a flexible pressure sensor with aligned-CNTs/PDMS nanocomposites (a) acrylic moulds fabricated by CNC milling; (b) aligned-CNTs forest growth; (c) cross-section view of PDMS filling, and (d) cross-section view of the three bonded thin membranes.

The technology process flow for fabricating the flexible pressure sensor is schematically presented in Fig 1. PDMS flexible membranes are obtained using acrylic moulds, fabricated by CNC milling (Fig 1a). This method allows fast production times and the costs involved are low. Nevertheless, it is difficult to reach dimensions less than  $50 \mu\text{m}$ , a reason why this technique is usually associated with poor dimensional control. The electric components are built with forests or “carpets” of vertically aligned-CNTs, grown via an atmospheric chemical vapor deposition (CVD) process, as shown in Fig 1b. A silicon substrate with patterned  $\text{Fe}/\text{Al}_2\text{O}_3$  catalyst is positioned on a horizontal quartz tube furnace at atmospheric pressure at  $750^\circ\text{C}$  [5] for the aligned-CNTs growth. This process allows growing high purity, high yield and vertically aligned continuous CNTs. After growth, the aligned-CNTs are embedded in the polymeric matrix of PDMS, positioning the substrate against the mold. The PDMS is introduced in the cavity through a hole to create the nanocomposite, followed by curing of the elastomer (Fig 1c) at  $80^\circ\text{C}$  for 30 minutes. The pressure sensor is composed of three thin layers (Fig 1d), with the top and bottom layers defining the sensor electrodes (each membrane has  $\sim 1\%$  CNTs volume fraction), and the middle one

defining the dielectric (air). This configuration requires bonding of the nanocomposite membranes. Uncured PDMS adhesive technique approach [6] was used for the bonding and has proven successful in our work, see Fig 2a.

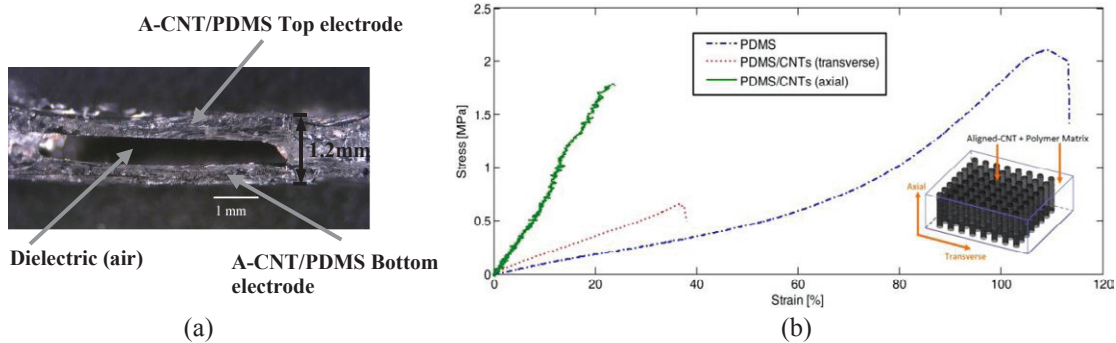


Fig. 2. A-CNT polymer nanocomposite pressure sensors: (a) Cross-section of an A-CNTs/PDMS flexible pressure sensor; (b) Stress-strain curves of pure PDMS and reinforced A-CNT/PDMS nanocomposites in the axial and transverse directions.

### 3. Experimental results

A very important step during the sensors’ fabrication process is embedding the aligned-CNTs in the PDMS matrix and its electrical and mechanical characterization, whose properties are required for the sensor design. Several individual aligned-CNTs/PDMS membranes, moulded into rectangular shapes with dimensions of  $32 \times 14 \times 0.4 \text{ mm}^3$  (LxWxH) were tested in tension to obtain the Young’s modulus in both axial and transverse directions (with the CNTs oriented normal and parallel to the load) using an *Instron 4505* mechanical materials testing system, using a load cell of 500N. All samples were clamped in custom grips with a crosshead speed of 0.8mm/min. An image strain monitor was used to create the stress-strain curves in the axial and transverse directions shown in Fig 2b. Pure PDMS membranes were also tested for comparison and they have a Young’s modulus (in the linear region) of  $\sim 0.9 \text{ MPa}$ , which is in line with literature values [7]. The CNTs/PDMS composite has an increase in the Young’s modulus in the transverse direction –  $1.7 \text{ MPa}$ . In the axial direction, the increase is very high – up to  $8 \text{ MPa}$ . These results show that the nanocomposites have non-isotropic elastic behavior. No assessment of strength can be made from Fig. 2b as the specimens failed outside the region of the A-CNTs.

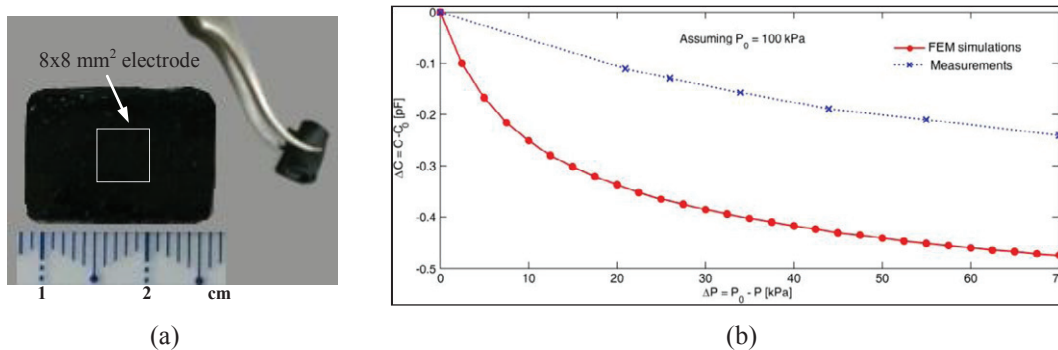


Fig. 3. CNTs/PDMS prototype pressure sensor: (a) optical image including flexibility demonstration; (b) capacitive changes vs. pressure, assuming ambient pressure inside the dielectric (air).

Some other samples were used to measure the nanocomposites electrical conductivity using the van der Pauw method. The measured conductivity was  $0.35 \text{ S.m}^{-1}$  with a standard deviation of  $0.37 \text{ S.m}^{-1}$ . The

rather low conductivity does not compromise the capacitive sensor, but since passive telemetry is required to measure and power the sensor, it has major implications if one wants to design an inductor using this approach. Other work with the same aligned CNTs, but embedded in an epoxy polymer, showed electrical conductivities in the axial direction of  $\sim 10 \text{ S.m}^{-1}$  [8]. Fabricated CNTs/PDMS flexible pressure sensors prototypes (Fig 3a), with a mechanical and dielectric thickness of  $675\mu\text{m}$  and  $250\mu\text{m}$  respectively, were tested in a vacuum chamber. The area of the electrodes is  $8 \times 8 \text{ mm}^2$  (WxL). The capacitive changes were measured when the sensor was placed inside a controlled pressure chamber for pressures ranging from ambient pressure (100kPa) to 30kPa. The results are shown in Fig 3b. Finite Element Modeling (FEM) was used to build an electromechanical model of the sensor and simulations results were compared with the experimental measured data. The nanocomposite layers were modeled as an orthotropic material with the values retrieved from the mechanical tests. The simulation results compare relatively well with the experimental data for large pressures differences (in terms of rate of change). However, when the external pressure is close to ambient pressure, differences between simulations and measured data regarding capacitive changes are significant. This can be due to some imperfection during the fabrication of the sensor and real sensor geometry, but mainly due to uncertainty about the actual pressure inside the hermetically sealed cavity (the pressure inside the dielectric cavity might not be at ambient pressure).

#### 4. Conclusions

We demonstrate that a technology based on aligned-CNTs embedded in a flexible matrix of PDMS has proven successful in the development of flexible pressure sensors. A surveillance mechanism based on pressure changes, to measure the pressure in an aneurysm sac, is an attractive solution to detect possible post-EVAR problems. Future work includes the development of an inductor embedded in the nanocomposite using conductive fibers that enables the fabrication of a LC network for passive telemetry.

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