# Pressure Sensor for Gastrointestinal Intraluminal Measuring

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Abstract: This paper reports an innovative technique to measure intraluminal pressure in the gastrointestinal tract (GI), which is typically performed through an exam called oesophageal manometry. This type of measurement is performed with a catheter, comprising several pressure sensors along it, and gives important information for the diagnosis of motility and peristalsis disorders in the GI tract. The presented work explores the use of PDMS polymer (Polydimethylsiloxane) as the support material for the pressure sensors. These PDMS layers are placed in the pressure measurements sites of the catheter. The presented work also explores different materials for the metal strain gauges that act as the pressure sensors. Due to the microfabrication techniques, the presented pressure sensors allow on-chip integration (with other microsensors for GI diagnosis), and its pressure measurements will add essential diagnostic information, not only for the GI motility and peristalsis disorders, but also in the early cancer detection. The initial mechanical tests showed promising results for the intended application. After optimization of the fabrication process, different experiments are scheduled for simulating the pressure signals that would occur in vivo conditions. In summary this method will permit high integration and good sensitivity measurement, while maintaining low fabrication costs.

## 1 INTRODUCTION

An oesophageal manometry provides crucial information for the diagnosis of motility and peristalsis disorders, such as diffuse esophageal spasm or nutcracker esophagus, and typically assesses the motor function of three main structures: Upper Esophageal Sphincter (UES); esophageal body; and Lower Esophageal Sphincter (LES) (ASGE, 2012, AGA, 2005). The pressures typically associated with this exam are in the range of 7-200 mmHg (Holloway, 2006). The manometry equipment is composed by a catheter and several pressure sensors along it (Murray et al., 2003). A manometry exam can be classified accordingly to the number of sensors that are employed: conventional (4 to 8 sensors) and high resolution manometry (20 to 36 sensors) (Kahrilas et al., 2008). The high resolution exam has been gaining ground in the last few years due to the higher spatial resolution within the oesophageal lumen, which enables to completely define the intraluminal pressure profile (Kahrilas et al., 2008).

The pressure sensors are typically based on two methods: water perfused and solid state sensors (Bodger and Trudgill, 2006). The solid state ones permit to downsize the sensor area (areas sensible to pressure as low as 1 $mm^2$), which is preferable for high resolution systems (ASGE, 2012).

This paper reports an innovative technique to measure the intraluminal pressure in the gastrointestinal tract (GI) using the concept of oesophageal manometry. The developed system explores the use of PDMS polymer (Polydimethylsiloxane) as the support material for deposited metal strain gauges that serve as the pressure sensors. In order to create pressure sensitive regions in PDMS, one or four diaphragms (four for intrasphincteric measurements due to asymmetric pressure profiles) per measurement site will be micromachined in the PDMS layers (Figure 1). An external layer of PDMS is also required to isolate the sensor from the organism.

The strain gauges are then distributed in these diaphragm's regions, where the elastic strain is higher, thereby improving the measurements' sensitivity. An external intraluminal pressure will act in these diaphragms, thereby deforming the deposited strain gauges, leading to a change of the gauges' electrical resistance, which directly relates with the applied pressure.


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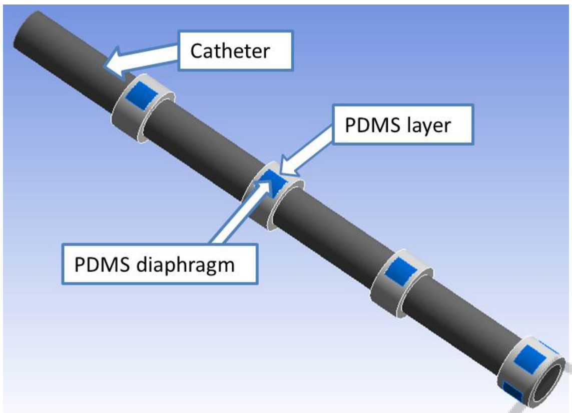


Figure 1: Catheter and the respective PDMS layers along it (diaphragms are highlighted). At the tip, four diaphragms are machined for intrasphincteric measurements.

## 2 PROPOSED SYSTEM

### 2.1 Catheter

A regular circular catheter with a diameter between 2.7 and 4 mm is typically used for intra-oesophageal pressure measurements. This catheter should be flexible and can be made of different polymeric materials, as polyvinyl chloride or silicone (ASGE, 2012). In the proposed system, a PDMS layer is placed externally to the catheter, in the pressure sensitive areas (Figure 1). The PDMS polymer was chosen due to its bio-compatibility and resistance to pH down to 2, which are required features for GI applications (Cao, 2013). Additionally, PDMS is a material with low cost, high flexibility and compatible with micro-electronic mechanical systems (MEMS).

The various diaphragms are presented in Figure 1. These regions are the pressure sensitive sites that will enable the pressure measurements. These diaphragms (Figure 2) enable a greater flection of the structure in response to exterior pressures. Figure 3 shows the strain on a PDMS layer, which has a central diaphragm (simulated in ANSYS software). In this simulation, both the bottom and side surfaces of the structure were defined as fixed supports. A 110 mmHg pressure signal was then applied perpendicularly to the exterior surface. As it can be seen, the diaphragm strain (i.e. the central area) is several orders of magnitude greater than the one in the surrounding area. Furthermore, the highest strain was in the borders of the diaphragm and in its centre. Therefore, the pressure sensors should be placed in these areas of interest, which significantly increases the pressure measurement sensitivity.

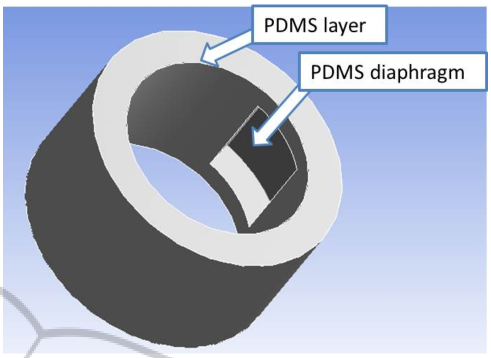


Figure 2: Representative section of the catheter with a diaphragm machined in the structure (centre of the structure).

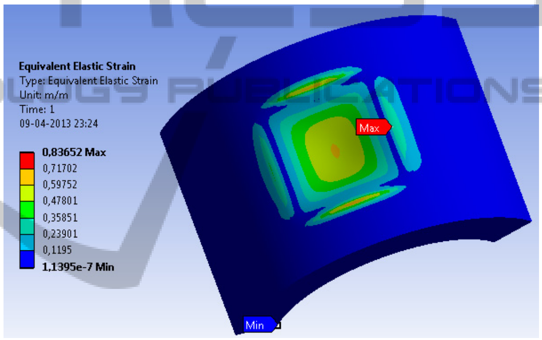


Figure 3: Elastic strain distribution along the diaphragm and surrounding structure for a 110 mmHg pressure signal (simulated using ANSYS software).

### 2.2 Pressure Sensors

As the name suggests, a pressure sensor is capable of converting a mechanical deformation caused by an external load into an electrical signal (Elwenspoek, 2001). In this work, metal strain gauges, deposited in PDMS, are used as pressure sensors. This gauge is deposited through lithography processes which are explained in detail in section 3.

A strain gauge consists of a flexible backing which supports a metallic foil pattern. This type of sensor is based on electrical resistance changes. Whenever a force is applied to this sensor, a deformation is developed in the metal pattern which in turn leads to a change of the strain gauge electrical resistance (Elwenspoek, 2001). This change is given by the following expression:

$$\frac{dR}{R} = (1+2\upsilon)\varepsilon \quad (1)$$

where $\upsilon$ is the Poisson's ratio of the material and $\varepsilon$ is the mechanical deformation of the material.

The resistance change is quantified using the well-established Wheatstone bridge circuit (Figure 4), which converts the resistance change in an output voltage proportional to this variation. The output voltage is given by the combination of the electrical resistances R1, R2, R3 and R4 that constitute the fully active Wheatstone bridge which results in (Elwenspoek, 2001):

$$V_{out} = V_{source} \times \left( \frac{R_4}{R_4 + R_2} - \frac{R_3}{R_3 + R_1} \right) \quad (2)$$

Given the elastic strain distribution obtained in Figure 3, the strain gauges should be placed in the central region and in the borders of the diaphragm, in such a way that the same pressure signal will generate opposite variations on the resistance of each pair of resistances ($R_1/R_4$ and $R_2/R_3$). The strain gauges final layout along the diaphragm is illustrated in Figure 5. For example, in response to a pressure signal, these strain gauges will either increase (R1 and R3) or decrease (R2 and R4) their resistance and vice versa. By placing the resistances this way a fully active bridge is ensured, which will result in a higher value of $V_{OUT}$ (see equation (2)), i.e. a higher output voltage of the Wheatstone bridge. Furthermore, by placing the four resistances as close as possible, undesirable changes of some parameters, such as temperature, are almost negligible, once all resistances will be subjected to the same variations, cancelling each other out. These resistors are then connected as presented in Figure 4. Different materials, particularly Al (Aluminium) and Au (Gold) are being study to act as the active element of the pressure sensor. Important parameters of the deposition process are being optimized, at this stage, to ensure the best adhesion to PDMS.

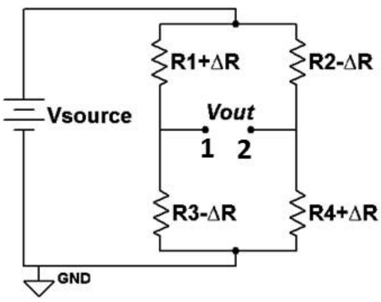


Figure 4: Wheatstone bridge (fully active).

## 2.3 Encapsulation

An external PDMS layer is necessary to isolate the strain gauges metal from the intraluminal medium. Consequently, this layer will result in a reduction of the measurement's sensitivity. A numerical study, through ANSYS, was done in order to optimize the thickness of both this external layer and the diaphragm. Figure 6 shows the theoretical electrical signal output that results in response to the same pressure signal for different thicknesses of both the external PDMS layer (cover) and the diaphragm. The inversion of the signal polarity is due to the ratio between the thickness of the cover layer and the thickness of the diaphragm.

As it can be seen, the highest sensitivities are achieved with lower cover thicknesses and the best result was obtained for a diaphragm's and cover's thickness of 30 and 20 µm, respectively. These values will serve as guideline for the fabrication steps.

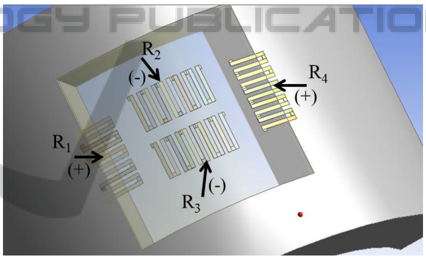


Figure 5: Strain gauges placement in the diaphragm (ANSYS) (diaphragm is transparent for better comprehension).

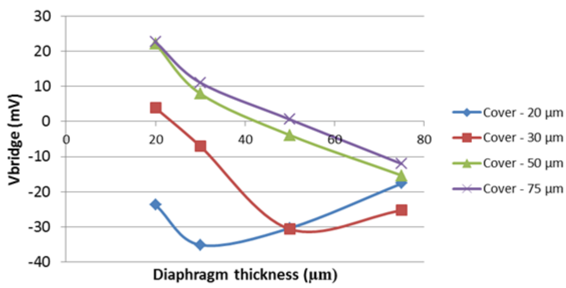


Figure 6: Voltage output of the Wheatstone bridge according to the thickness of the diaphragm and the PDMS cover layer, for Aluminium strain gauges (200 nm thickness) and a pressure signal of 225 mmHg.

# 3 FABRICATION

The fabrication steps of the diaphragm structure and its embedded strain gauges are described in Figure 7.

The diaphragm on the PDMS structure is fabricated using a SU-8 mold (height of 50 µm). The PDMS pre-polymer is mixed in the ratio of 10:1 (base/curing agent) and subsequent degassed in a vacuum desiccator in order to prevent bubble formation in the mold material (due to incorporated gas and crosslinking reaction by-products).

The PDMS is then deposited by spin coating over the mold at 500 rpm in order to obtain a PDMS 50 µm thick film. After this step, it is cured in a hot plate at a temperature of 85°C for a period of two hours. Subsequently the PDMS structure that contains the diaphragm is detached from the mold, with the help of a scalpel, that cuts the area around the patterned zone and it is placed over a glass slide. Then, a metallic thin film is deposited onto the PDMS to create the strain gauges. This film is deposited by Physical Vapor Deposition (E-beam) and patterned by standard photolithography. In this process the positive photoresist AZ4562 is deposited by spin coating at 6000 rpm for 20 seconds and cured in a hot plate at 100°C for 10 minutes. After this period the samples are left to cool for 10 minutes and, then, exposed to UV light with the MaskAligner equipment. In order to accomplish this process it is necessary to use the mask that contains the micro features to be transferred and exposed using the Soft Contact mode during 0.85 minutes. Then, the photoresist developer is used to remove the zones exposed to the UV light remaining only over the metallic zones that were protected. This removing process uses a solution that contains the AZ351-B developer diluted in distilled water (4:1) and a mixer to perform the photoresist development. After 10 minutes developing it is cleaned with distilled water and dried with a nitrogen flow.

With the previous steps successfully carried out, it is necessary to perform the etch of the metallic deposited films. For the aluminium etching a recipient that contains an Al etch solution is used. Next, it is visualized when all the non-protected areas have been removed. The samples are then removed, cleaned with IPA and dried with a nitrogen flow. Other etchants can be used for other metals. In the case of Gold, a Gold etch TFA can be used. To finish the patterning of the metallic film it is necessary to remove the photoresist that has been used to protect the zones of interest. For that, a solution of AZ100 is used during 15 minutes. The structure is then cleaned with distilled water. An example of the final structure obtained is presented in Figure 8. In order to maintain the electric contact from the strain gauges to the exterior, wires are then attached to the conductive pads with silver conductive paint. Finally, the external PDMS layer (30 µm) is spun (800 rpm) onto the metal to cover the sensors. Although the manufacturing process just described has been successfully used, several challenges must be overcome. First, it is necessary to improve the adhesion between the metal film and the surface of PDMS, which could be done with chromium adhesion layers or plasma surface treatment of PDMS prior to deposition.

Another problem is the presence of microcracks that can appear due to the pressure and temperature conditions involved in the deposition process. As such, an optimization of the process or the metal of choice is currently being carried out. The best results at this stage were obtained for aluminium and gold.

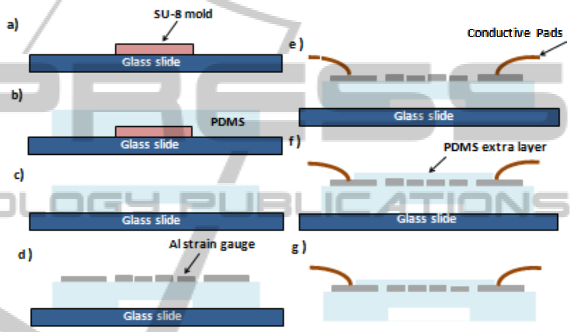


Figure 7: Schematic representation of the fabrication process of the strain gauges. a) SU-8 mold; b) pouring the PDMS pre-polymer on the SU-8 mold and curing; c) detaching the structure in PDMS and putting on a glass slide; d) deposition and patterning the metallic film; e) outer electrical contacts; f) covering the sensors with a second layer of PDMS; g) separating the sensor.

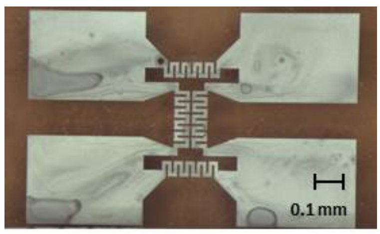


Figure 8: Aluminium strain gauges embedded in PDMS.

## 4 READOUT SYSTEM

The final readout system can be seen in Figure 9. As previously stated, a Wheatstone bridge is typically used for strain gauge pressure measurements and this case is no exception. Nevertheless, additional components are required, so as to amplify the resultant signal, which is of very low amplitude. The signal is also filtered in order to reduce the high

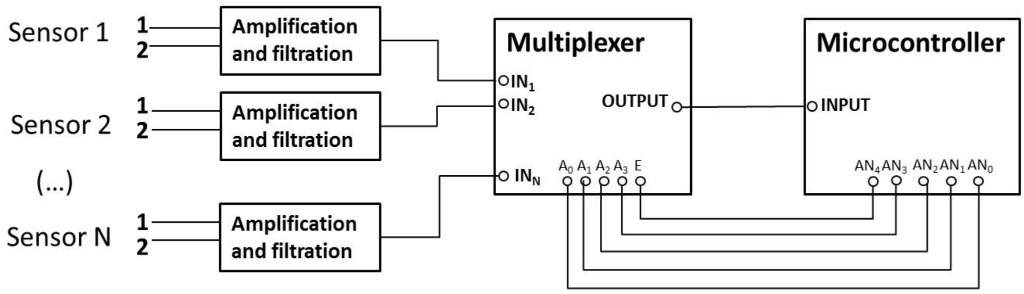


Figure 9: Different blocks that constitute the readout system and their connections. The sensors can be seen in Figure 4.

frequency noise signal and the power supply signal (~50 Hz) that could overlap the signal of interest.

In addition, a multiplexer is used enabling a sequential reading of the pressure sensors. The addressing of the multiplexer channels (which determines what sensor signal to read) as well as the reading and commutation frequencies between channels are defined through a microcontroller (PIC32MX795F512L). The microcontroller's programming is carried out by MPLAB IDE. Finally, the signal is acquired and converted to digital to be presented in a computer through a user friendly interface that is being developed with the software Qt Creator.

# 5 EXPERIMENTAL RESULTS

## 5.1 Resistivity Measurement

As reported in section 3 various materials are in study for being used as the strain gauge's active element. Two of these, more precisely, gold and aluminium, were already deposited with proven methodology. At this stage a resistivity measurement was carried out based on the Van der Pauw method. This method enables the resistivity measurement of a material, regardless of its form, considering that the test sample is approximately two-dimensional (i.e. width much larger than the thickness).

In that method, four electrical contacts are set in the different corners of the sample. An electric current is then applied between two contacts and the resulting voltage is measured in the other two. Altogether eight separate measurements are conducted so as to ensure a greater precision.

The experimental setup required for this test includes a current source, a voltage source and a multimeter with a four tips adapter (Figure 10). A computer software then controls and varies the applied current in all the four points (Figure 11) and sets parameters such as: error margin; number of readings; and film thickness for a correct calculation of the resistivity.

As shown in Table 1, the obtained results for the resistivity are dissimilar to the theoretical values expected for gold and aluminium bulk films. This was expected, since bulk material is typical a single crystal structure, and thin-films are polycrystalline, with much smaller crystal sizes, with many interface regions. In addition, the deposition process doesn't guarantee a homogenous or free of cracks film, due to PDMS substrate. For these reasons higher resistivity values are expected. However, these values are acceptable for the desired application.

Table 1: Theoretical and measured (mean value) resistivity for aluminium and gold.

| Metal | Resistivity (nΩ/m) | |
|---|---|---|
| | Theoretical (BYU, 1994) | Measured |
| Aluminium | 28.2 | 335±20 |
| Gold | 24.4 | 110±10 |

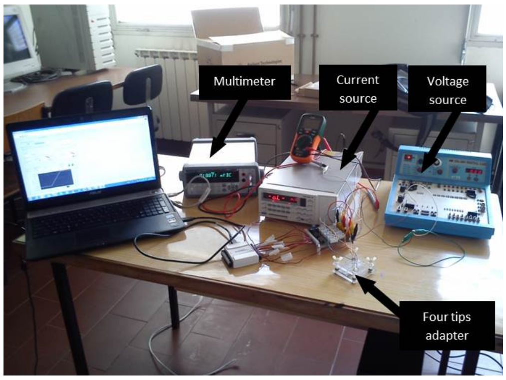


Figure 10: Experimental setup for the resistivity measurements (including a multimeter, current and voltage sources and a four tips adapter).

## 5.2 Mechanical Tension Test

At this stage mechanical extension tests were done.

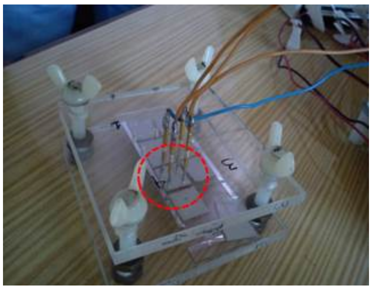

Figure 11: Four tips adapter.

Therefore, an experimental setup, shown in Figure 12, was used. The metallic film deposited in PDMS is then attached to two clamps which are responsible for the extension of the sample (PDMS/metal) in a controlled manner (by the displacement indicator seen in Figure 12). Simultaneously, the resistance of the film is recorded in order to associate the resistance change with the sample stretching. The main purpose of this experiment was to verify if the metallic film recovers its original resistance between cycles of extension, which is required for this application.

Figure 13 shows 6 distinct cycles of consecutive extension and recovery for gold films (6 x 2 cm with a thickness of 100 nm) in a 1 mm thick PDMS layer. As it can be seen, for an extension of 300 µm, the maximum resistance change was approximately 2.4 % of its initial value. Furthermore, the films recovered their initial resistance value in the recovery cycle as seen in the graph.

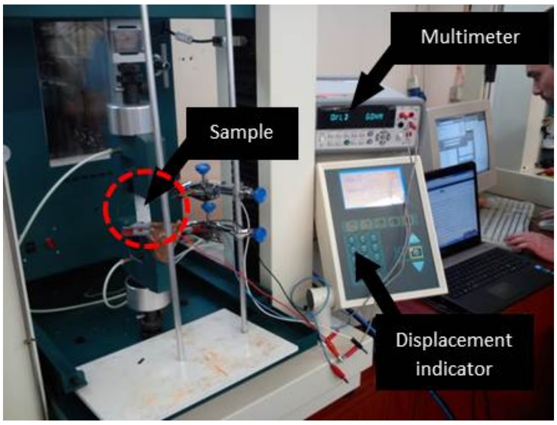


Figure 12: Experimental setup for the mechanical tests.

## 6 CONCLUSIONS

This paper relates to an innovative technique for measuring the intraluminal pressure in the

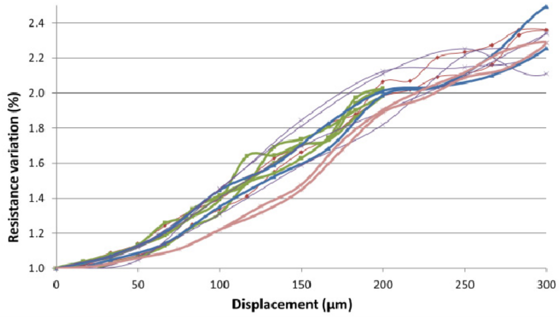


Figure 13: Displacement versus resistance change for gold films deposited in PDMS.

gastrointestinal tract (GI). A multiple sensor approach is proposed, which is based in strain gauges. The strain gauges are supported by a PDMS layer, which guarantees a small sensitive area, enabling a higher integration, while maintaining low overall cost. At this stage the deposition process for the strain gauges is being optimized. However, the initial mechanical tests with gold show promising results for the application intended. After this optimization step, different experiments are scheduled with the final geometry for the strain gauges and adequate manometry equipment so as to simulate the pressure signals that would occur in *in vivo* conditions.



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