A Novel PDMS Based Capacitive Pressure Sensor

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Abstract— **In this paper, a capacitive pressure sensor for aeronautical applications is presented. The sensor mainly consists of a thin structured layer of Polydimethylsiloxane (PDMS) that is embedded between two metal films. In this application the structured PDMS layer is used as dielectric and as spring element. The optimal design of the sensor was determined using a finite element analysis. The technological implementation of the first test samples using microtechnology is shown. The static and dynamic characterization of the pressure sensor validates the high sensitivity and temporal resolution of the sensor.**

I. Introduction

Polydimethylsiloxane (PDMS) is widely used in biotechnology and micro-processing. This silicone based elastomer is cost-efficient, chemically inert, it can be deposited with different layers, it is suitable for micro-moulding processes and large deflection can be achieved with this material. In this application PDMS is used as dielectric and spring element for a capacitive pressure sensor. To enable a higher deformation and therefore to increase the sensitivity of the sensor, the PDMS layer was structured.

For many aeronautical applications pressure sensors with a high temporal and spatial resolution that can be applied on curved surfaces, e.g. on airfoil models, are needed. Capacitive sensors have the advantage of high sensitivity, low power consumption and better temperature performance compared to piezoresistive devices. The benefits of this sensor are the simple manufacturing process and the robustness compared to commercial silicon pressure sensors.

II. Sensor Development

To determine the design of the capacitive pressure sensor, a finite element model was developed to evaluate the influence of the structuring of the PDMS layer on the mechanical and electrostatic properties of the sensor.

A. Design

This capacitive pressure sensor mainly consists of a thin structured layer of PDMS that is used as dielectric and as spring element. The layer is embedded between two metal layers that are used as electrodes. The sensor is manufactured on a thin flexible substrate material so it can be applied on curved surfaces (see Fig. 1).

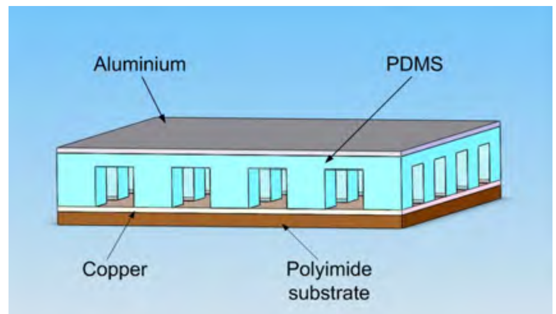

Figure 1. Schematic drawing of the capacitive pressure sensor

One advantage of the PDMS (AlpaSil Classic, Alpina) that is used in this application is the low Young's modulus of 180 kPa that allows a deformation under low pressure. Another benefit is the low viscosity of 1200 MPas of the uncured PDMS that makes it suitable for micro moulding processes [1].

B. Simulation

For the design of the capacitive pressure sensor static two-dimensional FEM simulations were performed with COMSOL Multiphysics 3.2. Thus the influence of the structuring on the mechanical and electrostatic characteristics of the sensor could be examined. The model includes the polyimide substrate with the copper metallization, the dielectric PDMS layer and the top electrode. During simulations one unstructured and two structured PDMS layers with a total thickness of 35 µm were investigated. The layers are structured in that way, that single elements with a height of 25 µm and a width of 25 µm are created. On top of these elements a complete layer with a thickness of 10 µm remains. The distance between these elements is 25 µm in the first variant and 12.5 µm in the second, respectively. The mechanical properties of the different materials were assumed as linear where the strain stress relation is

$$\sigma = \varepsilon E, \quad (1)$$

where σ is the stress, ε the strain and E the Young's modulus [9]. The divergence of the electrostatic field E can be described with Gauss' law [4]:

$$\nabla E = \rho/(\varepsilon_0 \varepsilon_r), \quad (2)$$

where ρ denotes the charge density, ε_0 the dielectric constant of vacuum and ε_r the dielectric constant of PDMS.

To simulate the distribution of the electric potential in the deformed PDMS layer a moving mesh using the ALE (Arbitrary Lagrangian-Eulerian) description was implemented. Fig. 2 shows the results of the simulations for a static pressure of 25 kPa for the complete and the structured PDMS layer with a distance of 25 µm between the elements

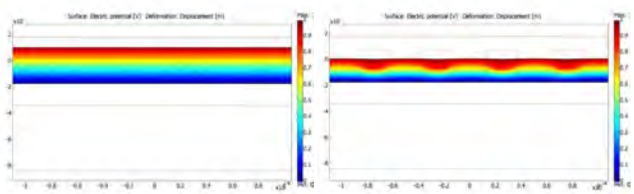

Figure 2. Deformation and distribution of the electric potential in the unstructured (left) and structured (right) PDMS layer

In the complete deformed PDMS layer the distribution of the electric potential is uniform between the two electrodes, while the air filled cavities in the structured layer influence the distribution of the electric potential. The structuring of the layer causes a higher change of the capacitance of the sensor. This effect increases with rising pressure. All sensors show an almost linear behaviour in this pressure range (see Fig. 3).

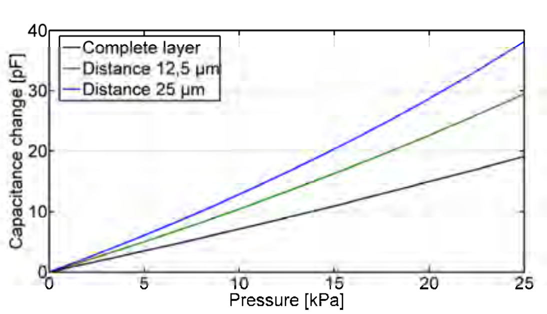

Figure 3. Change of capacitance of the sensor dependent on the static pressure

III. MANUFACTURING

The manufacturing process of the capacitive pressure sensor was arranged in two steps. First the structured PDMS layer and subsequently the complete sensor on the flexible substrate material were fabricated.

A. *Master structure*

The three-dimensional master structure for the micro-moulding process was fabricated in patterned photoresist. This material offers the advantage that the master structure can be dissolved with acetone, thus it is guaranteed that the thin PDMS structured is not damaged during demoulding [11]. To obtain the master structure, a thick positive resist was spun on a silicon wafer and structured photolithographically. After development photoresist structure with a thickness of 22 µm remains (see Fig. 4).

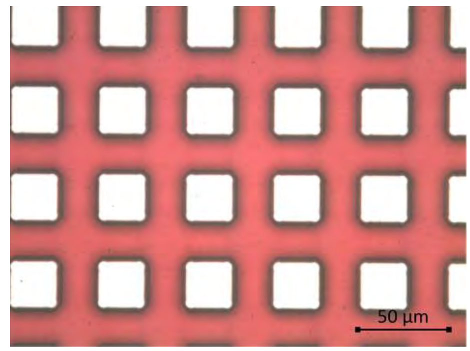

Figure 4. Photoresist master structure

B. *Structured PDMS layer*

Both components of the PDMS, the prepolymer base and the curing agent, were mixed in the standard ratio of 10:1 and then applied on the master structure using spin coating. With a rotation speed of 1500 U/min a 10 µm thick layer of PDMS remains on top of the master structure. Due to the low viscosity of the material a degassing in the vacuum chamber to remove air bubbles is not necessary. After curing of the PDMS the photoresist was dissolved with acetone (see Fig. 5).

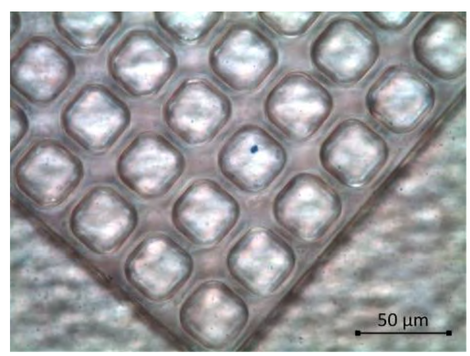

Figure 5. Structured PDMS layer

A 50 µm thick Kapton sheet with an additional copper metallization was used as substrate material for the pressure sensor. The structured PDMS layer was bonded on the copper layer that is used as electrode for the sensor.

C. *Metallization*

An aluminium layer with a thickness of 500 nm that is used as top electrode for the capacitive sensor was deposited on top of the PDMS surface. This layer supports the uniform deformation of the structured PDMS layer under pressure. Prior evaporation the surface of the silicone layer was treated with oxygen plasma. By using plasma, a hydrophilic surface and therefore the necessary adhesion of the aluminium layer are guaranteed [6, 8]. Without plasma treatment a cracked non-conductive layer is generated (see Fig. 6). After the deposition of the aluminium layer the typical formation of ordered structures is observable that is caused by the thermal expansion during the evaporation process [2, 5].

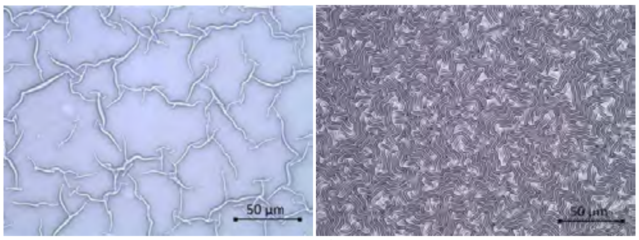

Figure 6. Aluminium layer without (left) and with (right) plasma treatment before evaporation

Finally, the sensor elements were separated and contacted electrically. The size of the first test samples is 15 mm x 15 mm. Fig. 7 shows the cross-sectional SEM micrograph of the capacitive pressure sensor.

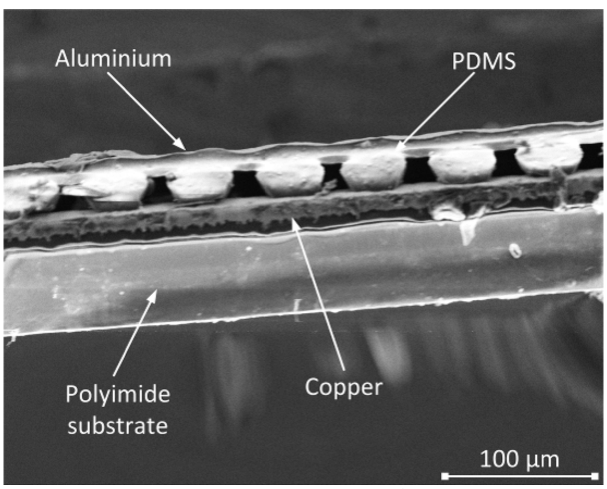

Figure 7. SEM micrograph: Cross section of the pressure sensor

IV. RESULTS

To evaluate the sensor, the first test samples were characterised statically and dynamically and the resonance frequency of the sensor was determined experimentally.

A. Static characterisation

For the static characterisation of the pressure sensor the capacitance was determined with a LCR meter with an accuracy of 0.1 pF. The capacitance of the first test samples were in the range of 120 pF. In order to analyse the dependence of the capacity change on the static pressure experimentally, a force was applied on the complete senor area. For this reason the sensor was fixed on a height adjustable table. A force sensor was in contact with the sensor. With this configuration the load on the sensor could be adjusted continuously.

Fig. 8 shows the change of the capacitance of the sensor dependent on the static pressure in comparison with the result of the FEM simulation. The mechanical deformation of the PDMS material was assumed linear in the simulation model, this may cause the deviation in the results. Another reason could be the variations in the geometry of the structured PDMS layer compared to the simulation model.

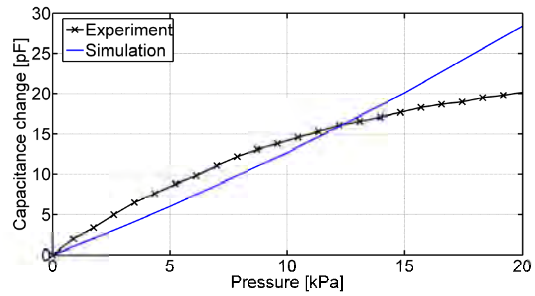

Figure 8. Capacity change dependent on the static pressure, comparison between measurement and simulation

B. Resonance frequency

An important aspect, if the sensor is suitable for the measurement of high frequency pressure fluctuations, is the resonance frequency. For the determination of the resonance frequency the sensor element was excited electrostatically with an alternating voltage of 200V and the displacement was measured with a laser Doppler vibrometer.

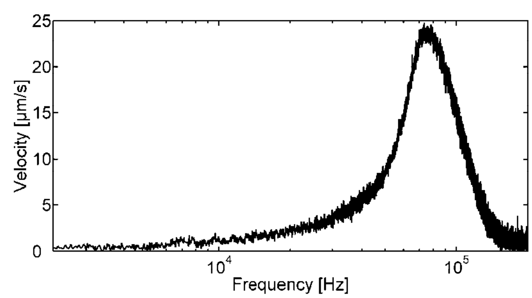

Figure 9. Resonance frequency of the capacitive pressure sensor

Fig. 9 shows the frequency spectrum of the measurement in a range from 200 Hz to 200 kHz. The resonance frequency of the sensor is about 75 kHz. This value is clearly above the measurement range of the sensor.

C. Dynamic characterisation

To measure high frequency pressure fluctuations a read out electronic that mainly consists of an AC bridge was developed. The sensor output signal was stored with a data acquisition system. To create high frequency pressure fluctuations a pipe was used that is connected to pressurised air. The acoustic tone of the pipe generates pressure fluctuations with a frequency of 4.4 kHz. This tone and the higher harmonic can be clearly identified in the spectral analysis of the sensor signal (see Fig. 10).

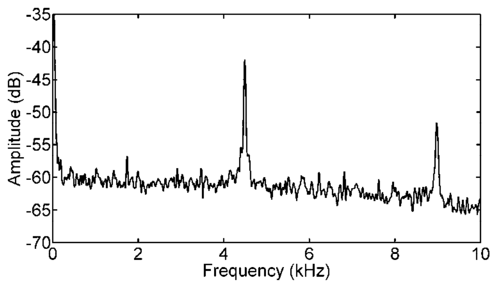

Figure 10. Spectral analysis of an acoustic tone signal

V. CONCLUSION

In this study, a novel capacitive pressure sensor with a structured layer of PDMS was developed. For the design of the sensor a finite element model was used. The implementation in microtechnology and the manufacturing of the first test samples was shown. The static and dynamic characterisation of the sensor was presented. The capacitive pressure sensor is useful for the detection of small high frequency pressure fluctuations.

The next steps would be the further development of the manufacturing process and additional tests of the sensor.

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