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Polydimethylsiloxane as an elastic material applied in a capacitive accelerometer

Joost C Lötters, Wouter Olthuis†, Peter H Veltink and Piet Bergveld

MESA Research Institute, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

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Abstract. Polydimethylsiloxane is a silicone rubber. It has a unique flexibility, resulting in one of the lowest glass-transition temperatures of any polymer. Furthermore, it shows a low elasticity change versus temperature, a high thermal stability, chemical inertness, dielectric stability, shear stability and high compressibility. Because of its high flexibility and the very low drift of its properties with time and temperature, polydimethylsiloxane could be well suited for mechanical sensors, such as accelerometers. A novel capacitive accelerometer with polydimethylsiloxane layers as springs has been realized. The obtained measurement results are promising and show a good correspondence with the theoretical values.

1. Introduction

Polydimethylsiloxane (PDS) is the simplest type of silicone rubber with respect to its molecular structure. It is used, for instance, as a mould release for rubber, as toner in photocopiers and as an internal lubricant for thermoplastics [1]. However, to our knowledge it has not been used as a flexible material in mechanical sensors.

When a photoinitiator is added, the fluid PDS polymer can be cross-linked when it is exposed to ultraviolet light. When the polymer is fully cross-linked, it has become a very flexible and stable (chemically, electrically and mechanically) rubberelastic material, which maintains its initial characteristic properties for a long time.

An accelerometer can be modelled as a mass–spring–damper system. In most accelerometers described in the literature the spring is represented by silicon beams (see e.g. [2]) which may be very fragile. Replacing the silicon beams by a structure of PDS may increase the robustness of the accelerometer. Furthermore, the PDS process is very simple.

In this paper, the characteristics properties of PDS, its rubberelastic behaviour and the sensor structure in which the PDS is applied are described, as well as the processing of the PDS, and some experimental results are discussed.

† e-mail: j.c.lotters@el.utwente.nl

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2. Characteristic properties of polydimethylsiloxane

Polydimethylsiloxanes exhibit the characteristic properties of the silicone family [1]:

(i) hardly any variation of the shear modulus G versus temperature between -100 and $+100\,^{\circ}$C (this temperature range is called the 'rubbery plateau') [3];
(ii) high flexibility at the rubbery plateau: G is of the order of 200 kPa [3];
(iii) a very low loss tangent $\tan\delta < 0.001$ and thus very low stress relaxation, very low creep (and thus low drift) and a wide mechanical frequency response [3];
(iv) high compressibility [1];
(v) chemical inertness; thermal, oxidative, shear and dielectric stability ($\varepsilon_r \approx 2.5$) [1].

3. Theory

3.1. Stress–strain relation in a rubberelastic material

For a rubberelastic material like polydimethylsiloxane it can be shown that the stress–strain relation for simple extension and uniaxial compression is [4]

$$F/A_r = G\left(\lambda - 1/\lambda^2\right) \qquad (1)$$

with F the applied force (N); $F = ma$; m the mass (kg); a the acceleration (m s^{-2}); A_r the area of the rubber on which force F is applied (m^2); G the shear modulus of elasticity (N m^{-2}); $G = \rho RT/M_{crl}$; ρ the mass density (kg m^{-3});

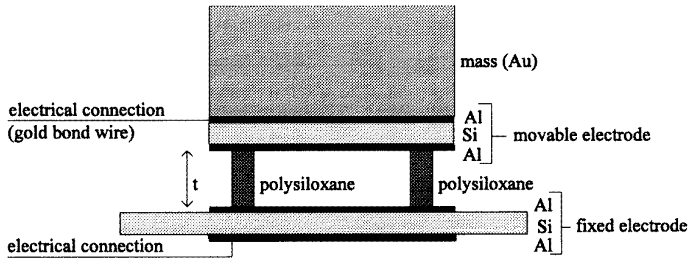

Figure 1. The acceleration sensor, consisting of one movable and one fixed electrode, with partly air and partly PDS between the electrodes.

R the gas constant per mole (J mol K^{-1}); M_{crl} the number average molecular weight of the polymer segments between cross-links (kg mol^{-1}); λ the extension ratio; $\lambda = 1 + \Delta t/t$; t the thickness of the rubber (m) and Δt the change in thickness of the rubber due to the applied force F (m).

When $\lambda \approx 1$ ($\Delta t/t < 1\%$)

$$F/A_r = E\,\Delta t/t \qquad (2)$$

with E Young's modulus of elasticity (N m^{-2}); in rubberelastic materials, $E \approx 3G$.

3.2. Sensor structure

The capacitive acceleration sensor consists of two rigid electrodes with both air and PDS in between, as shown in figure 1. The capacitance C of this structure is

$$C_0 = \varepsilon_0 \varepsilon_r A/t \quad \text{when no acceleration is applied} \qquad (3a)$$

$$C_a = \varepsilon_0 \varepsilon_r A/(t - \Delta t) \quad \text{under acceleration} \qquad (3b)$$

with ε_0 the dielectric constant of vacuum; $\varepsilon_0 = 8.85 \times 10^{-12}$ (F m^{-1}); ε_r the relative dielectric constant of the material between the moving and the fixed electrode; the PDS area is much less than that of the air, so $\varepsilon_r \approx 1$; A the area of the electrodes (m^2); t the distance between the electrodes when no acceleration occurs (m) and Δt the change in the electrode distance due to an applied acceleration (m).

The change in capacitance $\Delta C = C_a - C_0$ due to an applied acceleration a is given by $\Delta C = C_0\,\Delta t/(t - \Delta t)$, so, the relative change in capacitance $\Delta C/C_0$ is given by

$$\Delta C/C_0 = \Delta t/(t - \Delta t) \approx \Delta t/t \text{ (for small extensions : } \Delta t < 0.01t). \qquad (4)$$

This can be measured with a capacitance to voltage converter (CVC), which is specially designed for this application, resulting in an output voltage V_{out} (H is the amplification factor of the CVC)

$$V_{out} = H\,\Delta C/C_0 = H\,\Delta t/t = Hma/A_r E. \qquad (5)$$

4. Experimental details

4.1. Device preparation

The PDS (PS851 from ABCR) is spincoated on a silicon wafer with annealed aluminium on both sides. The primer used is TMSM from Aldrich. After the spincoating, the PDS can be processed photolithographically in order to obtain the specified dimensions. The photo-initiator used (1 wt%) is DMAP from Janssen Chimica.

The dimensions of the PDS structures are given in table 1. According to the data shown in the catalogue [1] $G \approx 1$ MPa and therefore $E \approx 3$ MPa.

After the PDS has been processed, the wafer is cut into separate dies. A die is mounted on a printed circuit board and the upper electrode, a piece of silicon wafer of the same dimensions with annealed aluminium on both sides and negative photoresist on one side, is attached by connecting the PDS to the photoresist via a temperature step of 60 °C for 1 h. Electrical contact is obtained via gold bond wires. Finally, the mass, which is a cylindrical piece of gold, is mounted on top of the upper electrode with silver glue. The total sensor structure is shown in figure 1.

4.2. Accelerometer test set-up and measurement protocol

Both the capacitive and a commercially available piezoresistive accelerometer (ICSensors 3021) are mounted on top of a shaker unit with their sensitive axes in the same direction. The capacitive sensor is connected to a CVC; the piezoresistive sensor is used as a reference accelerometer. A computer collects the output voltages of both accelerometers and converts the data into absolute accelerations.

5. Results and discussion

When equation (5) is used, the theoretical output voltage of each structure due to an applied acceleration can be obtained ($H = 2000$), displayed in figure 2 as lines, whereas points indicate the measurement results. It should be noted that sensors 1 and 2 have been realized with PS851 from a different ABCR supply from sensors 3 and 4. This may result in a difference in Young's modulus of the sensors.

When $E = 3$ MPa, according to the manufacturer's data [1], the measurement results of sensors 1 and 2 correspond well to the theoretical values. When $E = 4.5$ MPa, possibly resulting from the different ABCR supply of PDS, the measurement results of sensors 3 and 4 correspond well to the theoretical values. Further research is necessary

Table 1. Dimensions of the PDS structures; electrode area $A = 3 \times 3$ mm^2.

Structure	Area A_r (m^2)	t (m)	m (kg)
(1) circle, inner radius 0.94 mm, width 60 μm	4×10^{-7}	10×10^{-6}	440×10^{-6}
(2) square, 2×2 mm^2, width 60 μm	4.7×10^{-7}	16×10^{-6}	370×10^{-6}
(3) 4 square layers of 315×315 μm^2	4×10^{-7}	16×10^{-6}	300×10^{-6}
(4) 4 square layers of 120×120 μm^2	5.8×10^{-8}	8×10^{-6}	350×10^{-6}

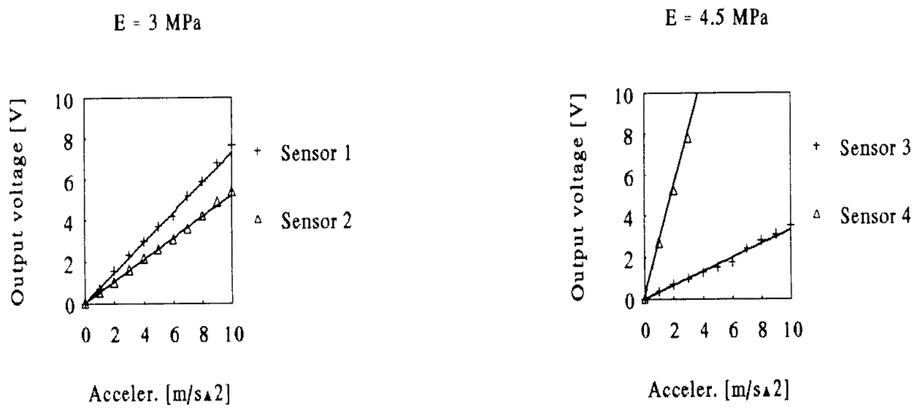

Figure 2. Calculated (lines) and measured (points) output voltage versus acceleration of four accelerometers each with a different PDS structure.

to understand these differences in order to optimize the realization process.

Each sensor shows a linear relation between output voltage and applied acceleration. The ratio between the output voltage $V_{sensor1}/V_{sensor2}$ and the ratio $V_{sensor3}/V_{sensor4}$, corrected for the applied masses, is equal to the ratio of the areas of the PDS structures, which indicates that only the area and not the shape of the PDS structures is important, as implicated by equation (5).

The measurements have been carried out repeatedly over a period of 1 month and the last measurement results are equal to the first. This shows that PDS is a stable rubberelastic material which can successfully be applied in mechanical sensors.

6. Conclusions

Polydimethylsiloxane (PDS) is a very flexible and stable material which can easily and successfully be used in mechanical sensors. In the accelerometer application, the PDS shows a Young's modulus $E = 3$–4.5 MPa.

The capacitive accelerometers with PDS springs show a good linear response and an easily adjustable high sensitivity, in this case varying between 0.33 V (m s^{-2})$^{-1}$ and 2.70 V (m s^{-2})$^{-1}$, only depending on the area of the PDS, not on its shape.

Further research will concentrate on process optimization and characterization.

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