Microsystem Technologies (1997) 64–67 © Springer-Verlag 1997

Polydimethylsiloxane, a photocurable rubberelastic polymer used as spring material in micromechanical sensors

J.C. Lötters, W. Olthuis, P.H. Veltink, P. Bergveld

Abstract Polydimethylsiloxane (PDMS) is a commercially available physically and chemically stable photocurable silicone rubber which has a unique flexibility ($G \approx 250$ kPa) at room temperature. Further properties of PDMS are a low elasticity change versus temperature (1.1 kPa/°C), no elasticity change versus frequency and a high compressibility. PDMS is an interesting polymer to be used as spring material in micromechanical sensors such as accelerometers. The spring constant of the PDMS structures was theoretically calculated and measurements were done on accelerometers with PDMS springs to validate the theory. The measured and calculated spring constants showed a good correspondence, so the measurement results showed that the PDMS structures can successfully be used as mechanical springs.

1
Introduction

Polydimethylsiloxane (PDMS) is a commercially available cleanroom processable type of silicone rubber. It is being used, for instance, as interconnection layer between two silicon wafers, Arquint et al. (1995), and as ion selective membranes on ISFETs, Antonisse et al. (1995).

Some qualitative physical and chemical attributes of PDMS are, Clarson and Semlyen (1993), a unique flexibility (the shear modulus G may vary between 100 kPa and 3 MPa), a very low loss tangent ($\tan\delta \ll 0.001$), small temperature variations of the physical constants (except for the thermal expansivity, $\alpha \approx 20 * 10^{-5}$/K, ABCR (1994)), a high dielectric strength (~ 14 V/μm, ABCR (1994)), a stable dielectric constant ($\varepsilon_r \approx 2.44$–$2.76$), ABCR (1994), a high resistivity ($10^{13}\,\Omega$m), ABCR (1994), a high compressibility and usable in a wide temperature range (at least from $-100\,^\circ$C up to $+100\,^\circ$C, Van Krevelen and Hoftyzer (1976)).

In many micromechanical sensors described in the literature the necessary springs are made of silicon beams. However, these silicon beams may be fragile or difficult to realize in special sensor configurations. Therefore, it is proposed to use PDMS structures as springs. An equation is derived with which the spring constant of PDMS structures can be calculated and measurements were done on accelerometers with PDMS springs in order to validate the theory.

In this paper, the structure of the accelerometer, the mechanical spring constant of the PDMS structures and the preparation of the PDMS structures are described and the obtained measurement results are discussed.

2
Sensor structure

The basic concept of the total sensor as shown in Fig. 1 consists of six electrodes surrounding one central cubic mass. Lötters et al. (1996/2). When the sensor structure is fully symmetrical, all capacitances between the electrodes and the central mass have an equal nominal capacitance value C_o [pF] of

$$C_0 = \frac{\varepsilon_0 \varepsilon_r A}{t} \tag{1}$$

with ε_0 [F/m] the dielectric constant of vacuum ($\varepsilon_0 = 8.85 * 10^{-12}$ [F/m]), ε_r the relative dielectric constant of the material between the moving and the fixed electrode (it can be considered that $\varepsilon_r \approx 1$), A [m^2] the area of the electrodes and t [m] the nominal distance between the electrodes and the mass.

The nominal distance t between the electrodes and the central mass is determined by the thickness of the PDMS structure. When an acceleration is applied, the mass moves a distance Δt [m] with respect to the fixed electrodes, resulting in a corresponding capacitance change ΔC [F]. For instance, when the acceleration is applied in the $+z$-direction the distance between the mass and the upper electrode increases to $t + \Delta t_z$ and the distance between the mass and the lower electrode decreases to t-Δt_z. So, the upper capacitance $C_{z,u}$ [F] is decreased and the lower capacitance $C_{z,l}$ [F] is increased:

$$C_{z,u} = \frac{\varepsilon_0 \varepsilon_r A}{t + \Delta t_z} = \frac{C_0 t}{t + \Delta t_z} = C_0 - \Delta C_{z,u} \tag{2a}$$

$$C_{z,l} = \frac{\varepsilon_0 \varepsilon_r A}{t - \Delta t_z} = \frac{C_0 t}{t - \Delta t_z} = C_0 + \Delta C_{z,l} \tag{2b}$$

When $\Delta t_z < 0.01t$, there is no appreciable difference between the absolute values of $\Delta C_{z,u} = C_o \Delta t_z / (t + \Delta t_z)$ and

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Received: *29 October 1996* / *Accepted*: *13 November 1996*

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The authors would like to thank Mr. J.G. Bomer, Mr. A.J. Verloop and Mr. Ed A. Droog for their assistance in technology and electronics and the Dutch Technology Foundation (STW) for its Financial support.

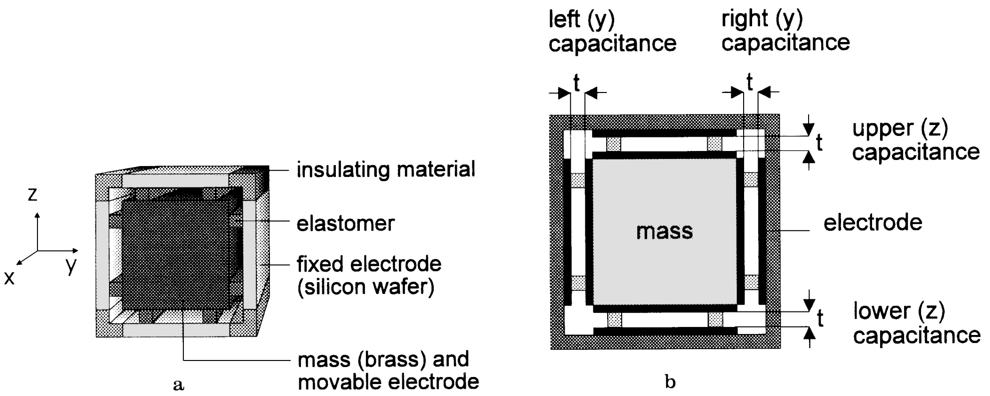

Fig. 1. Cross-sectional (**a**) 3D and (**b**) 2D view of the basic structure of the triaxial accelerometer

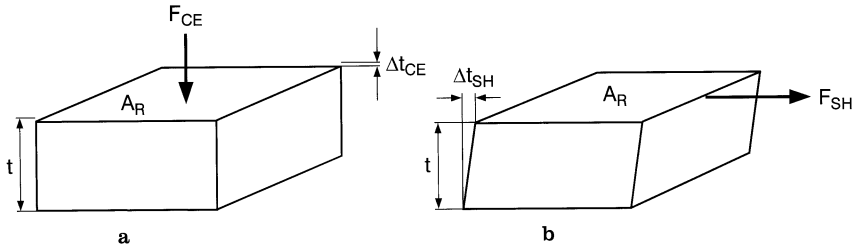

Fig. 2. Piece of rubberelastic material on which (**a**) a compressive or extensive force or (**b**) a shear force is applied

$\Delta C_{z,l} = C_0 \Delta t_z / (t - \Delta t_z)$. So, both the upper and the lower capacitance are considered to be varied with the same ΔC_z,

$$\Delta C_z = C_0 \frac{\Delta t_z}{t} \tag{3}$$

The relation between Δt, the dimensions and properties of the PDMS structure and the applied acceleration will be shown in the next section.

3
Spring constant of rubberelastic structures

For simple extension and uniaxial compression (see Fig. 2a) the rubberelastic stress-strain relation can be expressed as, Treloar (1975).

$$F_{CE} = A_R G \left(\lambda - \frac{1}{\lambda^2} \right) \tag{4}$$

with F_{CE} [N] the applied compressive or extensive force [N], $A_R\,[\mathrm{m}^2]$ the area of the rubber on which the force is applied, G [Pa] the shear modulus of the rubber, λ the rubber's extension ratio: $\lambda = 1 + \Delta t_{CE}/t$. $t\,[\mathrm{m}]$ the thickness of the rubber and $\Delta t_{CE}\,[\mathrm{m}]$ the change in thickness of the rubber due to F_{CE}. When this expression is linearized around $\Delta t_{CE}/t < 0.01$, Hooke's equation $F_{CE} = k_{CE} \Delta t_{CE}$ (where k_{CE} [N/m] is the spring constant for small compression/extension) can be used such that

$$k_{CE} = \frac{F_{CE}}{\Delta t_{CE}} = \frac{3 A_R G}{t} \tag{5}$$

Simple shear is a type of strain which may be represented by the sliding of a plane with area A_R [m^2] which is in parallel to a ground plane through a distance Δt_{SH} [m] proportional to the distance $t\,[\mathrm{m}]$ between the planes (Fig. 2b). The stress-strain relation is given by, Treloar (1975), $F_{SH} = A_R G \Delta t_{SH}/t$, so the shear spring constant k_{SH} [N/m] is

$$k_{SH} = \frac{F_{SH}}{\Delta t_{SH}} = \frac{A_R G}{t} \tag{6}$$

When the symmetrical accelerometer of Fig. 1 is accelerated along one axis, the PDMS structures which sense the acceleration in this direction will be extended or compressed whereas the other four PDMS structures will be subjected to a shear stress. The resulting total spring constant k_{tot} in one direction is therefore

$$k_{\mathrm{tot}} = 2k_{CE} + 4k_{SH} = \frac{10\, A_R G}{t} \tag{7}$$

(7) can be used for all axes (x, y and z) of the triaxial accelerometer. However, when the sensor is not fully symmetrical, the differences in the layer thicknesses should be taken into account, for instance in the z-direction:

$$k_{\mathrm{tot},z} = \frac{3A_R G}{t_{\mathrm{lower},z}} + \frac{3A_R G}{t_{\mathrm{upper},z}} + \frac{A_R G}{t_{\mathrm{left},x}} + \frac{A_R G}{t_{\mathrm{right},x}} + \frac{A_R G}{t_{\mathrm{left},y}} + \frac{A_R G}{t_{\mathrm{right},y}} \tag{8}$$

The indices in (8) should be subsequently changed to obtain the equation for the total spring constant $k_{\mathrm{tot},x}$ and $k_{\mathrm{tot},y}$ in the x and y direction, respectively.

4
Preparation of the PDMS structures

The following materials were used in the cleanroom processing: the PDMS PS851 of ABCR ((methacryloxypropyl)methyl siloxane), the primer TMSM of Aldrich (trimethoxysilylpropylmethacrylate) and the photo-initiator DMAP of Janssen Chimica (2,2-dimethoxy 2-phenylacetophenone).

One weight % photo-initiator DMAP (powder) was sprinkled into one weight% xylene, the solution was added to the viscous polysiloxane. The mixture was heated upto 60 °C and shaken in the Sarstedt CM-9 at 1400 rpm during circa 1 hour (the temperature was kept at 60 °C). The mixture was not used instantly, it had to be kept overnight. The silicon wafer on which the PDMS was spun was cleaned and wet oxidized. Ten percent of TMSM and a half percent of demi-water were solved in toluene and the mixture was heated up to 60 °C. The wafers were kept in this mixture for one minute so that methacryl groups were present at the wafersurface which were attached to the methacryl groups of the polysiloxane. The wafer was rinsed with demi-water to remove the surplus of TMSM and was spun dry.

The PDMS was spun upon the wafer with spin rates between 1000 and 5000 rpm during 20 or 60 s, Lötters et al. (1996/3). After the spinning, the PDMS layer was covered with Mylarfoil of 1.5 μm to avoid sticking of the PDMS to the mask. Thereafter, the PDMS was exposed to UV light for 40 s via a mask. Subsequently, the Mylar foil was removed and the PDMS was developed in xylene for 30 s, rinsed with isopropanol and spun dry. The obtained thicknesses of the PDMS varied between 2 and 40 μm, depending on the spin rate and spin time, Lötters et al. (1996/3).

5
Results and discussion

Several PDMS structures were realized, as shown in Fig. 3, with different areas and thicknesses, Lötters et al. (1996), as shown in Table 1. According to the Bohlin Rheometer system, $G_{PDMS} \approx 250$ kPa at room temperature with a slope of 1.1 kPa/°C, Lötters et al. (1996/3). Three prototypes of the capacitive triaxial accelerometer have been realized, Lötters et al. (1996/2), A, B and C, A and C having outer dimensions $5 \times 5 \times 5\,\mathrm{mm}^3$, electrodes of $3 \times 3\,\mathrm{mm}^2$ and a mass $m_A = 220$ mg and $m_C = 520$ mg and B having outer dimensions $2 \times 2 \times 2\,\mathrm{mm}^3$, electrodes of $1 \times 1\,\mathrm{mm}^2$ and a mass $m_B = 19$ mg.

The triaxial accelerometers are connected to a differential capacitance to voltage converter (CVC), Lötters et al. (submitted), which produces an output voltage V_{out} [V], e.g. in the z-direction, of

$$V_{out,z} = H\left(\frac{\Delta C_{upper(z)}}{C_{0,upper(z)}} + \frac{\Delta C_{lower(z)}}{C_{0,lower(z)}}\right) = H\left(\frac{\Delta t_{upper(z)}}{t_{upper(z)}} + \frac{\Delta t_{lower(z)}}{t_{lower(z)}}\right) = H\frac{F_{tot,z}}{k_{tot,z}}\left(\frac{1}{t_{upper(z)}} + \frac{1}{t_{lower(z)}}\right) \tag{9}$$

where H is the amplification factor of the CVC, $H = 1000$, $F_{tot,z} = m, a_z$[N] is the applied force, m [kg] is the seismic mass of the sensor and a_z [m/s^2] is the applied acceleration. From (9) the total spring constant can be calculated with

$$k_{tot,z} = \frac{Hma_z}{V_{out,z}}\left(\frac{1}{t_{upper(z)}} + \frac{1}{t_{lower(z)}}\right) \tag{10}$$

The indices in (9) and (10) should be subsequently changed for $V_{out,x}$, $k_{tot,x}$, $V_{out,y}$ and $k_{tot,y}$. The sensors are subjected to an acceleration $a = 1\,\mathrm{m/s}^2$ in each axis, supplied by a Gearing and Watson GWV20 shaker unit and controlled by an ICP 301A10 reference accelerometer system. The calculated and measured values are shown in Table I.

As can be seen in Table I, there is a good correspondence between the measured and the calculated spring constants in A_y, A_z, B_x, B_z, C_x, C_y and C_z. The spring constant in A_x is lower than expected, possibly due the not being

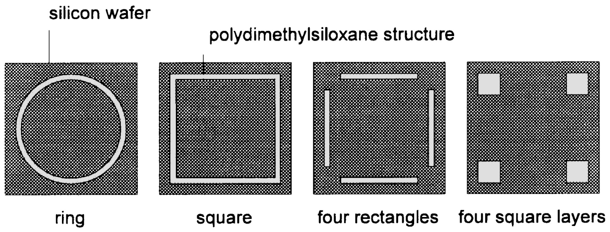

Fig. 3. Structures realized with polydimethylsiloxane

Table 1. Measured and calculated values of the total spring constant

Device _axis	A_R [m^2] Measured	$t_{left,right}$ [μm] Measured	k_{tot} [kPa] Eq. (8)	V_{out} [V] Measured	k_{tot} [kPa] Eq. (10)
A_x	$5.8{*}10^{-8}$	13.1, 6.3	22	6.0	9
A_y	$5.8{*}10^{-8}$	3.3, 4.8	30	3.6	31
A_z	$5.8{*}10^{-8}$	6.9, 6.1	24	2.6	26
B_x	$1.0{*}10^{-7}$	2.9, 2.3	96	0.15	102
B_y	$1.0{*}10^{-7}$	2.6, 2.6	95	0.02	740
B_z	$1.0{*}10^{-7}$	2.8, 3.0	91	0.19	71
C_x	$4.0{*}10^{-7}$	15.9, 15.6	63	0.8	82
C_y	$4.0{*}10^{-7}$	16.6, 16.6	61	1.0	63
C_z	$4.0{*}10^{-7}$	15.3, 17.3	62	0.9	71

active of the shear springs in the x direction of device A, which maybe caused by a bad adhesion of the PDMS structures to the electrodes. Namely, when the shear springs are not considered in the calculation ((8)), the spring constant in the x direction is reduced to 10 kPa. The spring constant in B_y is higher than expected, possibly due to the PDMS structures being pre-compressed in the assembly process, Lötters (1996/2), which causes them to be stiffer, according to (4). The results show that the PDMS structures can successfully be used as mechanical springs with a spring constant according to (5) through (8).

6
Conclusion

Polydimethylsiloxane (PDMS) is a commercially available physically and chemically stable silicone rubber which has a unique flexibility ($G \approx 250\,\text{kPa}$) at room temperature. PDMS is an interesting polymer to be used as spring material, instead of silicon beams, in micromechanical sensors such as accelerometers. Equations for the spring constant of several PDMS structures were derived. Measurements were done on triaxial accelerometers with PDMS springs in order to validate the theory. The measured and calculated spring constants showed a good correspondence, so the measurement results showed that the PDMS structures can successfully be used as mechanical springs with a spring constant according to one of the derived equations. Furthermore, by using the equations for the spring constants, it is possible to determine the shear modulus of all rubberelastic materials by adding a mass to the rubber, applying accelerations to the thus realized accelerometer and calculating the shear modulus from the obtained output voltage.

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