Cantilever-Based Poly(dimethylsiloxane) Microoptoelectromechanical Systems

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***Abstract*—Poly(dimethylsiloxane) (PDMS) has been considered for the first time for defining cantilever-based Microoptoelectromechanical Systems (MOEMS) by ways of soft lithography. The systems shown have a high degree of integration, comprising cantilever-waveguides, lenses, self alignment systems and seismic mass. The very low Young's modulus allows defining thick PDMS-MOEMS for mechanical sensors with sensitivities similar to its nanometer scale silicon counterparts. Experimental resonant frequencies of the proposed MOEMS are in agreement with the numerical simulations done, with Q factors in agreement with the PDMS properties. Finally, when a 1.58 mg droplet of ethanol is dispensed on the cantilever, there is a bending of the cantilever, causing an increase of the relative losses until 25 dB, returning to its initial value when the droplet evaporates.**

I. INTRODUCTION

Recently, there has been a rapid development of mechanical sensors in cantilever configuration. The relative simple mechanical behaviour and the ability to perform high resolution molecular recognition measurements are only some of the reasons that explain the acceptance that such microelectromechanical systems (MEMS) have. Its principle of operation is derived from the Atomic Force Micoscope (AFM) and is based on the bending induced at the cantilever either due to variations of its surface properties, as could be an increase of the mass (which produces a variation of the natural eigenfrequencies) or a biomolecular interaction on the surface (resulting in a surface stress). Demonstration of the strength of using cantilevers as biosensors has been widely reported, among which the landmark paper of Fritz and co-workers [1] should be highlighted, which demonstrated that cantilevers working in static mode were able to detect single nucleotide polymorphism (SNP) in DNA hybridization experiments and parallel DNA sequencing. Other researchers have also demonstrated its strength for the detection of different species, both in static [2],[3] and dynamic mode [4]. The cantilevers have also been used as waveguides, defining a microoptoelectromechanical system (MOEMS) as it was presented by Zinoviev and co-workers [5]. However, since the cantilevers are fabricated with silicon or silicon nitride (with high Young's modulus), to obtain low spring constants, it is required to have thin and/or long cantilevers, which requires the usage of expensive equipment. Hence, the massive implantation of such promising systems is prevented by the excessive fabrication costs.

Polymer technologies have been developed trying to tackle the previously mentioned drawback. Concretely, the UV-structurable SU-8 resist has a Young's modulus 30 times smaller than silicon (YSU-8=4-5 GPa; YSi=167 GPa) and hence, the requirements for defining cantilevers with low spring constant are relaxed while its adequate optical properties make it suitable for defining MOEMS [6]. Unfortunately, SU-8 does not have functional properties that can be exploited for sensing applications and therefore this

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capability has to be externally provided, as could be by integrating electrodes on the SU-8 structure [7], which makes the technology more complex. Additionally, this negative-tone epoxy polymer has high intrinsic stresses and the structures tend to swell unless post-processing is done. These drawbacks cause to be challenging to obtain reliable polymer-based MEMS.

Another low cost material that has recently gained a privileged position, especially for defining lab on a chip systems is Poly(dimethylsiloxane), PDMS. Its complete bicompatibility, high transmittance from the visible to the near infra-red, low cost and technological simplicity are only some of its main advantages. Concretely, this polymer has already been used for defining waveguides [8], tunable microlenses [9] and photonic lab-on-a-chip systems [10]. Surprisingly, and despite the excellent optical and structural properties of the PDMS (with a Young's modulus between 300 and 800 KPa), which permits obtaining large structures with low spring constant, up to date there has been no report concerning the usage of this polymer for the implementation of MOEMS.

In this contribution, we have used soft lithographic [11] methods to obtain a PDMS-based MOEMS with a high degree of monolithic integration, comprising self alignment systems, a cantilever (which also acts as a waveguide) with a seismic mass and a cylindrical microlens. The results obtained herein allow confirming the validity of the proposed technology for defining low cost advanced MOEMS.

II. DESIGN AND SIMULATION

The proposed optomechanical sensor consists on a PDMS cantilever with a seismic mass anchored to a bulk region made of the same material. Additionally, a self alignment system for the accurate positioning of the input fibre optic has been included on the bulk region. It consists on a microchannel with dimensions smaller than the optical fibre. Hence, the flexibility of the PDMS should allow the fibre to be inserted in the microchannel without damaging its facet end. Then, equal forces of different sign apply, clamping and keeping it at a centred position. Moreover, to improve the collection of the light at the end of the cantilever waveguide, a cylindrical lens has been incorporated at the structure. Fig. 1 shows the proposed optomechanical sensor with all its components, together with the input fibre optics fixed to the structure. The working principle of the system is as follows: light emerging from the fibre optics is coupled to the optical cantilever, which acts as a waveguide and confines the light until it reaches the mass. At this point, the air gaps significantly reduces the propagation losses (light coupled to the mass) and most of the light reaches the cylindrical lens, focusing it at its focal plane. The light collection can be done with a microscope objective or a fibre optic and a Si-photodiode. When actuation is done over the cantilever (as could be due to an increase of the mass), it bends on the z-axis, resulting in a variation of the power reaching the photodiode. Hence, the z-axis should be considered as the sensing axis, while the x- and y-axes represent the crossed directions. In analogy to the SU-8 based MOEMS the x-axis is the light propagation direction.

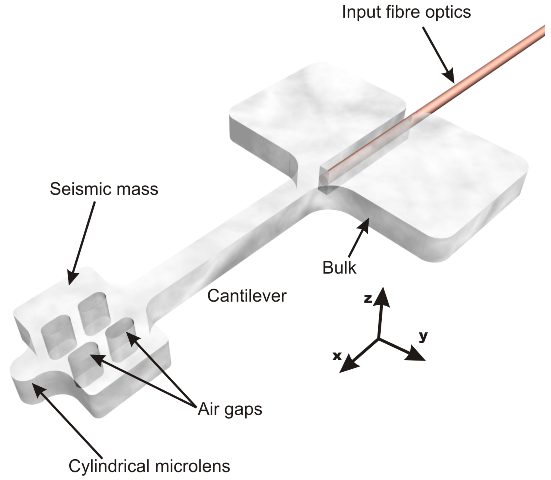

Fig. 1. Schematic view of the proposed PDMS cantilever based optomechanical sensor.

A. Mechanical behavior

A study of the mechanical behavior of the proposed PDMS cantilever based optomechanical sensor has been done to optimize its sensitivity. Due to the very low Young's modulus of the PDMS it is possible to obtaining large structures with a low spring constant. This allows designing robust structures with very large dimensions. Additionally, such large structures simplify the fabrication process. Hence, the width of the cantilevers has been fixed to 500 µm (being then the diameter of the cylindrical lens of the same value) and the height has been fixed to 250 µm. This difference between the width and the height should assure a higher mechanical sensitivity on the z-axis (sensing axis) that on the y-axis.

The dimensions of the seismic mass have been fixed to 2500x1600 µm, resulting on a mass of $9.65\cdot10^{-7}$ Kg. Finally, three different lengths have been used: 2400, 3400 and 4400 µm for the CS, CM and CL configurations, respectively. Table 1 summarizes all the parameters of the three cantilever configurations. The mechanical analysis of the different cantilever configurations has been done using ANSYS. The numerical results obtained are presented in table 2. The mechanical sensitivity has been determined applying an acceleration of 1g on the sensing axis, resulting on sensitivities ranging from 54.3 to 215 µm/g for the CS and the CL, respectively. Also resonant frequencies ranging between 40.6 Hz (CL) and 84.1 Hz (CS) have been achieved. As it can be seen, although the system has both thickness and width of the order of hundreds of microns, the fact that its Young's modulus is 10^5 times smaller than that of silicon allows defining very thick systems with sensitivities and resonant frequencies similar to their nanoscale silicon or silicon nitride counterparts. Additionally, a study of the displacement in front of a mass placed in the seismic mass has been done. Numerical mechanical mass sensitivities are also presented on table 2.

TABLE I. PARAMETERS OF THE DIFFERENT CANTILEVER CONFIGURATIONS STUDIED.

Geometry used	CS	CM	CL
Cantilever width (µm)	500	500	500
Cantilever height (µm)	250	250	250
Cantilever length (µm)	2400	3400	4400
Seismic mass ($x10^{-7}$ Kg)	9.65	9.65	9.65
Total mass ($x10^{-6}$ Kg)	1.44	1.56	1.69

TABLE II. NUMERICAL AND EXPERIMENTAL RESULTS OF THE DIFFERENT CANTILEVER CONFIGURATIONS STUDIED.

Applied acceleration [1 g]	CS	CM	CL
Numerical mechanical sensitivity z-axis [µm/g]	54.3	116	215
Resonant frequency [Hz]	84.1	56.6	40.6
Numerical mechanical mass sensitivity [µm/mg]	48.0	99.8	179
Numerically simulated resonant frequency [Hz]	84.1	56.6	40.6
Experimentally measured resonant frequency [Hz]	83	52	35

B. Optical behavior

The intrinsic losses of the proposed optomechanical sensor have to be minimized to enhance the SNR. Hence, to prevent the broadening of the light on the seismic mass an air gap periodicity has been implemented at both sides of the cantilevers. This system allows a good confinement of the light without increasing the technological complexity. Furthermore, as it was advanced, in order to improve the collection of the light emerging from the cantilever waveguide to the readout system and to increase the sensitivity of the sensor, a cylindrical lens has been included at the end of the optical structure. This lens should provide single-axis correction. It would be more adequate to have two-axes correction. Nevertheless, having a focal point instead of a focal plane could only be obtained with spherical or aspherical microlenses. In the proposed configuration, such lenses would be technologically difficult to obtain [12] or would require non-standard processing methods [13], with an increase of the cost, which is opposite to the aim of the present work.

III. FABRICATION AND CHARACTERIZATION

Fabrication of the PDMS based optical cantilevers starts with the development of the SU-8 (MicroChem, Corp., Newton, MA, USA) master. The process starts with the definition of a double adhesion promoter layer identical to that used in [14]. Then, with a single spin-on process, a 250-µm thick SU-8 layer (SU-8 50, MicroChem Corporation, Newton, MA, USA) is deposited. After that, the substrate is baked again at 95ºC for 3 hours and exposed to UV light using the appropriate mask. After that a PEB at 95ºC for 10 minutes is followed by the development of the structures in PGMEA finishing the definition of the master, as it is schematized on the Fig. 2a.

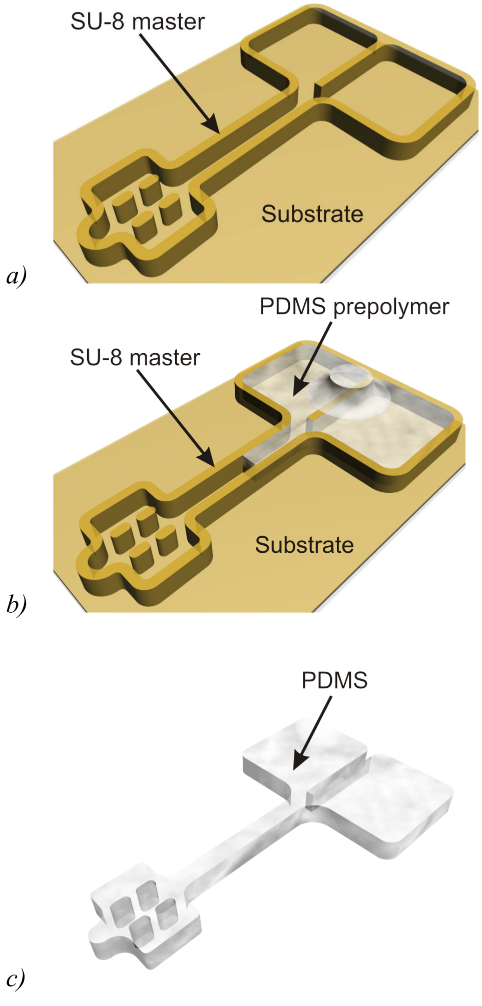

Fig. 2. Scheme of the PDMS based cantilever fabrication: (a) The SU-8 master is developed. (b) The pre-polymer is placed on the filling regions of the master. (c) When the PDMS is solid the devices are peeled off from the master.

The PDMS (Sylgard 184 elastomer kit, Dow Corning, Midland, MI, USA) pre-polymer is obtained by mixing the curing agent with the elastomer base in a 1:10 ratio (v:v). The subsequent mixture is degassed to remove the air bubbles. Since the master used has the upper side of the structure open to air, the viscosity forces involved in the process are highly reduced and the PDMS prepolymer can fill the master by capillarity. A controlled volume of the prepolymer mixture is dispensed on the filling regions of the master, as it is showed in Fig. 2b. Then, all the structure is filled by capillarity without having overflow and the pre-polymer is cured for 20 minutes at 80°C. Finally, the fabricated devices are peeled off from the master, see Fig. 2c. After that, the master can be re-used several times to develop more PDMS based cantilevers.

Two characterizations have been done to determine the behavior of the optomechanical sensor. On the both characterizations the input fibre, previously aligned and clamped to the cantilever, were connectorized to a LED working at 670 nm. Firstly, to determine resonant frequencies of the system, the readout consisted on a 15x microscope objective and a silicon position sensitive photodiode (PSD) (S4349 Hamamatsu). Hence, in this configuration, the light exiting the cantilever is collected by the objective lens and directed to the PSD. The actuation was externally performed with a piezo stack (PSt 150/5x5/7 Piezomechanik GmbH, Germany). The intrinsic losses of the system were measured to be 5.1 dB without any actuation over the microsystem. Dynamic characterization of the device was done by connecting the piezoelectric to a waveform generator. The chip with the cantilever was directly mounted on the piezo stack. Then a frequency sweeping in the range from 0 to 1000 Hz was realized. Results of the measured resonant frequencies of the three lowest order modes are also presented in table 2, together with the resonance frequencies numerically simulated. As it can be observed, there is a good agreement between numerical and experimental results, confirming the validity of the simulations done.

Although it is possible to apply the proposed PDMS optical cantilevers in resonance operation mode (with a Q of 5.1 ± 0.6), a better response is expectable in static mode. Hence, the device was continuously characterized with the following procedure: a small drop of ethanol (2 µL, or equivalently, an initial weight of 1.58 mg) was dispensed over the seismic mass, modifying the cantilever position in the vertical axis. A displacement of 49 ± 6 µm was measured after dispense the drop using an optical microscope (SteREO Discovery.V8, Zeiss) oriented at 90º from the cantilever. Such a displacement corresponds to a mechanical sensitivity of 31 ± 4 µm/mg. Moreover, the variation in the position of the cantilever after the complete evaporation of the drop was measured to be 3 ± 3 µm.

Fig. 3 shows the system with the ethanol drop on the mass and all its components. With this configuration, the proposed PDMS-MOEMS is based on intensity modulation and therefore its performance does not depend on the modal behaviour inside the waveguide-cantilever. The results of this experiment are presented in Fig. 4. Since the intrinsic losses do not affect the working principle of the device, they have been extracted from the experimental data so as to obtain the variation of the power due only to the working principle of the MOEMS (relative losses). As it can be seen, when the ethanol drop was dispensed at the seismic mass, there was a sharp increase of the relative losses, reaching a value of 25.02 dB. Although, the proposed optomechanical sensor does not have a linear behavior an experimental optical sensitivity of 15.82 dB/mg can be estimated. Then the droplet was progressively evaporated following the predicted mass flux behavior for highly volatile substances already presented in [15], which results in a continuous decrease of the weight over the cantilever. As a result, the alignment between the collecting fibre optics and the cantilever is gradually recovered, reaching again the value of zero relative losses when the droplet has been completely evaporated.

The presented results confirm the validity of the proposed optomechanical sensor configuration. Due to its mechanical and structural properties, it can be an excellent approach for developing biosensors but also MOEMS, as could be scanners or accelerometers.

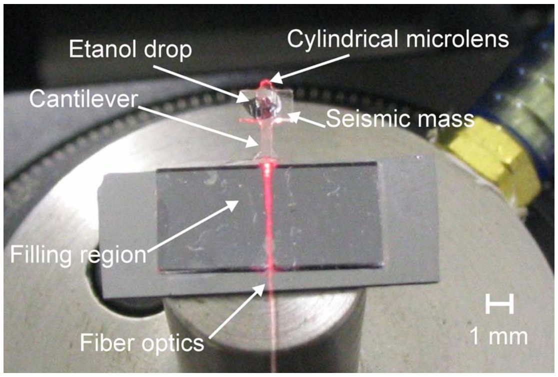

Fig. 3 Image of the fabricated PDMS-MOEMS, with the light emerging from the input fibre optics (placed on the self alignment system) coupled into the cantilever and an ethanol drop dispensed over the seismic mass.

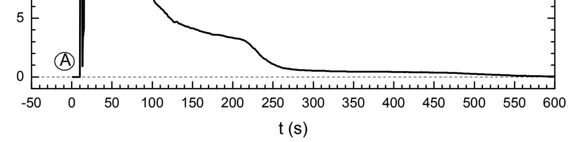

Fig. 4 Experimental results of the relative loss in front of time when a 2 µL ethanol drop was dispensed over the seismic mass of the cantilever.

IV. CONCLUSIONS

A low cost Poly(dimethylsiloxane)-based microopto-electromechanical system fabricated by soft lithography has been designed, fabricated and characterized. The proposed structure consists of a cantilever-waveguide with a seismic mass, a microlens and a self-alignment system. The experimental results using an LED working at 670 nm have shown resonant frequencies between 83.1 Hz and 40.2 Hz for the three cantilevers measured, which are in agreement with the numerical results. Finally, when a collecting fiber optic was faced to the cantilever and a 2 μL ethanol drop was dispensed over the seismic mass, the relative losses increase until 25 dB. These results validate the proposed technology for defining low cost complex MOEMS which, thanks to the biocompatibility of PDMS, could be used in a broad range of applications.

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