Published in Microelectronic Engineering 73-74, 157-160, 2004
which should be used for any reference to this work

Replication of optical MEMS structures in sol–gel materials

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Abstract

A replication method of fabrication for micro electro mechanical systems (MEMS) structures is presented, for use as an alternative to silicon processing. UV-curable ORMOCER® sol–gel is used as base material. The basic fabrication process involves deposition and patterning of a sacrificial spacer layer and a combined molding and photolithography step. This method allows creation of free-standing micro-mechanical elements with monolithic integration of high resolution micro-optical structures. Strain due to the shrinkage of the ORMOCER® sol–gel material during processing has been measured using test structures. Possible applications of this fabrication process are optical MEMS devices that incorporate lenses, diffractive optics or waveguides.

Keywords: Replication; Optical MEMS; Sol–gel; ORMOCER; UV-embossing

1. Introduction

Current design of micro electro mechanical systems (MEMS) is dictated by the fabrication technologies available in the semiconductor industry. Silicon is used as base material for most microsystems due to its excellent mechanical properties. Foundries offer CMOS-compatible processes with the possibilities of integration of IC circuitry into the device.

An alternative method for fabrication of MEMS structures is presented here. Replication technologies present a low-cost fabrication approach that is well-known and applied in the mass-production of everyday optical microstructures such as Compact Discs or security holograms for credit cards or bank notes. UV-casting, hot embossing or injection molding offer high resolution at a very competitive cost for high-volume production. These high precision approaches are well suited for optical applications [1].

The use of replication technologies for the fabrication of MEMS devices makes the integration of optical functions possible with very few process steps. Optical microstructures such as microlenses, waveguides or diffractive gratings can be incorporated in MEMS structures using a combined fabrication approach. This method applies molding and photolithography in the same

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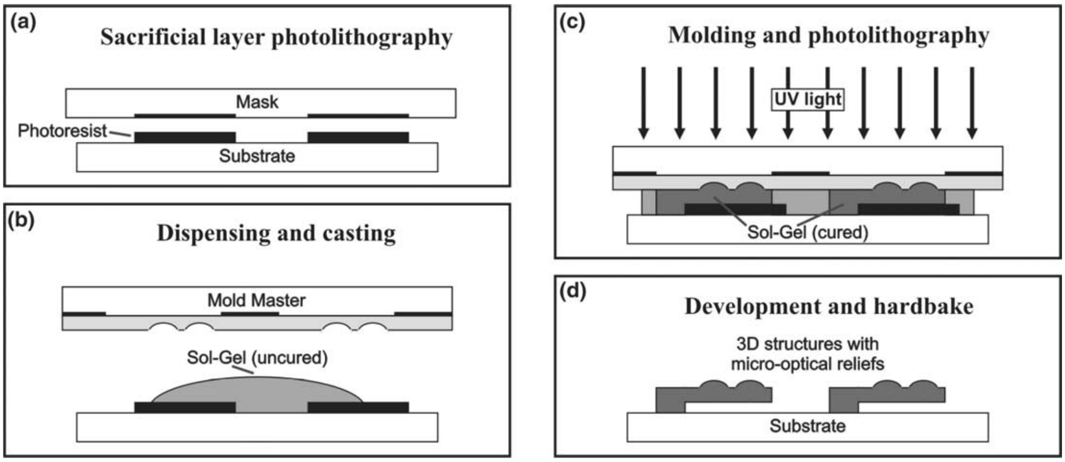

Fig. 1. (a) A sacrificial layer is formed by a high viscosity photoresist process (up to 40 μm). (b) Liquid sol–gel material is dispensed onto the sacrificial layer. The mold master consists of a standard photolithography mask including an additional layer incorporating optical microstructures. (c) The sol–gel material is illuminated with UV-light through the mold mask. Exposed parts are cured. (d) The microstructures are released in a development step, and hard baked in an oven.

process step. UV-curable ORMOCER® sol–gel is used as molding material [2,3]. ORMOCER®s are inorganic–organic hybrid polymer materials synthesized by the sol–gel process [4]. These materials cure into glass-like films that have excellent optical properties as well as mechanical and thermal stability [5].

2. Fabrication

The fabrication process steps can be summarized as shown in Fig. 1: first, a high viscosity positive photoresist of up to 40 μm in thickness is coated on a substrate to form a temporary spacer layer. This sacrificial layer is patterned using a standard photolithography process to create apertures to the substrate. The substrates used here have been borofloat glass wafers, but the process is also compatible with quartz, silicon or 3–5 substrates.

The UV-curable ORMOCER® sol–gel material is then dispensed in liquid form onto the sacrificial layer. The mold mask that is pressed on the liquid sol–gel consists of a standard photolithography mask including a chrome pattern plus an additional layer incorporating an optical microstructure relief. For the test structures shown here, microlenses have been chosen as optical microstructures.

The next step is the key part of the fabrication process. By illuminating the sol–gel material with UV light through the mold mask, the exposed parts are cured. A modified mask aligner (SÜSS MicroTec AG, Asslar, Germany) is used for alignment and exposure. The height of the final structures is given by the thickness of the ORMOCER® layer. Structures with heights between 40 and 300 μm have been created so far.

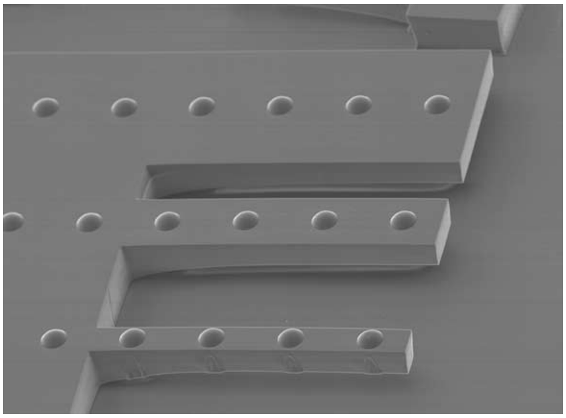

Fig. 2. Replicated ORMOCER® cantilever beams with microlenses on top. The beams are 1 mm in length, 50 μm in height and 500, 200 and 100 μm in width. The gap under the beams is 30 μm. The curvature below the beams towards the socket is given by the photoresist used as sacrificial layer.

After demolding, both the unexposed sol–gel material and the sacrificial layer are dissolved away in the same developer solution. Finally the ORMOCER® structures are hard baked in an oven at 150 °C for 8 h. The hard baking guarantees excellent thermal, mechanical and chemical stability. During this final curing, shrinkage of 2–8% in volume occurs [3].

Various microstructures have been fabricated with this process. Fig. 2 shows 3 cantilever beams of different sizes. The microlenses are typical examples of high-precision micro-optical elements that can be replicated with this process. Replication is a cost effective way to produce such elements because one high-resolution master can be used to create many replicas.

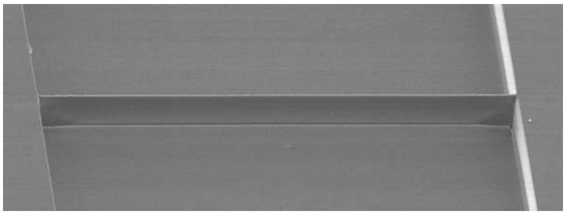

Fig. 3. High aspect ratio (20:1 in *z*-direction) ORMOCER® sol–gel beam. The beam is 1 mm in length, 100 μm in height and 5 μm in width. The gap under the beam is 10 μm.

Fig. 3 shows the minimum width of a beam which is fixed at both ends. The beam is 1 mm in length and 100 μm in height, but only 5 μm in width. This is the maximum aspect ratio in *z*-direction obtained with this process so far (20 to 1).

3. Test structures

The effect of the shrinkage of the ORMOCER® sol–gel material during processing has been analyzed with test structures. The structures shown in Fig. 4 convert tensile strain into compressive strain. These free-standing ring structures with a center beam across were distributed on different locations on the substrates. If the center beam is too slender, it will buckle [6,7]. In this case, the beams that are 20 μm and smaller in width are buckled; beams of 50 μm and more in width remain stable. The theory of these structures was established by Guckel et al. [8]. Here, a first approximation for the rings was used to calculate the resulting strain.

For a very slender ring, the tensile strain in the ORMOCER® film is

$$\varepsilon_0 = \frac{\Pi^2 \cdot b_{\mathrm{b}}^2}{12 \cdot g(R) \cdot R^2},$$

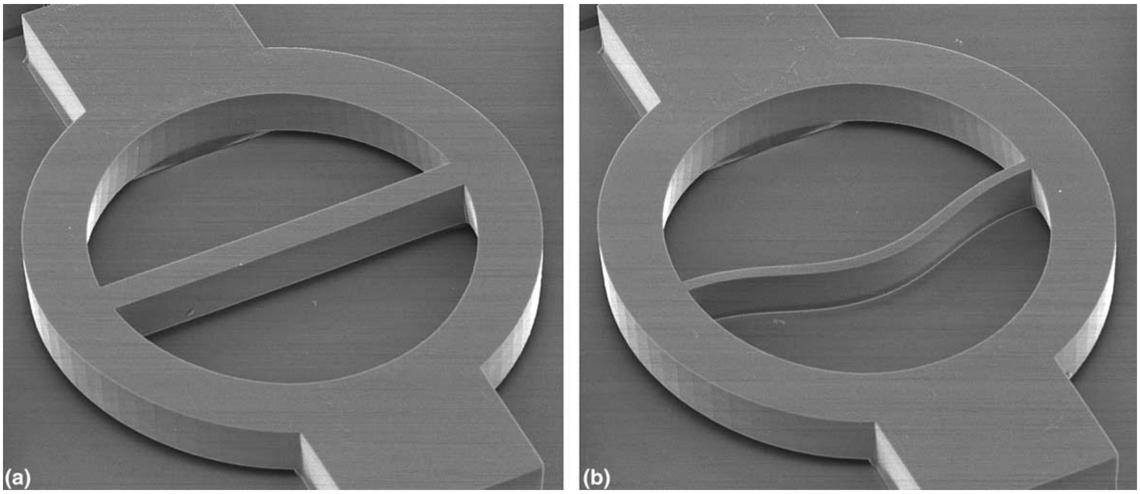

Fig. 4. Free standing ORMOCER® sol–gel rings with strain indicator beams. The diameter of the rings is 700 μm and the width of the rings is 100 μm. (a) The width of the central beam is 50 μm and it shows no buckling. (b) The central beam is buckled because it is only 20 μm in width.

where b_b is the width of the center beam, R is the radius of the ring and $g(R)$ is the conversion efficiency of tensile strain into compressive strain. For an ideal ring $g(R) = 0.918$.

Strain values found in the fabricated test structures lie in between 0.25% and 1.8%. Note that the formula is an approximation for a very slender ring. The conversion efficiency of the real rings is probably lower and the resulting strain values should be higher.

4. Conclusions and outlook

The replication of free-standing optical microstructures in ORMOCER® sol–gel material has been demonstrated. The fabrication process allows the monolithic integration of high precision micro-optical elements like microlenses on the surface of MEMS structures. Also, high aspect ratio structures have been obtained. Only a few essential steps are needed in the fabrication. A combined molding and photolithography step is essential. No etching is involved. And the whole process is executed at wafer scale, what makes it potentially very cost effective.

Some of the fabricated test structures have been analyzed. Depending on the shape of the structure, the shrinkage of the ORMOCER® material during processing may cause deformations.

Envisaged applications of the described method include optical MEMS devices (MOEMS). Work is currently underway to integrate metal layers in the freestanding structures to build electrostatic actuators. Due to the excellent optical properties of the ORMOCER® sol–gel material, various optical functions can be integrated into MEMS devices. Besides refractive lenses, diffractive optics or waveguides present further possibilities.

Acknowledgements

The contributions of Christiane Gimkiewicz and Susanne Westenhöfer are gratefully acknowledged. This work was partly supported by the Swiss BBW funding agency. We thank them for their support.

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[2] ORMOCER® is a registered trademark of the Fraunhofer-Gesellschaft.

[3] The optical materials ORMOCORE and ORMOCLAD are available from Micro Resist Technology, Berlin, Germany.

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