Effect of thermal annealing on the stiffness of an SU-8 torsional spring

Y. Li\textsuperscript{a}, S. Kühne\textsuperscript{a}, D. Psychogiou\textsuperscript{b}, and C. Hierold\textsuperscript{a}

\textsuperscript{a}Micro- and Nanosystems, Department of Mechanical and Process Engineering, ETH Zurich, 8092 Zürich, Switzerland
\textsuperscript{b}Laboratory for Electromagnetic Fields and Microwave Electronics, Department of Information Technology and Electrical Engineering, ETH Zurich, 8092 Zürich, Switzerland

Abstract

The effect of thermal annealing on the torsional and bending stiffness of a polymeric torsional spring is studied, by analyzing the static and dynamic behavior of an SU-8 spring attached to the bottom of a silicon comb-drive actuator. The results suggest that, after thermal annealing, the torsional stiffness has been reduced (16.7 \%) while the bending stiffness has been increased, which is desirable for the operation of the spring. The phenomenon is explained by the influence of the bi-axial residual stress variation in the SU-8 spring.

Keywords: Comb-drive actuators; SU-8; large deflection; micromirror.

1. Introduction

SU-8, commonly known as a negative photoresist, has been increasingly used as structural layers of various MEMS devices because of its commercial availability, easy process and low stiffness [1, 2]. One of its novel applications is the torsional spring for comb-drive actuators to enhance the static deflection angle of micromirror-like MEMS structures [3, 4]. Such applications require the spring to have a low torsional but high bending stiffness to maintain the device in-plane stability [4]. In this paper, we report a method to reduce the torsional stiffness and increase the bending stiffness simultaneously by a thermal annealing step.

* Corresponding author. Tel.: +41-44-632-31-98; fax: +41-44-632-14-62.
E-mail address: liyun@micro.mavt.ethz.ch.
2. Device design

The actuator device used in the present study is schematically illustrated in Fig. 1. It is composed of two pairs of stator/rotor comb-drives, suspended by an SU-8 spring attached below the entire rotor bar (X-direction) and anchored at both ends. Due to the electrical insulator nature of the SU-8 spring, it is impossible to apply a voltage directly to the rotor comb-drive directly. Therefore, the actuation scheme is based on charge separation [4], i.e., a positive and negative voltage is applied to the two stator comb-drives, respectively, as shown in Fig. 1.

Fig. 1. Schematic illustration of the actuator device with an SU-8 spring. Inset (a) shows the magnified view of the SU-8 spring. Inset (b) shows the representation of the stress tensor on an infinitesimal cube from the SU-8 spring.

3. Experimental

The fabrication process of the actuator is presented in [4]. The annealing process is conducted at a temperature of 195°C for 1 hour with N2 atmosphere. The static and dynamic behaviors of the actuator are studied before and after the annealing step. The static mechanical deflection angle of the actuator is measured with a white light interferometer, under different actuation voltages. The dynamic behavior of the actuator is measured with a Laser Doppler Vibrometer. When measuring, a periodic chirp signal is applied to actuate the device while a laser beam scans over the sample surface with a predefined pattern, in order to extract the resonance frequency and the mode shape of the vibrational modes.

4. Results and discussion

4.1. Dynamic and static behavior

The dynamic behavior of the actuator is of interest as the torsional or bending stiffness of the spring can be determined by the resonance frequency of its corresponding vibrational mode [4]. Therefore, the dynamic response of the actuator before and after annealing is measured and compared in Fig. 2(a) and Table 1. The torsional resonance frequency shift from 219.1 Hz to 199.6 Hz corresponds to a shift in torsional stiffness from $1.04 \times 10^{-7} \text{N} \cdot \text{m/rad}$ to $8.66 \times 10^{-8} \text{N} \cdot \text{m/rad}$. The increase of resonance frequency of
other 3 vibrational modes indicates an increase in the bending stiffness in both Y and Z direction of fig. 1, which is favorable for the operation of the actuator.

![Graph showing vibrational modes](image)

**Fig 2:** (a) Dynamic behavior of the actuator, before and after annealing; (b) measured static deflection before and after annealing, as well as models with torsional stiffness extracted from the dynamic measurements.

Fig. 2(b) shows the static deflection of the actuator versus voltage before and after annealing. As can be seen, both curves show a quadratic behavior as a function of the actuation voltage. At the given voltages, all the static deflection angle values have increased after annealing, indicating a decrease in torsional stiffness of the SU-8 spring. The deflection angle at 20V has increased from 6.3° to 8.1° by annealing. Models with torsional stiffness extracted from the resonance frequency are also plotted [4]. It can be seen that the change in the static behavior of the device before and after annealing is in good agreement of the shift of resonance frequency.

| Vibrational mode       | f (Before annealing) | f (After annealing) |
|------------------------|----------------------|---------------------|
| Tilting                | 219.1 Hz             | 199.6 Hz            |
| Out-of-plane piston    | 1680.5 Hz            | 2093.8 Hz           |
| In-plane sliding       | 2351.6 Hz            | 2675.8 Hz           |
| Out-of-plane rocking   | 2964.5 Hz            | 3788.3 Hz           |

**Table 1:** Measured resonance frequency (f) of the actuator before and after annealing.

4.2. Finite Element Method (FEM) study

An FEM study is performed to analyze the influence of the bi-axial residual stress in the spring (Fig.3). The increase of tensile stress $S_{xx}$ (0-25MPa) increases all 3 bending modes resonance frequencies significantly, while the torsional mode stays almost unchanged (variation: ~5Hz). Meanwhile, an increase of $S_{yy}$ (0-10KPa) influences mainly the torsional resonance frequency (~30Hz@10kPa), and has little effect on the resonance frequencies of the bending modes (variations<0.5Hz). During the annealing, the suspended parts of SU-8 spring are only free to deform along Y direction since they were anchored on both sides along the X direction. Therefore, $S_{xx}$ is increased while $S_{yy}$ is decreased by the annealing step. Under the assumption that $S_{yy}$ has been fully relaxed after annealing, the approximate residual stress values in the SU-8 could be extracted and shown in table 2. It can be seen that residual stress $S_{xx}$ in the SU-8 has increased by 10MPa by the annealing step.
Fig 2: (a) Static deflection and (b) dynamic behavior of the actuator; before and after annealing.

Table 2: Residual stress derived from the comparison of measurement data and FEM analysis.

| Residual stress | Before annealing | After annealing |
|-----------------|------------------|-----------------|
| $S_{xx}$ (MPa)  | 12               | 22              |
| $S_{yy}$ (kPa)  | 8                | 0               |

5. Conclusion

In this paper, the effect of thermal annealing on the torsional and bending stiffness of an SU-8 torsional spring is studied, by analyzing the static and dynamic behavior of an SU-8 spring attached to the bottom of a silicon comb-drive actuator. It has been shown that a thermal annealing step could decrease the torsional stiffness (by 16.7%) and increase the bending stiffness of the SU-8 spring, which is desirable for the operation of the spring. The phenomenon is explained by the influence of the bi-axial residual stress variation in the SU-8 spring and verified by FEM simulation.

Acknowledgements

The authors would like to acknowledge the support of Swiss National Science Foundation under project No. 200021-129832.

References

[1] Abgrall P, Conedera V, Camon H, Gue AM, and Nguyen NT. SU-8 as a structural material for labs-on-chips and microelectromechanical systems. *Electrophoresis* 2007; 28:4539–4551.
[2] Nordström M, Keller S, Lillemose M, et al. SU-8 Cantilevers for Bio/chemical Sensing; Fabrication, Characterisation and Development of Novel Read-out Methods, *Sensors* 2008; 8:1595-1612.
[3] Bachmann D, Schoberle B, Kühne S, Leiner Y, and Hierold C. Fabrication and characterization of folded SU-8 suspensions for MEMS applications. *Sensors and Actuators A-Physical* 2006; 130:379-386.
[4] Li Y, Kühne S, Psychogiou D, Hesselbarth J, and Hierold C. A microdevice with large deflection for variable-ratio RF MEMS power divider applications. *Journal of Micro-mechanics and Microengineering* 2011; 21:074013/1-9.