STUDY OF DYNAMIC RESPONSE OF SILICONE ELASTOMER MICROFABRICATED HYBRID MEMBRANES VERSUS TEMPERATURES AND AGING TIME

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Abstract. This study concerns the dynamic behaviour of microfabricated Room-Temperature-Vulcanizing (RTV) silicone elastomers based Hybrid Membranes (HMs) when subjected to different operating temperatures and after aging. The micro fabricated HMs structures aimed at being implemented in micromachines, such as for instance a micro-Stirling engine. The hybrid membranes consist of a silicon spiral structure embedded with a thin layer of an elastomeric RTV-silicone. The different process temperatures are consistent with clean room process, such as anodic bonding. In addition to an experimental study, Finite Element Model (FEM) numerical simulations are presented. The simulations include the location of the stress concentration points during a solicitation and membrane dynamic frequency, which are consistent with the experimental test results.

1. Introduction

When miniaturizing, sliding piston are replaced by membranes in micro engines to avoid friction losses and fluid leakage through the cylinder–piston gap, designated as one of the main limitations [1, 2]. However, the stability of their natural frequency is a critical aspect for optimization. A design of a thick fluidic diaphragm based on silicone Hybrid Membranes (HMs) has been proposed in [3]. Knowing that the temperature has an influence on the mechanical properties of silicone membranes [4], one of main issues of these membranes could be their dynamic behavior under severe temperature conditions, such as during wafers assembly by high temperature anodic bonding process or during the operation of a thermal microengine. The applied temperature during anodic bonding is usually in the range [200-500] °C [5]. In the field of microtechnologies, it is particularly used for sealing silicon (Si) and glass wafers, leading to an irreversible bonding. In this paper, we propose a study of the dynamic behavior of those microfabricated silicone-based HMs when subjected to different operating temperatures.

2. Membrane design

The HMs geometry is based on the work of Chutani *et al.* [6]. They demonstrated the microfabrication of thick hybrid fluidic membranes with a low resonance frequency consisting on a planar Si spiral with a central disc (cf. Figure 1), embedded in a Room Temperature Vulcanizing elastomeric silicone (RTV-silicone). The RTV-silicone is a single component that has good adhesion to Si and cross-links when exposed to air moisture to form a tough, flexible, silicone rubber [7]. The planar Si spiral spring with its central disk (embedded in the RTV-silicone) increases the stiffness of the membrane, and allowed a controlled deformed shape to attain a larger swept volume for microengines.

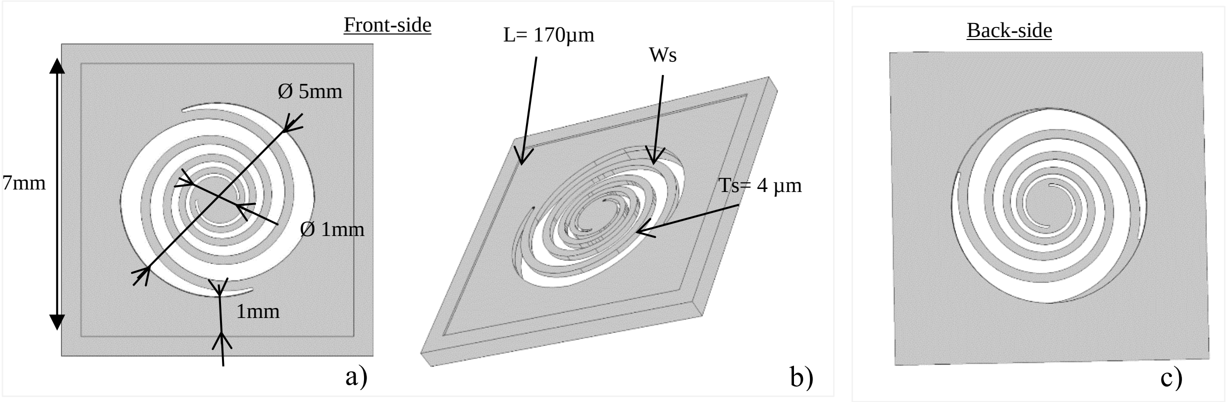


Figure 1. Silicon spiral spring architecture and geometrical parameters; L is the location of the RTV-silicone layer deposited by a squeegee, Ws is the width of the turns of the upper part of the spiral.

The logarithmic spirals geometry (defining the planar springs) is shown in Figure 1. On this figure, "Ts" is the chosen thickness of the spiral, "L" is the thickness of the RTV-silicone layer above the spiral and "Ws" is the width of the spiral. To aim at uniform stress distribution along the structure, their width (Ws) varies proportionally with the spiral angle [5].

3. Microfabrication

The microfabrication process flow for HMs is described in figure 2a. The SEM and optical images of the fabricated components are shown in figure 2b and 2c respectively. Embedded RTV-silicone allows here hermetical membrane to be obtained and a drastic improvement of the Si spring robustness [6]. A Si spring with a 1mm diameter central disc was used for both experimental tests and FEM modelling.

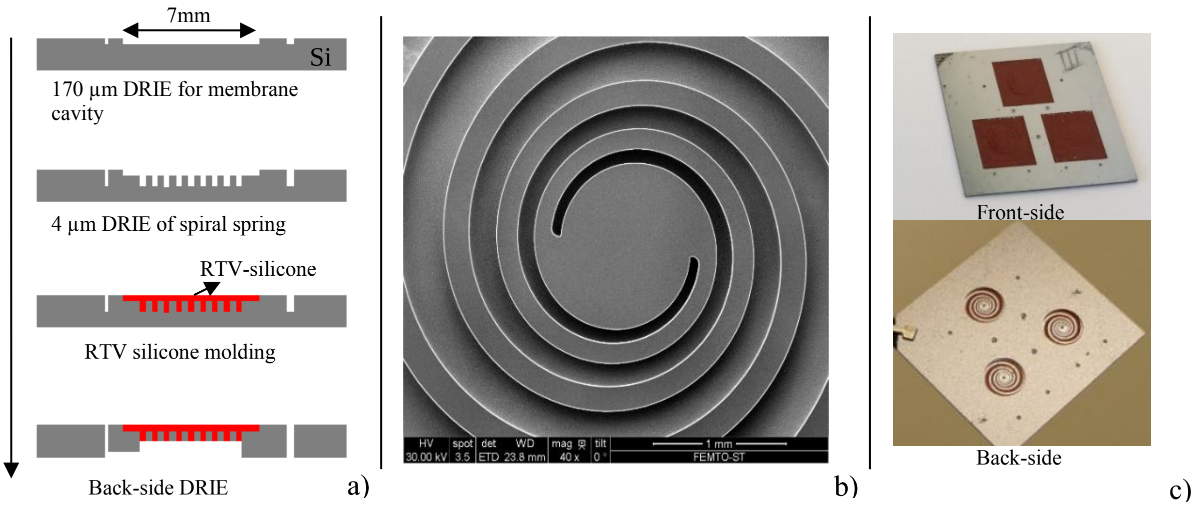


Figure 2. Microfabrication a) HMs microfabrication process flow b) SEM images of the silicon spiral c) Optical images of front and back-side of HMs sample.

4. FEM modelling

A COMSOL Multiphysics mechanical-structural model of the HMs was simulated, including the planar spring alone (cf. figure 3a) and with RTV-silicone (cf. figure 3b) at room temperature. Geometrical parameters and properties of the RTV-silicone used for the FEM model are given in table 1. The 3D FEM model can be used to study the effects of HM thickness, and/or the effect of the type of elastomer, while designing the spiral spring to aim at the desired stiffness value or frequency. The geometric parameters of the structure can be easily adjusted to provide inertial effects by increasing the thickness and / or width of the central disc. This adjustment allows an increase in the mass of the HM.

Table 1. RTV-silicone parameters. D_{cd} is the diameter of the central disc; h_{HM} and h_{sp} are respectively the thickness of the HM and the spiral; E is the Young modulus; ν is the Poisson ratio; ρ_m is the density

	Geometry			Material		
RTV-Silicone layer	h_{HM} = 174 µm	D_{cd} = 1 mm	h_{sp}= 4 µm	E = 1.5 MPa	ν = 0.49	ρ_m = 1100 kg/m^3

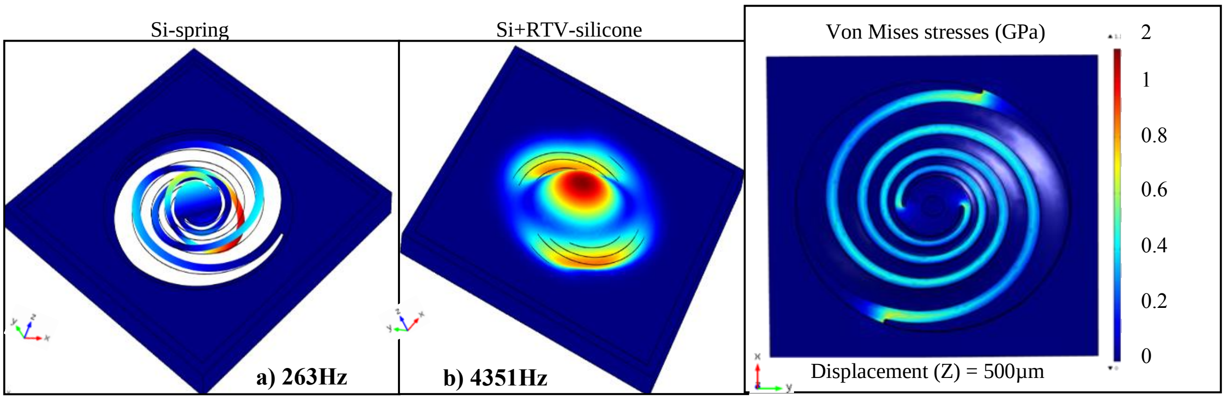


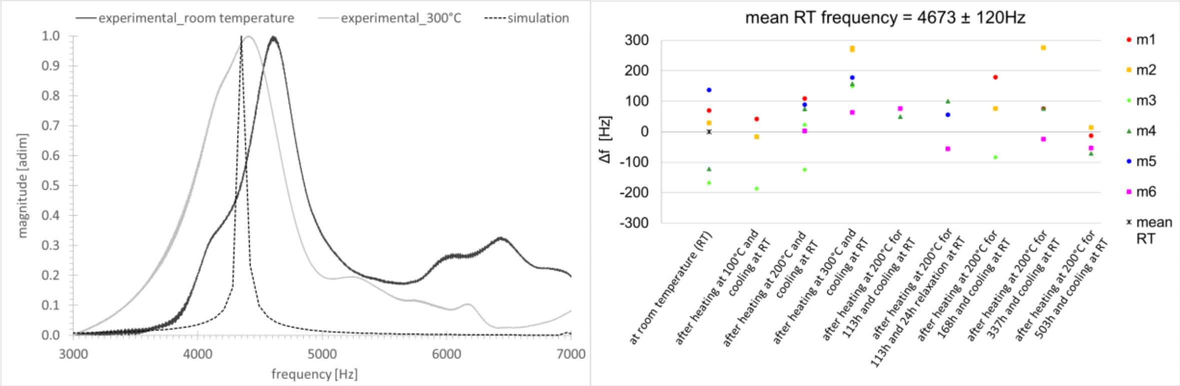
Figure 3. FEM model: a) Resonance frequency (conic deflection, 6th mode) of the Si spiral. b) Resonance frequency of the Si spiral and RTV-silicone assembly. c) Location of the Von Mises stresses concentration points during a 500 µm prescribed displacement on the HM.

According to the FEM, the sixth mode of deflection corresponds to the maximum displacement of the membrane, therefore we considered only this mode. FEM model of the Si spring alone shows a frequency of 263 Hz (figure 3a) whereas the HMs exhibits a resonance of 4351 Hz (figure 3b). Figure 3c shows the zones of strong mechanical constraints and a maximal displacement of the central disc of 500 µm while remaining within the yield strength of the two materials [8]. The zones of strong mechanical constraints were maximal at the salient points of the spring.

5. Characterization, results and discussions

A Polytec laser vibration sensor was used to evaluate HMs frequencies (figure 4) when the structure was submitted to harmonic excitation. These dynamic characterizations were performed for six different membranes, denoted m1 to m6. At room temperature, the HMs presented a 6th harmonic frequency around an average of 4673 ± 120 Hz. The Figure 4a presents the comparison between experimental and numerical results. A discrepancy of 7% is observed between the FEM model frequency when compared to the experimental one: the model is thus consistent with experimental results.

The samples characterized at room temperature were then subjected to given temperatures (100, 200 or 300°C) during given time periods consistent with those of an anodic bonding total process time. Further, membranes were also submitted to aging at 200°C. Results of both experiments are given on the figure 4b. After heating, frequencies of membranes were measured at room temperature. For each membrane, we present the difference between the mean value of the initial frequencies before temperature treatment, and the ones found after being submitted to given operating conditions. Taking into account the reproducibility of the membranes natural frequencies, no significant change was found after heating at 100, 200 or 300°C: therefor the cleanroom process does not damage or modify significantly the membranes properties. Moreover, the resonance frequency of HMs remained almost the same after 113h, 168h, 337h and 503h of aging at 200°C. The HM mechanical properties does not seem to change very much after high temperature exposure. The HMs should thus be suitable for applications at rather high temperature conditions.



a) b)

Figure 4. a) Experimental (at room temperature and after heating at 300°C) and numerical resonance frequencies, b) Variations of Δf versus operating conditions for each HM (mi, with $1 \leq i \leq 6$). With Δf = [mean RT (room temperature) frequency – measured HM frequency].

6. Conclusion

We have modelled, and experimentally demonstrated the stability of hybrid membranes resonance frequency (6th mode), which are thus suitable for micromachines, especially thermal microengines. The numerical simulation made it possible to highlight the zones of strong mechanical constraints and the expected piston-mode resonance frequency. Numerical results were in agreement with the experimental test results. Experimental results showed that high temperature processes, like anodic bonding, should therefore not change the mechanical properties of the hybrid membranes.

Acknowledgments

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