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Miniaturization of Compensational Spring System using the Highly Nonlinear Curved beams in MEMS

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Abstract. In this work an approach to minimize a non-linear system with a flat region in the force-displacement characteristics is studied. Design, simulation, fabrication and characterization of the initial system with the linear compensational spring and that of a miniaturized one without it are presented. The presented highly nonlinear curved beam system shows the same behavior as that with compensational spring system in terms of force-displacement both in the finite element simulation and in the experiment. Thus, an equivalent miniaturized system is proposed with the surface footprint reduced by 2.38 times only by designing means, without changing the technological steps.

1. Introduction

The problematics of miniaturization of separate mechanical elements in micro-electro-mechanical systems (MEMS) remains actual [1]. There are two main techniques that are can be referred in miniaturization of the MEMS devices: either the straightforward decrease in the size of elementary components [2] (which is limited by the available technology of fabrication and design rules, mainly related to anisotropic etching), or by the design of alternative structural elements shapes [3] (general design methodology is not defined in this approach).

Springs, as a structural element in MEMS, are considered to be of crucial importance, as far as they are used in an extremely wide variety of devices [4,5]. Typically, non-linear springs are widely used in a variety of energy harvesting applications [6], resonators [7], switches and actuators [8].

In our research, a need for miniaturized nonlinear springs with a flat force-displacement region has arisen. In the present work, a design, simulation, fabrication and experimental verification of a miniaturized spring is presented in comparison to the original non-miniaturized system.

2. Design of the Double Curved Beams system

A schematics of the compensational springs system and of the highly nonlinear curved beam springs system is shown on the Fig. 1. The compensational spring system (studied in our previous work [9]) is composed by a bistable double curved beam mechanism [10] with attached linear springs with a stiffness of k=21N/m chosen to obtain a flat region in the force-displacement curve. The highly nonlinear curved beam shape was obtained by varying the curvature of the original bistable beam. All considered beams have width of 20µm and thickness of 85µm.

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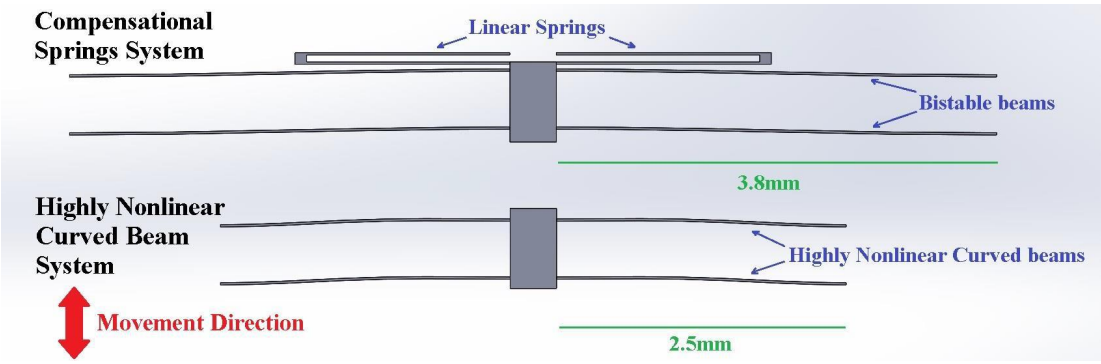

Figure 1. Schematic representation of the original Compensational Springs system and of the miniaturized Highly Nonlinear Curved beams system.

The useful footprint of the layout of the proposed miniaturized system is 0.73mm² versus 1.735mm² of the initial system, which yields a miniaturization of almost 2.38 times in surface using only design means.

3. Simulation

To simulate the mechanical properties of the compensational spring system and its high nonlinearity, a finite element model (FEM) approach had been used. ANSYS models are created for each system, and a static analysis of force-displacement is performed. As it is depicted on the Fig. 2, the force-displacement curves of the two systems fit almost perfectly.

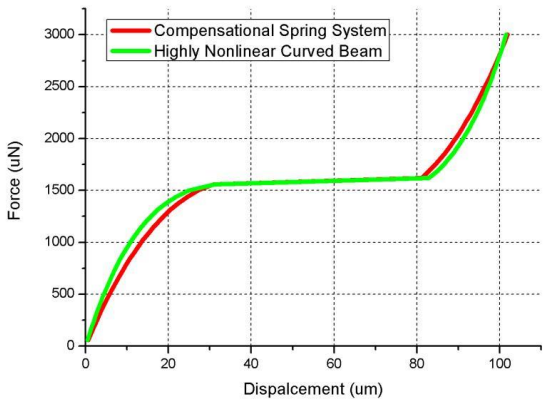

Figure 2. The force-displacement curves of Compensational Spring System and Highly Nonlinear Curved Beam system obtained with FEM simulation.

There are 3 regions present on the presented force-displacement curve: 1 : progressive softening, 2: large compliance (plateau) and 3: progressive hardening [10,11]. The behavior on the first and last regions is the typical for a bistable mechanism, whereas the central nearly-flat region comes from the modification of initial nonlinearity.

4. Experimental part

The systems are fabricated using SOI wafer of 85µm device Si thickness, with Bosch process of Deep Reactive Ion Etching (DRIE). The schematics of the process of fabrication is shown on the Fig. 3. First, a photoresist film is deposited by spin-coating (Fig. 3, A), which is followed by UV lithography and development (Fig. 3, B). Then the device pattern is etched using DRIE of Si device layer (Fig. 3, C). At the last step, the system is liberated with HF vapor etching of the buried oxide layer and the photoresist is stripped off (Fig. 3, D). The optical images of the fabricated spring systems is shown on the Fig. 4.

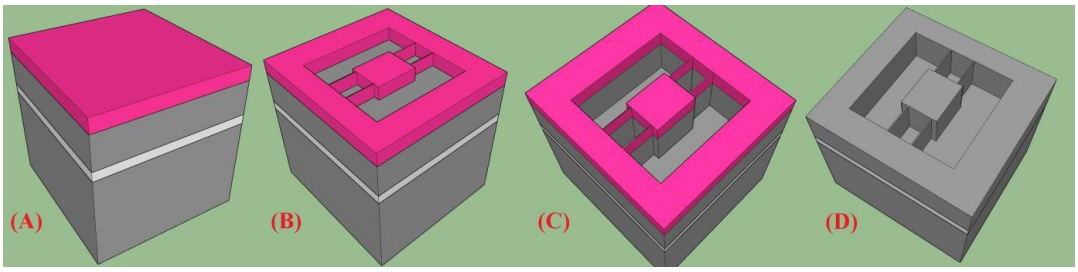

Figure 3. Schematics of the fabrication process. Grey color corresponds for silicon, light grey – for silica, and rose for photoresist.

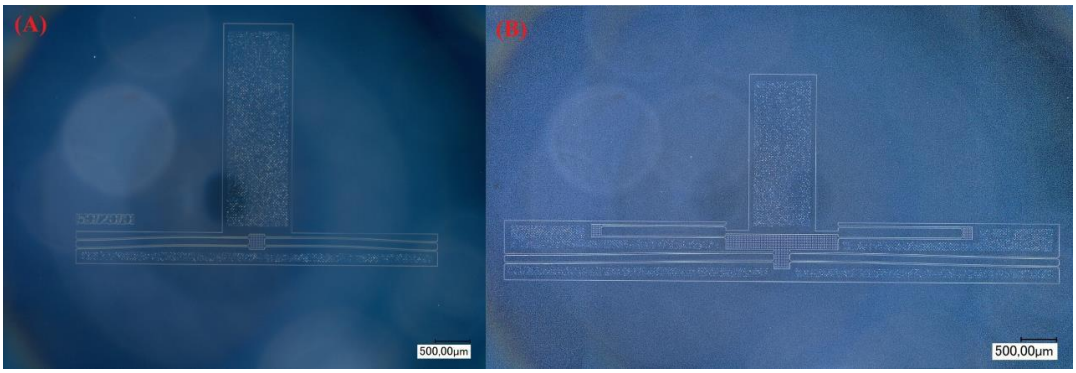

Figure 4. Photos of the fabricated Highly Nonlinear Curved Beam system (A) and Compensational Springs system (B). Note the difference in the footprint size.

To characterize experimentally the fabricated systems a micromechanical testing instrument (FT-MTA02, FemtoTools [12]) is used. It consists of an actuation unit with a micro force sensing probe needle and a microscope that allows aligning the probe with the tested microstructure. Photo of experimental set-up is shown on the Fig. 5, (A). Mechanical reaction force of the studied spring systems is measured with force sensing probe with a 30° inclination of the probe. This angle has been considered in the post-treatment of the measurement results, which are demonstrated on the Fig. 5, (B).

5. Discussions

The measured force-displacement characteristics of both systems are relatively close, and the slight difference is coming from the limitations of the used fabrication techniques. Experimental curves have a shape that is similar to that obtained by FEM. However, the measured reaction force values are almost two times smaller than the ones predicted by simulation, which is easily explained by the roughness and notching present on the sides of the beams due to DRIE process imperfections. Side walls of the springs are observed to be not perfectly vertical due to the limitations of DRIE process. Equivalent (mean) beam thicknesses have been estimated as 17.5µm instead of the 20µm designed.

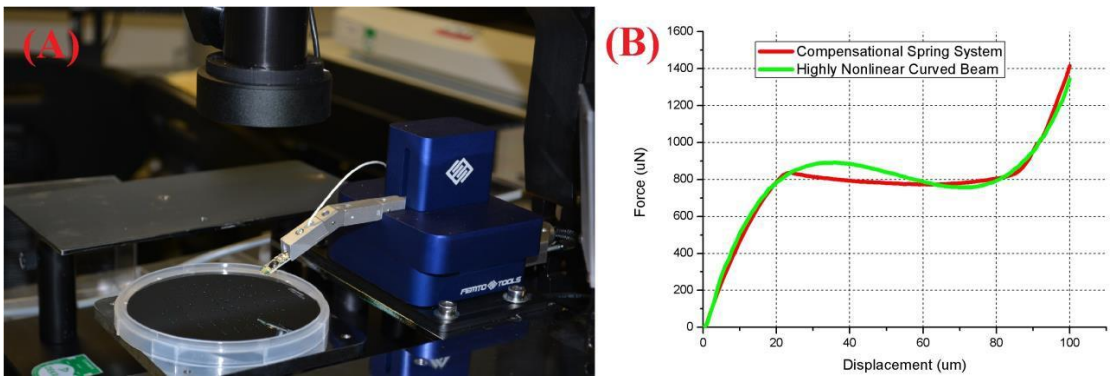

Figure 5. (A) Experimental set-up; (B) Measured force-displacement curves of fabricated Compensational Spring System and Highly Nonlinear Curved Beam system.

6. Conclusion

In the present article, the design, simulation, fabrication and characterization of a highly nonlinear spring system with an almost flat force-displacement region is presented. This system is shown to be mechanically equivalent to compensational spring system, which consists of the combination of two pairs of bistable curved beams and linear spring. However, the footprint on the mask is decreased significantly (2.38 times).
The finite element model is built for both the initial (the one with compensational spring) system and the miniaturized highly nonlinear curved beams system. Both systems are fabricated in silicon using a classical microfabrication technologies. Characterization is performed using a micromechanical testing instrument with a force-displacement sensing probe. The measured force-displacement characteristics for both initial and miniaturized systems are close to each other, and similar to that predicted by FEM analysis. The difference in absolute values between simulations and measurements are coming from the imperfections of the fabrication. Due to the all presented results, it can be said that the initial compensational springs system is successfully miniaturized by using only highly nonlinear curved beams.

Acknowledgements

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