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Bistable arch-like beams with modulated profile as perspective supporting structures of a microelectromenchanical actuator

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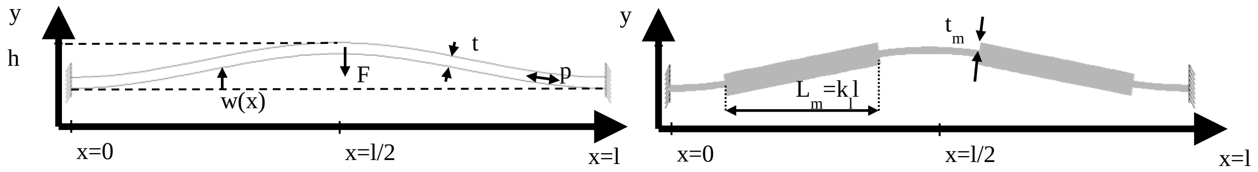
Abstract. The static mechanical properties of a bistable electromechanical drive with arcuate suspension is investigated. The behaviour of an arcuate suspension and the influence of the beam thickness modulation on the stability of both stationary states is studied experimentally and theoretically. The influence of the beam shape modulation on its potential energy was determined with finite element analysis. The simulation results were verified experimentally. In the study, the optimal modulation configuration is determined. With help of this modification the sustainability of both mechanically stable states is significantly improved.

1. Introduction

The major element of micro-electro-mechanical systems (MEMS) is an elastic microstructure in the form of spring, a beam or a membrane. These elements are usually the linear elastic systems, wherein its linearity enables mechanical – electrical energy conversion both in sensors and in actuators. However, in the last decade, the use of nonlinear supporting beams becomes more popular. The active actuation of the nonlinear suspensions enables the formation of multistable systems. The work is particularly focused on arch-shaped suspensions, which profile is determined by the mode of buckling. The nonlinearity of such suspensions causes a sharp increase in the axial load of the suspension under an applied lateral load of the suspension [1]. This structure has two minimum of the potential energy i.e. the mechanical structure has two stable states. The transition between the potential energy minima of such mechanical system causes loss of stability during the transition between states. However, in such systems a serious asymmetry of bifurcation points is noted, i.e. the difference of the potential energy minima is large, which indicates reduced stability of one of the states [2]. The method of localized stiffness enlargement of the arcuate suspension beam augment at the sustainability of the “weaker” state. Here we consider the influence of the arch thickness modulation of and optimization of the initial profile of an arcuate suspension.

2. Method description

The profile (w(x)) of an arch beam of thickness t is determined by the first form of buckling (Figure 1a). The arch ends are clamped at x=0 and x=l. The stability loss of the arched beam which occurs under the influence of an axial restriction leads to a sudden change of the beam shape. The second stable state is a result of the beam shape transformation (known as snap-through) under the lateral load (F)governed by the axial one (p). The potential barrier between the stable states can be enlarged introducing two stiff segments into the arch structure (Figure 1b).



a

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Figure 1. a) A uniform beam arch-like beams profile; b) An arch-like beam with modulated profile.

The stability of the snapped-through state of a “thin-thick-thin-thick-thin” shaped arch beam is significantly better compared to a uniform arch beam [3]. The mechanical stability of an arcuate beam is determined with the length of the ridged beam section L_m.

3. Design and fabrication

Bistable microdrive is an electromechanical system comprising an array of comb electrodes, where the motile group of electrodes is supported with the elastic arcuate beam system. The prototype of the bistable microactuator is fabricated using bulk technology via DRIE of silicon in a 100 µm thin structural layer of a silicon-on-glass wafer substrate (Figure 2). The initial shape of the actuated beam are directly controlled through the lithography and DRIE.

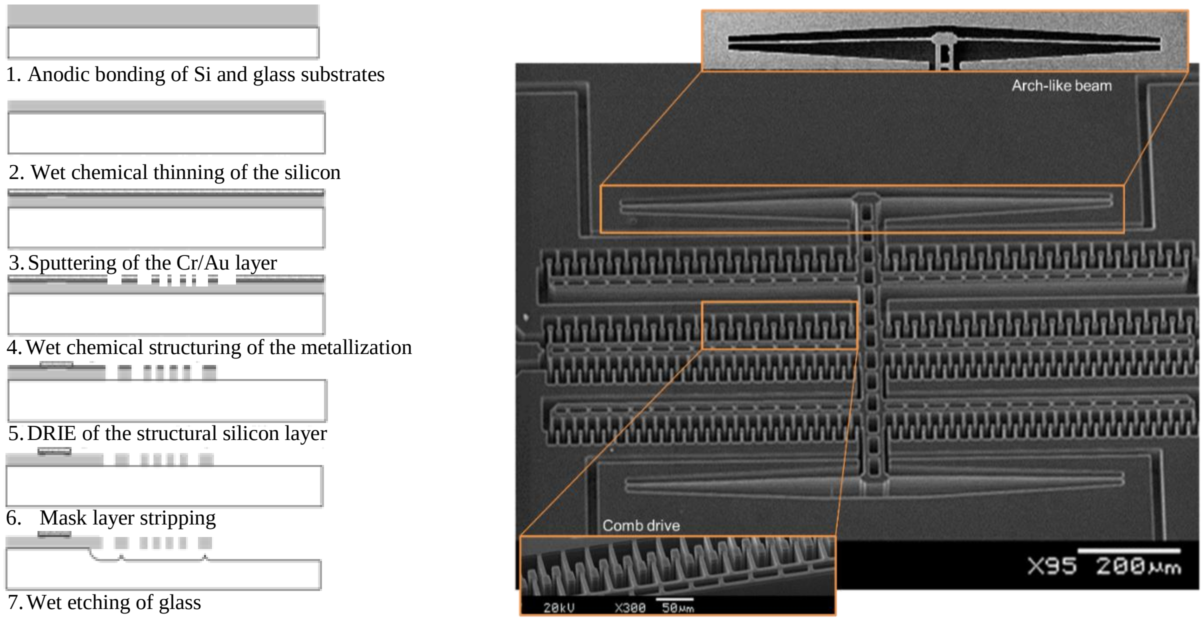

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Figure 2. a) Fabrication process; b) Bistable actuator (REM image).

4. Numerical and experimental study of a uniform beam behavior

The reaction of the arcuate structure to the central lateral load is estimated analytically using the method of J Qiu et al. [2] and the finite element analysis (FEA) (Figure 3). The forces at snap-through transition are determined experimentally via the potential at which up and down transitions occur. These critical forces are denoted with horizontal lines (Figure 3). The resulting theory/experiment mismatch is mostly justified by the geometrical imperfection of the resulting etched beam.

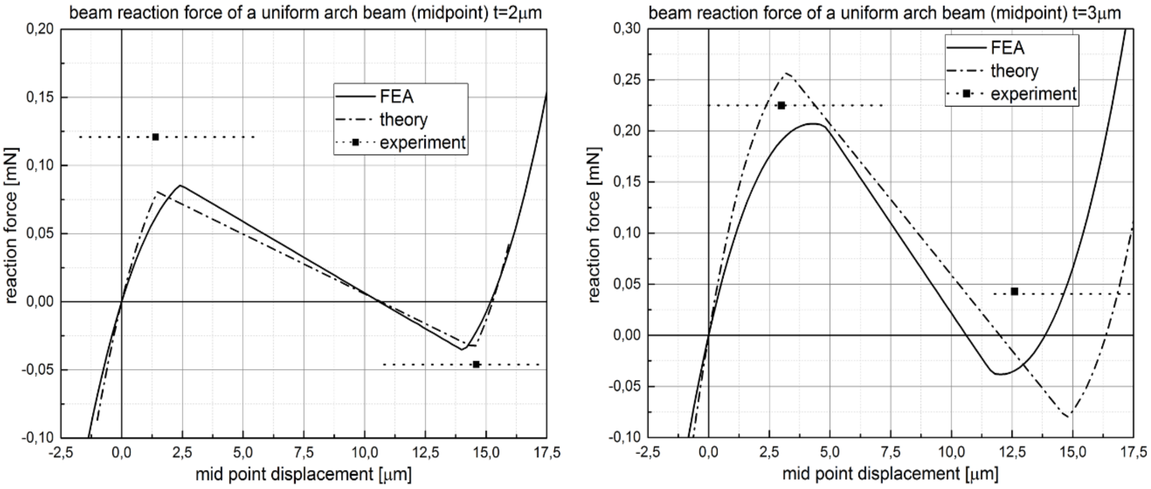

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Figure 3. The uniform arch beam reaction force vs displacement. Analytical estimation, FEA simulation, and experiment: a) beam thickness 2um; b) beam thickness 3um.

The results achieved by means of the numeric simulation match well to the analytical solution of the problem with a large ratio of the height of the deflection to the thickness of the beam (Figure 3a). However the beam thickness enlargement brigs a deviation between the analytical and FEA models. The experiment demonstrates deprivation of second stable state as shown on figure 3b.
The relation of axial and lateral reaction forces within the beam determine the stability of this secondary state. This relation can be expressed as the bow of the arch to thickness ratio. If the bow is fixed, the depth of the potential energy minimum of the arch decreases with its thickening, as it is illustrated below (Figure 4a, b).

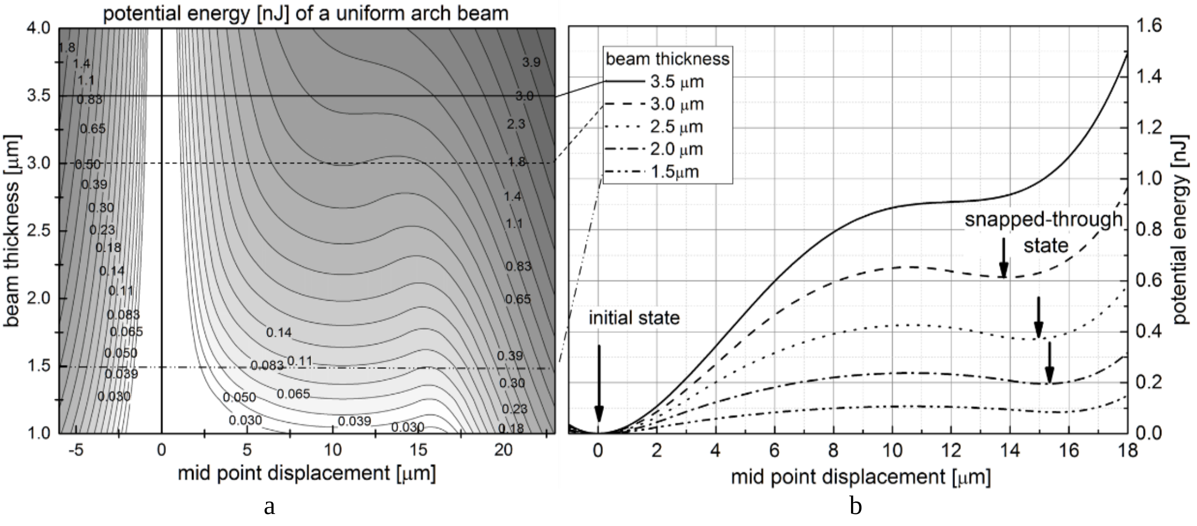

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Figure 4. Estimated potential energy of the uniform arch beam with a bow of 8 μm; a) potential energy topography in space arch thickness/displacement b) 2D slices of the elastic potential energy of selected thickness.

The relative mechanical stability R of the snap-through state can be expressed as the ratio of the top potential energy minimum depth to the bottom one. One can notice that at a beam height of the arch rise of 9 μm and thickness of 3.5 μm and above the stable state of the structure can no longer be reached (Figure 4). On the other hand thinning of the arch will reduce the absolute depth of the second minimum.

5. FEM Stability Analysis

5.1 The arch beam with rectangular modulation

The potential barrier between the stable states can be enlarged by introducing two stiff segments into the arch structure (Figure 1b). Figure 5-7 represents the numerically simulated potential energy of such arch structures of modulated thickness and stiffness. The most important optimization parameters of such thickness modulation are the length of the modulation segment Lm and its thickness, tm. The proper set of this parameters help to improve the stability of the snap-through stable state. The ratio of the potential energy barrier height to the minimum depth R is at Figure 5a. The optimal length of the modulation segment km is achieved at k_l=0,25. The real value of the potential energy well depth is highest at this point as well Figure 5b.

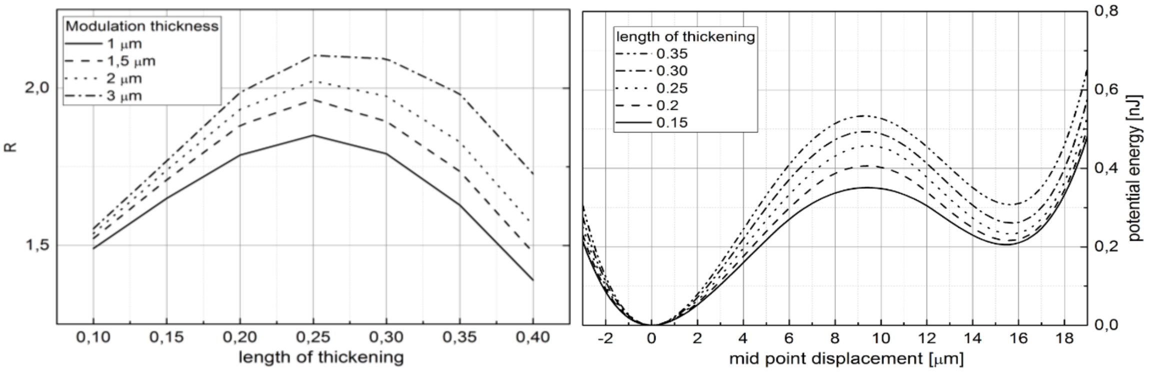

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Figure 5. Estimated potential energy of an arch beam with rectangular modulation.
a) 2D slices of the relative depth of the elastic potential well vs length of thickening (k_l); b) 2D sections of the elastic potential energy beam at t_m=1.5 μm at selected length/ displacement values.

The stiffness of the “shoulder” beams of the arch plays an important role as well. However the major contribution of the thickening occurs mostly at its lower end 0.5 μm to 2.5 μm at the initial thickness of beam 2 μm (Figure 6a.).

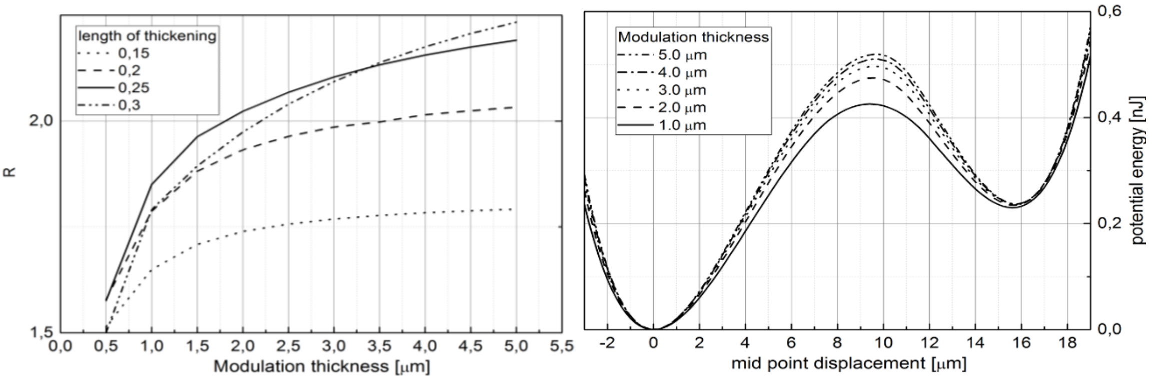

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Figure 6. Estimated potential energy of aт arch beam with rectangular modulation.
a) 2D sections of the relative depth of the elastic potential wellvs thickness (t_m); b) 2D cross section of the elastic potential energy beam of k_l=0.25 regarding the selected thickness/ displacement.

On the basis of results represented at Figure 5 and Figure 6 the optimal shape of the arcuate suspension beam is chosen. The optimization criterion is in maximizing the relative depth of the potential well.

5.2 The arch beam with sinusoidal modulation

Another beam rigidity modification of the arch thickness is accomplished using a smooth function as a cosine. The beam thickness modulation can be written as

$$t_m = \frac{t_b}{2}\left(1 - \frac{3}{5}\cos\left(4\pi\frac{x}{l}\right)\right), \tag{1}$$

where t_b is modulation amplitude. As it is shown in Figure 7, the arcuate beam with modulation of the cosine shape demonstrates higher specific energy well depth. The R factor decreases with modulation amplitude. At the same the energy well depth increases (Figure 7).

The figure 8 represents the comparison of the elastic reaction force of the beams with various modulation patterns (uniform, rectangular and cosine). Reaction force of the beams modulated with rectangular insets and the cosine one are similar, whereas the energy, required to switch the beam to the upper energy state is higher for the cosine modulated arch.

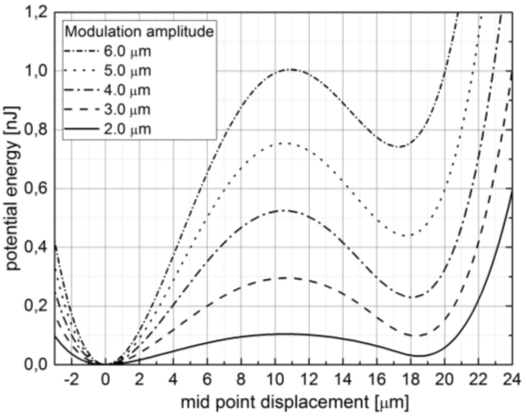

Figure 7. Estimated potential energy of an arch beam with cosine modulation of selected modulation amplitude vs. beam displacement.

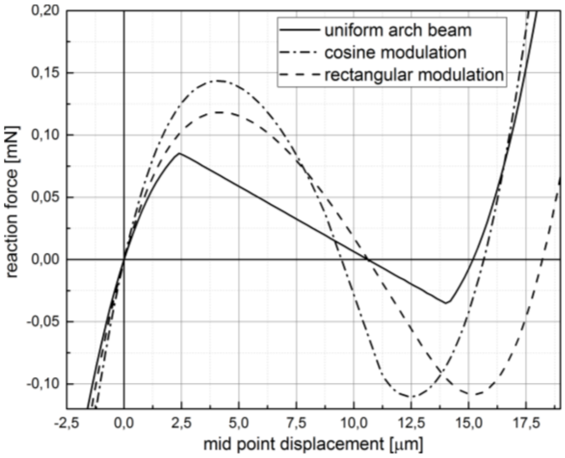

Figure 8. FEA simulation of the beam reaction force: uniform arch beam (t=2um); arch beam with rectangular modulation (k_l=0,25μm; t_m=1,5μm); arch beam with cosine modulation (t_b=3,5μm).

The stability of the snapped-through state of a “thin-thick-thin-thick-thin” shaped arch beam is significantly better compared to a uniform arch beam. This stability can be achieved without compromising the force, required for this transition.

6. Conclusion

This work illustrates that the initial profile of the arched beams and external or internal axial loads are the key factors that determine behavior and nonlinear properties of the arched beams. The modulation of the arch beam profile thickness recesses the depth of the potential energy minimum of the second stable state of the pre-shaped arch beam. Thus increasing the sustainability of the second stable state.

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