The development of a bistable microdrive for the micromechanical gyroscopes

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Abstract. In present work, the model and methodology for designing of arcuate arc-shallow MEMS with buckling was developed and tested. The efficiency of the model is confirmed experimentally. The result of the present survey is an increase of the efficiency of the exciting electrostatic comb drive MMG of high precision. The result of this research allows to reduce the control voltage and noise of a microgyroscope.

1. Introduction

Microelectromechanical systems (MEMS) are an evolution of microelectronics and are based on main microelectronics technological processes but it needs some kind of specific technological solutions and processes for development and manufacturing of MEMS devices. Semiconductor materials and technological processes help to produce micromechanical devices (such as gyroscopes) with improved parameters in smaller scales. Combination of mechanical elements and electronic components based on the same technologies makes it possible to improve the parameters and workability of a device.

Nowadays, there is a discussion in microsystems technology (MST) about usage of postprocess with the addition of supplementary active functional elements to avoid limitations of deep plasma-chemical etching and formation of the electrostatic pectenate structure with a high profile and narrow gaps [1]. These methods suppose the usage of additional active elements for the displacement and fixation of a comb drive. These active bistable systems are described in [2]. Supplementary elements significantly complicate the construction and reduce the reliability of MEMS due to a large number of active elements. In this paper, we propose to use a bistable actuator based on the buckling [3]. This solution allows to form the structure for displacement of the comb drive without adding active elements that will significantly improve the device parameters. The main limitation of the construction of the comb drive structures is deep plasma-chemical etching.

2. Technology of post-process for micromechanical gyroscopes

A micromechanical gyroscope (MMG) is a device that is used for measuring the angular velocity by generating the Coriolis force in the mechanical system. The mechanical structure is formed by the resonator exciting primary oscillations and the measuring resonator of secondary oscillations caused by the Coriolis force. There are known designs of vibratory MMG differing by the number of oscillating masses, the direction of oscillation, the structure and construction of an actuator and a measuring unit, manufacturing technology and materials [4]. A micromechanical gyroscope is a
measuring device for navigation, it has high requirements to the sensitivity, a level of noise, stability under mechanical loads, etc.

Figure 1 shows the frame structures of MMG, where 1 and 4 are the resonators of the primary and secondary oscillations, 2 and 3 are the exciting and measuring sense combs consisting of a system of movable and stationary electrodes formed in the body of the resonators. Increase of the profile depth can result in a significant increase of the ratio of the flexible suspension stiffness of the resonators and an increase of the comb drive area. The comb drive area increasing while maintaining the gap between the electrodes will significantly increase the excited electrostatic force or reduce the drive voltage for excitation of oscillations. The presence of parasitic capacitive links in the structure of MMG leads to mutual influence of the exciting and measuring electrodes. The reduction of the Drive voltage will reduce the influence of the excitation signal in the measuring electric circuit.

During the creation of the volumetric structure, the main technological operation is Deep Reactive Ion Etching (DRIE) of silicon. The limitation for this process is a depth of etching (DRIE) in the form of the aspect ratio. Nowadays, the achievable ratio is approximately 1:30 and during the formation of structures with a high profile, a large gap is necessary. For an electrostatic actuator, increasing of the gap will lead to a significant reduction of the excited force.

![Figure 1. Model of the framework structure of MMG](image)

There are known solutions for reduction of the gap, using the postprocess and setting [3, 4]. In case of the active adjustment, the additional mechanical structure with its own actuator (electrostatic or thermal) is formed, removing and holding the structure in the position with a reduced gap. The postprocess also uses a supplementary mechanical structure for changing the gap but involves the fixation of this structure after the movement. These methods allow to increase the capacity, however, require additional mechanical components that increase the size of the device and reduce reliability. The present study proposes the usage of a bistable system with buckling for displacement of the comb drive and the creation of pectinate-like structures with a high electrostatic force.

3. Bistable structures for postprocess
The buckling of mechanical elements which occurs under the influence of an axial load causing an abrupt changing of the deflection curve, is one of the commonly considered types of instability in
microsystems technology. For the majority of devices, buckling leads to uncontrolled variance of the device parameters. For the bistable system, the presence of bifurcation points and two energy minima is characteristic, which allows the system to stay in one of two stable positions without energy consumption. Such systems need energy only for the conversion from one stable condition to another.

There are known solutions for the usage of flexible elements with buckling for designing of electrostatic and optical switches, band pass filters, valves, etc. There are two options of formation of such flexible elements: due to internal tension in thin films [2] or etching (plasma-chemical etching) of an arc-shallow suspension [5, 6]. In the first case, the parameters of the bistable element have a low repeatability and are used in surface MEMS. In this article, we consider the production of an arc-shallow suspension using the second method, due to its predictability, repeatability, and compatibility with the fabrication technology of the MMG.

An arc-shallow flexible element is a silicon beam formed by DRIE. The shape of its frontal profile is described by a function of the height of the deflection \( \omega \):

\[
\omega(x) = \frac{h}{2[1 - \cos \left( \frac{2\pi x}{l} \right)]},
\]

where \( l \) is the distance between the clamped tips, \( x \) is the lengthwise coordinate, \( h \) is the amplitude of the displacement of the beam midpoint (\( x = l/2 \)). One condition must be met for this structure: \( t \ll b \), where \( t \) is the thickness and \( b \) is the height of the profile (arc) [5]. The structure of the bistable device including alike beam is also called snap-through.

The behavior of this structure is well described by the dependence of the displacement of the point \( \omega(l/2) \) on the external load, as shown in figure 2. Initially, the system stays in equilibrium without an applied load, which corresponds to the point A. With application of an external force \( F \), high axial loads arise because of high stiffness against stretching and compression. Thus, the displacement of \( \omega(l/2) \) in the direction to points A and B is minimal. Near the point C, the response of the system increases, the stiffness of the beam decreases because of the bending deformations. When the force reaches the value corresponding to the point C, there is a buckling and abrupt transition to the point D. In the same way as for the segment AB, a further increase of the external load leads to a minimal movement due to the high stiffness against stretching. In the absence of active forces, the system will not return to the point A, but will remain on the segment DE. The stationary position is determined by the presence of a second energy minimum and stability of this position depends on the depth of the potential well. The limit stable value corresponds to the point E (negative forces), where the system loses the equilibrium position and an abrupt transition to the point B occurs. When the load is removed, the system returns to the original state corresponding to the point A. Therefore, the points C and E are the points of transition (bifurcation), and their mutual arrangement determines the presence of two stable positions and their stability.

In the present survey, it is proposed to use the structure hung on a system of arcuate arc-shallow suspensions instead of the stationary part of the excitation actuator (figure 1). In the initial position, the pectinate drive stays in a separated condition, that is, the area of overlap tends to zero. One part of the actuator is formed on the body of the resonator of the primary oscillations, and the second one, on the arcuate arc-shallow suspension. The manufacturing of a gap for etching satisfies the condition of the aspect ratio, and the structure with a high profile is formed. However, the gap value exceeds any technological capabilities while working. The transition to the working position occurs by supplying a voltage (of about one hundred volts) between the pectinate drives. In this case, buckling and abrupt transition to the stationary comb occur. A high value of stiffness against stretching (much greater than the stiffness of the resonator of the primary oscillation) gives the opportunity to suppose that the actuator hung on the arcuate arc-shallow suspension is conventionally static. The resulted structure allows to increase the efficiency of the comb drive due to a smaller gap while maintaining the reliability.
4. The prototype of the bistable structures

The problem of modeling an arcuate arc-shallow suspension relates to the field of nonlinear systems with two potential minima. The position of the bifurcation points corresponding to figure 4 can be found analytically. The approximate values will be determined as:

\[ F_C = \frac{8\pi^4 EIh}{l^3}, \quad F_E = \frac{4\pi^4 EIh}{l^3}, \quad dx_{CE} = 1.33h, \quad dx_C = \frac{8\pi^4}{3Q}, \quad dx_E = 2h - \frac{8\pi^4}{3Q}, \quad dx_{ED} = 2h - \frac{4\pi^4}{3Q}, \]

where: \( F \) is the force, \( E \) is the Young's modulus, \( Q \) is the ratio of the thickness of the beam to the height of deflection.

However, this approach cannot give a complete picture of the system behavior over the entire range of displacement.

For a buckling research, modeling in the software package COMSOL was used. Based on the theoretical dependence in figure 2, it shows that there is a region of uncertainty leading to a non-unique solution. The considered system acquired the first and third modes of the middle line (figure 3) during buckling. The aim was to avoid the second (rotational) mode of buckling.

![Figure 2](image)

**Figure 2.** The dependence of the displacement of the center point of an arcuate suspension on the attached external loads [6]

![Figure 3](image)

**Figure 3.** The map of displacements in the first (a) and third (b) buckling modes

In the course of the calculation, the dependence was obtained that described the behavior of the buckling in the "force-displacement" coordinates (figure 4). As shown, the results are in good agreement with the data of the analytical calculation.
To validate the modeling results, the test samples were fabricated (figure 5), in which the external force was formed by a double-sided electrostatic pectinate drive. The values of electrical tension were obtained for the bifurcation points C and E, and the discrepancy with the results of buckling calculation is within 8%.

**Figure 4.** The dependence of the force on displacement

![Graph showing force versus displacement](image)

**Figure 5.** The pectinate actuator of the bistable suspension

After fabrication of micromechanical gyroscopes, the bistable actuator is transferred to the second stable condition. The system must be stable and able to withstand significant external loads. The usage
of a structure with bistable beams of a variable thickness was proposed for this. From figure 6 it follows that the height of the potential barrier near the point E is substantially higher. This means that the system of beams of a variable thickness is more stable. During the analysis of the shape of transition and internal tension, it was decided to use a construction with a non-uniform beam profile across the thickness. An arcuate arc-shallow beam can be represented as a V–shaped beam with strong shoulders and joints at the point of fastening and in the center.

![Figure 6](image)

**Figure 6.** The dependence of potential energy on displacement of bistable beams with a constant (mono) and variable thickness (diff)

5. Conclusion
The present survey considers an actual issue of designing bistable MST devices. The model and methodology for designing arcuate arc-shallow MEMS with buckling was developed and tested in this research. The efficiency of the model is confirmed experimentally. The developed model will significantly simplify and improve designing of bistable systems, and can be used for designing microwave MEMS switches, optical switches, valves and elements of the nonvolatile memory. The main result of the present survey is an increase of the efficiency of the exciting electrostatic comb drive MMG of high precision. The result of this research allows to reduce the control voltage and noise of a microgyroscope.

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