Nonlinear Micromachined Flexure for Stiction Reduction

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ABSTRACT

This paper reports the nonlinear micromachined flexure to reduce the stiction in MicroElectroMechanical Systems (MEMS). Good electrical contacts are essential in the applications like MEMS switches or relays. In this case high contact forces are required for reliable fully-metallic contacts. However the forces can also cause frequent stction failures. The proposed micromachined flexure shows highly nonlinear mechanical stiffness induced by a dimple under it. The parallel-plate actuator with the proposed flexures shows higher restoring forces to reduce the stiction failure without the increase of pull-in voltage. An analytical model that describes the deflection of the flexure is developed and verified using Finite Element Analysis (FEA). Finally the flexure is fabricated with general surface micromachining processes.

Keywords: Stiction, Nonlinear micromachined flexure, Restoring force.

1 INTRODUCTION

Stiction problems are present due to inherent structural nature of MEMS devices. Stiction occurs in release processes (release-stiction) or in operations (in-use stiction). There are various techniques to overcome release-stiction. The super critical CO_2 drying method [1] takes advantage of the supercritical transition of a fluid to avoid the formation of interface between the liquid and gas. Vapor-phase HF etching [2] at elevated temperature has been often used for dry etching of the sacrificial layer. Another drying etching technique is based on polymer columns sustaining the released structures [3]. The surface coating methods using Self-Assembled Monolayers (SAM) [4] techniques are more successful. These coatings not only eliminate release-stiction effectively but also reduce the apparent adhesive energy of in-use stiction by nearly four orders of magnitude in comparison with SiO_2–coated structures.

But most of them do not work on in-use stiction. Although SAM coating can reduce in-use stiction it is not adequate for the contact-critical devices like MEMS swtiches or relays. Those devices require good electrical contacts and any film in contact points will degrade their preformance. Moreover the repeated mechanical contact causes problems in durability of the SAM.

External release force can be used to free pinned MEMS structures. In the Lorentz force technique [5], an upward force is generated by the current through wires. However an external magnetic field is required. Another technique using a high-frequency ultrasonic pulse has been developed recently [6]. But it requires a piezoelectric PZT plate mounted on the wafer backside. In terms of structural design, high restoring force can be obtained by increasing the stiffness of flexures in MEMS actuators. But it will increase not only the pull-in voltage but also stiction failures due to high pull-in forces.

This paper describes nonlinear micromachined flexure to reduce the in-use stiction. Fig.1 (a) illustrates the paralle-plate microactuator with the nonlinear micromachined flexures. Fig.1 (b) shows the side view in pull-in position. The mechanical stiffness of the flexure will increase highly with the touch of the dimple under the flexure. But it is not necessary to apply a higher pull-in voltage with the appropriate design of the nonlinear flexures. So the proposed flexures are helpful for the design of contact-critical electrostatic actuators requiring high restoring forces to reduce the in-use stiction and low pull-in voltage.

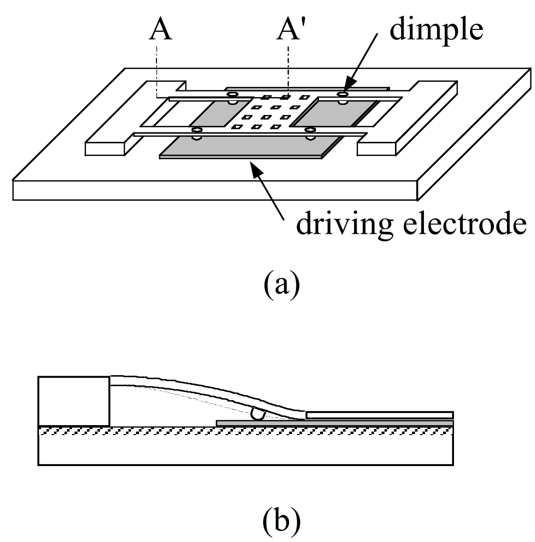


Figure 1: (a) The parallel-plate microactuator with nonlinear micromachined flexures. (b) The cross section of A-A9 at the pull-in position.

2 MODELING AND SIMULATION

A simplified analytical model of the nonlinear flexure is shown in Fig.2. The dimple under the flexures modelized as a fulcrum. From linear beam theory, the restoring force f is given by:

$$f = \frac{3EI}{l_o^3}\delta, \quad \text{for } 0 < \delta < \delta_c$$

$$f = \frac{12EI\left(4l_o - 3l_d\right)}{l_o^3\left(l_o - l_d\right)^3}\delta - \frac{3EI\left(3l_o - 2l_d\right)}{l_d\left(l_o - l_d\right)^3}\left(g - h_d\right), \quad \text{for } \delta \ge \delta_c \qquad (1)$$

where δ is deflection at the end of the flexure, l_o is the length of the flexure, l_d is the distance from the post to the dimple, g is the gap of parallel plates, h_d is the height of dimple and δ_c is δ when the dimple touches the substrate. E denotes the elastic modulus and I denotes the area moment of inertia of a flexure.

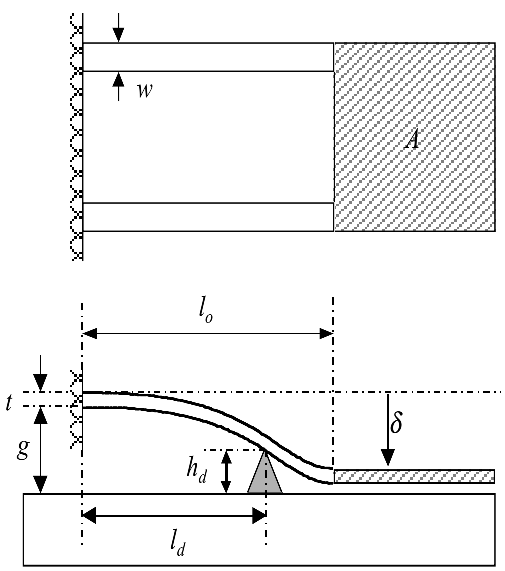


Figure 2: Schematic of the nonlinear flexure for linear beam analysis.

In Fig.2 A is the area of the moving plate, t is the thickness of structures and g is the gap between the moving plate and the substrate. w and l_0 are the width and length of the flexures respectively. Table 1 shows the dimension of the designed parallel-plate actuator. The bias is set to very low voltages, 3V. Table 2 shows the parameters used in case study to see the effect of position and height of the dimples. Three diffenent values of l_d's and h_d's are used respectively.

The restoring forces are calculated using equation (1). Fig.3 (a) shows the results of 3 cases for different l_d's under the fixed h_d (C1, C2, C3). The solid line shows the restoring force predicted by the analytical model. f_e denotes the electrostatic force inversly proportional to the square of the gap between the plates.

A [μm^2]	**3003300**
w [μm]	**18.5**
t [μm]	**2**
g [μm]	**2**
l_0 [μm]	**250**
E [GPa]	**80**

Table 1: Physical parameters of the designed parallel- plate actuator.

Case	***l_d*** [μm]	***h_d*** [μm]
C1	**220**	**0.4**
C2	**210**	**0.4**
C3	**200**	**0.4**
C4	**210**	**0.6**
C5	**210**	**0.2**

Table 2: Case study on various l_d's and h_d's.

The nonlinear flexures are properly designed to use this highly nonlinear behavior of electrostatic force. The dimple should be placed close to a moving plate to obtain higher stiffness. In case of C1 the restoring force is 33 times larger than that of flexures without dimples. The restoring force is equivalent to that of the dimpleless flexure of which the pull-in voltage is 17V. Fig.3 (b) shows the results of 3 cases for different h_d's under the fixed l_d (C4, C2, C5). We can obtain higher restoring forces with longer dimples. After the dimples reach the substrate three solid lines have same slope because the stiffness is independent of h_d as shown in equation (1).

The markers in Fig.3 denote the results of finite element analysis (FEA) using ABAQUS. The restoring force from FEA is always larger than the value of the analytical model. The nonlinear force due to the stretching of deflecting flexures can explain the differences. Fig.4 shows the resultant deflection shape of the flexure from FEA. 1272 elements are used and the vertical displacement is exaggerated 20 times.

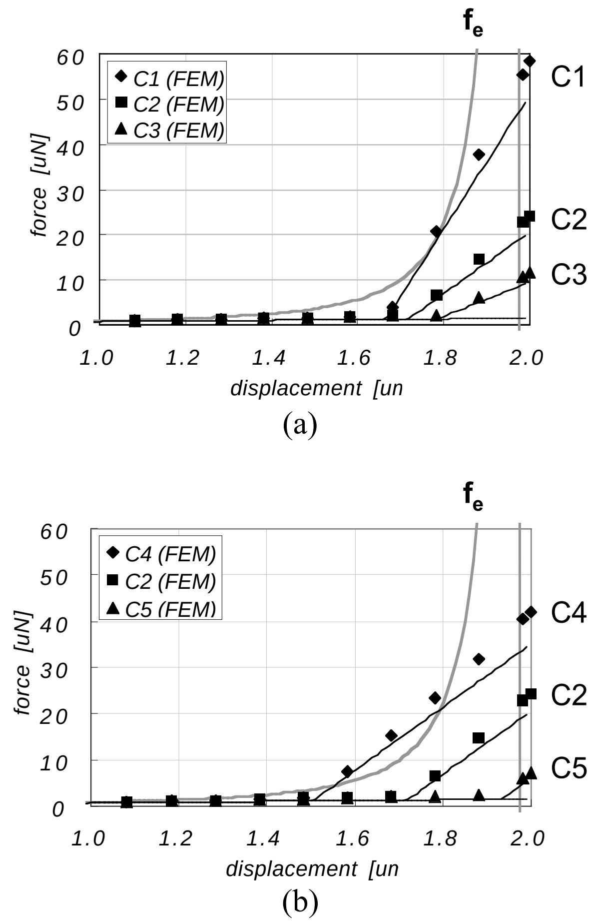


Figure 3: Restoring force vs. deflection of nonlinear flexure (a) for the case C1, C2, C3 (b) for the case C4, C2, C5.

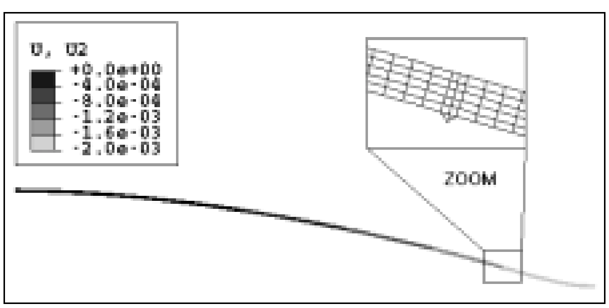


Figure 4: Finite element analysis (FEA) of a nonlinear flexure using ABAQUS.

3 FABRICATION

The parallel-plate electrostatic actuators with proposed nonlinear flexures are fabricated with surface micro-machining processes. In this case dimples are usually constructed by etching small indentations into the sacrificial layer before the deposition of the suspended member. However the restoring force of the nonlinear flexure is very sensitive to the height of a dimple. So we constructed dimples using two sacrificial layers to control the height of dimples precisely.

The brief fabrication process of nonlinear flexure is shown in Fig. 5. (a) The lower electrode is defined with LPCVD low stress polysilicon film (400 nm). Then a layer of TEOS oxide is deposited and planarized using Chemical-mechanical polishing (CMP). (b) The first Al sacrificial layer (0.4 μm) is deposited and defined for dimples. (c) The second Al sacrificial layer (2 μm) is deposited through sputtering and posts for the suspended structure are defined. (d) 2 μm of Au is deposited and the moving structure is defined. (e) Both Al sacrificial layers are removed using Al etchant finally.

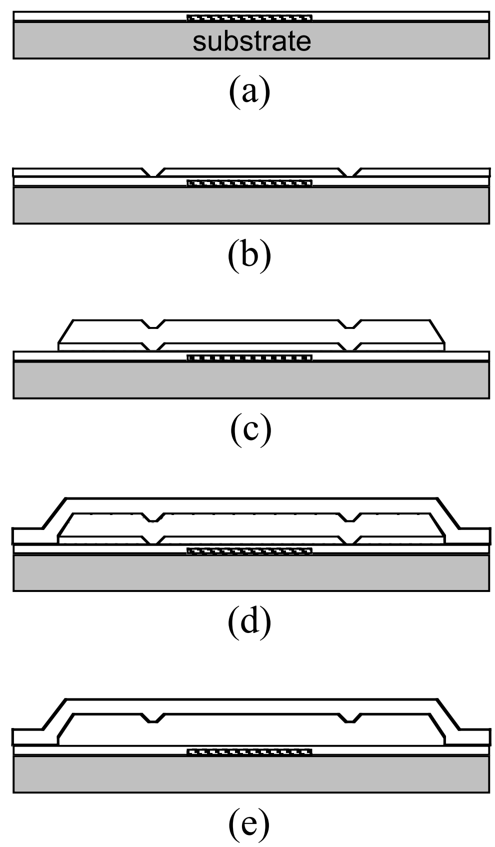
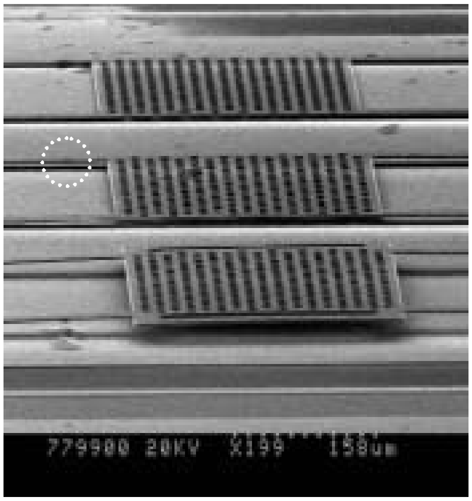


Figure 5: Fabrication process of the nonlinear flexure.

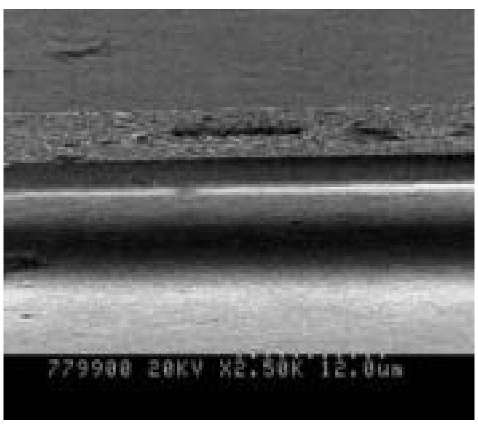
4 CONCLUSIONS

The modeling of the nonlinear micromachined flexures was developed and verified. The proposed flexure was designed to have a large restoring force to reduce the in-use stiction without increase of pull-in voltage. The analytical model showed good agreement with FEA results.

The microactuators with the proposed flexure were fabricated with suface micromachining processes. But we could not obtain the feasible experimental data because of the excessive deformation of the suspended structures.



(a)



(b)

Figure 6: (a) SEM photo and (b) the close-up of fabricated parallel-plate micro-actuators with the nonlinear flexures.

5 ACKNOWLEDGEMENTS

The authors wish to thank Mr. E. Lee, Mr. M. Lee and Ms. H. Kim for the fabrication of the present microactuators.

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