Study of Snap-through Behavior of a Bistable Mechanism for a MEMS Optical Switch

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ABSTRACT

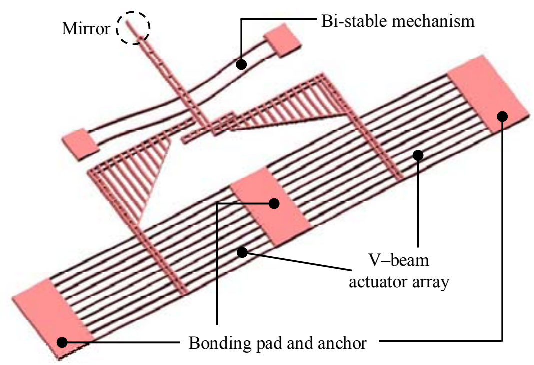
In this work, we present the study of both the transient and static behaviors of a bi-stable mechanism which will serve as the switching mechanism for an optical switch. The major part of the bi-stable mechanism consists of two constrained curved structures (the double-curved beam). The device modeled in this work is fabricated using a simple SOI process. As the applied force exceeds a critical value, the double-curved beam snaps through to the other stable state. We use the finite element method (FEM) to simulate both the static and transient snap-through behaviors of the bi-stable mechanism. Also, the simulated results will be compared with the measured results to study the influence of post-snap-through dynamics on the optical performance of the optical switch.

Keywords: transient, bi-stable, MEMS, optical switch, snap-through

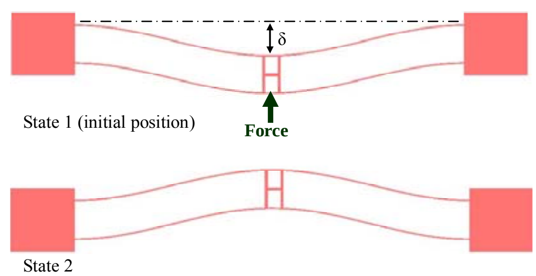
1 INTRODUCTION

Bi-stable mechanisms [3] can be used in many MEMS devices such as micro-relays, optical switches, and micro-valves. An advantage of the bi-stable mechanisms is that no power is needed to keep the mechanism at either of its two stable states. Previous studies of bi-stable mechanisms focused on their static analysis [1][2]. Understanding the transient behavior is beneficial for enabling the optimal use of such mechanisms. Hence, in this work, we focus on the transient behaviors of a bi-stable mechanism which serves as the switching mechanism of an optical switch. In addition, the post-snap-through dynamics, which might be highly nonlinear and probably affects the system's performance significantly, will also be studied in this work.

The device modeled in this work is realized using a simple SOI process with one photo-mask. Figure 1(a) shows the schematic of the optical switch which is integrated with a bi-stable mechanism and two electro-thermal actuators. The bi-stable mechanism, which consists of two clamped curved beams, is capable of providing two mechanically stable positions (i.e., State 1 and State 2), as shown in Figure 1(b). The SEM picture of the bi-stable mechanism is shown in Figure 2. The external force to achieve snap-through action is applied on the middle of the double-curved beam. The FEM (finite element method) software, ABAQUS®, is used to analyze the system. We also set up a laser Doppler vibrometer interferometer system [6] to measure the dynamic displacement and vibrating response for the bi-stable mechanism.



(a)



(b)

Figure 1: (a) The schematics of the electro-thermal V-beam actuators and the bi-stable mechanism that are used in the SCB (split crossbar) switch. (b) The two stable positions (State 1 and State 2) of the bi-stable mechanism.

2 DESIGN AND FABRICATION

Since the bi-stable mechanism supplies two stable positions, the movable mirror can retain at stable positions without consuming any electrical power. When the force applied on the center of the curved beam surpasses a critical value, the curved beam will jump to the other stable position (snap-through behavior). According to the theoretical model, the initial shape of the curved beam is designed as the first buckling mode of a straight fixed-fixed beam that is subjected to an axial load. The detailed geometry design of the curved-beam is shown in Table 1 and Equation 1, where $\varpi(x)$ denotes the distance of the beam from the straight line connecting its two boundaries, l is the span, and h is the initial apex height of the beam.

$$\varpi(x) = \frac{h}{2}\left[1 - \cos(2\pi \frac{x}{l})\right] \tag{1}$$

The external force to achieve snap-through action is applied on the middle of the double-curved beam. The displacement of the center of the curved beam between State 1 and State 2 is designed to be 60 μm. Note that the length and the thickness of the curved beams are 3000 μm and 80 μm, respectively.

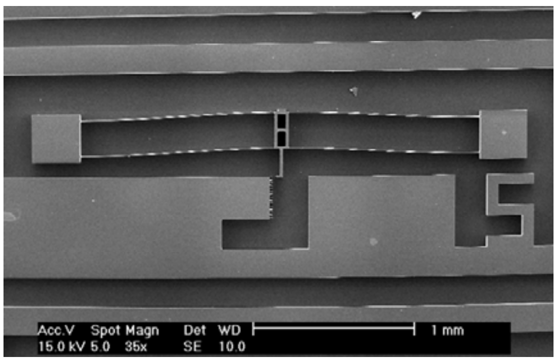


Figure 2: The SEM picture of the device

Table 1: Dimensions of the V-beam actuator and the bi-stable mechanism * the displacement of the bi-stable mechanism is 60 μm (2δ)

V-beam actuator		Bi-stable mechanism	
Beam length	3000 μm	Curved beam length	3000 μm
Beam width	10 μm	Curved beam width	8 μm
Inclined angle	0.6°	Central offset (δ)*	30 μm

The device modeled in this work is realized using a simple SOI process. The SOI-based fabrication process that requires only single photo-mask is shown in Figure 3. Firstly, a thermal oxide layer is grown on the SOI wafer by thermal oxidation. Then a photoresist layer (AZ4620) is spun over the thermal oxide layer and patterned. Using reactive ion etching (RIE), the device pattern is transferred to the thermal oxide layer which will be used as the etching mask for the device structures. Then, deep reactive ion etching (DRIE) by an inductively coupled plasma (ICP) etcher is used to create the device layer. The movable structures are subsequently released by using hydrofluoric (HF) acid to remove the buried oxide layer below the movable structures. Finally, a thin aluminum layer of about 1500Å is deposited (sputtered) on the device for improving the reflectivity of the mirrors.

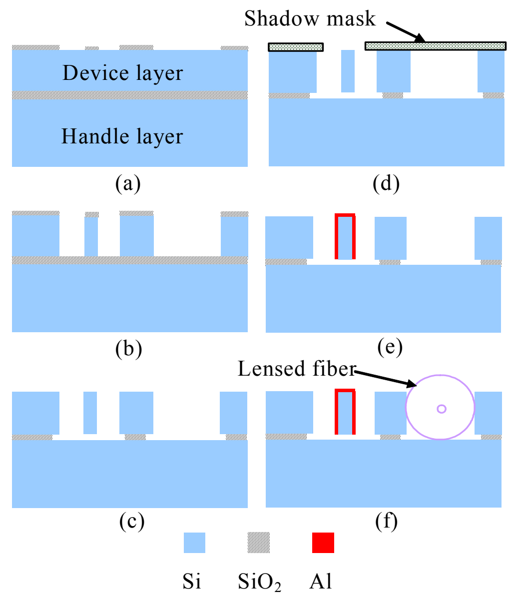


Figure 3: The fabrication process for the SCB switch: (a) Device pattern transferring, (b) deep reactive ion etching, (c) structure released by HF etching, (d) V-beam actuators covered with a shadow mask, (e) Al sputtering, (f) assembling with lensed fibers.

3 ANALYSIS

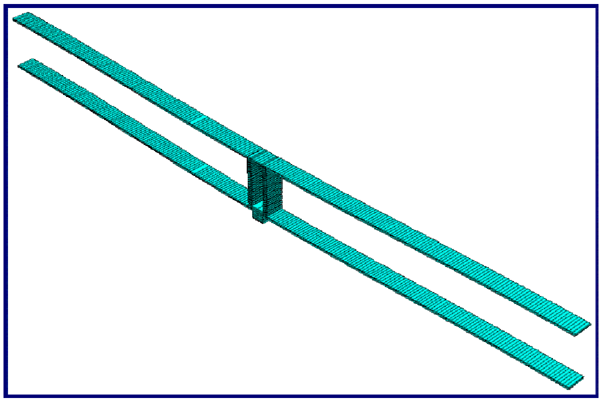
3.1 Static Analysis

Figure 4(a) shows the FEM solid of the bi-stable device. Figure 4(b) is the deformed shape of the structure after snap-through. The results of static analysis are shown in Figure 5. In the forward direction, the pressure is applied from 0 to 0.96 mN. When the applied force is equal to or larger than 0.768 mN, snap-through action occurs. And in the backward direction, the applied force is decreased from 0.96 mN to -0.96 mN when the structure is in State 2. For this case, as the critical force is about -0.24 mN. The complete relationship of deflection vs. applied force, which clearly indicates two stable states, is shown in Figure 5. Note that the snap-through points for forward and backward direction are not symmetric. The critical force in backward direction is much less than that of the forward direction.

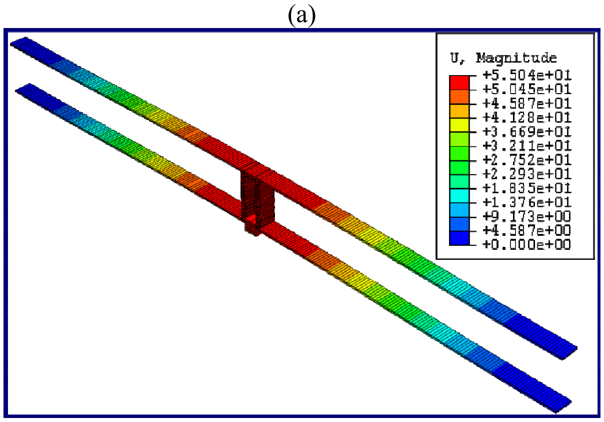
3.2 Transient Analysis

The results of transient analysis are shown in Figures 6. When a force that is equal to or larger than 0.768 mN is applied, "snap-through action" occurs. Also, it is observed that a fast non-linear transition occurs from one stable state to the other during the snap-through action. Then, oscillations arise as the mechanism reaches to the other stable state. The oscillations will decay gradually, as shown in Figure 6(a). The number of the post-snap-through oscillation cycles is determined by the damping effects. As the applied force increases, the time interval (t_i in Figure

6(b)) to achieve the snap-through action becomes shorter. Note that for each case shown in Figure 6(b), the displacement of the central point of the curved-beam will converge to the same final deflection (55.50 μm) as the applied force is removed after the snap-through action.



(a)



(b)

Figure 4: (a) The mesh of the model (b) The deformed shape of the bi-stable mechanism

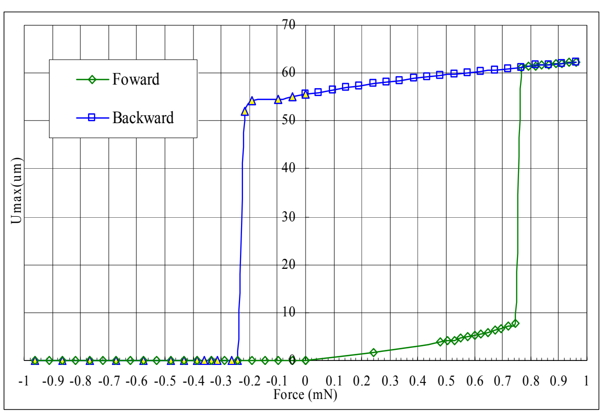
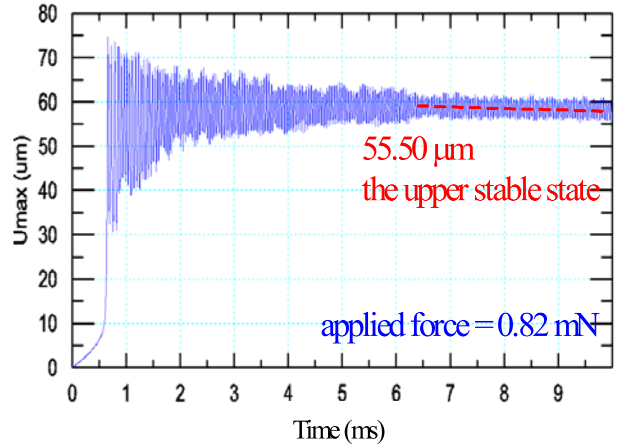
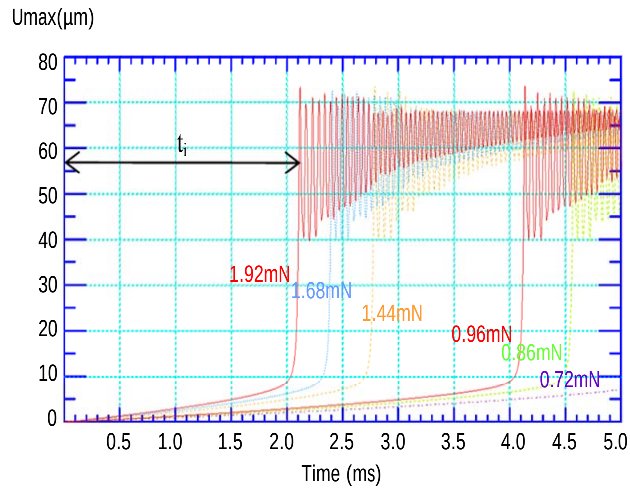


Figure 5: The simulated results for static analysis. Forward direction: The force is applied from 0 to 0.96mN. Backward direction: the applied force is decreased from 0.96 mN to -0.96 mN. U_{max} is the displacement of the central point of the curved-beam



(a)



(b)

Figure 6: The simulated results (displacement v.s. time) of dynamic snap-through motion. U_{max} is the displacement of the central point of the curved-beam. The simulation time step is $5x10^{-6}$ sec.

3.3 Experimental Set Up

An instrument specifically designed to quickly record static force-displacement curve of MEMS flexures can be found in [1][5]. In this work, we use a laser Doppler vibrometer interferometer system, AVID (Advanced Vibrometer Interferometer Device), to measure the dynamic displacement and vibrating response for the bi-stable mechanism, as shown in Figure 6. We put the bi-stable mechanism vertically so that the direction of the laser beam of the AVID system will be in parallel with the direction of curved-beam motion. A probe is used to push the bi-stable mechanism until snap-through occurs, then the AVID system will measure the dynamic behaviors. The experiments are still in progress, and the detailed experimental results will be compared with analytical results and discussed soon.

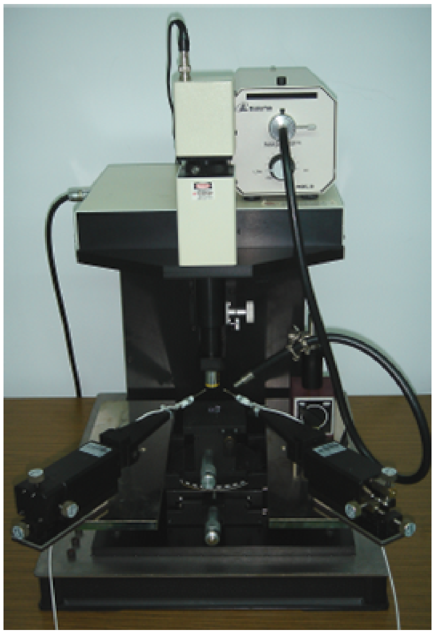


Figure 6: The AVID (Advanced Vibrometer Interferometer Device) system.

4 CONCLUSIONS

In this paper, we present the study of the bi-stable mechanism used for a MEMS optical switch. The major part of the bi-stable mechanism is a pair of constrained double-curved beams. We use a simple SOI process to fabricate the micro bi-stable mechanism. We use the finite element method (FEM) to simulate both the static and transient snap-through behaviors of the bi-stable mechanism. The analysis results show that as the applied force exceeds a critical value, the double-curved beam snap-through from the lower stable state to the upper stable state. The transient analysis results also show that during the snap-through action, a fast non-linear transition occurs from one stable state to the other one. Then, oscillations occur as the mechanism reaches to the other stable state. The oscillations will decay gradually. We set up a laser Doppler vibrometer interferometer system to measure the dynamic displacement of the bi-stable mechanism to observe the transient snap-through behaviors. The simulated results will be compared with the measured results to study the influence of post-snap-through dynamics on the optical performance of the optical switch.

ACKNOWLEDGEMENT

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REFERENCES

[1] Jin Qiu, Jeffrey H. Lang, Alexander H. Slocum, and Alexis C. Weber, "A Bulk-Micromachined Bistable Relay With U-Shaped Thermal Actuators", IEEE/ASME Journal of Microelectromechanical Systems, Vol. 14, No. 5, Oct. 2005.

[2] Daniel L. Wilcox, Larry L. Howell, "Fully Compliant Tensural Bistable Micromechanisms (FTBM)", IEEE/ASME Journal of Microelectromechanical Systems, Vol. 14, No. 6, Dec. 2005.

[3] Michael S. Baker and Larry L. Howell, "On-chip actuation of an in-plane compliant bistable micromechanism", IEEE/ASME Journal of Microelectromechanical Systems, Vol. 11, No. 5, Oct. 2002.

[4] D. A. Horsley, W. O. Davis, K. J. Hogan, M. R. Hart, E. C. Ying, M. Chaparala, B. Behin, M. J. Daneman, and M. H. Kiang, "Optical and Mechanical Performance of a Novel Magnetically Actuated MEMS-Based Optical Switch", IEEE/ASME Journal of Microelectromechanical Systems, Vol. 14, p.274-284, 2005.

[5] J. Qiu, J. Sihler, J. Li, M. Smith, V. Sturgeon, and A. Slocum, "An Instrument to Measure The Stiffness of MEMS Mechanism," in Proc. 10th International Conference on Precision Engineering, Yokohama, Japan, pp. 599-603, July 2001.

[6] Microscopic Laser Doppler Vibrometer, Model: MLDV-M-DP, User Manual, Sunwave Optoelectronics, Inc.