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Nonlinear Spring of Thin Film Torsion Bar with Tension for Micromirror

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1. Introduction

The electrostatic driving is used in many micromirror devices. The electrostatic actuator is preferred especially for achieving the mirror array. Because the actuator consumes little power, the heat generation and the risk of the degradation of the reliability is small. However, there is the difficulty of the electrostatic driving for obtaining the large rotation angle.

When the electrostatic actuators are used, the maximum rotation angle is frequently limited by the pull-in instability of the electrostatic actuators including comb drive actuators [1]. In case of gap-closing actuators, the pull-in instability directly limits the movable range since the pull-in occurs along the driving direction. Electrostatic force must balance with the spring force to maintain stability. However, as the gap decreases, the electrostatic force increases much faster than the linear spring force. At the specific gap, the stability of the equilibrium is broken.

The mechanism of the pull-in has been investigated to obtain the larger displacement. Modifying the shape of electrodes is effective [2]. The shifts of the pull-in point of the parallel-plate electrostatic actuators are observed by attaching series capacitors [3]. Another approach is the use of the nonlinear spring. This includes the strain stiffening of the fixed-fixed beam combining with the piston-only actuator [4,5].

We have introduced the tensile thin film torsion bar to realize low-voltage-driving of the micromirror [6]. The tension is included in the torsion bar, and found to widen the stable range of the mirror rotation. As far as we know, the strong nonlinearity is first observed in the rotational spring [7]. In this study, the nonlinear spring effect is investigated in detail.

2. Micromirror device

We have developed a new rotational spring by replacing previous SiN film [7] with polycrystalline (poly-) Si film. Figure 1 shows the micromirror device using the tensile poly-Si film. The tension is induced by the crystallization of amorphous Si. The thin film torsion bar supports the bulk Si mirror plate. This is the first MEMS device which uses the combination of the tensile poly-Si film and the bulk Si. The vertical comb drive actuator is incorporated. The thin film torsion bar consists of a single doped poly-Si layer. The electrical connections are obtained between the film and c-Si layer. The design dimension of the thin film torsion bar is 200μm x 5μm x 0.3μm. The tensile stress σ_0 is confirmed to be 300-400 MPa. The tension T ($\sigma_0 wt$) is estimated to be 0.45-0.6 mN. This value is quite large compared with the electrostatic driving force of ~7 nN.

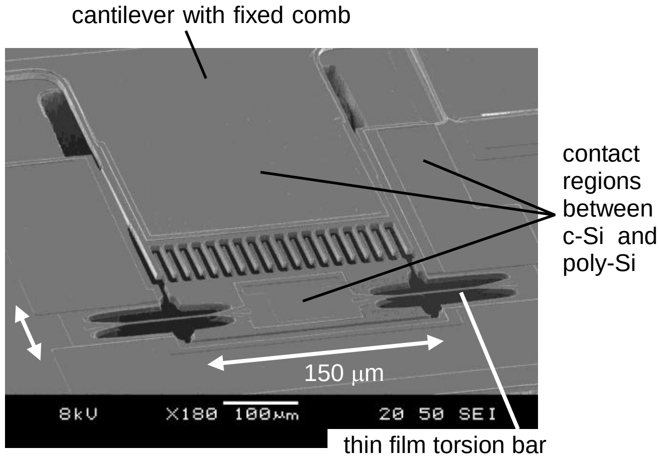

Fig. 1. Micromirror device.

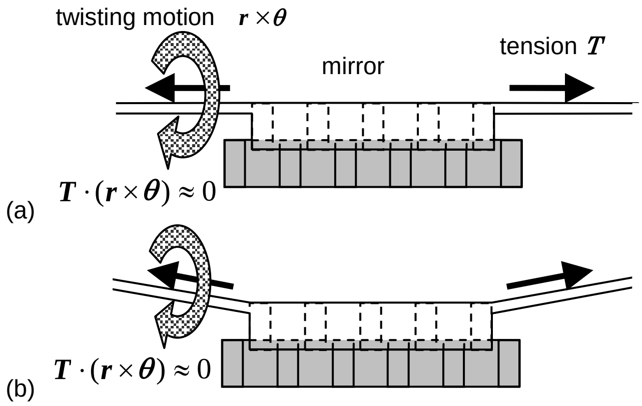

Fig. 2. Schematic drawing for explaining the increase of the rotational spring constant of the thin film torsion bar with its vertical displacement. (a) Condition when the tension is perpendicular to the twisting motion of the torsion bar. (b) Condition when the above perpendicular relation is broken.

3. Results and discussions

Figure 2 shows the schematic drawings for explaining the directional relation between the tension $\boldsymbol{T}$ and the twisting motion $\boldsymbol{r} \times \boldsymbol{\theta}$ of the torsion bar. The electrostatic attraction $\boldsymbol{F}$ generates rotation and vertical displacement of the mirror. The tension works against this vertical displacement. Figure 2(a) is when the tension is perpendicular to the twisting motion of the torsion bar. This configuration corresponds to around 0 driving voltage. The tension has little influence upon the rotational spring constant of the torsion bar. Figure 2(b) is when the above perpendicular relation is broken. This occurs at high driving voltage. Since the twisting motion of the torsion bar proceeds with requiring additional energy which is determined by the inner product of the tension and the twisting motion, the non-linear factor is generated in the spring constant of the torsion bar. The analysis is described previously [7].

The step responses are measured at the driving voltage of 3, 5, and 10 V. Figure 3(a) is the case of rise up. With increasing the rotation angle, the ringing period decreases from 1.7 ms (0.59 kHz) to 0.74 ms (1.4 kHz). Figure 3(b) shows the case of the fall down. The ringing periods are same 1.8 ms (0.56 kHz). Sharp bursts in responses for 10 V in rise up can be attributed to the large nonlinearity. The increased ratio of the spring constant is 1.4/0.56=6.3. This value is significantly large compared to the reported value obtained from the hard-spring effect observed in the normal crystal Si torsion bar (for example, the mirror rotation of 50° generates ~0.63% increase [8]). The nonlinear spring force can balance with the nonlinear electrostatic force with expanding the stable operation region and suppressing the pull-in instability.

Figure 4 shows the resonant frequency as the function of the rotation angle. The data is measured up to 3.4°. Clear sinusoidal ringing curve is observed up to 3.4°. The resonant frequency increases with increasing rotation angle. This relation is well explained by theoretical calculation.

Since the thin film torsion bar has so unique characteristics, the durabilities of the fabricated devices are investigated. After the driving cycles of 10^6, one device shows the decrease in rotation angle from 5.4° to 4.5°. On the other hand, another shows almost no degradation of rotation angle even after 16.8×10^6 driving cycles as shown in Fig. 5. This will relate to the minute grain structure of poly-Si. The long-term durability (at least ~10^7 cycles) will be achieved when the poly-Si grain structure is controlled.

4. Conclusions

The nonlinear nature of the thin film torsion bar is investigated. The resonant frequency clearly increases with the mirror rotation angle generated by the electrostatic attraction force. The fabricated micromirror device has a potential for long-term operation.

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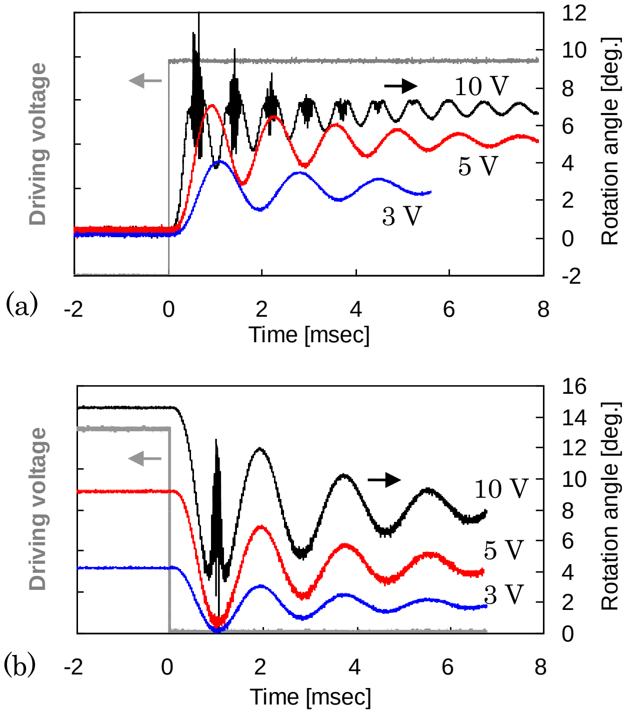

Figure 3: Step responses for different driving voltages of 3, 5, and 10 V. (a) Rise up and (b) fall down steps.

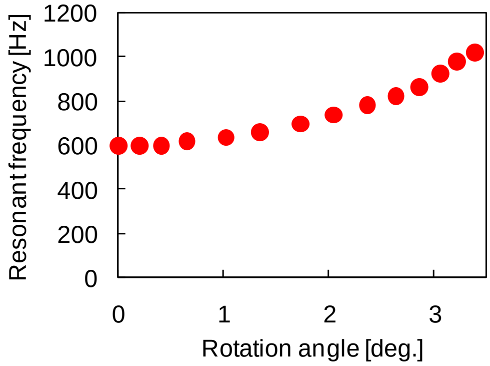

Figure 4: Resonant frequency as a function of the mirror rotation angle.

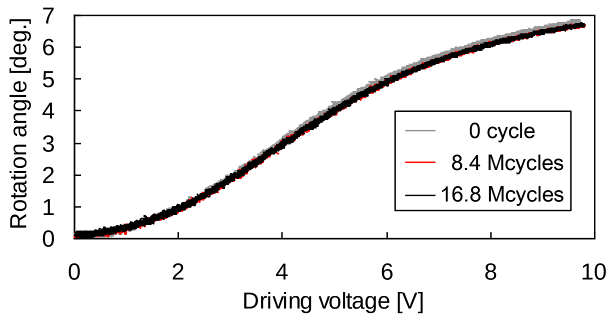

Figure 5: Mirror rotation curves with a parameter of driving cycle.