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A Nickel Micro Switch Operating in a Wide Range of Torsion Angles

Seong-Joong Kahng*, Jae-Hyeok Kim and Young-Min Kim†**

Abstract - We report a nickel optical MEMS switch, being able to rotate through a large angle and to accommodate multiple channels. The proposed optical switch consists of a thin nickel mirror and two torsion springs supporting the mirror. The torsion springs are designed using a finite element method (FEM) such that plastic deformation of the thin nickel is avoided during the large torsion actuation. For switching speed improvement, transient vibration of the released mirror is suppressed by optimizing the mirror design and a fast switching response of 200 μs (pull-down)/300 μs (pull-up) is demonstrated.

Keywords: MEMS, Optical switch, Switching response, Yield strength

1. Introduction

Optical MEMS switches have been of much interest due to their compact size, scalability and low cost. Most reported optical MEMS switches are fabricated using silicon because silicon offers excellent mechanical properties, which are very crucial for mechanical movement of the switching element [1-4]. However, use of silicon often requires wafer bonding [2, 3], in which alignment and high temperature processing are required, resulting in a complicated fabrication process. Another silicon based switch, which is free of wafer bonding, was also proposed, but it would be very vulnerable to friction during actuation [4]. As an alternative, an electroplated metal has been considered because the fabrication process is very simplified, but the low yield strength of the metal has been a concern and has limited its usage to where the movement range is very narrow [5, 6]. Recently, it was reported that the yield strength of a metal can increase in the form of a thin film compared to the bulk value [7, 8]. In this work, we investigate the feasibility of a metal-based optical switch for a wide range of rotational operations without plastic deformation. The switching microstructure is designed using a Finite Element Method (FEM) such that plastic deformation is avoided during a large torsion actuation. Furthermore, the design consideration of a mechanical optical switch for improving the switching response is discussed.

2. Mechanical Properties of Electroplated Thin Nickel

Mechanical properties of an electroplated thin nickel were first measured prior to designing an optical switch because the mechanical properties of thin metal are known to be quite different from those of bulk metal [7-12]. To measure the electroplated nickel density prepared in this work, eight 40 μm-thick samples were fabricated using the current density of 30 mA/cm^2. Based on the measured volume and mass, the nickel density was found to be 8.58 g/cm^3± 5 %, which is slightly lower than the bulk value [9]. Next, Young's modulus of the electroplated thin nickel was estimated by measuring the resonant frequency of a micro cantilever (300 × 600 μm^2).

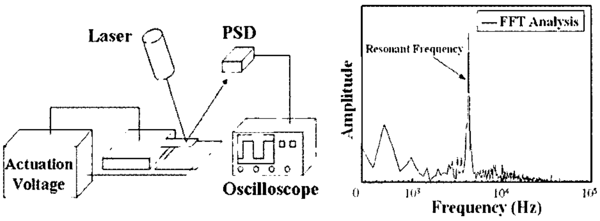

Fig. 1. (a) Experimental setup for Young's modulus measurement (b) A resonant frequency of the micro-cantilever was extracted using transient vibration response.

Fig. 1 shows the experimental setup for the measurement. The resonant frequency of the micro-cantilever was determined using a position sensitive photodetector (PSD), which measured the reflected light from the released cantilever. The measured resonant frequency is compared against simulated values obtained using a FEM modal analysis (ANSYS 8.0). The measured Young's modulus of the nickel film is found to be 150 GPa

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± 4 %, which agrees well with previously published values (Fig. 2) [10-12]. Based on the measured Young's modulus and the density, the yield strength of the nickel microstructure is measured in-situ using the electro-static actuation method published elsewhere [7]. The yield strength of 1 μm thick nickel was measured at 750 MPa, which is much greater than known bulk value (140 MPa). The measured mechanical properties indicate that a nickel in the form of a thin film becomes more elastic and can endure much higher stress than the bulk nickel.

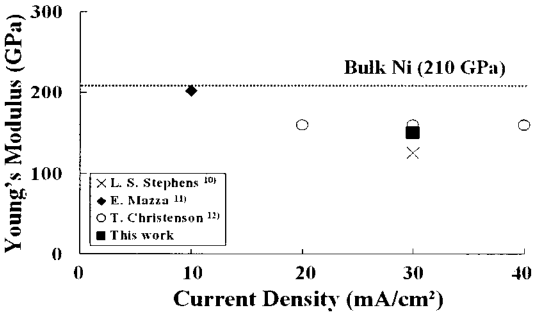


Fig. 2. Comparison of measured Young's modulus of a nickel film against published data.

3. Design and Fabrication

Using the measured mechanical properties of the nickel film, the spring structure is designed for a maximum rotational angle of the micro mirror within the yield strength limit. Fig. 3 indicates the simulated stress developed inside the supporting springs when the mirror is fully actuated to the bottom electrode, which is 75 μm below, using the FEM static analysis (ANSYS 8.0).

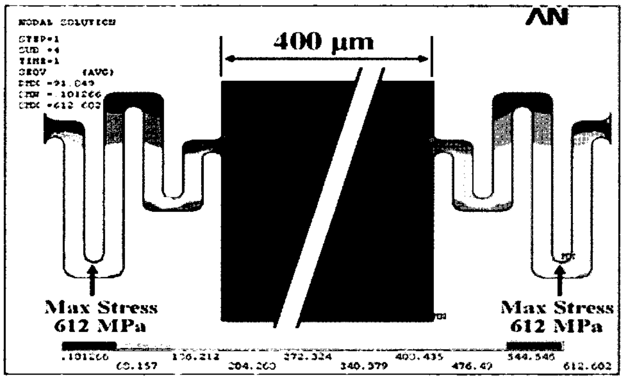
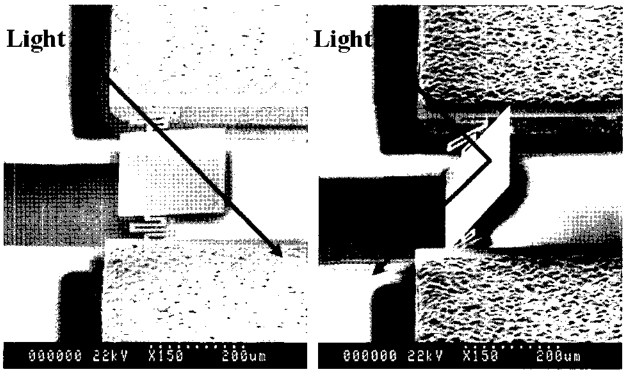


Fig. 3. Simulated stress distribution in the torsion springs when the optical switch is fully actuated. Maximum stress loaded on the torsion springs can be kept below the yield strength of the thin nickel by optimizing the design of the spring.

The mirror geometry is 400 × 220x1.2 μm^3. The width of the spring arm is 10 μm.

The modeling results estimate that the maximum stress inside the springs developed during the actuation becomes 612 MPa, suggesting that the maximum stress can be kept below the yield strength (750 MPa) of the thin nickel by optimizing the design of the spring arms.

With the optimized torsion springs, an optical MEMS switch is fabricated using an electroplating process and a double layer photoresist patterning. More details of the process can be found in our previous work [7]. A complete device is shown in Fig. 4 (a). The gap between the mirror and the bottom electrode is 75 μm. The image of the electro-statically actuated mirror is also shown in Fig. 4 (b). The bottom electrode is coated with a 2 μm thick silicon dioxide film to avoid electrical conduction to the mirror during actuation. During the first electroplating for posts, electroplating conditions, such as a current density or a stirring rate, were optimized to minimize the intrinsic stress of the post. The stress within the posts was found to be built up during the electroplating process and was significant enough to peel off the electroplated post. The surface of the electroplated mirror appeared to be optically very smooth as shown in Fig. 4, and the roughness of the surface was measured to be 10 nm (rms) using a mechanical surface profile meter. Meanwhile, the surface of the post appeared to be rough after a relatively lengthy electroplating process. A 100 nm Au was deposited on the top of the mirror and reflectance of the Au deposited mirror was measured to be 0.85 at 670 nm wavelength. The mirror is actuated at 300 V and touches down to the bottom electrode at an angle of 40° ~ 45°. Using this structure, a 2×2 array was successfully fabricated.

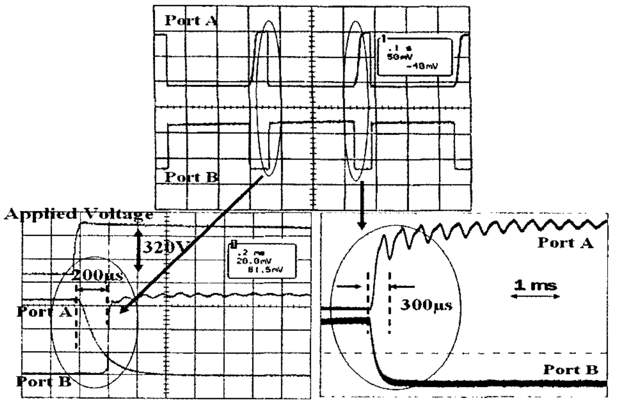


(a) (b)

Fig. 4. SEM images of the fabricated optical switch. (a) prior to actuation and (b) fully actuated optical switch. The mirror is 300x220x0.9 μm^3 on 75 μm high posts.

4. Switching Measurements

Using the fabricated 2x2 array, an optical switching test was performed in the free space using a 670 nm laser. For reliability testing, the optical switch was actuated over 1000 times and plastic deformation of the mirror has not been observed. The mechanical fatigue of the nickel is also of much interest, but it will be considered in a future study. The optical switching response between the two ports was measured as shown in Fig. 5. Prior to the actuation, the light was set to go to port A and then it switched to port B when the mirror was actuated. The delay time was measured to be 200 µs as indicated in Fig. 5(a), which is one of the best performances reported to date [2-4]. The switching response appears to be limited by the releasing action of the mirror, which vibrates in the transient response at the natural frequency of the mirror. The mechanical oscillation of the released mirror is clearly seen in Fig. 5(b).



(a) (b)

Fig. 5. Optical switching response between two ports. Switching responses of (a) actuated and (b) released mirrors are measured at 200 µs and 300 µs, respectively

To improve the switching response, the vibration amplitude of the released mirror should be minimized. According to a damped spring-mass model [13], the transient displacement (x(t)) of the released mirror, shown as equation (1), can be reduced by either decreasing the mass or increasing the damping coefficient. Taking the size of an optical beam into account, the thickness of the mirror should be minimized for less mass instead of reducing the size of the mirror. However, when the thickness of a mirror reduces below 0.8 µm we have found the mirror tends to bend when it touches down, raising a concern about the mechanical integrity of the thin mirror. Further optimization of the mirror design is under investigation to improve the transient response of the released mirror.

$$x(t) \propto e^{-\frac{c}{2m}t}\sin(\omega_d t+\phi) \qquad (1)$$

where c is the damping coefficient, m is the mass and ω_d is the damped natural frequency.

5. Conclusion

A metal optical MEMS switch with large torsion actuation was successfully demonstrated. Thanks to the high yield strength of the thin nickel and optimized spring design, large torsion actuation has been obtained without plastic deformation. Also, it was found that the transient response of the released mirror accounts for a larger fraction of the total response delay than that of the actuated mirror. Through optimization of the mirror design, transient vibration was suppressed and a fast switching response of 200 µs (actuated)/300 µs (released) was achieved.

Acknowledgements

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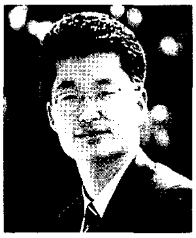

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