2002년도 대한전기학회 하계학술대회 논문집 2002.7.10-12

기판으로부터 수직 반사를 위한 실리콘 마이크로 미러의 설계와 제작

장윤호, 김용권
서울대학교 전기공학부

Design and fabrication of a micromirror using silicon bulk micromachining for out-of-plane right angle reflection

Yun-Ho Jang and Yong-Kweon Kim
School of Electrical Engineering and Computer Science, Seoul National University

Abstract - Silicon bulk micromachined micromirrors are designed and fabricated for out-of-plane right angle reflection. The micromirror is comprised of a mirror plate, springs, magnetic bars and electrodes. Single crystalline silicon is used for a flatness improvement of a mirror plate. Out-of-plane right angle reflection requires a 45 degree operation of the micromirror. The micromirrors are operated by applying a magnetic field, which is generated by a coil located below a substrate. For an individual mirror operation, each mirror is clamped using an electrostatic force against the electromagnetic force. Angular deflections are measured and compared with theoretical data. The micromirror operates up to 45 degree when magnetic field is 4 kA/m which is generated by a 115 mA coil current. Simple addressing is tested, and it is shown that a clamping voltage is less than 5V.

1. Introduction

Various micromirror devices are commercialized or under development for various applications such as display purpose, optical modulation or optical communication. Many micromirrors have adopted aluminum as a mirror surface and photoresist as a sacrificial layer because it is easily combined with conventional circuitry and various designs are possible. But heat effect during the sacrificial layer removing step is a main cause for the aluminum structure deformations. This can affect actuation inaccuracy or optical performance degradations[1]. Therefore single crystalline silicon micromirror has been reported to solve above problems[2,3]. Silicon micromirrors have different structures and different actuation methods according to their applications.

A matter of prime importance in silicon micromirror fabrication is how to get a silicon mirror plate under structure and fabrication restrictions. Deep silicon etch, silicon-glass anodic bonding and thinning process are used in this research for a silicon mirror plate. This approach offers a flat silicon mirror plate and the thickness of a silicon plate can be thinned up to 25㎛.

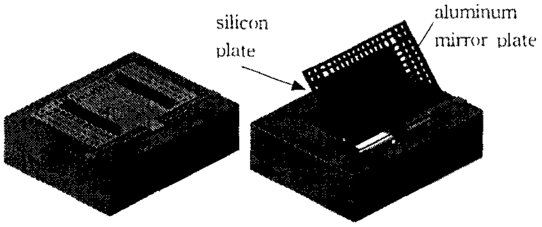
The micromirror should rotate with 45 degrees for out-of-plane right angle reflection. Therefore it is difficult to use stiff materials as a torsional spring. Aluminum is a good candidate for such a large angular motion though its residual stress may also affect operation performances.

2. Design

2.1 Structural design

Figure 1 shows the schematic views of micromirrors at a rest position and an actuation position. The micromirror in a rest position passes a light for the reflection on the backward micromirror. The micromirror in an actuation position reflects an incident light into a vertical direction. For these functionals, the micromirror consists of several parts.

The most important part in a rotational motion is torsional springs which support a mirror plate and offer a restoring force. The spring is a thin and long aluminum rod, which connects a mirror's lower end to substrate. Spring also has a role as a electrical path from outer pads to mirror plates. There exists a piece of silicon under the aluminum mirror plate.



(a) (b)

Figure 1. Schematics of micromirrors at each state (a) at a rest position (b) at an actuation position

Aluminum grids are formed on either sides of the mirror plate for addressable operation. The mirror plate, grids and springs are fabricated using aluminum at the same time. A soft magnetic material, nickel, is on the mirror plate for an electromagnetic actuation.

2.2 Torsional spring design

Aluminum is a ductile material and it has a low yield strength (170MPa in a bulk specimen). Torsional spring experiences stress during electromagnetic actuation. It is required to analyze the spring stress in order that an elastic operation of a spring is guaranteed.

$$\tau_{\max} = \frac{c_1 c_2 G t_s \phi}{l_s} < \tau_{\max,Al} \qquad \text{Eq. (1)}$$

Equation (1) indicates that the stress is proportional to a thickness, an angular deflection and the inverse of a length. The maximum stress in operation must be less than a yield strength for confident operation. The maximum stress with 45 degrees is calculated using reported yield strength and two kinds of criteria - Mises criterion and maximum shear stress criterion.

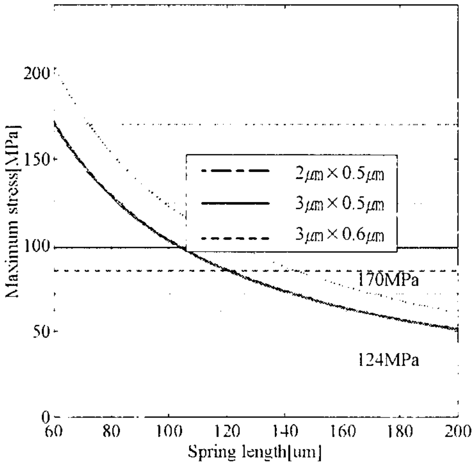


Figure 2. The maximum stress according to spring dimensions. Three kinds of cross-sectional dimensions are considered as the length is increased from 60μm to 200μm. Horizontal lines shows the reported yield strength without or with criteria. Violet line is for a bulk specimen and magenta line for a thin film specimen.

As shown in Figure 2, the maximum stress decrease as the spring length increases, therefore a proper length can be chosen under given cross sectional dimensions. If a spring width is 3μm and a thickness is 0.5μm, 165μm long spring can satisfy all criteria.

3. Fabrication

Deep silicon etch and silicon-glass bonding process is utilized for a single crystalline silicon mirror plate. Figure 3 shows a simplified fabrication process.

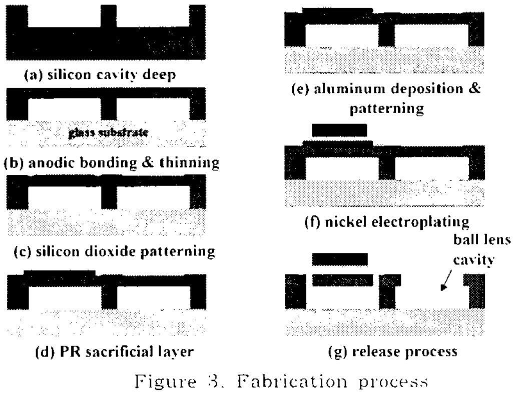
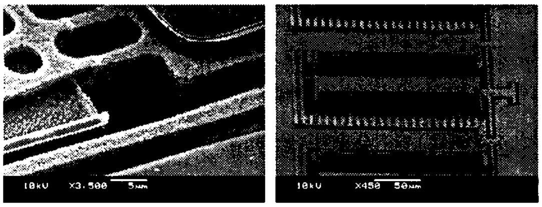


Figure 3. Fabrication process

The first step is to form cavities on the silicon surface using deep silicon etch. Cavities is formed under the mirror plate to release a silicon mass from the substrate. After the silicon wafer is bonded to a glass wafer, the silicon side is thinned and polished for the remaining steps. The thinner silicon mass is preferable for proper actuation. But a trapped air inside a cavity can cause a damage to the silicon diaphragm if silicon diaphragm is too thin. We find that 25μm thick silicon diaphragm is free from a damage. A thin photoresist is used as a sacrificial layer to release grid structures. Aluminum deposition and patterning is followed on the basis of a calculated spring thickness. After nickel electroplating on the mirror plate, the final step is release process using silicon deep etch, plasma ashing and silicon isotropic etch. Silicon isotropic etch works every exposed silicon surface so that unetched regions during silicon deep etch can be removed easily.

4. Results

4.1 Fabrication results



(a) (b)

Figure 4. Micro photographs from the fabricated sample. (a) magnified view after silicon deep etch and plasma ashing. Remaining silicon mass under aluminum grids and a spring is shown. (b) Using silicon isotropic etch, a mirror plate is successfully released from the substrate. Grid structures are a little deformed because of the heat effect inside the plasma asher.

Figure 4 shows fabricated samples. Silicon deep etch removes exposed silicon surface over the sample. So silicon mass under aluminum grids and springs is remained. Silicon isotropic etch is required for the perfect release of a mirror plate. Grid structures have narrow width so that short ashing time is sufficient to remove a sacrificial layer.

4.2 Magnetic actuation

Magnetic anisotropy is induced in the nickel by applying magnetic field after fabrication. In other words, nickel tends to align along external field. This property makes the mirror to rotate up when magnetic field is applied. Three different torques - torque by torsional springs, torque by anisotropy, torque by external field - appear during magnetic operation when the magnetic material is combined with torsional springs like this device [4]. When three torques are in equilibrium condition, the mirror stops to rotate.

Figure 5 shows how the angular deflection changes according to magnetic field. The required magnetic field is about 4 kA/m for 45 degrees. Among assumed four coercivities, measured data is agreed well in case of H_c = 2 kA/m. The micromirror used in this experiment has torsional springs with dimensions 3×0.8×165 ㎛^{3}. Maximum stress around 45 degrees is calculated about 98 MPa, which is lower than Mises criterion calculated with 170 MPa but it cannot satisfy other criteria. In repetitive actuations with 45 degrees, restoring motion comes to be slow, which implies that maximum stress can be over yield strength.

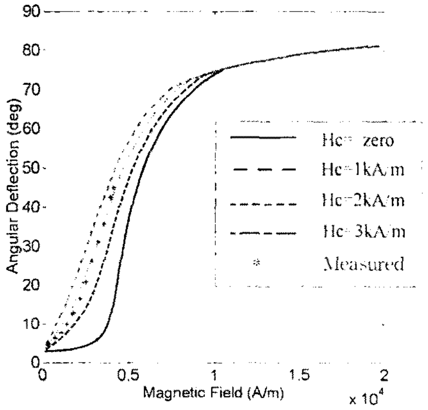


Figure 5. Magnetic operation. Four coercivities are considered for angular deflection calculations using MATLAB^{TM}.

4.3 Addressing test

Addressing is accomplished by applying voltage difference between grid and substrate. Electrostatic torque by clamping voltage should be greater than magnetic torque for addressable operation. Electrostatic torque can be expressed by

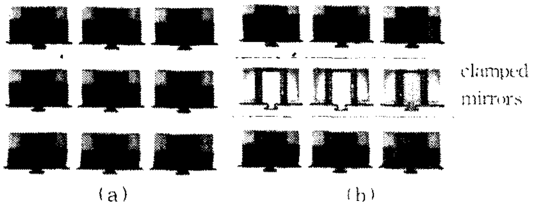
$$T_e = \frac{1}{4}\varepsilon\frac{1}{g^2}V_e^2 A \qquad \text{Eq.(2)}$$

where g is a gap between grid and substrate. A is constant determined by grid area and etch hole distribution. Also magnetic torque can be expressed by

$$T_m = MV_{mag}H \qquad \text{Eq.(3)}$$

where M is saturated magnetization, V_{mag} is total volume of nickel and H is magnetic field.

Using equation (2),(3), the calculated clamping voltage is around 1~2V according to the gap.



(a) (b)

Figure 6. Addressing test. (a) nine micromirrors are actuated (b) three middle micromirrors are clamped by applying 5V to the grids.

Clamping voltage is determined experimently using line actuated micromirrors (Figure 6). Middle line micromirrors are clamped using 5V and the clamping voltages for other micromirrors are also below 5V. Experimental results are resonable judging from calculated values. Some errors between the experiment and a theory may be resulted from the irregular gaps between micromirrors.

5. Conclusion

Silicon micromirrors are designed and fabricated using silicon deep etch and silicon-glass bonding for out-of-plane right angle reflection. The silicon plate is thinned up to 25㎛ and has no problems at the remaining steps. Release process successfully detached the mirror plate from the substrate. About 4 kA/m magnetic field is required for 45 degree actuation and 5 V clamping voltage is required for addressable operation. The maximum stress of fabricated aluminum torsional springs is calculated to be 98 MPa. In repetitive actuations with 45 degrees, the memory effect is shown, which implies that the yield strength is less than Mises criteria of 170 MPa. Silicon micromirrors can be used as a out-of-plane reflector array with one incident light, which can improve an optical property among vertically emitted light array.

Acknowledgement

This research was supported by the Ministry of Commerce, Industry and Energy and partly supported by Brain Korea 21 project

[Reference]

[1] Yun-Ho Jang, Yong-Kweon Kim, " Design and fabrication of a micro mirror array for right angle reflection", The proceedings of Optical MEMS 2001, pp. 93-94, 2001

[2] Chang-Hyeon Ji, Yong-Kweon Kim, and Gyo-Bum Chung, "Design and fabrication of electromagnetic micromirror with bulk silicon mirror and aluminum spring", Japan Journal of Applied Physics, Vol. 39, Part 1, No. 12B, pp. 7138-7141, 2000

[3] R. A. Miller, G. W. Burr, Y. C. Tai, D. Psaltis, C. M. Ho and R. R. Katti, Electromagnetic MEMS Scanning Mirrors For Holographic Data Storage , Technical Digest, Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 3-6, 1996, pp. 183-186

[4] J. W. Judy, R. S. Muller, "Magnetically Actuated, Addressable Microstructures" , Journal of MEMS, Vol. 6, No. 3, pp. 249-256, 1997