A Two-Step Micromirror for Low Voltage Operation

Yong-Ha Hwang*, Seungoh Han*, Byung-Kab Lee*, Jae-Soon Kim and James Jungho Pak†**

Abstract - In order for the application of the in-vivo endoscopic biopsy, a micromirror which can be driven at a low voltage is required. In this paper, a two-step micromirror composed of bottom electrodes, moving plate and top mirror plate is proposed. Because an electrical wiring of two plates are separated, they can be actuated separately. Therefore, an intermediate moving plate plays an important role in reducing the driving voltage in half. The designed device was fabricated by the surface micromachining. Maximum rotation angle of 6.3° was obtained by applying DC 48V, while a conventional one-step mirror pulled down at DC 120V. The designed structure can be used in microphotonic applications requiring low driving voltage.

Keywords: two-step micromirror, moving plate, surface micromachining technology, low driving voltage

1. Introduction

In order to offer the detailed information regarding the affected area, the in-vivo endoscopic biopsy using a confocal microscope has been proposed[1]. Compared with conventional microscope, the confocal microscope minimizes the spot size of illumination light inside a sample by using a source pinhole and detects only the light which is re-radiated from that focusing point by using a detecting pinhole. For this reason, the confocal microscope improves the radial resolution of the system and also has an advantage of acquiring 3-D image by improving the optical sectioning ability. In the confocal microscope system, micromirrors play an important role of scanning pinholes.

For in-vivo application, the most important part of the confocal microscope is the image scanner, which should work at low voltage and be microminiaturized. Several research groups have proposed the following methods; optical coherence tomography using the galvanometric mirrors[1], gradient index-lens systems[2], moving fiber using piezoelectric actuators[3], two axes micro scanning mirrors[4], etc. Nevertheless, these are not good enough in the size of the devices, driving voltage, and speed of detecting images. An ordinary confocal microscope system using the DMD(Digital Micromirror Device) from Texas Instruments has been commercialized[5], but it is not suitable for in-vivo applications.

In this paper, a novel electrostatic two-step micromirror is presented. The designed two-step micromirror consists of bottom electrodes fixed on a substrate, torsional moving plate supported by posts and a mirror plate as the reflectors. The rotation angle of the moving plate is limited by the gap between the substrate and the top mirror. Both torsional moving plate and mirror plate are designed to be able to move separately, and the total torsion angle is decided by the sum of them. By having the intermediate moving plate, the distance between the plates is reduced into half, and hence the voltage to drive the moving plate and the mirror plate can be reduced. Therefore the two-step micromirror can rotate to the same extent as the conventional micromirror at half the driving voltage.

2. Design

2.1 Operation principle [6-9]

Fig. 1 shows a schematic view of a micromirror including mirror plate, torsional beams, and driving electrodes. The capacitance in the incremental section is given as

$$\Delta C = \frac{\varepsilon L \Delta x}{g - x\tan\theta} \tag{1}$$

where ε is the permittivity of the space between the mirror plate and underlying electrode and $x\tan\theta$ is the

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Received September 30, 2005 ; Accepted November 8, 2005

amount of gap reduction of an incremental Δx, which is a function of x. When the driving voltage with the magnitude of V is applied between the mirror plate and underlying electrode, the electrostatic force is generated as follows.

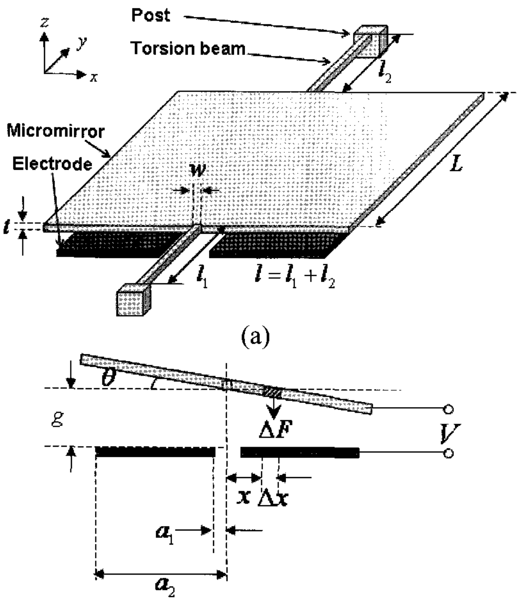

Fig. 1 Schematic view of the torsional micromirror; (a) 3D diagram, (b) cross section of the tilted micromirror.

$$\Delta F_e = \frac{\partial}{\partial z}\left(\frac{1}{2}\Delta C V^2\right) = \frac{\varepsilon\,\Delta x\, L\, V^2}{2}\frac{1}{(g - x\tan\theta)^2} \tag{2}$$

Thus, the total electrostatic torque due to the electrostatic force can be obtained by integrating the contributions of all plate elements as shown in the following equation.

$$\begin{aligned} T_e &= \int_{a_1}^{a_2} \Delta F_e\, x\cos\theta \\ &= \frac{\varepsilon V^2 L\cos\theta}{2\tan^2\theta}\left[\frac{a_2\tan\theta}{g - a_2\tan\theta}\right. \\ &\quad \left. - \frac{a_1\tan\theta}{g - a_1\tan\theta} + \ln\left(\frac{g - a_2\tan\theta}{g - a_1\tan\theta}\right)\right] \end{aligned} \tag{3}$$

The rotation angle of the mirror plate is determined by the balancing the above electrostatic torque and mechanical torque given as

$$T_m = \frac{2G\theta}{l}\, t^3 w\left[\frac{1}{3} - 0.21\frac{t}{w}\left(1 - \frac{t^4}{12w^4}\right)\right] \tag{4}$$

where $G = E/[2(1+\upsilon)]$ and E and υ are Young's modulus and Poisson's ratio, respectively. When the driving voltage is applied, a stable condition, where the electrostatic torque is equal to the mechanical torque, is established and hence the rotational angle is determined. As the driving voltage increases, the electrostatic torque becomes larger than the mechanical torque. Therefore, the plate starts to pull down until one edge reaches the substrate surface.

As shown in these equations, the driving voltage and the square root of the electrostatic force is proportioned to the dimension of the gap, g. From a structural point of view, the driving voltage can be reduced by decreasing the gap size between the plates; nevertheless, the maximum rotational angle does not have to be limited by the modification. Hence, an introduction of the intermediate movable mirror plate, where the driving voltage can be applied in distinction from bottom electrode and mirror plate, is necessary.

2.2 Design and simulation

Fig. 2 shows a perspective view of the designed device. The structure is mainly fabricated with the doped poly-silicon by the surface micromachining technology. The area of the one bottom electrode is 92 x 37um^2. The moving plate is made of silicon nitride, poly-silicon and silicon nitride layers, and supported by two posts which have a height of 3.6um. The length of each support beam is 45um, and the width of them is 3um. The mirror plate has one post, which has a height of 3.3um and is connected to the support beams of the moving plate. This post also functions as the link of two support beams of the moving plate. The mirror plate and the moving plate occupy an area of 95 x 95um^2.

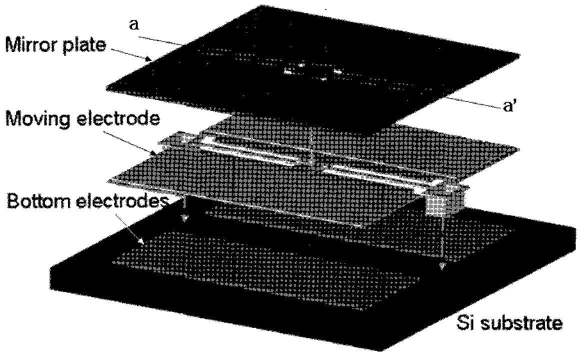

Fig. 2 Conceptual schematic of the two-step micromirror.

In order to drive the two-step micromirror, two channel driving voltages have to be supplied. As illustrated in Fig. 3, each electrode of the bottom, the middle and the top plate is electrically isolated. A driving sequence of this mirror is as follows. First, the moving plate and the mirror plate are grounded(V2, V3). When driving voltage is applied on the bottom electrode(V1), the moving plate is pulled down. Because the top mirror has the post is fixed on the moving plate's beams, it is also rotated with same rotation angle of the moving plate. But the height between the moving plate and the mirror plate is not changed. Next, the other driving voltage(V3) is applied to the mirror plate while maintaining the V1 and V2 voltage, the pull-in voltage and the ground respectively, and then the pull-in of the mirror plate occurs. After all, the two-step mirror is actuated at half the driving voltage of conventional one-step micromirrors.

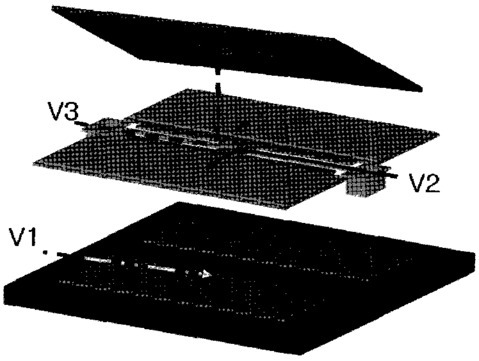

Fig. 3 Electrical connections of the two step micromirror.

The balance between the torque of electrostatic force and the torsional stiffness of the mechanical torsional beam determines the rotation angle of the micromirror. By using CoventorWare, which is a commercial simulation tool for MEMS, the designed micromirror's actuation was estimated. As shown in Fig. 4, the pull-in voltage of the two-step micromirror was predicted to be 34V. It was compared to a conventional one-step micromirror which is merely composed of the bottom electrode and the mirror plate with a pull-in voltage of 69V.

3. Fabrication process

The designed two-step micromirror was fabricated by surface micromachining technology. Fig. 5 illustrates the fabrication process by means of a series of cross-section diagrams. The fabrication process began with deposition 0.25um silicon nitride layer for electrical isolation. Then 0.5um poly-silicon for bottom electrodes was deposited and Patterned[see Fig. 5(a)].

After 3.6um TEOS(tetraethylorthosilicate) was deposited as the sacrificial layer, the holes were etched to define the opening of posts of the moving plate[see Fig. 5(b)]. The moving plate, which consists of 0.15um silicon nitride, 0.85um poly-silicon, and 0.15um silicon nitride, were formed[see Fig. 5(c)]. Two silicon nitride layers prevent poly-silicon plates from shorting electrically, and the sandwich structure prevent the moving plate from deformation due to the residual stress.

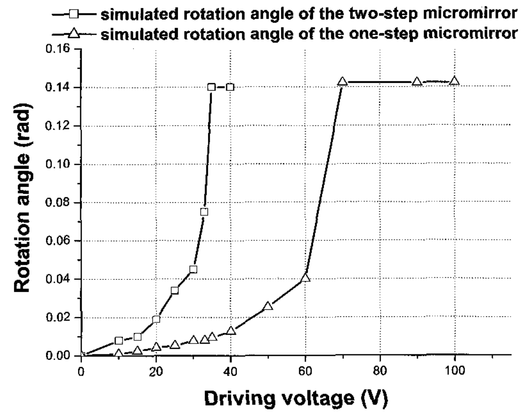

Fig. 4 Simulation results of the two-step micromirror and the one-step micromirror.

After 3.3um second TEOS layer was deposited and defined[see Fig. 5(d)], 0.1um silicon nitride post was deposited to connect two support beams of the moving plate. Therefore these beams were isolated electrically, but also connected mechanically. Next, in order to link the mirror plate with one moving plate's post electrically, 0.25um silicon nitride was partially etched[see Fig. 5(e)]. Then through this hole it was possible to electrically connect only one support beam of the moving plate with the mirror plate.

0.7um poly-silicon was deposited and patterned, and then the top mirror plate was formed[see Fig. 5(f)]. By this novel design, one post of the moving plate is connected to V2 route, and the other is connected to V3 route so that the mirror plate can be separately driven. In order for connecting poly-silicon pads to a dual inline package chip using gold ball bonding method, chrome/gold pads were deposited and defined[10]. Then a photoresist passivation layer(AZ4620) was patterned for protecting the metal pads from being attacked by etchant of the sacrificial layer[11].

Finally, TEOS which was employed as the sacrificial layer was etched by a 49.9% HF(hydrogen fluoride) solution at room temperature during 8 minutes, so that the structure could be released[see Fig. 5(g)]. In order to prevent the stiction of the plates, p-dichlorobenzene sublimation drying method was used[12]. Fig. 6 shows the fabricated two-step micromirror, the conventional one-step micromirror and Au wire bonded pads for electrical connecting with power source.

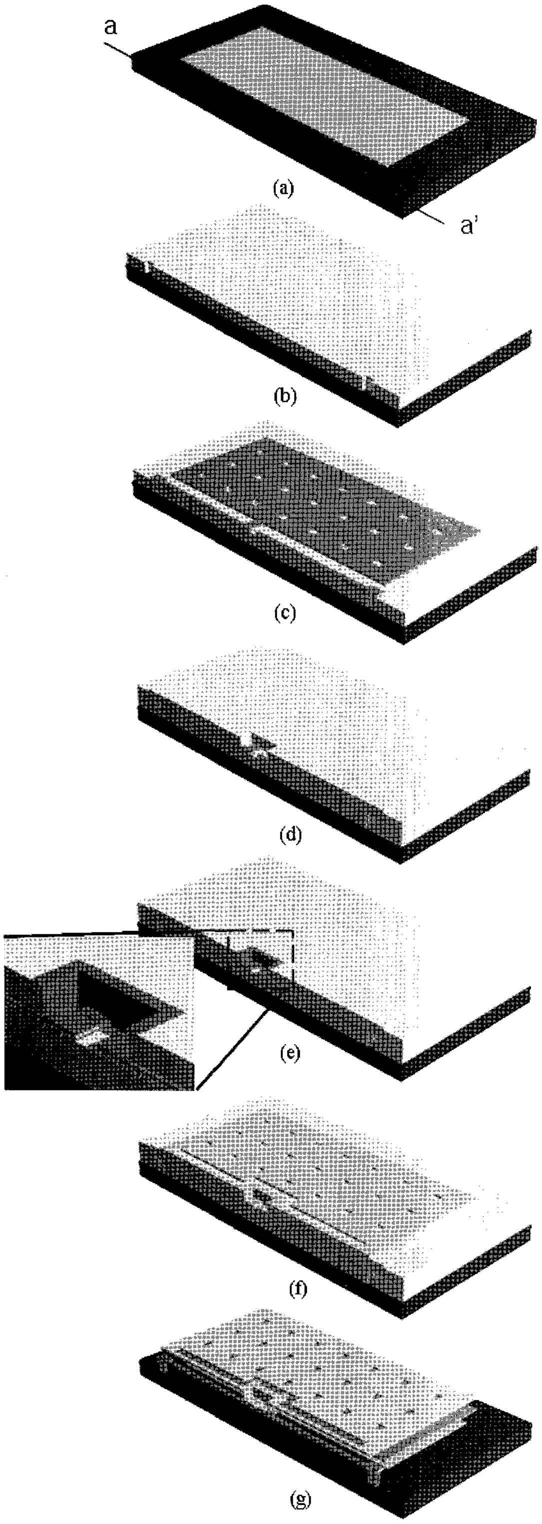

Fig. 5 Fabrication process along aa' in Fig. 2; (a) bottom electrodes formation, (b) 1st sacrificial layer deposition and moving plate's posts formation, (c) moving plate formation, (d) 2nd sacrificial layer deposition and mirror plate's post formation, (e) silicon nitride isolation post formation, (f) mirror plate formation, (g) sacrificial layers removal.

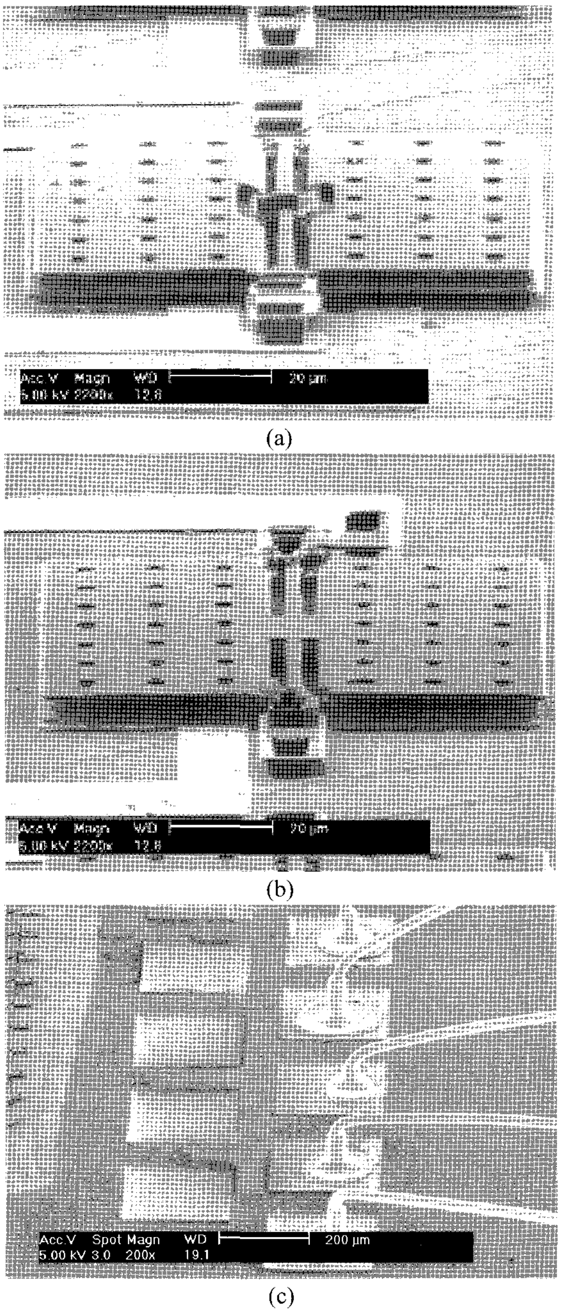

Fig. 6 SEM pictures of the micromirrors; (a) the one-step micromirror, (b) the two-step micromirror, (c) the Au wire ball bonded Cr/Au pads.

4. Actuation

To compare the reduced driving voltage of the two-step micromirror, the conventional one-step micromirror was fabricated at same time. The latter has the same construction except for having no moving plate of the former. The motional characteristics of the micromirrors were measured by noncontact laser profiler micrometer.

The moment the DC driving voltages of the moving plate and the mirror plate were supplied individually, the displacement of them was measured.

Fig. 7 shows the experimental result of the two-step micromirrors. The fabricated two-step micromirror pulled down to the substrate at 48V. On the contrary, the downward threshold voltage of the one-step micromirror was 120V. The displacement of vertical direction is 6.800um, calculated rotation angle in terms of degree is 6.296°. It was confirmed that the pull-in voltage of the proposed micromirror was reduced by half or less than the driving voltage of conventional micromirrors. However, these experimental results are higher than those of the simulation. These differences might be attributed to errors in fabrication such as 1) inaccurate deposition thickness of each layer, 2) irregular mechanical properties of employed materials, and 3) vertical direction deformation of the whole mirror structure while driving. These problems can be improved by precise control of the fabrication factors and the simulation parameters revised virtually.

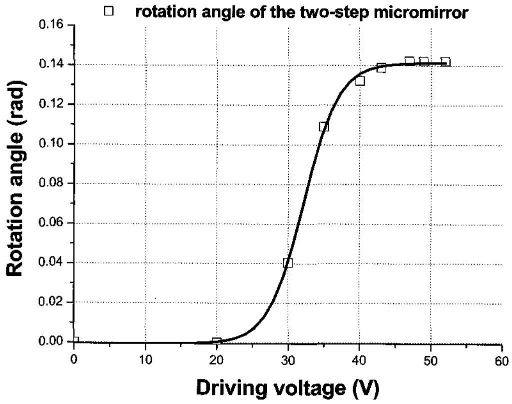

Fig. 7 Experimental results of the two-step micromirror and the one-step micromirror.

5. Conclusion

We have designed, fabricated and tested the two-step micromirror. It has the novel structure, that is, the intermediate moving plate. The fabricated device has successfully demonstrated the reduction of the driving voltage. The proposed micromirror can be used in low voltage optical applications such as in-vivo endoscopic biopsy.

Acknowledgements

This work was supported by grant No. R01-2003-000-10740-0 from the Basic Research Program of the Korea Science & Engineering Foundation.

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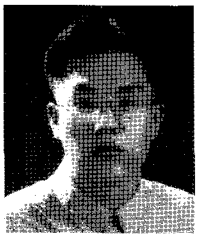

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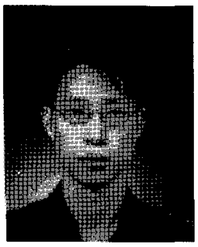

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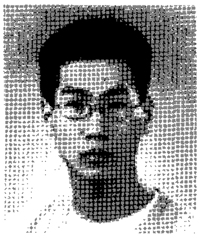

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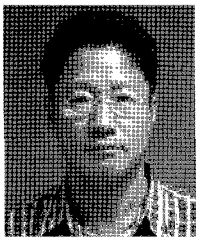

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