Uniformity Improvement of Micromirror Array for Reliable Working Performance as an Optical Modulator in the Maskless Photolithography System

Kook-Nyung Lee and Yong-Kweon Kim

Abstract — **We considered the uniformity of fabricated micromirror arrays by characterizing the fabrication process and calculating the appropriate driving voltages of micromirrors used as virtual photomask in maskless photolithography. The uniformity of the micromirror array in terms of driving voltage and optical characteristics is adversely affected by factors, such as the air gap between the bottom electrode and the mirror plate, the spring shape and the deformation of the mirror plate or torsion spring. The thickness deviation of the photoresist sacrificial layer, the misalignment between mirror plate and bottom electrode, the aluminum deposition condition used to produce the spring and the mirror plate, and initial mirror deflection were identified as key factors. Their importance lies in the fact that they are related to air gap deviations under the mirror plate, asymmetric driving voltages in left and right mirror directions, and the deformation of the Al spring or mirror plate after removal of the sacrificial layer. The plasma ashing conditions used for removing the sacrificial layer also contributed to the deformation of the mirror plate and spring. Driving voltages were calculated for the pixel operation of the micromirror array, and the non-uniform characteristics of fabricated micromirrors were taken into consideration to improve driving performance reliability.**

Index Terms— **Micromirror array, uniformity improvement, mirror operation, maskless photolithography applications.**

I. INTRODUCTION

Micromirror devices have various applications in optical devices, such as projection display systems [1-3], and optical scanners and switch in optical communication systems[4,5]. More recently, micromirrors have found applications in the biotechnology area. The micromirror array is used as a virtual photomask in maskless photolithography system to synthesize DNA strands using a photochemical method for DNA chip fabrication [6-8].

Micromirror arrays can generate random pattern array like card-section. It could play a role as a virtual photomask for selective surface modification by immobilizing biomolecules on the chip target surface area. Maskless photolithography using a micromirror array has the merits as photomasks and mask alignment are not required. Instead of using a photomask, a simple driving circuit is used for mirror operations.

The requirements of micromirrors for maskless photolithography devices include good reflectivity in the 365 nm UV region, uniform properties with respect to the driving characteristics and the optical reflectance of mirror plate, and a relatively large deflection angle to avoid interference between reflected lights by neighboring mirrors. High speed response time in dynamic characteristics of micromirror is not critical in photochemistry applications because the required exposure time required for chemical reaction is relatively much longer than that required for display devices.

In this paper, several factors, which cause spring and mirror plate deformation and driving voltage differences, are considered with the aim of improving the driving

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School of Electrical Engineering & Computer Science, Seoul National University, San 56-1, Shinlim-dong, Kwanak-gu, Seoul, 151-742, Korea
(e-mail : plummy@chollian.net) Tel : +2-888-5027, Fax : +2-873-9953

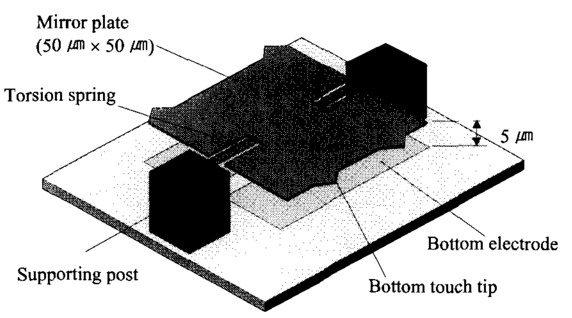


Fig. 1. Schematic view of micromirror.

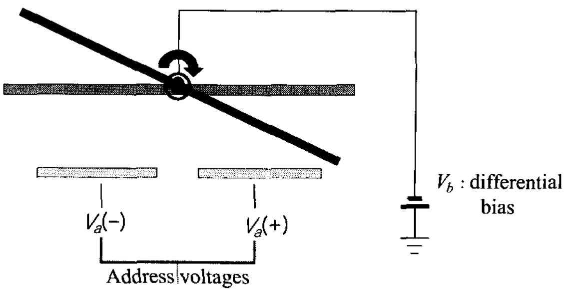


Fig. 2. Micromirror operation in digital mode with bias V_b.

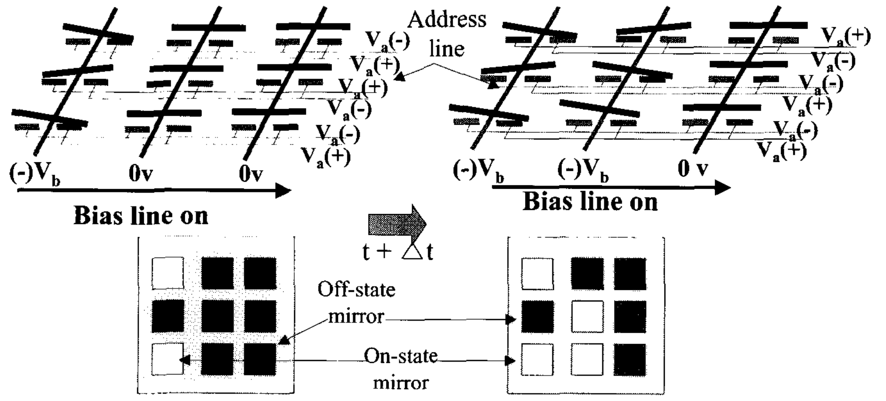


Fig. 3. Pixel operation scheme of the micromirror array. We use a right deflected mirror for on-state, and the left deflected and flat state mirrors for 'off'. The deflected mirror keeps its state if the bias is on, regardless of the variation of the low address voltage.

performance and the reflective characteristics of these mirrors for use as virtual photomasks in maskless photolithography systems as used for photochemical surface modification. The driving voltage is calculated by considering the uniformity of the micromirror array.

II. MICROMIRROR ARCHITECTURE AND OPERATING PRINCIPLE

Micromirrors are fabricated by aluminum surface micromachining, which is a well-known micromachining technology [9-13], moreover, Al mirror plate has good UV reflectance[11]. The micromirror consists of two bottom electrodes, a mirror plate, a torsion spring and a mirror plate supporting post. Two bottom electrodes are position to facilitate mirror tilting, like a sea-saw. The mirror plate is fabricated to maximize light reflectance and the electrodes are used to apply electrostatically generated torque. The torsion springs are used to mechanically counter the electrostatically generated torque. The fabricated micromirror has a tilting angle of approximately 10degree, which corresponds to a relatively large deflection. The mirror plate is 50㎛ in width and 1㎛ in thickness. Micromirror architecture is shown in figure 1.

Mirror deflection is obtained by applying a driving voltage above the downward threshold voltage on bottom electrode, which is called the address electrode. To achieve low voltage operation, the mirror plate and the bottom electrodes are connected to a negative bias voltage V_b, called the differential bias voltage. The voltage V_b produces no torque at a zero deflection, unless there is a difference in the voltage on the two address electrodes. This differential bias generates a torque, which lowers the address voltage requirements. Figure 2 shows the mirror operation in digital mode with bias V_b

Micromirrors are arrayed 8x8, 2-dimensionally. The electrodes of micromirrors in the same row and column lines are interconnected for connection to the external mirror driving circuits. The bias lines are connected to the mirror plates through the torsion spring in the column and the address lines are connected to the bottom electrodes of the micromirrors in rows. It is necessary to use a bias driving scheme for pixel operation of micromirror array, as shown in the figure 2 and figure 3. Mirrors are turned on, when their address and bias lines have on input signal simultaneously. The mirrors keep their on- or off-state regardless of the address voltage while the bias voltage is applied. The bias driving scheme has merit because the pixel operation is possible with a relatively low addressing voltage. However, non-uniformity in the threshold voltage between pixel mirrors can cause unexpected mirror operation.

III. CALCULATION OF THRESHOLD VOLTAGE OF MICROMIRROR & NON-UNIFORM FACTORS

The downward threshold voltage of a micromirror depends on the air gap of the mirror plate, the size of the mirror plate and the dimensions of the torsion spring, such as its length, width and thickness. The static characteristics of the micromirror were obtained using the net torque equation, $\tau_e - \tau_m$ applied to a torsion spring in the equilibrium state, where τ_e is the attractive electric torque and τ_m is the restoring mechanical torque exerted by the torsion spring.

$$\tau_e(\alpha,\beta)=\frac{1}{8}\varepsilon_o\frac{V_a^2L^3}{Z_o^2}g(\alpha,\beta) \tag{1}$$

$$\tau_m=-\frac{\theta}{c}=-\alpha\left(\frac{2Z_o}{cL}\right) \tag{2}$$

$$\tau_e-\tau_m=0 \tag{3}$$

$$\left(\frac{V_a}{V_o}\right)^2 g(\alpha,\beta)-\alpha=0 \tag{4}$$

where, c is the torsion spring constant determined by spring dimension and

$\alpha=\frac{Z_T}{Z_o}$ is the normalized deflection angle,

$\beta=\frac{L'}{L}$ is the loading factor,

$$g(\alpha,\beta)=\left\{\frac{\frac{\alpha\beta}{1-\alpha\beta}+\ln(1-\alpha\beta)}{\alpha^2}\right\}, \text{ and}$$

$$V_o\equiv\left(\frac{32Z_o^3}{\varepsilon_o L^4 c}\right)^{\frac{1}{2}}$$

are sensitivity parameters.

The micromirror architecture shows the parameters used for calculating the static characteristics of the micromirror in figure 4.

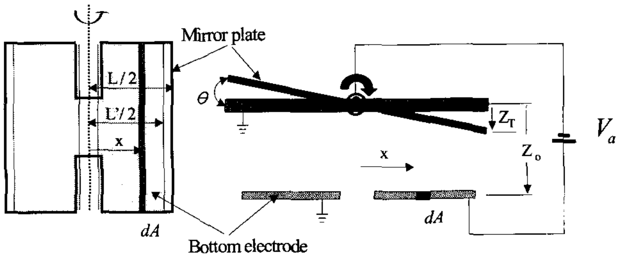


Fig. 4. Parameters used for calculating the static characteristics of a micromirror.

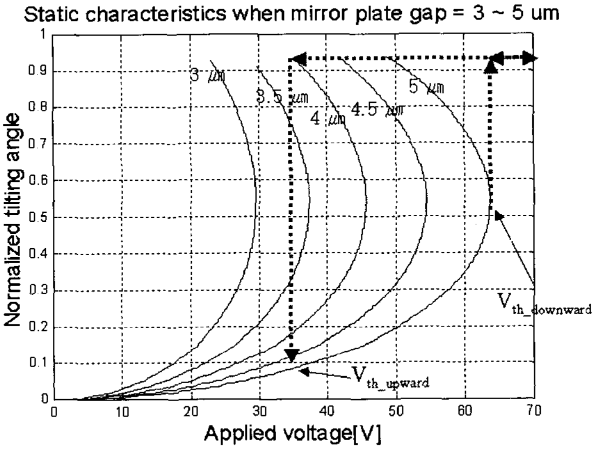


Fig. 5. Static characteristics of micromirror for the different air gap between mirror plate and substrate.

From the equation of net torque, we describe the steady statPe angular deflection as a function of applied voltage. Figure 5 shows the downward threshold voltage according to the air gap between the mirror and the substrate assuming that β is 23/28, mirror is 49㎛ on a side and spring thickness, length and width is 3600Å, 23μm, 3.8μm respectively.

It can be seen that there are differences in downward threshold voltage if mirrors have the different air gaps between mirror and substrate, which are caused by errors produced during the fabrication process of the micromirror array. Therefore, the driving voltage applied to the electrodes for the digital operation of mirror has upper and lower limits because of the non-uniformity of the downward threshold voltage of the micromirror array. There are some factors to cause non-uniformity in downward threshold voltage as follows.

A. *Deviation of thick photoresist sacrificial layer*

The air gap between the mirror plate and the bottom electrode is the thickness of sacrificial layer, which is removed in an O_2 plasma ashing process. To form the sacrificial layer, a thick photoresist, AZ4620 is spin-coated and heat treated in a convection oven to prevent photoresist flow and bubbling problem during subsequent processing steps. Heating cycles of heat treatment were as follows; 30min at 95°C, 60min at 120°C, 60min at 150°C, 60min at 180°C and 60min at 200°C. The relationship between the thickness of the sacrificial layer and the coating spin speed after heat treatment, is summarized in figure 6. The deviation of the photoresist thickness decreases as the coated PR thickness becomes thinner. It can be seen that a thin photoresist sacrificial layer is more advantageous than a thick one to obtain an uniform sacrificial layer thickness, if mirror size and deflection angle are not taken into account. When the target thickness of sacrificial photoresist is 4.6μm, which was used to obtain a 10degree deflection angle, the thickness deviation of PR obtained by 5 point measurements on the wafer was 0.11μm, which corresponds to a 1.8V driving voltage deviation. However, it is not such a critical value because the deviation is a value in a wafer not in the same mirror array and the deviation is negligible for the case in the same mirror array.

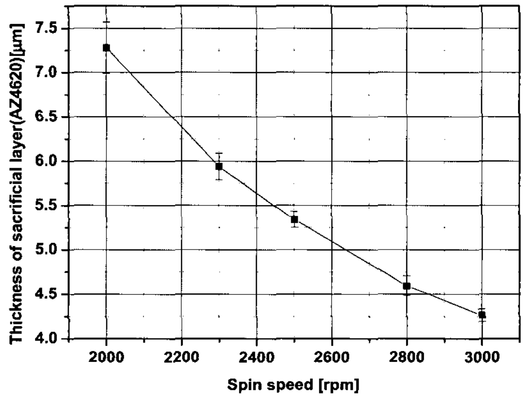


Fig. 6. Thickness deviation of thick PR(AZ4620) versus spin speed for coating

B. *Misalignment between bottom electrode and mirror plate*

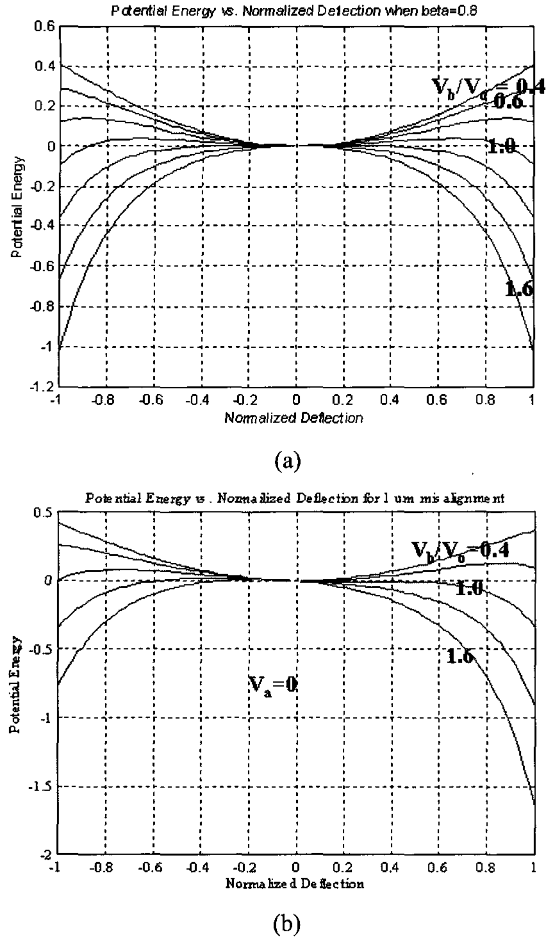
The attractive electric torque depends on the loading factor β. If deflection axis of the mirror plate is moved the left direction from the intended central position because of mirror plate misalignment during the fabrication process, the downward threshold voltages required to deflect the mirror in the left and right direction are different because of the different loading factor.

The effect of mirror plate misalignment is determined by potential energy analysis[14]. The potential energy stored in torsion spring and electric field is obtained by integrating the net torque $\tau_e - \tau_m$ with respect to α

$$U = \int_0^{\alpha} \left\{ \left(\frac{V_a}{V_o} \right)^2 g(\alpha, \beta) - \alpha \right\} d\alpha \tag{5}$$

The potential energy U can be obtained by numerical integration using MATLAB simulation software.

In case of a misalignment of the mirror plate 1μm to the left, the asymmetric nature of the potential energy according to the deflection angle is as shown in figure 7. The deflection angle obtained by applying an address voltage to the right electrode (β =24/28) is larger than that of the left (β =22/28) at the same address voltage. It can be seen that a higher addressing voltage is required to deflect to the left than to the right to obtain the same deflection angle due to the misalignment. To remove the errors due to misalignment, the bottom electrode should be larger than the mirror plate. It is desirable that the overlapping area of the electrodes should be larger than the misalignment margin if possible.



(a)

(b)

Fig. 7. Potential energy analysis for the misalignment of mirror plate (a) No misalignment, β=23/28, symmetric (b) 1㎛ misalignment, β_{right} = 24/28, β_{left} = 22/28, asymmetric.

C. *Mirror plate deformation*

Micromirror plate is deformed after it is released by removing the sacrificial photoresist using the O_2 plasma in dry ashing process, because of residual stress of the Al thin film[15]. The deformed mirror plate degrades the optical reflective property of the plane micromirror plate and the uniformity of the air gap between the mirror plate and the substrate. The deformation of mirror plate is improved a little by improving control during ashing because the high temperatures used affect the stress of Al thin film. The bending of mirror plate caused by sacrificial layer removal by 200sec of plasma ashing, a 300sec break for 7cycles was below 0.2㎛, which compared with 0.24㎛ or 0.34㎛ after 300sec of plasma ashing, a 300sec break for 5cycles or a continuous 600 sec of plasma ashing, a 300sec break for 4cycles, respectively.

D. *Spring deformation*

Micromirror spring deformation has critical effects on the non-uniformity of the air gap between the mirror plate and substrate. This is related to the deflection angle of mirror plate during digital operation and downward threshold voltage of micromirror. Because the Al torsion spring of micromirror is of the bridge type and is supported by two posts, the bending of torsion spring becomes worse when the thin Al film is under compressive stress. It is desirable to place the Al spring under low tensile stress to reduce spring deformation and improve the uniformity of the Al spring. To obtain the tensile stress and the uniform stress gradients of the Al spring, a Cr adhesion layer of 50Å thickness was used under the Al layer for the spring and the Al was deposited by thermal evaporation with heating to 170°C. The tendency of the Al spring to deform, is dependent on the plasma ashing condition during the process of sacrificial layer removal, and is not observed in bridge type of spring structure. Improvements in the uniformity of the spring were obtained, as shown the figure 8 and figure 9.

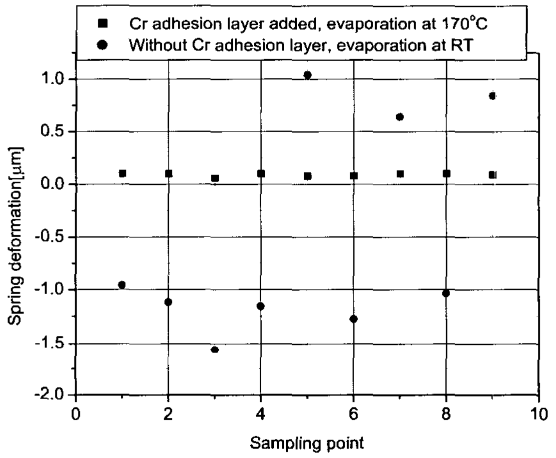
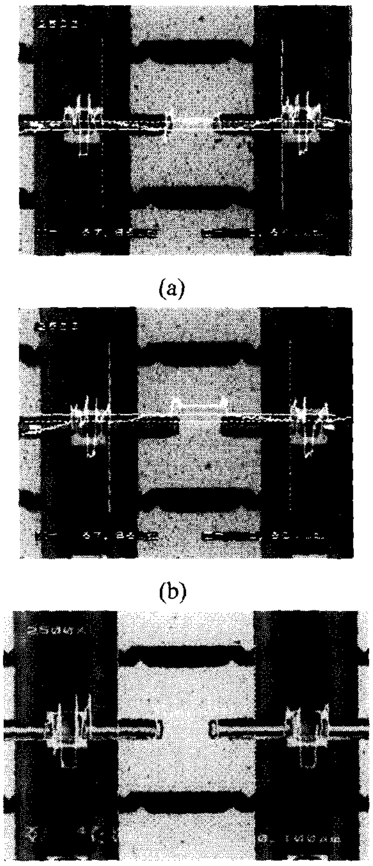


Fig. 8. Improvement of Al torsion spring deformation using Cr adhesion layer and substrate heating at 170°C while thermal evaporation.

E. *Initially deflected mirror*

The mirror can affect the angular deflection without applied addressing voltage because of memory effect caused by driving in one direction or Al deformation. If the mirror plate has an initial angular deflection, the mirror tends to deflect in the initially deflected direction when the bias voltage is applied with zero address voltage, as shown in figure 10(a). Address voltage must be applied beyond the extent of the angular initial deflection to the bottom electrode to rotate the mirror in the reverse direction to the initial deflection. Figure 10(b) shows the minimum address voltage, $V_a = -0.1V_b$ required to deflect a mirror in a state $\alpha = +1$ from an initial deflection angle $\alpha = -0.1$ to the potential energy analysis determined position of the initially deflected mirror. In the calculation of figure 10(b), $V_b = -1.6V_o$, $\beta = 0.8$ were used as an example.



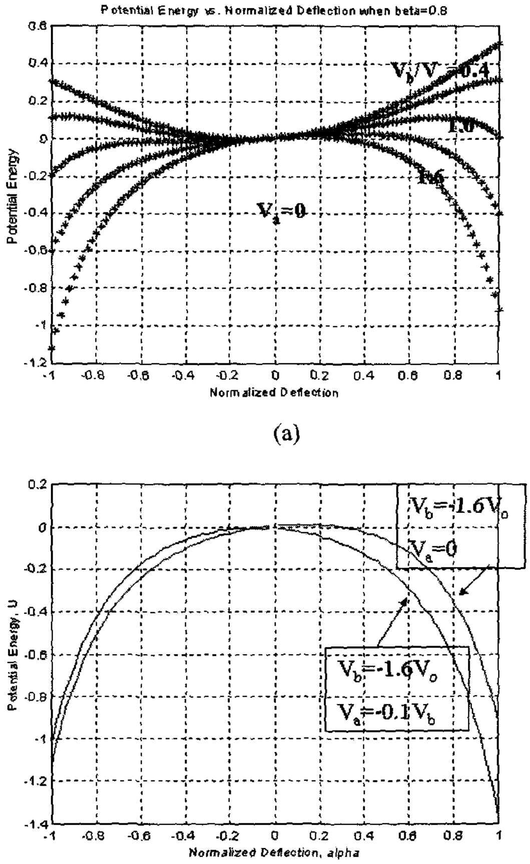
(a)

(b)

(c)

Fig. 9. Deformation of torsion spring, (a) downward bending spring, (b) upward bending spring, (c) flat spring obtained by stress control of Al thin film.

When air gap deviations are present, the initial deflection angle and the misalignment emerge *simultaneously, the mirror does not work in the intended* way because the driving voltage differences between mirrors in an array is beyond the controllable voltage range of the address and bias voltages.



(a)

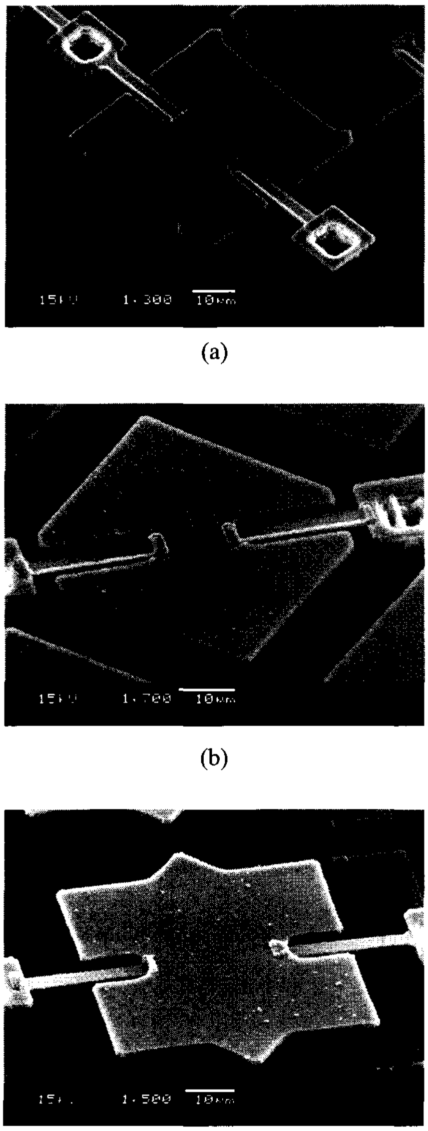
(b)

Fig. 10. Potential energy analysis of initial deflection angle with α=-0.1(a) and energy variations while driving voltage applied for deflection to α=1 direction at digital operation mode(b).

IV. STICKING OF MIRROR PLATE TO THE SUBSBATE

Sticking of the mirror plate to the bottom in digital mode operation causes an irreversible change to the mirror. Bias voltage should be low enough to avoid this problem, because excessively high voltage differences between the mirror plate and the substrate tend to cause this sticking problem. Generally, a hydrophobic thin film like FC (fluorocarbon) is used to prevent the mirror plate from sticking to the substrate, and is applied using thermal evaporation or plasma deposition [16].

The sticking phenomenon is reduced remarkably if the contact surface area of the mirror plate to the substrate is small and if the electric potential of landing tip and its contact surface on the bottom is the same even without anti-stiction coating. of landing tip. Figure 11 shows the three types of micromirrors with different touchdown tips. Sticking of the mirror plate with a contact tip and a landing electrode on the substrate was not observed after 10^5 tilting cycles. On the other hand, the mirror with two contact tips and that touches down on the SiO_2 surface easily sticks to the substrate.



(a)

(b)

(c)

Fig. 11. Three types of micromirror, (a) 2 touchdown-tip type, (b) diagonal type, (c) one touchdown-tip type. One touchdown-tip and diagonal types of micromirror which have landing electrodes on the substrate, show better anti-stiction characteristic than 2 touchdown-tip type.

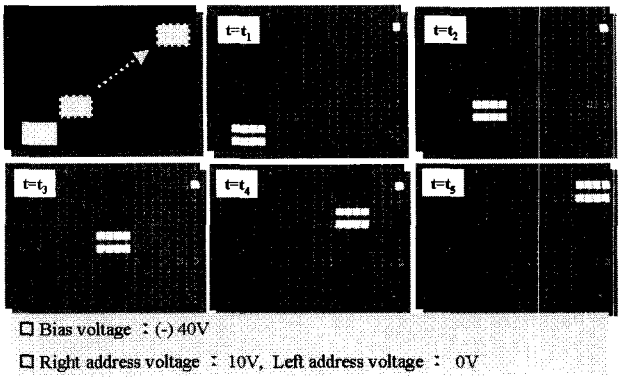


Fig. 12. Diagonal mirror operation test by applying bias and address voltage.

With respect to the sticking problem, it is not desirable to keep micromirror in the on-state for a long time. Instead of exposing continuously by keeping mirror turn-on, it is necessary to deflect the mirror on and off repeatedly at the proper times to obtain enough exposure time for maskless photolithography applications.

V. CONCLUSIONS

We improved the uniformity of the micromirror array and characterized the working properties of micromirror with respect to known non-uniformities, which are attributed to fabrication process errors.By so doing, we obtained reliable operating performance and uniform optical property from a micromirror array suitable for use in the maskless photolithography system. The factors that affect the uniformity of the micromirror array are as follows; thickness deviations of the photoresist sacrificial layer, misalignment of the mirror plate with respect to the bottom electrode, initial mirror deflection, and deformation of the mirror plate and torsion spring.

The primary factor among the above factors was the deformation of the Al spring and mirror plate. We reduced the deformation of spring below $0.1\mu m$ deviation by making Al thin film experience tensile stress. To obtain low tensile stress over the PR sacrificial layer, the Al was deposited with heating to 170°C, which produced a significant improvement compared to that obtained at room temperature.

By calculating the potential energy stored in the electric field and in the torsion spring, and the downward threshold voltage of micromirror, we found that unexpected mirror deflection occurs if the address voltage and bias voltage are not adjusted to compensate for the driving voltage differences of micromirrors in an array, as induced by fabrication process errors.

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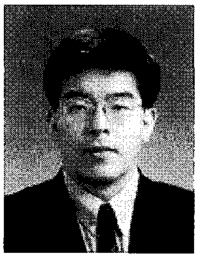
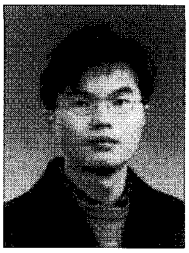


Yong-Kweon KIM received the B.S. and M.S. degrees in electrical engineering from Seoul National University in 1983 and 1985, respectively, and the Dr. Eng. degree from the University of Tokyo in1990. His doctoral dissertation was on modeling, design, fabricationand testing of micro linear actuators in magnetic levitation using high critical temperature superconductors. In 1990, he joined the Central Research Laboratory of Hitachi Ltd. in Tokyo as a researcher and worked on actuators of hard disk drives. In 1992, he joined Seoul National University, where he is currently an Associate Professor in the School of Electrical Engineering. His current research interests are modeling, design, fabrication and testing of electric machines, especially micro electro-mechanical systems, micro sensors and actuators.



Koo-Nyung Lee He received his B.S. and M.S. degree at the School of Electrical Engineering of Seoul National University in 1998, 2000 respectively. And now he is a graduate member in MiSA(Micro Sensors and Actuators) lab. Since 1998, he has been working on the design and fabrication of micromirror array for optical modulation, which is used to make surface modification for biochip fabrication. He also worked on the design and fabrication of microwell array with glass bottom for micro ELISA(Enzyme Linked Immuno Sorbent Assay) chip. He is now interested in the fabrication of protein chips and microfluidic devices for Lab-on-a-chip implementation.