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정보통신 소자 응용을 위한 단결정 실리콘 마이크로 미러 어레이

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Single crystalline silicon micromirror array for data communication applications

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Abstract

We have designed and fabricated a micromirror array using single crystalline silicon (SCS) for data communication applications. The mirror array has 16×16 micromirrors and each mirror has 120μm ×100μm reflective surface. Electrostatic force was adopted as a driving mechanism. The spring dimensions were determined using relationship between spring dimensions and driving voltage. The designed tilting angle was 9.6°, and measured tilting angle according to applied voltages were experimented. The response time was measured using He-Ne laser and position sensitive diode (PSD), and lifetime was checked for reliability proof.

1. Introduction

Micromirror arrays are currently applied to various optical systems such as projections, spatial light modulations, and maskless photolithography [1]. Also data communication systems can be improved by adopting a micromirror array.

Common requirements for micromirror array are optically flat surface and stable structures. Micromirror array has adopted aluminum as a preferred material for its high reflective surface, easy fabrication and CMOS compatibility [2]. But a mirror plate fabricated with aluminum can be easily deformed by fabrication environments or residual stress, which makes the optical efficiency poor. Memory phenomena and mechanical fatigue are other obstacles to improve performances. In brief, aluminum is a good material for compatibility and reflectivity, but disadvantages are low optical efficiency and poor mechanical stability.

To improve performances of micromirrors, recent researches are focusing on single crystalline silicon as optical and mechanical materials. SCS has optically flat surface, negligible residual stress and superior mechanical property [3, 4]. But it is difficult to fabricate complex microstructure using SCS since it is impossible to deposit SCS on other materials. The only way to fabricate microstructures with SCS is using SCS bulk wafers.

In this paper, to improve the optical and mechanical performances of a micromirror array, we have designed and fabricated a micromirror array using SCS as a mirror plate and torsional springs.

2. Design

The designed micromirror is shown in Fig. 1. The mirror has a simple torsional bridge structure and its structural material is all SCS except aluminum for bottom electrodes and a reflective surface. The SCS mirror plate can improve optical properties and SCS torsional springs can improve mechanical stability.

The torsional beam is easy to fabricate with SCS than other complex spring structures and analysis is simple after fabrication. The silicon posts at the end of the springs are anodically bonded with a glass substrate. The posts support the mirror structure and conduct the electrical signal for operation.

The mirror plate and springs are designed to have the same thickness of about 3 • . A thin mirror plate is preferred because small mass can increase resonance frequency and operational speed. But too thin plate is weak from the external force and it can be broken during fabrication processes. The length and width of the springs are 70 • and 1 • , respectively in the design. The width and length of the mirror plate are 120 • and 100 • , respectively. The array is composed of 16 x 16, 256 micromirrors.

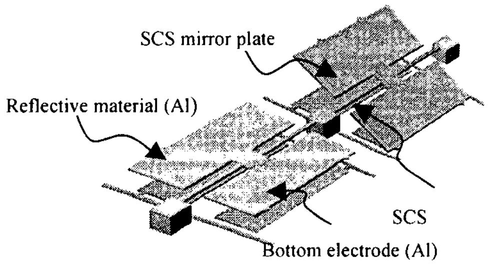


Figure 1.. *Schematics of micromirrors : left mirror is in initial state, right one is in operation.*

The right mirror in the figure 1 is addressed by electrostatic force between the mirror plate and the bottom electrode. The mirror plate is grounded and the bottom electrode is negative biased. The electrical potential of the mirror plate is supplied by springs, so all mirrors in the same row are equi-potential states. The bottom electrode is connected column by column The mirror is inclined to the left or right at ten degrees and landing tips touch down the substrate when the pull-in voltage is applied. The landing tips are for reducing a contact area and in-use stiction problems.

Table 1. Dimemsions of a micromirror

		Design	Fabrication
Spring	Width (w)	1μm	1.56μm
	Length (l)	70μm	69μm
	Thickness (t)	3μm	3.5μm
	Stiffness(k)	1.04×10^{-9}Nm/rad	7.1×10^{-9}Nm/rad
Gap (g)		10μm	9.6μm
Tilting angle (θ)		9.6°	8.2°
Pull-in voltage (V_p)		73V	124 V (Calculated)

3. Fabrication

Figure 2 shows the whole fabrication process. The first step is to form cavities (~10 • depth) on a silicon surface. The cavities are formed under a mirror plate and the springs. Evaporated aluminum (0.2 •) is patterned as electrical lines on a glass wafer. Next, the silicon wafer is flipped over and bonded to a glass wafer in the alignment bonding system (EV501, EVG Co.,Ltd.) as shown in Fig.3 (c). The desired thickness of silicon mirror plate should be 3 • , the silicon thickness should be 12 • after polishing step. Then, we deposit and pattern a thin aluminum layer to define the mirror structure including mirror plate, springs and post. After the wafer is diced into several samples, silicon structures are defined using silicon deep etch. Because there is no sacrificial layer, all structures are released in the final etch step. Fluorocarbon film (FC) can be deposited to reduce stiction problems in-use stictions.

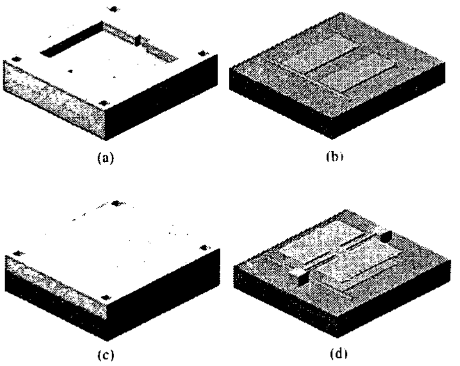


Figure 2. *Fabrication process : (a) silicon deep etch for cavity formation, (b) electrode patterning on a glass wafer, (c) anodic bonding, thinning and polishing, (d) mirror structure patterning and release*

Figure 3 shows microphotographs of fabricated micromirror array. The fabricated silicon spring is thickened and widened than the designed values. The main factors for spring dimension variations are fabrication process errors. Spring stiffness is changed to 7 times large value, which increase resonant frequency and pull-in voltage. Also the gap between mirror plate and bottom electrode has lower value than the designed one, because the gap is defined by deep silicon etcher.

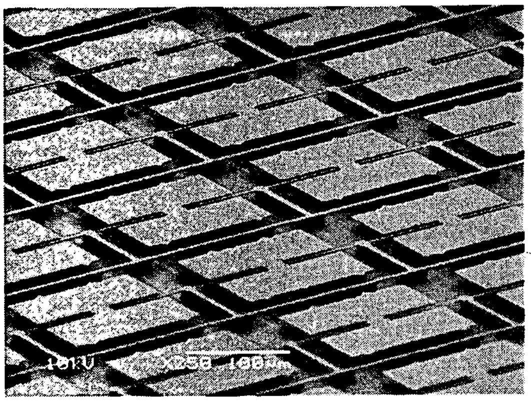


Figure 3. *SEM photograph of fabricated SCS micromirror array.*

Since the potential of mirror plate are supplied the springs by springs in same row, dummy electrical lines are added to cope with the failure by broken springs.

The flat surface of the micromirror is also depicted in figure 4, which is measured using laser profiler (VF7500, Keyence Co., Ltd.). The averaged surface roughness (R_a) measured by the laser profiler is less than 40nm.

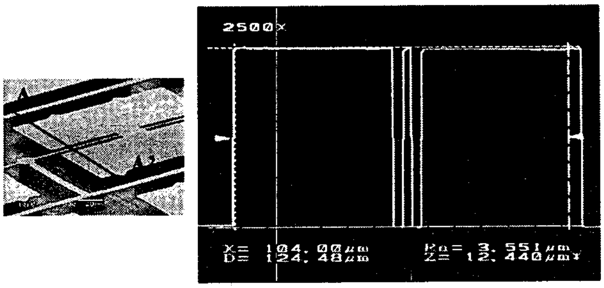


Figure 4. *Laser profiler measurement: when scanned along AA', The height of the mirror surface from the bottom is measured 12.44$^{\mu}$m.*

4. Results

Pull-in voltage is determined by dimensions of springs and electrode and can be expected from numerical equations. Pull-in voltage can be varied if bottom electrode and mirror plate are misaligned each other. We have measured the tilting angles with respect to applied voltages and plotted experimental data with the numerical analysis as shown in figure 7.

In table 1, misalignment between the electrode and the mirror plate was not considered, so that pull-in voltage was calculated to 124 V. But 3 μm misalignment was occurred during alignment bonding process, which decreases the pull-in voltage of 116 V as shown in figure 5. The tilting angle increases slightly when the applied voltage increases and abruptly touches down a substrate when voltage reaches pull-in value. The minimum voltage for holding voltage (V_h) is 40 V for both numerical analysis and experimental results.

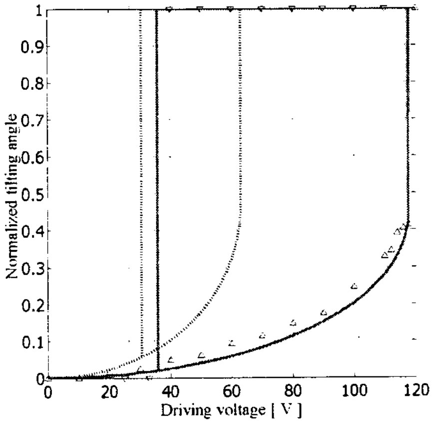


Figure 5. *Normalized tilting angle according to driving voltage: The solid line represents numerical calculation with measured dimensions of springs and electrodes as shown in Table 1. Calculation also includes 3$^{\mu}$m misalignment between the electrode and the mirror plate. Up triangles (Δ) mean tilting angles when the voltage increases, and down*

triangles (∇) for decreasing voltages.

Next, we applied step input to bottom electrode while the mirror plate was grounded. This experiment was for measuring the response time and restoring time. The used experimental setup includes He-Ne laser and position sensitive diode (PSD) as shown in figure 6 [6].

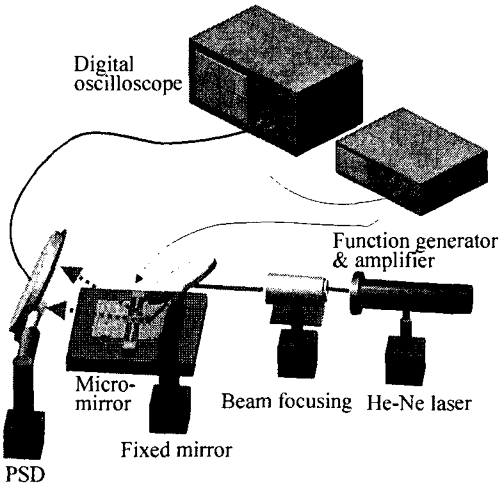
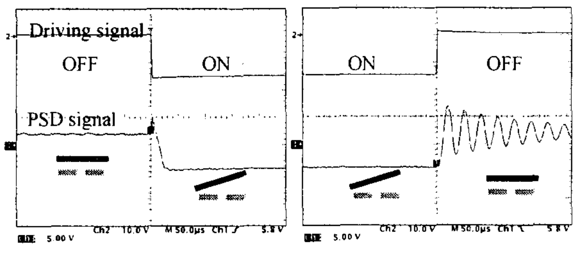


Figure 6. *Experimental setup for step response and lifetime measurements*

Laser beam is incident on the micromirror surface through the focusing lens. When the micromirror is driven by amplified voltage signals from a function generator and voltage amplifier, the reflected beam from the micromirror surface reaches PSD detectors. The PSD translate the position data into voltage signals, which is plotted with a digital oscilloscope.

Figure 7 shows the oscilloscope outputs when the driving voltage is turned on and off.



(a) (b)

Figure 7. *Step response measurements: (a) When the voltage is applied abruptly, the mirror is tilted and the tips touches down the substrate. (b) When the voltage is removed, the mirror is released from the electrostatic force*

In figure 7 (a), the mirror is switched on and the fully tilted. The response time for switching on is about 25 μsec and there are no rebouncing phenomena. When the voltage is turned off, the mirror is released and back to an original position. There are oscillations during settlement, and the settling time is about 500 μsec. Since the mirror is oscillated with own resonant frequency, the resonant frequency can be assumed as 32 kHz. The long settling time can be reduced by applying voltages on second electrode and tilting the mirror to opposite directions.

We have experimented life time using same experimental setup shown in figure 8. As the mirror was driven by square function, the output position signal was observed by the oscilloscope. The position signal was not changed after 3.5×10^8 cycles.

5. Conclusion

Micromirrors that have SCS mirror plate and SCS torsional springs are designed and fabricated using silicon deep etch and anodic bonding process. The silicon membrane is thinned for the mirror plate and the springs. The average surface roughness is below 40nm. The pull-in voltage was 120V and minimum holding voltage after pull-in was about 40V. The switching times were 25 μsec and 500 μsec for On and Off transitions, respectively. Even though the mirror operated 3.5×10^8 cycles, there was no degradation. The fabricated SCS micromirror array has potential applications as stable light modulators in micro optical systems including maskless photolithography systems.

Acknowledgement

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