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ELECTROSTATIC MICRO MIRROR ARRAY WITH BATCH-FABRICATED TORSION BEAM OF SILICON NANOWIRE

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ABSTRACT

A new design of arrayed micro mirror device for a high performance spatial light modulator of high resonant frequency, large deflection angle with high mechanical reliability has been proposed. The mirror has 100-μm square plate of 5 μm thick, which is suspended by thin silicon nanowire of about 1 μm thick and wide. The device was fabricated using Bosch process and isotropic plasma etching. We successfully demonstrated array operation of 4×4 devices at relatively low actuation voltage (~20 Vpp) and large mechanical deflection amplitude (~9°). However, the deviation of vibration amplitude was large among unit resonators. By fitting the frequency response to the Duffing equation we found that self-enhancing actuation force caused by nonlinearity of the vertical combs was a main reason.

KEYWORDS

Micro mirror array, torsional resonator, electrostatic, vertical comb, nonlinear vibration.

INTRODUCTION

Torsional micro mirror scanners are compact, light and low power consumption optics and used in spectrometer, laser display, and LiDAR [1]. In these applications, it is always demanded to improve the performance both in the resonant frequency for higher frame rate and the deflection angle for higher resolution. However, it is difficult to satisfy both because the high speed drive causes higher stress in the device structure and the large diameter of mirror with small mass causes low bending stiffness of mirror and resulted in large optical aberration[2]. To solve the problems, the synchronized mirror scanner array has been proposed [3-4]. However, its scanning speed is 250 Hz, which is much lower than that of previously reported scanners. Therefore, a smaller mirror device with higher resonant frequency is needed.

In this research, we designed a 4×4 array of small torsional mirrors operated by electrostatic vertical comb actuators. The unit mirror is in 200 μm square and the resonant frequency is higher than 10 kHz. This report presents the design and fabrication of the mirror array, electrostatic operation and analysis of the measurement results.

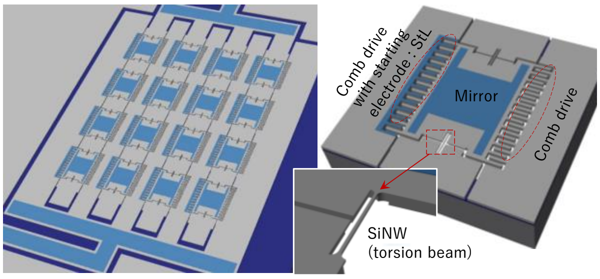

Figure 1: Schematics of mirror array device. 4 by 4 array (left), and unit mirror (right).

MICROMIRROR ARRAY

Fig. 1 shows the proposed mirror array device. The unit mirror has a 100-μm-square aluminum mirror and tilted by electrostatic actuation using vertical comb actuators on the both sides. The mirror plate made of single crystal silicon is suspended by a pair of torsional beams. Sixteen mirrors were arranged and operated by the common electrodes. The mirrors were placed as 4×4 array and total size is 1 mm square. The small aperture of the unit mirror will be compensated by the arraying.

The main purpose of arraying the miniaturized mirrors is mechanical reliability enhancement. The maximum torsional stress τ_{max} on a square cross-section beam with torsion angle θ is;

$$\tau_{max} = 0.678\frac{Gw\theta}{l}, \tag{1}$$

where G is the rigidity and w and l are width and length of the beams. Eq.1 indicates that longer and thinner beams are preferred. However, the resonant frequency f_N of the torsional mirror is;

$$f_N = \frac{1}{2\pi}\sqrt{0.28\frac{Gw^4}{Jl}}, \tag{2}$$

where J is the moment of inertia of the mirror plate. The resonant frequency and stress on the beam conflict each other. In order to maintain high mechanical reliability without sacrificing the resonant frequency, the smaller device of small J is required. However, thinning the plate is not a good solution because of mirror plate deflection during resonant vibration, which causes the aberration of the reflected light. When a square mirror plate is oscillated at its resonant frequency f_N and angle amplitude θ, the deformation δ is estimated as [2],

$$\delta = 0.217\frac{\rho f_N^2 d^5}{Eh^2}\theta, \tag{3}$$

where ρ and E are the density and Young's modulus of silicon and d and h are the width and thickness of the plate. Therefore, the mirror size is fixed to 100 μm square and the thickness h of the plate is 5 μm. The mirror plate deformation by vibration at 10 kHz, 10 deg is 20 nm, which is small enough to avoid aberration.

However, the beam thickness should be much smaller to reduce the stress. The thickness (= width w) of the beams is decided as 1μm and the length was 26 μm to let the resonant frequency 10 kHz.

The schematic design of the unit resonator is shown in Fig. 2. The side edge of the mirror plate was extended to increase the number of the comb electrodes for actuation. The gap and comb width are 3 μm and the length of comb

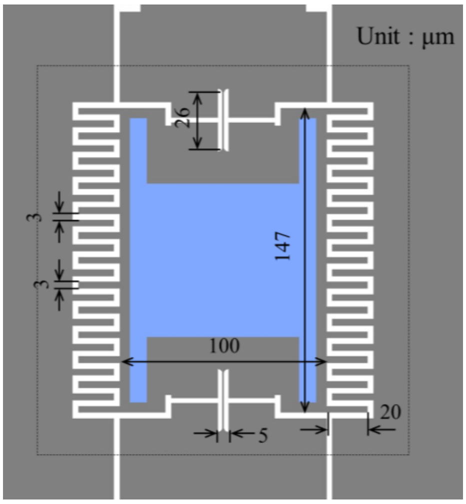

Figure 2: Design of unit mirror.

finger was 20 µm. The one side of the fixed comb has additional aluminum layer to make vertical asymmetry for smooth actuation, since the comb fingers do not have a vertical offset between each other.

EXPERIMENTAL METHODS

Fabrication process

We designed the beam diameter to 1 µm and that of other device structures was designed to be 5 µm. To fabricate a structure consisting of two different thicknesses in single layer of single crystal silicon, we have developed a batch-fabrication process for integrating silicon nanowire to the device layer of a 5-µm-thick SOI wafer [5]. The total fabrication process of the mirror array device is shown in Fig. 3.

The first step is to pattern 200-nm thick aluminum film for electrodes and mirrors on 4-inch SOI wafer, then the mirror structures except for the torsion beams of silicon wires were patterned on the device layer using the Bosch process. The top surface was covered with silicon dioxide film of 600 nm thick using plasma enhanced chemical vapor deposition and tetraethyl orthosilicate (TEOS) as a source material. Openings on the oxide passivation were made at the positions of torsional beams for electron beam (EB) lithography. The chromium hard mask for etching the handle layer of 400µm thick was patterned. The resist patterning until this step was done by ultra-violet (UV) lithography. After dicing into 7 mm square chips, deep reactive ion etching (RIE) from the backside was conducted to make a cavity at the bottom of the mirror plate. Then, the fabrication step of torsional beams of 1 µm wide was followed and finally the mirror plate was released by vapor-phase hydrofluoric acid etching of silicon oxide to remove the top passivation and buried oxide layer of 2 µm thick.

The details of fabrication process of the torsional beams were described in Fig. 4. The patterning was done using EB lithography. Fabrication of 1µm wide and thick silicon beams were done by two step plasma etching of silicon. The first step is the Bosch process and the etch depth is 2.2µm considering the undercutting in the next step. The second step is isotropic plasma etching using SF_6 gas and etching depth was 3.5 µm. The etching depth of the two steps was carefully designed to etch fully to the bottom of the device layer and the final thickness of the undercut silicon beams became 1 µm.

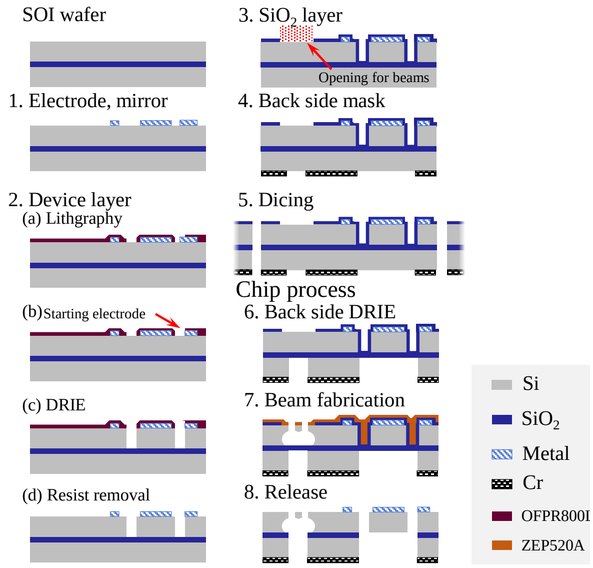

Figure 3: Fabrication process. Fabrication details of torsional beam of 1-µm square cross section are in Fig. 4.

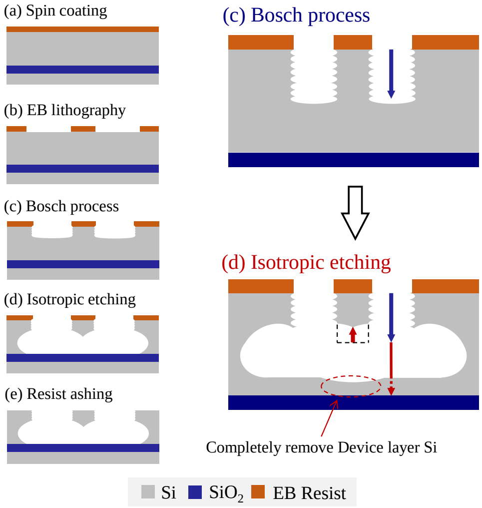

Figure 4: Fabrication process of torsional beam of 1-µm square cross section.

Device characterization

The fabricated chips were mounted on a 28 pin ceramic dual-in-line package (DIP) and wire bonded. The unit mirror devices and 4×4 array were tested. The unit device were operated by applying ac voltages of 180° phase difference comb electrodes on each side, since the vibration amplitude was much larger than that of no phase difference condition. For the array device, the same phase of ac voltage was applied because the electrodes were not electrically separated. The measurement was performed both at atmospheric pressure and in a vacuum (5 Pa). The motion was measured using a scanning laser Doppler vibrometer (MSA-500, Polytec). The vertical vibration velocity of the mirror plate was measured.

RESULTS AND DISCUSSION

A mirror array with the torsional beams of 1.0-µm wide was successfully fabricated. Fig. 5a shows a top view of a 4×4 array device and the sixteen mirrors were fabricated uniformly. Figs. 5b and 5c show the unit mirror device and one of the torsional beams from a oblique angle. The thickness (height) of the beam was measured as 1.3µm, which is thicker than designed value. The isotropic etching reached to the bottom of the device layer and the mirror part was released and suspended by two torsional beams.

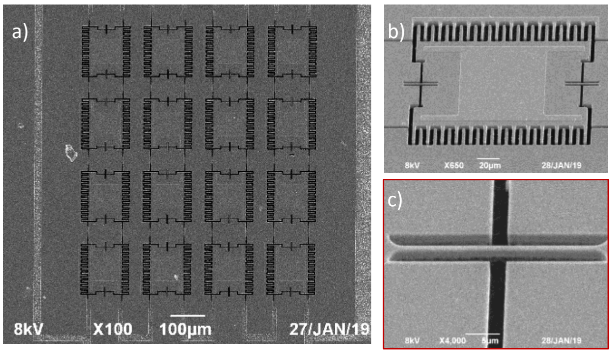

Figure 5: Fabricated mirror device. a) 4 by 4 array, b) single mirror segment and c) SiNW torsion beam.

First, the unit mirror device was tested in the air. Figure 6 shows the frequency response around the resonant frequency at different actuation voltage amplitudes. The maximum mechanical amplitude of 4° was observed with an actuation voltage of 10 V, which is much lower than the previous reports. The resonant frequency was about 11 kHz, which is larger than the design. The fabricated beam was thicker than the design, which explains well the measured frequency. By increasing actuation amplitude, the resonant frequency increased slightly. Moreover, the vibration amplitude increased very rapidly. Whereas the mechanical amplitude should be proportional to the square of the actuation voltage to 7 V, the amplitude was suddenly 4 times bigger by the voltage change from 7 V to 10 V. At 10 V, the frequency response shows nonlinearity indicating soft spring effect due to electrostatic actuation.

In addition, the frequency response of different devices showed large difference. Fig. 7 shows the frequency response of two unit devices operated at 10-V amplitude. The upward and downward sweeps were measured but no hysteresis was observed. Even though the devices were fabricated on the same 7-mm square chip, the large difference of the peak amplitude was observed. To analyze the reason, the frequency response was fitted to the duffing equation as follows;

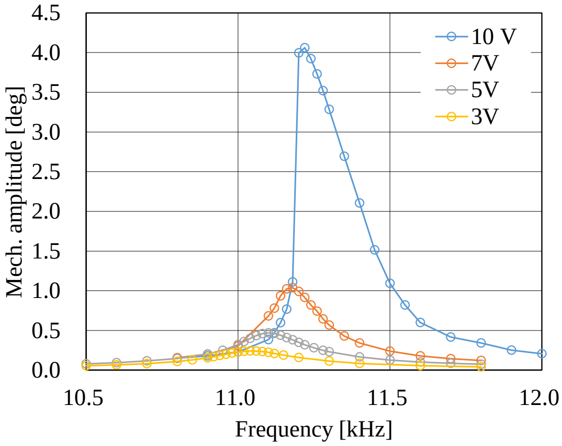

Figure 6: Frequency response of single mirror device (device A) in the air as function of actuation voltage.

$$\frac{d^2\theta}{dt^2} + 2\zeta\frac{d\theta}{dt} + \omega_0^2\theta + \alpha\theta^3 = T_0 \cos\omega t, \qquad (4)$$

where ζ is the dumping ratio, α is nonlinear parameter and T_0 is the normalized actuation torque. The fitting results are shown in Table I.

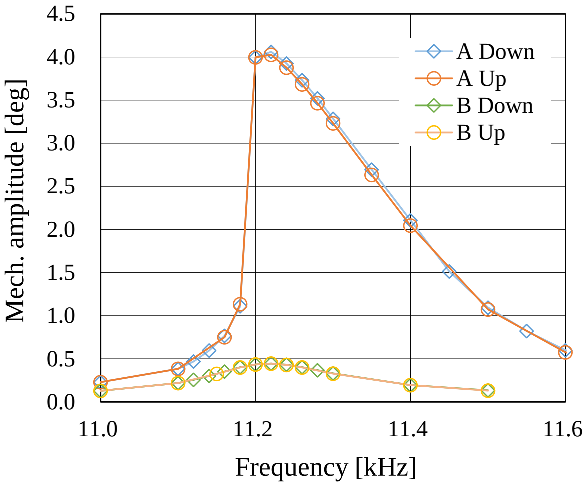

Figure 7: Frequency response of two different single mirror devices (device A and B) operated at 10 V.

Table I: Fitting parameter to Duffing equation of unit mirrors showing different frequency responses.

Sample	**ζ [1/s]**	**α [$\times10^4$/s^2]**	**T_0 [$\times10^6$/s^2]**	**ω_0 [$\times10^4$/s]**
A	228.6	-680.7	131.0	7.1
B	549.8	-19.9	34.5	7.1

We found that the resonant frequency deviation was small and the deviation of damping parameter is not large (differed by double). The major reason is the nonlinearity of vertical combs which have same thickness and no offset between moving and fixed combs. The actuation force becomes small near the origin, so small difference of damping coefficient causes large difference in vibration amplitudes. The rapid increase of the device A amplitude at 10 V is explained by this effect.

Then, the device A was operated in vacuum at 5 Pa. The frequency responses of different actuation voltage were shown in Fig. 8. The mechanical amplitude of 9° was obtained with only 1.0 V actuation. The frequency responses showed generally soft spring effect.

The frequency responses of Fig. 8 were fitted to the duffing equation and the results were shown in Table II. However, the frequency responses of 0.5 and 1.0 V actuation do not fit well to Eq. 4. Because of the large amplitude, the nonlinearity parameter might decrease at large deflection angle. It is also anticipated by the results of 10-V actuation in the air, where the no hysteresis was observed.

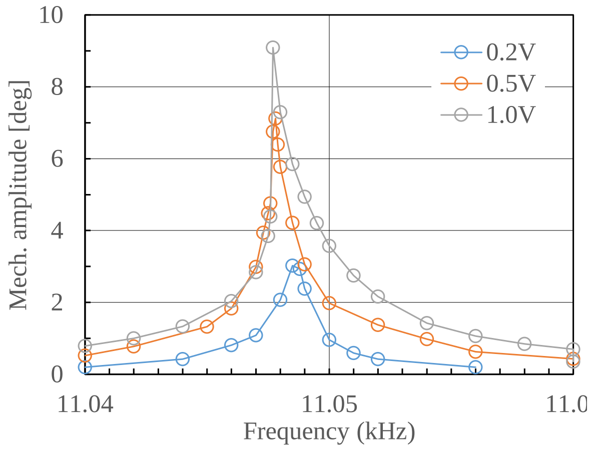

Figure 8: Frequency response of single mirror device (device A) in vacuum of 5 Pa as function of actuation voltage.

Table II: Fitting parameter to Duffing equation of mirrors of different frequency response

Voltage	**ζ [1/s]**	**α [$\times 10^4$/s^2]**	**T_0 [$\times 10^6$/s^2]**	**ω_0 [$\times 10^4$/s]**
0.2 V	3.63	-2.75	1.48	6.94
0.5 V	3.59	-0.17	3.53	6.94
1.0 V	5.16	-2.75	6.53	6.94

Finally, a 4×4 array device was operated in the air. Fig. 9 shows the mirror deflections at 11.22 kHz, 5V. All mirrors were vibrated in the same phase because of the aluminum top layer on the one side of comb fixed electrodes. However, the vibrating amplitudes differ because of the resonant frequency variations. In addition the deflection is small. The amplitude of largest amplitude mirror was 0.025°, which is one fortieth of that of device A. This is because the actuation methods where the same phase ac voltages were applied on the both sides of comb electrodes. The reason of small amplitude in this actuation would be the high resistance of the torsional beams, which makes the potential at the mirror plate, was higher and the actual voltage applied on the comb actuator became small. When the anti-phase (180° phase difference) voltage applied, the potential at the mirror plate became zero and the same voltage as the function generator was applied on the comb.

In order to operate the all unit mirrors at the same frequency and amplitude, we need to tune the frequency response. Mechanical tuning by trimming and electrical tuning by adding additional tuning electrode will be conducted.

CONCLUSION

The 4×4 array of 100-µm square torsional mirror devices was fabricated and tested. The mirror plate is 5 µm thick and the torsional beams had 1-µm square cross section and they were formed on the same 5-µm thick device layer of SOI wafer. The resonant vibration was successfully observed at around 11 kHz. The mechanical deflection amplitude of unit mirror device was 4° with 10-V actuation in the air and 9° with 1-V actuation in the vacuum. The array device operation was conducted and all sixteen mirrors were vibrated at same time. We verified the potential of the array of small mirrors for the application to the spatial light modulator of large aperture, high speed and large deflection.

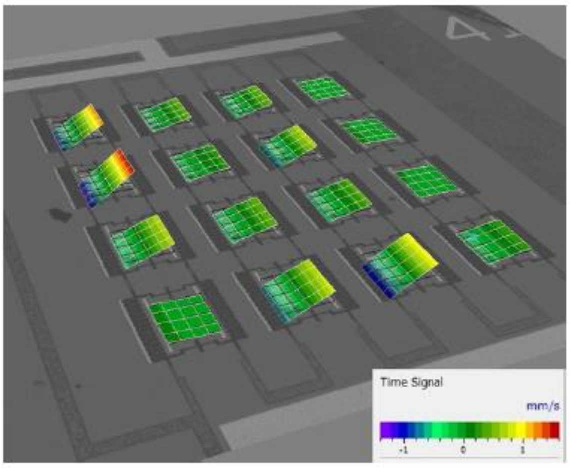

Figure 9: Torsional vibration of 4×4 mirror array actuated in the air actuated at 11.22kHz with 5 V voltage amplitude.

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