2D Asymmetric Silicon Micro-Mirrors Fabricated by Anodic Bonding of an Ultra-thin Silicon Film on a Glass Substrate by Laser Micro-Processing

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Abstract

Asymmetric silicon micro-mirrors are fabricated by the anodic bonding of an ultra-thin silicon film on a glass substrate, followed by the fabrication of ultra-thin silicon microelectromechanical systems (MEMS) mirror structures by laser micro-processing. Laser micro-processing, which merges the direct laser fabrication of ultra-thin silicon and anodic bonding, is easier than the silicon-on-insulator–MEMS process. Typically, polished ultra-thin silicon warps under residual stress. However, a flat surface profile was achieved on the scanning mirror of the silicon micro-mirror by anodic bonding and uniform pressure application. By vibrating the asymmetric silicon micro-mirror with an external vibrating element, we obtained a horizontal operation of 118 Hz and a vertical operation of 11040 Hz at the resonance frequency. The Lissajous pattern was also projected on the screen using the horizontal and vertical operations.

I. Introduction

Silicon microelectromechanical system (Si-MEMS) application devices have been studied for application to the development of projectors. The characteristics of a Si-MEMS device are miniaturization, high reliability, and low power consumption. Various projection methods have been developed. The digital light processing (DLP) method uses a digital micromirror device (DMD) [1]; however; DMD is ineffective against dynamic shocks because of its ultra-thin compact mirror structure. On the other hand, the laser projection method uses the MEMS mirror, and there is no limitation to the projection screen [2]. The MEMS mirror application has been studied in the development of a glass-like retinal display and the screen display for car navigation systems [3].

The rotation angle of optical scanners using conventional static electricity has been limited at the gap between the mirror and silicon micro-mirror. A high voltage is required to enlarge the rotation angle of an optical scanner.

Recently, a simple asymmetric micro-mirror excited by an external piezoelectric ceramic vibrating element has been shown to be effective for scanning an optical beam [4]. The asymmetric silicon micro-mirror can obtain a much larger rotation angle by adding a translational motion that is equal to the resonance frequency of a rotation oscillation system. Because an asymmetric silicon micro-mirror can achieve rotational movement near a regular sign wave, two axes are controllable by independent frequency. However, the silicon-on-insulator-MEMS (SOI-MEMS) process requires high temperature, and it is a complicated stress-controlling process.

This study established the validity of the direct laser fabrication of ultra-thin silicon and anodic bonding. We investigated the characteristics of 2D asymmetric silicon micro-mirrors fabricated by the anodic bonding of a laser micro-processing ultra-thin silicon film on a glass substrate.

II. Fabrication experiments

A. Picosecond laser micromachining system

For the following experiments, we used a picosecond laser micromachining system, as shown in Table 1. The picosecond micromachining system was composed of a picosecond laser and 2D nano-motion stage. The picosecond laser system (Japan Laser and Time-Bandwidth, Duettino-SHG) delivered pulses at a repetition rate ranging from 1.26 kHz to 8.2 MHz, with energies of up to 100 μJ at a wavelength of 532 nm. We used a 100-cm focal length lens to focus the Gaussian beam to a nominally round spot. The part was placed before the beam focus to achieve an effective spot size of 27 μm diameter ($1/e^2$ intensity). The beam hit the part at normal incidence, and the fluence was changed by adjusting the energy using pulse on demand, while the spot size remained constant. The material used was a 20-μm ultra-thin silicon film (Apollo Engineering).

In micromachining with a picosecond laser, the 20 μm ultra-thin silicon was set on the 2D nano-motion stage (Aerotech, ANT130-160). The 2D nano-motion stage was driven by motion controlled software (Aerotech, Automation 3200).

Table 1. Picosecond laser micromachining system specification

Picosecond laser	
Lasing wavelength	532nn
Pulse width	9.5ps
Pulse energy	Max. 100μJ@532nm
Repetition rate	1.26kHz ～ 8.2MHz@532nm
Pulse energy stability	<0.5%rms
Pointing stability	<40μrad/℃
$M^2(TEM_{00})$	<1.3
Pulse train control	Possible
2D nano-motion stage	
Travel	160mm
Resolution	3nm
Repeatability	±25nm
Straightness	X-axis 250 nm, Y-axis 500 nm
Sample chuck	Vacuum chuck
Control	Motion controlled software

B. 2D asymmetric silicon micro-mirror design

To demonstrate the advantages of the new processing technique, we designed 2D asymmetric silicon micro-mirrors. Fig. 1 shows the layout of the 2D asymmetric silicon micro-mirrors designed in this study. The 2D asymmetric silicon micro-mirror size is designed to be 12 mm × 13 mm, as shown in Fig. 1. The scanning mirror area is 1 mm × 1 mm.

The resonance frequency of the 2D asymmetric silicon micro-mirror was evaluated using the Intellisuite software (IntelliSense, ver8.7). First, we used the blueprint, which is a physical design tool, as shown in Fig. 1. The 3D model was built in Intellisuite's 3D builder, which is a 3D mesh generator. The frequency analysis was performed by ThermoElectroMechanical. The minimum mesh was 8.5 μm at torsion, and the parameters used in the analysis are summarized in Table 2. The scanning resonance frequency is 144 Hz in the horizontal direction and 12948 Hz in the vertical direction.

If the 2D asymmetric silicon micro-mirror is excited by an external vibrating element, the asymmetric silicon micro-mirror can obtain a much larger rotation angle by adding a translation motion that is equal to the resonance frequency of a rotation oscillation system. By changing the resonance frequency, two axes are controllable by independent frequency.

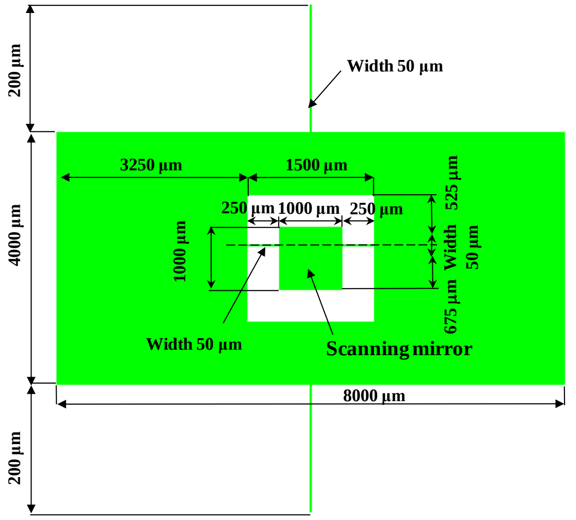


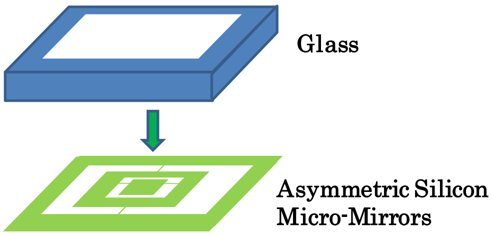
Fig. 1. Layout of a 2D asymmetric silicon micro-mirror

Table 2. Parameters used for Intellisuite analysis

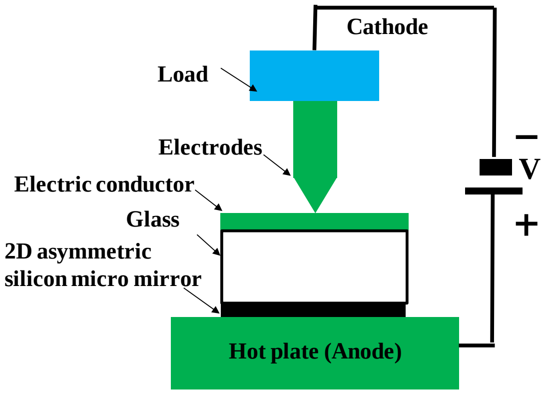
Material	Silicon
Young' modulus	160GPa
Density	$2.30g/cm^3$
Poisson ratio	0.226

C. Fabrication processes using anodic bonding

The 2D asymmetric silicon mirrors are fabricated by a picosecond laser micromachining system. Next, an ultra-thin silicon film was bonded to a glass substrate (HOYA CANDEO OPTICS, SD2) by the vacuum anodic bonding method (DIAVAC, DAB-A-40) while applying pressure uniformly, as described in Fig. 2. The glass substrate has a width of 13 mm, length of 10 mm, and thickness of 0.5 mm. We set the 2D asymmetric silicon micro-mirror on the hotplate. On the 2D asymmetric silicon micro-mirror, we stack a glass substrate and electric conductor as shown in Fig. 2(a). Silicon-to-glass anodic bonding is performed at 380°C in air atmosphere, as shown in Fig. 2(b). An anodic bonding voltage of 1.0 kV was applied for 1 min. An anodic bonding voltage was applied during cooling from 380 to 320°C. The surface was observed using a digital microscope (KEYENCE, VHX-1000).



(a) Setup of mirrors and glass



(b) Experimental setup

Fig. 2. Schematic of experimental setup for anodic bonding

III. RESULTS

Using a picosecond laser micromachining system, a 2D asymmetric silicon micro-mirror was obtained with a width of 34 µm at torsion. The obtained torsion width became smaller than the desired value. This was due to the formation of the taper caused by laser processing.

Fig. 3 shows a photograph of the asymmetric silicon micro-mirror fabricated by the anodic bonding of an ultra-thin (20 µm) silicon film on a glass substrate. The bonding current was 0.27 mA. There was no air bubble between the asymmetric silicon micro-mirror and the glass substrate.

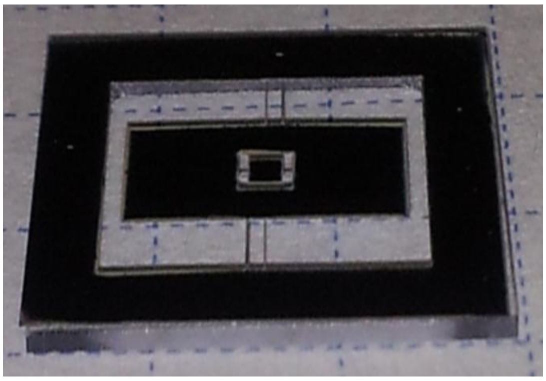


Fig. 3. Photograph of the asymmetric silicon micro-mirror fabricated by the anodic bonding of an ultra-thin (20 µm thickness) silicon film on a glass substrate

Fig. 4 shows the photograph and surface profile of the scanning mirror. No large distortion was observed. The oblique scratches are polish marks.

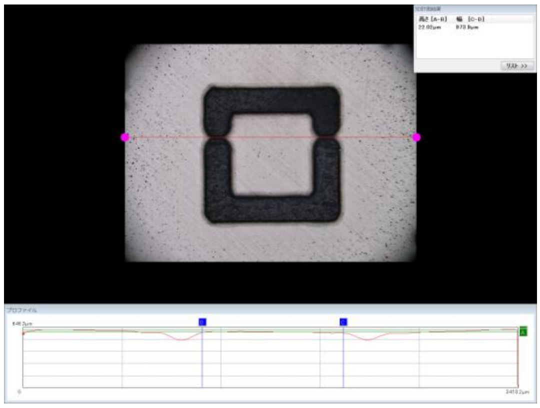


Fig. 4. Photograph and surface profile of the scanning mirror

Fig. 5 shows the surface profile of the scanning mirror. The flatness was ±1 µm in the horizontal direction and ±2.2 µm in the vertical direction.

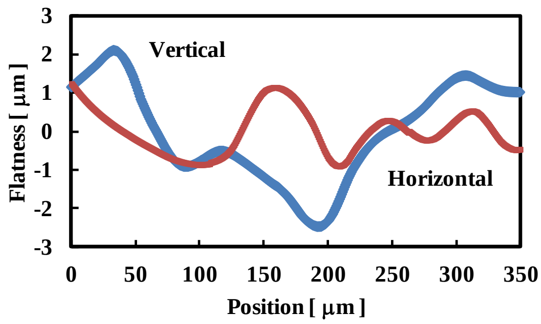
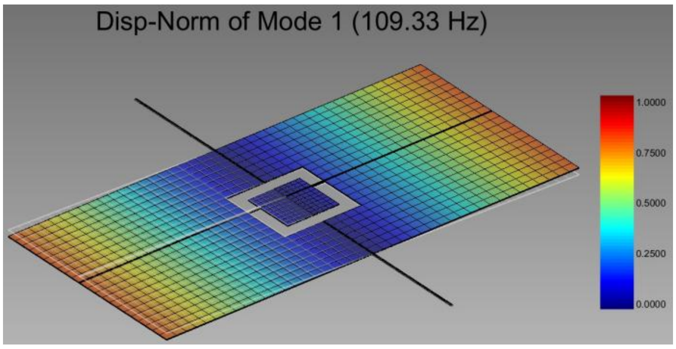


Fig. 5. Surface profile of the scanning mirror

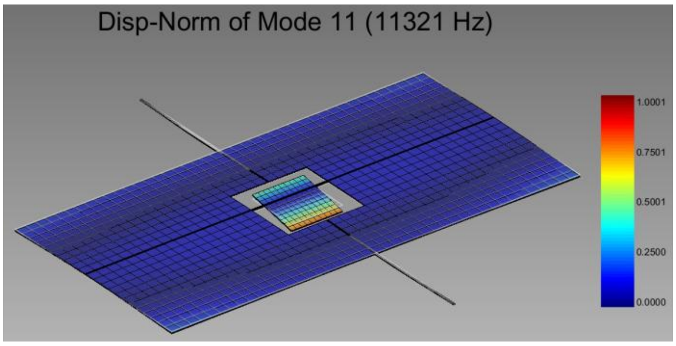
We investigated the resonance frequency of the 2D asymmetric silicon micro-mirrors fabricated by the anodic bonding of an ultra-thin silicon film as shown in Fig. 6. We used the giant-magnetostrictive speaker (FOSTEX, GY-1) as the vibrating element. The 2D asymmetric silicon micro-mirror was set on the vibrating element, and was excited by the external functional generator. As a result, the scanning resonance frequency was 118 Hz in the horizontal direction and 11040 Hz in the vertical direction. Also, we investigated the resonance frequency using the cone speaker. However, only the resonance frequency at 118 Hz was observed, even though the range was 0–25000 Hz.

Fig. 6. Photograph of the experimental setup for vibrating the asymmetric silicon micro-mirror

With regard to the measured torsion width, we again performed frequency analysis using Intellisuite. Fig. 7 shows the frequency analysis of 2D asymmetric silicon micro-mirrors. The Thermoelectromechanical module of Intellisuite gave almost the same results as the experimental results.



(a) Resonance frequency in the horizontal direction



(b) Resonance frequency in the vertical direction

Fig. 7. Frequency analysis of 2D asymmetric silicon micro-mirrors

We performed the projection of Lissajous patterns by scanning the 2D asymmetric silicon micro-mirrors. By vibrating the asymmetric silicon micro-mirror with an external vibrating element, we obtained a horizontal operation of 118 Hz and a vertical operation of 11040 Hz at the resonance frequency. The wave function generator was used to generate each operation signal. Fig. 9 shows the results of the Lissajous pattern projected onto the screen.

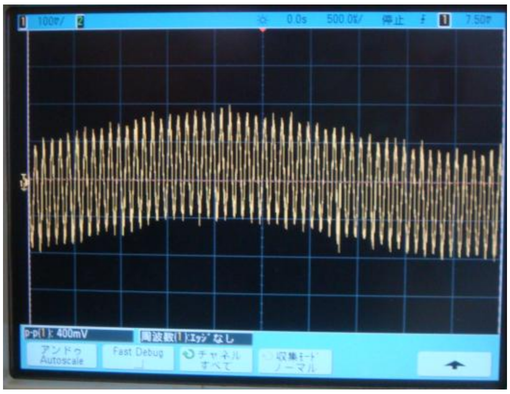


Fig. 8. Photograph of the experimental setup for vibrating the asymmetric silicon micro-mirror

Fig. 9. Lissajous pattern projected on the screen

IV. DISCUSSIONS

In this study, we investigated the validity of the direct laser fabrication of ultra-thin silicon and anodic bonding. We investigated the characteristics of 2D asymmetric silicon micro-mirrors fabricated by the anodic bonding of a laser micro-processing ultra-thin silicon film on a glass substrate. The results indicate that the scanning resonance frequency was 118 Hz in the horizontal direction and 11040 Hz in the vertical direction. This scanning rate was compared with that of SOI-MEMS for the projection. The Thermoelectromechanical module of Intellisuite gave almost the same results as the experimental results. However, the process of direct laser fabrication of ultra-thin silicon and anodic bonding is easier than the SOI–MEMS process. Therefore, it has been shown to be valid for the direct laser fabrication of ultra-thin silicon and anodic bonding.

The silicon MEMS process has been proposed utilizing anodic bonding of an extremely thin silicon film (60 µm) on a glass substrate, followed by photo lithographically defining micro spring structure on the silicon film and by dry etching the silicon film using an inductively coupled plasma (ICP) dry etcher [5]. However the high temperature may give damage to anodically-bonded interface.

SOI-MEMS have residual stress. Destruction may arise during SOI process. Therefore the complicated process is needed for gradual stress release.

Typically, polished ultra-thin silicon warps under residual stress. Because imperfect sticking arises between bent silicon and glass, air bubbles are formed in space. Therefore, the bonded area becomes small for these air bubbles, and distortion remains in the silicon micro-mirror. However, an almost flat surface profile was achieved on the scanning mirror due to the uniform pressure applied in the case of anodic bonding.

The burr and debri generate in the laser micro-processing. The burr is the cause of the leakage current by anodic bonding. Fig. 10 shows the surface image of a 20-µm ultra-thin silicon film after laser micro-processing. The surface was measured with Zygo interferometer (Zygo). As a result, the surface shows burr-free edge, with HAZ and no deposited debris. No leakage is observed by anodic bonding.

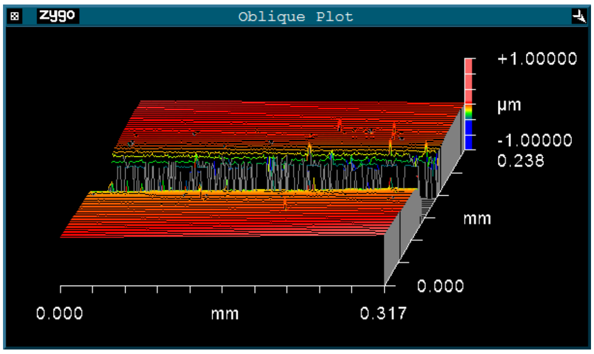


Fig. 10. Surface image of a 20-µm ultra-thin silicon film after laser micro-processing

There was no difference in the vibrating properties of 2D asymmetric silicon micro-mirrors before and after anodic bonding. It appeared that another method, for example, low melting glass for bonding purpose is also effective.

Although the giant-magnetostrictive speaker excited 2D asymmetric silicon micro-mirrors at a frequency below 11100 Hz, the resonance range of the cone speaker was below 400 Hz. The giant-magnetostrictive speaker has the characteristics of strong stretching and small hysteresis. However, the cone speaker break-up occurs at higher frequencies. Therefore the giant-magnetostrictive speaker was suitable for the vibrating element excited by the external function generator.

V. COCLUSIONS

Asymmetric silicon micro-mirrors are fabricated by the anodic bonding of an ultra-thin silicon film on a glass substrate, followed by the fabrication of ultra-thin silicon microelectromechanical systems (MEMS) mirror structures by laser micro-processing. Using a picosecond laser micromachining system, a 2D asymmetric silicon micro-mirror was obtained with a width of 34 µm at torsion. The asymmetric silicon micro-mirror fabricated by the anodic bonding of an ultra-thin (20 µm) silicon film on a glass substrate and uniform pressure application. There was no air bubble between the asymmetric silicon micro-mirror and the glass substrate. The flatness was ±1 µm in the horizontal direction and ±2.2 µm in the vertical direction. We used the giant-magnetostrictive speaker (FOSTEX, GY-1) as the vibrating element. The 2D asymmetric silicon micro-mirror was set on the vibrating element, and was excited by the external functional generator. As a result, the scanning resonance frequency was 118 Hz in the horizontal direction and 11040 Hz in the vertical direction. The Thermoelectromechanical module of Intellisuite gave almost the same results as the experimental results. The Lissajous pattern was also projected on the screen using the horizontal and vertical operations. Therefore, it has been shown to be valid for the direct laser fabrication of ultra-thin silicon and anodic bonding.

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