AN ELECTROTHERMAL SCS MICROMIRROR FOR LARGE BI-DIRECTIONAL 2-D SCANNING

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ABSTRACT

This paper reports the design, fabrication and operation of a two-dimensional (2-D) micromirror that can generate large bi-directional scans at low actuation voltages. The micromirror device has been fabricated by using a unique DRIE CMOS-MEMS process that can simultaneously provide thin-film and single-crystal silicon microstructures. A fabricated micromirror has negligible initial tilt angle, and can perform large bi-directional 2-D optical scans (over ±30°) at less than 12 Vdc. 2-D scanning using this mirror has been demonstrated by obtaining a 14° by 50° angular raster scan pattern.

Keywords: Bi-directional scanning, Large rotation angle, Optical scanner, Two-dimensional (2-D) mirror.

INTRODUCTION

Two-dimensional (2-D) scanning micromirrors are required by applications such as optical displays, biomedical imaging, optical switching, and laser beam steering. Various single-crystal-silicon (SCS)-based 2-D micromirror devices have been reported for these above mentioned applications [1-5]. Most of these optical scanners require high actuation voltages for large rotation angles due to their use of electrostatic actuation. However, optical scanners needed by endoscopic biomedical imaging applications are required to scan large optical angles with high scanning speed, but at low driving voltages.

In prior work, we developed a 2-D micromirror that used electrothermal actuation to achieve large angular displacement at low driving voltages [6]. However, its unidirectional operation and large initial tilt angle complicated the packaging and optical design. These issues are resolved in this new mirror design by using two sets of large-vertical-displacement (LVD) microactuators [7], which keep the mirror surface parallel to the substrate and also provide bi-directional scanning capability.

In this paper, we report the design, fabrication, and operation of a new 2-D micromirror device which has a small initial tilt angle and can perform large bi-directional scans at low dc voltages.

MICROMIRROR DESIGN

The SEM of a fabricated micromirror, highlighting the electrothermal actuators, is shown in Fig. 1. The

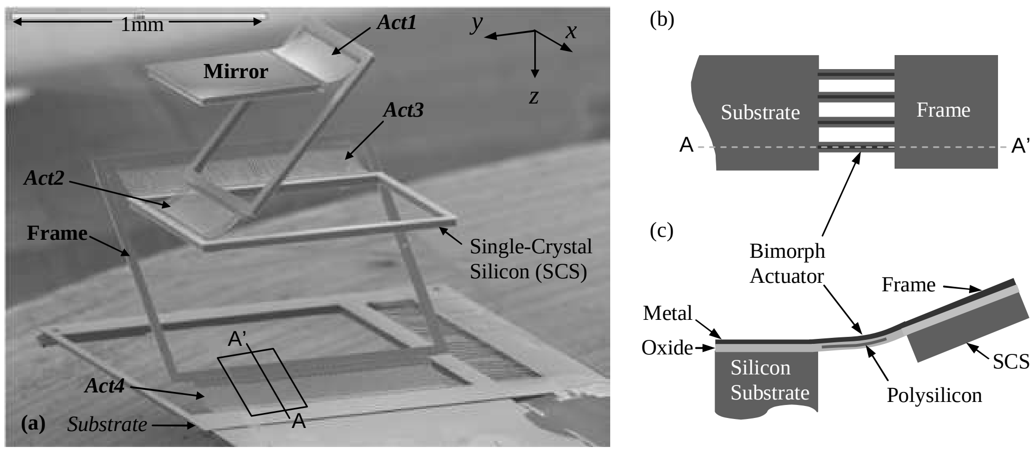

Fig. 1: Micromirror design. (a) SEM of a fabricated device, highlighting the 4 bimorph actuators. (b) Top view of the

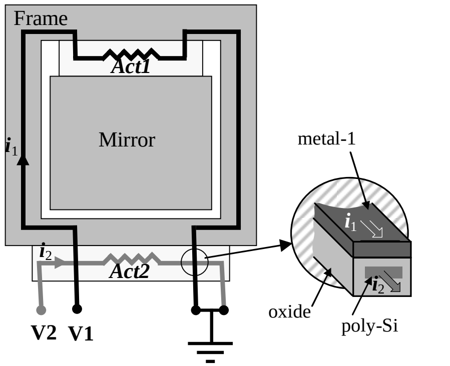

Fig. 2: Wiring schematic for the LVD actuators. Inset: Section of an *Act2* bimorph beam showing that *Act1* current (i_1) is carried by metal-1 layer.

aluminum-coated mirror plate is 0.5mm by 0.5mm in size, and is attached to a rigid silicon frame by a set of aluminum/silicon-dioxide bimorph beams, referred to as actuator 1 (*Act1*). This frame is connected to a second outer frame through an identical bimorph actuator (*Act2*). *Act1* and *Act2* together form an LVD microactuator set, in which the curls of the two sets of bimorph beams compensate each other resulting in zero initial tilt of the mirror plate. As shown in Fig. 1(c), polysilicon resistors embedded in the bimorph beams are used for electrothermal actuation. Bi-directional 1-D line scanning is possible by alternately applying voltage to actuators *Act1* and *Act2*. In order to enable 2-D scanning, a second set of LVD actuators (*Act3* and *Act4*) is attached to the first, as shown in Fig. 1(a). The orthogonal orientation of the two sets of LVD actuators results in two perpendicular axes of rotation for the mirror. The primary mirror-rotation direction for actuators 1, 2, 3, and 4 are along $+y$, $-y$, $+x$, and $-x$, respectively, if thermal coupling between the actuators is negligible.

In order to enable independent electrical excitation for each of the four actuators, a wiring schematic as shown in Fig. 2 is used. The metal-1 Al layer on top of the bimorph beams is electrically divided into several paths to carry the different actuation currents for the inner actuators. As seen in the inset of Fig. 2, the actuator's own actuation current, flowing though the polysilicon layer, is electrically isolated from the metal-1 current by a thin oxide layer.

Each side of the three rectangular frames is 40 μm wide, and has a 40-μm-thick SCS layer under it to provide rigidity and thermal conduction to the substrate. The heating element in the bimorph beams is a set of 200-μm-long, 7-μm-wide polysilicon strips oriented along the beams. As the applied current through the embedded polysilicon resistor increases during actuation, the temperature of the bimorph

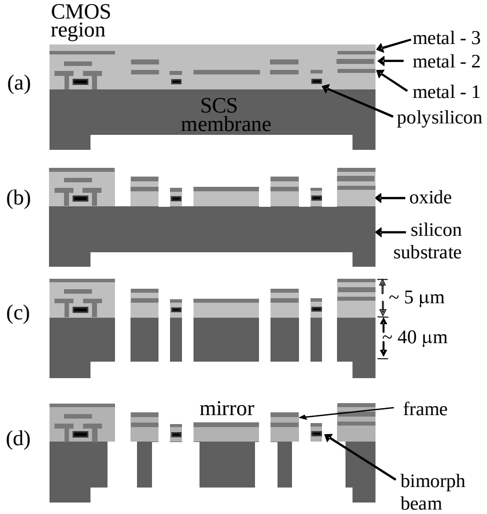

Fig. 3: DRIE CMOS-MEMS process. (a) Backside Si etch. (b) Oxide etch. (c) Deep Si trench etch. (d) Si undercut.

greater thermal coefficient of expansion than the bottom silicon dioxide, the bimorph beams bend downward with increasing temperature, and this results in a downward angular displacement of the attached mirror/frame.

DEVICE FABRICATION

The micromirror is fabricated using a deep-reactive-ion-etch (DRIE) CMOS-MEMS process [8]. The process flow, outlined in Fig. 3, uses only four dry etch steps and can simultaneously produce both thin-film and bulk-Si microstructures. The process starts with a backside anisotropic silicon etch to form a 40-μm thick SCS membrane (Fig. 3(a)). This SCS membrane is required to keep the mirror flat, and it also provides rigidity to the movable frames. The second step is a frontside anisotropic oxide etch that uses the CMOS interconnect metal (i.e., Al) as an etching mask. Next, a deep silicon trench etch is performed to release the microstructure (Fig. 3(c)). The last step is an isotropic silicon etch, performed to undercut the silicon to form bimorph thin-film beams which are about 2 μm thick (Fig. 3(d)). These thin-film beams provide z-axis compliance for out-of-plane actuation, and form bimorph actuators with an embedded polysilicon heater (Fig. 1(c)). There is no substrate or other microstructures directly above or below the mirror microstructure, so large actuation range is allowed. The initial tilt angle of a fabricated mirror plate is less than 0.5°, and its rest position is 1.24 mm above the

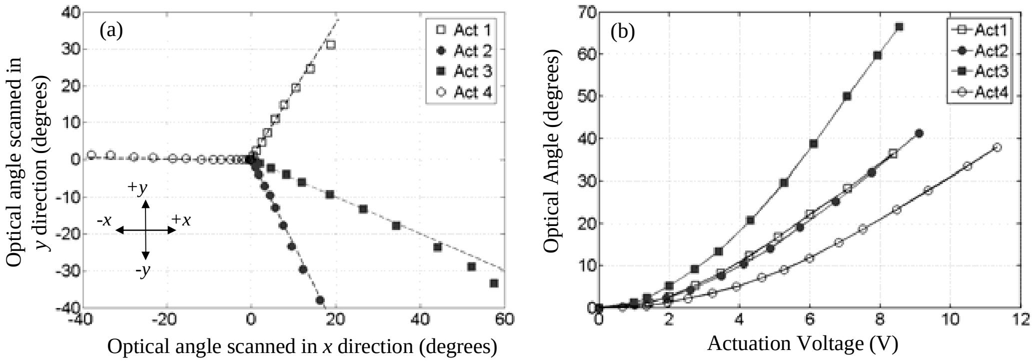

Fig. 4: (a) Plot showing the optical angles scanned in 2D space when each actuator is individually actuated. (b) Plot of the effective optical angle scanned versus actuation voltage for each actuator. *Act4* scans along –*x*, while *Act1*, *Act2* and *Act3* scan at +60°, -66°, -28° with respect to the *x*-axis, respectively.

EXPERIMENTAL RESULTS

An experimental setup with a laser beam incident on the mirror and dc voltages applied to the actuators was used to determine the static 2-D scanning response of each actuator. Fig. 4(a) shows the 2-D line scans obtained by actuating each actuator individually, in which only *Act4* scans along its primary axis (-*x*) while the other scan lines deviate from their primary axes. The corresponding scan-angle versus actuation-voltage characteristics for each of the four actuators are shown in Fig. 4(b). This micromirror device scans optical angles greater than ±40° in the *x*-direction, and over ±30° in the *y*-direction at dc actuation voltages less than 12 V. The deviation of a line scan from its primary axis in Fig. 4(a) is caused by thermal coupling between the actuators. Since *Act4* is directly connected to the silicon substrate it is least affected by thermal coupling, and this can be observed in Fig. 5(a), where *Act4* scanned consistently along the –*x* direction for different *Act1* bias voltages. Thermal coupling between the actuators can be modeled by extending the LVD electrothermal model reported in [9, 10].

A linear correlation between the optical scan angle and the polysilicon resistance for each of the four actuators was observed, as shown in Fig. 5(b). This correlation allows for independent control of the rotation angle of each actuator by monitoring the resistance of each individual polysilicon heater.

2-D SCANNING

2-D scanning using this device was demonstrated by simultaneously exciting both *Act1* and *Act4* actuators with small ac voltage signals. The frequency and phase of the ac signals were varied in order to generate the Lissajous figures shown in Fig. 6. The micromirror exhibits resonant peaks at 870 Hz, 452 Hz, 312 Hz, and 170 Hz. A 2-D raster-scanning pattern was generated

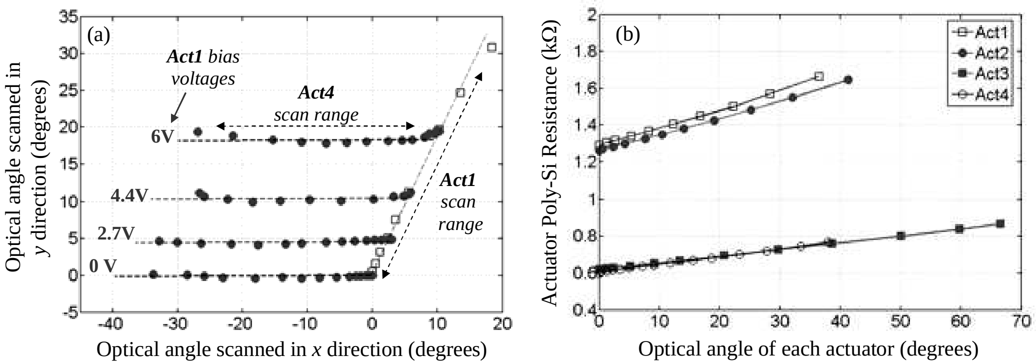

Fig. 5: (a) Plot showing the linear scan pattern during static 2-D scanning of *Act1* and *Act4* only. *Act4* was actuated at

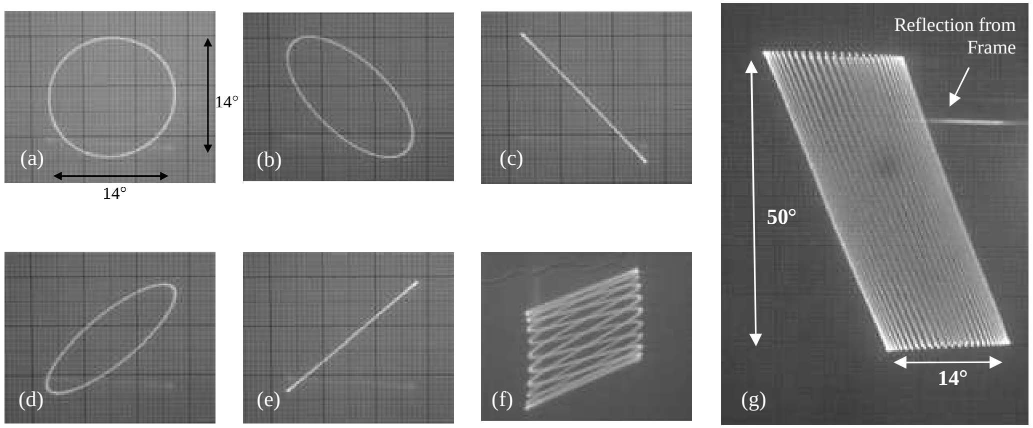

Fig. 6: Photographs of 2-D scan patterns. (a)-(e) Lissajous figures scanned by the micromirror by varying only the phase of the excitation signals. (f) Lissajous figure scanned at an excitation frequency ratio of 1:10. (g) Resonance scan pattern obtained when *Act1* was supplied with 1 Vdc plus 1 Vac at its resonance of 870 Hz, and *Act4* was supplied with 2 Vdc plus 2 Vac at 15 Hz.

by the micromirror when *Act1* and *Act4* were simultaneously actuated, with *Act1* operating at its resonance. As shown in Fig. 6(g), 58 parallel lines were scanned in a raster-scan pattern by the laser beam covering a 14° by 50° parallelogram angular area.

CONCLUSION

An electrothermally-actuated, bi-directional scanning 2-D micromirror was successfully demonstrated. 2-D optical scan angles larger than ±30° have been obtained at driving voltages less than 12 V. The mirror fabrication process is mask-less, uses only dry etch steps, and is completely compatible with foundry CMOS processes. Since this fast-scanning micromirror scans large optical angles at low actuation voltages, it is suitable for use in biomedical imaging applications.

ACKNOWLEDGEMENT

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