A Metal-Coated Polymer Micromirror for Strain-Driven High-Speed Multiaxis Optical Scanning

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***Abstract*—We have developed a new polymer-based micromirror device capable of high-speed multiaxis out-of-plane scanning motion. The whole device structure integrates a metal-coated three-dimensional polydimethylsiloxane micromirror structure with an optically smooth surface and a single layer of silicon-on-insulator electrostatic comb-drive actuators. The high-strain mechanical elasticity of the polymer material allows for translating the in-plane comb-drive motions into three-degree-of-freedom scanning motion with a single actuator layer. The simple structure design and rapid response characteristics of the demonstrated device may lead to high-yield high-performance scanning micromirror technology.**

***Index Terms*—Electrostatic actuation, microelectromechanical devices, multiaxis optical scanning, polymer micromirror, three-dimensional (3-D) elastomer microstructures.**

SCANNING micromirror technology plays a critical role in optical switching, imaging, and beam steering applications that require miniaturization, light weight, low energy consumption, and reduced manufacturing complexity. With the advancement of microelectromechanical systems (MEMS) technology, a large number of scanning micromirrors have been demonstrated for a wide variety of applications including optical communications [1], optical microscopy [2], [3], display technology, and biological detection [4]. The key functionality to the MEMS optical scanning mirror is micrometer-scale actuation of their mirror surface with multiple degrees of freedom [5], [6] and fast response [1]. One of the most common approaches to driving a MEMS scanning micromirror in previous work is electrostatic actuation using comb drives due to their complementary metal–oxide–semiconductor (CMOS) compatibility, high speed, and low power consumption. There are two other major advantages with this approach: 1) both of the micromirror component and the actuator can be fabricated using standard silicon micromachining and 2) the force generated by comb drives is constant and well predicted regardless of the electrode engagement length, thus making it easy to control the motion of scanning mirror [7]. However, a single comb drive can only generate one-dimensional motion, which usually lies parallel to the substrate plane [6], [8]. Previous studies show that this approach has the shortcoming that it requires multilayer structures and relatively complex mechanisms to achieve multiaxis manipulation of the micromirror component [3], [5], [9], making the fabrication processes challenging and time-consuming.

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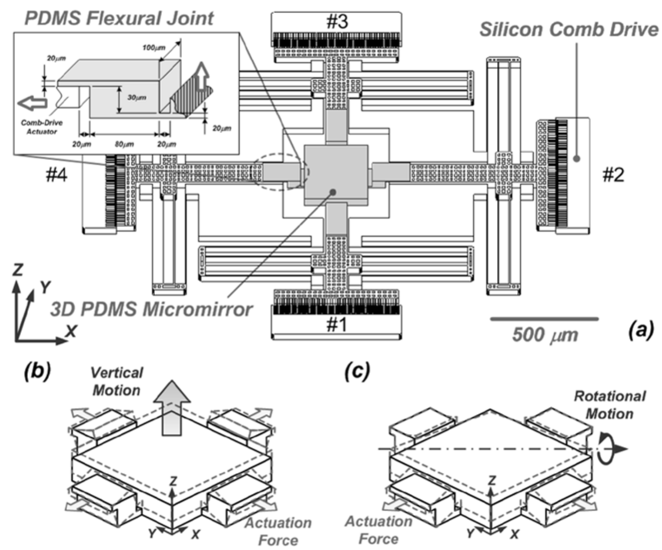

Fig. 1. (a) Schematic drawing of polymer-based scanning micromirror with single-layer silicon comb drives. (b) Vertical motion of micromirror. (c) Rotational motion of micromirror.

In this letter, we demonstrate a new CMOS-compatible scanning micromirror technology. Our approach employs an elastomeric microstructure which is reversibly deformable under mechanical strain introduced by comb drives. The use of three-dimensional (3-D)-shaped elastomer in MEMS allows us to achieve multiaxis scanning motion without increasing the structural complexity of the silicon comb-drive system. Fig. 1 illustrates a device that we present in this letter. It consists of two major parts: 1) multiple comb drives on a silicon-on-insulator wafer and 2) a 3-D polydimethylsiloxane (PDMS) micromirror structure connected to each of the comb drives via its flexural joint. PDMS is an organic elastomer, and it has excellent mechanical flexibility and large maximum strain limit near 40% (for silicon material, it is $\sim$1%.) The PDMS microstructure is fabricated using soft lithography [10]. The soft lithography allows us to fabricate 3-D PDMS microstructures based on replica molding. With its manufacturability, mechanical flexibility, and robustness, PDMS serves as an excellent structural material of the flexural joints, which are the key device components to achieve the multiaxis mirror motion in our device.

The connections between the PDMS micromirror and the comb drives translate the in-plane motion of the comb drives into the out-of-plane motion of the mirror through strain-induced elastic deformation. The entire PDMS microstructure including the mirror and the four flexural joints can be viewed as a four-bar linkage mechanism with two sliders, one of which moves in the lateral direction while the other moves in the vertical direction. While the mechanical strain is induced, it will only be concentrated on the flexural joints, which prevents the distortion of mirror surface. This mechanism yields two modes of mirror motion: 1) rotational mode and 2) vertical mode. In the rotational mode, actuating two orthogonal (#1 and #2) comb drives results in rotational motion of the mirror with respect to the axes along its diagonal. Furthermore, actuating another set of orthogonal comb drives (#3 and #4) permits rotation in the opposite direction, which doubles the rotational angle range for the same axis. Similarly, the rotation to the axis perpendicular to the above-described axis can be achieved by actuating other combinations of comb drives (e.g., comb drives #2 and #4; #1 and #3). On the other hand, actuating all four comb drives or comb drives facing each other results in the vertical mode of the micromirror. Thus, the optical scanning micromirror can achieve out-of-plane motion with three degrees of freedom. The single-layer actuator design can minimize the mechanical crosstalks between the actuation motions in the different axes, which are difficult to avoid in previous designs, and allows the device to be fabricated in a simple manner.

To integrate the 3-D PDMS microstructure and the silicon actuators all together, we developed a new CMOS-compatible fabrication method named "soft lithographic liftoff and grafting (SLLOG)." The SLLOG process involves release of soft-lithographically fabricated 3-D PDMS microstructures from micromolds and precise attachment of them onto a separate silicon-based MEMS structure. This process permits seamless integration of the PDMS micromirror structure on the silicon comb drives with ± 2-μm alignment accuracy. This accurate alignment is made possible by introducing a fluidic microassembly technique [11]. In order to make the surface of the PDMS mirror optically reflective, we coated the device with an Au film ($\sim$400 Å) using evaporation after oxygen plasma surface treatment to enhance the adhesion of Au to the PDMS surface. Fig. 2 shows scanning electron microscope (SEM) images of the fabricated device and an optically scanned profile of the micromirror surface. The figure shows a 3-D PDMS microstructure that has been successfully integrated with the silicon comb drives. From SEM images, it has also been observed that there is no crack on the Au film coated on the PDMS surface. Furthermore, the resulting flatness of the fabricated mirror surface is comparable to those of the polysilicon micromirrors demonstrated in previous work [12]. If a higher degree of surface flatness is required, a single-crystal silicon mirror can be easily bonded onto the surface of the PDMS microstructure using room-temperature oxygen plasma surface treatment.

We conducted optical experiments in the atmospheric environment to characterize the scanning performance of the micromirror device. We first employed laser vibrometry to measure the vertical motion of the PDMS micromirror. A laser beam guided by a set of mirrors was focused on the PDMS mirror surface using an objective lens. The focused laser spot size was about 20 μm in diameter. The vertical motion of

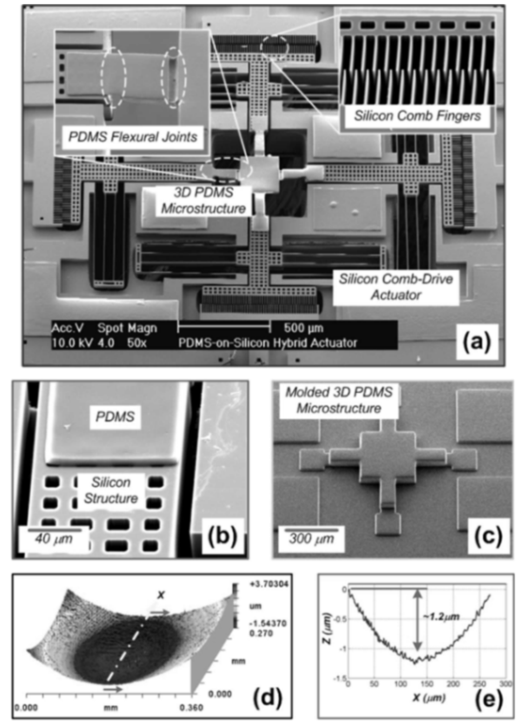

Fig. 2. Fabricated scanning micromirror. (a) SEM images of entire device. (b) Bonding interface between PDMS and silicon. (c) Molded 3-D PDMS microstructure by soft lithography. (d) and (e) Optical interferometric profile measurement results of mirror surface.

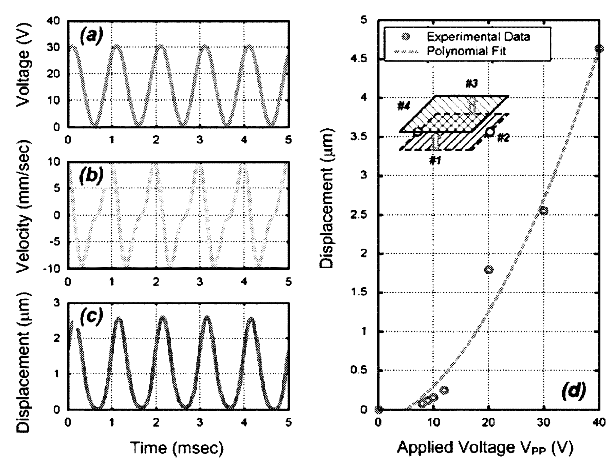

Fig. 3. Vibrometry results of vertical motion measurement. (a) Voltage signal applied on comb drives. (b) Velocity signal detected by laser vibrometer. (c) Calculated vertical displacement of mirror by integrating detected velocity signal. (d) Measured vertical motion of mirror corresponding to voltage applied on comb drives at 1 kHz.

the mirror was detected while activating two facing comb drives. Fig. 3(a)–(c) shows the time-domain measurement results of vertical motion driven by a 30-V peak-to-peak actuation voltage at 1 kHz with a 15-V dc offset. The detected displacement signal profile in Fig. 3(c) shows little distortion with respect to the sinusoidal input actuation load in Fig. 3(a), which indicates excellent linearity of the actuation motion as we originally designed. Fig. 3(d) shows measured vertical displacement of the mirror as a function of the 1-kHz actuation voltage. Vertical displacement of about 4.6 μm was achieved at a 40-V peak-to-peak actuation voltage with a 20-V dc offset.

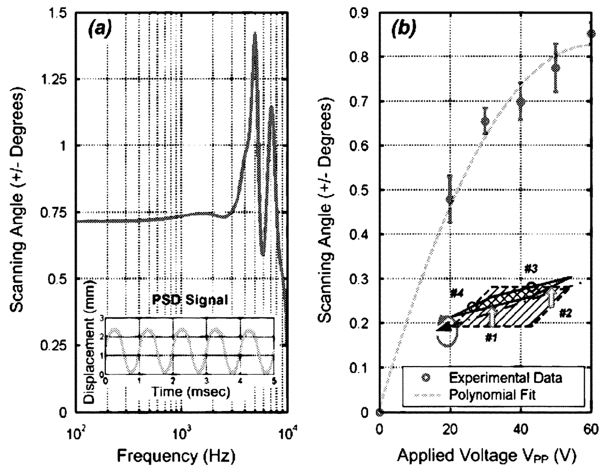

Fig. 4. Experimental results of rotational motion measurement. (a) Frequency response of micromirror rotational motion. The figure inset shows positional signal detected using the PSD at a sinusoidal actuation voltage of 1 kHz. (b) Static scanning mirror rotational angle estimated from the experimental results at 1 kHz as a function of actuation voltage.

In addition, the resonant frequency was measured to be about 5.0 kHz from the vertical motion vibrometry measurement.

We next characterized the rotational motions of the mirror by measuring the position of light reflected from the mirror surface. A multimode optical fiber with an embedded collimator was used to guide incident light from a He–Ne laser to the mirror surface. The light beam reached the mirror surface with a 500-μm diameter at a divergence angle of 14 mrad. The reflected beam was projected onto a two-dimensional position-sensitive detector (PSD) located about 140 mm from the device. The tested device was aligned such that the reflected light spot moves along the vertical axis of the PSD panel when the reflector rotates. The position of the light spot hitting the PSD panel was detected in terms of the output voltage of the detector. The rotational motion of the mirror was measured with two orthogonal comb drives activated, and the rotational angle was calculated from the displacement signal detected by the PSD.

Fig. 4(a) shows the dynamic spectrum of the optical scanning performance with the actuation frequency varying from 100 Hz to 10 kHz. The actuation signal has a 40-V peak-to-peak actuation voltage and a 20-V dc offset here. The result shows that a rotational angle as large as $\pm 1.43^\circ$ can be achieved at the lowest-mode resonant frequency of about 5.0 kHz. This rotational angle is approximately 2.2 times as large as the one driven at the low frequency regime. The figure inset shows the time-domain positional signal along the vertical axis of the PSD panel at 1 kHz, which corresponds to the rotational scanning motion of the fabricated micromirror at the same frequency. The little distortion found in the scanning signal indicates linear rotational motion response of the device. The flatness of the mirror surface for dynamic actuation was also verified by applying laser vibrometry to five locations on the diagonals of the mirror plane. The result shows the mirror can maintain its flatness during the dynamic scanning. In addition, the crosstalk of the rotational motions with respect to two orthogonal axes was also investigated by simultaneously monitoring the time domain signals for the both motion. The crosstalk was found less then 8% for open-loop actuation.

The rotational angle amplitude remains nearly constant at frequencies far below the resonant frequency as shown in Fig. 4(a). This allows us to use the data at 1 kHz to extrapolate the static performance with an error less than 5%. This approach eliminates the effect of the low frequency background noise from the experimental setup and the environment on the characterization of the static scanning performance. Fig. 4(b) shows the extrapolated static optical scanning angle of the micromirror as a function of the actuation voltage. The data show a scanning angle of about $\pm 0.85^\circ$ at a 60-V peak-to-peak actuation voltage with a 30-V dc offset.

In summary, we have developed a new multiaxis optical micromirror device incorporating single-layer silicon comb-drive actuators and a metal-coated 3-D PDMS microstructure. The light steering performance of the micromirror device under dynamic strain introduced to its PDMS flexural joints was experimentally tested. The results clearly demonstrate the device's capability of generating both vertical and rotational fast-response motions with a simple design, which is difficult to achieve with a single actuation layer for conventional silicon-based MEMS scanning mirror devices. This work proves that our new approach combining a polymer material with silicon micromachined devices can lead to the development of a multiaxis MEMS scanning mirror device without complicated fabrication and external actuation mechanism. The developed device may have potential to integrate with other microsystems and find a wide variety of applications, especially in lab-on-a-chip fluorescence biological assays.

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