A BI-DIRECTIONAL LARGE-STROKE ELECTROTHERMAL MEMS MIRROR WITH MINIMAL THERMAL AND TEMPORAL DRIFT

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ABSTRACT

This paper reports a novel bi-directional electrothermal MEMS mirror with its mirror plate's position insensitive to ambient temperature and stable over time. In contrast, the electrothermal MEMS mirrors demonstrated previously are unidirectional and the position of the mirror plate changes significantly with ambient temperature and drifts over time. The new MEMS mirror design has been fabricated and characterized. The bi-direction piston scan range reaches ±177 µm. The position of the released MEMS mirror plate is only 0.2 µm above the substrate surface, and changes merely 0.5 µm for a large ambient temperature change of 0-100°C. The temporal drift is just 0.7 µm over 600 hours. Both the thermal and temporal drift are reduced by nearly two orders of magnitude compared to previous unidirectional thermal bimorph MEMS mirrors.

INTRODUCTION

Fourier transform spectrometers (FTS) are powerful tools for various chemical and biomedical sensing applications and hazardous materials detection. Compared to the grating-based spectrometers, FTS has the advantages of high spectral resolution, wide spectral range and high SNR, but, the conventional FTS are bulky and expensive and for lab use only. In the recent years, as the trend of portable instrumentation for on-site applications grows, it is highly demanding to develop miniaturized FTS systems that can be used for real-time in-field analysis. MEMS technology has been exploited to transform FTS into portable or even handheld low-cost devices [1-4]. Many MEMS based FTS have been demonstrated utilizing electrothermal [1], electromagnetic [2], or electrostatic [3] MEMS movable mirrors. The larger the scan range of the MEMS mirror, the finer the spectral resolution can be achieved. Thus, one of the key requirements to MEMS mirrors for FTS is large piston displacement in the order of hundreds of microns. Among the various actuation mechanisms, electrothermal bimorph actuation has the advantage of generating large scan range without the need of operating at resonance. However, it was found from our prior MEMS FTS systems based on electrothermal bimorph actuators [4] that the initial position of the mirror plate changes considerably with ambient temperature and also drifts over time. This effect reduces not only the spectral resolution but also the interferogram repeatability. Furthermore, the displacement of the current electrothermal bimorph actuator is unidirectional, leading to asymmetric interferograms.

In this paper, we present a novel bi-directional electrothermal micromirror design. In this new design, the mirror plate is driven both above and below the substrate with the initial position maintained at the substrate surface level. Consequently, both the temporal and thermal drift are compensated by the symmetric upward and downward actuation.

MEMS DESIGN AND FABRICATION

The Principle of Electrothermal Bimorph Actuation

The electrothermal bimorph actuation is accomplished by the temperature change via Joule heating, which results from applying the electrical current through the embedded heater of the bimorph.

Two layers of materials with different coefficients of thermal expansion (CTEs) constitute the basic structure of a thermal bimorph. Aluminum (Al) and silicon dioxide (SiO_2) are selected to form the bimorph due to their large CTE difference, which leads to large actuation angle and large vertical displacement. So the main processes of fabricating the bimorph are Al and SiO_2 deposition and patterning on silicon wafers. There exist significant residual stresses in the bimorph, including thermal stress due to various deposition temperatures and intrinsic stress introduced during deposition, which leads to the initial curling or bending of the bimorph after being released from the substrate. For a released Al/SiO_2 bimorph, the initial curling always bends towards the Al side since Al has higher CTE. Upon a temperature change, an angular deformation is induced by the difference of the CTEs of the two layers. When the temperature increases, the bimorph bends to the side with lower CTE. As shown in Fig. 1(a), the bimorph with the Al layer on the top initially curls upward after released, and bends downward when heated up; the bimorph with SiO_2 on top has exactly the opposite behavior, as shown in Fig. 1(b).

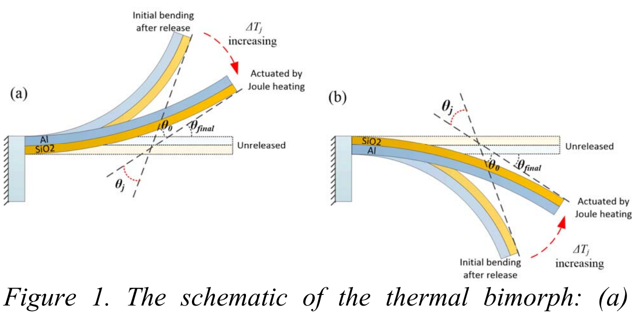

Figure 1. The schematic of the thermal bimorph: (a) upward bimorph, and (b) downward bimorph.

A properly designed inverted-series connected (ISC) structure [5] is employed to convert the angular deformation into vertical displacement. The combination of an inverted bimorph and a non-inverted bimorph compensates each other's tilt and lateral shift, so that pure vertical displacement can be achieved. According to the connection sequence of the inverted and non-inverted bimorph, the ISC structures can either pop up above the substrate (U-ISC) or fall down below the top surface of the substrate (D-ISC) after they are released from the substrate, as shown in Figs. 2(a) and 2(b), respectively. Note that upon thermal heating, U-ISC structures generate downward displacement while D-ISC structures generates upward displacement. In our previous works, some electrothermal MEMS mirrors based on either D-ISC or U-ISC design have been reported [5, 6] as shown in Fig. 2(c) and 2(d). The actuation of either D-ISC or U-ISC is unidirectional.

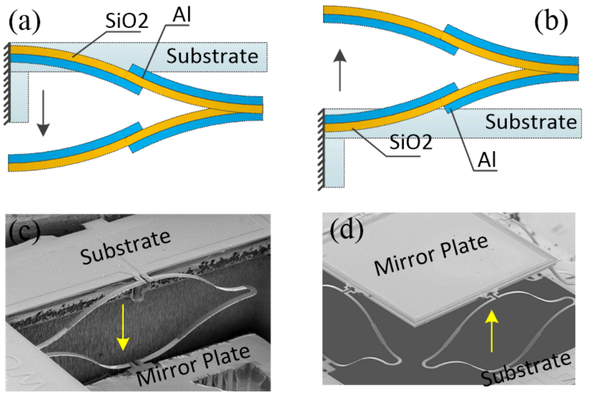

Figure 2. Thermal bimorph actuator designs: (a) D-ISC, (b) U-ISC, (c) D-ISC MEMS, and (d) U-ISC MEMS.

Bi-directional Actuation Design Concept

In this work, we propose a new electrothermal MEMS mirror that can be actuated bi-directionally.

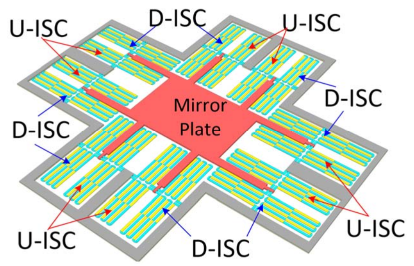

Figure 3. The concept of the bi-directional MEMS mirror

As schematically illustrated in Fig. 3, both U-ISC and D-ISC structures are integrated and properly arranged on a single MEMS mirror device, where the mirror plate stays at the substrate surface level. There are 8 U-ISCs and 8 D-ISCs that are symmetrically connected around the central mirror plate. Each U-ISC or D-ISC unit includes multi-level ISC structure, so that the piston motion range of the MEMS can be extended. When all the U-ISCs are actuated, the mirror plate moves downward, as shown in Fig. 4(a), while the mirror plate moves upward when all the D-ISCs are actuated, as shown in Fig. 4(b).

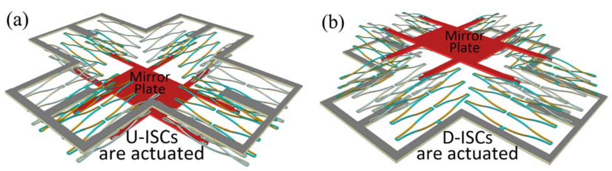

Figure 4. The working principle: (a) downward motion, and (b) upward motion.

Fabrication Result

The device is fabricated using a hybrid bulk and surface micromachining process on SOI wafer [1]. The fabrication mainly includes SiO_2 and Al deposition and pattering for bimorph structures, titanium (Ti) deposition and patterning for embedded heaters, and silicon DRIE for device releasing. The process flow is shown in Fig. 5.

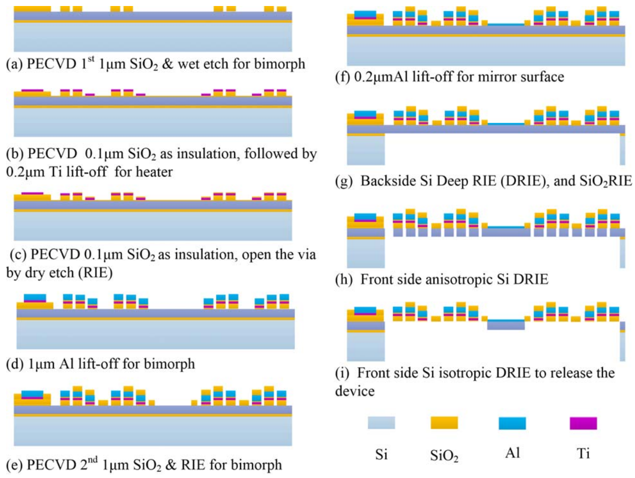

Figure 5. The cross-sectional view of the fabrication process flow of the bi-directional MEMS.

Fig. 6(a) shows an SEM of a fabricated bi-directional MEMS mirror, where the mirror plate, with the size of 1.5mm×1.2mm, is almost flat to the substrate surface, only 0.2 μm above the substrate surface. Fig. 6(b) shows an SEM of a pair of U-ISC and D-ISC structures. The upward residual stress in the U-ISC structure is balanced by the downward residual stress in the D-ISC, and thus the mirror plate does not pop up and fall down when there is no differential heating applied to the U-ISC and D-ISC structures. In contrast, Fig. 6(c) shows a previous U-ISC -only MEMS mirror whose mirror plate has an initial elevation above the substrate after being released [4].

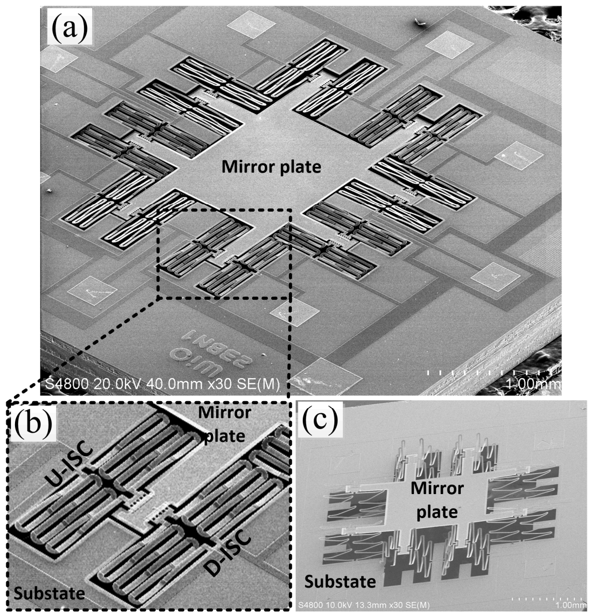

Figure 6. SEMs of fabricated devices. (a) Bidirectional MEMS. (b) Closed-up view of a pair of U-ISC and D-ISC. (c) Prior U-ISC-only MEMS.

EXPERIMENTAL RESULT

Device Characterization

Fig. 7 shows the quasi-static response of the bi-directional MEMS mirror. When a 12 V voltage was applied on all of the U-ISCs while a zero voltage on all of the D-ISCs, a 177 μm downward piston displacement was achieved. When 12 V was applied to the D-ISCs while 0V to the U-ISCS, a 177 μm upward piston displacement was achieved. Thus a bidirectional piston actuation is realized with a total 354 μm physical scan range. According to the frequency response test, the first resonance mode is piston motion with the measured frequency of 563 Hz.

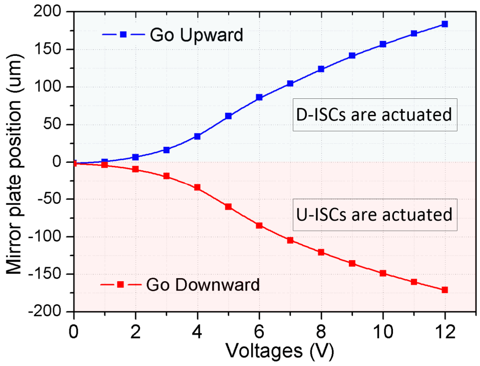

Figure 7. The measured quasi-static piston response.

Temporal & Thermal Drift Test

Fig. 8 shows the measured temporal drift of the mirror plate over time, where the position drift of the bi-directional MEMS mirror was only 0.7 μm over 600 hours, which is a drastic reduction from 35 μm of a previous unidirectional MEMS mirror [4].

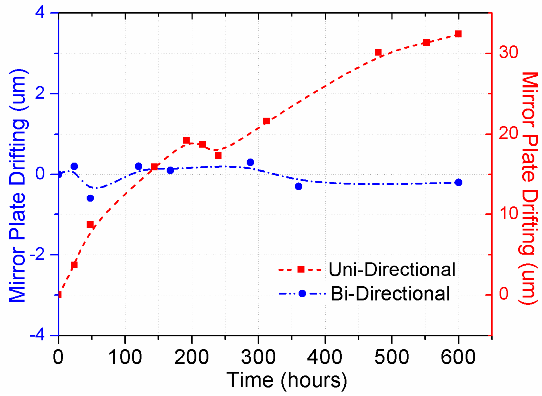

Figure 8. Measured temporal drift of the position of the mirror plate. (Measurement error: ±0.1 μm)

The new bi-directional MEMS design's capability of minimizing thermal drift was also tested. The result is shown in Fig. 9. When the ambient temperature varied from 25°C to 100°C, the mirror plate position of the unidirectional MEMS mirror drifted over 100 μm while the bi-directional MEMS drifted only about 0.5 μm.

When all the ISC actuators are not activated, the mirror plate always returns to its initial position, which is flat to the substrate surface. According to the long-term observation and testing, both the temperature dependence drift and temporal drift of the U-ISCs and D-ISCs are opposite for the position of the mirror plate. Therefore, both the temporal and thermal drift of the MEMS mirror plate are effectively minimized with the proposed vertically-symmetric ISC actuator design.

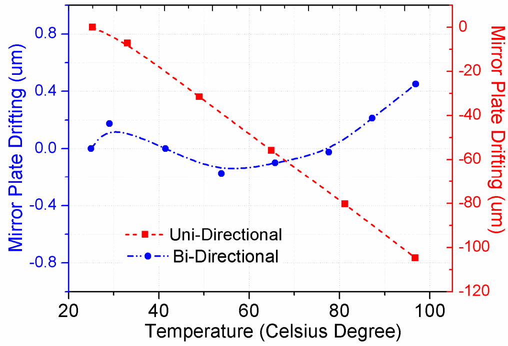

Figure 9. Measured thermal drift of the position of the mirror plate. (Measurement error: ±0.1 μm)

MEMS FTS Demonstration

The large bi-directional scan range and small temporal and thermal drift make the new MEMS design very suitable for FTS. Fig. 10 illustrates the principle of the FTS system. The core of the FTS is a Michelson interferometer, where a fixed mirror and a movable mirror are placed respectively in the reference and sample arm. The light source and the photodetector should be properly chosen to cover the spectral range of interest, which vary from application to application.

In this work, a compact FTS setup shown in Fig. 11 has been built using the bi-directional MEMS mirror whose mirror plate is coated with Al as the reflection surfaces on both sides. So there are two Michelson interferometers formed around the dual-reflective MEMS mirror. On one side of the MEMS mirror plate, a wavelength-stabilized laser (λ = 1310 nm, #TSPL1E06D, Tibtronix. Co., Ltd.) is used as the reference light, which can be used for spectral calibration and correction of the variable velocity of the MEMS scanning [7]. On the other side of the MEMS mirror plate, a broadband light source (#ecoVis, Ocean Optics, Inc.) with the wavelength range of 400nm–2500 nm transmitting through the sample pool is coupled in as the sample light, which contends the spectral information of the specific sample. Both the interferogram signals of the reference laser and the sample light are obtained by a data acquisition (DAQ) system.

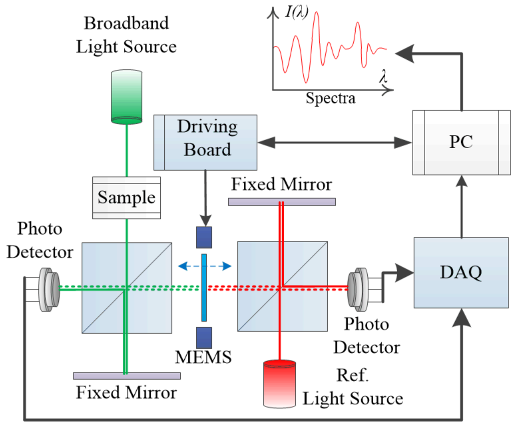

Figure 10. The schematic of the FTS system based on a bi-directional MEMS.

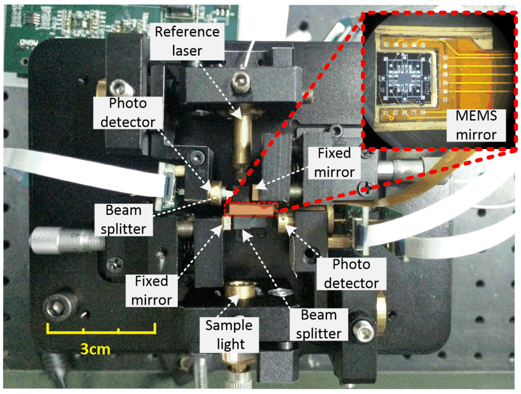

Figure 11. Photo of the compact FTS setup.

An InGaAs photodetector is employed to cover the entire short-wave infrared spectral range from 1400nm to 2400 nm, in which there are two main characteristic spectral peaks of polystyrene--1681.3nm and 2166.4nm. Fig. 12 shows the interferograms of the reference laser and the sample light that transmits through a polystyrene sample, which corresponds to the MEMS mirror plate scanning back from the top to the substrate surface by applying a ramping-down voltage to the D-ISC actuators and then continuing to moving below the substrate surface by applying a ramping-up voltage to the U-ISC actuators. The corresponding maximum OPD of double-sided scan is 267 μm. The interferogram to spectrogram conversion is done via a specific data process, including FFT (Fast Fourier Transform) and Mertz phase correction [8]. The measured spectrum of the polystyrene using the bi-directional MEMS based FTS is plotted in Fig. 13, where the measured peaks are located at 1684.1 nm and 2165.8 nm, respectively, indicating a maximum spectral error of 2.8 nm. The spectral resolution is about 37 cm^{-1}.

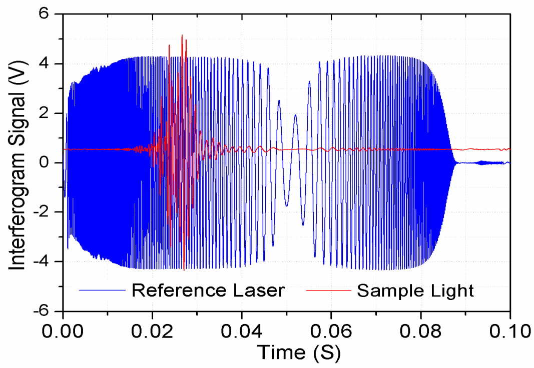

Figure 12. Measured interferogram of polystyrene.

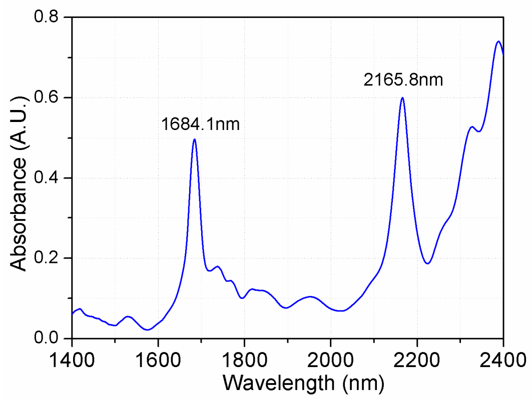

Figure 13. Recovered spectrum of the polystyrene.

CONCLUSION

In this work, we demonstrated a novel large-stoke, stable, bi-directional electrothermal MEMS mirror that is enabled by integrating U-ISC and D-ISC actuators on a single device. Due to the mutual complementarity and restriction between U-ISCs and D-ISCs, the position of the released MEMS mirror plate is flat to the substrate surface, and insensitive to the ambient temperature fluctuation. Both the temporal drift and the thermal drift of this new MEMS mirror have been reduced by nearly two orders of magnitude, compared to the previous unidirectional thermal bimorph MEMS designs [4]. A FTS setup has been built using this bi-directional MEMS mirror, and a functional demonstration is achieved. The much-improved scanning stability of the MEMS mirror will in turn improve the repeatability of the MEMS FTS systems. This provides a promising future for using portable MEMS FTS for various real-time on-site applications.

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