LARGE-STROKE, CONTINUOUS MEMBRANE MEMS DEFORMABLE MIRROR FOR FUTURE SPACE-BASED ADAPTIVE OPTICS

Interim Report

JPL Task 1059

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A. OBJECTIVES

The objective of this work is to develop proof-of-principle fabrication technology for a large-actuator-stroke deformable mirror (DM) that can provide the large wavefront correction that will be needed by a number of planned NASA missions featuring mechanically-flexible space-based telescope apertures.

B. PROGRESS AND RESULTS

Adaptive optical systems for future ultra-large telescopes require optical-quality, large-area, single-face-sheet DMs (concept as shown in Fig. 1 [1]). High-density (e.g. 1000 x 1000) underlying microactuator arrays will be incorporated in these DMs, so low-voltage (~ 50V) operation is essential. Also, thick (>10 μm) single-face-sheet mirror membrane will be needed for large-area DMs, in order to increase the surface quality of the mirror. Micromachined DMs have been reported; however, they require high-voltage operation (200-700V) [2-5], and show marginal surface quality [2,3] or high influence function (inter-actuator coupling) [3,4]. Major requirements of an actuator membrane, for DMs with ~30-cm-diameter mirror membrane, are > 5 μm stroke (> 10λ to λ/15 at λ= 0.5 μm) at ~50 V and > 500 N/m stiffness (>>10 times stiffer than the mirror membrane for lower influence function). Ultimately, optical-quality DMs can be fabricated using the membrane-transfer technique demonstrated by our group [1].

We have fabricated and characterized a series of PZT membrane actuators with various membrane designs, in order to optimize the actuator geometry (Table 1). Fig. 2 (a) shows a photograph of fabricated arrays of actuators, and (b) a schematic illustration of the structure. The actuation principle is as follows: an electric field applied vertically to the piezoelectric layer induces contraction in the lateral direction, causing the membrane to deflect downward (d_{31} mode). It is also possible to apply a field in the lateral direction using a pair of adjacent electrodes patterned on top of the PZT (d_{33} mode).

Actuator vertical deflection (stroke) measurements were taken using a WYKO optical profiler (Fig. 3). Fig. 4 depicts deflection vs. voltage curves for d_{31}- and d_{33}-mode actuators.

The d_{33}-mode actuation usually yields larger deflection, but requires higher voltage [4]; therefore, our focus was on optimizing the d_{31}-mode actuators. The amount of deflection is strongly dependent upon electrode/membrane size ratio, as well as Si membrane/PZT film thickness ratio, as presented in Fig. 5. For membranes 2.5 mm in diameter, the optimized Si/PZT thickness ratio was approximately 6. Optimum electrode diameter was found to be 40%~60% of the membrane diameter. For a 2.5-mm diameter membrane (PZT 2 µm thick, Si 15 µm thick), the measured vertical stroke is 5.4 µm at 50V. More experimental work is underway to further increase the membrane stroke, while maintaining the size, stiffness and low applied voltage; the improved results will be included in a full final report. PZT membrane actuators with spiral and concentric ring electrodes have also been characterized, and shown to give an improvement in deflection for thin Si membranes. However, for Si membrane thickness of 10 µm or greater, plain circular electrodes gave more deflection.

The measured resonant frequency of the membrane is 40 kHz (Fig. 6), far exceeding the bandwidth performance of most MEMS-based deformable mirrors (1~3 kHz). From this measured resonant frequency, the stiffness of the actuator is determined to be approximately 1600 N/m, which exceeds the actuator stiffness requirement for typical large-area, continuous-membrane DMs.

C. SIGNIFICANCE OF RESULTS

Space-based astronomical imaging systems are inherently challenged by the need to achieve near-diffraction-limited performance with lightweight optical components. For many future space-based systems, such diffraction-limited performance will require the use of deformable mirrors as wavefront correctors. NASA is planning ultra-large, lightweight space telescopes for the scientifically critical UV-visible (0.1-1 µm), mid-infrared (3-30 µm) and far-infrared (30-300 µm) wavelength regimes. Missions being considered include SUVO, a 4-8 m UV-visible telescope, SAFIR, an 8-10 m far-IR telescope, and Planet Imager, a 30 m telescope. Launching conventional rigid primary mirrors is prohibitively expensive, so it is planned to deploy either a segmented aperture, as with the James Webb Space Telescope (JWST), or relatively flexible monolithic primary mirrors whose large surface errors are corrected by subsequent active or adaptive wavefront control. These concepts potentially involve wavefront errors much greater than several wavelengths. The key optical component needed for effective wavefront compensation is a large-stroke, continuous-membrane deformable mirror with high actuator density that is scalable to large areas (high actuator count). Our ultimate goal is to develop deformable mirrors meeting the requirements of these demanding missions.

D. FINANCIAL STATUS

The total funding for this task was $200,000, of which $40,000 has been expended.

E. PERSONNEL

Yoshikazu Hishinuma (384) has contributed to the demonstration of the concept.

F. PUBLICATIONS

None.

G. REFERENCES

[1] E. H. Yang and D. Wiberg "A wafer-scale membrane transfer process for the fabrication of optical quality, large continuous membranes," *IEEE/ASME Journal of Microelectromechanical Systems, Vol. 12, No. 6*, Dec. 2003.

[2] T. Bifano *et al.*, “Continuous-Membrane Surface-Micromachined Silicon Deformable Mirror,” *Opt. Eng. 36 (5)*, p.1354 May 1997.

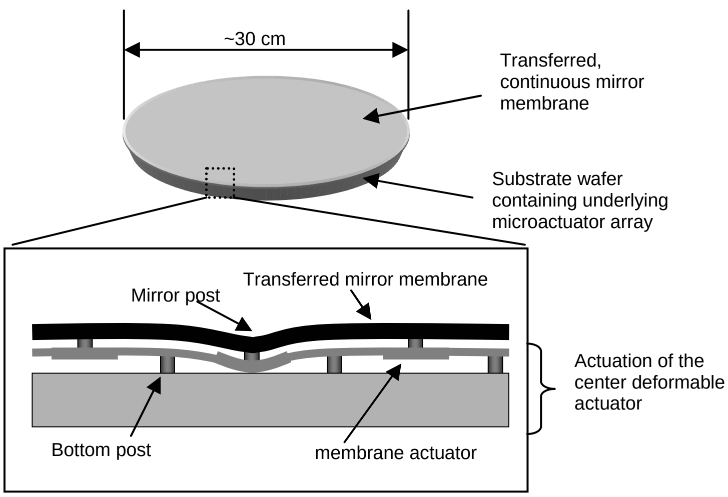
[3] J. Mansell *et al.*, “Silicon Deformable Mirrors and CMOS-based Wavefront Sensors,” *SPIE International Conference*, *High-Resolution Wavefront Control*, San Diego, USA, Aug., 2000, pp. 15-25.

[4] G. Vdovin, “Optimization-based Operation of Micromachined Deformable Mirrors,” *SPIE Conf. On Adaptive Optical System Technology*, Kona, Hawaii, March 1998, pp. 902-909.

[5] M. J. Mescher, “A Novel High-Speed Piezoelectric Deformable Varifocal Mirror for Optical Applications”, *Proceedings of IEEE, Sensors*, June, 2002, 1, pp.541-546.

Table1: Membrane actuator design parameters

PZT thickness	1~5 µm
Silicon membrane thickness	2~20 µm
Membrane diameter	0.5, 1.0, 2.5mm
Electrode types	plain circle, lateral (d33) mode, concentric rings, spiral, segmented
Electrode diameter	30~80% of membrane



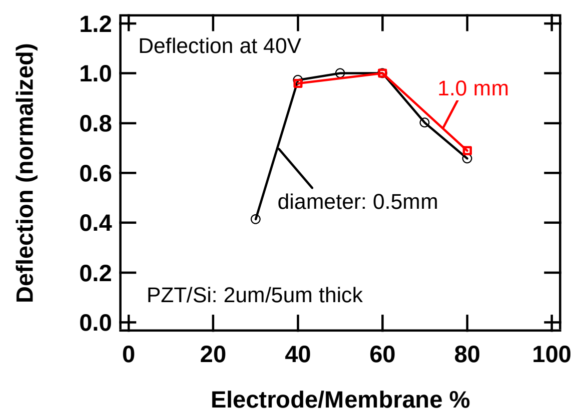


Fig.1 Concept schematic for a large-area continuous membrane deformable mirror (DM) [1]. For quality mirror surface, the mirror membrane thickness is required at > 10 µm.

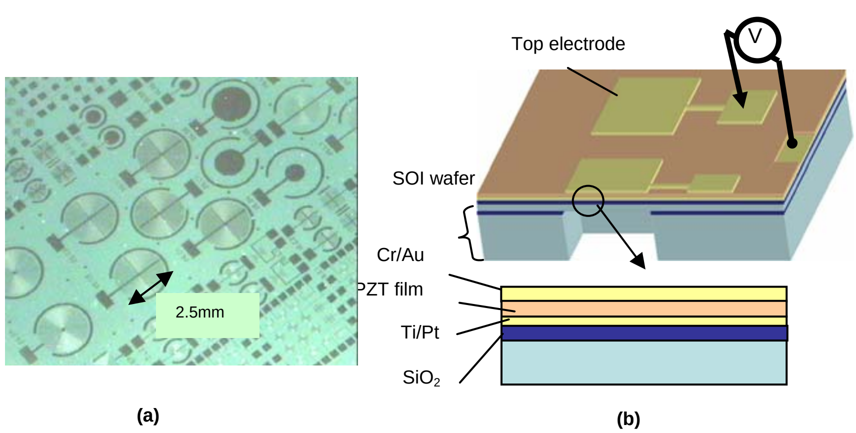


Fig.2 (a) A photograph of PZT actuator array. (b) The structure of the PZT unimorph actuator.

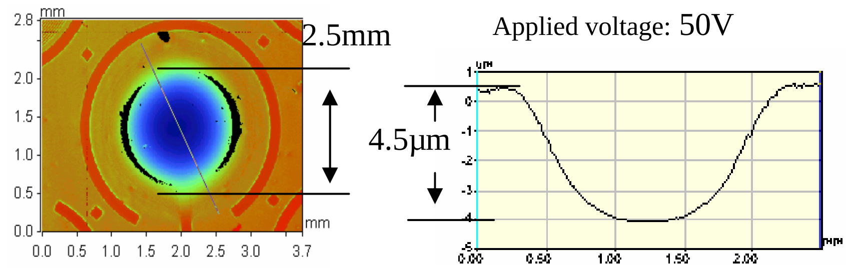
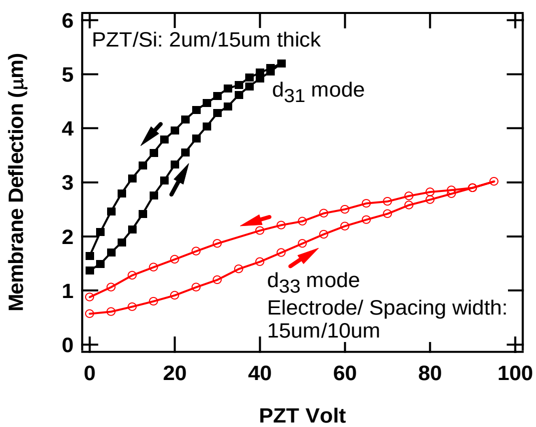


Fig. 3: Deflection profile of a PZT unimorph actuator. Thickness of PZT/Si are 2µm/15µm.

Fig. 4: Deflections of PZT unimorph membrane (d_{31} & d_{33} modes), diameter of 2.5mm. Each membrane is poled prior to this measurement.



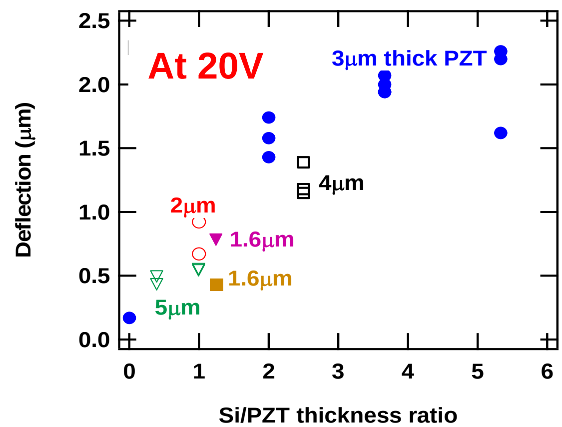


Fig. 5: (a) Membrane deflections for different electrode sizes. (b) Deflections at 20V for actuators with various Si/PZT thickness ratios.

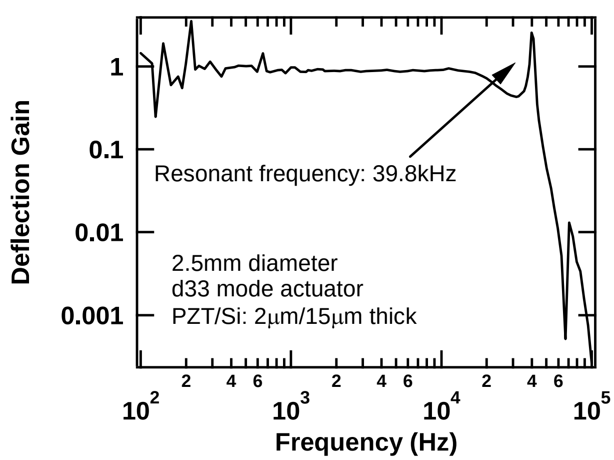


Fig. 6: Frequency response of PZT unimorph actuator.

ADVANCED OPTICAL SYSTEMS