SINGLE-CRYSTAL SILICON CONTINUOUS MEMBRANE DEFORMABLE MIRROR WITH PZT UNIMORPH MICROACTUATOR ARRAYS

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ABSTRACT

For the first time, this paper reports on the piezoelectric unimorph-based deformable mirror (DM) with continuous single-crystal silicon deformable membrane. PZT unimorph actuator of 2.5mm diameter with optimized PZT/Si thickness and design showed a deflection of 5μm at 50V. DMs consisting of 10μm thick single-crystal silicon membranes supported by 4×4 actuator arrays were fabricated and optically characterized. The fabricated DM showed a stroke of 2.5μm at 50V with resonant frequency of 42 kHz and influence function of ~25%.

INTRODUCTION

Ultra-large, light weight space telescopes are envisioned by NASA. Deploying conventional, rigid primary mirrors in space is prohibitively expensive. Therefore, it is planned to construct telescopes with either segmented apertures or with relatively flexible monolithic primary mirrors whose large surface errors can be corrected using subsequent active or adaptive wavefront control **[1]**. These concepts could potentially involve wavefront errors greater than several wavelengths. Thus, the key optical component needed for effective wavefront compensation is an optical quality, large-stroke, continuous-membrane DM with high actuator density over large areas (Fig. 1). DMs with mirror surface quality of <10 nm can be fabricated using the membrane transfer technique demonstrated by our group **[2]**. Other desirable characteristics of DMs include mirror actuation of >2μm at <50V (<1μW per pixel), with a bandwidth of > 1kHz, and influence function of <30%. Micromachined DMs have been previously reported (Table 1), however they needed high-voltage operation due to electrostatic operation (100-700V) **[3-7]**, small stroke (<2μm) **[3-5, 7]**, marginal surface quality **[3,5]**, or high influence function (crosstalk) **[4, 5]**. In this paper, we present a single-crystal silicon continuous membrane DM, incorporated for the first time with underlying piezoelectric unimorph actuators.

	Require ments	Boston University[3]	Stanford[4]	Grenoble, France[6]	Bell Lab[7]	JPL
Stroke	> 2 μm	2 μm	1 μm	2 μm	2 μm	2.5μm
Actuation Voltage	Low	300 V	200 V	150 V	100 V	50 V
Actuation mecha-nism	-	Electrostatic	Electro-static	Electro-static	Electro-static	Piezo-unimorph
Surface quality	< 10 nm	36 nm RMS	-	180nm RMS	-	30 nm
Mirror membrane	-	2μm poly-Si	10μm Si	1-5μm SC Si	1-3μm SC Si	10μm SC Si

Table 1. *Comparison table of existing MEMS DM specifications.*

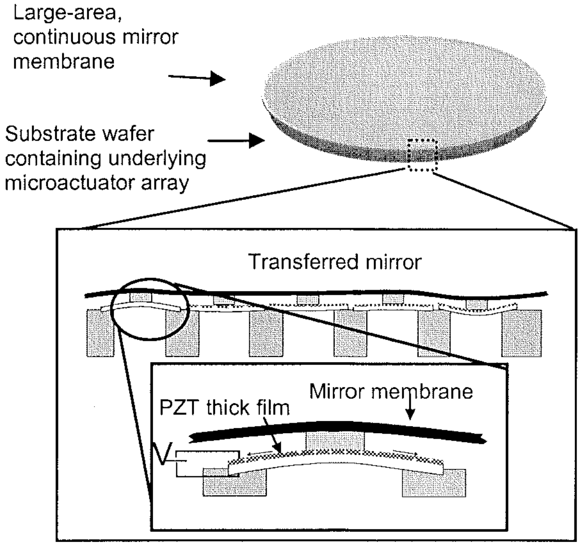

Figure 1. *Large-area continuous membrane deformable mirror (DM) concept. For minimizing the effect of print-through, the silicon mirror membrane is required at > 10 μm thick. The mirror membrane is backed by an array of piezoelectric unimorph microactuators. The advantage of this approach is that the small strains obtainable from a piezoelectric material at modest voltages are translated into relatively large displacements.*

PZT UNIMORPH ACTUATOR

We have modeled, fabricated and characterized a series of PZT unimorph membrane actuators with various membrane designs in order to optimize the DM actuator geometry. Fig. 2 contains (a) a photograph of fabricated actuators of various types and (b) a schematic illustration of the structure. Electrode designs which have been tested include: plain circle, concentric rings, spiral, and segmented.

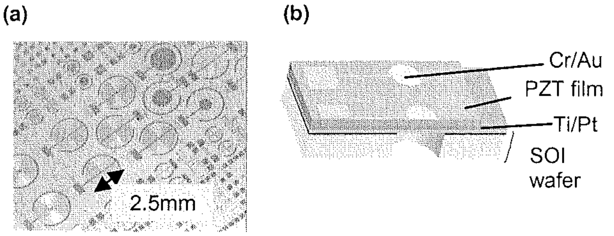

Figure 2. *(a)A photograph of PZT actuator array (b)A schematic of PZT unimorph actuator*

The actuation principle is as follows: An electric field applied perpendicular to the piezoelectric layer plane induces contraction in the lateral direction, providing a large out-of-plane deflection because of its unimorph geometry. Compared to piezoelectric stacks that are widely used in commercial DMs, this actuation mechanism requires far less voltage and power to produce same amount of deflection. It was soon discovered that there are two regimes of unimorph membrane actuators depending upon the PZT film / silicon membrane thickness ratio. For thin silicon membrane thickness (about PZT thickness or less), concentric rings and spiral electrode design produced more deflection than ones with plain circle electrode, implying the stress in electrode film reduce the amount of deflection significantly. For actuators with thick silicon membranes (> ×2 PZT thickness), simple plain circle electrodes produced more deflection than other electrode designs. Since actuators with thick membranes were more promising to be used as DM actuators because of more deflection and easier handling during fabrication, we focused our efforts in optimizing actuator design with plain circle in thick membrane regime.

In order to optimize the geometry of the unimorph actuator structure, a mathematical modeling was performed using an energy minimization method. In this modeling, the total energy of the unimorph membrane under deflection is calculated using a deflection profile given by thin plate theory. Then the total energy which consists of elastic energy in silicon membrane, energy due to PZT film stretch, and energy due to bending moment is minimized with respect to the deflection profile using Lagrange multiplier method. Fig.3 shows a WYKO interferometer image of unimorph actuator under deflection. The measured membrane deflection characteristics show excellent agreement with the modeling for membrane thickness dependence (Fig. 4). Fig. 5 shows deflection dependence on size of electrodes relative to membrane. The measured deflection of an optimized actuator is 5.4µm at 50V (for an actuator with 2.5mm diameter, PZT/Si = 2µm/15µm thick, 60% electrode diameter).

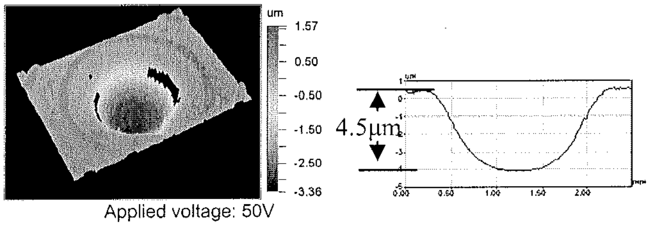

***Figure 3**. WYKO interferometer image of a PZT unimorph actuator under deflection. Thickness of PZT/Si are 2µm/15µm.*

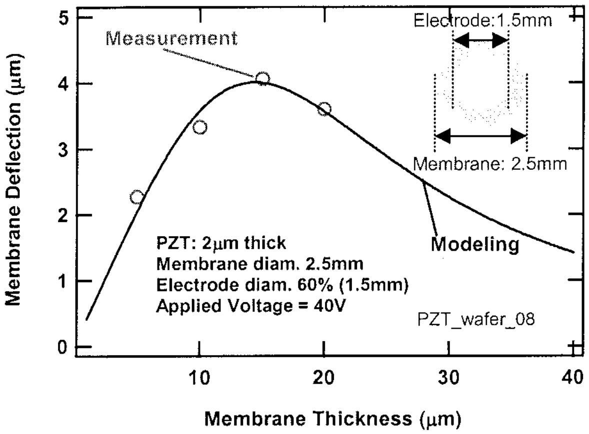

***Figure 4**. Dependence of membrane deflection on silicon membrane thickness. For membranes 2.5mm in diameter, the optimized Si/PZT thickness ratio is approximately 6. The data points represent an average of 10 separate measurements on 2 different pixels within a typical array.*

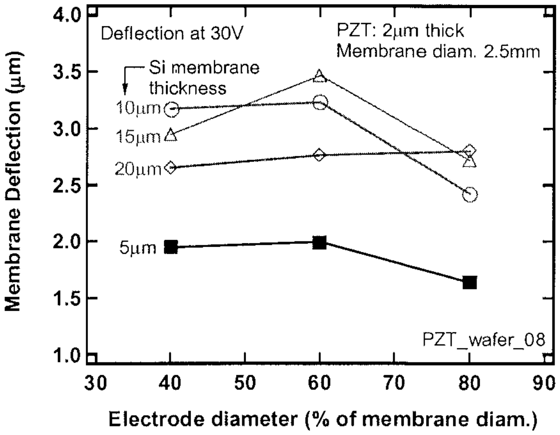

Figure 5. Dependence of membrane deflection on electrode diameter. Optimum electrode diameter is approximately 60% of the membrane diameter.

DEFORMABLE MIRROR

DMs consisting of 10µm thick single-crystal silicon membranes supported by 4×4 actuator arrays were fabricated and optically characterized. Fig. 6 contains (a) a schematic illustration of the DM structure and (b) a photograph of fabricate arrays of actuators (mirror membrane is intentionally removed). The mirror membrane was transferred and bonded onto the actuator wafer via indium posts at centers of each actuator (Fig. 7).

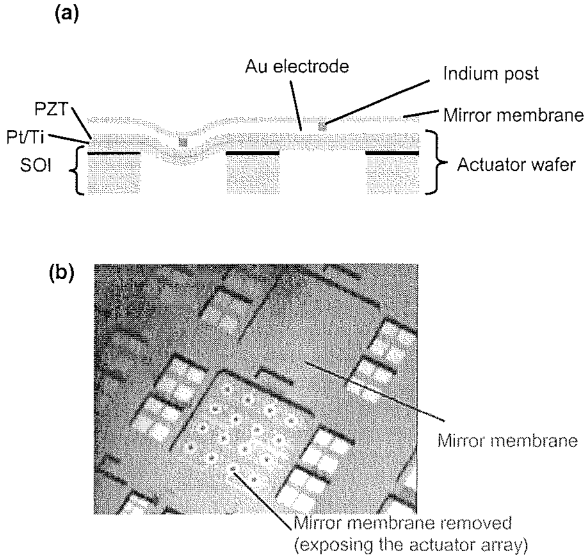

***Figure 6**. (a) Cross-sectional schematic of deformable mirror (b) Photograph of fabricated deformable mirrors with 4×4 actuator arrays*

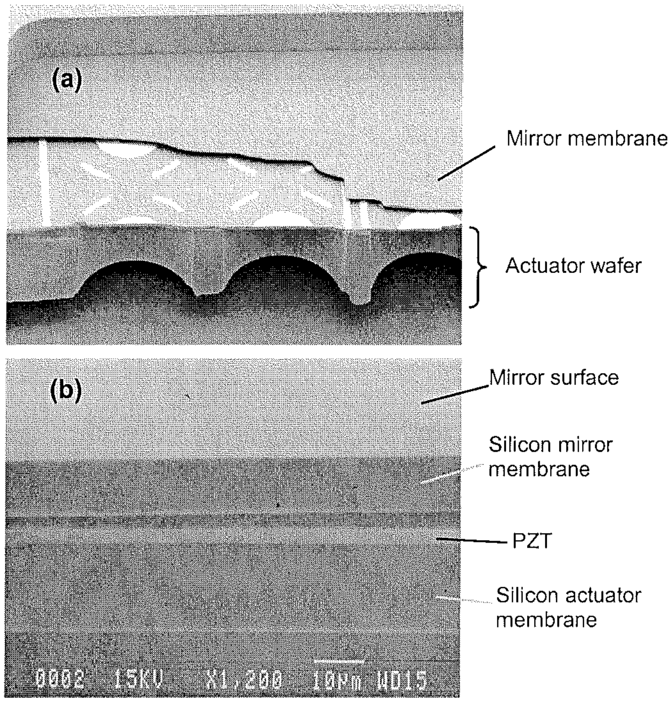

Figure 7. SEM micrographs of deformable mirror. (a) DM with mirror membrane partially removed. (b) Cross section of DM: the mirror membrane is 10 μm thick to provide necessary optical quality for DM.

The surface profile of an *actuated* deformable mirror using one underlying actuator is appeared in Fig. 8. The measured influence function is 25%. Fig. 9 presents the measured deflection *vs.* the applied voltage for an actuator and a DM actuated using a single actuator. The DM shows stroke of 2.5 μm at 50 V. The stroke of the mirror membrane is approximately 40% less than that of the actuator alone. This can be adjusted by changing the mechanical compliance (e. g. optimizing the PZT/ actuator membrane/ mirror membrane thickness ratio). The measured resonant frequency of 42 kHz far exceeds the bandwidth requirement of most DMs (Fig. 10).

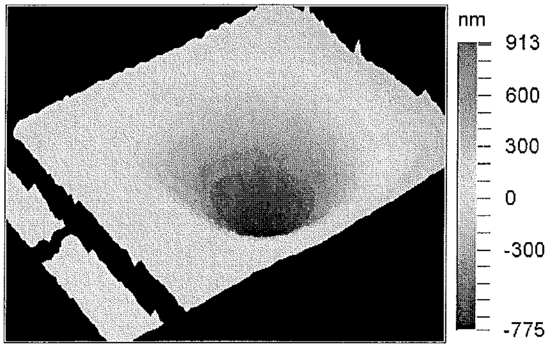

Figure 8. Deflection of a deformable mirror with one actuator activated. From this profile, the influence function (crosstalk between pixels) is ~25% as predicted from our modeling.

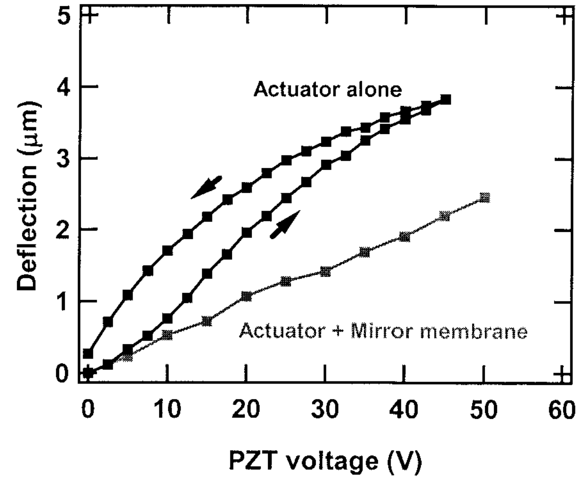

Figure 9. Relative deflection vs. voltage applied for 2.5mm diameter actuator alone and with mirror membrane.

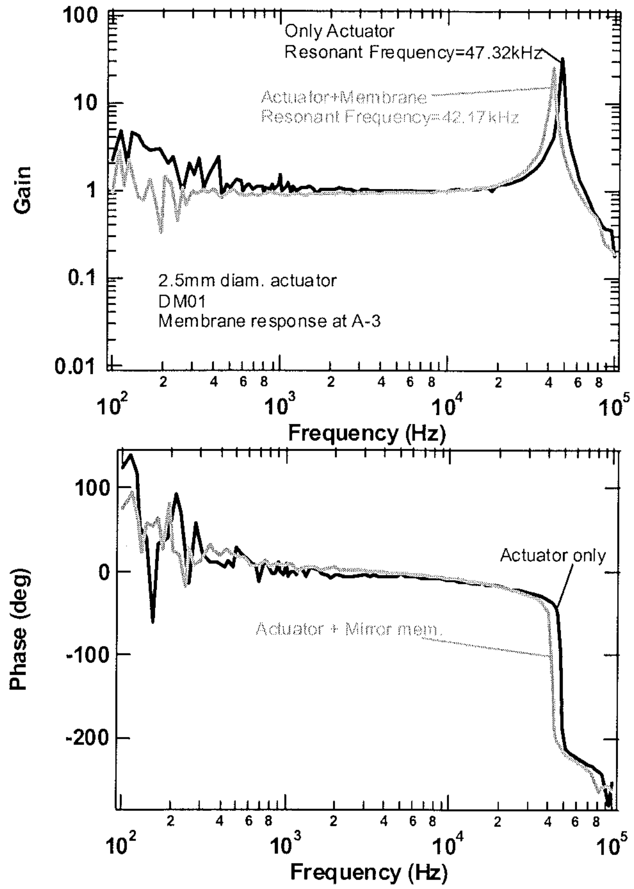

Figure 10. Frequency response of the piezoelectric unimorph actuator alone and with mounted mirror membrane. These plots signify that the DM has a high bandwidth operation. They also indicate the high-stiffness of the actuator membrane, which is important to enhance the mirror quality by allowing the fabrication of a thicker mirror membrane.

CONCLUSIONS

In summary we have demonstrated a proof-of-concept DM with continuous single-crystal silicon membrane supported by piezoelectric unimorph actuator arrays. Piezoelectric unimorph actuator with optimized PZT/Si thickness and design is able to produce a large stroke (5μm) at low voltage (50V). DMs consisting of 10μm thick single-crystal silicon membranes supported by 4×4 actuator arrays were fabricated and optically characterized. Improvement in the fabrication process for better optical quality of the mirror membrane and optimization of the DM for larger stroke are underway. More complete optical characterization of fabricated DMs will be performed.

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