A micromachined deformable mirror for optical wavefront compensation

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ABSTRACT

A silicon micromachined deformable mirror (μDM) has been developed by Boston University and Boston Micromachines Corporation (BMC). The μDM employs a flexible silicon mirror supported by mechanical attachments to an array of electrostatic parallel plate actuators. The integrated system of mirror and actuators was fabricated by surface micromachining using polycrystalline silicon thin films. The mirror itself measures 3 mm x 3 mm x 3 μm, supported by a square array of 140 electrostatic parallel-electrode actuators through 140 attachment posts. Recently, this μDM was characterized for its electromechanical and optical behavior and then integrated into two laboratory-scale adaptive optics systems as a wavefront correction device. Figures of merit for the system include stroke of 2 μm, resolution of 10 nm, and frequency bandwidth of 6.7 kHz. The device is compact, exhibits no hysteresis, and has good optical quality.

Keywords – Adaptive optics, MEMS, MOEMS, micromachining, deformable mirror, electrostatic actuation, phase conjugation, aberration compensation, optical phase correction, wavefront correction

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INTRODUCTION

Micro-opto-electromechanical systems (MOEMS) will transform the field of adaptive optics by providing compact, inexpensive, high-speed micromachined deformable mirrors. Such mirrors will be used as wavefront correctors in imaging and beam-forming systems that are affected by optical path aberrations. Applications for which MOEMS deformable mirrors are currently being tested include astronomical telescopes, ophthalmic surgery, retinal imaging, point-to-point laser communication, and UV lithography.

One micromachined deformable mirror (μDM) system has been developed recently by Boston University and Boston Micromachines Corporation for use in adaptive optics applications. Figure 1 is a photograph of the system. The deformable mirror is shown mounted in a ceramic chip carrier, which is in turn mounted to a component board. Ribbon cables (not shown) connect the 140 actuators to a 19” wide array driver, which receives power from an adjacent power supply. The system is controlled through a digital I/O bus in a desktop computer.

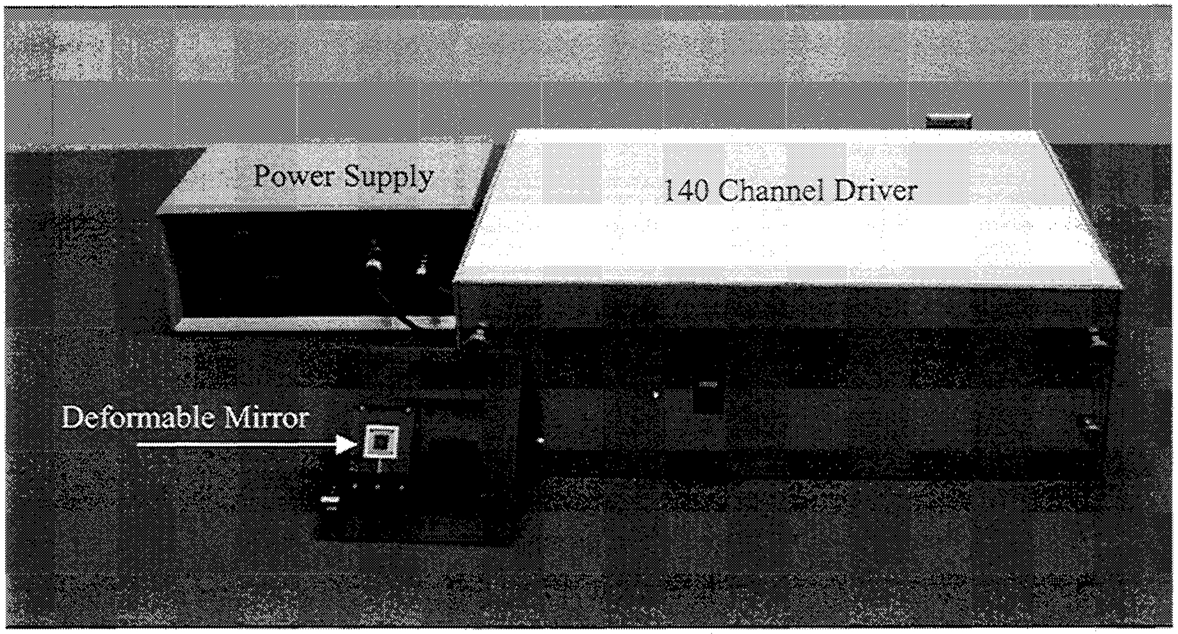


***Figure 1:** Photograph of BMC μDM with driver and power supply.*

Table 1: Attributes of the DM.

Mirror & Actuator Array Geometry	
Number of actuators	140
Actuator array configuration	12 x 12 Square grid (w/o corners)
Actuator spacing	300μm
Clear aperture of mirror	3.3mm
Effective fill factor	99.95%
Unpowered overall mirror surface figure	50nm RMS, 470nm PV
Unpowered inter-segment surface figure	6.7nm RMS, 36nm PV
Electromechanical Performance:	
Stroke	2μm
Repeatability	10 nm (99% reliability)
Hysteresis	0%
Drive voltage	240V max
Lifetime	>1 billion cycles @ 1/2 full stroke
Temporal open loop bandwidth	6.6kHz (-3dB @ 20% full stroke)
Impulse response	Damped, 25μs time constant
Addressing Options	
Type I: Analog (not shown):	140 channel parallel low-level (0-5V) analog input, 24 channels per stackable board. Controlled by VLSI analog chips
Type II: Digital (Driver shown in Figure 1):	140 channel serial digital input (8 bit data, 9 bit address) 8 channels per board, integrated with backplane in 19" panel rack. Computer controlled through 24 channel DIO card.

DESIGN AND FABRICATION

The μDM consists of an array of electrostatic parallel-plate actuators that are directly coupled to a continuous mirror through mechanical attachment posts. A schematic cross section of a small portion of the device is depicted in Figure 2. When voltage is applied between the movable and fixed electrodes of an electrostatic actuator, electrostatic force deflects the movable electrode, and the attached portion of the mirror, toward the substrate. The amount of deflection depends monotonically but nonlinearly on the magnitude of the applied voltage. In the schematic, the actuator in the center is deflected, while the others are unpowered.

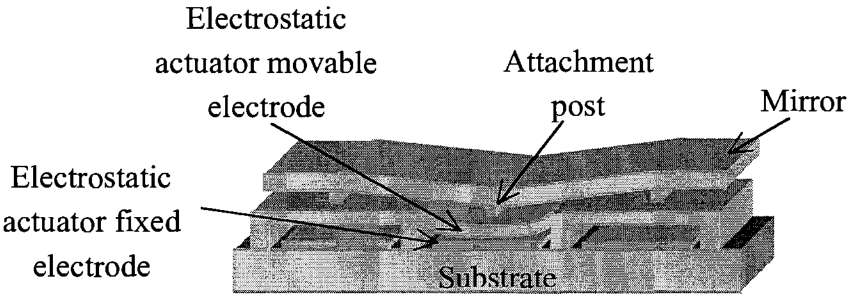


***Figure 2:** Schematic cross section of deformable mirror.*

The μDM was fabricated in a three-level silicon surface micromachining process. Alternating thin films of structural polycrystalline silicon (polysilicon) and sacrificial phosphorous silica glass (PSG) were deposited, patterned, and etched to create the mirror and actuator array. A 0.5 μm thick base nitride layer was used to electrically insulate the micromachined layers from the underlying silicon wafer. The first polysilicon layer, measuring 0.5 μm thick, was used to form an array of fixed electrode pads for the electrostatic actuators. It was also used for routing polysilicon wires on the substrate surface. Next, a 5 μm thick PSG layer was used to define a gap for the electrostatic actuators. On top of the PSG, a 2 μm thick polysilicon layer was deposited and patterned into an array of fixed-end double cantilevers, which formed an array of movable electrostatic actuator electrodes. Another PSG layer, 2.5 μm thick, was used to create a gap between the actuators and the mirror. The mirror itself was formed with a 3 μm thick polysilicon layer. Anchor holes in the second PSG layer anchored the mirror to the center of each electrostatic actuator. Features not shown include etch release holes (in the upper two polysilicon layers) and metal on the mirror for optical reflectivity.

The μDM's electromechanical performance was evaluated by driving the actuators with a high-speed voltage controller (Figure 3), and measuring the dynamic motion response. It was found that actuators exhibited no hysteresis and that they could be positioned to a precision of 10 nm over a 2μm range of motion with 99% reliability. Typical deflection characteristics are illustrated in Figures 4 and 5. The mirror frequency response was measured to be about 6.7kHz (Figure 6).

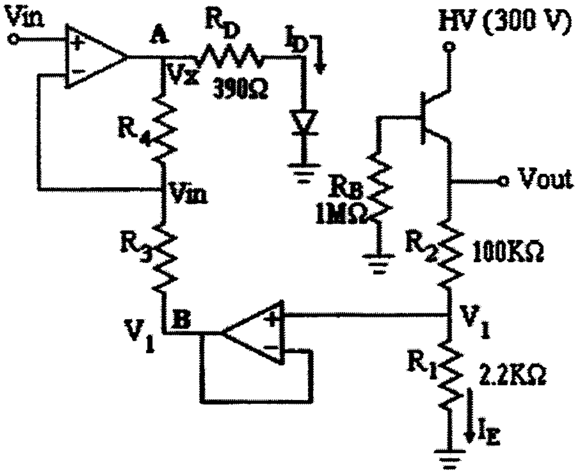


Figure 3: *Schematic of electronic amplifier.*

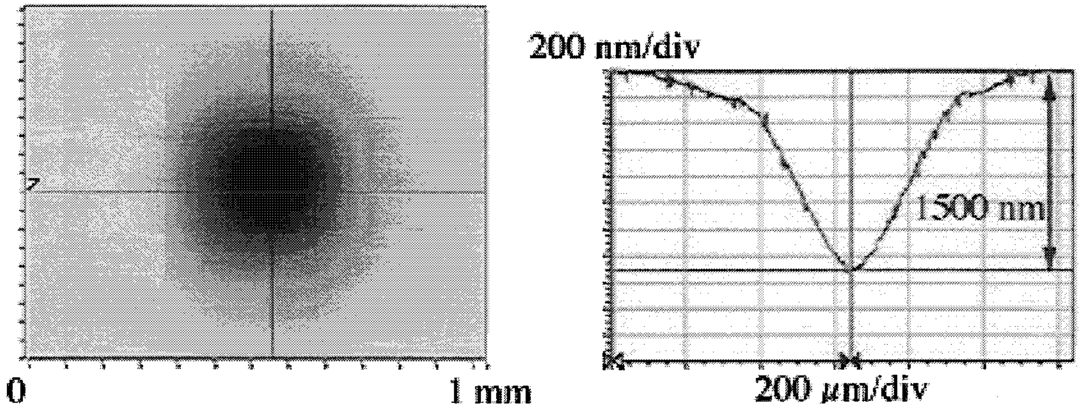


Figure 4: *Measured mirror deflection with one actuator driven by 220 V. Deflection is 1500 nm (2/3 of full stroke). Left: Interferometric surface contour map. Right: Cross sectional profile. Influence function, defined as mirror deflection over an unpowered neighbor actuator, is ~15%.*

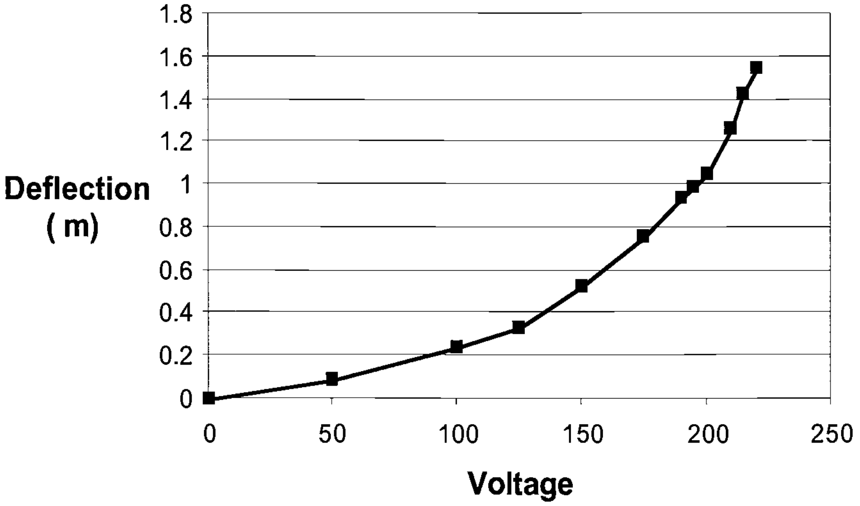


Figure 5: *Measured voltage vs. deflection for a typical actuator.*

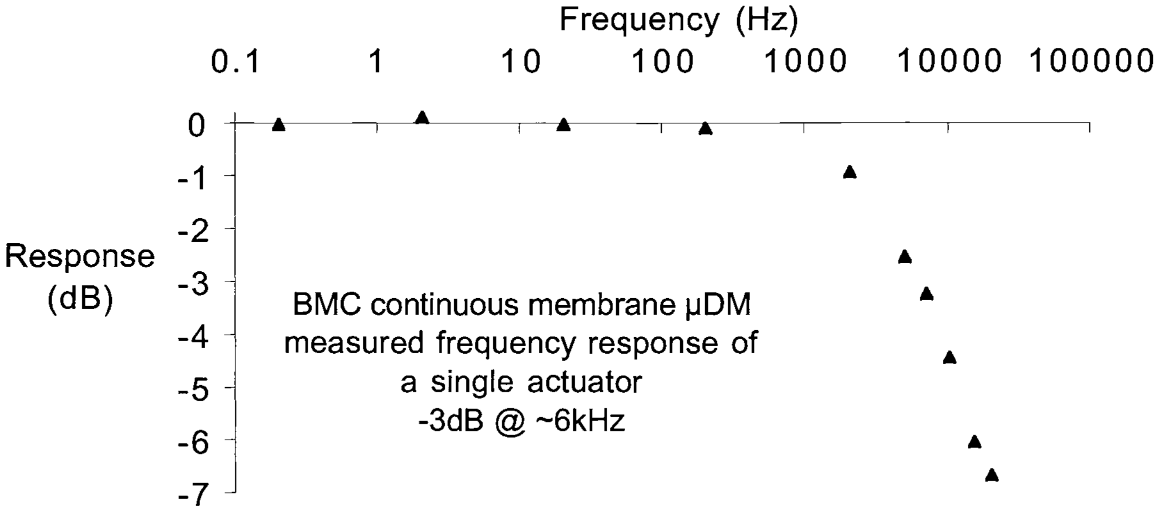


Figure 6: *Frequency response of the mirror with a single actuator driven over 400 nm range (20% full stroke) with a swept sinusoidal input.*

OPTICAL QUALITY

As fabricated, the mirror surface was distorted by residual strain gradients in its polysilicon film. Local (interactuator) radius of curvature was typically 50 mm, corresponding to a peak-to-valley deviation from flatness of up to 200 nm between adjacent actuator attachment posts (300 µm). A custom post-processing step consisting of bombardment by neutral ion beams was used to modify the strain gradient. After ion bombardment, the mirror surface was flattened to a radius of curvature larger than 2000 mm – a deviation from flatness of less than 5 nm between attachment posts. Essentially, the ion bombardment process imposes a surface compressive strain that changes the shape of the film in a predictable way, flattening the mirror. Figure 7 is a graph of radius of curvature versus ion bombardment time. Measured interferometric contour maps of segmented mirror test structures are shown for mirrors at the beginning and end of this test in Figure 8.

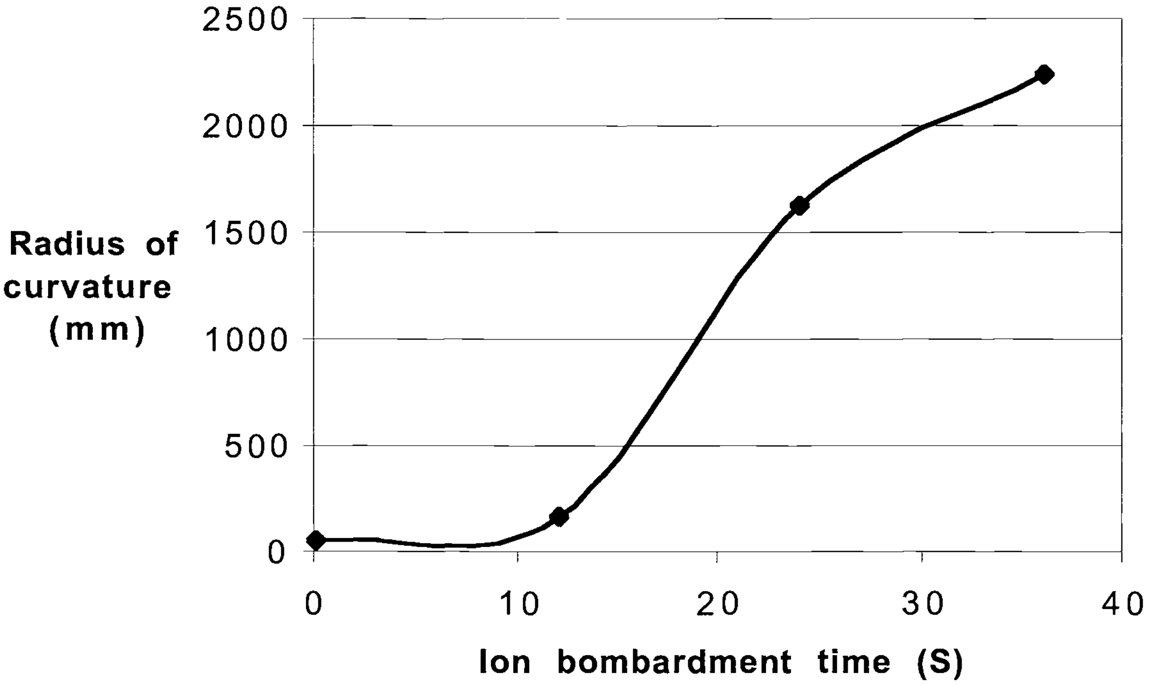


Figure 7: *Improvement of optical surface contour for mirrors using neutral ion bombardment.*

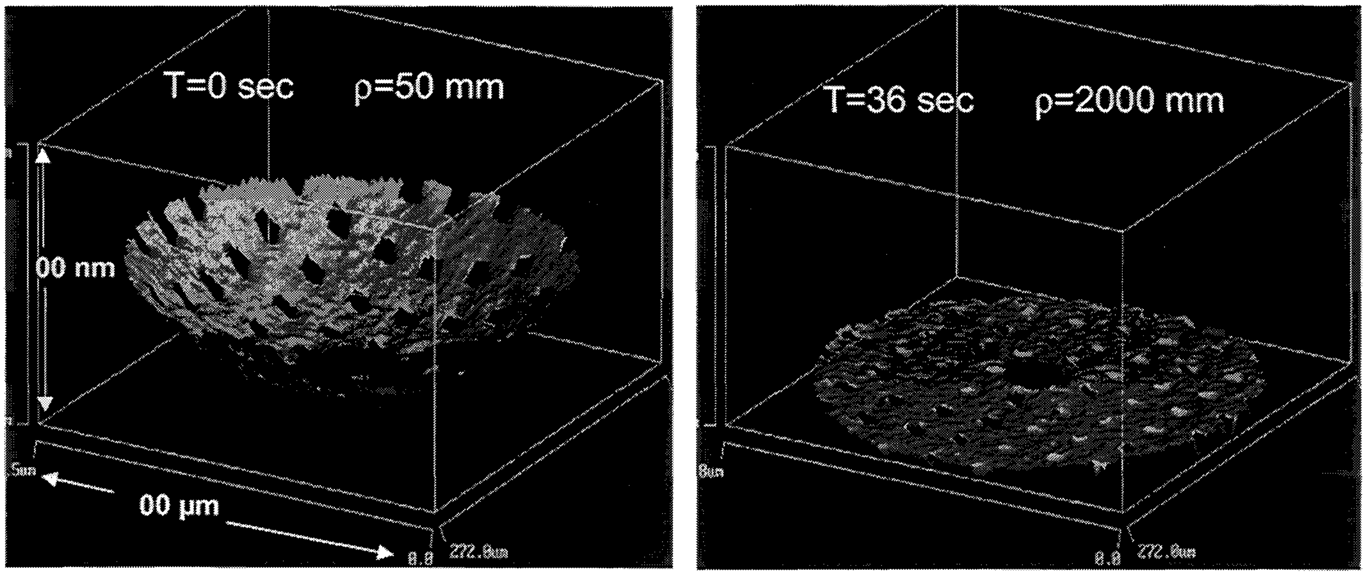
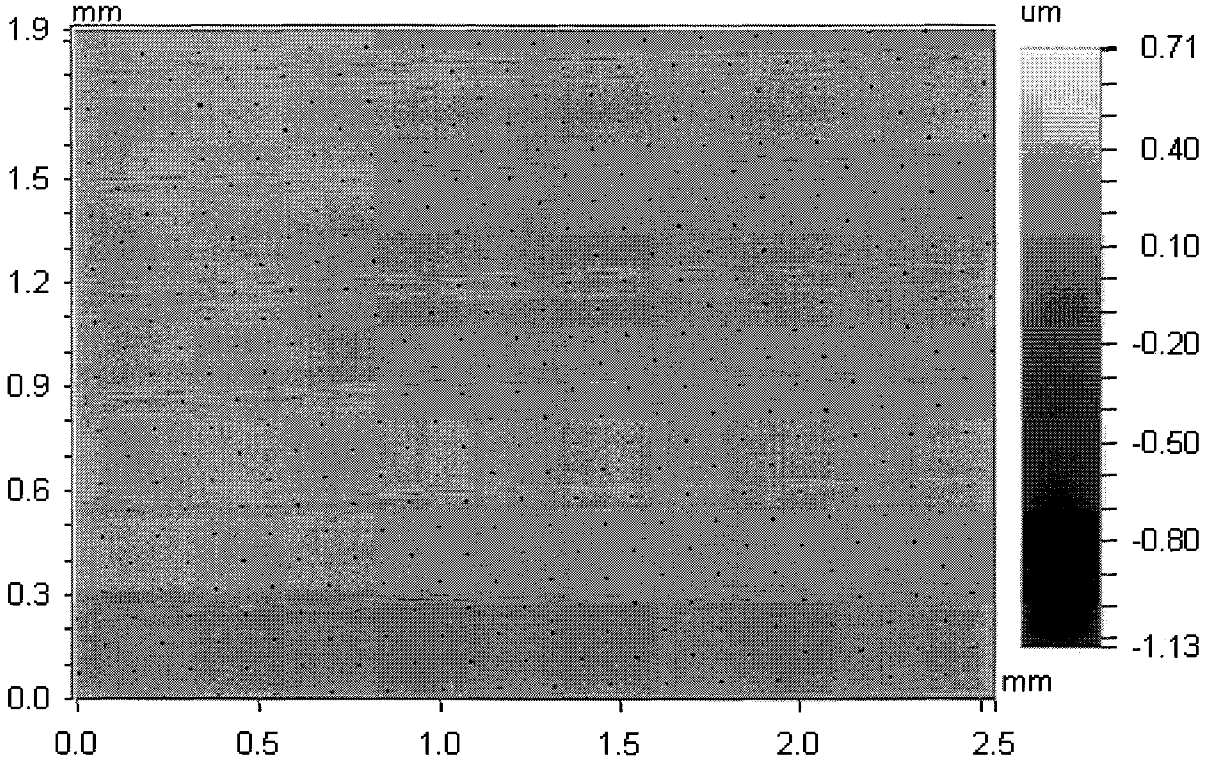


Figure 8: *Measured contours of test structures subjected to neutral ion bombardment. Left: As fabricated, with residual strain gradient due to thin film deposition process. Right: Same structure after 36 seconds of bombardment. Radius of curvature increased from 50 mm to 2000 mm.*

A measured contour map of the unpowered mirror surface is shown in Figure 9, and an SEM photo enlargement of the surface is shown in Figure 10. The surface contour deviation from flatness, over its entire 3.3 mm aperture, is approximately 50 nm. Local inter-actuator surface roughness measures approximately 6 nm RMS. In both images, 5 μm etch release holes and actuator print-through can be observed. These samples were chemomechanically polished before the final release, reducing print-through effects considerably in comparison to that of unpolished samples.

***Figure 9:** Interferometric contour map of a μDM.*



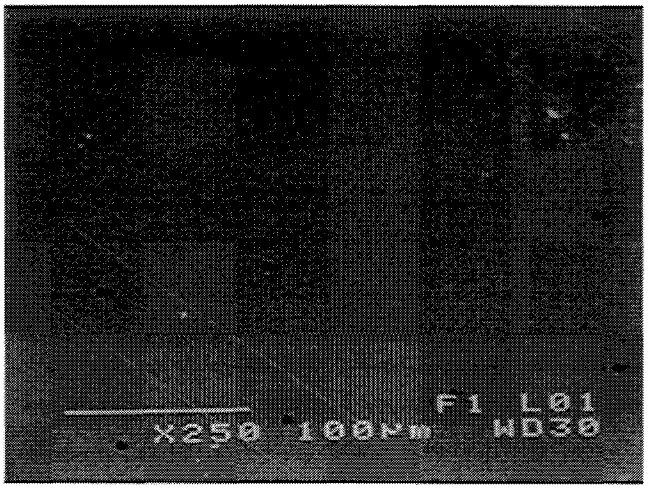


***Figure 10**: SEM Photo of the μDM surface.*

CONCLUSIONS

A surface micromachined deformable mirror system has been developed. Its design, electromechanical performance, and optical quality have been characterized. This device offers potential as an advanced adaptive optics wavefront corrector, particularly in applications where speed, compactness, or cost is important. These μDM systems are currently being tested in a number of adaptive optics test beds for imaging and beam-forming applications.