MEMS segmented deformable mirror for adaptive optics

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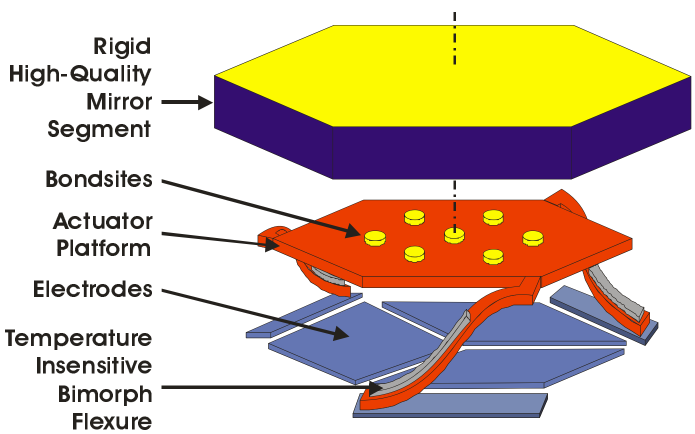
ABSTRACT

This paper presents the Iris AO MEMS segmented DM technology to the AMOS community. The Iris AO 37-segment S37-X DM is a large stroke (5-10 µm), piston/tip/tilt device capable of many kilohertz operation. The DM is mated with high-resolution electronics and a calibrated position controller that enables precision open-loop operation using intuitive position commands. The robust design has shown excellent segment flatness over large temperature ranges. Actuator arrays have survived liquid-nitrogen temperatures as well, demonstrating possible use in cryogenic applications.

1. INTRODUCTION

Microelectromechanical system (MEMS) technology has long been touted as a way to fabricate compact, high-performance deformable mirrors (DM). The MEMS technology has the ability to build large-actuator-count DMs in a compact form factor. The compact size combined with extremely low-power electrostatic actuation enables excellent size, weight, and power (SWAP) characteristics.

Iris AO has been developing MEMS DMs, controllers, and adaptive-optics (AO) systems since 2002. The cornerstone of the proven technology is the segment design shown in Fig. 1 on the left. Thirty-seven of these segments are tiled into an array to create the S37-X DM as shown in the die photo on the right in Fig. 1. Tuned residual stresses in the bimorph-flexure materials raise the DM segment 20-50 µm (depending on design) above the substrate after microstructure release. Piston/tip/tilt actuation is achieved with electrostatic forces. When the three lower electrodes shown in Fig. 1 are energized simultaneously, the segment moves downward in a piston motion. Applying a differential voltage across the electrodes forces a tip (grad X) or tilt (grad Y) motion or a combination of tip and tilt depending on the voltage values. By biasing the segment midway through the safe operating range, bidirectional motions are possible.



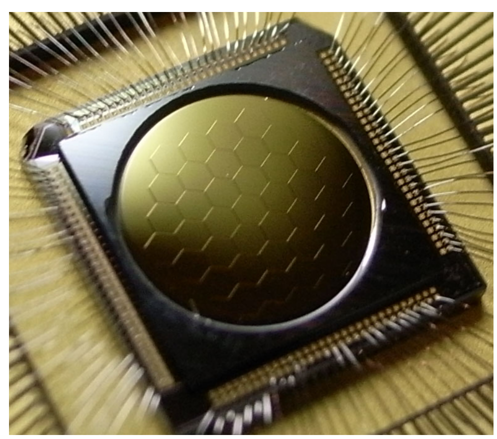


Fig. 1. (Left) Schematic diagram of an Iris AO DM segment. Tens, hundreds, and even thousands can be tiled in an array. (Right) Die photograph of the 37-segment Iris AO S37-X DM.

The MEMS fabrication process used to build Iris AO segmented DMs is a hybrid approach, whereby polysilicon micromachining is used to fabricate the actuator platforms and bulk micromachining is used to fabricate the 20 µm or thicker mirror segments [1]. Polysilicon thin films are excellent for creating large out-of-plane deflections, however these same films make for poor optical surfaces because of residual topography from print through after polishing, etch holes, and deformations from strain gradients in the films. In contrast, the rigid, single-crystal-silicon, segments form a nearly ideal mirror surface. The semiconductor grade silicon from which the segments are derived is a pure material polished mirror smooth with no strain gradients or subsurface damage. Because the segments are assembled on top of the actuators, they cover all of the underlying features including etch holes and the flexures. As such, fill factors for the segmented device are greater than 98.5%.

Protected-aluminum coated mirror arrays have been built with better than 8 nm *rms* residual surface figure errors as seen in the interferometer measurement in Fig. 2. Segment flatness typically ranges from 3-20 nm *rms*. The rigid segments enable many different types of optical coatings to be applied without excessive bowing. The S37-X DM is currently offered with both gold and protected-aluminum coatings. Protected-silver coatings are under development and prototype DMs with dielectric coatings have been demonstrated.

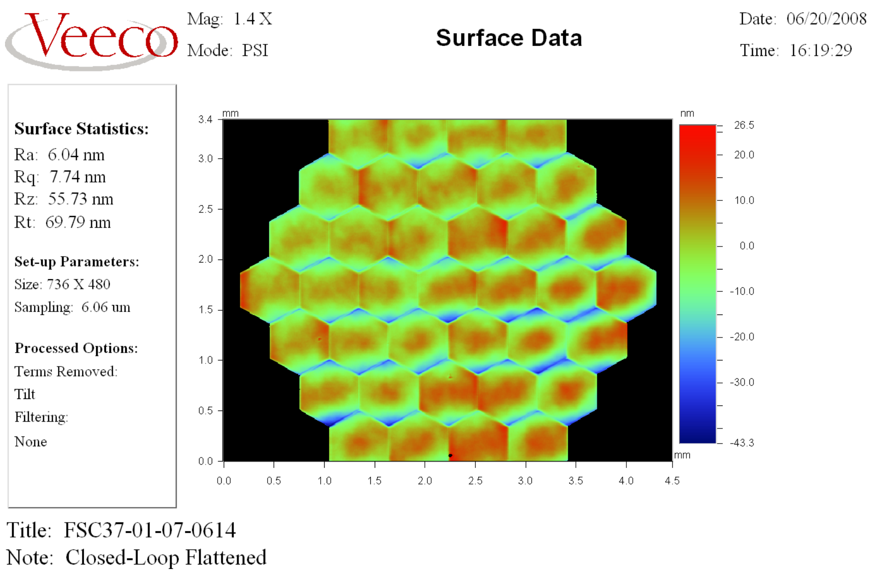


Fig. 2. An S37-X DM with protected-aluminum coating. The surface figure errors for this flattened array are 7.74 nm *rms*.

2. ROBUST SEGMENTED DM DESIGN

The segment design shown in Fig. 1 can meet the demands of many different applications ranging from high stroke and low speed (e.g. biological imaging) to low stroke and high speed (e.g. atmospheric correction) using the same fabrication process. This is possible because the gap between the actuator platform and the lower electrodes is set by the design of the bimorph flexures and not by the sacrificial layer thickness as is done with other MEMS DMs [2, 3]. By creating a long bimorph flexure with a supple connection to the actuator platform, a large gap, and hence large stroke, is achievable. Stiffening the flexure by a combination of widening, shortening, and/or thickening it will increase stiffness and thus increase response speed at the expense of stroke. Because these changes occur at the end of the actuator fabrication process, many wafers can be fabricated up to the last steps and kept on hold for further processing with customized designs. Therefore, implementing a change to reach a different area in the performance space can be achieved quickly with less cost than fabricating an entirely new design.

Commercially available S37-X DMs are available with 5 µm stroke (S37-5) and a slightly under-damped 2.3 kHz frequency response. The 20%-80% step response for these is 120 µs for the rise time and 140 µs for the fall time as seen in Fig. 3. Larger stroke (8-10 µm) and faster (3-5 kHz) DMs implemented using the design trades described above are nearing the end of the fabrication process. Prototypes of these DMs will be ready by the end of 2008.

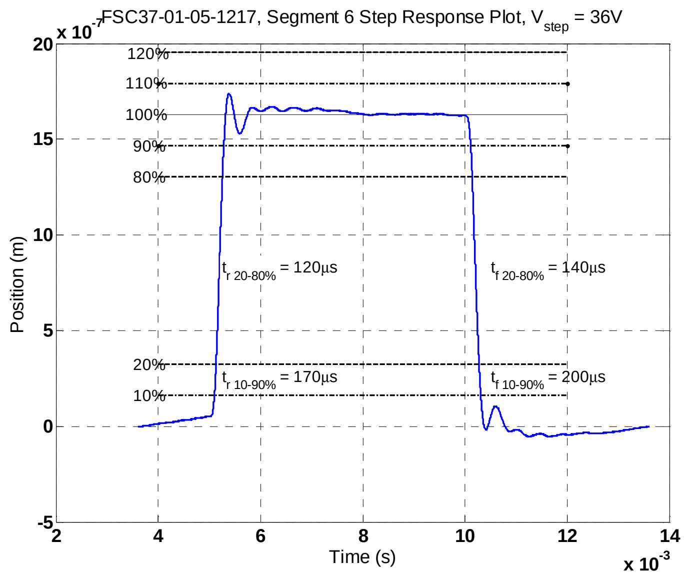


Fig. 3. Rise and fall times for a 1.63 µm step (36V). The vertical scale is in 100s of nanometers and the horizontal scale is in milliseconds. Rises times are 120 and 170 µs for the 20-80% and 10-90% bounds respectively. Fall times are 140 µs and 200 µs for the 20-80% and 10-90% bounds respectively.

Temperature Stability:
Unlike thin-film polysilicon layers, the thick single-crystal-silicon mirror segments stay flat over large temperature ranges. Deformable mirrors tested from 10°C to 70°C showed peak-to-valley segment deformations of only 0.56 nm/°C with no permanent change in shape when they were returned to room temperature [4].

The actuator platforms show a change in gap of only 18 nm/°C as a result of small mismatches in the coefficients of thermal expansion (CTE) of the two bimorph layers. This results in a negligible change in the initial 20-50 µm actuator gap across the array. The variation in platform heights because of mismatches across the array is 0.8 nm *rms*/°C. A survivability test showed that actuator platforms can endure liquid nitrogen temperatures demonstrating the potential of cryogenic operation for infrared applications.

3. EASE OF USE

The S37-X DM comes standard with a factory-calibrated piston/tip/tilt (PTT) position controller that maps position commands to the requisite actuation voltages and sets these voltages onto the 14-bit electronics. The user only needs to enter individual PTT values or Zernike coefficients to position the DM array. This greatly simplifies the use of the DM in an AO system as the segment positioning is linear and the DM has a known influence function. Furthermore, the AO system can be built up and aligned with the DM in place and flattened by setting all PTT values to zero. If a DM is later replaced with a higher performing one, the replacement can simply be dropped in, aligned, and operated with its factory calibration values stored on board. In contrast, *all* other DMs require that an influence function be generated by the user. The position controller serves an additional function by limiting voltages sent to the DM segments to within the safe operating space of the DM.

Fig. 4 demonstrates the position controller open-loop flattening accuracy for the same DM shown in Fig. 2. Residual surface-figure errors are slightly greater, 9 nm *rms*, when the DM is open-loop positioned. The accuracy further degrades a small amount as the DM segments are positioned at the extents of the safe operating region. Measurements have shown that over the majority of the safe operating region, segments can be positioned to better than 30 nm *rms* [5]. Fig. 5 demonstrates piston positioning of a DM segment. Within the safe operating space, the positioning is very accurate. Outside of the safe operating region, the position controller limits the segment position and returns a flag to the user warning that the particular segment is saturated. The controller also provides the resulting position it sent the saturated segment to.

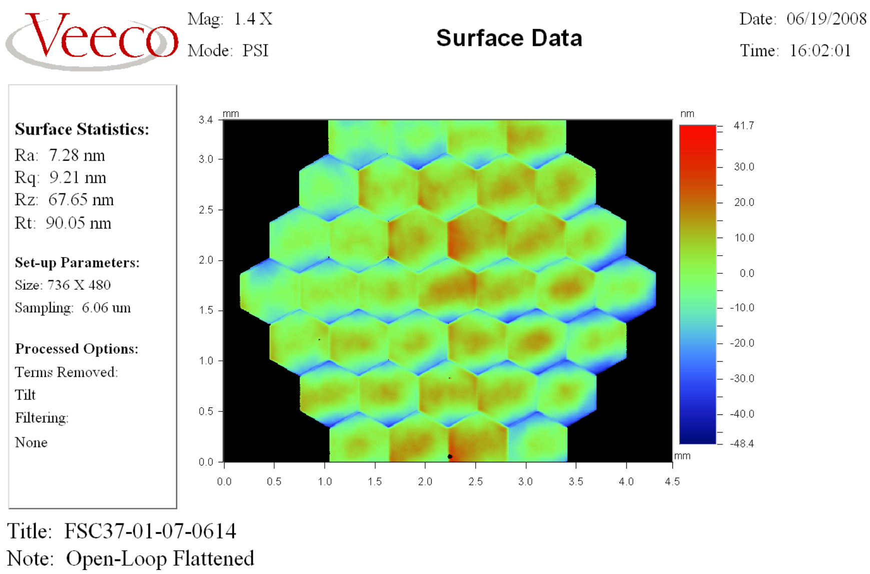


Fig. 4. The same S37-X DM as shown in Fig. 2 open-loop flattened with the PTT position controller. The surface figure errors for this open-loop flattened array are 9.21 nm *rms*.

The segmented design and excellent open-loop positioning greatly simplify AO control and increase the overall performance of the AO system as well. There is no cross-coupling between segments, making for a diagonal control matrix. Furthermore, the position controller is an excellent linear model of the segments within the safe operating region as seen in Fig. 5. This reduces uncertainty in mirror position allowing the AO controller to be safely designed with higher gains. Cycles that would normally be spent on converging the DM to the desired shape are dramatically reduced with the precision open-loop control. Better positioning in fewer iterations increases the correction bandwidth of the AO system.

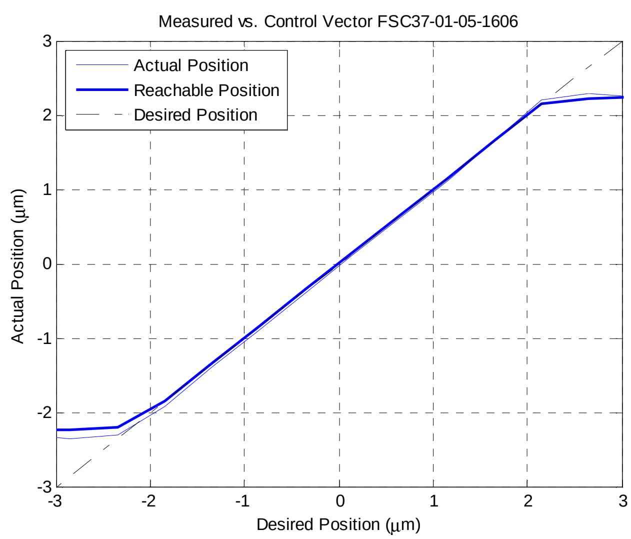


Fig. 5. Experimental data showing performance for z positioning of a segment. The dashed line shows the commanded positions. The thick line shows the positions the controller commands the segment to go to. The thin line is the actual position the DM segment goes to [5].

The compact (6.5” x 6.5” x 2”) 128-channel, 14-bit electronics used to drive the S37-X DM are factory calibrated as well. Calibration values are stored on board the electronics and are passed transparently to the position controller when operating an S37-X DM or to a voltage controller when operating another DM or any other device. Interfacing to the electronics is via a USB interface. The USB interface is currently limited to 150 Hz frame rates. For high-speed applications, the existing electronics can be operated with an LVDS (low-voltage differential signal) interface to provide frame rates up to 35 kHz. A 1-2 kHz PC DIO interface will be available by December 2008.

4. CURRENT AND FUTURE DEVELOPMENT

Iris AO has focused efforts on developing the S37-X DM to its current easy-to-use form that is unparalleled by any other deformable mirror. Additional development is underway to further broaden the application space the DMs are suitable for. Advances from this development include commercially available 8 µm-stroke DMs and a 1+ kHz PC interface by the end of 2008. For high-contrast imaging applications, DMs with 1-3 nm *rms* residual surface figure errors will be demonstrated by the end of 2008. Protected-silver coatings will be available by the end of 2008 as well. Dielectric coatings for laser-guide-star uplink correction (589 nm) are currently under development. Expected availability for these is April 2009. Even higher-stroke (10+ µm) DMs will be available by June 2009.

Iris AO is actively developing larger DM arrays based on the same DM segment design and MEMS fabrication techniques as the S37-X. Therefore, all of the development for the S37-X DM will seamlessly transfer to the larger arrays.

The next larger array will be a 163-segment PTT DM. Actuator wafers are currently being fabricated as seen in the die photo in the left of Fig. 6. We expect prototypes of the 163-segment DMs to be available by June 2009. Concurrently, 512-channel drive electronics for the 163-segment DM are being developed and will be commercially available by December 2008.

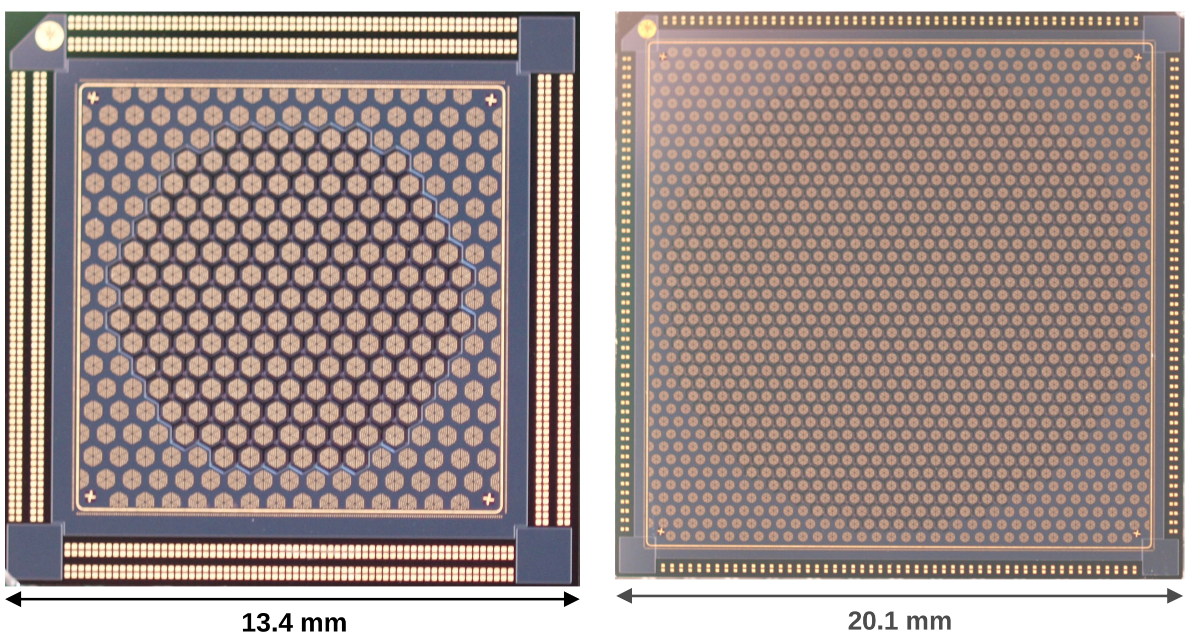


Fig. 6. (Left) Die photo of a 163-segment actuator array currently being developed by Iris AO. Prototype 163-segment devices will be available by June 2009. (Right) Die photo of a 925-segment actuator array. The demonstration array is meant for path-finding research into building 1000 segment arrays.

Even larger arrays are on the roadmap for Iris AO. A 925-segment actuator array is being co-fabricated with the 163-segment arrays as path-finding research into building 1000-segment DMs. The demonstration array shown in the right in Fig. 6 has many segments electrically ganged so the entire array can be operated using existing 128-

channel drive electronics. As the development continues and fully-wired 1000-segment DMs are fabricated, six of the 512-channel driver boxes will be used to actuate them.

5. SUMMARY

Iris AO is building high-performance piston/tip/tilt segmented DMs suitable for many different applications. The rigid segments remain flat over large temperature ranges and can be coated with many different optical coatings including gold, protected-aluminum, protected-silver, and dielectric. A factory calibrated position controller converts position commands to the requisite actuation voltages and also limits the mirror positions to the safe operating space, greatly simplifying operation of the DM. Despite the thick segments assembled onto the actuators, step responses are as fast as 120 µs. Finally, Iris AO is further developing its DM technology to increase stroke, increase speed, increase coating options, and increase the number of segments.

6. ACKNOWLEDGEMENTS

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