# MEMS Wavefront Correctors

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**Abstract:** Deformable mirrors made using MEMS processes have become commodity products. New capabilities include nanometer-scale predictive open-loop control and scaling to >4000 actuators, while maintaining exceptionally low size, weight, and power.

**OCIS codes:**

## 1. MEMS DMs

A new class of deformable mirrors (DMs) has been successfully deployed in a wide range of adaptive optics (AO) applications. These DMs substantially extend the scientific capabilities of microscopes and telescopes (Figure 1).

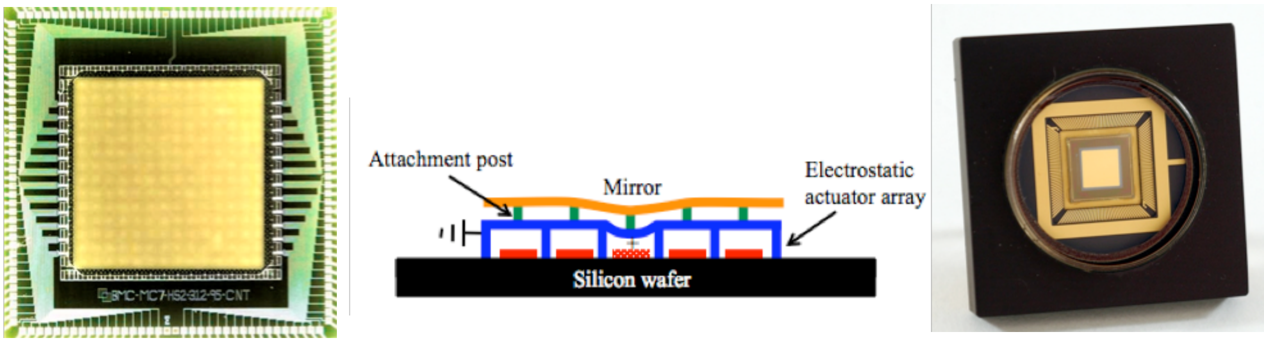


*Figure 1: MEMS deformable mirror. Left: Optical microscope image of a 140-actuator, 3.5µm stroke, gold-coated DM as fabricated on a silicon wafer. Center: Schematic cross-section of a portion of the DM including five actuators. The mirror (gold) is connected by posts (green) to an array of compliant electrostatic actuators (blue). Actuator deflection increases with voltage applied to the independently addressable electrodes (red) on the wafer substrate (black). Right: Photo of DM mounted in a ceramic package with a protective window.*

About ten years ago, my students and I at the Photonics Center at Boston University began a research program on silicon microelectromechanical (MEMS) DMs. Our primary goal was to find an alternative to the expensive hand-assembled macroscale DMs that represented the state-of-the-art in wavefront correction at that time. An additional goal was to use a new MEMS "foundry" for product research, which was unprecedented at the time. By conforming to predefined rules and process recipes, we were able to concentrate our research on device electromechanical design and optical performance, with less focus on materials science and processing. This allowed us to design and build a family of DMs that proved particularly robust and manufacturable. Within a little more than a year we produced our first working MEMS DMs.

The success of this design and manufacturing approach led to devices that were in demand by researchers outside of BU, even as they were still being developed. In 1999 a former student and I founded a company to make the DMs commercially available. Boston Micromachines Corporation (BMC) is the exclusive licensee of BU's MEMS DM technology. The family of innovative products that we have produced, in continuous collaboration with academic researchers and students from BU, share a heritage in the original design and manufacturing approach used. These products now include mirrors with 32 to 4096 actuators, mirror apertures from 1.5mm to 26mm, and stroke from 2µm to 8µm. BMC products in widespread use include a MEMS DM with 140 actuators and a USB controlled driver, and the segmented versions of a 1024 actuator device that can be controlled at >20kHz frame rate with a compact driver.

The principal application for these DMs is to compensate aberrations in microscopes and telescopes using AO. Open-loop, precise, and high-resolution control, is made possible uniquely by MEMS-DM, and is indispensible for the next generation of telescope instruments.

## 2. Deformable mirrors: current state-of-the-art

Conventional macroscale DMs, made with either piezo-bimorphs or stacked piezo-actuators are limited as astronomical telescope wavefront correctors by a number of factors. They require closed loop control due to inherent actuator hysteresis and temperature dependent performance, their manual assembly makes it costly and difficult to scale to devices with large actuator numbers, and their large mass results in relatively low temporal bandwidths. In potential space-based applications, large power requirements and bulky electronics drivers compound these limitations. The design and manufacturing approaches developed in our MEMS DM research offer inherent advantages:

Design

- The device is scalable: increasing the size of the DM is achieved by adding identical actuators to the array.
- The device is mechanically stiff and has low mass, allowing control bandwidths of tens of kilohertz.
- The actuation mechanism is repeatable to sub-nanometer precision, consumes almost no power, exhibits no hysteresis, and is unaffected by billions of cycles of operation.

Manufacturing

- The device can be made using a MEMS foundry and begins with an optically flat, inexpensive substrate.
- Devices are batch-produced twenty wafers at a time: development costs are high, production costs are low.
- Hundreds of devices can be produced on each wafer, allowing parameter variation that accelerates prototyping.

MEMS-DM research offers the rare opportunity to introduce technology that is both more economical and more capable than the state-of-the-art. MEMS-DMs already achieve stroke comparable to that of conventional systems (up to 8μm of physical stroke has been demonstrated using our devices), and exceed all reported macroscale DMs in temporal bandwidth and actuator count. They reduce size, weight and power by considerably more than an order of magnitude, and are available commercially for a fraction of the cost of conventional DMs.

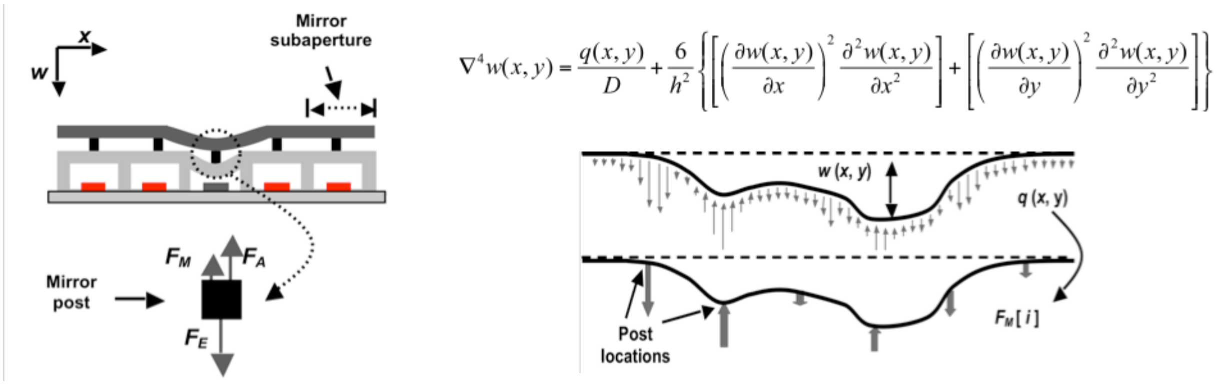
## 3. AO and MEMS DMs: relevance to astronomy and space science

Adaptive optics on large ground-based telescopes has resulted in a surge of new astronomical discoveries over the past few years. Astronomical *instruments* are also undergoing rapid evolution, especially large ground-based telescopes. Promising and relatively new AO instruments include multi-conjugate adaptive optics (MCAO), multi-object adaptive optics (MOAO), extreme adaptive optics (ExAO), and space-based adaptive optics. MOAO is an instrument concept to us multiple guide stars to selectively improve image quality in a sub-region of the telescope's field of view [*1*]. In MOAO, multiple DMs would be used in parallel to allow high-resolution imaging of science objects distributed across a large field of view. ExAO refers to a planned ground-based instrument intended for observation of Jovian exoplanets, with the help of high spatial resolution DMs having thousands of control points and flawless performance (no dead actuators). In addition to exoplanet detection, such an ExAO system would be capable of characterizing dust disks around stars and will allow high Strehl ratio imaging at visible wavelengths [*2-4*]. Space-based imaging offers the opportunity to avoid the dynamic aberrations introduced by the atmosphere. Space based AO compensate for imperfections in the telescope optics, and is needed for high contrast coronagraphy. These new instruments offer the potential to greatly advance astronomical science, but each requires DMs that improve upon those currently used in astronomical telescopes.

- **MOAO** requires *open loop* control of the DM: corrections made by the DM are not accessible to the wavefront sensor, so closed feedback is not possible. That makes it important that the DM can be shaped to the required precision in a single step – something that is difficult or impossible to do using piezo-actuated conventional DMs. MEMS DMs offer a unique path to MOAO.
- **ExAO** demands DMs with *several thousand actuators*, and shape control to within a few nanometers. MEMS-DMs have shown promise in this application. A 4096 actuator engineering grade DM has been produced for the Gemini Planet Imager, and a science grade version is in production. This has been challenging, since the larger DM area coupled with ExAO's need for flawless DM performance imposes a requirement to reduce areal defect density at the MEMS foundry. In ExAO, control loop iterations could plausibly require hours of integration, so open loop "go-to" precision is again valuable [*5*].
- **Space based AO** is highly constrained by *size, weight, and power* consumption of the AO system. MEMS DMs are well-matched to those constraints, because of their compact dimensions and low-power drivers, enabled by low capacitance (~100fF) electrostatic actuators. Overall, MEMS DMs reduce by more than an order of magnitude the volumetric size, total weight, and consumed power of in comparison to commercially available alternative DMs. Our MEMS DMs have been built into a compact telescope scheduled for launch in 2010 using a NASA sounding rocket, and we developed a unique tip-tilt-piston segmented DM with segment flatness of better than 5nm RMS for a NASA prototype as part of a space based visible nulling coronagraph project.

## 4. Precise control approaches for MEMS DMs

One important feature of MEMS DMs that has been confirmed by precise measurement [*6*] is that they can be shaped predictably in a single step to nanometer-scale precision, enabling open loop AO control. Controlling a MEMS DM, in open or closed loop, is complicated by the fact that independently addressed actuators are mechanically coupled to one another through the mirror facesheet. As a result, the displacement of any DM actuator alters the forces experienced by its neighboring actuators.



$$\nabla^4 w(x,y) = \frac{q(x,y)}{D} + \frac{6}{h^2}\left\{\left[\left(\frac{\partial w(x,y)}{\partial x}\right)^2 \frac{\partial^2 w(x,y)}{\partial x^2}\right] + \left[\left(\frac{\partial w(x,y)}{\partial y}\right)^2 \frac{\partial^2 w(x,y)}{\partial y^2}\right]\right\}$$

*Figure 2: Open loop control of a MEMS DM. Left: Equilibrium force balance at an actuator post. Top right: Constitutive equation of elastic mirror plate mechanics, including both stretching and bending. Bottom right: Using the modified biharmonic equation, one can rapidly determine mirror forces at each post, given the desired mirror shape w(x,y).*

An efficient open-loop control algorithm can be achieved if one first establishes a DM model that consists of two coupled mechanical subsystems: the continuous facesheet and the array of actuators connected to the facesheet via rigid posts. The rigid posts are the points of connection for the two subsystems. This can be seen in the free body diagram and equations of Figure 2, where $F_M$ is the force imparted by the mirror facesheet, $F_A$ is the force imparted by the actuator diaphragm, and $F_E$ is the electrostatic attractive force associated with an applied actuator voltage. Using this equation mirror force acting at each post can be calculated by simple numerical integration of the desired mirror shape. Once the mirror force $F_M$ is known at each actuator post, it is possible to reduce the open-loop control problem to one that is entirely local and uncoupled. As a result, the calibration is achieved through a compact set of empirical measurements coupled to a linear elastic model. We recently implemented this computationally simple and inherently fast algorithm on a 140 actuator MEMS DM. Randomized shapes containing all achievable spatial frequencies of the MEMS DM with up 3.0µm amplitude were produced repeatedly with no more than 30nm RMS error [*7, 8*]. Others have also implemented open loop AO control with our mirrors, demonstrating comparable results [*9*]. Open loop control with a MEMS DM was demonstrated in the first civilian use of MEMS-based astronomical AO in the past year [*10, 11*]. In the coming year, we will extend that model to improve precision further [*12*].

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