

Megapixel wavefront correctors

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Abstract

Optical-quality microelectromechanical deformable mirrors (DMs) and spatial light modulators (SLMs) are described. With such mirrors, the shape of the reflective surface can be modified dynamically to control an optical wavefront. A principal application is to compensate for aberrations and thereby improve image resolution in telescopes or microscopes: a process known as adaptive optics. μ DMs are an enabling component for adaptive optics. Over several years, researchers at Boston University and Boston Micromachines Corporation have developed manufacturing processes that allow production of continuous and segmented deformable mirrors. We have produced mirror arrays with up to 22,500 actuators, 3.5 μ m of useful stroke, tens of picometer position repeatability, >98% reflectivity, and flatness better than 15nm RMS. Challenges to manufacturing optical quality micromachined mirrors in particular have been addressed: reducing surface roughness, increasing reflectivity, and eliminating post-release curvature in the mirror. These silicon based deformable mirrors can modulate spatial and temporal features of an optical wavefront, and have applications in imaging, beam-forming, and optical communication systems. New developments in DM design are discussed, and manufacturing approaches to micromachined DM and SLM production are presented, and designs that will permit scaling to millions of actuators are introduced.

Introduction

In many optical systems, it is desirable to alter the optical wavefront dynamically. Prominent examples include adaptive optical systems, in which performance degradation due to the existence of aberrations in the system's components or beam path is overcome by measuring and compensating the effect of aberrations on the wavefront. Other examples include display systems, in which dynamic modulation of amplitude can be used to produce high-quality projected images. (e.g. Texas Instruments DLP). A third category of dynamic wavefront control involves holographic beam shaping, which has been used as a tool in holographic optical tweezers.

In all of these systems, wavefront control is achieved by subdividing the optical wavefront and adjusting the phase or amplitude of the beam using a spatially distributed

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array of actuators beneath a continuous membrane mirror (DM) or an array of uncoupled mirror segments (SLM).

For some of these applications, the production tools of microelectromechanical systems (MEMS) offer the promise of rapid advancement. MEMS technology is well known for delivering products with attributes that are important in wavefront control: compactness, scalability, nanometer-scale actuation resolution, low cost, and low power consumption. In this paper, several MEMS micromirror devices produced at the Boston University Precision Engineering Research Laboratory, and in collaboration with Boston Micromachines Corporation are described.

The devices that are described in this paper can be divided into two categories that are delineated not so much by final application as by manufacturing approach. Devices have been made using silicon surface micromachining or aluminum surface micromachining.

In silicon surface micromachining, MEMS structures are constructed by depositing, lithographically patterning, and then etching alternate layers of structural and sacrificial thin films on a polished silicon wafer. This patterned thin film approach uses polycrystalline silicon as a structural material, and silicon dioxide as a sacrificial material, and borrows much of its tooling and process-knowledge base from the semiconductor fabrication industry. Upon completion of the build-up of layers, the wafer is diced and the sacrificial materials are dissolved, leaving a fully assembled silicon device. In practice, the processes used in MEMS fabrication have diverged considerably from their roots in semiconductor fabrication, and many adjunct processes have been incorporated into the MEMS toolkit to improve electromechanical performance or to allow additional functionality.

For development of optical devices, a primary advantage of silicon surface micromachining is that devices can be made using standardized processing tools (e.g. foundries), and the starting point is a flat, smooth, high-quality wafer. A disadvantage is that the processes used to create free-standing MEMS structures generally do not yield optically flat structures over spans of more than a few tens of micrometers, due to intrinsic material stresses and stress gradients. Also, deposited thin-films of polycrystalline silicon are neither reflective nor smooth, and their thinness makes them difficult to polish or coat.

A disadvantage particular to *silicon* surface micromachining is that the thin film deposition and annealing processes require temperatures in processing that exceed 1000°C. As a result, these devices cannot be integrated directly with complementary metal oxide semiconductor (CMOS) electronics, which are limited to processing temperatures lower than ~350°C. Instead, such silicon MEMS devices must be wirebonded to packages or flip-chip bonded to a separate electronics drivers. These hybrid integration approaches do not scale well for more than a few thousand connections. Many optical wavefront correctors do not require so many actuators, but those that do must use an alternative manufacturing approach.

One such approach is aluminum surface micromachining. In this process, a CMOS driver array is first manufactured through a conventional semiconductor foundry process. The resulting wafer, or a chip extracted from the wafer, becomes the substrate upon which the aluminum surface micromachining is conducted. The process is similar to silicon surface micromachining, except that the structural and sacrificial thin films are comprised of aluminum and polyimide, respectively. Because both of these materials can be deposited in low-temperature processes (sputtering for aluminum and spin-on coating for polyimide) it is possible to position each actuator directly on top of its associated electronic driver. Arrays built using this architecture can be scaled to sizes as large as a million pixels without inherent difficulty.

Silicon Micromachined DMs and SLMs

Silicon micromachining has been used to produce deformable mirrors and spatial light modulators with exceptional optical quality and repeatability, and up to 1024 actuators. This work builds on several generations of silicon micro-machined deformable mirrors and spatial light modulators that were fabricated over the past nine years. Previous work focused on smaller arrays and on improving optical quality of MEMS DMs and SLMs. The kilo-pixel SLM is made up of 1024 individually addressable surface-normal electrostatic actuators with center posts that support individual optical mirror segments. Each electrostatic actuator consists of a silicon membrane anchored to the substrate on two sides above a silicon electrode (Figure 1).

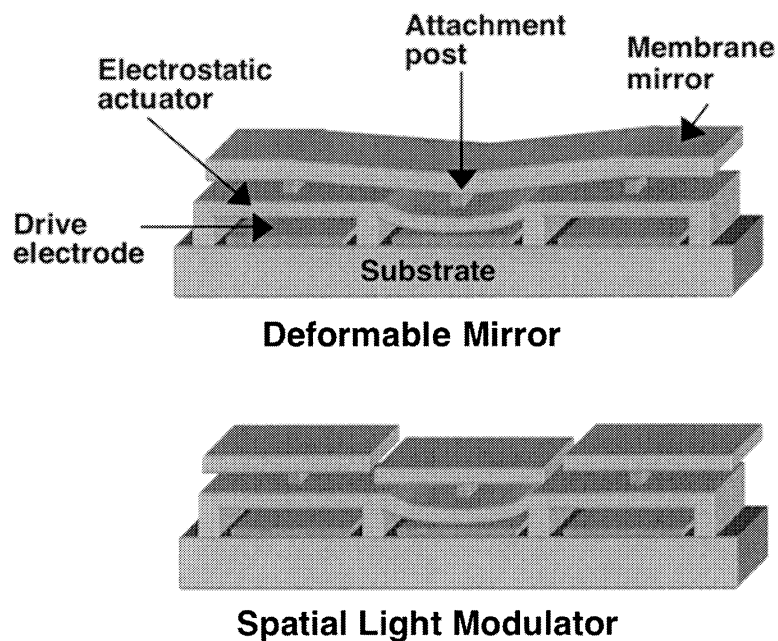


Figure 1. Schematic cross section of a deformable mirror (top) and a spatial light modulator (bottom) using electrostatic parallel-plate actuation.

Devices were fabricated with a combination of silicon surface micromachining and several custom fabrication processes to ensure optical quality. Chemo-mechanical polishing was used to remove surface roughness and ion machining was used to remove curvature. A stress-free gold coating process was also developed to increase reflectivity. An abbreviated processes flow describing device manufacture is provided in Table 1.

Table 1: Processing Steps for Silicon DMs/SLMs

Step	Layer/Process	Thickness	Description	Purpose
1	Nitride	1 μ m	Deposit pattern and etch nitride	Insulating layer.
2	Poly 0	0.5 μ m	Deposit pattern and etch polysilicon	Wire layer
3	Oxide 1	5 μ m	Deposit pattern and etch PSG	Sacrificial material
4	Poly 1	2 μ m	Deposit pattern and etch polysilicon	Actuator structure
5	Oxide 2	2.5 μ m	Deposit pattern and etch PSG	Sacrificial material
6	Chemo-polish	200nm	Polish surface topography on Oxide2	Reduce topography
7	Poly 2	3 μ m	Deposit pattern and etch polysilicon	Mirror structure
8	Pad Metal	2 μ m	Deposit gold on wirebond pads	Wirebond pads
9	Metal	500nm	Evaporate gold on mirror surface	Improve reflectivity

The devices were die-attached to a custom-made ceramic pin-grid-array (PGA) package, and then wire-bond connections were made from each actuator electrode to one of the 1024 bond pads on the package periphery (Figure 2).

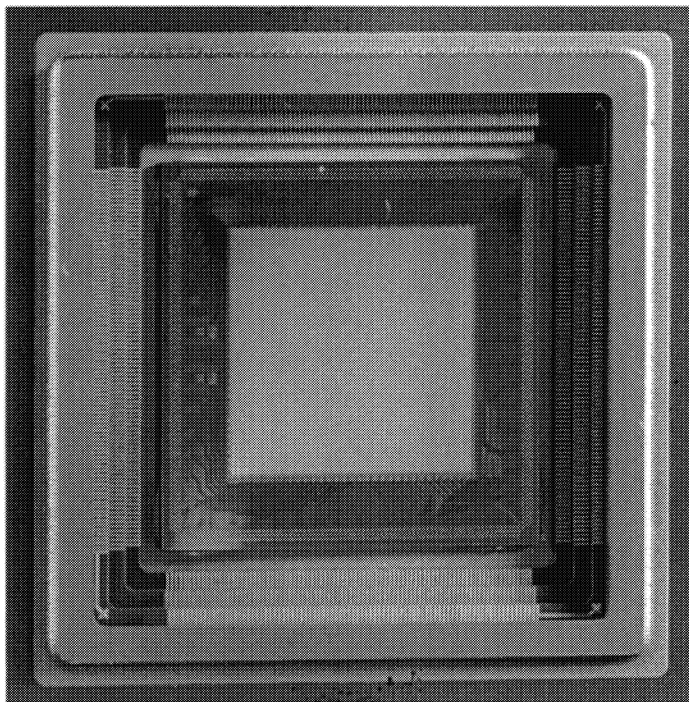


Figure 2. Photograph of kilo-pixel SLM

Mirror characterization included measurements of electromechanical actuator stroke, repeatability, hysteresis, optical flatness, optical reflectivity, and actuator frequency response in air and vacuum.

Deflection was found to be monotonic and smoothly varying with voltage. Response was nonlinear, with an approximately quadratic relationship between applied voltage and actuator deflection. Peak deflection, depending on actuator design, ranged from 2.0 μm to 3.5 μm , corresponding to a peak applied voltage in the neighborhood of 200V. Repeatability was measured using a dynamic interferometer, and found to be better than 2nm. No hysteresis was measurable in the actuator. A typical voltage vs. deflection measurement for an actuator is shown in Figure 3.

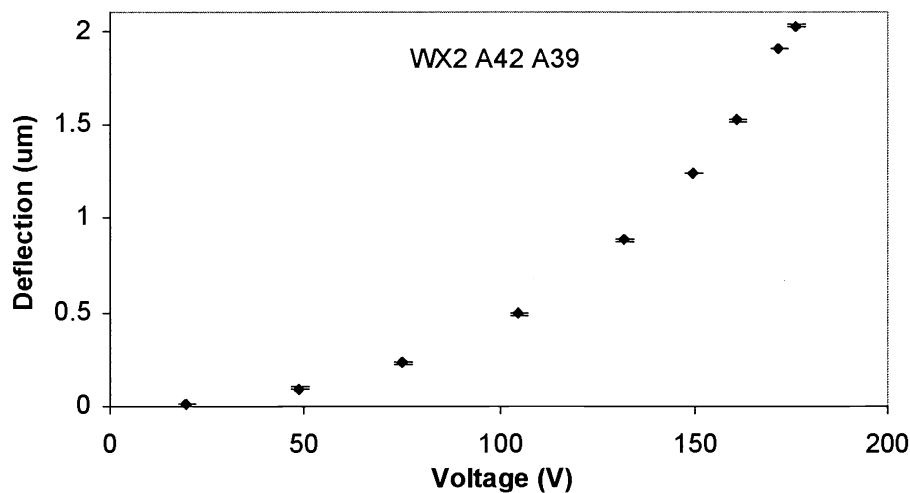


Figure 3. Voltage versus deflection measurements made on a mirror segment above a typical actuator on a spatial light modulator.

Optically, the mirror has a reflectivity better than 98%, and an uncorrectable deviation from flatness of $\sim 15\text{nm}$ RMS. A summary of device behavior is provided in Table 2.

Table 2: Performance characteristics of silicon DMs/SLMs

Characteristic	12 x 12 Array	32 x 32 Array
Number of actuators	140	1024
Stroke/Repeatability	2 μm -3.5 μm / $\sim 2\text{nm}$	2 μm -3.5 μm / $\sim 2\text{nm}$
Hysteresis	0 %	0 %
Clear aperture	3.3 mm	10 mm
Reflectivity	>98%@633nm	>98%@633nm
Flatness	15nm RMS	15nm RMS
Bandwidth (air/vacuum)	300 μm	338 μm

Aluminum micromachined SLMs with integrated CMOS driver

While the silicon devices leverage a considerable heritage in semiconductor processing techniques, the architecture described in the previous sections is limited to array sizes of a few thousand actuators because of the requirement to wirebond the device to make connection with its driver. To overcome this limitation, a new kind of spatial light modulator (SLM) has been demonstrated. The core innovation is the use of a multi-segment, micromachined mirror array fabricated on a complementary metal-oxide semiconductor (CMOS) electronic array. A low-temperature microfabrication process was developed to permit fabrication of the microelectromechanical system (MEMS) on the CMOS electronics wafer.

In this low temperature MEMS fabrication process, patterned thin layers of structural and sacrificial materials are built up on a substrate through sequential deposition and lithography. Ultimately, the sacrificial layers are etched away, leaving a self-assembled, integrated opto-electromechanical device. Each individual pixel (phase modulator) in the device can be controlled using an underlying array of CMOS electronics.

Though production processes for this device are currently still being refined, some important milestones have been achieved:

1. A low temperature fabrication technology for μ SLM structures was developed using polyimide sacrificial layers and aluminum alloy structural layers
2. Actuator arrays were manufactured with acceptable electromechanical performance in array sizes of up to 150 x 150.
3. A CMOS electronics driver array was manufactured using commercially available foundry fabrication
4. Successful process integration included overcoating CMOS chips with silicon nitride, planarizing and polishing the overcoat layer, etching and filling via holes in the overcoat layer, and fabricating actuator arrays in 150 x 150 and 32 x 32 formats.

The baseline design for the metal SLM is illustrated in Figure 4. Each pixel is made up of three main components: 1) electrodes, 2) actuator, and 3) mirror, shown in Figure 2. As illustrated in Figure 2b, the electrodes consist of four concentric pads, each of which has double the area of the neighboring interior electrode. Therefore, if the smallest center electrode, E1, has area A_1 , then electrode E2 has a total area of $2A_1$, electrode E3 has an area of $2A_2=4A_1$, and electrode E4 has an area of $2A_3 = 4A_2=8A_1$. This electrode layout will allow the 16-level control of the actuators. Small vias connect individual electrodes with the underlying CMOS driver. Centered directly over the electrodes is an actuator made up of a square membrane supported by four flexures on each side. The membrane area is the equal to the total area available for the four underlying electrodes to

maximize the electrostatic force exerted by the electrodes on the actuator – the effective area is reduced from the maximum available area by the lateral gaps between the electrodes. The membrane perimeter corresponds with the outer perimeter of the largest electrode to maximize the electrostatic force.

The μ SLM is made up of an array of identical pixels, placed on a pitch of $100\mu\text{m}$. The pitch determines the maximum pixel size and constrains the maximum size of the CMOS drive electronics, the available electrode area, the actuator layout, and the mirror size. The segments are manufactured on top of the actuator and each segment is attached to an actuator by a small post located in the center of the actuator membrane and the mirror surface.

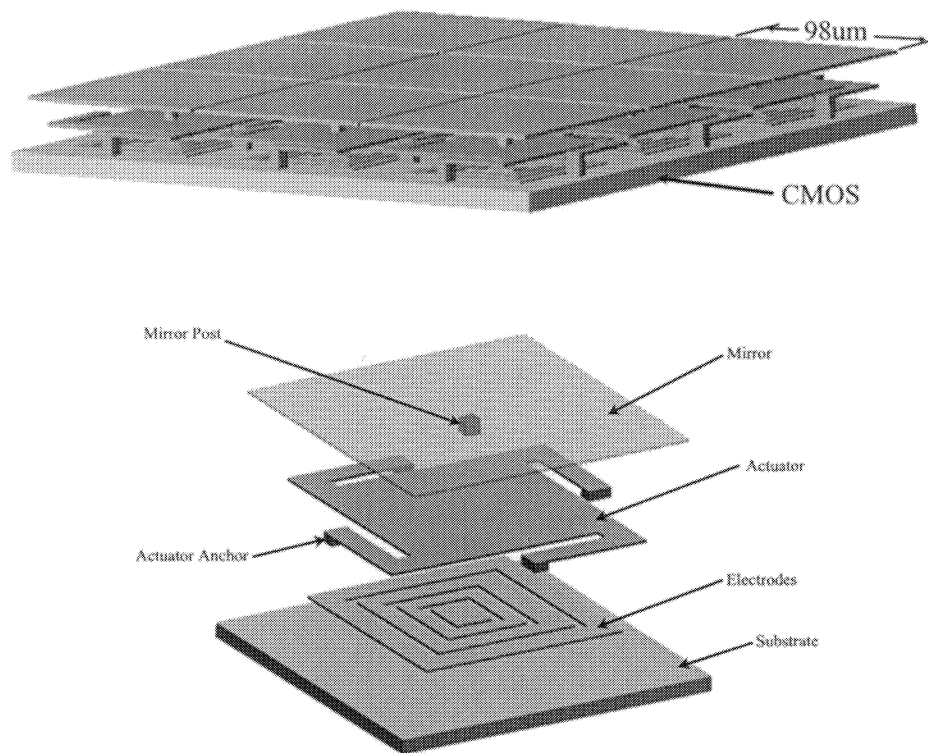


Figure 4. Top - Schematic of 3×3 micro-fabricated spatial light modulator. Bottom - Single μ SLM pixel illustrating the three main components of the device.

The 4-bit CMOS driver array is produced on silicon wafers, which are subsequently diced. A principal challenge in this device development is that the CMOS electronics array itself is an unsuitable platform for optical fabrication, because of its excessive topography. By overcoating the CMOS with an insulating layer, polishing it flat, and then etching through the layer to make via-attachments to the drive circuitry, this problem has been successfully addressed (Figure 5).

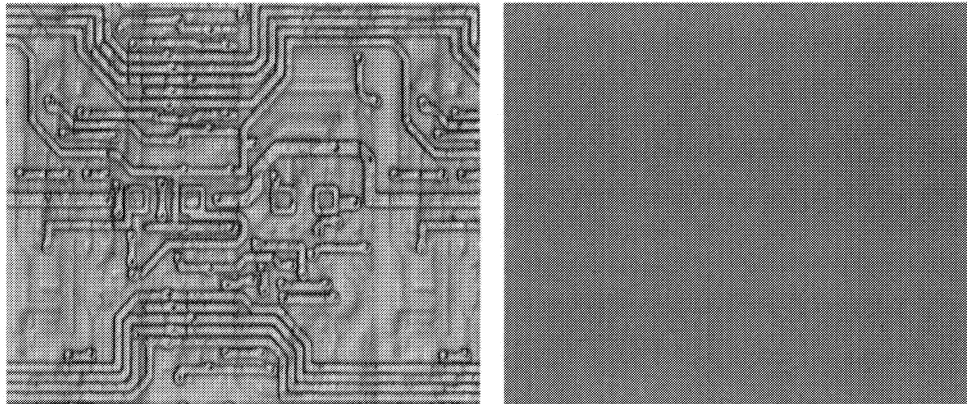


Figure 5. Planarized CMOS electronics. Left: as-received chip showing considerable topography; Right: Planarized CMOS surface, free of pinholes or cracks.

Figure 6 shows the surface profile of the planarized CMOS electronics after 60min polishing (WYKO NT2000, Veeco). Initial flatness of $>500\text{nm}$ RMS before planarization and polishing was reduced to $<20\text{nm}$ RMS after planarization and polishing.

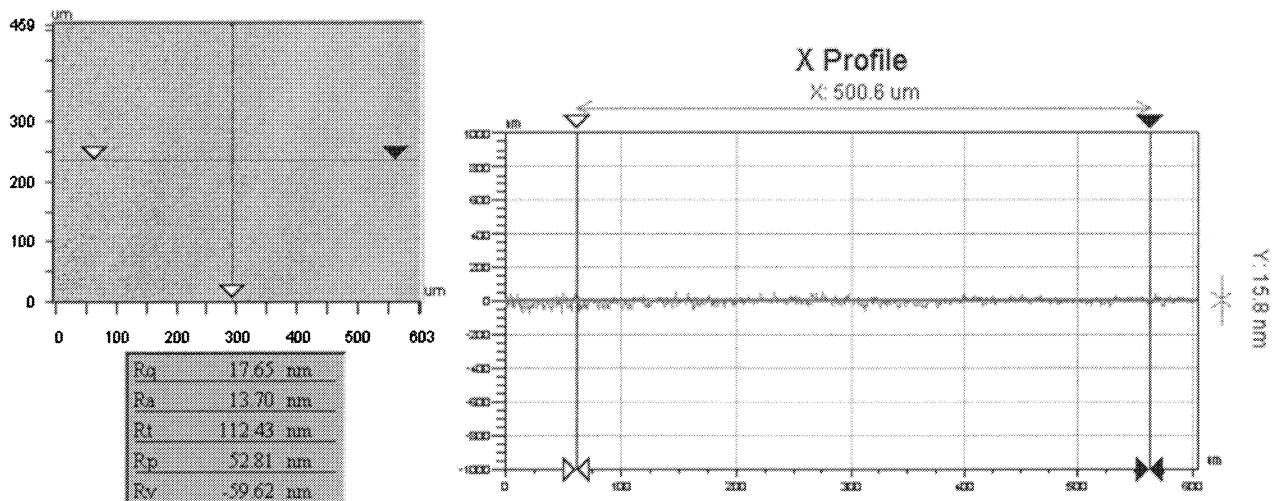


Figure 6. Surface profile of the planarized CMOS electronics (polishing time: 60min, scan length: 500um.)

MEMS actuator arrays both 32×32 and 150×150 actuators in size, were successfully integrated with the CMOS driver chips. Figure 7 shows both devices, packaged in ceramic pin grid array carriers. The devices were integrated using aluminum and polymer surface micromachining processes.

In these prototype devices, individual pixels were addressed as shown in Figure 8. No cross talk or other influence on the neighboring pixels was measurable. Using an electrode voltage of 30V, each of the four electrodes were individually addressed and the resulting deflection measured.

Conclusions

MEMS deformable mirrors and spatial light modulators have been described. These devices have been made in two different materials: silicon and aluminum. Silicon DMs and SLMs have exceptional optical and electromechanical behavior, and are suitable for advanced wavefront control applications requiring up to a thousand actuators. Aluminum SLMs are fabricated in a new manufacturing approach, and will extend the achievable scale of SLMs to devices with many tens of thousands of actuators. Static and dynamic behavior of individual actuators in these silicon and aluminum devices have been reported, and current technical challenges have been discussed. These high-resolution wavefront correctors may become an important element in future adaptive optical compensation systems.

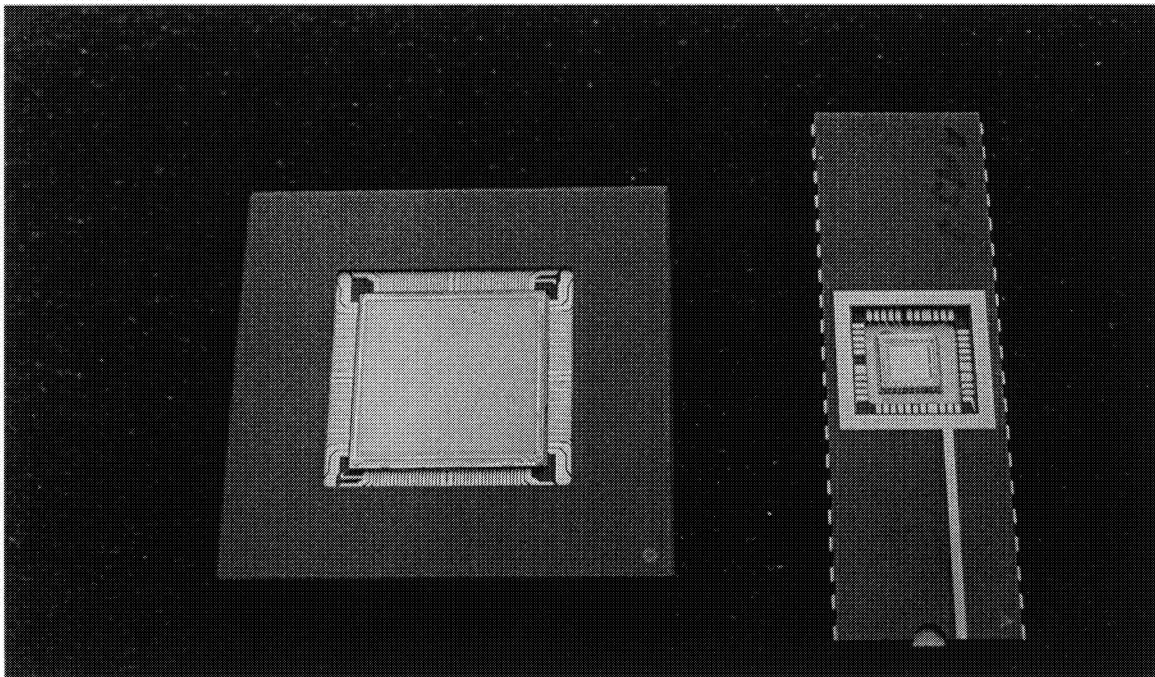


Figure 7. Integrated actuator arrays in ceramic packages. Left -22,500 element (150x150) array. Right - 1024 (32x32) array.

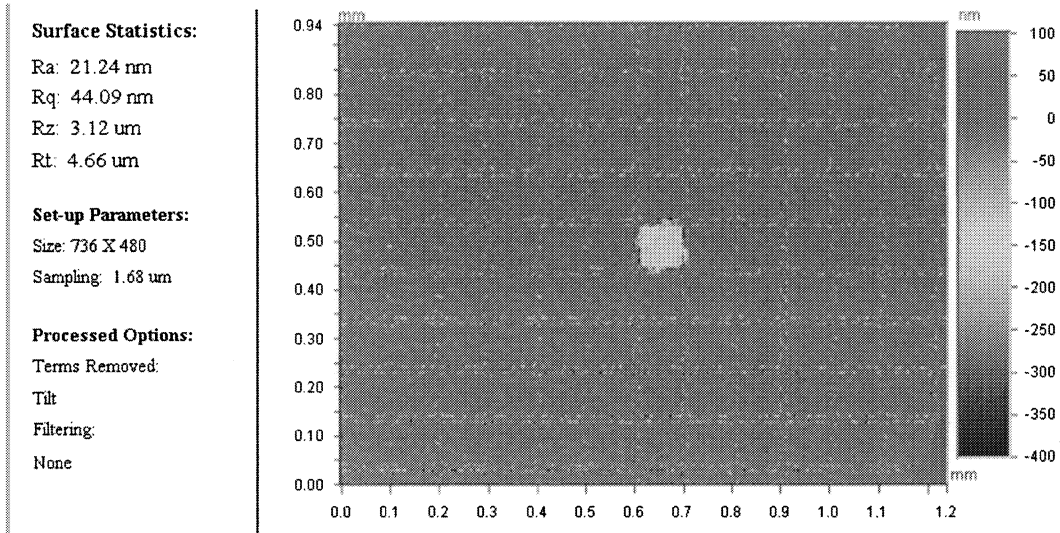


Figure 8. Single pixel in aluminum SLM deflected.

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