mirrorcle
TECHNOLOGIES, INC.

# Mirrorcle Technologies MEMS Mirrors – Technical Overview

## OVERVIEW

**Mirrorcle Technologies Gimbal-less Two-Axis Scanning MEMS Mirror Devices** are based on proprietary **ARI-MEMS** fabrication technology initially developed through research projects at the Adriatic Research Institute ("ARI") in Berkeley, CA.They provide very fast optical beam steering across two axes, while requiring ultra-low power. The mirrorsdeflect laser beams or images to optical scanning angles of up to 32° on each axis. Compared to the large-scale galvanometer-based optical scanners, these devices require several orders of magnitude less driving power: continuous full-speed operation of the electro-static actuators that drive mirror tip-tilt rotation dissipatesless than 1mW of power.

Mirrorcle TechnologiesMEMS mirrors are made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces are coated with a thin film of metal with desired reflectivity. Smaller and medium mirror sizes are manufactured as integrated parts of the silicon MEMS chip, while larger mirrors are bonded onto actuators, allowing custom mirror sizes.

## HIGH SPEED POINT-TO-POINT TIP/TILT CAPABILITY

Most of Mirrorcle MEMS Mirror device types are designed and optimized for point-to-point optical beam scanning. A steady-state analog actuation voltage results in a steady-stage analog angle of rotation of the micromirror. There is a one-to-one correspondence of actuation voltages and resulting angles: it is highly repeatable with no detectable degradation over time. This is in great part due to the electrostatic drive methodology and single-crystal silicon material selection.Positional precision of mechanical tilt in open loop driving of the mirror actuators is at least 14 bits (16384 positions) on each axis. For most devices, with mechanical tilt range of -5° to +5° on each axis, this tilt resolution is within 0.6 milli-degrees or within 10 micro-radians.A sequence of actuation voltages results in a sequence of angles for point-to-point scanning.Mirrorcle Technologies Inc. (MTI) devices can be operated over a very wide bandwidth from dc (they maintain position at constant voltage with nearly zero power consumption at the device) to several thousand Hertz. Such fast and broadband capability allows nearly arbitrary waveforms such as vector graphics, constant velocity line scanning, point-to-point step scanning, object tracking, etc.

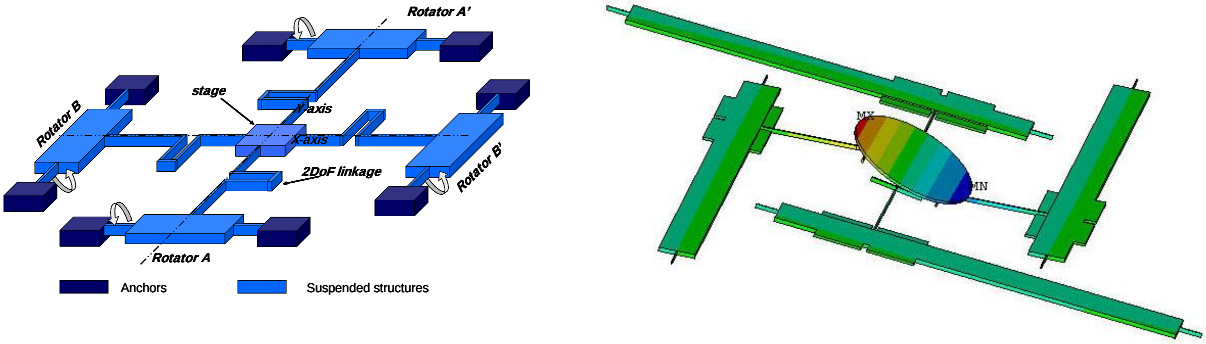


*Figure 1. Schematic diagram of a gimbal-less two-axis scanning actuator based on four high aspect ratio rotators connected to the central pedestal by two degrees-of-freedom (2 DoF) linkages.*

Multiple awarded patents describe our proprietary**gimbal-less design methodology** and the unique **multi-level beam fabrication methodology** for creating a complete actuator out of one monolithic piece of single crystal silicon. A major advantage of the gimbal-less design is the capability to steer optical beams or images at equally high speeds in both axes. A typical device with a 0.8 mm diameter-sized mirror achieves tilt angles from -6° to +6°, non-resonant optical beam steering of over1000 rad/s and has first resonant frequency in both axes above 3.6kHz. Large angle step response settling times of <100 *μs* have been demonstrated on devices with up to 0.8 mm diameter micromirrors when open-loop driven with specialized input shaping filters.

## MULTIPLE SCANNING MODES

MTI devices can also operate in the dynamic, resonant mode. When operated near the resonant frequency, devices give significantly more angle at lower operating voltages and sinusoidal motion. Namely, the MEMS actuators utilize single-crystal silicon springs to support the micromirror and to provide restoring force during actuation. The combination of the springs and the mirror's inertia result in a 2nd order mass-spring system with a relatively high quality factor (Q) of 50-100. Therefore, in this mode, low actuation voltages at frequencies near resonance result in large bi-directional rotation angles. Resonant frequencies are in the range of several kHz.

It is possible to define three modes of operation, as described here and depicted in photos of green laser beam steering in Fig. 3:

a) First mode is **point-to-point mode** or **quasi-static mode**. In this case both axes are utilizing the wide bandwidth of operation of the device from dc to some frequency, and not allowing for resonance and ringing. Therefore mirror can hold a dc position, or move in a uniform velocity, or perform vector graphics, etc.

b) Second mode is **resonant mode**. In this case both axes are utilizing the narrow, high gain resonance to obtain large angles of deflection and relatively low voltages and high speeds. Motion is limited to very narrowband, sinusoidal trajectories with a phase lag to the applied voltage. It is not necessary to drive the device at the exact resonant peak as the resonant mode can be obtained within few percent of the highest gain point. Resulting 2D motion describes circles, ellipses, and various higher order Lissajous patterns and can be modulated at some rate. Devices designed for point-to-point mode, when driven near and at resonance, easily exceed safe operating angles and break. It is important to approach resonant mode of operation with very small sinusoidal driving voltages about the bias position and very carefully search for a desired operating point and angle, so as not to exceed a given device's maximum mechanical angle limit.

c) The third mode is basically a mixed mode of the previous two in which one axis is used in **quasi-static mode**, and the other axis is used in **resonant mode**. A typical use case is to run one axis very fast (e.g. few kHz,) to create horizontal lines, and to run the other axis with a sawtooth-like waveform to create a raster pattern that covers a rectangular display or imaging area.Again, the axis operating at resonance should have its parameters carefully obtained, initially at low voltages and angles, to avoid exceeding maximum mechanical angles.

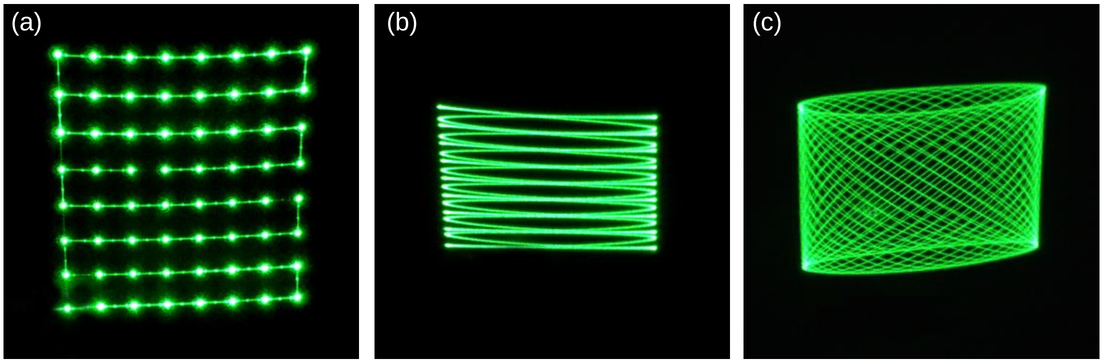


*Figure 2. Photographs of examples of using Mirrorcle MEMS Mirror in **(a)** point-to-point scanning mode (quasi-static) on both axes with the laser beam stopping at each angle, and then stepping to the next angle, **(b)** resonant scanning mode on the x-axis (sinusoidal beam motion) and quasi-static on the y-axis (triangle wave motion in this example), and **(c)** resonant scanning mode on both axes, showing a 2D resonant Lissajous pattern.*

## MODULAR DESIGN

MTI actuators lend themselves inherently to a modular design approach.Each actuator can utilize electrostatic rotators of arbitrary length, arbitrarily stiff linkages, and arbitrarily positioned mechanical rotation transformers. In addition, the device can have an arbitrarily large mirror diameter. A schematic diagram of the conceptual operation of the gimbal-less 2D designs is shown in Figure 1. Due to this modularity, devices easily lend themselves to customization for a particular application requirement. Depending on the available area/size of the silicon die (in some applications such as bio-medical imaging size is restricted by imaging equipment specs), we can design appropriately sized actuators to obtain maximum performance within allowable parameter space.

Due to this design flexibility and a wide variety of applications that require beam steering, with widely different specifications, we provide many types of gimbal-less two-axis actuator designs. With fourteen major design and manufacturing generations, multiple sub-generations of design tuning for a specific customer or set of specifications, the complete list of working designs has over 60 device types. Most of those device types are available in R&D quantities to give our customers the best chance of quickly finding the best set of parameters and trade-offs for their application development.

## SPEED VS. MIRROR SIZE TRADE-OFF

Devices with larger-diameter mirrors are correspondingly slower due to the increased inertia. Inertia of a round mirror is proportional to the fourth power of the radius. Therefore, speed reduces quadratically (square power) with increase of mirror size. This is a general rule for a very rough estimate, but many other parameters affect the actual performance, especially die size and angle swing. An example would be to compare a 0.8mm diameter integrated mirror with a 1.7mm diameter integrated mirror, both having the same silicon die size and both having very similar mechanical tip/tilt angles (-5° to +5°). The 0.8mm device's first resonant frequency is ~4kHz, while the 1.7mm device's is ~1.1kHz.

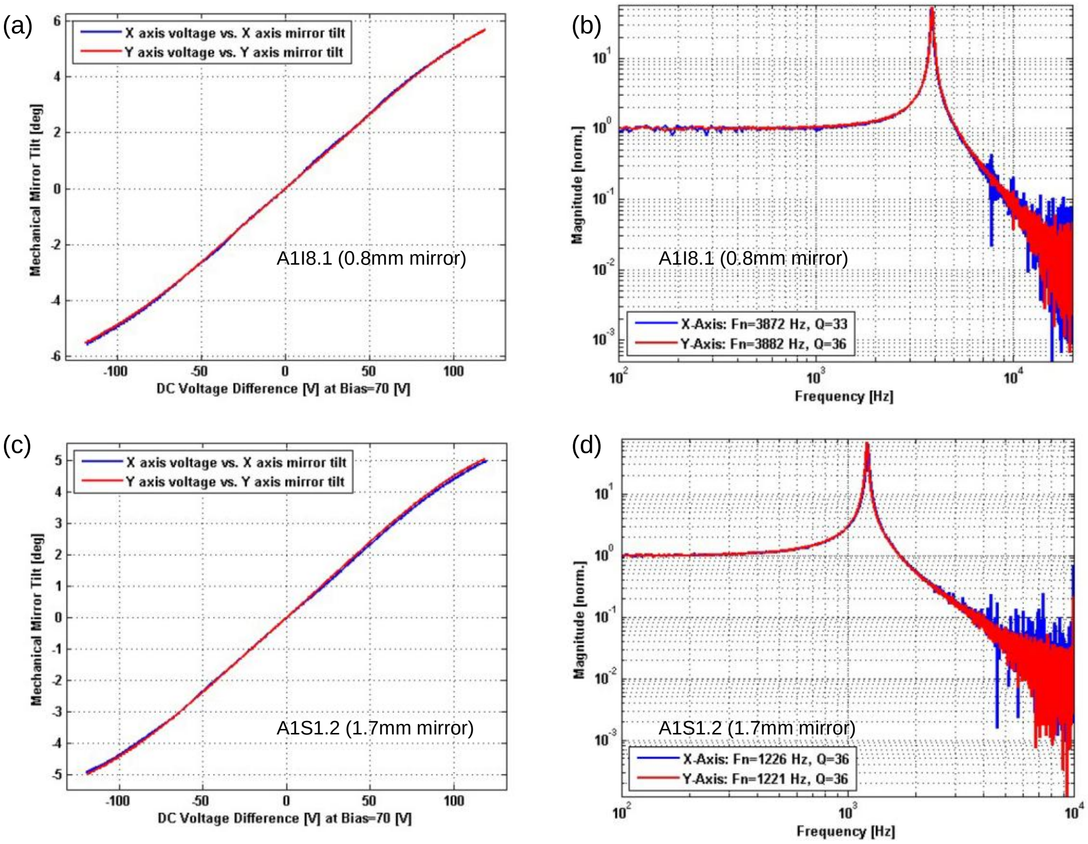


*Figure 3. Voltage vs. Angle (static response), and small signal (frequency) response plots of two device examples. (a) and (b) for A1I8.1 device with integrated 0.8mm mirror, and (c) and (d) for A1S1.2 device with integrated 1.7mm mirror.*

## OPTIMAL ACTUATOR SIZES

Over 60 distinct device types have been designed and manufactured. A very significant design parameter with a strong influence on key performance specifications is actuator (silicon chip) size. Larger actuators provide higher forces and torques for driving larger mirrors at faster speeds, but also cost more to produce and require larger packages. Small actuators are best match for smaller mirrors as the actuators themselves also have smaller inertia. Presently, the in-stock designs fall into 4 size categories:

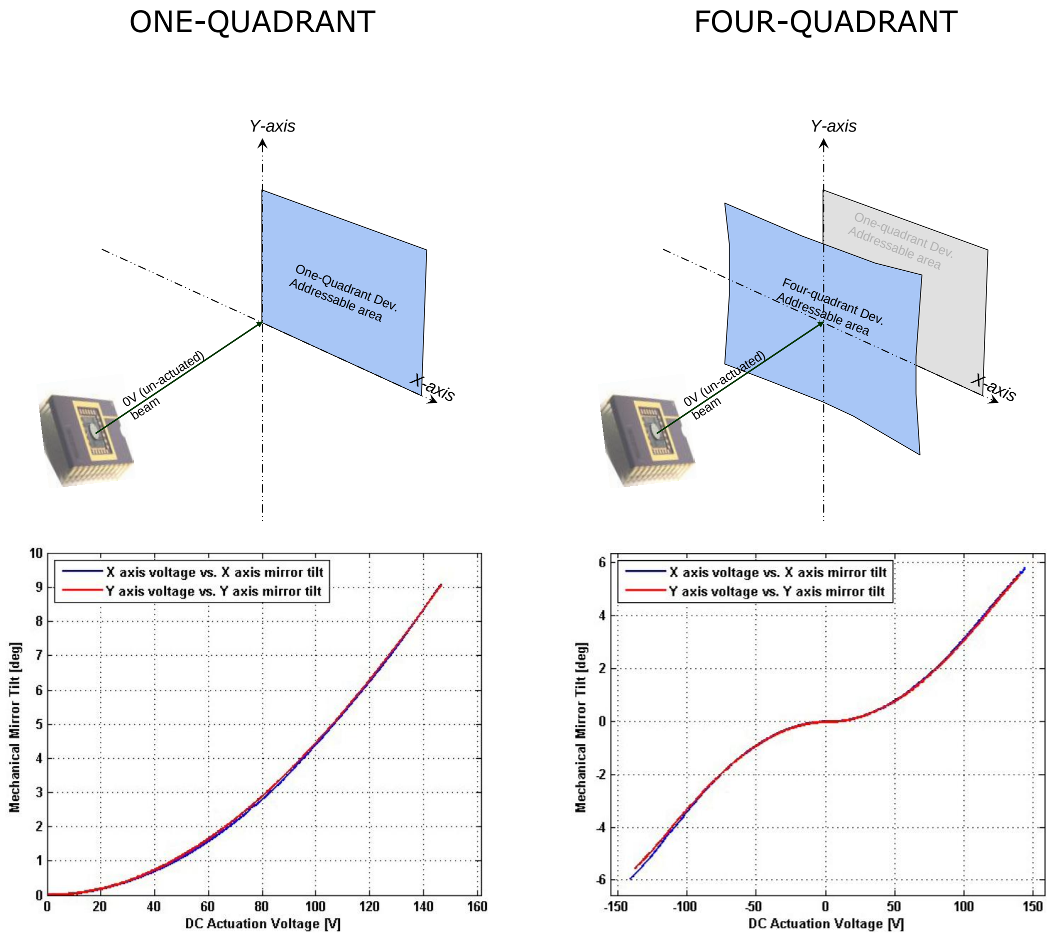
1) 4.23mm x 4.23mm actuator
2) 4.76mm x 4.76mm actuator
3) 7.25mm x 7.25mm actuator
4) 8.00mm x 8.00mm actuator

It is important to look at each specific design to decide for an appropriate match for a certain application and set of specifications. Broadly speaking, mirrors with diameters equal to or larger than 3.0mm should be used with sizes #3 and #4 for best performance, while mirrors with diameters equal to or smaller than 1.2mm should be used with sizes #1 and #2.

## FOUR-QUADRANT (4Q) TIP-TILT CAPABILITY

Several years ago when MirrorcleTech's gimbal-less technology was in early stages of development, all devices fabricated in generation ARIMEMS1 through ARIMEMS6 were one-quadrant (1Q), or uni-directional type devices. This refers to the fact that each axis (these are still two-axis or dual-axis or 2D devices) is able to deflect a mirror from rest position (0°) to one side (e.g. 8°,) but not to the opposite side (e.g. -8°.) So a typical one-quadrant (1Q) device achieves mechanical tilt of 0° to 8° on the X axis and 0° to 8° on the Y axis. More recently, all device types provide four-quadrant (4Q) beam-steering capability which typically allows for overall larger total tip/tilt angles and has additional benefits of linearization, described in the next section.

Figure 4 below provides a graphical explanation as to the difference between the two types of devices. In both examples, device is optically setup such that at 0V actuation, the laser beam is deflected normally to the wall at the origin of the co-ordinate system. Under such conditions, 1Q devices will address points only in the 1st quadrant, while 4Q devices in all four quadrants. Note that the 1Q device can be optically setup to address all 4 quadrants by shifting its non-actuated 0V position left and down so that it is not normal to the wall. The figure also shows typical characterization results for representative devices of each type. Note that negative DC actuation voltage in the bi-directional device represents voltage applied to rotators that provide negative rotation, and not actually necessarily negative voltage.



ONE-QUADRANT

FOUR-QUADRANT

*Figure 4. Comparison of addressable angles/areas by uni-directional and bi-directional devices;the representative voltage vs. angle measurement of each.*

## LINEARIZED DRIVING OF FOUR-QUADRANT (4Q) DEVICES

**Four-quadrant** development kit amplifiers utilize a device-specific method of driving the 4Q MEMS actuators with a Bias+Differentialscheme. We have been using this scheme to linearize actuators' voltage-angle relationship, as well as to improve smooth transitions from one quadrant to another, i.e. form one actuator to another within the device. In this mode both the positive rotation portion and the negative rotation portion of each rotator are always (differentially) engaged, and therefore the voltages and torques are always continuous. This type of driving significantly linearizes the devices voltage vs. angle characteristics, akin to a push-pull transistor circuit design technique. The benefits of this driving method are multifold and we provideit in all MirrorcleTech MEMS drivers and development kit hardware, for use with any MirrorcleTech device. A schematic diagram of the methodology and a measured device is shown in Figure 5 below.

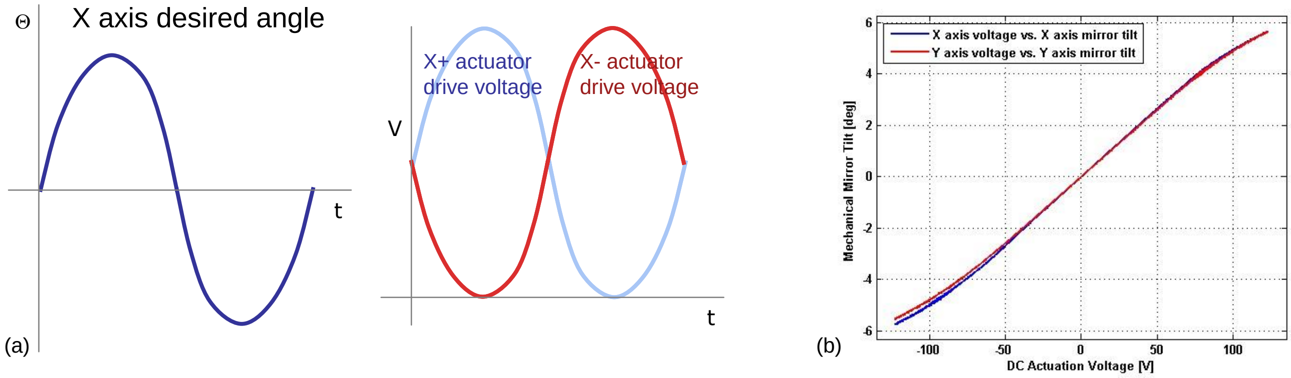


*Figure 5. Methodology of linearized driving the 4-Quadrant devices: a) desired angle of the x-axis has positive and negative angles, which is possible with 4Q devices. Amplifier has 2 channels for the x-axis, one drives the X+ actuator with the desired angle voltage at a positive dc-bias. The other drives the X- actuator with the inverted desired angle voltage, at same positive dc-bias. The actuators are therefore opposing each other. b) voltage vs. angle characteristic for a 4Q device using the 4-channel linearized amplifier.*

## MIRROR MATERIAL, QUALITY, AND COATING

**Mirrorcle Technologies MEMS Mirrors** are fabricated out of single-crystal silicon wafers of the same prime grade and quality that is used for the manufacturing of integrated circuits such as PC microprocessors. Because similar mass production processes are utilized to obtain highest manufacturing repeatability, quality, and lowest cost, silicon is used as the base material. The choice of using same starting material as the vast silicon chip industry has further benefits, specific to optical applications. The wafer surfaces and therefore fabricated mirror surfaces are polished to below 1nm roughness with world's best polishing technologies. Also unique to silicon-based microfabrication is the availability of methodologies to make the surfaces ultra-clean prior to mirror metallization. Furthermore, the silicon material is inherently without any residual stress from its manufacturing and maintains this property after mirror microfabrication. Therefore silicon mirrors have extremely high flatness, with curvature often below level measurable with conventional interferometers. As the base material in a MEMS mirror, silicon has the optimal properties of smoothness, cleanliness, and flatness.

In the final manufacturing step for optical beam steering applications, the silicon mirror must be coated for high reflectivity at required optical wavelengths. In our standard processes, we coat the silicon mirrors with a thin layer of Aluminum or Gold. All in-stock MEMS mirrors are available in one of those two coating categories. In specialized, research projects, our mirrors have been coated with protected silver, dielectric layers, and MoSi layers for extreme UV applications. In most cases other materials can be used, however it is necessary to find thin and low-stress coatings that would not significantly degrade the mirrors' excellent flatness characteristics. In our standard processes with Al or Au coatings, we maintain >5m radius of curvature in any mirror type and size.

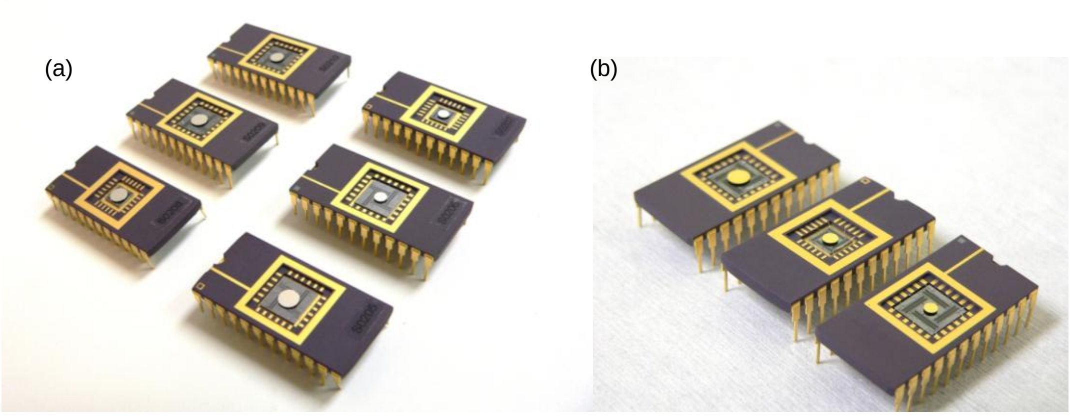


*Figure 6. MEMS Mirrors coated with (a) Aluminum, and (b) Gold.*

## MIRROR TYPES AND SIZES

**IntegratedMirrors** of up to 1.7mm diameter are monolithically fabricated as an integrated part of the gimbal-less actuatordevice structure. They are the central area of the silicon die and share the same microfabrication steps as the surrounding electrostatic actuators. These mirrors are constructed of the same available silicon layers, featuring nearly perfectly flatand smooth silicon surfaces. On four sides, the mirrors are connected to bi-axial linkages that provide two-axis movement. Since January 2011, we continually stock devices with integrated mirrors in the following diameters: 0.8mm, 1.2mm and 1.7mm. All in-stock integrated mirrors are coated with pure Aluminum, which gives high reflectivity across a very wide range of wavelengths. Metallization with Gold can be done on wafer scale, and is therefore available for larger, production orders.

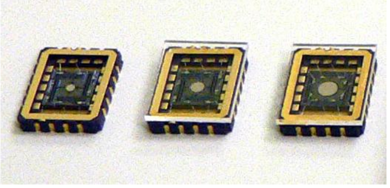


*Figure 7. Integrated MEMS Mirrors, three sizes from left to right, 0.8mm, 1.2mm, 1.7mm.*

**Bonded Mirrors**are fabricated separately from the silicon actuator structure and are intended for subsequent microassembly on top of devices. Because these mirrors are attached from above the device actuator structure, they do not occupy a part of the actuator area and therefore can be essentially made in arbitrary sizes. The Bonded Mirrors methodology allows users to select the size, as well as the geometry of mirrors for each individual application, in order to optimize the trade-offs between speed, beam size, and scan angle. Mirrors are bonded onto ready-made actuators, providing the ability to economically adapt a small set of fabricated devices for a wide range of applications.

In the past, batch fabrication of silicon devices such as two-axis micromirrors allowed for only one type/size of micromirror as part of the overall device. In order to produce devices with varying mirror sizes, most technologies require not only a new fabrication cycle, but in some cases complete actuator redesign. At Mirrorcle Technologies, we provide a MEMS-based, customizable aperture size beam steering technology for the first time. Namely, sets of electrostatic actuators optimized for speed, angle, area footprint or resonant driving are designed and realized in a self-aligned DRIE fabrication process. Metalized, ultra low-inertia single crystal mirrors stiffened by a backbone of thicker silicon beams are created in a separate fabrication process. The diameter, as well as geometry, of the mirror is selected by our customers, in order to optimize performance for their specific application. Suitable mirrors are subsequently bonded onto adequate actuators. This modular approach allows either the absolute optimization of a device prior to fabrication, or the ability to economically adapt a small set of fabricated devices for a wide range of applications.

Currently available bonded mirror diameters in R&D quantities are: 0.8mm, 1.0mm, 1.2mm, 1.6mm, 2.0mm, 2.4mm, 3.2mm, 3.6mm.

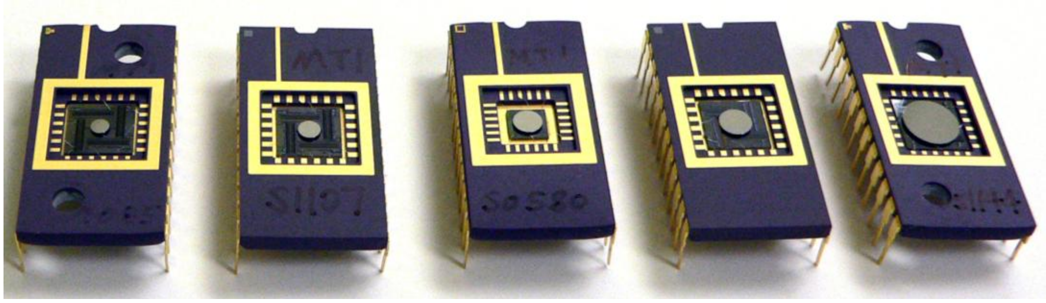


*Figure 8. Various actuators with bonded mirrors of increasing sizes. Diameters from left to right: 2.0mm, 2.4mm, 3.0mm, 3.6mm, 6.4mm.*

[1] V. Milanović, "Multilevel-Beam SOI-MEMS Fabrication and Applications," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 13, no. 1, pp. 19-30, Feb. 2004.

[2] V. Milanović, D. T. McCormick, G. Matus, "Gimbal-less Monolithic Silicon Actuators For Tip-Tilt-Piston Micromirror Applications," *IEEE J. of Select Topics* in Quantum Electronics,Volume: 10 , Issue: 3 , May-June 2004, Pages:462 - 471

[3] Veljko Milanović, Wing Kin Lo, "Fast and High-Precision 3D Tracking and Position Measurement with MEMS Micromirrors,"*2008 IEEE/LEOS Optical MEMS and Their Applications Conf.*, Freiburg, Germany, Aug. 12, 2008.

[4] Veljko Milanović, Kenneth Castelino, Daniel McCormick, "Highly Adaptable MEMS-based Display with Wide Projection Angle,"*2007 IEEE Int. Conf. on Microelectromechanical Systems (MEMS'07),* Kobe, Japan, Jan. 25, 2007.