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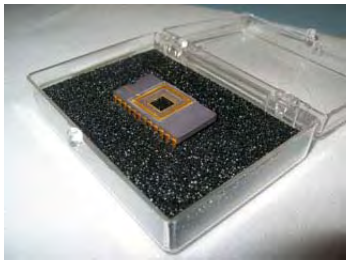

Gimbal-less Two-Axis Scanning Micromirrors

DEVICE DESCRIPTION

Gimbal-less Two-Axis Scanning Micromirror Devices based on **ARI-MEMS** fabrication technology initially developed through research projects at the Adriatic Research Institute (“ARI”) in Berkeley, CA, provide ultra low-power and very fast optical beam scanning in two-axes. The devices deflect laser beams to optical scanning angles of up to 32° at very high speeds in both axes. Compared to the large-scale galvanometer-based optical scanners, our devices require several orders of magnitude less driving power. Continuous full-speed operation of the electro-static actuators that drive our devices dissipates less than 1 mW of power.

Our devices are made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces can be coated with a thin film of metal with desired reflectivity. Larger mirrors can be bonded onto actuators for custom aperture sizes.

HIGH SPEED POINT-TO-POINT OPTICAL BEAM SCANNING

The devices are designed and optimized for point-to-point optical beam scanning mode of operation. 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 that is highly repeatable with no degradation over time. Positional precision in open loop driving of the micromirrors is at least 14 bits, i.e. within 0.5 milli-degree or within 10 micro-radians. A sequence of actuation voltages that are properly conditioned 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) to several thousand Hertz. Such fast and broadband capability allows nearly arbitrary waveforms such as vector graphics, constant velocity scanning, point-to-point step scanning etc.

The major advantage of our proprietary **gimbal-less design** is the capability to scan optical beams at equally high speeds in both axes. A typical device with a 0.8 mm diameter-sized micromirror achieves angular beam scanning of up to 500 rad/s and has first resonant frequency in both axes above 4.0 kHz. Large angle step response settling times of <100 μs have been demonstrated on devices with up to 0.8 mm diameter micromirrors. Devices with larger-diameter micromirrors are generally correspondingly slower due to the increased inertia.

DYNAMIC MODE SCANNING

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 devices 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 2^{nd} 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.

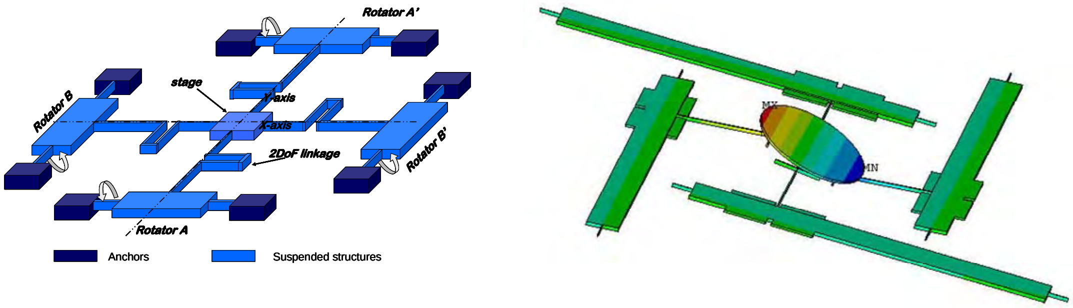

Figure 1. Schematic diagram of a gimbal-less two-axis scanning actuator based on four high aspect ratio rotators connected to the central pedestal by two degrees-of-freedom (2 DoF) linkages.

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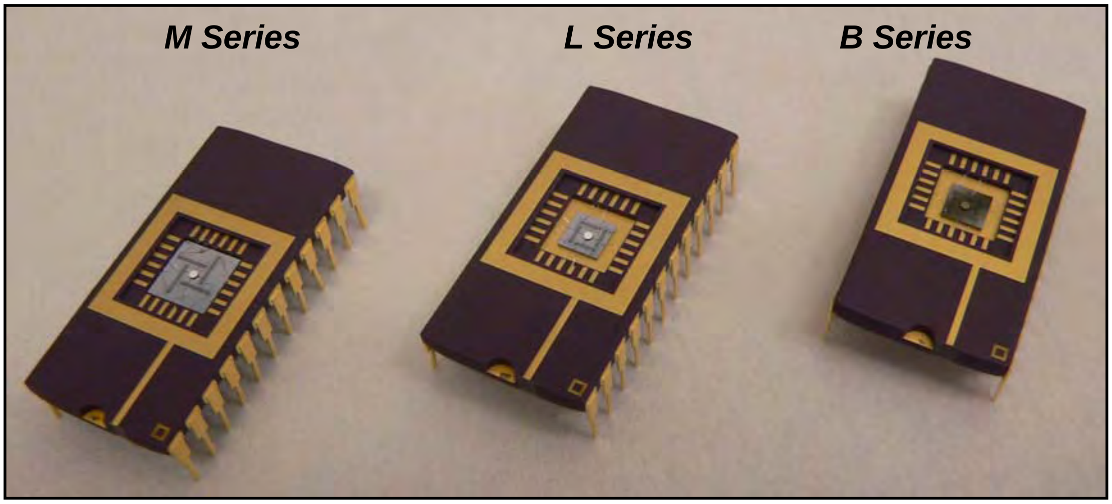

Figure 2. Photographs of three types of generation ARIMEMS6 actuators in 24-pin DIPs. Each actuator is combined with an ultra-thin and metalized 0.8mm diameter micromirror.

MODULAR DESIGN

MTI actuators lend themselves inherently to a modular design approach, hence, several types of gibmal-less two-axis actuator designs are available. Each actuator can utilize 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.

To demonstrate a range of performance and size possibilities, we have developed 3 types of actuators with somewhat differing specifications.

The three device types are: “B series” device, “L series” device, and “M series” device. The B series devices are designed to operate at low voltages (>8° of mechanical tilt at 100V,) exhibit the largest maximum scan angle and occupy a small die size (3mm x 3mm.) The L series devices operate at higher voltages and occupy a slightly larger die size (3.1mm x 3.1 mm.) In return, they provide higher scanning speeds. Finally, the M series devices require the highest driving voltages and occupy the largest die size (5.1mm x 5.1mm,) in order to provide the fastest scanning speeds.

As of January 2007, we have released a new generation (ARIMEMS7) of devices with improved performance specifications over the above listed devices (ARIMEMS6.) In general, devices are now grouped into the “M-type” category with a very large die and maximum speed capability for large mirror sizes, and the “B-type” category of smaller die actuators which are more applicable for smaller packages and smaller mirror apertures.

ONE-QUADRANT (1Q) VS. FOUR-QUADRANT (4Q) DEVICES

Traditionally, all devices fabricated in generation ARIMEMS1 through ARIMEMS6 have been one-quadrant, 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.

Figure 3 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.

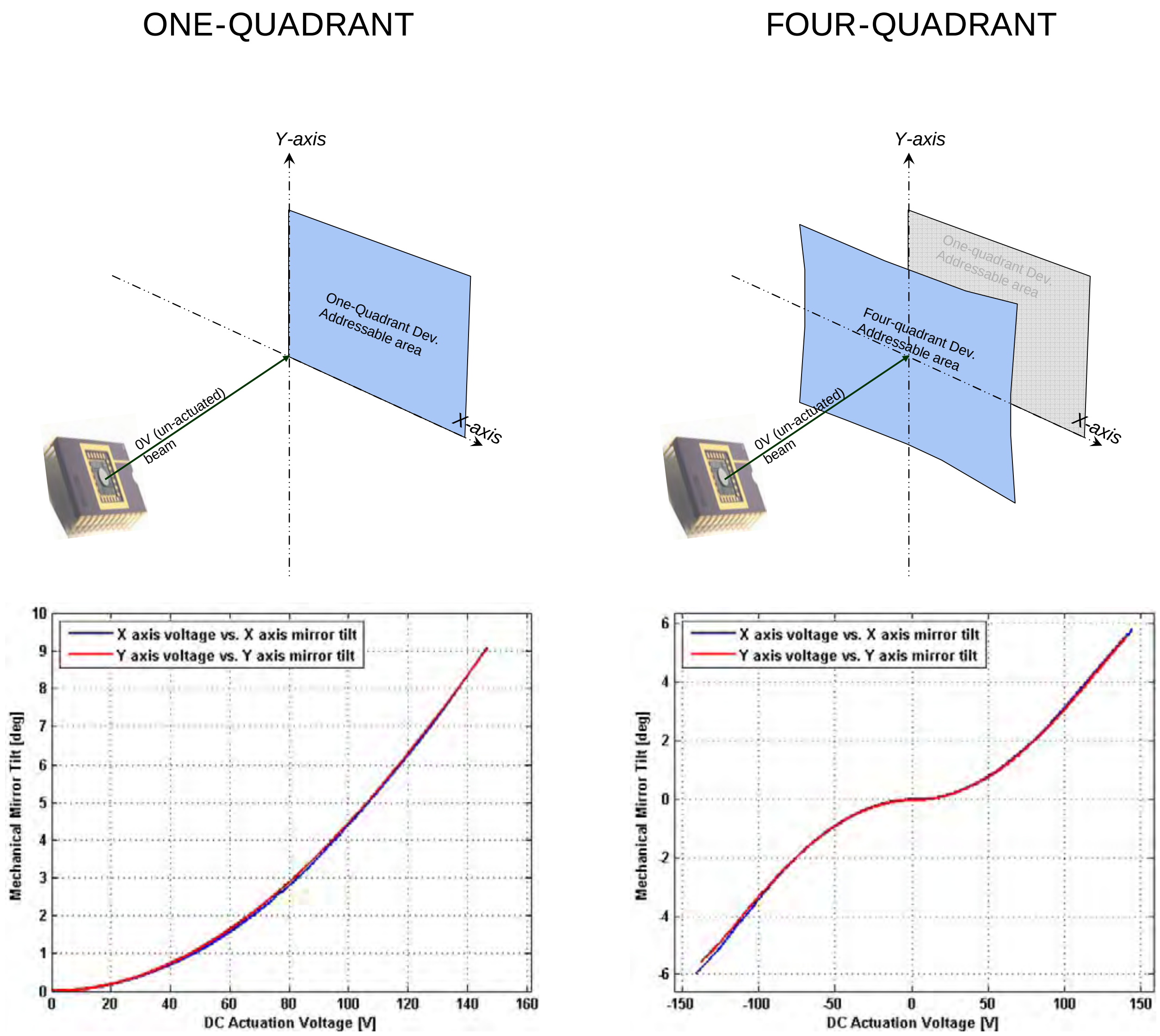

Figure 3. Comparison of addressable angles/areas by uni-directional and bi-directional devices, and representative voltage vs. angle measurement of each.

Note:
Bi-directional two-axis devices in general require 4 control channels – 2 for each axis, since separate actuators are responsible for actuation in opposing directions.

Uni-directional two-axis devices in general require 2 control channels – 1 for each axis.

LINEARIZED DRIVING OF FOUR-QUADRANT (4Q) DEVICES

Four-quadrant development kit amplifiers utilize a new method of driving the 4Q (bi-directional) devices with Differential+Bias scheme. We have been using this scheme to linearize our devices 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 removes the cross-over ringing we have seen in 4Q devices when opposing actuators are intermittently engaged. This type of driving does also significantly linearize the devices voltage vs. angle characteristics, especially around 0V region and therefore removes the need for the sqrt look-up-table function. A shematic diagram of the methodology and a measured device is shown in Figure 4 below.

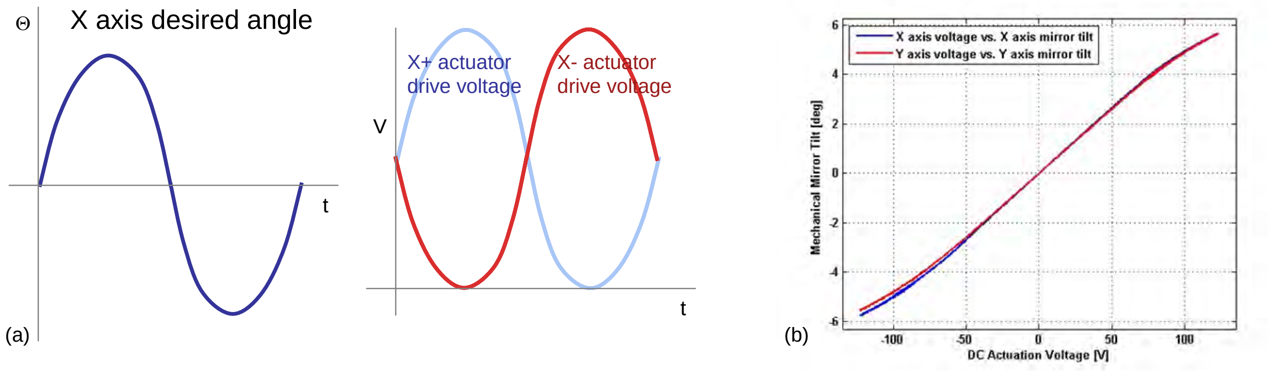

Figure 4. Methodology of linearized driving of the 4-Quadrant devices: a) desired angle of the x-axis has positive and negative angles, which is possible with 4Q devices. Amplifier has 2 channels for the x-axis, one drives the X+ actuator with the desired angle voltage at a positive dc-bias. The other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

MIRROR TYPES AND SIZES

Integrated Silicon Mirrors of 0.8 mm diameter and up to 1.2 mm diameter can be fabricated as a monolithic part of a device. Namely, they are monolithically fabricated with the gimbal-less actuator structure. Due to the limitations of the fabrication steps of the actuator, the integrated mirrors are relatively thicker. This means that they have nearly perfect flatness and polished surface, and are not normally metalized in our process. In some cases we provide metalized integrated mirrors, after evaporating metal through a shadow mask.

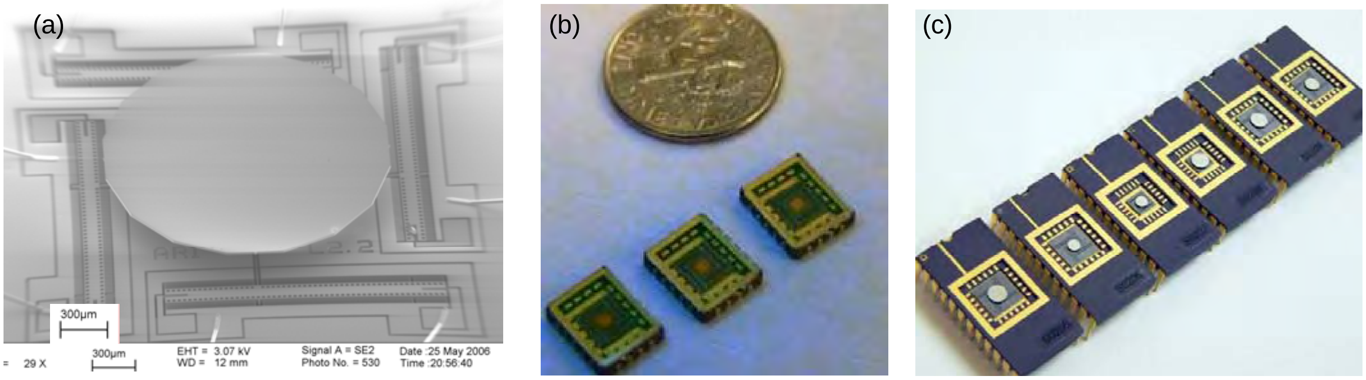

Figure 5. Various actuators with mirrors of different sizes (from left to right:) 2.0mm diameter bonded mirror, 1.2 mm integrated mirrors, various bonded mirror sizes.

Bonded Silicon Mirrors allow the users to select the diameter, as well as the geometry of the mirror for each individual application, in order to optimize the trade-offs between speed, beam size, and scan angle for each individual application. The mirrors are subsequently bonded to the 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 to be fabricated as part of the overall device. In order to produce devices with a different mirror size, 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 customer, in order to optimize the trade-offs between speed, beam size, and scan angle for each individual application. The mirrors are subsequently bonded to the actuators. The 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. Figure 6 below shows the approximate relationship between mirror diameter and lowest resonant frequency for mirrors mounted in three types of actuators from ARIMEMS6 generation of devices. Bonded mirrors have the clear advantage of significantly lower inertia, metalized surface, and larger size than the standard silicon mirrors.

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.

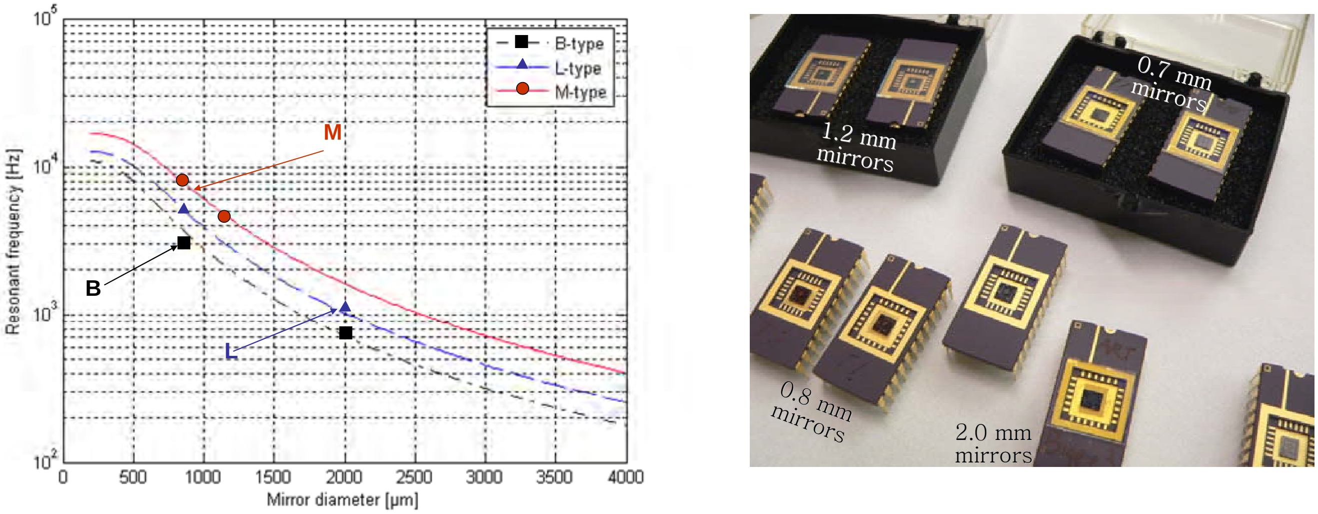

Figure 6. A plot of theoretical and measured resonant frequency as a function of bonded mirror diameter, and a photograph of devices based on B and L series actuators with 4 different types of micromirrors.

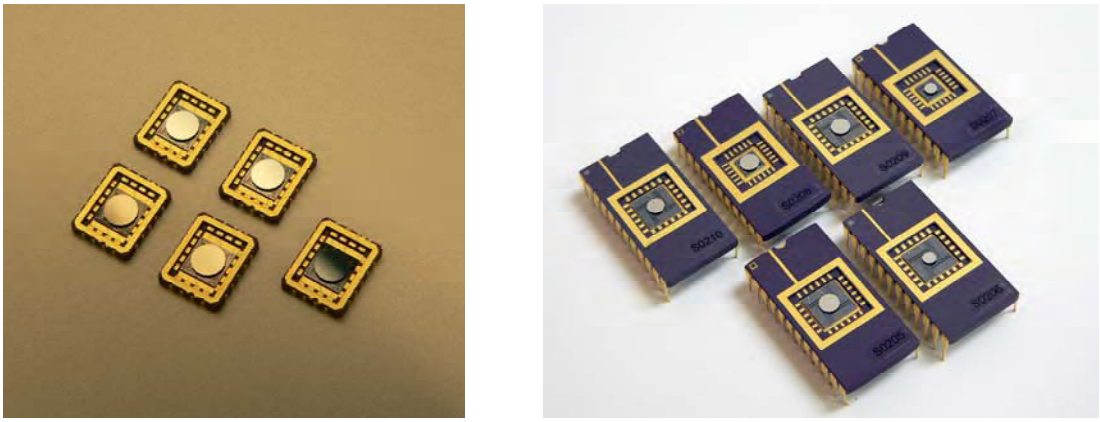

Figure 7. (left) 4.2mm x 4.2mm 4-quadrant devices with 3.6mm diameter mirrors bonded fit into a small 18-pin LCC package shown here. (right) Various actuators from generation ARIMEMS7 and ARIMEMS9 with micromirrors of different sizes ranging from 3.6mm diameter down to 2.0mm diameter. Packaged in a 24-pin DIP.

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