A MEMS Mirror for Optical Scanning

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Abstract
Optical bar-code scanning requires an actuated mirror to steer a beam of laser light. Future consumer product applications will require scanning mirrors that are smaller, cheaper, and more rugged than are currently available. Applied MEMS has designed a MEMS micro-mirror to meet these requirements. The micro-mirror is completely fabricated from single-crystal silicon to insure optical planarity and repeatable performance over time and temperature. The micro-mirror is electrostatically actuated and offers a large rotation angle of at least $\pm 14^\circ$ (mechanical). The micro-mirror incorporates novel design features that enable a shock tolerance, in all axes, in excess of 2000G. The architecture and fabrication technology support cost-effective high-volume manufacturing, and the packaging scheme results in a surface-mountable component. Functional prototypes have been successfully implemented into working bar-code scanners. This technology can be applied to other applications such as optical switching, retinal scanning, and image projection for portable displays.

Background

Since the adoption of the Universal Product Code (UPC) as the standard for retail grocery stores in the late 70’s, bar codes have become an everyday experience for most people. The UPC (and most other common bar codes) use 1D encoding and serve to identify the tagged item and relate that item to a database of stored information relating to the item.

Consumer applications of bar code scanning are emerging. For example, Digital:Convergence, Inc. is currently offering technology to allow readers of printed media (e.g., newspapers, magazines, catalogs, etc.) to scan codes associated with stories and advertisements and be instantly linked to corresponding content on the Internet. The evolution of this business process involves integration of scanners into all types of common appliances (i.e., TV remotes, phones, cell phones, PDAs, etc.) for ubiquitous e-commerce and shop-at-home applications.

Bar code scanners fall into two broad technical categories, laser scanners and CCD scanners. Laser scanners offer several performance advantages over CCD scanners including their ability to read bar codes from greater distances (less than ½ inch for CCD, several feet for lasers), their ability to read codes on curved surfaces, and their ability to read bar codes through glass and other transparent media.

Laser bar-code scanners use an oscillating mirror to steer a laser beam across the bar-code label. Currently, the mirrors are macro-sized devices made from plastic components that require significant hand assembly. MEMS oscillating mirrors are smaller and are manufactured by automated batch processes. The reduced size, improved performance and cost benefits are provided by MEMS fabrication are necessary to enable future consumer applications.

MEMS Micro-Mirror Design Overview

Figure 1. MEMS micro-mirror assembly.
Figure 1 shows the assembly of the MEMS micromirror. The assembly consists of four components: top cap, mirror die, bottom cap, and ceramic base. The top and bottom cap wafers and the ceramic base are bonded to the mirror wafer using wafer-level bonding techniques for improved manufacturability and reduced cost. In this discussion the x- and y-axis lie in the plane of the mirror. The x-axis is parallel to, and the y-axis is normal to, the axis of mirror rotation. The z-axis is normal to the plane of the mirror.

Travel-stop fingers of the top cap protect the mirror from shock while minimizing the shadowing/overlap of the mirror. Tapered walls around the inside perimeter of the top cap capture the mirror during an input shock while the mirror is rotated out-of-plane. The left and right rim cuts in the top cap reduce optical clipping. Similar to the top cap, two travel-stop fingers of the bottom cap protect the mirror from z-axis directed shock while maximizing the area of the drive pad electrodes. The travel-stop finger arrangements of the top and bottom caps constrain the mirror from z-axis directed translational motion while promoting torsional rotation of the mirror about the x-axis.

The released and free-standing mirror is connected to the surrounding frame region by two T-shaped silicon hinges. Attached to the mirror are four auxiliary travel stop fingers for overswing protection of the mirror. A very precise, narrow gap between the mirror and the surrounding frame completely confine translational motion within the x- and y-axis directions and provides shock protection. The proprietary T-shape hinges allow the collection plate to have sufficient translational motion in x- and y-axis directions, which allows the mirror to be shock-stopped by the frame, while simultaneously maintaining low stress levels within the hinges to avoid fracture. Though the T-shape hinges are relatively compliant in the x- and y-axis directions, they are sufficiently rigid for rotational motion about the x-axis for establishing the resonant frequency of the mirror.

The ceramic base provides electrode access to the micromirror for electrostatic actuation and capacitive position sensing through the two drive pad electrodes. The metal ring around the perimeter of the ceramic base in conjunction with the conductive-epoxy bond process of the ceramic-base wafer to the bottom cap wafer, provide electrical contact to the bottom cap. The wafer bonding process allows the bottom cap to be in electrical contact with the mirror wafer, therefore, the mirror element can be electrically accessed by the ceramic base. The drive pad and mirror contact metallization on the ceramic base are brought out to pads on the backside of the ceramic base, utilizing conventional thick-film through-hole via technology, which effectively makes the entire micromirror assembly a surface-mount component.

![Figure 2. Photograph of several MEMS mirrors.](image)

Figure 2 shows several completed MEMS micro mirror assemblies. The stamp in the photograph offers a relative scale to the size of the assembly. The surface mount feature of the assembly is evidenced by the pads on the single overturned device near the bottom of the photograph.

**MEMS Micro-Mirror Performance**

The MEMS mirror has undergone extensive testing. Table 1 summarizes two different designs optimized for bar-code scanning applications. Both designs incorporate common design features, as described in the preceding section, but differ in geometric dimensions.

Figures 3A&B show a Design #1 mirror mounted in an in-house designed/fabricated tester where a laser is being reflected by the mirror surface onto a screen while the mirror is being electrostatically actuated at different voltage levels and different frequencies.
Table 1. Summary of MEMS mirror performance.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Design #1</th>
<th>Design #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror</td>
<td>3 mm x 3 mm</td>
<td>1 mm x 1.4 mm</td>
</tr>
<tr>
<td>Die size</td>
<td>6.8 mm x 4.1 mm x 1.5 mm</td>
<td>4.4 mm x 2.5 mm x 1.5 mm</td>
</tr>
<tr>
<td>Rotation angle</td>
<td>+/-12° (operational)</td>
<td>+/-12° (operational)</td>
</tr>
<tr>
<td></td>
<td>+/-14° (maximum)</td>
<td>+/-14° (maximum)</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>40-50 Hz</td>
<td>75-85 Hz</td>
</tr>
<tr>
<td>Actuation voltage</td>
<td>330V static, &lt;120V dynamic</td>
<td>365V static, ~120V dynamic</td>
</tr>
<tr>
<td>Shock tolerance</td>
<td>2000g all axes (0.5 mS ½-sine)</td>
<td>2000g all axes (0.5 mS ½-sine)</td>
</tr>
<tr>
<td>Sag x, y, z</td>
<td>5 µm, &lt;1 µm, 13 µm</td>
<td>Not available</td>
</tr>
<tr>
<td>Droop</td>
<td>1.3°</td>
<td>&lt;1.0°</td>
</tr>
</tbody>
</table>

(from DC to multiples of the primary resonant frequency). The voltage required to actuate the mirror is a function of the desired angular displacement (larger displacements require larger voltage) and the frequency at which the mirror is being displaced (nearer resonance requires less voltage). In Table 1, the levels of actuation voltage refer to a full (operational) angular displacement of the mirror. The term static refers to a DC displacement of the mirror, and the term dynamic refers to a periodic displacement at a frequency near (+/- 20 percent) the resonant frequency. Mirrors have shown repeatable performance over 200M cycles.

Figures 4A&B show laser-vibrometer testing (a PSV-300-F system from Polytec PI) being performed on a Design #1 mirror to measure the various resonant modes and to confirm that the mirror maintains optical planarity while undergoing electrostatic actuation. The measured vibrational modes have confirmed the design intent of Table 1 and the mirrors have been shown to be both statically and dynamically flat.

Preliminary modeling analysis work has shown that an enabling aspect of our proprietary mirror-hinge technology may allow our single-axis mirror to be operated in a dual-axis mode. There is a primary rotational mode about the x-axis (where the hinges exhibit torsional motion) and a secondary rotational mode about the y-axis (where the hinges exhibit bending motion). This has been confirmed by laser-vibrometer measurements, shown in Figures 4A&B, which show two distinct, orthogonal rotational modes of the mirror.

Figures 3 A&B. Measurement of actuation voltage and angular displacement of the scanning mirror. Fig. 3A shows the complete test set-up and Fig. 3B shows a close-up of the mirror scan pattern (notice the ± 12° of mechanical angular displacement).
Figures 4A&B. Laser-vibrometer measurements of the MEMS mirror. Fig. 4A highlights the primary rotational mode about the x-axis. Fig. 4B shows the secondary rotational mode about the y-axis.

MEMS Micro-Mirror Commercialization

The MEMS micro-mirror is being commercialized under the DuraScan™ product name. The DuraScan™ micro-mirror fabrication process flow is shown in Figure 5. The fabrication technology specifically utilizes bulk micromachining techniques on single-crystal silicon wafers. This process technology insures that the mirror plates can be made sufficiently thick for good static/dynamic flatness [1], that the mirror plates offer optical-grade surface quality, that the mirrors are sufficiently robust to meet the shock requirements, and that the mirrors offer repeatable performance over time and temperature.

The DuraScan™ micro-mirror was fabricated at Applied MEMS’ state-of-the-art six-inch wafer fabrication facility, located in the Houston suburb of Stafford, Texas. This facility was purpose-built in 1997 to develop and manufacture in volume a broad range of commercial MEMS devices for Applied MEMS customers, with an emphasis on bulk micromachining and multi-wafer bonding. This facility possesses process capabilities that are uncommon in a high-volume MEMS production environment, including double-sided lithography, deep reactive ion etching, precision multiple wafer registration and bonding, wet etching to support bulk micro-machining and vacuum packaging.

A significant effort was put into optimizing the equipment automation and design, process design and micro-mirror design to achieve high yields and a high-volume production capability.

The wafer fabrication processes were performed in a 7,000+ square foot Class 100 clean room. MEMS micro-mirror packaging and test processes were performed in a 3,000+ square foot Class 100,000 clean room. Figure 6 shows the wafer fabrication clean room.
Current and Future Applications

This paper has primarily focused on a single-axis mirror for barcode scanning applications. But, this DuraScan™ micro-mirror technology can be logically extended in two dimensions: fabrication of a dual-axis mirror and incorporation of the mirror technology (single- or dual-axis) into other product applications, such as 2D bar-code scanning applications, raster-scanned displays, and optical switches for telecommunications.

A composite dual-axis mirror could be achieved by mounting two single-axis mirrors in an orthogonal arrangement [2]. For reduced size and complexity, a double-gimbaled mirror design is commonly utilized to form a monolithic dual-axis MEMS mirror [3-4]. With the appropriate development effort, we could achieve a double-gimbaled mirror design using our DuraScan™ mirror technology. As discussed earlier in the paper, our DuraScan™ micro-mirror design is capable of being operated in a dual-axis mode – this would offer a competitive size reduction over a double-gimbaled mirror design.

Conclusions

Applied MEMS has designed and fabricated single-axis MEMS micro-mirrors for optical bar-code scanning applications. The micro-mirror is fabricated completely from single-crystal silicon to insure optical planarity and repeatable performance over time and temperature. The micro-mirror is electrostatically actuated and offers a large rotation angle of at least $\pm 14^\circ$ (mechanical), and is exceptionally shock tolerant (exceeding 2,000G in all axes). The packaging scheme results in a surface-mountable component. Extensive testing has confirmed key design performance parameters and functional prototypes have been successfully implemented into working bar-code scanners. The design and fabrication processes support cost-effective high-volume manufacturing.

The single-axis mirror technology can be logically extended along several paths towards the fabrication of a dual-axis mirror. Additionally, the mirror technology (single- or dual-axis) can be incorporated into other product applications, such as 2D bar-code scanning applications, raster-scanned displays, and optical switches for telecommunications.

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References