Pivoting micromirror designs for large orientation angles

Ernest J. Garcia

Electromechanical Engineering Department

Sandia National Laboratories, Albuquerque, New Mexico, 87185-0329 USA

ABSTRACT

This paper describes mechanical design concepts for a class of pivoting micromirrors that permit relatively large angles of orientation to be obtained when configured in large arrays. Micromirror arrays can be utilized in a variety of applications ranging from optical switching to beam-front correction in a variety of technologies [1, 2]. This particular work is concerned with silicon surface micromachining (SMM). The multi-layer polysilicon surface micromachining process developed at Sandia National Laboratories is used to fabricate micromirror arrays that consist of capacitive electrode pairs which are used to electrostatically actuate mirrors to their desired positions and suitable elastic suspensions which support the 2 μm thick mirror structures. The designs described have been fabricated and successfully operated. Figure 1 illustrates a 100- μm x 100- μm micromirror actuated to 10°.

Keywords: Optics, Micro Optics, Micromirrors, MEMS, MOEMS, Micro Optical Switches

Figure 1 Micromirror Prototype

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INTRODUCTION

Earlier SMM mirror designs have been rotation limited due to the thickness of the original spacer layer also termed sacrificial layer. Figure 2 illustrates the conventional scheme used to rotate a micromirror. The maximum angle obtainable depends upon the spacer layer thickness t and the pivot radius r yielding a maximum angle of rotation $\theta = \arcsin [t/r]$.

Figure 2 Conventional Tilting Scheme

If, due to processing limitations, the spacer layer thickness cannot be increased, then the next choice is to reduce the pivot radius r as shown in Figure 3. This allows the mirror to rotate to larger orientation angles, which is the configuration used in the mirrors shown in Figure 1.

Figure 3 Modified Pivot Radius

However, if the mirror must also rotate in the opposite direction, it can be seen that the maximum angle that can be obtained again suffers from the problem of large pivot radius. This problem can be circumvented by the use of a compound pivoting mechanism design that allows the use of two pivots with small pivot radii. The design of the micromirror suspension is configured such that the mirror can pivot about either of two pivots shown schematically in Figure 4.

Figure 4 Compound Pivoting Mirror

Micromirrors using the compound pivoting configuration have also been fabricated and successfully tested. This paper will describe the details of the mechanical design for pivoting and the technique used to achieve reduced actuation voltages.

DESIGN

The goal of this effort is to develop micromirrors capable of large rotations, while at the same time arranged in tightly packed arrays. The mirrors shown in Figure 1 are 100-microns square with 1-micron gaps between mirrors. Earlier mirror work [3, 4] demonstrated single micromirrors capable of large rotations. Figure 5 illustrates a micro-flex mirror in the actuated position. An external electrostatic actuator buckles an element and the moment produced by the buckled element is used to raise the mirror to a desired position. However, because these devices are actuated by mechanisms external to the perimeter of the mirror, they are not capable of being packaged into dense configurations.

Figure 5 Actuated Micro-Flex Mirror

Micromirrors in densely arrayed configurations require that the suspension and actuation mechanisms be located entirely beneath the mirror surface. This presents more of a design challenge since space for actuation and pivoting elements is greatly reduced. The next issue relates to what is the minimum size mirror that can be constructed with the necessary actuation and pivot elements beneath the mirror. Micromirrors of initial interest are 50-100 micron square. The 100-micron square mirrors do allow more variation in design parameters, such as the suspension stiffness, when compared to the 50-micron square mirrors.

The design of a micromirror array is dependent upon the process available. The silicon surface micromachining process developed at Sandia National Laboratories uses a multi-layer process that provides an electrical interconnection layer deposited and patterned on an insulating nitride layer and three to four independent silicon layers that can be used to construct the desired structures and electrical elements. The surface micromachining process consists of alternate depositions of spacer (also called sacrificial) material and the silicon construction materials. With each deposition, the material is

selectively patterned using photolithography and etching to create the desired geometries. This process continues until all of the successive layers have been deposited and patterned. The final structures are then freed when the remaining sacrificial layers (silicon dioxide) are removed by etching. Figure 6 shows the chemical-vapor-deposited polycrystalline silicon that remains after the final etch of a microengine output gear. The layer thickness ranges from approximately 1-2 microns. Note that the etchant used to remove the sacrificial layer has a relatively small effect on the construction layers of silicon. References [5, 6] give further information on the specifics of the process. The process may also include coatings to reduce stiction [7] and other surface modifications [8].

Figure 6 Focused Ion Beam Cross-section Illustrating the Multi-level Fabrication Process

The micromirror pixel or single element consists of the top mirror surface (which is supported by some type of suspension), the actuation mechanism (which functions to move the mirror surface to a desired orientation), and electrical connections. The actuation scheme uses electrostatics to move the mirror.

The pivot arrangement shown in Figure 3 is used to produce the large orientation angles of the micromirror arrays. This pivoting arrangement coupled with the reduced voltage electrostatic actuation scheme shown in the schematic of Figure 7 produces a torque about the pivot sufficient to rotate the mirror.

Figure 7 Reduced Voltage Electrostatic Actuation Method

The upper capacitive plate element is attached to the mirror through a flexible torsion element that allows the upper plate to rotate downwards when attracted to the fixed lower capacitive plate element. When a potential is applied between the two plates the upper plate deflects downward as shown in the figure and the force between the plates increases due to the $1/(\text{gap})^2$ relationship for force between capacitive plate pairs. As the plates are brought together, the mirror pivots about its' pivot axis to the actuated position as shown. The use of a flexible plate element results in lowered actuation voltages.

The micromirror is fabricated using three mechanical construction layers of polysilicon and one electrical interconnect layer of polysilicon that is deposited directly on the substrate. The top mirror surface shown in Figure 1, which was fabricated from the third construction layer, is supported by the suspension configuration shown in Figure 8. The suspension element is fabricated from the second construction layer.

Figure 8 Micromirror Suspension Element

The mirror is only shown as an outline in the figure above. The suspension is anchored to the mirror above on the left side of the figure, and is anchored to the substrate on the right side of the figure. Figure 9 is a SEM showing the suspension and capacitive plate elements.

Figure 9 SEM of Micromirror Suspension

Figure 10 is a cross-section showing the attachment of the suspension to the mirror and substrate. The electrostatic actuation elements are also shown in this cross-section.

Figure 10 Micromirror Suspension

The upper capacitive plate element is connected to the mirror by an elastic torsion element. This element is shown more clearly in Figure 11. The locations where the plate element is anchored to the mirror above are identified and can also be seen in Figures 8 and 9.

Figure 11 Upper Capacitive Plate Element

Upon application of a potential to the capacitive plate pair, the plates deform as described earlier and ultimately result in the mirror element tilting upward to the desired orientation. The pivot shown in the schematic of Figure 7 is illustrated in Figure 12, which shows the mirror in the actuated position. A pivot is formed when an edge attached to the mirror element contacts a pedestal attached to the

substrate. The mirror section pivots about this point as shown. The capacitive plate element deforms downward until its touchdown features make contact with a portion of the substrate that is held at the same potential as that of the mirror/upper plate section.

Figure 12 Micromirror in Actuate Position

Figure 13 is a SEM showing the mirror in the actuated position.

Figure 13 Actuated Micromirror

Figure 14 shows a rendering of the micromirror in the actuated position. Portions of the suspension and suspension anchor can be seen. The holes seen in the mirror element are to facilitate etch release of the entire structure. In the ideal case there would be no holes present. For this particular device, which is 100-microns square, we ultimately expect that we will only need one or two etch release holes. Figures 8 and 9 also show another capacitive plate element on the right side of each figure. This capacitive plate is used to pull the mirror down against four fixed stops (or pedestals). The purpose of the stops is to accurately locate the mirror in the horizontal position, which is required for a specific application. The locations of the stops can be seen in Figures 12 & 13. The stop on the left side is also part of the pivoting arrangement.

Figure 14 Actuated Micromirror

The pivoting concept described above can be extended to more than one axis. Figure 4 illustrates a two-axis compound pivoting device that can rotate about two shifted axes. Again two pivot axes are configured, one at each end of the mirror. The pivot and suspension arrangement for a 50 x 50-micron square mirror is described in Figure 15. Actuation occurs when one of the two capacitive plate pairs is energized. The suspension is configured so the mirror is capable of rotation in either direction.

Figure 15 Compound Pivoting Micromirror

The pivot arrangement is similar to the configuration shown in Figure 12. The suspension consists of two pairs of interleaved spring elements. The cross-section in Figure 15 shows the suspension attachments to ground and to the mirror element.

The two-axis design can be extended to four axes. A 50 x 50-micron square mirror design is shown in Figure 16. Here the four axes about which the mirror pivots are identified. As the number of axes increases we are faced with the problem of getting suspension elements that are quite stiff. There are several modifications to this suspension however that can be made to reduce the stiffness.

Figure 16 Four Axis Compound Micromirror

Figure 17 is a SEM of a four-axis compound pivot micromirror (50 x 50 microns) with the top mirror surface omitted. The suspension elements are connected to ground at the center of the structure. The suspension elements are connected to the upper mirror at the periphery. The locations where the four upper capacitive plate elements connect to the mirror can also be seen.

CONCLUSION

A variety of designs using offset and compound pivoting micro-mechanisms with the reduced voltage actuation method [9] have been designed and fabricated. These micromirror designs have been

demonstrated to successfully rotate micromirror arrays to large angles of orientation with all of the necessary mechanisms positioned beneath the mirror surface. This type of mechanism is therefore extremely useful for densely packed micromirror arrays that require that the pivoting and actuation mechanisms reside beneath the mirror itself and can produce large rotations ($\theta \geq 10^\circ$). The reduced voltage actuation method, which uses mechanisms that fit entirely beneath the micromirror, has also been shown to reduce the voltage level required to achieve mirror actuation when compared to capacitive plate arrangements that do not incorporate compliant plate elements.

The very interesting modeling of these micromirrors reveals motions governed by snap-through behavior. The modeling of various micromirrors, which use the reduced voltage actuation method shown in Figure 7, will be described in a separate report. The 100-micron square mirror shown in Figure 1 has an actuation voltage of ~ 35 V. The two-axis 50-micron square mirror has an actuation voltage of ~ 60 V and the four-axis 50-micron square mirror has an actuation voltage of ~ 85 V.

Figure 17 Four-Axis Compound Micromirror Diagnostic Structures

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