A magnetically actuated MEMS scanning mirror

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ABSTRACT

A 4mm by 5mm, magnetically actuated scanning MEMS mirror is fabricated by integration of bulk silicon micromachining and magnetic thin film head techniques. Large mirror deflection angles (0-70°) are achieved. The MEMS mirror is demonstrated as a laser beam scanner in both conventional and compact holographic data storage system configurations.

Keywords: MEMS, magnetic, scanning mirror, holographic memory

1. INTRODUCTION

Micro-Electro-Mechanical-Systems (MEMS) are micro-devices or systems combining electrical and mechanical components batch-fabricated using micromachining techniques.[1] These devices have several attractive properties. They are small, low in mass, and low-cost to produce. The MEMS mirror presented here (Figure 1) is fabricated by combining bulk micromachining techniques and magnetic thin film technology. Bulk micromachining enables the formation of the mechanical structure of the mirror through the selective removal of silicon from the wafer. It also provides the mirror with a smooth reflector by using part of the original wafer surface. In addition, it allows relatively thick (>40μm), ridged, and large (>3mm) structures to be made. The magnetic thin film technology used (permalloy electroplating), enables the mirror to be deflected by an external magnetic field. While the MEMS scanning mirror can have application in many optical systems requiring angle steering, here we use it for holographic data storage.

Holographic memories use the interference patterns between beams of coherent light to store images. A volume medium can store thousands of pages of information, each of which can be independently recalled by changing the incident angle of the reference beam.[2] Holographic systems with both large capacity and rapid access require wide-angle, high-speed beam steering devices. Mechanically rotating conventional mirrors or acoustooptic deflectors are currently used in experiments. These devices are bulky, expensive, and add noise through pointing inaccuracies or wave-front distortions. Liquid crystal deflectors are an emerging technology, but devices with large deflection angles are difficult to fabricate. The MEMS mirror with its capability for continuous tuning over wide-angle ranges, low cost and small mass, is an attractive device for holographic systems.

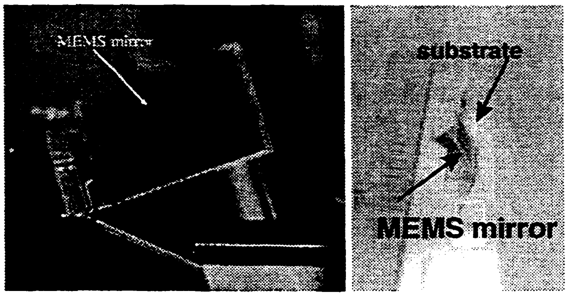

Figure 1: An actuated MEMS mirror and an array of mirrors

2. DESIGN AND FABRICATION

The MEMS mirror, shown in Figure 2, consists of a 16mm^2 plate supported by two planar serpentine springs. The mirror is fabricated by first creating a 40μm membrane in the silicon substrate. A 0.5μm layer of thermal oxide is then grown on the membrane, and a titanium-copper seedlayer evaporated onto the underside of the membrane. Photoresist is applied and patterned, and a 20μm thick permalloy square (9mm^2 in area) is electroplated onto the exposed seedlayer. Once electroplating is completed, the photoresist and seedlayer are stripped. A 5μm permalloy mesh structure is then electroplated on the top side of the membrane. This mesh extends beyond the intended border of the plate. The mirror is freed from the substrate in two steps. First, in the areas outside the plate region, the permalloy mesh is detached from the silicon substrate by removing the oxide layer with an HF etch. Then the plate and springs are lithographically defined on the membrane, and the exposed silicon is Reactive Ion Etched. The silicon under the permalloy mesh is also removed in this process, which releases the mirror from the substrate. The mesh remains overhanging the edge of the freed plate, constraining the mirror to deflections above the plane of the wafer. In addition, the presence of the mesh increases the durability of the flaps and makes them significantly less fragile during handling. The surface roughness of the exposed silicon is on the order of 10nm, comparable to commercial highly polished mirrors. A thin (200-700nm) layer of aluminum is evaporated on this surface to increase reflectivity.

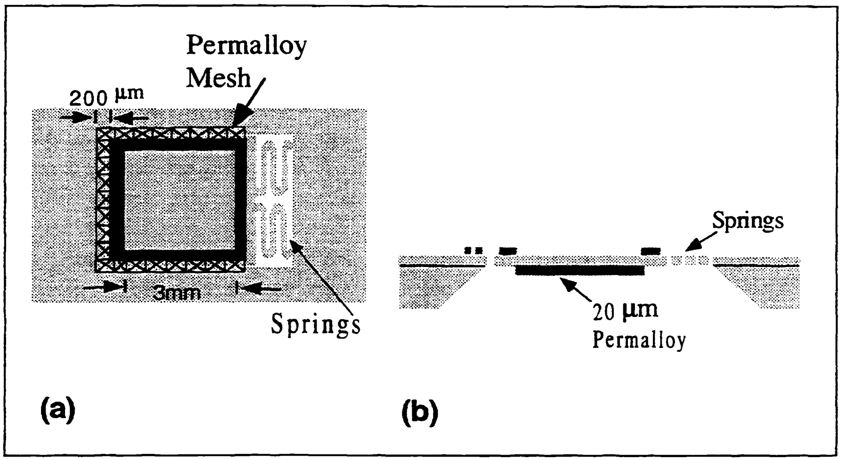

Figure 2: (a) Top view of MEMS mirror (b) Cross-sectional view of mirror showing permalloy plated on underside.

3. OPERATION

A magnetic moment in an external magnetic field experiences a torque, which attempts to align the moment with the field direction. This principle is used in actuating of the MEMS mirror (Figure 3). By applying a magnetic field perpendicular to the wafer surface, an out-of -plane displacement can be induced.[3,4] This deflection is opposed by the restoring force of the spring, so the deflection angle of the mirror can be controlled by adjusting the magnetic field strength. Figure 4 shows a typical plot of deflection angle at different applied magnetic flux densities, for a mirror with spring width of 55μm. Mirrors with spring widths ranging from 45μm to 65μm have been fabricated.

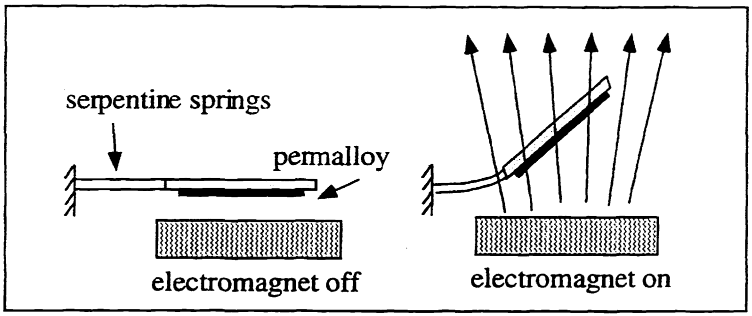

Figure 3: MEMS mirror actuation principle.

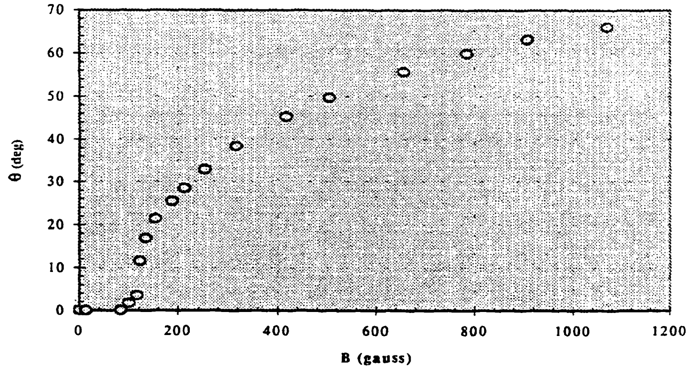

Figure 4: Angular deflection of mirror from the horizontal, at different magnetic flux densities

Mirrors made with the above process are slightly convex due to stress in the permalloy underlayer. A collimated laser beam (1.5mm diameter) incident at 45° is reflected into an asymmetric diverging cone. The horizontal cone half angle (0.85°) is larger than the vertical cone half angle (0.45°) due to the oblique incidence. This curvature is expected to be greatly reduced in the next device generation, by placing an identical permalloy layer on both the top and bottom sides of the mirror (leaving a 3mm x 3mm silicon region exposed). This configuration will allow the stresses induced by the two layers to virtually cancel, leaving the mirror flat.

The MEMS mirrors were used in two holographic data storage configurations. The first, shown in Figure 5, uses the mirror as a deflector for angle multiplexed holographic storage. In this setup a single laser beam is split into a reference and signal (object) path. The latter contains an information presentation device (Spatial Light Modulator, SLM), a storage crystal (photorefractive Fe-doped $LiNbO_3$) and a detector (CCD camera). The reference beam, after deflection by the MEMS mirror, is used to imprint the page of information within the crystal for later recall and display in parallel at the CCD camera. The MEMS mirror is placed on an electromagnet, which is then driven by a DC voltage regulator to generate the magnetic field. The deflected beam is imaged onto the storage medium with a pair of lenses. These lenses serve to expand the beam to overlap the image-bearing beam, but also tend to limit the range of deflection angles which can be used. The volume nature of the holograms allows a page of data to be stored for each deflection angle, provided that these angles are sufficiently separated. In this demonstration, we stored 100 holograms using the MEMS mirror. Some reconstructions of random binary data is shown in Figure 6. The holograms are of excellent quality as evident by the clearly distinguishable black and white pixels. Although each hologram was spaced from its neighbor by 0.143°, much smaller deflections could be generated with the MEMS mirror and the control circuit used. We could control and observe deflection changes as small as 0.007°. The spacing between holograms was dictated by the non-plane wave reference beam generated by the reflection of the curved mirror surface.

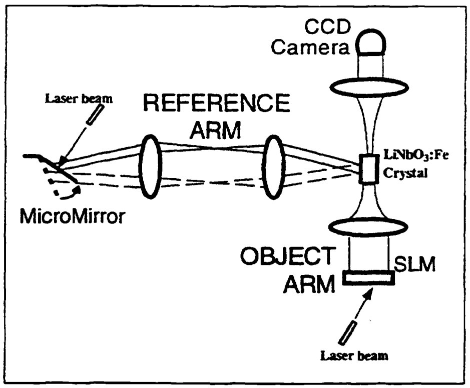

Figure 5: Conventional optical setup incorporating the MEMS mirror

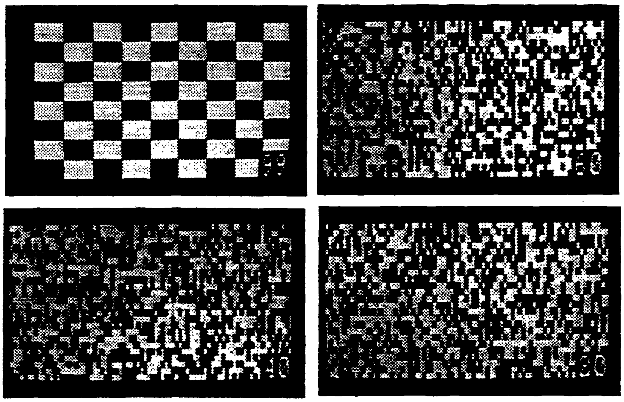

Figure 6: Holograms stored and retrieved using MEMS mirror

The second configuration used (Figure 7), places the MEMS mirror right at the crystal, eliminating the lenses from the reference beam path that were used in the previous experiment. The mirror now varies both the incident angle of the reference beam on the crystal, as well as the beam position within the crystal. Once again, 100 holograms were stored using this configuration. This arrangement is more attractive since the holographic system size is significantly reduced.

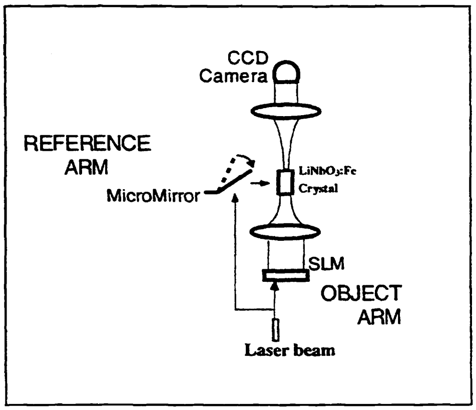

Figure 7: Compact holographic system configuration

The time response of the MEMS mirror was measured by repeated jumping between pairs of holograms. The transit time was heavily dependent on the angle swing. For small deflections (less than 0.7°), a one-step jump could be used and the MEMS mirror would settle in less than one video frame (33 milliseconds). For larger angular deflections, a one-step jump induced unacceptable ringing. When the large deflection is sub-divided into a series of smaller jumps, the settling time required is much shorter. With this approach, a deflection of 10.7° could be performed in 200 milliseconds.

The MEMS mirror is sensitive to heating from the incident laser beam. This heating causes both a change in mirror curvature and deflection angle. The magnitude of this effect is noticeably reduced by a thin (200-700nm) aluminum coating. A time sequence of photographs are shown in Figure 7, which show the laser beam spot at a distance of 2.5m from the MEMS mirror, at various times after illumination. The incident laser beam was $50W/cm^2$ in intensity, and no magnetic field was present. This intensity is approximately 10 times what we used in the holographic storage experiment. The left-hand column shows the changes in curvature and deflection angle for an uncoated MEMS mirror, while the right-hand column corresponds to a MEMS mirror with 600nm of aluminum. Both the aluminum-coated mirror and uncoated mirror take over a second to settle, after which no change in spot size or angle is observed. However, the change in curvature and angle is much more pronounced for the uncoated mirror. To avoid this long thermal settling time, the laser beam is arranged to continuously illuminate the MEMS mirror. This ensures that the intensity on the mirror changes only with laser power fluctuations and changes in the deflection angle (which changes the size of the illuminated area). For the conventional holographic system configuration, a mechanical shutter, placed between the micromirror and the photosensitive crystal, is opened when the crystal must be addressed. In the compact holographic system experiment no shutter was used-however, a small liquid crystal shutter can be easily integrated.

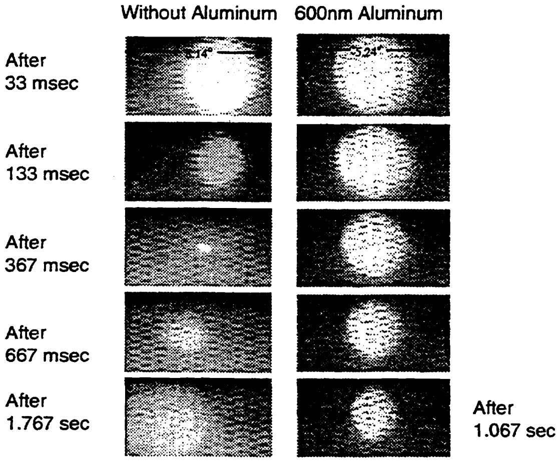

Figure 8: Change in curvature and deflection angle due to laser heating (incident laser power 50.9W)

4. CONCLUSION

From the perspective of holographic storage, the mirrors are an attractive angle multiplexing technology. They posses a very large continuous angle deflection range, are compact, and use only moderate power. Several improvements of the mirror are planned to address thermal effects, mirror curvature, and improve time response. Thermal effects were bypassed in our holographic experiments by keeping the average power on the mirror constant. We hope to reduce thermal sensitivity of the mirror by increasing the mirror reflectivity (currently 84%). This can be achieved by coating the mirror with other metals such as silver, or by using multilayer coatings. To eliminate the mirror curvature, we can use the new permalloy configurations discussed previously. Another option is to illuminate the device with a matching converging beam (so the reflected beam becomes collimated). Such a collimated reference beam, in combination with an optical system that takes advantage of the large deflection angles possible with the micromirror, should significantly increase the number of stored holograms. Finally, we can improve the mirror time response by reducing residual vibrations of the mirror. This can be achieved by modifying the driving circuit (avoid using a square wave), or coating the springs with materials such as polyimide to increase damping.

In conclusion, we have successfully fabricated magnetically actuated MEMS scanning mirrors and demonstrated them in a holographic data storage application.

5. REFERENCES

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