Parallel-plate MEMS Mirror Design for Large On-resonance Displacement

S. R. Bhalotra, J. D. Mansell, H. L. Kung and D. A. B. Miller
Edward L. Ginzton Laboratory
Stanford University, Stanford, CA 94305-4085

Abstract: **We present an electrostatically actuated MEMS mirror with 65 mm of displacement. This design provides a 2 mm square reflective surface and allows for easy fabrication, making it suitable for a wide range of applications.**

In this paper we present a MEMS mirror that combines long throw at moderate voltages, high load capacity, and fabrication simplicity. It is an electrostatically actuated parallel-plate design with a large mirror surface, operated in AC mode for large displacement on resonance. These characteristics make it suitable for implementation in several application areas such as spectroscopy, optical delay lines, and adaptive optics.

There exist other types of movable mirrors with a variety of features. Magnetically actuated mirrors generally have large displacement and can drive large loads, though they are less compatible with silicon micromachining and often require cooling[1]. Other mirrors that move large distances, i.e. PZT devices and those made with the LIGA process[2], involve more complicated fabrication. Electrostatically actuated mirrors can be divided into two groups: interdigitated transducers (comb-drive) and parallel-plate actuators. Comb-drive mirrors usually require low drive voltage and avoid bistabilities (i.e. snap-through to electrode), though they have small mirror areas[3]. Parallel-plate actuators are appropriate for moving large loads; thus large mirror sizes are possible. The range of motion for typical devices of this type at moderate voltages is usually limited because their mirror membranes are supported in tension[4].

We have developed an architecture that allows the support structures to bend rather than stretch. Figure 1 shows a photograph of the front plane and a cross-sectional diagram of the mirror. On the front plane the inner square is the reflective surface, measuring 2 mm on a side; the outer square has a side length of 13 mm. The connecting flexures, four rectangular pieces, are the key to large displacement of the central square. Figure 2 shows the flexure deformation as the mirror is pulled down. The long sides of each rectangular flexure bend, therefore the stiffness of this structure is lower than a comparable structure built with its support flexures in tension. This architecture decreases the effective spring constant and thus allows for a larger range of motion.

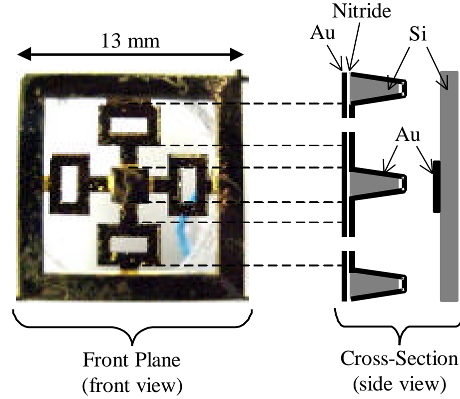

Figure 1. Left: photograph of mirror front plane. Right: side view schematic of mirror cross-section. Gold, nitride, and silicon layers comprise the front plane; the back plane is an electrode of gold-coated silicon.

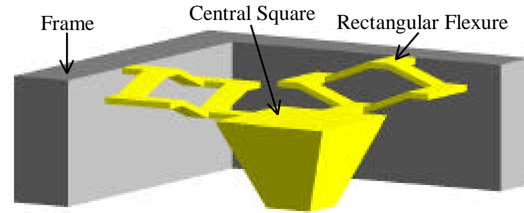

Figure 2. The rectangular flexures deform out of the plane, allowing the central square to move a large distance out of its equilibrium plane.

To obtain greater motion of the mirror structure, we drove the mirror at its resonance frequency. To determine the behavior of the mirror, the differential equation balancing the forces was solved. Applying a potential difference between the front and back plane causes the inner square on the front plane of the mirror to move because of electrostatic attraction. This is countered by a spring-like restoring force due to the bending of the rectangular segments that connect the center to the outer frame. AC motion is described by the following equation:

$$m\frac{\partial^2 z}{\partial t^2} + b\frac{\partial z}{\partial t} + kz + \frac{V^2 \mathbf{e}_0 A}{2(z_o + z)^2} = 0 \qquad (1)$$

The displacement is represented by z. The first element is the acceleration term with mass m. Second is the friction term where b is a general friction coefficient. Third is the first-order restoring force, with spring constant k. Last is the electrostatic force between two ideal parallel plates (ignoring possible deformation of the surface and fringe effects) for voltage V between the plates, common surface area A, and equilibrium separation distance z_o; ϵ_0 is the permittivity of free space. For a sinusoidal applied voltage with a DC-offset, the solution to Equation 1 is similar to the motion of a driven, damped harmonic oscillator. Thus the electrostatic driving force should cause the mirror system to oscillate approximately harmonically at the driving frequency.

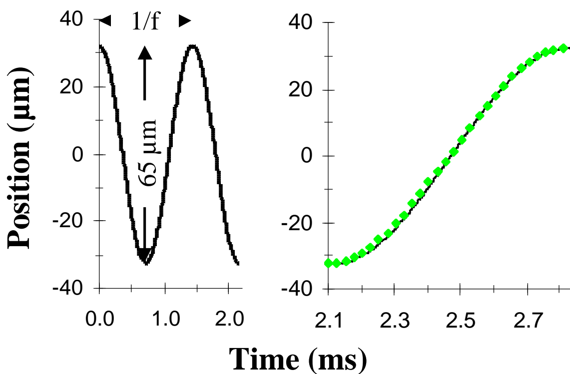

Figure 3. Left: numerical solution to mirror's equation of motion. The mirror oscillates around its equilibrium at the driving frequency f, with total displacement 65 µm. Right: one half period of motion. Data markers represent experimental results; solid line represents theoretical solution.

To fabricate the mirror, we deposited ~1 µm low stress silicon nitride by low-pressure chemical vapor deposition onto both sides of a double side polished <100> silicon wafer. The 500 µm thick wafer was patterned with photoresist on the front using the mask pattern shown in Figure 1. The backside was patterned with a mask containing only the frame and the central square. The nitride was then removed from the exposed areas by a plasma dry-etch, after which the wafer was placed in a 75°C bath of 20% potassium hydroxide with isopropanol until about 20 µm silicon remained. Finally both sides were coated with 2000 Å gold. The second electrode was fabricated by depositing gold onto another silicon wafer, thus eliminating the need for the release step associated with surface micromachining.

To test the device in the laboratory, both the mirror and the back electrode were mounted on separate 1" tip-tilt optical mounts, and placed on translation stages. The plane faces were aligned parallel to each other and normal to the incident light. By moving the position of the mirror along the optical axis, the separation between front and back plane could be varied. With this setup we measured displacement for given drive voltages and plane separations. We have also made integrated structures that have fixed separation between the two planes.

We measured the operation of the mirror with a Michelson interferometer. By scanning the frequency of the drive voltage we found a resonance at approximately 700 Hz with a full-width half maximum of about 10 Hz. Displacement of 65 µm was achieved for the ~4.5 mg moving mirror, for an applied voltage of 215 volts peak-to-peak. Figure 3 shows the measured position of the mirror with respect to time and the fit to the theory. This simple interferometer is perhaps the easiest way to take advantage of the long-throw MEMS mirror to create a high resolution spectrometer. The best possible resolution would be determined by the maximum half-period displacement of the mirror; here, 65 µm motion implies a wavenumber resolution of 77 cm^{-1}.

In conclusion, we have demonstrated a MEMS mirror with a large reflective surface that is easy to fabricate using a new parallel-plate design for large displacement on resonance. Future plans involve working toward integration of this type of mirror with other devices; possibilities include compact spectrometers, delay lines, and adaptive optics systems with new architectures.

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