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High fill-factor micromirror array using a self-aligned vertical comb drive actuator with two rotational axes

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Abstract
We present a two-axis micromirror array with high fill-factor, using a new fabrication procedure on the full wafer scale. The micromirror comprises a self-aligned vertical comb drive actuator with a mirror plate mounted on it and electrical lines on a bottom substrate. A high-aspect-ratio vertical comb drive was built using a bulk micromachining technique on a silicon-on-insulator (SOI) wafer. The thickness of the torsion spring was adjusted using multiple silicon etching steps to enhance the static angular deflection of the mirrors. To address the array, electrical lines were fabricated on a glass substrate and combined with the comb actuators using an anodic bonding process. The silicon mirror plate was fabricated together with the actuator using a wafer bonding process and segmented at the final release step. The actuator and addressing lines were hidden behind the mirror plate, resulting in a high fill-factor of 84% in an $8 \times 8$ array of micromirrors, each $340 \mu m \times 340 \mu m$. The fabricated mirror plate has a high-quality optical surface with an average surface roughness (Ra) of 4 nm and a curvature radius of 0.9 m. The static and dynamic responses of the micromirror were characterized by comparing the measured results with the calculated values. The maximum static optical deflection for the outer axis is 4.32° at 60 V, and the maximum inner axis tilting angle is 2.82° at 96 V bias. The torsion resonance frequencies along the outer and inner axes were 1.94 kHz and 0.95 kHz, respectively.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Our group has proposed a novel type of telescope called MTEL (MEMS space telescope for extreme lightning) for the observation of transient luminous events (TLEs) from space. The details of the operational principle and structure of the telescope are presented in [1]. The proposed telescope has the following important functions: a wide field of view (FOV) surveillance, zoom-in on the object of interest and tracking of fast-moving objects. The MTEL consists of two cameras, ‘trigger camera’ and ‘zoom-in camera’. The mirrors in the telescope play the role of pinholes for the obscura telescope and reflect images seen through the aperture onto the photo detector. The mirror in the ‘trigger camera’ positioned closer to the detector is used for locating the object within the wide FOV, while the rotatable mirror in the ‘zoom-in camera’ is installed with a longer focal length and enables detection of the object image with higher lateral resolution, which provides a zoom-in effect. Every time an event is discovered by the ‘trigger camera’, the position information of the event is converted to the proper voltage signals by the control circuit. They are applied to the rotatable mirror in the ‘zoom-in camera’, so that the reflected zoomed-in image of the event is located at the center of the detector.
It is important that the mirror should rotate its viewing angle rapidly enough to observe the event immediately after the trigger, so as not to miss a significant part of the event under investigation. The speed of the tilting mirror in the ‘zoom-in camera’ should be stabilized within several milliseconds, since the purpose of the MTEL is to observe fast-evolving objects like TLEs, which usually last for a period of tens of milliseconds. As a possible solution for this purpose, the fast rotatable MEMS micromirror array is able to direct light quickly to photo detectors and allows important functions such as fast zoom-in and tracking of a moving light source. The micromirror should be rotatable in two orthogonal directions, because it has to align the event image with the center of the focal plane. The tilting angle should be over 2.8° to cover the FOV of the ‘trigger camera’. Moreover, adjacent reflector segments should be located close to each other to obtain a fill-factor of more than about 70% considering the number of photons emitted from typical TLEs and the lower limit of the detectable range of the photo sensor.

For the proposed telescope application described above, we employed the vertical comb-actuating scheme of the micromirror. Vertical comb drive (VCD) actuators have been studied for years, for their superior electrostatic energy density. Moreover, to increase the controllable range of the VCD actuator, fabrication methods of self-aligned VCD were developed by many researchers [2–5]. Micromirror arrays utilizing VCD actuators with high fill-factors have also been researched. Hah et al [5] proposed hidden actuators under the mirror plates utilizing polysilicon surface micromachining technology. However, the stress control of the thin film becomes difficult when multiple film layers are utilized to build the actuator. To overcome the limitations of the surface micromachining technique, bulk micromachined, high fill-factor micromirror arrays have been proposed by Jung et al [7]. A method adopting an additional fusion-bonding step was used to self-align the top and the bottom comb electrodes. The small contact area between comb electrodes in the additional fusion bonding process, however, may increase the possibility of local bonding failure. Milanović et al [8] proposed a 4 × 4 micromirror array with high fill-factor, in which the mirror reflectors were attached manually one by one after the actuator part was fabricated using a bulk micromachining technique. However, their fabrication process was not performed on the full wafer scale, which makes it difficult to fabricate uniform micromirror arrays with a number of reflectors.

In this paper, a self-aligned two-axis vertical comb drive micromirror array with high fill-factor and large static optical deflections is proposed. The device was fabricated by using a newly developed fabrication procedure on the full wafer scale. The small contact area between comb electrodes in the additional fusion bonding process, however, may increase the possibility of local bonding failure. Milanović et al [8] proposed a 4 × 4 micromirror array with high fill-factor, in which the mirror reflectors were attached manually one by one after the actuator part was fabricated using a bulk micromachining technique. However, their fabrication process was not performed on the full wafer scale, which makes it difficult to fabricate uniform micromirror arrays with a number of reflectors.

Figure 1. Schematic view of the micromirror for two-axis rotation.

Using a fusion bonding process and segmented at the final release step. The bias lines are patterned inside previously etched grooves on a glass wafer to address all the electrodes in an array and integrated with the actuators by a wafer-level anodic bonding process. The actuator and addressing lines are hidden underneath the mirror plate. Therefore, the proposed fabrication process enables manufacturing a two-axis micromirror array with high fill-factor on the full wafer level.

2. Design

A vertical-comb-type two-axis gimbaled micromirror is sketched in figure 1. A micromirror consists of an actuator with top and bottom comb electrodes, a mirror plate and a glass substrate with electrical lines. Vertical comb structures are formed on an SOI wafer to construct the actuation part of the mirror. The bottom silicon layer of the SOI wafer is patterned to form comb electrodes to which the actuation voltage is applied, and the top silicon layer of the SOI is used as the ground electrode. All the individual bottom electrodes are electrically isolated by a buried oxide (BOX) layer. The moving part of the actuator has a gimbal-like frame. The mirror plate (with a size of 340 × 340 μm²) is supported at the inner plate of the actuator. The actuator part and the glass substrate with electrical lines are bonded to make electrical contacts between the comb electrodes and the addressing lines. It has been reported that if a dielectric substrate exists under the actuator, the actuator might drift during the operation [9]. However, in our application, the actuator needs to maintain its static deflection for about 100 ms, only after the luminous event with sufficient photon emission is discovered in the FOV of the ‘trigger camera’. Since all electrodes are immediately grounded after the operation, the influence of the charging effect might not be crucial.
A dc bias at the comb electrodes attached to the frame provides an electrical torque for tilting the frame itself, while the dc bias at the comb electrodes located inside the frame generates the torque to tilt the inner stage of the actuator. Two sets of springs allow the mirror plate to be tilted independently in two orthogonal directions. We have adopted the gimbal-like frame to minimize the coupling between the inner and outer axis rotation.

Figure 2 shows schematic drawings of the vertical comb structure and torsion springs of the proposed micromirror. An outer spring has a thin silicon structure underneath the BOX layer as depicted in figure 2(c). It is extended from the bottom electrode to maintain electrical connection between the electrode and the lower comb structures at the inner peripheral of the gimbal stage. On the other hand, the underside of the inner spring is completely removed to reduce the torsion stiffness (figure 2(d)).

A VCD actuator can be modeled as a simple mass-spring system. The electrostatic torque is generated from the variation of the coenergy \(U_{\text{coenergy}}\) stored between the vertical comb electrodes when the voltage \(V\) is applied, as shown in equation (1):

\[
\tau_e = \frac{\partial U_{\text{coenergy}}}{\partial \theta} = \frac{\partial (\frac{1}{2} C(\theta) V^2)}{\partial \theta}.
\]

The total capacitance \(C(\theta)\) between comb structures as a function of the actuator tilting angle \(\theta\) is expressed by

\[
C(\theta) = \frac{\varepsilon_0 A}{g} = \frac{\varepsilon_0 (R_2^2 - R_1^2) N\theta}{g},
\]

where \(\varepsilon_0\) is the permittivity of air, \(g\) is the gap between comb fingers, \(A\) is the overlapping area of comb structures, \(R_1\) is the length of the comb fingers, \(R_2\) is the distance between the rotational axis and the tip of the fixed comb electrode, and \(N\) is the number of comb fingers, as shown in figure 2. The mechanical restoring torque \(T_m\) is determined by the spring dimensions, the width \(w_s\), length \(l_s\) and thickness \(t_s\) of the torsion spring as shown in equations (3)–(5):

\[
2k_t = \frac{2k G t_s w_s^3}{l_s},
\]

\[
k = \frac{1}{3} \left\{ 1 - \frac{192}{\pi^5} \frac{w_s}{l_s} \sum_{n=1,3,5}^{\infty} \frac{1}{n^2} \tan \left( \frac{\pi n l_s}{2w_s} \right) \right\},
\]

\[
\tau_m = 2k_t \theta,
\]

where \(k_t\) is the torsion stiffness of a spring, \(G\) is the shear modulus of a single crystalline silicon and \(k\) is a cross-sectional shape-dependent factor. The static tilt angle of the mirror is determined when the electrical torque balances with the mechanical restoring force. From the above equations, the relation between the input voltage and the mechanical tilt angle of a mirror can be derived as equation (6):

\[
\theta = \frac{\pi \varepsilon_0 N (R_1^2 - R_2^2) l_s V^2}{4k G t_s w_s^3}.
\]

As depicted in equation (6), the spring width is a crucial parameter to be controlled in the fabrication process. In addition, the comb fingers should be highly integrated in the limited area to maximize the force density of the actuator. Considering the lithography limit and the lateral etching of silicon structures, the width of the comb finger \(w_s\), the gap between fingers \(g_c\) and the spring width \(w_s\) are designed to be 3 \(\mu m\), to avoid fabrication failure.

The micromirror array consists of 8 \(\times\) 8 reflectors and was designed to be installed in the MTEL described in the introduction. For the proposed application, all electrodes driving one of the tilting directions are connected to a single metal pad positioned outside the mirror array. As a result, all mirrors are designed to tilt in a single direction when the control voltage is applied. Each metal line, starting from the individual bottom electrode, should reach the corresponding metal pad without making any undesirable connection with other electrodes. In contrast, the gap between mirror cells must be minimized, to ensure a high fill-factor for the device. For these reasons, a glass wafer is partially engraved to form shallow grooves, and the metal lines are patterned inside the grooves. Only the ends of the lines protrude out of the grooves to join each silicon electrode. For other applications, the addressing line pattern could easily be modified to control individual mirrors independently.

3. Fabrication

3.1. Fabrication of a VCD actuator and bonding of the substrate for a mirror plate

A self-alignment method was developed for fabricating the VCD actuator array, using a single SOI wafer. In the proposed fabrication procedure, the upper and lower comb structures are predefined using a self-alignment process from the topside of
Figure 3. Fabrication process for the topside of the SOI wafer including the substrate bonding for mirror plate: (a) three mask patterning, (b) the first DRIE, (c) the second DRIE, (d) the third DRIE, (e) oxide mask removal and (f) fusion bonding and CMP process.

Figure 4. SEM image taken after the topside multiple etching process.

the SOI wafer, and the lower comb structures are completed from the underside. The torsion springs are thinned down and unnecessary silicon structures on the top and bottom of the comb fingers are removed by multiple DRIE processes, to maximize the static tilting angle with respect to the applied voltage. The substrate for the mirror plate is attached in the middle of the actuator fabrication process.

Figure 3 shows the detailed fabrication steps for the topside of the SOI wafer, including the substrate bonding for the mirror plate. An SOI wafer with a 15 μm device layer and a 1 μm BOX layer is used to fabricate the gimbaled actuator. First, three etch masks are patterned on the wafer (figure 3(a)). For the alignment between multiple masks, the comb patterns of the first and second etch masks with an oxide layer are coarsely patterned to provide enough margin for the third mask alignment. The third mask with a photoresist is patterned and followed by the oxide mask etching, so that all three masks are self-aligned. Critical dimensions of the device, such as the gap between the comb fingers, spring width and comb width, are defined in this step. The first DRIE process continues until the BOX layer is exposed (figure 3(b)). It was done by using an STS Multiplex ICP etching tool with an SOI kit to minimize the notching effect. All other deep RIE processes were done by an SLR-770 of Plasmatherm. The traditional 5/3/5 Bosch process was used for DRIE processes. The BOX layer is etched anisotropically to uncover the silicon surface inside the 15 μm deep trenches. The silicon trenches exposed in this process continue to be deepened by the next DRIE steps, in which the lower comb structures are formed and precisely aligned to the upper comb fingers. After the third mask is removed, the second DRIE is performed. In this process, silicon structures are etched to produce a height difference between the spring part and the silicon structures on top of the lower comb fingers (figure 3(c)). The second oxide mask is removed by the timed etching of the oxide layer to reveal the part for the springs. The third DRIE step reduces the torsion spring thickness and removes the silicon structures on top of the lower comb fingers (figure 3(d)). After the third DRIE process, the BOX layer on the lower comb is exposed and the thickness of the spring on the BOX layer is determined. The exposed oxide mask is removed by 6:1 buffered oxide etchant (figure 3(e)). In this fabrication step, the BOX layer between the lower and upper combs should remain. Without this BOX layer, the lower side of the upper comb structures might be attacked in the DRIE steps from the backside of the SOI (figure 3(d)). Therefore, to minimize the etching of the BOX on the lower comb and between layers, the thickness of the final etch mask on the topside of the SOI was controlled so that it would be about 200 nm right before the BOE etching step. Also, in the mask removing process (figure 3(e)), the wafer was not immersed in the BOE but floated ‘on’ the BOE to minimize the etching of the BOX on lower combs as well as to remove the mask oxide layer. Figure 4 shows a scanning electron microscope (SEM) image taken after the three-step silicon etching process. As
shown in figure 4, the spring is thinned properly, and the comb structures are well defined. The inner spring thickness on the BOX layer is 3 \( \mu \text{m} \) and the etch depth under the BOX layer is 12 \( \mu \text{m} \).

The mirror plate is formed on a separate silicon substrate. The mirror post is defined by a 20 \( \mu \text{m} \) DRIE on a double-side-polished wafer. On the other side of the wafer, alignment keys are patterned. Then, fusion bonding is performed to bond the mirror posts to the centers of the actuators. In this case, the bonding alignment margin is 10 \( \mu \text{m} \). After the mirror plate substrate is bonded, the underside of the SOI wafer is ground and chemically–mechanically polished (CMP). The silicon thickness under the BOX layer becomes 40 \( \mu \text{m} \), which is for the bottom comb electrodes and space for tilting of the actuator (figure 3(f)).

The underside of the SOI wafer is patterned similarly to the etching process on the topside. Through the triple DRIE process, the bottom layer of the outer spring is thinned and the lower comb structures are completed. A cavity is also formed beneath the actuator to allow a large tilting angle of the actuator. Figure 5 shows the overall fabrication process of the SOI wafer underside multiple etching. Three etch masks are patterned like those on the topside of the SOI wafer prior to the multiple etching process (figure 5(a)). In the first DRIE step, the silicon is etched 20 \( \mu \text{m} \) to produce the height difference between the spring and the silicon structures under the upper comb fingers (figure 5(b)). After the third mask layer is removed, the exposed silicon structures are thinned (figure 5(c)). In the final etching step, the silicon structures on the bottom of the upper comb fingers are completely removed and the thickness of the outer spring under the BOX layer is defined. In parallel, a cavity beneath the actuator is achieved by reducing the thickness of the lower comb fingers and all the silicon bottom electrodes are electrically isolated (figure 5(d)). During this step, the etched silicon trenches lead to the ‘cavities’ which were previously formed during the topside fabrication of the actuator (figure 3(f)). From this moment, the etch rate of the silicon comb and spring structures is increased significantly. Hence, even though we have provided a large height difference between the spring and other structures in the first DRIE step on the backside of the actuator (figure 5(b)), the difference is reduced after the final DRIE step; the thicknesses of the outer spring under the BOX layer is 3 \( \mu \text{m} \) after the final DRIE process.

3.2. Address line formation and mirror segmentation

Metal lines are fabricated on a glass substrate for the connection between a voltage source and the mirrors. After the substrate with the electrical lines is combined with the actuators, the mirror plate is thinned and segmented in the final release step. Figure 6 shows the process for the fabrication of electrical lines on a glass substrate and the mirror segmentation. First, the grooves are formed, using amorphous silicon as an etch mask for the HF solution (figure 6(a)). After the mask is removed (figure 6(b)), the Cr/Ni metal lines are patterned inside the grooves using a lift-off process (figure 6(c)). The glass substrate with electrical lines is bonded to the reflector/actuator wafer using an anodic bonding process. The mirror plate is thinned to 50 \( \mu \text{m} \) using grinding and CMP, and coated with a 0.15 \( \mu \text{m} \) thick aluminum layer to make a highly reflective surface (figure 6(d)). After the aluminum layer is patterned, the mirror plate is segmented and released with a final DRIE etching process (figure 6(e)).

Figure 7(a) shows an image of the electrical lines taken from the rear side of the glass wafer. The bottom silicon electrodes are connected to the ends of the electrical lines. Figure 7(b) is an SEM picture of the metal lines inside the engraved glass pattern. The thickness of the metal line and the depth of the groove are 0.11 \( \mu \text{m} \) and 1 \( \mu \text{m} \), respectively.

3.3. Fabrication results

Figure 8 shows SEM images of the various fabricated structures. The fabricated micromirror array is shown in figure 8(a) with some of the reflectors removed to reveal the actuators. The actuator and addressing lines are located
underneath the mirror plate and the high fill-factor of 84% was achieved in an 8 × 8 array of micromirrors. The self-aligned VCD actuator without a mirror plate is illustrated in figure 8(b). The gimbal structure, self-aligned comb fingers and springs are shown. We can see that the thickness of the torsion springs has been lowered by the multiple etching steps. Figure 8(c) shows the top view of the comb electrodes and illustrates that the upper and lower comb fingers are well aligned. The mirror plate attached to the inner actuator is shown in figure 8(d). The engraved patterns on the underside of the reflector are formed during the SOI wafer backside etching. The dimensions of the designed and fabricated devices are summarized in table 1.

The surface roughness and flatness of the mirror were measured using a 3D surface profiler ($\mu$surf©, NanoFocus). The measured roughness and flatness of a single mirror plate are shown in figure 9. The average roughness (Ra) is 4 nm and the curvature radius is 0.9 m, which shows that the mirror plate has a surface profile sufficient for UV and optical wavelengths.

Table 1. Designed and fabricated dimensions of the micromirror.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Designed</th>
<th>Fabricated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb width ($\mu$m)</td>
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<td>2.8</td>
</tr>
<tr>
<td>Comb gap ($\mu$m)</td>
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<tr>
<td>Top comb thickness ($\mu$m)</td>
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<td>Bottom comb thickness ($\mu$m)</td>
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<tr>
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<td>Outer spring thickness ($\mu$m)</td>
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<tr>
<td>Inner spring thickness ($\mu$m)</td>
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<td>3.9</td>
</tr>
<tr>
<td>Mirror post height ($\mu$m)</td>
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<td>21</td>
</tr>
<tr>
<td>Mirror plate thickness ($\mu$m)</td>
<td>50</td>
<td>49</td>
</tr>
</tbody>
</table>

4. Characterization of the micromirror

The static deflection characteristics of the mirror were measured by a position-sensing detector (PSD). The laser source (S1FC635, Thorlabs Inc.) was collimated by a lens with 20 mm focal length and was aligned at the center of a mirror plate. The light reflected from the mirror cell makes a
figure 8. SEM images of the various fabricated structures: (a) micromirror array, (b) VCD actuator, (c) comb electrodes and (d) mirror plate attached to the inner actuator.

Figure 9. Surface profile of the fabricated micromirror. The roughness and the flatness of a single mirror plate were measured.

The laser spot on the center of the PSD. The angular displacement of the mirror plate was measured directly using the output signal of the PSD. When a voltage is applied to an electrode of a mirror cell, all the other electrodes are grounded. The static response of a single cell is characterized by applying a voltage to each electrode. In figure 10, static angular response graphs are shown for two axes. A single point in the graphs represents the average value of the tilt angle obtained from the 8 × 8 micromirror array. The average value of the maximum angular deflection for the outer axis was 4.32° under a bias voltage of 60 V, and a 2.82° maximum angular deflection was measured for a bias voltage of 96 V for the inner axis tilt. The standard deviation of the optical tilt angle was then calculated, and is denoted by the error bars in figure 10. The length of each bar represents a distribution of 2σ.

In the proposed telescope application, the upper bound of the spatial resolution is limited by the size of a single detector cell. If the differences in position between the respective images on the detector are less than the size of the detector cell, then the effect from the dissimilarities in the static angle can be ignored. The permissible extent of a distribution in tilt angle for the proposed telescope was estimated to be 0.3° when a static voltage input was applied to the array. In figure 10(a), the 2σ values of the deflection angle are either close to, or less than 0.3°. Hence, in terms of the outer axis rotation, only a small number of the mirrors are expected to produce a blurred image. On the other hand, the static angle deviation of the inner axis is greater than 0.3°, especially when a high voltage input was applied. Nevertheless, the images reflected by the mirrors with a tilt angle error larger than 0.3° can be reorganized and an undistorted image of the event can be recovered. This is because the image distortion from the mirrors can be predicted by characterizing the static response of each mirror in the array.

The resonant frequency of the mirror was measured using a laser displacement meter (LC2420, KEYENCE) and dynamic signal analyzer (HP 35670A). The signal analyzer
produces an input voltage signal and its frequency varies within the specified range in real time. Meanwhile, the laser displacement meter provides a voltage signal that is proportional to the deflection angle of the micromirror. Figure 11 shows the measured resonance frequency of the micromirror for the two orthogonal rotation axes. The measured resonance frequency for the outer axis is 1.94 kHz, and the torsion resonance for the inner axis is 0.95 kHz. The designed resonance frequencies of the mirror are 3.23 kHz and 1.78 kHz, for the outer and inner axes, respectively, so the measured resonance frequencies are smaller than the designed values. One reason for this is that the spring stiffness is decreased because of the reduction of the spring width in the fabrication process, as shown in table 1. We have calculated the resonant frequency with the measured dimensions of the fabricated device; for the outer and inner rotation of the mirror, the calculated results are 1.74 kHz and 1.20 kHz, respectively. Calculations correspond relatively well to the measured values.

The reduction of the spring stiffness caused by the spring width shrinkage during the multiple DRIE process is a dominant factor to change the static tilting angle of the mirror. This is because the static tilting angle is inversely proportional to the third power of the spring width, while the tilting angle is inversely proportional to the comb gap, as shown in equation (6). Moreover, the shrinkage of the spring width is more serious than the widening of the comb gaps in the fabrication process, as shown in table 1. Consequently, we can expect that the measured tilting angle should be approximately twice as large as the designed value. However, the measured static tilting angle for the outer axis is not significantly different from the designed value, while for the inner axis rotation, the measured static deflection is smaller than the calculated value. A possible reason for this is that the input voltage may be divided somehow before it is applied to the comb electrodes, because no mechanical defect was observed in the fabricated actuator. For example, a capacitance may exist between the silicon comb electrodes and the metal addressing lines because of poor contact between the silicon and the metal line in the fabrication process. Only a portion of input voltage could then be applied to the silicon comb electrodes, so the voltage signal applied to the electrodes will be attenuated. To test the validity of this hypothesis, the contact resistance of several silicon-to-metal contacts was measured. All exceeded 1 MΩ, which is...
quite a large value for the resistance of a normal, ohmic contact. Not only the inner axis, but also the outer axis static deflection may have shrunk because of the voltage division. To address the inner axis rotation, there are three silicon-to-metal contacts between a comb electrode and an external metal pad to prevent short circuits with metal lines for other electrodes. On the other hand, there is only a single silicon-to-metal contact between a metal pad and a silicon electrode for the outer axis rotation. As a result, the outer axis rotation is relatively less influenced by the effect of the voltage attenuation, compared with the inner axis rotation. One method of solving the contact problem is to use a eutectic bonding process instead of anodic bonding for the integration of the bottom substrate with electrical lines.

The micromirror array will be equipped in the MTEL to be delivered into the earth’s orbit by a Russian microsatellite, Tatiana-II. Therefore, the shock and vibration tests were performed in environmental conditions regarding the earth’s orbit satellite. Shock and vibration robustness of the micromirror was tested in three mutually perpendicular directions based on a Russian satellite test procedure. The qualification level random vibration tests ranged from 20 to 2000 Hz. A 40 g shock at the orbital stage was the maximum operational g-load used to qualify the test. After the shock and vibration tests were complete, no damage was observed, and the resonance frequency of the micromirror had not changed.

The reliability of the micromirror was measured by actuating the micromirror repeatedly to a tilting angle of ±3.1° at atmospheric environments. The mechanical lifetime of the structure can be determined by the detection of the spring memory phenomenon and breakdown due to fatigue crack during repeated actuation. The memory phenomenon manifests as a change of the tilting angle at the same driving voltage, while the breakdown of the spring is indicated by changes in the resonant frequency. To produce repeated actuation of the micromirror, a sinusoidal ac voltage was applied. The frequency of the applied bias voltage was 250 Hz. Even after 10⁸ cycles of repeated actuation, there was no change in the resonant frequency and no degradation in the static responses, which means that the micromirror has a lifetime of over 100 million actuation cycles.

5. Conclusion

A two-axis VCD micromirror array with high fill-factor was designed and fabricated on the full wafer scale. A self-aligned vertical comb drive actuator and thin torsion springs allowed a large static tilting angle of the mirrors at a relatively low voltage. A high fill-factor of 84% was achieved in an 8 × 8 array of micromirrors by hiding the actuators and addressing lines beneath the mirror plate. The fabricated reflector has a high-quality optical surface, because the silicon substrate is used for the mirror plate. The maximum optical tilting angle for the outer axis is 4.32° with an applied bias of 60 V, and the maximum inner axis tilting angle is 2.82° at a voltage of 96 V. The resonant frequencies of the inner and outer torsion axes were 0.95 kHz and 1.94 kHz, respectively.

We expect that the proposed micromirror array can be applied to various applications such as optical telecommunications, display projectors and diffractive optics, as well as our space telescope, MTEL, to enable high-speed light tracking in space.

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References