Electrostatically Actuated Micromirror Array Assembled by Using Solder Flip Chip Bonding and Electro-Thermal Fuse-Away Tethers

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Abstract
We propose a new electrostatically-actuated micromirror array. Using solder flip chip bonding technology, the desired electrode gap and the mirror rotation range can be easily created and enlarged. The use of solder assembly technology also provides us not only design flexibility but also precise gap height and mirror position control. In the mirror assembly process, a new MEMS transfer method using temporary fuse-away tethers is used to achieve robust and clean batch assembly. The mirror array is designed through FEM analysis and design optimization using a surface response method. The driving power of the optimized mirror system is reduced to one-third that of the initial design. The testing results of the fabricated mirror device show consistency with the predicted mirror performance and assembly precision.

Key Words: MEMS, OXCs, Flip Chip, Micromirror, Solder, Tether, Surface Response Method

1. Introduction
With increasing the number of Internet users, growing information commerce, and globalization of intellectual resources, wavelength division multi/demultiplexing (WDM) systems have been developing in optical communication field. A single fiber carries multiple wavelength channels in the WDM system and both data rate and port count have been increasing. Hence a large scale optical crossconnects (OXCs) have been required for not only switching but also traffic routing, load balancing and restoration. Conventional optical-electronic switching systems have low scalability due to limitation of size and electrical interconnects.

Micro-electro-mechanical systems (MEMS) have attracted attention to build large scale OXCs. MEMS are micro scale devices based on semiconductor processing technology and it is possible to sense, control and actuate precisely on the micro scale by using a combination of electrical and mechanical functions. Compared with gigantic electronics based switching systems, MEMS optical switches are promising in the future high speed network communications because of their inherent size advantage, scalability and optical-optical data switching fabrics. In many of MEMS OXCs using surface-micromachined electrostatically actuated micromirrors, however, it is difficult to achieve large rotation angle due to their small gap height between the micromirror and substrate. Although different micromirror systems that have the gap height expanding mechanism were also demonstrated, they typically have complex structures for 3-D assembly and positional assembly errors during the fabrication.

We have designed and fabricated a new electrostatically actuated micromirror array. Using solder flip chip assembly, the desired electrode gap is created and the
mirror rotation range can be easily enlarged. The use of solder bumps also provides us flexible gap height control by adjusting solder volume and solder pad size. In addition, precise mirror position alignment can be achieved thanks to the solder self alignment function\(^8,9\). Consequently, simple large scale OXCs will be established without bulky structures. Moreover, in the flip chip process of the surface micromachined mirror plate onto the substrate, a new MEMS batch transfer method using temporary electro-thermal fuse-away tethers is proposed. Several efforts of post-release process of functional surface micromachined layers have been reported\(^10^-12\). However, most of them are only lab-level techniques and cannot be expanded to commercial production. Our reliable and robust transfer is achieved using electro-thermal links that can suspend released MEMS structures and are broken away when fusion current is applied. In this paper, the details of design, analysis, fabrication and testing of the micromirror system are described.

2. Design and Fabrication

Fig. 1 shows a schematic view of the micromirror system. The micromirror system consists of a mirror plate, solder bumps and an electrode substrate. The micromirrors are driven by electrostatic force that generates by providing the voltage between the micromirrors and the bottom electrodes on the substrate. The micromirror chip is designed and fabricated using the multi-user MEMS processes (MUMPs)\(^13\). The MUMPs process provides two structural polysilicon layers (2.0 μm thick poly-1 layer and 1.5 μm thick poly-2 layer) and a metal layer (0.5 μm thick gold). The mirror plate includes four 250×250 μm movable micromirrors and a supporting frame. Both parts are made from two polysilicon layers and sandwich a 0.75 μm thick layer of silicon dioxide. Each mirror is suspended by two winding-shape 2 μm width torsional springs, which are all connected to the supporting frame. Four 140 μm diameter metal pads for solder joints are created at four corners of the supporting frame. The mirror plate is flip-chipped and jointed to the electrode substrate through the Sn63Pb37 eutectic solder bumps with a 33 μm gap height, which is determined from the Surface Evolver\(^14\).

Fig. 2 shows the micromirror array system assembly process flow. The step-by-step details of the process are as follows;

(a) Before the removal of sacrificial layers, 100 μm di-
ameter solder balls are placed on the metal pads and solder bumps are created on the surface-micromachined mirror plate by the first solder reflow.

(b) After removing the sacrificial layers, the mirror plate is separated from the mirror substrate and only suspended by temporary tethers.

(c) Using a flip chip bonder, the mirror chip is flip-chipped surface down and placed on the electrode substrate. Then both chips are jointed through the solder bumps with the treatment of second solder reflow.

(d) Applying the current through the polysilicon tethers, the tethers are heated up and melted.

(e) Pulling the mirror substrate up, the mirror plate is only transferred on the electrode substrate and the mirror surfaces are exposed.

The silicon substrate of the mirror plate should be removed in order to expose the mirror surface in this flip chip fabrication process. A transfer method of the layer structures is a key technique in our surface-micromachined micromirror system. Various methods of removing the silicon substrate have been demonstrated. One method is removing sacrificial layers after the flip chip fabrication\textsuperscript{10}). Depositing a sacrifice layer all under the micromirror plate, the mirror plate is released and the silicon substrate is flowed away after etching the sacrificial layer. However, this method cannot be used when other electronic devices such as integrated circuits and laser chips on an electrode substrate might be also attacked by etchant. This negates the advantage of batch process and results in unproductive fabrication. A structure transfer method using mechanical tethers has been also demonstrated as a high-throughput technique\textsuperscript{11), 12}). The method requires no etching processes after flip-chip bonding thanks to temporary support beams called “break-away” tethers. Although the method using mechanical tethers provides a simple fabrication process, break-away tethers are generally fragile and need to be handled with extra care according to our experience.

Thus we propose a new transfer method using “fuse-away” tethers that can be easily broken away when the current for fusion is applied on the tethers. Fig. 3 shows scanning electron microscope (SEM) photos of a released mirror plate and a close-up view of the tether structure. The tether is a $2\times9\times1.5\,\mu$m polysilicon link connected between the micromirror plate and the substrate. 28 side tethers and 4 corner tethers are arranged around the sides of mirror plate. Sequentially applying the voltage between the tether ends through the mirror plate and the anchor, the tethers that have higher resistivity are selectively heated up and fused away due to Joule heat. After side tethers are all broken away one by one with cascade current, four corner tethers, which have two anchors, are individually fused away. Compared with mechanical tethers, the precise breaking location can be designed in the thermal tethers. Moreover the fuse-away tether structure is more robust because the transfer method does not need to pull the structure up in order to break mechanically. Therefore this method enables to remove the substrate stably and reduce the damage to the micromirror.

3. Modeling

Modeling is an important part of the MEMS design process as it can eliminate a large amount of trial and error in the initial stage. Heat transfer simulation for studying tether characterization and electrostatic-mechanical simulation for analyzing micromirror behavior are conducted. The micromirror structure is also optimized to reduce the driving power by using a response surface method.

3.1 Fuse-Away Tether

An electro-thermal combined analysis of temporary fuse-away tethers was carried out to estimate the required current for fusion by using a commercial finite element method (FEM) software, CoventorWare\textsuperscript{15}). The model in Fig. 4 (a) consists of a simplified 1/4 polysilicon mirror plate, a side tether and a corner tether. The tethers are all anchored to the Si substrate whose temperature is fixed at 300 K. The voltage is applied between two tethers through the anchors from the substrate. Initial temperature of all structures is set to 300 K. Heat conduction and natural heat convection to the air are taken into account in all structures. Moreover, heat conduction of 2 μm air gap between tethers/mirror plate and Si substrate is considered as micro scale heat transfer. The ma-
Fig. 4 (a) FEM analysis model of tether (b) temperature distribution result of electro-thermal simulation

Fig. 5 Applied current vs. temperature of tether

terrial properties and boundary conditions are: electro conductivity (at 300 K) and thermal conductivity of polysilicon are 0.048 (S/um) and 29.0 (W/m·K) respectively, thermal conductivity of air is 0.027 (W/m·K) and natural convection coefficient to the air is set to 10.0 (W/m²·K). Fig. 4 (b) shows the analysis result when 32.5 mA current is applied and Fig. 5 shows the relationship between temperature at the tether and the applied current. As shown in the temperature distribution, the tethers are selectively heated up and the temperature reaches more than 1700 K. No critical heat influence is observed in other mirror structures. Thus the current reaching 32.5 mA, the fusion occurs at the fuse-away tethers and separation of the mirror plate from the substrate will be achieved without any thermal damages.

3.2 Electrostatic Micromirror

A design of the micromirror and electrostatic-mechanical combined simulation were conducted by using CoventorWare. At the same time the consistency between theoretical analysis and the CoventorWare was examined. Fig. 6 shows the micromirror model for the analyses. The simplified model includes a movable mirror plate, torsion springs and electrodes for electrostatic actuation. The mirror plate is 250 μm×250 μm×2 μm and two bottom electrodes whose size is half of the mirror plate are located beneath the mirror. The two torsion springs of 2 μm×43 μm×2 μm are connected to the two sides of the mirror plate and the other ends are set to fixed ends. The voltage for electrostatic rotation is applied between the fixed bottom electrode and the mirror plate. In the FEM analyses, a “pull-in” phenomenon is considered as a contact condition between the micromirror and the electrodes. The pull-in occurs when electrostatic force becomes dominant over the mechanical restoring force. The power balance between the linear mechanical restoring force and the nonlinear electrostatic force decides the micromirror position. When the rate of change in voltage versus deflection distance is zero, imbalance occurs.

Varying the gap height between the mirror plate and the electrodes, required voltage for 5 degrees torsional angle is calculated. Theoretical analysis is conducted based on Eq. (1) and (2)\textsuperscript{16}). The restoring torque of the flexure is

\[ T_{\text{mechanical}} = 2k\theta = 2Gh\theta^{3} \left[ 1 - \frac{192t}{\pi b} \tanh \left( \frac{\pi b}{2t} \right) \right] \theta \]  

where \( k \) is the torsional spring constant, \( G \) is the shear modulus, \( b, t \) and \( l_s \) are the torsion beam width, thickness and length respectively, and \( \theta \) is the mirror rotation angle. The electrostatic force is defined as

\[ T_{\text{electrical}} = \frac{1}{2} \varepsilon_{0}wV^{2} \int_{0}^{l_s} \frac{x}{[(d/\sin \theta - x)\theta]} \, dx \]  

where \( w \) and \( l_s \) are the width and the half length without flexure width of the micromirror respectively, \( d \) is the gap between a micromirror and electrodes, \( \varepsilon_{0} \) is the permittivity of free space and \( V \) is the applied voltage.
Fig. 7 Required voltage for 5 degree rotation angle versus gap height (Comparison of theoretical and FEM analysis)

The equilibrium condition can be described as

\[ T_{\text{Mechanical}} = T_{\text{Electrical}} \]

The required voltage for 5 degree rotation angle versus the gap height and the comparison of the theoretical analysis and the FEM analysis are shown in Fig. 7. The both calculation results are consistent enough to say that the modeling is reasonable to estimate the mirror behavior for initial prototyping stages. As shown in the FEM results, 5 degree rotation angle cannot be achieved with less than 33 \( \mu \)m gap height due to the pull-in phenomenon, so that such height is at least necessary to establish a stable 5-degree steering micromirror system. In the mirror system of a 33 \( \mu \)m gap height, the snap-through voltage is approximately 220 V and continuous mirror steering from 0 degree to 5 degrees will be achieved at the voltage range from 0 V to 220 V. It is important to note that a gap height is one of the key design factors to tune mirror torsional angle and driving voltage. In the micromirror system using solder flip chip bonding, the gap height can be flexibly adjusted with the control of solder shapes in order to fit the system requirement.

As for dynamic operation, the torsional resonant frequency \( f \) can be calculated using a single degree-of-freedom, lumped mass equation

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{J}} \]  

where \( J \) is the mass moment of inertia for the mirror plate about the axis of rotation. Using the same design parameters as the static model, a resonant frequency of 7.6 kHz is predicted and the mirror can be stably controlled with a 0.13 msec switching speed. The switching response of this initial design is fast enough to use as a micromirror system for OXCs, whose required response is less than 5–10 msec in commercial optical networks\(^2,17\). The main reason of high resonant frequency is that the torsional spring constant \( k \) is excessively high and it causes that a large driving voltage of 220 V is desired to steer the mirror. Whereas we recognize the importance of switching speed, it seems reasonable to suppose that the structure should be optimized as a total switching system, which has practical driving voltage and switching speed range. In the next section, we will optimize and redesign the micromirror structure to adjust the switching speed. Modifying the mirror suspension structure, it is expected that the driving voltage can be also decreased.

### 3.3 Optimization of Micromirror Structure

A response surface method called the statistical design support system (SDSS) is used to optimize the mirror structure\(^18,19\). Based on an experimental plan method, the SDSS leads a response surface for target performance as a function of design factors and the design parameters. In order to obtain the response surface, it is necessary to do simulations and/or experiments with various kinds of design factor combinations. Design parameters of the micromirror such as spring thickness and width are used as SDSS factors and level values of each factor are decided based on an experimental plan method. A schematic view of the micromirror and the SDSS design parameters \( x_1-x_7 \) are shown in Fig. 8. The design parameters, which mainly influence the switching response, are chosen based on Eq. (3). Note that modification of the spring structure will affect the driving voltage on the basis of Eq. (1) and (2). The level values for the SDSS are also shown in Table 1. The ranges of all level values are selected under the MUMPs fabrication limitation. The layer thickness of poly1, poly2 and metal are 2.0, 1.5 and 0.5 \( \mu \)m respectively. The mirror size is fixed to 250×250

![SDSS model of micromirror and design factors](image)
μm and the winding-shape springs are used to reduce the spring constant. The optimal values of resonant frequency are pursued by analyzing 27 kinds of simulations, which the design values of each parameter are designated by the orthogonal table of the experimental plan method. The response surface provided by the SDSS for the torsional resonant frequency $f$ of the micromirror is

$$f = 3655 + 3202x_1 - 603.8x_1^2 + 157.2x_2 - 0.465x_2^2$$
$$+ 1518x_3 + 424.1x_3^2 - 1199x_4 + 386.4x_4^2 - 170.7x_5$$
$$+ 0.925x_5^2 - 4252x_6 + 615.1x_6^2 - 3841x_7 + 394.6x_7^2$$  \( (4) \)

Each design parameter for adjusting to a resonant frequency of 1.5 kHz, which is 1/5 of initial resonant frequency and sufficient for optical switching operation, is decided based on the Eq. (4). Optimal values to obtain the resonant frequency are $x_1 = 4.25 \mu m$, $x_2 = 200 \mu m$, $x_3 = 2 \mu m$, $x_4 = 2 \mu m$, $x_5 = 80 \mu m$, $x_6 = 2 \mu m$, $x_7 = 3$. The micromirror is redesigned based on the optimal values, and an electrostatic-mechanical combined analysis is carried out to examine whether the driving voltage is decreased or not. The relation between the driving voltage and the rotation angle of the optimized micromirror is shown in Fig. 9. The driving voltage for 5 degrees rotation angle is lowered to 70 V from 220 V that the initial mirror system needs. Thus the driving voltage is optimized in a practical-use range as well as the maximum operation resonant frequency is adjusted. In addition, it is concluded that the SDSS is very effective for MEMS structure optimization in initial design stages.

4. Assembly and Testing

4.1 Flip Chip Assembly with Solder Bumps and Fuse-Away Tethers

The first prototype of large displacement micromirror system was fabricated by using MUMPs and successfully assembled by using solder flip chip bonding and fuse-away tethers. Fig. 10 (a) and (b) show an overview and a close-up side view photographs of the assembled micromirror array respectively. Four 250 μm × 250 μm micromirrors are arranged in one chip and flip-chipped on the substrate. The mirror plate is placed on the substrate through the solder bumps. An approximately 33 μm of gap height is achieved using 100 μm diameter solder balls and 140 μm diameter solder pads. It should be added that the there is ±10 μm tolerance in 100 μm diameter solder balls and this causes a ±2 μm gap height error. The fact suggests that a size classification of solder balls or particular tuning of the gap height is necessary when switching systems need precise control of driving voltage. Turning now to the fuse-away tethers, it is ex-
Fig. 11 A close-up view of tether after electro fusion

Fig. 12 A photo of micromirror undergoing static steering testing

Examined that the tethers are cut off at the fusion points we expected. Fig. 11 shows a close-up view of the tether after fusion with 30 mA. The polysilicon tether was melted at the neck and no critical damages are observed on the mirror plate. Since there are no particles causing the break, this transfer process is a clean process different from conventional methods using mechanical tethers.

4.2 Micromirror Behavior

The tilting micromirror is tested by reflecting a laser off a mirror surface onto an adjacent screen. The movement of the laser spot on the screen as the driving voltage is increased can be converted into a mirror torsional angle using the setup geometry. A photograph of a micromirror undergoing static steering testing is shown in Fig. 12. The bright spot is the laser spot and it is observed that the mirror is tilted with 60 V driving voltage. The upper left micromirror is removed to observe the bottom electrodes. Varying the driving voltage from 0 V to 60 V, the mirror characterization is obtained. The voltage is supplied to the bottom electrode and the mirror plate through the solder bumps from the probes. Fig. 13 shows the steering testing result with theoretical torsional angle. The experimental steering angle is approximately the same as the angle we predicted. Therefore it is concluded that the micromirror modeling and SDSS optimization are valid and the fabrication and assembly are also done without critical errors. Moreover, the consistent results show that solder flip chip bonding provides precise position and height control without extra manipulations. Solder bonding will be a high throughput solution in MEMS batch assembly processes.

5. Conclusion

We proposed a new large displacement electrostatically actuated micromirror array. Using solder flip chip assembly, the design flexibility of the gap height is enhanced. A suitable rotation angle and minimum driving voltage can be achieved to meet the system requirements. In addition, a new batch transfer method of surface-micromachined structure using electro-thermal “fuse-away” tethers was proposed and demonstrated. The transfer process is quite simple and no damages and contaminations occurred. The mirror structure was designed based on theoretical and FEM analyses. The obtained structure was optimized by using SDSS to adjust the resonant frequency and driving voltage. A mirror array, which has 5 degree steering angle with a 70 V driving voltage, was designed as the final device. A prototype of the switching array with four 250 μm×250 μm mirrors was successfully fabricated and assembled with solder flip chip bonding and thermal tethers. The mirror tilting characterization was tested and the testing results
are corresponded to the analytical solutions.

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