

# Design and Fabrication of an Electrostatically Actuated Parallel-Plate Mirror by 3D-Printer

J. Mizuno, S. Takahashi

**Abstract**—In this paper, design and fabrication of an actuated parallel-plate mirror based on a 3D-printer is described. The mirror and electrode layers are fabricated separately and assembled thereafter. The alignment is performed by dowel pin-hole pairs fabricated on the respective layers. The electrodes are formed on the surface of the electrode layer by Au ion sputtering using a suitable mask, which is also fabricated by a 3D-printer. For grounding the mirror layer, except the contact area with the electrode paths, all the surface is Au ion sputtered. 3D-printers are widely used for creating 3D models or mock-ups. The authors have recently proposed that these models can perform electromechanical functions such as actuators by suitably masking them followed by metallization process. Since the smallest possible fabrication size is in the order of sub-millimeters, these electromechanical devices are named by the authors as SMEMS (Sub-Milli Electro-Mechanical Systems) devices. The proposed mirror described in this paper which consists of parallel-plate electrostatic actuators is also one type of SMEMS devices. In addition, SMEMS is totally environment-clean compared to MEMS (Micro Electro-Mechanical Systems) fabrication processes because any hazardous chemicals or gases are utilized.

**Keywords**—MEMS, parallel-plate mirror, SMEMS, 3D-printer.

## I. INTRODUCTION

3D-printers are widely used for fabrication of 3D models or mock-ups in order to assist an understanding of realistic models and evaluate basic mechanisms (component interference, performance behavior and appearance check) prior line production. Recently, several technologies are available, such as plaster-based 3D printing as in [1], stereo lithography, fused deposition modeling and laminated object manufacturing as in [2]. The authors have recently proposed that models fabricated by 3D-printers can perform electromechanical functions such as actuators by suitably masking and metallizing them thereafter. These devices are named by the authors as SMEMS (Sub-Milli Electro-Mechanical Systems) devices since the minimum possible fabrication size is in the order of sub-millimeters.

On the other hand, with the advance of MEMS (Micro Electro-Mechanical Systems) technology, several important micro electro-mechanical devices such as gyroscopes, accelerometers and micromirrors have been developed. Since MEMS design concept is applicable from micrometer to millimeter scales, the SMEMS mirror has been designed based on this concept.

Regarding the fabrication processes, SMEMS is totally

J. Mizuno and S. Takahashi are with the Department of Mechanical Engineering, Ishinomaki Senshu University, Ishinomaki City, Miyagi Prefecture, 986-8580, Japan (phone: +81-225-22-7716; fax: +81-225-22-7746; e-mail: mizuno@isenshu-u.ac.jp, s-takahashi@isenshu-u.ac.jp).

environment-clean compared to MEMS processes because any hazardous chemicals or gases are utilized. Besides, MEMS key processes inevitably utilize greenhouse gases (GHG) that cause global warming [3]–[5] such as fluorinated gases ( $\text{SF}_6$ ,  $\text{C}_4\text{F}_8$ ) for deep-RIE (Reactive Ion Etching) of silicon [6],  $\text{CO}_2$  gas for supercritical drying of device releasing and post-process drying [7] and, so on.

In this paper, as a demonstration of a SMEMS device, design of an electrostatically actuated parallel-plate mirror fabricated by plaster-based 3D-printer is described for the first time.

## II. DESIGN OF SMEMS MIRROR

### A. Design Considerations

Basic schematic of an electrostatically actuated parallel-plate mirror is shown in Fig. 1. This mirror consists of a plate for reflecting a laser beam (hereinafter called reflector plate) which is supported by a pair of beam shape torsional springs (hereinafter called hinges) that extend from both opposite sides of the plate. The end faces of the hinges are anchored on a fixed frame. Beneath the reflector plate, there are two electrodes which are arranged symmetrically with respect to the mirror rotation axis. The cross sectional view of the mirror is shown in Fig. 2. Facing surface of the reflector plate and electrodes are separated by a gap  $g$ .

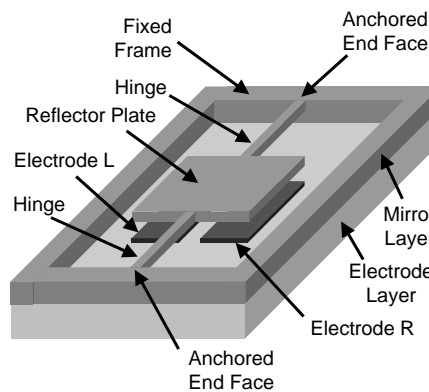


Fig. 1 Schematic of an electrostatically actuated parallel-plate mirror

The drive principle is also shown in Fig. 2. When a voltage is applied to one of the electrodes (e.g., electrode R), electrostatic force tries to pull the reflector plate toward the electrode R. Since the reflector plate is constrained by the hinges, it is forced to rotate around the hinge axis. Thus, by applying a voltage alternately to the electrode A and B, the reflector plate starts to perform a rotational motion. Basically, the reflector plate is electrically grounded.

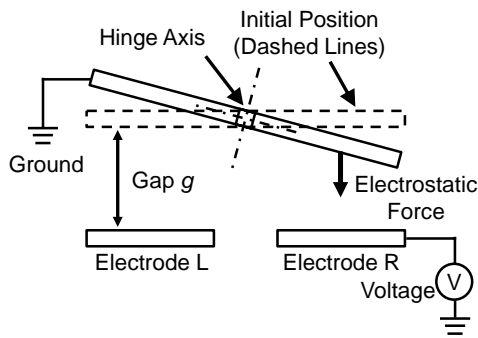


Fig. 2 Drive principle

Based on this basic structure, we have designed a specific mirror. Although a monolithic structure can be easily designed and fabricated by a 3D-printer, metallization of the backside of the reflector plate and electrode formation are not possible in such a structure. Therefore, the mirror which includes the reflector plate and the electrodes have been designed as a separate layer and assembled after metallization.

### B. Mirror Layer Design

The mirror layer consists of a squared reflector plate supported by a pair of hinges which are connected to a frame. The frame thickness has been designed in order to give the gap between the reflector plate and the electrodes. The backside view of the designed 3D model is shown in Fig. 3 and the dimensions of the main parts are given in Table I.

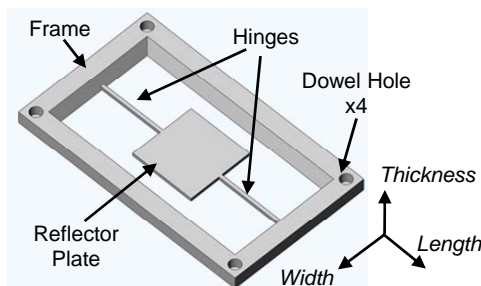


Fig. 3 Designed mirror layer (backside view)

TABLE I  
DIMENSIONS OF THE DESIGNED MIRROR LAYER

Part	Dimensions (Width x Length x Thickness) mm
reflector plate	20 x 20 x 1
hinge	1 x 20 x 1
gap $g$	3
frame external size	43 x 73 x 4

The four dowel holes on the four corners of the frame have been designed for aligning the mirror and electrode layer during the assembly.

### C. Electrode Layer Design

The electrode layer consists of a bulk substrate with four dowel pins for alignment. Electrodes are formed by Au ion sputtering on the substrate surface by using a mask. The design

of this layer is relatively simple because it is only a flat plane with four dowel pins. Regarding the mask, only one side of the electrode pattern has been designed for the convenience of our Au ion sputtering equipment. Since the electrodes are symmetrical, once the right side electrode is formed, the mask is reversed and then the left side electrode is formed precisely in the specified position. The mask as well as the mirror layer has four dowel holes for alignment. This mask consists of three connect patterns: an inner electrode pattern which will be underneath the reflector plate, electrode path pattern to connect the inner electrode and the electrode pad and the electrode pad pattern. The mask has been designed to have a gap of 1mm between the right and left electrodes. The designed 3D model of the mask is shown in Fig. 4 and the dimensions of the three parts are given in Table II. The electrode pad pattern has been designed large in length for the convenience of post-wiring.

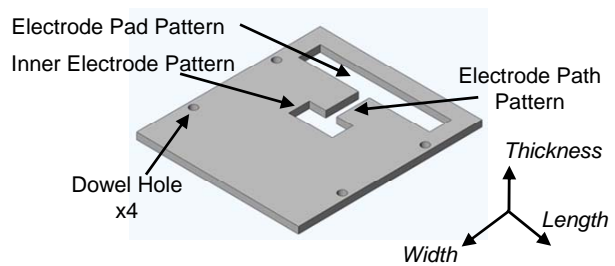


Fig. 4 Designed electrode mask

TABLE II  
DIMENSIONS OF THE DESIGNED ELECTRODE MASK

Part	Dimensions (Width x Length x Thickness) mm
inner electrode pattern	9.5 x 20 x 7
electrode path pattern	15 x 5 x 7
electrode pad pattern	10 x 60 x 7
mask external size	85 x 75 x 7

### III. FABRICATION

We fabricated the mirror and electrode layers according to the designed 3D model described above by plaster-based 3D-printer (Z Printer 450, 3D Systems Corporation). The mirror layer before and after Au ion sputtering is shown in Figs. 5 and 6, respectively. Both part of the frame has been masked by polyimide tape in order not to short circuit with the electrode path as shown in Fig. 6 (described as non-metallized parts).

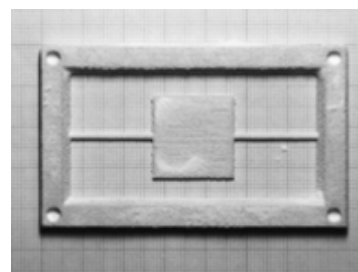


Fig. 5 Fabricated mirror layer just after 3D printing

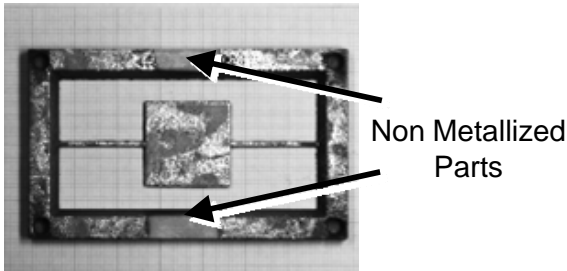


Fig. 6 Fabricated mirror layer after Au ion sputtering

The fabricated mask and the electrode layer are shown in Figs. 7 and 8, respectively. Static (e.g., deflected angle  $\times$  applied DC voltage) and dynamic (e.g., deflected angle  $\times$  frequency, resonance frequency, Q-factor) characterizations are currently being conducted.

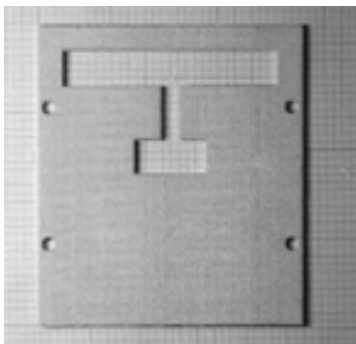


Fig. 7 Fabricated mask for electrode patterning

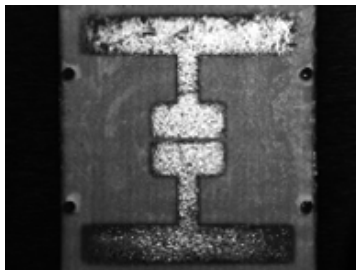


Fig. 8 Fabricated electrode layer

#### IV. CONCLUSION

A SMEMS mirror based on parallel-plate electrostatic actuator type has been designed and fabricated. The fabrication process has been conducted by a plaster-based 3D-printer.

After 3D-printing the designed models, they have been suitably masked and metallized in order to achieve electro-mechanical functionalities. At this time, a bottom cavity underneath the mirror structure to give a gap between the reflector plate and the electrodes has been considered. However, in practical applications, the upper side of the mirror must be covered by a glass lid for handling and dusty protection. The 3D-printer technology can easily solve this issue by monolithically constructing an upper cavity on the mirror layer. In usual MEMS technology such a monolithic structure is very challenging. A spacer is one of the solutions; however, the

number of processes and fabrication time would increase. Although the size is still not in the micrometer scale, SMEMS mirrors can be used in several applications where the size limitation is not severe such as confocal laser microscopes, laser scanners for factory automation, theater laser projectors, and so on. SMEMS is an attractive technology because the fabrication process is totally environment-clean and in addition, it can also easily realize complex 3D structures.

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