PIEZOACTUATOR-INTEGRATED MONOLITHIC MICROSTAGE WITH SIX DEGREES OF FREEDOM

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ABSTRACT

In comparison with miniature XY-stages in term of driving methods: electrostatic, electromagnetic and piezoelectric actuators, the piezoelectric actuators have high area efficiency but no machinability by conventional microfabrication techniques. In this paper we have proposed the novel fabrication method of a double-layered piezo-stack actuator made from a monolithic PZT plate based on a planer fabrication method, and integrated the actuators into a XYZ-stage with six degrees of freedom, i.e., X, Y, Z, θ_x, θ_y and θ_z directions. The stacked piezoactuators were formed on the both side of the PZT plate. The double stacked-piezoactuators, which are arranged around the stage, can stretch in plane or bend to Z-direction. The fabrication method includes dicing, electroplating, and laser machining. After making grooves by dicing, metal electroplating was performed and buried Ni into the grooves, which was done on both side of the PZT plate. After polishing the surface, metal electrodes were formed on an insulating photosensitive polyimide layer. Finally, the complete structure was defined by laser machining. The test results show that the X direction displacement of the actuation arms was about 2 μm when 40V was applied to both of double-layered piezo-stacked actuators. The Z direction displacement of the actuation beam was about 2 μm when 40V was only applied to one stacked actuator. These results show the possibility of the microstage with six degrees of freedom.

INTRODUCTION

A microstage with multi-degrees of freedom is considered as a key component of multiprobe storage systems, micro-optical systems, and various measurement devices etc. One of the objectives of this study is integration of XYZ-stage into the multiprobe storage system based on Scanning Probe Microscopy (SPM) (for example, see reference [1]). Up to now, the reported microstage has only two degrees of freedom, i.e., X and Y directions [2-5]. However, to our best knowledge, no microstage with six degrees of freedom made by means of micromachining technology has been reported. The mechanism for XY-microstage to provide a linear motion, referred to as parallelogram mechanism, had been devised [7]. In this mechanism, the square stage is supported by four-parallelogram arms, and driven by integrated piezoactuators that is supported by two narrow beams for enlarging of the displacement. The integration of actuators offers advantages of compactness, simplicity and the large enlarging ration of displacement. However, the cross-axis coupling between X and Y-axes is difficult to improve unless rigidity of the whole system is raised.

In order to fabricate a microstage by means of micromachining on a plate, the actuator material and design must be chosen above consideration in mind. Up to now, the miniature XY-microstages developed are mostly based on electrostatic or electromagnetic actuation [2, 4-5]. In generally, the microfabrication of piezoelectric material with precise dimensions is difficult by means of conventional dry-etching process [3, 7]. The commercial XY- or XYZ-stage with linear motions is assembled from the individual PZT actuator elements, which is difficult to miniaturize. The features of electrostatic, electromagnetic and piezoelectric actuators from the point of performances and miniaturization for XY-microstage are compared as shown in table 1.

Table 1. Comparison of typical actuators for miniaturization of XYZ-stage

Properties \ Actuators	Electrostatic	Electromagnetic	Piezoelectric
Volume power	X	△	○
Area efficiency	X	△	○
Volume efficiency	△	X	○
Machinability	○	X	△
Displacement	X	○	△
Frequency	△	X	○
Accuracy	△	X	○

In the case of electrostatic type stage, the microfabrication techniques of silicon including deep-RIE (Reactive ion etching) can be employed to define precise structures and narrow gaps, so that this type of actuators is used most widely in MEMSs, but the area efficiency, i.e. ratio of usable area (for example, used for data storage) and total area of system, for the advanced integrated-system is very poor because of the low driven force, the small displacement. Usually the area efficiency of electrostatic XY-stage is quite low; therefore it is a great disadvantage for the miniaturization of whole system, for example in the multiprobe datastorage system.

Electromagnetic type stage has higher area efficiency and lager displacement stroke than that of the electrostatic type stage, but the volume and weight of whole stage are very large, and the assembling process of permanent magnets is required in fabrication process. Therefore, it is considered as the disadvantage for miniaturization.

In the case of piezoelectric type stage, the volume power and the displacement accuracy of piezoactuator are very higher than that of above two-type of actuators, so large area efficiency will be obtained even if the structure has a large rigidity.

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In order to solve the difficulty of machinability for piezo material, a novel planer fabrication method of monolithic piezo-stack actuator had been developed by Gaku Suzuki et al. [6]. This planer fabrication method includes the following processes: dicing of shallow grooves on the plate, sputtering and electroplating to full groove-face, second dicing for making deep grooves from other side of the piezo plate, and electroplating of deep grooves from the bottom of metalized shallow-grooves. However, this method is only applicable for the fabrication of one layer piezo-stacked actuator and the design of the system is limited by this fabrication method. In this paper we presents an advanced fabrication method in which electroplating of the blind grooves for the electrodes of double-layered piezo-stack actuators and laser machining for fabrication of whole structure allow higher flexibility for the design of the device. Based on this fabrication method, we have developed the microstage with six degrees of freedom where all structure is made of the monolithic PZT plate.

In this paper we present an improved fabrication method that can electroplates the blind grooves of double-layers piezo-stack actuator. Based on this fabrication method, we design a microstage with six degrees of freedom that is made of one PZT plate.

STRUCTURE DESIGN

The displacement of piezoactuators themselves is very small, therefore, many kinds of mechanisms for enlarging displacement of XY-linear traveling have been adapted. In order to achieve accurate X and Y linear travel of the stage, the XY stage should have higher symmetric structure to minimize the cross-axis coupling. In this microstage, the stage corners or sides should be supported by above enlarging mechanisms. 'Parallelogram mechanism' has a high symmetry in their structure for enlarging the displacement, but most of them are driven by asymmetrically arranged piezoactuators [3] [7]. In parallelogram mechanism, if one corner is fixed and the opposite corner is feely suspended to drive the center stage, the stage will exhibit poor accuracy in Z direction.

We present a novel parallelogram mechanism for the stage with six degrees of freedom, in which actuator is integrated into the parallelogram mechanism. This integration allows a high symmetric structure in the design. Figure 1(a) show the schematic figures of the stage design and the parallelogram mechanism. Four arms with parallelogram mechanism support the center stage and the double-layered piezo-stack actuator is integrated in each center of the arm. The double-layered piezo-stack actuator, as the cross section is shown in the top of Figure 1(c), consists of two stacked piezoactuators, and the stacked piezoactuators can be individually driven by applying a appreciate voltage. The double-layered piezo-stack actuators can elongate to drive the stage in XY-plane as shown in Figure 1(b), and can bends to move in vertical direction as shown in Figure 1(c). Individual operation of the four parallelogram arms can drive the stage with six degrees of freedom in X, Y, Z, θ_x, θ_y and θ_z directions. The enlarging ratio K_{XY} of XY displacement of the built-in parallelogram mechanism is given by:

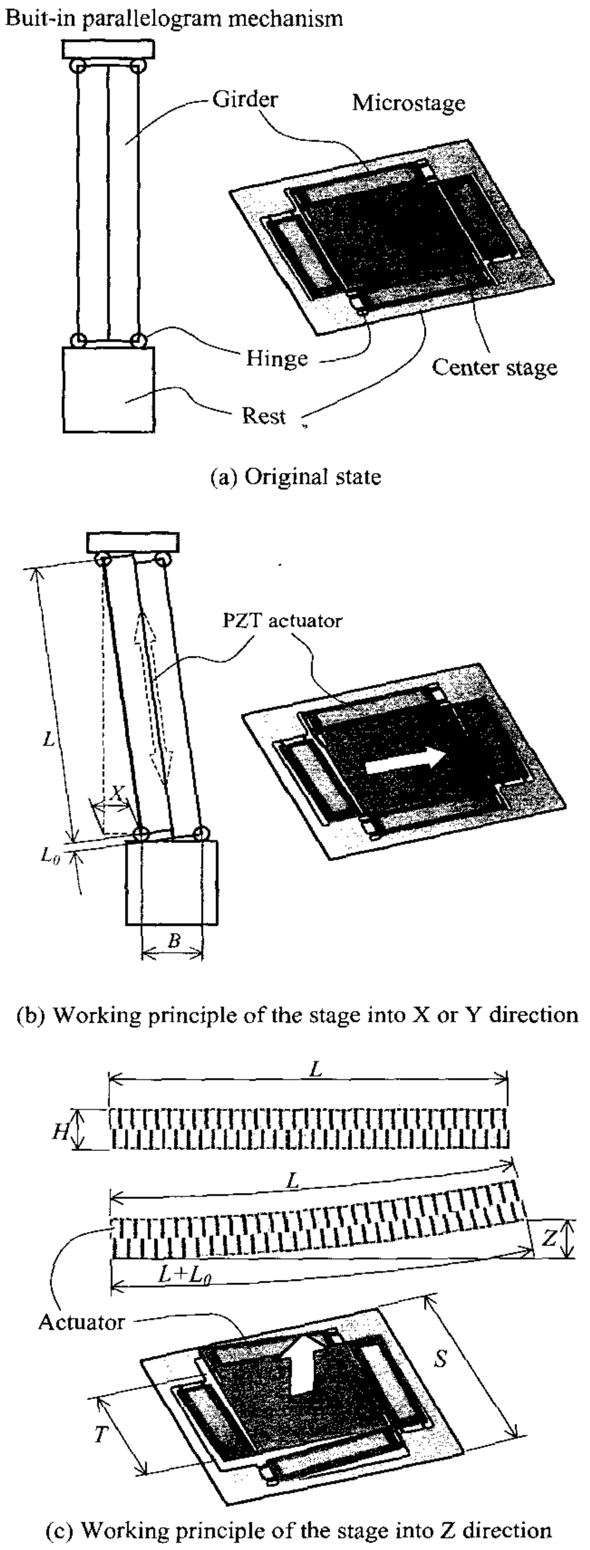


Figure 1. Schematic view of the designed structure and working principle of microstage.

$$K_{XY} = \frac{X}{L_0} = \frac{L}{B} \qquad (1)$$

Where L_0 is the elongate displacement of the double-layered piezo-stack actuator; X is the stage displacement in X direction; L is the arm length, and B is the distance between the hinges as shown in Figure 1(b). In our design, L=7.8mm, B=1.3mm, then K_{XY}=6. The enlarging ratio K_Z of Z displacement of the parallelogram mechanism can be approximated as follows:

$$K_Z = \frac{Z}{L_0} \approx \frac{L}{H} \qquad (2)$$

Where L_0 is the elongate displacement of one layer of the double-layered piezo-stack actuator; Z is the stage displacement in Z direction; L and H are the length and the thickness of the double-layered piezo-stack actuator, respectively. In our design, L=7.8mm, H=0.8mm, then K_Z=9.75. The area efficiency K_A of the microstage is given by:

$$K_A = \frac{T^2}{S^2} \qquad (3)$$

Where T^2 is the area of the center stage, and S^2 is the total area of this microstage. In our design, T=7.7mm, S=14mm, then the high area efficiency over 30% has been achieved.

FABRICATION AND TESTING

The key elements of the microstage with six degrees of freedom are the double-layered piezo-stack actuators. The fabrication flow of the inner electrodes is shown in Figure 2. An 800μm-thick PZT plate was prepared by polishing the both surfaces, and photoresist as a masking layer was spun on its one-side. The blind grooves with a depth of 400μm were formed by dicing. In order to fabricate the double-layered piezo-stack actuators, the deep blind grooves were formed by dicing saw and electroplated to form the inner electrodes for stacked piezoactuator. The complete filling of electroplated metal into the blind groove was difficult due to the generation of voids or hollows if the seed metal layer for electroplating was remaining on the sidewall or top surface. Therefore, the electroplating processes were performed as follows. First the blind grooves with 30 μm width and 130μm pitch were formed for the inner electrodes of the stacked piezoactuators, as well as the grooves with 70μm width were formed for the hinges and reinforced ribs as shown in Figure 4(a). After sputtering an Au/Cr seed layer, the metals at sidewall were removed by the dicing saw. The Au/Cr on the photoresist surface were removed by dissolving the photoresist, result in leaving the seed layer only at the bottom of grooves. From the seed layers, Ni for forming the inner electrodes, hinges and reinforced ribs, were electroplated, as the cross sectional view and top view are shown in Figure 4(b) and (c), respectively. It can be seen that the 30μm• 400μm grooves were diced very accurately with about 5μm width difference between the top and bottom of grooves, and there are was no hollows in the inner electrodes. After polishing of the electroplated face of the PZT plate, the same processing was repeated on other side of the plate, and then the electroplating processes were completed.

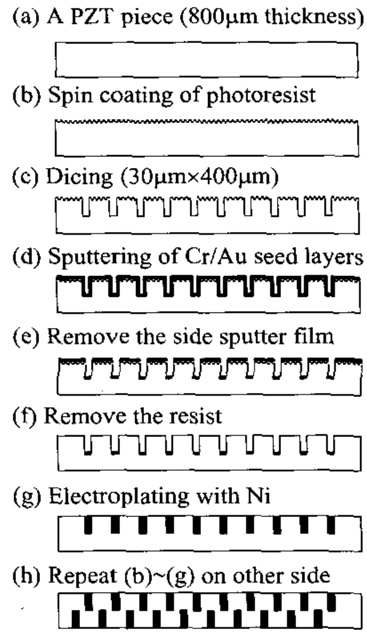


Figure 2. The fabrication flow of inner electrodes of double-layered piezo-stack actuators

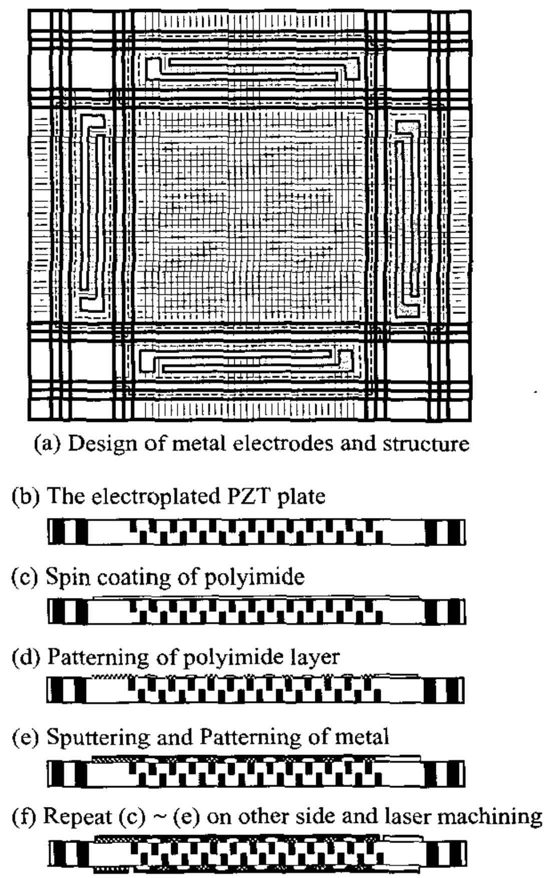
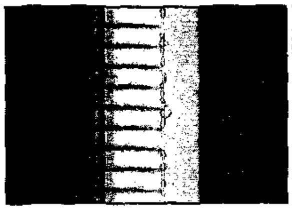
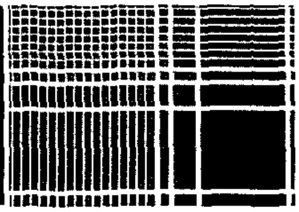


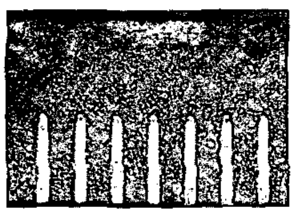
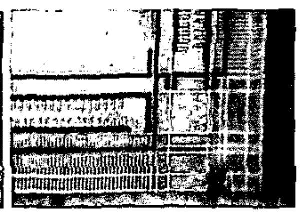
Figure 3. Design and the fabrication chart. Solid lines(—) show the dicing line, gray lines (▭)show top electrode pattern, and dot lines (····) show the cutting line by laser.

The following fabrication flow is shown in Figure 3. The photosensitive polyimide as an insulating layer was patterned by photolithography. Then Au/Cr was deposited by sputtering and patterned by photolithography and by etching of Au/Cr. Then the completed PZT plate was defined by machining with a femtosecond laser, as the part of the structure is shown in Figure 4(d). Finally, the lead lines were bonded to the metal pads with conductive glue. The width of the cut grooves by the laser was about 150μm, and the hinge width was about 150μm. The completed microstage with the size of $14 \times 14 \times 0.8mm^3$ is shown in Figure 5.

The polarizing process of these piezoactuators were performed by applying a DC voltage of 50V at 100°C for 30min, Then, the displacements of the microstage in X, Y and Z directions were characterized by laser interferometer equipped with a microscope. The X-displacement of the double-layered piezoactuator was about 2 μm when a DC voltage of 40V was applied to both layers of the piezoactuator. It should be noted that this displacement was smaller than that of expected. To avoid the electric shortage during the polarizing process, the polarizing voltage might be insufficient. The Z-displacement of the piezoactuator was about 2 μm when a DC voltage of 40V was applied to only the single stacked actuator. The cross-axis couplings in X, Y and Z directions were very small. Individual actuation of the actuator elements will compensate the cross-axis coupling. These testing results show the possibility of the microstage with six degrees of freedom.

(a) Grooves diced (c) Electroplating pattern

(b) Electroplating of blind grooves (d) Laser cutting pattern

Figure 4. Photographs of the microstage at each processing

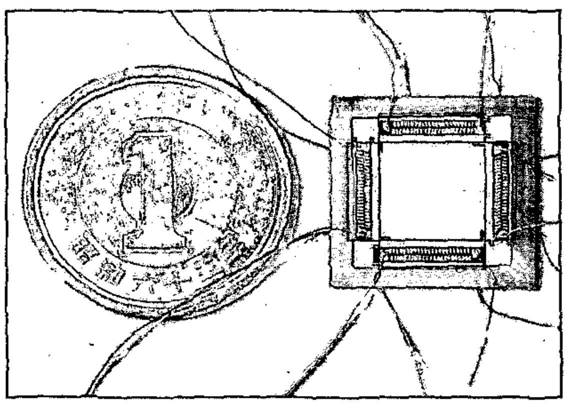


Figure 5. The photograph of the completed microstage, of which size is compared with Japanese 1 yen.

CONCLUSIONS

In this paper, we designed and fabricated the novel microstage with the possibility of six degrees of freedom, i.e., X, Y, Z, θ_x, θ_y and θ_z directions. Whole structure, including the actuators, the center stage, and the supporting base were made from the monolithic PZT plate. The integrated piezoactuators are constructed with a double-layered piezo-stack actuator. The inner electrodes of these double-layered piezo-stack actuators were electroplated into the blind grooves. Metal sputtering and following dicing can leave the seed-layer for electroplating only at the bottom of the grooves. The electroplating deposition was conducted from the bottom seed-layer of the grooves. This electroplating method filled Ni into the grooves without hollows. The size of the completed microstage was $14 \times 14 \times 0.8mm^3$. As the results of the actuation test, the fabricated microstage could move along X-axis with the displacement of 2μm as well as Z-axis with the displacement of 2μm when 40V was applied to both layers of actuator or only single layer of these actuators, respectively.

Acknowledgements

A part of this work was performed in Venture Business Laboratory (VBL), Tohoku University.

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