Fabrication and Characterization of Microstacked PZT Actuator for MEMS Applications
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Mohd Faizul Mohd Sabri, Takahito Ono, Suhana Mohd Said, Yusuke Kawai, and Masayoshi Esashi

Abstract—A microstacked PZT actuator of dimensions 8 mm x 8 mm x 0.4 mm and capable of 2.3-µm actuation under a voltage of 100 V was fabricated and characterized. This actuator was then integrated into a silicon microstage with dimensions of 20 mm x 20 mm x 0.4 mm requiring actuation by a miniaturized actuator. The microstage was designed containing a Moiré amplification mechanism in order to further amplify the actuation of the stacked PZT actuator. Experimental characterization of the microstage performance indicated that the combination of a stacked PZT actuator with the Moiré amplification mechanism was successful in enabling high amplification of the microstage to 15 times the original displacement of the PZT actuator. A displacement of 16.5 µm at an applied voltage of 60 V and a resonant frequency of 146 Hz in the lateral vibration mode was observed. The relationship between the actuator parameters and the microstage design and performance was also discussed in order to show that the customized fabrication of a miniature actuator was imperative for the successful design of a high area-efficiency microstage. Analytical derivation of the displacement of the stacked PZT actuator was also carried out in order to evaluate the effectiveness of the fabricated actuator compared with the ideal stacked PZT structure.

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Index Terms—Piezoelectric actuator, silicon stage, micropositioning, amplification mechanism, microelectromechanical systems (MEMS).

I. INTRODUCTION

RAPID DEVELOPMENTS in semiconductor processes have been the driving force in the proliferation of micro and nanoscale devices. The progress in micro and nanoscale devices has rapidly accelerated with corresponding progress in its fabrication methods, such as semiconductor fabrication processes. Micro and nanoscale devices have evolved to a sophisticated level, and have contributed to the establishment of nanotechnology as a cutting edge technology in today’s world. The applications of nanotechnology have a far-reaching impact in our daily lives, for example, in the form of nanosensors, biomedical devices, data storage devices and scanning probe technology [1]–[6]. One significant family of devices in nanotechnology is the micropositioning device or microstage, which allows translational motion in the microscale. It is a key component in applications where it is crucial to precisely move and manipulate objects, such as in data storage devices [1], [3], optical applications such as microrobot positioning [4], [5], and nanopositioning for biomedical applications [6]. Such systems generally require large actuation strokes with a resolution of the order of nanometers. These actuation strokes also need to be accurate and repeatable. In addition, a high resonant frequency is required for achieving high driving speed for micropositioning. High power density or low driving power is also a concern for the devices, as are size and cost considerations. The degree of miniaturization of the micropositioning mechanism is significant, as larger stage dimensions will incur drawbacks such as thermal drift, reduced dynamic performance and larger occupied volume.

The heart of the microstage system is the actuator, as it provides the driving mechanism for translational motion of the stage. The majority of the current microactuator designs utilize electromagnetic or electrostatic actuators. However, each of these actuation methods have their drawbacks. The electrostatic microstage is very low in area efficiency [7]–[9], thus resulting in a large area occupancy by the actuator, instead of the area that can be utilized for translation. Electrostatic actuators also require large driving voltages [7]. The electromagnetic microstage requires the incorporation of a three dimensional coil or the deposition of magnetic materials [10]–[12], hence complicating its fabrication process. In terms of performance, electromagnetic actuators suffer from low operational frequency compared [10]–[12] to other actuation methods such as electrostatic [7]–[9] and piezoelectric actuation [13], [14], due to its material characteristics and the use of a large mass of magnetic material.

This paper presents the fabrication and characterization of a stacked PZT (PbZrTiO3) actuator which is integrated into a silicon based microstage. A stacked PZT actuator is required in order to optimize the displacement of the actuator, which is notoriously low for a bulk PZT actuator, typically of the order of 0.02%. The choice of piezoelectric actuator results in high operational frequency, fast response, low driving voltage and precise positioning ability [13], [14]. For this work, a miniature PZT actuator was custom-made in order to fit into a compact...
microstage containing a Moonie structure. The role of the Moonie structure is to further amplify the inherent displacement of the stacked PZT actuator. The overall emphasis of this investigation is to produce a high area efficiency microstage, where the area efficiency is defined as the ratio of effective area of the moving stage, compared to the total microstage area. As such, miniaturisation of the PZT actuator and the inclusion of the Moonie structure are key elements which enable the achievement of a high area efficiency stage. The whole structure is fabricated using standard semiconductor fabrication processes, hence allowing for batch production to reduce cost.

II. THE STACKED PZT ACTUATOR

Piezoelectric ceramics are suitable for actuators, as they possess intrinsic characteristics such as fast response, precise displacement, large force and high operation frequency [4]. Displacement of piezoceramic actuators is mainly dependent on the applied electric field strength $E$, the length of the actuator $L_o$, the forces acting upon it and the properties of the chosen piezoelectric material. The material properties can be characterized by the piezoelectric strain coefficient $d_{33}$, which describe the relationship between the applied electric field and the resulting mechanical strain.

The change in length, $\Delta L_{o}$, of an unloaded single-layer piezoelectric actuator can be approximated by

\[ \Delta L_{o} = S L_{o} \approx \pm E d_{33} L_{o} \]  

(1)

where $S$ is strain (relative length change $\Delta L/L$, dimensionless), $L_{o}$ is ceramic length, $E$ is electric field strength and $d_{33}$ is the piezoelectric coefficient of the material in the poling direction.

Typically, a bulk PZT actuator as described so far is only capable of 0.02% strain. A strategy to improve the displacement of piezoactuators is to fabricate piezoelectric actuator in a stacked form of alternating piezoelectric material and electrodes, compared to a bulk PZT actuator which is only capable of 0.02% strain. For example, a commercially available stacked piezo actuator by NEC Tokin Co. shows about 0.1% strain [15].

A. Displacement of the Stacked PZT Actuator

The magnitude of displacement for an actuator may be calculated from its dimensions and number of stack layers. If a voltage $V$ is applied to the PZT stack actuator, every single stack layer will respond according to the following equation [15]:

\[ \Delta L_i = d_{33} V \]  

(2)

where $\Delta L_i$ is the mechanical displacement for a layer, and $d_{33}$ is the piezoelectric coefficient, which is $635 \times 10^{-12}$ m/V for N-10 type PbZrTiO$_3$. Therefore, the total displacement for a particular stacking PZT actuator containing $n$ layers is:

\[ \Delta L = \sum_{i} \Delta L_i = n d_{33} V \]  

(3)

where $n$ is the total number of stack layers. Discussion on the analytical prediction and the experimental performance of the displacement of the fabricated PZT stacked actuator shall be detailed in Section 5.

The displacement obtained, together with the stiffness of the system, can then be directly used to calculate the blocking force, in Equation (4). The maximum force (blocking force) a piezo actuator can generate depends on its stiffness and maximum displacement, and generated under conditions of infinitely rigid restraint, where its spring constant is infinite.

\[ F_{\text{max}} \approx k_{\text{act}} \Delta L_{o} \]  

(4)

where $\Delta L_{o}$ is maximum nominal displacement without external force or restraint and $k_{\text{act}}$ is piezo actuator stiffness.

In real applications, value of the spring constant of the load may be different from the piezoactuator’s spring constant. In this case, the actual force generated by the piezo actuator is:

\[ F_{\text{max,eff}} \approx k_{\text{act}} \Delta L_{o} \left( 1 - \frac{k_{\text{eff}}}{k_{\text{act}}} \right) \]  

(5)

where $k_5$ is stiffness of external spring.

B. Fabrication of the Stacked PZT Actuator

The stacked PZT actuator was fabricated in-house using Ni electroplating. The in-house fabrication of the PZT actuators was motivated by the fact that the dimensions of the actuator for this microstage design had to be specifically chosen to fit the designed slot for the actuator, and is generally smaller than the commercially available PZT actuators. Precise positioning into the required slot in the microstage would not have been possible using a commercial activator. In addition, the characteristics of the actuator could be tailored specifically to the requirements of the microstage design, through in-house fabrication of the actuator. For example, the smaller dimensions of the in-house actuator corresponds to an actuator of lower mass, hence enabling a higher resonance frequency for the overall microstage system. The value of the actuation
<table>
<thead>
<tr>
<th>Process</th>
<th>Condition/Remark</th>
</tr>
</thead>
</table>
| PET | Ceramics PET plate (PhZrTiO₃)  
Type: N-10 (NEC/Tohoku)  
Size: 40 x 40 x 1 mm |
| Photosist coating | OPFR 100 200µm  
Spin coat: 2000 rpm, Bake: 110°C, 10 min |
| Trench-dicing - Dicing | Blade: NBC/Z 2000 508 x 0.002 x 60  
Cutting depth: 100 µm, Pitch: 130 µm  
Number of trench: 37, Blade rotation: 3600 rpm  
Cutting speed: 2 mm/min, Coolant flow: 0.6 l/min |
| C/Au deposition – Spattering (Shibaura spatter) | Back pressure: <5 x 10⁻⁶Pa  
Power: 300 W, Sample rotation: 30 rpm  
C: 50 mm, Au: 200 nm |
| Top metal removal – etching | MS2001 – 80°C, 15 min, Rinse 4 times Isocol  
Rinse 4 times DI water, Ultrasound: 70 sec, Spin dry |
| Sidewall metal removal – Dicing | Blade: NBC/Z 2000 508 x 0.002 x 60  
Cutting depth: 500 µm, Blade rotation: 30000 rpm  
Cutting speed: 2 mm/sec, Coolant flow: 0.6 l/min |
| Nickel electroplating | Solution: Ni (NH₄SO₄)₂ – 600 g/L, NiCl₂ (NH₄)₂ – 3 g/L, H₂O₂ – 10 g/L, CH₃COONa·6H₂O – 6 g/L, C₂H₂(NH₂)₂ – 2 g/L, pH: 4.5, Nickel rod 99.99% Ni  
Current density: 500 mA/cm², 10 min at ON, 10 min at OFF, 50 mA/cm², 10 min at ON  
Temperature: 55°C, Time: 250 hours |
| Both sides Polishing | Load: 800 g, Speed: 30 rpm  
Sizing: 25-250%, Abrasive: 8 µm |
| Polyimide coating (Photorece UB410) | AOP coating – 2000 rpm, 20 sec, bake 80°C, 1 min  
Photorece UB410 – 1500 rpm, 25 sec, 3000 rpm, 1 sec, bake 80°C, 90 min, Exposure – 600 mJ/cm²  
Develop – D-495, 3 min (a), spin dry, Cure in N₂ Environment 180°C, 10 min, 275°C, 20 min, 400°C, 1 hours |
| C/Au deposition – Spattering (Shibaura spatter) | Back pressure: <5 x 10⁻⁶Pa  
Power: 300 W, Sample rotation: 30 rpm  
C: 50 mm, Au: 200 nm |
| Photolithography and C/Au etching | OAF coating – 2000 rpm, 20 sec, bake 90°C, 1 min  
OPFR 200 µm – 1700 rpm, 25 sec, 3000 rpm, 1 sec, bake 80°C, 10 min, Exposure – 450 mJ/cm²  
Develop – KM-3, 250 sec, dry spin, Post bake – 110°C, 10 min  
Wet etching  
An exhaust – 10 min, Rinse in DI water 4 times  
C/Au etch – 3 min, Rinse in DI water 4 times, Spin dry |

force will also influence the design of the microstage, as will be further elaborated in Section 3.1.

The stacked PZT actuator was fabricated from an N-10 type (NEC/Tohoku) 1-mm-thick PET plate. The details of the design parameters and PhZrTiO₃ ceramic properties are shown in Table 1. The 1 mm thick PhZrTiO₃ was first coated with OPFR 200 µm photosist on its top surface and baked at 110°C for 1 hour. Later, 600 µm deep grooves with a pitch of 130 µm were produced using a 25 µm thick dicing blade. C/Au were then deposited on the top side. At this stage, the metal deposited will act as a seed metal for growing the Nickel electrodes. Therefore, only C/Au at the bottom of the trenches are needed and the C/Au on top of photosist and on the trenches walls are removed by removing the photosist and dicing into the trenches, respectively. Nickel, which functions as the internal electrodes, were then formed in the grooves using electroplating process. The detailed conditions of the process are shown in Table 2. After polishing both sides of the plate, polyimide was coated and patterned on the top side as an insulator. Next, C/Au was deposited and pattern for electrical connection was formed using the photolithography process. The plate was then cut into 8 x 0.8 x 0.4 mm pieces. In total, each miniature actuator contained 58 alternating layers of Ni and PhZrTiO₃. Figure 1 shows the fabricated stacked PZT actuator with interdigitated electrodes connected by C/Au pattern.

III. THE SILICON MICROSTAGE

The fabricated actuator was used as a driver for an X-Y translational microstage, with additional amplification provided by a Mooney-type structure [16] as shown
ratio, the higher the microstage area efficiency. A close up of the support springs for the microstage and hinge for the Moenie structure are shown in Figure 2(a). These two components allow flexibility in movement for the microstage, and their dimensions determine the resonant frequency of the microstage. The Moenie structure serves to further amplify the stroke of the stacked PZT microactuator. The center stage is supported by two sets of support beams, and can be actuated by the Moenie amplification mechanism. In addition, the center stage is placed in the movable outer frame, which is also supported by support beams and can be actuated by another Moenie amplification mechanism. The Moenie amplification mechanism is based on four beams arranged in a “diamond” configuration, which is used to drive translation along one axis, as shown in Figure 3. Its basic amplification factor can be calculated by the following equation:

\[
R_{AMP} = \frac{L_m}{W} = \frac{\cos \theta}{\sin \theta} = \cot \theta
\]

where \(R_{AMP}\) is the amplification factor, \(L_m\) is the half length of the Moenie mechanism in the expansion direction, \(W\) is the half height of the Moenie mechanism and Moenie angle (\(\theta\)) is the angle of diamond rhombic to the longitudinal direction of the actuator. This equation implies that smaller values of Moenie angle will result in larger amplification factors. Further details of the mechanism of operation for the Moenie structure and microstage fabrication has been discussed in a previous publication [14].

A. Design Considerations for Integrating the Microactuator Into the Microstage

Geometrical matching of the microactuator dimensions, in order to fit into the microstage slot for the microactuator is a key consideration in the design of the microstage, and thus in this case was chosen to be \(8 \times 0.8 \times 0.4\) mm. In addition, performance characteristics of the microactuator such as force and actuator mass, have a significant effect on the microstage design. Even though the stacked PZT actuator promises high driving frequency [15], the fundamental frequencies of the stage are limited by its overall design, such as the microstage mass, and restraining forces from friction and support springs. Therefore, it is necessary to predict the resonant frequency of
the stage, through consideration of stiffness of support springs and hinges.

The close up for the hinge and flexible support beams for the microstage for Figure 2 (c) can be simplified into an equivalent spring system as shown in Figure 4.

In this arrangement, the restoring force of the system is given by

$$F_s = (k_m + k_{b_{total}}) x$$

(7)

where stage stiffness

$$k_{sta} = k_m + k_{b_{total}}$$

(8)

where $k_m$ is the stiffness of Mooney mechanism and $k_{b_{total}}$ is the stiffness of support spring [14]. Therefore, the fundamental resonant frequency of in-plane motion is expressed as follows

$$f = \frac{1}{2\pi} \sqrt{\frac{k_{sta}}{m_{sta,eff}}}$$

(9)

where $m_{sta,eff}$ is the effective mass of the moving stage. $m_{sta,eff}$ can be calculated from the volume of the respective parts. Comparison with the experimental performance of the microstage containing the miniature actuator shall be discussed in Section 5.

### B. Integration of the Microactuator Into the Microstage

The fabricated actuator was then integrated into the microstage using a dedicated series of microassembly steps, specifically designed for this microstage design as presented in reference [17], [18]. This microassembly strategy will enable reliable and repeatable assembly of this MEMS microstage, and will also set a precedent for the successful microassembly process of similar MEMS devices requiring integration of independently fabricated components. Using this microassembly procedure, integration of a moving part, i.e. in this case the actuator, onto a solid Si substrate is implemented, whilst allowing electrical and mechanical interconnection between the actuator and microstage base. This integration has advantages over a monolithic fabrication process, which incurs higher production costs and dedicated fabrication processes.

In order to optimize the operation of the miniature actuator in the microstage, simulation of the microstage was carried out, and shall be discussed in the following section.

### IV. FEM SIMULATION OF THE MICROSTAGE

#### A. Simulation Procedure

FEM simulation of the microstage was carried out using ANSYS workbench. The objectives of this simulation are to predict the stage displacement, resonance frequency and amplification factor of the Mooney mechanism. Furthermore, the simulation was also used to identify the parameters of hinges and support springs, which are a function of the maximum force (blocking force) exerted by the actuator. Results of the simulation were then compared with experimental results from the fabricated microstage. Comparison between experiment and simulation results were used to verify the validity of the simulation.

The design of the silicon microstage was used as the basis for FEM simulation, and its volume was divided into a mesh in order to perform finite element analysis on its body. Details of the simulation parameters are shown in Table 3. A loading force from 9 N to 3.5 N, which is in the same order of magnitude exerted by PZT actuators was applied to the Mooney structure. A static solution was obtained in terms of overall deformation as a function of the X and Y directions. The simulation results in terms of i) Displacements of the stage as a function of loading force; and ii) Amplification factor as a function of Mooney angle, which shall be discussed in the following section. In addition, modal analysis was performed in order to obtain the resonance frequency of the microstage in the X and Y directions.

#### B. Simulation Results

1) Displacement of the XY-Microstage: The displacement in the X and Y directions were obtained directly from the simulation, as a function of loading force. Figure 5 shows

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Parameters and Conditions Used in Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus: $1.9 \times 10^3$ MPa</td>
<td>Maximum Element size: 0.2 mm</td>
</tr>
<tr>
<td>Tensile strength: $3.79 \times 10^6$ MPa</td>
<td>Element type: tetrahedron</td>
</tr>
<tr>
<td>Density: 2.32 g/cm$^3$</td>
<td>Analysis type: 3D</td>
</tr>
<tr>
<td>Poisson ratio: 0.27</td>
<td>Nodes: 136735</td>
</tr>
<tr>
<td>Number of Elements: 22636</td>
<td></td>
</tr>
</tbody>
</table>

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