A ceramic–ceramic actuator composed of two piezoelectric ceramic layers with opposite poling directions was developed. One layer of the actuator had a high coercive electric field (PZT (Pb(Zr,Ti)O₃)-I; \( E_c = 1.1 \) kV/mm), while the other had a relatively low coercive electric field (PZT-II; \( E_c = 0.6 \) kV/mm). The actuator was fabricated by cofiring a green compact composed of the PZT-I powder on top of the PZT-II powder. When an electric field > 1.1 kV/mm was applied to the sintered body, the whole specimen was poled in one direction. Subsequently, by applying a field between 0.6 and 1.1 kV/mm, only the PZT-II layer was switched to the other direction. When an electric field was applied to this oppositely poled two-layer specimen, one layer of the specimen expanded while the other layer shrank. As a result of these reverse dilatations, the actuator was bent into a dome shape, yielding a large axial displacement at the center. The displacement of this actuator with dimensions of 20 mm (diameter) \( \times 1 \) mm (thickness) was 16 \( \mu \)m at 0.9 kV/mm.

### I. Introduction

A piezoelectric transducer that can generate large displacement while withstanding a sizable load is essential for actuator applications. Currently, PZT (Pb(Zr,Ti)O₃) or other Pb-based relaxor materials are widely used as actuators. However, the electric-field-induced displacements of these materials are much less than 1%, and in most cases, they are too small for actual applications. In order to enhance the displacement, various types of actuators have been developed. Recently developed flextransional actuators, such as Rainbow or Thunder types, exhibited a large displacement and a reasonable force-bearing capability. These actuators convert a lateral strain into an axial one with the assistance of residual stress.

In this research, a ceramic–ceramic actuator composed of two piezoelectric ceramic layers was developed. The layers were controlled to have opposite poling directions by adjusting the electric field during poling. When an electric field was applied to the poled specimen, one layer expanded laterally while the other shrank. As a result of these opposite dilatations, the specimen was bent into a dome shape, which yielded a large displacement at the center. The newly developed actuator exhibited a relatively large displacement, high interfacial strength, and possibility of mass-production.

### II. Experimental Procedures

Specimens were made by using two different types of PZT powders: one with a relatively high coercive electric field \( E_c \) (PZT-I) and the other with a relatively low \( E_c \) (PZT-II). The PZT-I powder was prepared by doping a PZT with a composition of \( \text{Pb}(Zr_{0.52}T i_{0.48})O_3 \) with 2.4 mol% \( \text{Nb}_2\text{O}_5 \). High-purity PbO (Aldrich Chemical Co. Inc., Milwaukee, WI), ZrO₂ (Kanto Chemical Co. Inc., Tokyo, Japan), TiO₂ (Junsei Chemical Co. Inc., Milwaukee, WI), and \( \text{Nb}_2\text{O}_5 \) (99.95%, CERAC Inc., Milwaukee, WI) were used as the starting materials. These powders were mixed by ball milling using zirconia balls and ethanol as media. After milling, the mixture was dried in a rotary evaporator and subsequently calcined in air at 800 °C for 2 h. The final composition of the powder was \( \text{Pb}_{0.988}(Zr_{0.52}T i_{0.48})O_3 \). Commercially available powder (Type-D; Taiheiyo-cement, Tokyo, Japan) was used as the PZT-II powder. According to element analyses with EPMA, high concentrations of Mg and Nb were detected (Pb 47.8 at.%, Zr 13.1 at.%, Ti 18.9 at.%, Nb 11.9 at.%, Mg 6 at.%, and Sr 2.3 at%) from this commercial powder, indicating that the material contains a significant amount of relaxor \( \text{Pb(Mg}_{1/3}\text{Nb}_{2/3})O_3 \).

The composite actuator was fabricated by compacting the PZT-I powder placed on the top of the PZT-II powder. The green compact was sintered at 1200 °C for 2 h in air with PbO-rich atmosphere. The dimensions of the specimen after densification were 20 mm (diameter) \( \times 1 \) mm (thickness). The microstructure of the specimen was observed by using a field emission scanning electron microscope (FE-SEM; JSM-6330F, JEOL, Tokyo, Japan) and an optical microscope (PMG3, Olympus, Tokyo, Japan). To distinguish the interface between the layers, Pt powder was scattered between the layers during pressing.

After the formation of silver electrodes on two major faces, the specimens were poled in silicon oil at 140 °C. First, both layers of the specimen were poled in one direction by applying a DC field of 3 kV/mm to the specimen. The poling direction of the PZT-II layer was then reversed by applying 0.8 kV/mm in the opposite direction.

The piezoelectric properties of each layer (PZT-I and PZT-II) as well as the composite actuator were measured using a fiber-optical displacement sensor (D-20, PHILTEC Co., Annapolis, MD) and a d₃₃ meter (model ZJ-3D, Institute of Acoustics, Beijing, China). The axial displacement of the actuator was monitored by placing the tip of the optical sensor at the center.

### III. Results and Discussion

The morphology of the composite actuator is shown in Fig. 1. An optical micrograph of the polished cross-section shows two distinct layers (Fig. 1(A)). The thickness of each layer was approximately 0.5 mm as intended. An SEM micrograph in Fig. 1(B) shows that the microstructures of the two layers are almost identical, so that without the Pt marker, it was very difficult to distinguish one layer from another. This micrograph clearly indicates that there is no mismatch or discontinuity at the interface.

The X-ray diffraction patterns of each layer are shown in Fig. 2. These patterns show that both layers are composed of pure perovskite without any pyrochlore phases. However, the peaks representing the (002) and (200) planes around 20 = 45°...
indicate that they are different phases. The peak for the PZT-I was split into three, as shown in Fig. 2(A), suggesting that this material is composed of the tetragonal and the rhombohedral phases, which correspond to the MPB composition of the material. On the other hand, the peak for PZT-II was not split (Fig. 2(B)), indicating that the specimen is composed of the rhombohedral phase only.\textsuperscript{14}

The strains of each layer as a function of the electric field are shown in Fig. 3. According to these measurements, the coercive field ($E_c$) of the PZT-I is 1.1 kV/mm and that of the PZT-II is 0.6 kV/mm. The difference in $E_c$ is closely related to the phase as well as the composition of the bodies. Generally, the size of the rhombohedral domain is much smaller than that of the tetragonal domain, which results in easier switching of the poling direction.\textsuperscript{14} The piezoelectric coefficient ($d_{33}$) of the PZT-I was 393 pC/N and that of the PZT-II was 610 pC/N. The $d_{31}$ of the PZT-I and PZT-II were $172 \text{ pC/N}$ and $256 \text{ pC/N}$, respectively.\textsuperscript{15}

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The displacement of the two-layer actuator is shown in Fig. 4. When an electric field was applied in the opposite direction of poling, the displacement at the center of the specimen exhibited three distinct steps, as shown in Fig. 4(A). At a field lower than the $E_c$ of the PZT-II, both layers were supposed to expand. Because the $-d_{31}$ of the PZT-II is larger, the actuator should bend into a concave dome shape. However, Fig. 4(A) indicates that the actual displacement was minimal. When the field reached 0.6 kV/mm, the poling direction of the PZT-II layer was switched. Therefore, the PZT-II layer began to shrink while the PZT-I layer kept expanding with increasing electric field. As a result of these opposite dilatations, the specimen was bent into a convex dome shape, yielding a large displacement. When the field reached the $E_c$ of the PZT-I (1.1 kV/mm), the poling direction of the PZT-I was also switched and the displacement began to reduce. Therefore, large displacement can be achieved only when the poling directions of the layers are opposite.

The displacement of the specimen with the opposite poling direction is shown in Fig. 4(B). When the dimensions of the specimen were 20 mm (diameter) × 1 mm (thickness), the displacement reached 16 µm at 0.9 kV/mm and exhibited a slight hysteresis behavior. The measured displacement closely matched to the calculated value, supporting the validity of the design. These results indicate that the newly developed actuator has high potentials for large displacement, strong, interfacial strength, and mass production.

IV. Conclusions

A ceramic-ceramic actuator composed of two piezoelectric ceramic layers with opposite poling directions was developed. The coercive electric field of one layer was 1.1 kV/mm (PZT-I) and that of the other was 0.6 kV/mm (PZT-II). The actuator was fabricated by the pressureless sintering of a green compact composed of a PZT-I powder on top of a PZT-II powder. After sintering, the whole specimen was poled in one direction by applying an electric field > 1.1 kV/mm. Subsequently, by applying a field between 0.6 and 1.1 kV/mm, only the PZT-II layer was switched to the other direction. When the electric field was applied to this actuator, one layer expanded while the other shrank. As a result of these opposite dilatations, the actuator was bent into a dome shape, giving a large axial displacement at the center.

References