Shape memory piezoelectric actuator

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The shape memory piezoelectric actuator can be operated using a pulsed voltage, so that small energy consumption and small voltage operation can be realized. To realize shape memory operation, the imprint electrical field was induced by treatment with a high electrical field of 3.5 kV/mm in a 150 °C environment. The actuator had two stable positions that were dependent on the piezoelectric polarization and could be maintained without the use of an external electrical field. This shape memory effect indicated that the imprint electrical field contributes to other functional properties, such as a permittivity, optical refractive index, and mechanical compliance.

Ferroelectric materials have multifunctional properties, such as a piezoelectricity, nonvolatile charge, and electrooptic functions. For a memory device, the ferroelectric random access memory (FeRAM) has been intensively studied. a)–d) This nonvolatile memory utilizes the remanent polarization in the ferroelectric materials; the principle of operation is based on charge detection. Another application of ferroelectric materials is for piezoelectric devices. e)–g) A large permittivity and electromechanical coupling factor are advantages for use of these materials as piezoelectric microactuators and sensors. In general, however, it is thought that the strain that is obtainable for a piezoelectric actuator is so small, and the use of a large input voltage is indispensable.

For the operation of conventional piezoelectric actuators, the driving voltage is considered so as not to exceed the coercive electrical field. This is due to polarization reversal, because control of the piezoelectric displacement becomes difficult, due to the change in the sign of the piezoelectric coefficient. With a perfectly reversed polarization, displacement of the piezoelectric results in the same position, because the piezoelectric strain versus electrical field is symmetric (butterfly hysteresis curve), so that reversal of the piezoelectric polarization is not useful for actuator application.

In this letter, we propose a shape memory piezoelectric actuator and report fundamental experimental results. Operation of the actuator is based on polarization reversal; therefore, this approach is totally different from that used for traditional piezoelectric actuators. In the case where a piezoelectric butterfly curve is symmetric with respect to the piezoelectric strain axis, the actuator will not have a shape memory effect. However, the butterfly curve can be asymmetric; for example, in the form of the piezoelectric thin films, asymmetric butterfly piezoelectric curves were reported to be due to an electrical imprint field. 7–11 Figure 1 shows the principle of the piezoelectric shape memory effect by control of the imprint field. The mechanism of this imprint field was studied in detail and it is thought to be related to lattice mismatching, the dead layer, and the space charge, 7–9 although this is not yet been confirmed. For FeRAM applications, the imprint electrical field results in different operation voltages for reversing the polarization. Therefore, for simple FeRAM operation, an attempt was made to remove this imprint electrical field. For actuator operation, this shift yields two stable piezoelectric strains without application of an external electrical field. In other words, with reversal of the polarization, the piezoelectric strain changes to another stable position, which is maintained even after the electrical field is disconnected.

There are some important advantages of a shape memory piezoelectric actuator. For example, when a conventional piezoelectric actuator is utilized as a mechanical relay switch, the operation voltage must be continuously applied to maintain “off” and “on” conditions. Under these conditions, the power consumption is not zero, because the leakage current is not zero. In addition, conventional piezoelectric actuators require a large dc voltage to maintain a certain position, so that large electric amplifiers are usually required.

On the contrary, the shape memory piezoelectric actuator does not require an electrical field to maintain an on or off condition, because it has two stable positions that are maintained without the use of an electrical field. If the switch mode must be changed from on to off, the polarization is reversed with a pulsed voltage. After this operation no electrical field is required, as shown in Fig. 2. Therefore, after reversal of polarization the electrical source can be disconnected and the energy consumption is zero. Another advantage is a low voltage requirement. This claim could be considered as unusual, because the operation principle of the shape memory piezoelectric actuator is based on the reversal

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FIG. 1. Principle of the piezoelectric memory effect by control of the imprint electrical field.
of the polarization, which requires a large voltage. However, the voltage shape can be driven using a pulsed shape. A pulse-shaped voltage can be generated by combining a small voltage source with capacitors and transformer. After the accumulation of charge to the capacitor, the charge can then be used for the operation of the shape memory piezoelectric actuator through the transformer as a pulse-shaped voltage.

The concept of the shape memory piezoelectric actuator is applicable for all piezoelectric actuators. It is not limited to certain piezoelectric material forms (thin films, bulk ceramics, or single crystals), certain actuator types (bimorph, unimorph, or multilayered type), and certain materials [Pb(Zr,Ti)O₃ (PZT), BaTiO₃ or LiNbO₃]. In this letter, to confirm the operation principle for the shape memory piezoelectric actuator, a PZT unimorph-type actuator was used. The actuator was 0.6 mm thick, 37 mm long within 28 mm part was PZT, and 13.4 mm wide. The actuator was supplied as a bimorph actuator (Nihon Ceratec Co., Ltd., LPD3713), with 0.2 mm thick stainless steel sandwiched by two 0.2 mm PZT layers. A signal wire for one PZT layer was disconnected, and one PZT layer was operated as a unimorph actuator for simplified operation.

One end of the unimorph actuator was clamped to an aluminum base, and the operation voltage was supplied from a signal generator (NF Co., Ltd., WF1946) through an amplifier (NF Co., Ltd., 4010). The piezoelectric displacement was measured with a laser displacement sensor (Keyence Co., Ltd., LC2450). To apply the imprint electrical field, a 700 V dc voltage was applied at a temperature of 150 °C in an electrical oven (Yamato Co., Ltd., DKN302). The electrical field was applied from the top electrode to the bottom electrode (stainless plate). After treatment for 2 h, the piezoelectric butterfly curve was measured. The result is not shown here; however, the measurement indicated that the imprint electrical field induced a shift of the butterfly curve to the left side. The direction of shift corresponded to the direction of the applied imprint electrical field, from the top electrode to the bottom electrode. A negative polarization direction was much more stable than the opposite direction. This results in the asymmetric shift of the piezoelectric butterfly curve. To confirm this, treatment was carried out for additional 2 h, resulting in an increase of the imprint electrical field, as shown in Fig. 3. Another unimorph actuator was treated with the opposite electrical field, from the bottom to the top electrode, for application of the imprint electrical field. The measured piezoelectric butterfly curve showed the same amplitude, but the opposite direction of voltage for a 2 h treatment at the same temperature. As expected, the electrical field imprint was opposite to the previous one. These results demonstrated that the imprint electrical field can be controlled.

A pulse operation was carried out using the unimorph shape memory piezoelectric actuator. The actuator was treated twice (total time of 4 h), with 700 V dc from the top electrode to the bottom electrode at 150 °C. With application of the pulse-shaped voltage, the piezoelectric displacement was changed to another stable position, as shown in Fig. 4. After return to zero electrical field, the piezoelectric actuator exhibited two stable positions, according to the polarization direction, as shown in Fig. 3. The gap between one stable position to the other was 0.12 mm, which corresponds to the gap displacement with zero electrical field on the shifted piezoelectric butterfly curve shown in Fig. 3. This demonstration reveals that this shape memory piezoelectric actuator could be operated as proposed.

In summary, a shape memory piezoelectric actuator was proposed and its operation was demonstrated in this letter. The shape memory piezoelectric actuator is based on the
imprint electrical field, and this imprint electrical field was controlled by a high electrical field treatment at high temperature. The piezoelectric butterfly curve was also shifted in the direction of the electrical field. With an imprint electrical field, the piezoelectric strain has two stable positions under a condition of no electrical field, but depending on the polarization direction. The polarization direction is reversed by a pulse voltage and this operation results in a piezoelectric displacement switch.

Control of the imprint was performed under the severe conditions of a very high electrical field and high temperature. Similar to a FeRAM imprint, this shape memory effect is thought to come from the induced charge at the boundary face between the ferroelectric material and an electrode. The mobility of the induced charge has to be taken into account; therefore, for practical applications, reproducibility is important.

This proposal is only for a shape memory piezoelectric actuator; however, the imprint electrical field is not limited to only actuator application. Ferroelectric characteristics exhibit not only piezoelectric performance but also nonlinearity of permittivity and refractive index. Therefore, as for the shape memory piezoelectric actuator, an imprint electrical field could impart memory characteristics to a ferroelectric material for permittivity and refractive index.