Study of RAINBOW Actuators Made of PSZT

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Abstract: A new type of large-displacement actuator called RAINBOW (Reduced And Internally Biased Oxide Wafer) was fabricated by a chemical reduction of PSZT antiferroelectric ceramic. It is found that PSZT was easily reduced and the optimal conditions for producing RAINBOW samples were determined to be 870°C for 2-3 h. The AFE-FE phase transitions occur at lower field strength in RAINBOWs compared with normal PSZT. Larger axial displacement (about 190 μm) was obtained from the RAINBOWs by application of electric fields exceeding the phase switching level. The field-induced displacement of the RAINBOWs is dependent on the manner of applying the load on the samples.

Key words: actuator; RAINBOW; chemical reduction; antiferroelectric ceramic; phase switching.

During the past several years, actuators based on piezoelectric ceramics have received numerous investigations and undergone a remarkable advance. Piezoelectric actuators offer many advantages including quick response, high-induced stress, low energy consumption and low cost, which makes them very attractive for a number of applications. However, the electric field-induced strain levels (0.1%) in normal piezoelectric ceramics are very limited, which considerably limits their use on advanced applications such as smart structures, linear motors, cavity pumps and noise canceling devices that require a relatively large physical displacement. To achieve a higher displacement from piezoelectric ceramics, a number of strain magnification mechanisms such as bimorph benders and "moonie" structures have been employed. But, an increase of the induced displacement is achieved at the expense of lowering the generated stress significantly.

Recently, a new type of monolithic bending actuator called reduced and internally biased oxide wafer (RAINBOW) device was developed through a special processing technique by Haertling. Compared with conventional actuators, the RAINBOW actuator demonstrated some features: (1) a dome-shaped monolithic composite structure, by which delamination problems usually found in conventional benders can be avoided; (2) larger axial displacement due to its dome saddle-like configuration.
tion; (3) higher mechanical strength due to the existence of internal pre-stresses. It is fabricated by reducing one surface of ceramics on the flat carbon block at an elevated temperature as shown by Fig. 1. Since the reduced layer and the remaining unreduced layer have different thermal expansion coefficients, internal thermal stresses and the dome structure will be generated when the ceramic is cooled down to room temperature after reduction. Generally, traditional piezoelectric ceramics such as PZT, PLZT were often used to produce the RAINBOW \(^{[4,5]}\).

On the other hand, it has been found that the Pb\((\text{Sn}, \text{Zr}, \text{Ti})\)O\(_3\) (PSZT) ceramics with compositions in the vicinity of the AFE-FE phase boundary exhibit very large field-induced strains resulting from the transition from the AFE (antiferroelectric) to FE (ferroelectric) states. A strain of 1.1%, the highest ever reported in the literature for ferroelectric ceramics, was claimed in the report \(^{[6]}\). Furthermore, the strain characteristics of these ceramics can be modified through selection of appropriate compositions \(^{[7]}\). PSZT ceramics may have a shape memory effect similar to some alloys (as SMA) or digital-like strain characteristics depending on the location of its composition in the phase diagram. Some possible applications have been proposed to utilize the strain properties of the PSZT \(^{[8]}\). So, the strain property of the PSZT is a very useful actuating mechanism for actuators, but the relatively high field strength needed for the phase switching makes it impractical.

The objective of this work was to combine the high-induced strains of PSZT with the RAINBOW technology to produce a new kind of large displacement actuator that can be operated in relatively low field and used in more applications, especially in smart structures. In this paper, the fabrication and properties of RAINBOW actuators made of PSZT are described in detail.

### 1 Experimental Procedure

The RAINBOW samples used were prepared from PSZT (Pb\(0.97\text{La}_{0.02}(\text{Zr}_{64}\text{Sn}_{26}\text{Ti}_{10})\)O\(_3\)) sintered ceramics. The ceramic wafers (\(\varnothing\) 27 \(\times\) 0.5) obtained from PSZT slugs were chemically reduced by placing them on a graphite block and heat-treating in certain temperatures. After reduction, the samples were cooled quickly during air, which makes the samples have a unique dome shape.

The thickness of the reduced layer of the RAINBOWs was measured from the sample cross-sections by means of an optical microscope. Conventional dc hysteresis loop equipment was employed to measure the relationship between the polarization and electric field. Electric fields greater than the AFE-FE phase transition levels were applied gradually to the samples. A measuring device with LVDT, transmitter and PC as seen in Fig. 2 was used to determine the change of the field-induced displacement with the electric field. A RAINBOW sample with electrodes on its both surfaces was placed on a metal ring in a container that was filled with silicon oil for insulating purpose. The movable core of the LVDT was adjusted to contact the center of the RAINBOW sample. Mechanical loading on the RAINBOW samples was accomplished by placing weights on the top of the LVDT. The variations of the polarization and axial displacement with the electric field were measured simultaneously as the samples were loaded.
2 Results and Discussions

2.1 Reduction of PSZT ceramics

Temperature and reducing time are important factors in controlling the reduction process during fabrication of RAINBOW actuators. The relations between reduced thickness and time in high temperature depend on the material itself. At a given temperature, the reduction thickness is approximately linear with time for PLZT ferroelectric ceramics (the most frequently used RAINBOW materials); however, the parabolic law is followed by PZT. A significantly thicker reduced layer in PSZT than in PLZT was produced when they were reduced at the same temperature for a given time. Fig. 3(a) shows the reduced layer thickness of the RAINBOW sample as an appropriately an linear function of the reduction temperature for one hour. An approximately 600μm thick reduced layer was created at about 975°C. In addition, Fig. 3(b) shows the change of the reduced layer thickness with time at a constant temperature of 870°C for the PSZT sample. A nearly linear relationship was observed.

Fig. 3 Variation of thickness of PSZT reduced layer with reduction conditions

At a higher temperature, the rapid reaction in PSZT ceramics leads to the loss of a large portion of the lead phase from the reduced region. As a result, the reduced region has poor electrical conductivity, which is detrimental to the performance of RAINBOW actuators since the reduced layer must be electrically conductive in order for a RAINBOW to operate properly. To prevent the heavy loss of the lead content from occurring, lower reduction temperatures must be used. However, a very low temperature implies impractical and long reduction times. It was found that the useful temperature range for the production of PSZT RAINBOW is actually narrow, approximately 820°C-900°C. The optimal conditions for producing RAINBOW samples from PSZT ceramics were determined to be 870°C for 2-3 h in this study.

2.2 Properties of PSZT RAINBOWs

The polarization (P)–electric (E) field hysteresis loop of RAINBOW ceramics is significantly different from that of normal (non-RAINBOW) ceramics. From Fig. 4, differences between two loops are seen. First, a finite net polarization $\Delta p$, indicating a partially poled ferroelectric state, was found to exist in the virgin state of the RAINBOW ceramics. This phenomenon is believed to be associated with the no uniform internal stress in RAINBOW ceramics. Second, the AFE-FE phase switching in the RAINBOW occurred at a much lower field level and was less abrupt compared with the normal sample. Since the composition of samples is located near the AFE-FE phase boundary, an intermediate P-E hysteresis loop characteristic of the two phases, namely double hysteresis loop with an appreciable remnant polarization, was

Fig. 4 Polarization-Electric field hysteresis loops of RAINBOW and normal PSZT
(a) RAINBOW; (b) Normal

observed.

Table 1 summarizes the basic properties obtained from RAINBOW and normal PSZT ceramics in this study.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Dielectric tanδ</th>
<th>$E_{AF}/E_{FA}$</th>
<th>$P_s/P_{Rm}$</th>
<th>$Y_M/\mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAINBOW</td>
<td>821</td>
<td>3.9</td>
<td>16.5/3.0</td>
<td>30/187</td>
</tr>
<tr>
<td>Normal</td>
<td>913</td>
<td>1.9</td>
<td>28/1.0</td>
<td>31/120</td>
</tr>
</tbody>
</table>

$E_{AF}$ - antiferroelectric to ferroelectric switching field;
$P_s$ - saturated polarization;
$E_{FA}$ - ferroelectric to antiferroelectric switching field;
$P_{Rm}$ - remnant polarization; $Y_M$ - maximum axial displacement with an applied electric field of $1.2E_{AF}$

Table 1

As shown in Table 1, the PSZT RAINBOW, in general, possessed a lower dielectric constant and a higher loss factor than the normal PSZT. The phase switching fields, $E_{AF}$ and $E_{FA}$, of the RAINBOW PSZT are much lower than those of normal PSZT. However, the saturated polarization was almost similar in two materials. The total field-induced axial displacement of the RAINBOW PSZT is much larger than that of the normal PSZT.

Although a larger axial displacement (about 190μm) has been achieved in this study, it was also found that the loading directions have great influence on the actuating displacement of the PSZT RAINBOW actuators. As clearly illustrated by Fig. 5, there is only a slight change in the displacement up to 5.7 N when the load was placed on the unreduced layer; however, the displacement with the load on the reduced layer decreased continuously with increasing loading.

![Graph](image)

Fig. 5 Variation of axial displacement with loading

The different characteristics under the two loading conditions may be explained by the behavior of ferroelastic domains under stress. Ferroelastic domains tend to be in line with the directions in which the stress is effectively relieved. When the load is applied vertically to the unreduced layer surface of a RAINBOW, ferroelastic domains are preferably aligned parallel to the surface due to the compressive stress in the planar directions produced by the loading. Similarly, when the load is placed on the reduced layer, ferroelastic domains tend to be oriented vertical to the surface as a result of the planar tensile stress. It is obvious that a PSZT RAINBOW actuator is more advantageous when operated with loading on the unreduced side.

There are also other factors, which are important to the properties of the RAINBOW ceramics. For instance, different thickness ratios of ceramic layer and reduced layer will generate different axial displacements of RAINBOW ceramics.

Conclusions

The fabrication and properties of PSZT RAINBOW actuators have been investigated. The optimal reduction conditions for the manufacture of PSZT RAINBOWs are $870^\circ$C for 2–3 h. The AFE-FE phase transitions occur at lower field strength in RAINBOWs compared with normal ceramics. Larger axial displacement (about 190μm) was obtained from the RAINBOWs by application of electric fields exceeding the phase switching level. The field-induced displacement of the RAINBOWs is dependent on the manner of applying mechanical load on the samples. There is only a slight change on the displacement for loads up to 5.7 N with load on the unreduced layer. However, when the load is placed on the reduced layer, the displacement decreases markedly with the increase of the load.

References

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Biography:

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