Domain configuration and switching contributions to the enhanced performance of rainbow actuators

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ABSTRACT

Stress-biased actuators, such as Rainbow and Thunder™ devices, offer enhanced displacement performance compared to unimorph and bimorph actuators. Quantifying the relative contributions of mechanics (layer thickness ratio) versus stress effects on actuator performance has proven difficult. In this paper, the importance of domain switching and altered domain configuration on actuator performance is considered. X-ray diffraction has been used to characterize the initial domain configuration in the surface region of the actuators, as well as the domain switching characteristics of the devices under moderate electric fields. Samples with different reduced layer thicknesses were fabricated to alter device stress state, and consequently, domain configuration and switching characteristics. Compared to poled polycrystalline ceramics of the same composition, Rainbow actuators display a slightly higher a-domain population in the surface region of the devices. Interestingly, despite the presence of comparatively large lateral tensile stresses in this region of the device, x-ray diffraction indicates these devices also display greater 90° (a- to c-domain) switching, which contributes to the large displacement responses that are observed. The contribution of stress to the enhanced performance of Rainbow and Thunder™ devices is, thus, more accurately described as arising from a change in the initial domain configuration together with minimal suppression in the switching response under high lateral tensile stresses, rather than simply a stress-enhancement of domain switching. The effects of stress on the initial domain configuration and switching response were quantified to define the specific role of stress on the electromechanical response of the devices.

Keywords: Rainbow, Thunder, stress-biased actuator, domain configuration, domain switching

1. INTRODUCTION

Rainbow (Reduced And INternally Biased Oxide Wafer)[1-3] and Thunder™ (THin UNimorph DrivER)[4-6] stress-biased actuators are the subject of intense investigation due to their unique performance characteristics[1] compared to unimorph and bimorph devices, as well as traditional direct extensional actuators. Both of these stress-biased devices are composite structures that incorporate a piezoelectric layer bonded to a metal (Thunder™), or cermet (Rainbow), layer. While the specifics of the fabrication procedures differ for the two devices,[2,4] for both, a domed structure is formed after processing. The driving force for the doming of the devices is the thermal expansion mismatch between the two layers, and because the lower metal or reduced layer has a greater thermal coefficient of expansion, during cooling, the devices dome upward, yielding a device that has a convex shape when viewed from above. As the devices dome, lateral stresses of high magnitude, both tensile and compressive, are developed.[7-10]

There have been a number of studies that have attempted to investigate the factors that contribute to the improved performance of these devices. Device aspects such as mass loading (from the metal or reduced cermet layer of the composite),[10,11] engineering mechanics (due to the similarity to unimorph structures),[12-15] and enhanced domain switching (due to the presence of tensile stresses within the upper portion of the piezoelectric layer) have all been reported as contributing to the greater displacement response that is observed. While further work is required to better understand the relative importance of these different factors, a number of studies have been carried out that have begun to provide insight in this area. These studies have employed a range of techniques, including finite element analysis,[7-10] equivalent circuit modeling,[11,16] and the use of unimorph theory to predict device electromechanical response.

Unimorph theory is a technique that was originally developed to characterize the displacement and tip force response of planar piezoelectric/metal structures.[17] The use of this method for the study of stress-biased actuators has been pioneered by

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Wang and coworkers,[12,13] who have developed equations that clearly identify the impact of variables such as device geometry on actuator response. These investigators then used their approach to model the effects of device geometry on displacement response by fabricating Rainbow actuators with different reduced layer/piezoelectric layer thickness ratios and characterizing tip displacement with a fiber optic probe. Summarizing their study,[13] it may be stated that non-constant variations between predicted and observed electromechanical response were noted. This implies that, as expected, mechanics aspects alone cannot satisfactorily explain observed performance of the devices.

A modified approach based on unimorph theory was later used by Schwartz and coworkers to quantify the mechanics contributions to Rainbow performance.[15] Depending upon device fabrication conditions, the mechanics contribution to overall performance was observed to vary from a high of 72% to a low of 53%, for an applied electric field of 10 kV/cm. By assuming that the differences between the observed response and those predicted by unimorph theory were attributable to stress and field induced non-linearities in the piezoelectric coefficients, values for "effective" d_{31} coefficients were calculated for different geometry devices.[15] It was found that devices fabricated with the highest stress levels, as estimated by finite element simulation,[7-10] demonstrated the highest d_{31} coefficients; values of approximately – 600 pm/V, or twice that of the poled polycrystalline ceramic, were noted. This study is among the first reported that has begun to quantify the importance of the various factors that contribute to the enhanced performance of stress-biased piezoelectric devices.

In addition to mechanics effects, stress enhancements to 90° domain switching have also been reported to contribute to the improved performance of these devices.[8,18] Evidence for this mechanism has been presented by Li, Furman, and Haertling,[8] who used x-ray diffraction techniques to confirm the greater switching response in the surface region of these devices compared to standard poled polycrystalline ceramics. These results were used in finite element simulations of device displacement response by assuming that the d_{31} coefficient varied from – 70 at the interface with the reduced layer (compressive stress region) to – 490 pm/V at the surface (tensile stress region).[8] This range of values is less than would be expected based on the results of Schwartz and coworkers,[15] and it is also less than those reported by Sherrit and coworkers.[19] However, it should be noted that differences in device shape (round vs. rectangular) may be at least partially responsible for these differences. It should be pointed out that in both the Li, Furman, and Haertling study[8] and the study by Schwartz and coworkers,[10] the ferroelastic nature of the devices was not accounted for. Therefore, the reported stress levels for these devices are likely higher than those actually present, since ferroelastic switching will occur to reduce the stress level.

Despite previous investigations, questions remain regarding the exact nature of the effects of stress on effective piezoelectric coefficients and device performance. Whether the greater switching response of these devices is due truly to an enhancement in 90° domain switching under stress, or if the behavior is more appropriately described as an alteration in domain configuration coupled with minimal suppression of the switching response due to lateral tensile stresses present has not been studied.[20] The importance of fabricating devices with domain configurations that are characterized by a high percentage of a-domains, i.e., domains whose polar axis is perpendicular to the field direction (polar axis parallel to the device surface), was first suggested by Zhang and Cross.[21] In a device that these authors referred to as domain bimorph actuator, a single crystal, polydomain barium titanate layer was bonded to a metallic layer to form unimorph and bimorph structures. Due to the presence of a-domains in the device and enhanced 90° domain switching under application of the electric field, high strain responses were noted; following removal of the field the metal layer provided a mechanical restoring force to return the device to its original shape. The increase in domain switching, i.e., a more pronounced extrinsic contribution to the effective piezoelectric coefficient, was reported to significantly enhance the electromechanical response of the device.

In this paper, we have further explored domain configuration and 90° domain switching effects in Rainbow actuators. Both poled polycrystalline piezoelectric ceramics (stress-free) and Rainbow devices fabricated with different stress levels in the surface region have been studied. One goal of this study was to begin to quantify the effects of stress on the d_{31} piezoelectric coefficient of lead-based ferroelectrics exposed to tensile stresses perpendicular to the poling and field directions. A second goal was to define the specific role of stress on performance with regard to domain populations before and after the application of the electric field. Our results suggest that the stress contribution to the enhanced performance of Rainbow and Thunder™ devices is due to two features. First, for the upper part of the piezoelectric, the tensile stress creates an altered domain configuration compared to the poled polycrystalline ceramic; slightly higher a-domain populations were observed, as suggested by Zhang and Cross[21] for their single crystal domain bimorph actuator. Second, despite the fact that significant tensile stresses are present in this region of the device, following the application of an electric field, a nearly equivalent domain configuration to that seen for the poled polycrystalline ceramic results. Thus, the presence of large lateral tensile stress does not strongly inhibit a-domain switching. This behavior results in devices that possess greatly enhanced extrinsic electromechanical responses, at least for the region of the device that is under lateral tensile stress.

2. EXPERIMENTAL

2.1 Fabrication of poled polycrystalline ceramic and Rainbow actuators

A conventional mixed oxide route was used to prepare the lanthanum doped lead zirconate titanate (PLZT) materials. Reagent grade raw powders of PbO, La_2O_3, ZrO_2, and TiO_2 were combined in appropriate mol fractions to obtain an overall stoichiometry of PLZT 1/53/47 ($Pb_{0.99}La_{0.01}Zr_{0.53}Ti_{0.47}O_3$). One to two mol percent excess PbO was incorporated in the batch to compensate for lead oxide volatilization during sintering and compositions were batched assuming a B-site vacancy formula. Standard ball milling procedures were employed and calcination was carried out at 925°C for two hours. After calcination, the powders were again ball milled for one hour and dried.

Ceramic discs were prepared using a mortar and pestle to mix 100 grams of PLZT powder with 1.6 grams of a 4 wt% PVA solution which acted as a binder. The mixture was placed in a cylindrical mold with a diameter of 2.9 cm, and using a hydraulic press, a pressure of 350 kg/cm^2 was applied to obtain a pressed specimen with a thickness of about 0.9 cm. The pellet was then placed inside a double crucible containing PbO/ZrO_2 atmosphere powder and this assembly was then placed in a Lindberg box furnace for binder burnout and sintering. To obtain samples with grain sizes varying from 2.5 to 7.4 μm, sintering temperatures were varied from 1100 to 1250°C and times from 5 to 15 hours. A flow of oxygen was maintained into the crucible during sintering to promote densification. The PLZT ceramic pellet was removed from the furnace after cooling and was sliced into discs of approximate thickness 0.05 cm using a diamond wafering saw. Finally, 400 grit sandpaper was used to improve the surface finish of the samples prior to actuator fabrication and electroding.

Rainbow actuators were fabricated using the standard procedures discussed by Haertling.[1-3] Briefly, a high temperature chemical reduction process was carried out by placing the PLZT discs onto the surface of a graphite block in a box furnace held between 850 to 950°C. The graphite block and oxygen react to form CO and CO_2 which chemical reduce the PLZT, forming a mixture of oxides and metallic Pb. The reduction kinetics and properties of the reduced layer have been characterized by several investigators.[22,23] Soak times from 10 to 240 minutes were employed to vary the extent of reduction, and thus, the thickness of the resulting cermet (reduced) layer. Reduced layer thicknesses were verified by cross-sectional optical microscopy. Complete details of the powder preparation process and actuator fabrication are reviewed in Ref. 22.

After lightly sanding the bottom (concave) surface to remove solidified lead particles, the Rainbow devices were then electroded for poling and characterization of domain configuration and displacement response. The bottom electrode was prepared using silver paste (DuPont 5504N) that was applied to the sample surface using a brush followed by curing at 200˚C for thirty minutes. To improve transmission of the x-ray beam through the top electrode for study of domain populations in the surface region of the samples, a thin evaporated aluminum electrode was deposited. It is estimated that the thickness of this layer was below 0.1 μm.

2.2 X-ray diffraction and domain configuration analysis

To study the initial domain configuration and switching behavior under applied electric field, $\theta - 2\theta$ diffraction studies were carried out using a Scintag XDS 2000 diffractometer.[7,22] The spectral region from 42 to 45˚ 2θ, which includes the (002) and (200) peaks for the PLZT composition of interest, was characterized. Using the "transparent" aluminum electrode described above, in-situ measurements of the a-domain (200) and c-domain (002) populations under different electric fields were carried out. Peak areas of the two diffraction peaks were then analyzed using a Gaussian fit, and the peak intensity ratios were calculated. The results were then interpreted in terms of domain populations (% a- and %c-domains). While the domed nature of the sample makes some displacement error inevitable,[24] to the extent possible, the center of the actuator was positioned as close as possible to the optimum height for each measurement. Displacement error is expected to have the most impact on d-spacings; minimal effects on peak intensity and peak intensity ratio are expected.[24]

Once the (002) and (200) peak areas are measured, calculation of domain populations is straightforward. To calculate the percentage of a- and c-domains, the following expressions were used:

for (002)/(200) peak ratio data:

$$\%\text{ a-domains} = 100 - 100 * \frac{c/a}{c/a+1} \tag{1}$$

$$\%\text{ c-domains} = 100 * \frac{c/a}{c/a+1} \tag{2}$$

for (200)/(002) peak ratio data: % a-domains = $100 * \frac{a/c}{a/c+1}$ (3)

% c-domains = $100 - 100 * \frac{a/c}{a/c+1}$ (4)

where c/a equals the (002)/(200) and a/c equals the (200)/(002) peak area ratio, respectively. A randomly oriented material has an a-domain population of 67% and a c-domain population of 33%. We also note that because the (002)/(200) peak intensity ratio is typically a fairly large value (two or higher) for most of our samples, it is a sensitive measure of the domain configuration. It may be easily demonstrated that slight changes in domain populations (1% or less) cause dramatic changes in the peak intensity ratio. Determination of domain populations before and after field application thus permits characterization of domain configuration, switching behavior, and extrinsic contributions to electromechanical response. It should be reiterated, however, that due to the limited penetration of the x-ray beam, the information acquired represents only the behavior for the surface region of the device.

2.3 Estimation of stress levels

A complete description of the approach used to estimate stress levels is beyond the scope of this paper. However, the method employed is briefly described below, and full details are reported in Ref. 7 and 22.

To quantify the effects of stress on the effective (extrinsic) piezoelectric coefficients of the devices, knowledge of the lateral stress levels (σ_{xx} and σ_{yy}) in the surface region of the devices is required. As a first step to obtain an estimate of stress magnitude, thermoelastic theory for heterogeneous thin plates was used.[25,26] The device shape (large lateral dimensions vs. thickness) justify the use of this approach. However, because no closed form solution exists for the non-linear equations, linear plate theory was employed. The bending deformations that occur in these devices due to thermal expansion mismatch suggest that the results obtained will provide a reasonable estimate of the stress levels. Because no non-linear terms are included, it would be expected that the predicted stress levels would be lower than those actually present. However, as with finite element methods,[7-10] in this analytical approach, the ferroelastic response of these materials was again not accounted for. This factor should result in estimates of stress levels that are higher than those present in the devices. Since the two errors tend to offset one another, we feel that stress estimates that are at least reasonably representative of the stresses present within the devices are obtained.

In the present situation, because Rainbow ceramics possess a uniform temperature distribution and no external or body forces exist, we used the specific approach described by Oel.[27] This method assumes that the influence of temperature on bending is converted to a strain (dimensional) mismatch at the interface of the two layers, which greatly simplifies the calculations that are associated with the conventional boundary value problem. Table I shows the material properties that were used in the analysis. We have used this approach to estimate the stress levels at the device surface for actuators with different geometries.

TABLE I

Material properties utilized in the thermoelastic analysis of stress magnitude for the surface region of the device.

Young's modulus – Piezo layer	7.42×10^{10} N/m^2
Young's modulus – Reduced layer	6.26×10^{10} N/m^2
Poisson's Ratio – Piezo layer	0.390
Poisson's ratio – Reduced layer	0.342
Thermal Expansion coefficient – Piezo layer	5×10^{-6} K^{-1}
Thermal Expansion coefficient – Reduced layer	1×10^{-5} K^{-1}

While the effects of the reduced layer thickness on domain population and switching were the focus of these investigations, actuators with different grain sizes were also studied to determine the effects of this variable on the extrinsic electromechanical response. In addition to the effects of thermal expansion mismatch during cooling, high temperature deformation also plays a role in defining the stress levels within these devices,[22] and this behavior is grain size dependent: smaller grain size materials demonstrate more extensive deformation. Therefore, to accurately assess the stress levels within these devices, this factor must be accounted for in the stress calculations.

Deformation has the affect of altering the high temperature Young's modulus and Poisson's ratio of the piezoelectric material. Allowance for this behavior was made by curve fitting measured dome height versus thickness ratio data for samples with grain sizes from 2.5 to 7.4 µm.[22] Using this technique, dimensional mismatches at the interface and mechanical factors were determined that were then used in the linear thermoelastic analysis. These calculations indicate that the actuators prepared with different grain sizes show a maximum stress level at the actuator surface for the same reduced/piezoelectric layer thickness ratio (~ 0.30 – 0.35); only the magnitude of the stress is different. For equivalent thickness ratios, the 2.5 µm sample displays a maximum stress of ~ 2.5 x 10^7 Pa while the actuator prepared from a piezoelectric layer with a grain size of 7.4 µm shows a maximum stress level of ~ 5.0 x 10^7 Pa. The calculated stress values thus obtained are used below in the investigation of stress effects on domain population and switching behavior and effective piezoelectric coefficient determination.

3. RESULTS AND DISCUSSION

3.1 Analysis of as-fabricated domain configurations

X-ray diffraction has been used to study both (200)/(002) and (002)/(200) peak intensity ratios for Rainbow actuators of different geometry.[7,8,22] The most thorough investigation for as-fabricated actuators has been carried out by Li,[7] and is also reported in the work of Li, Furman, and Haertling[8] for devices with reduced/piezoelectric layer thickness ratios that range from 0 to nearly 1. In these investigations, more than 25 samples with various thickness ratios were characterized.

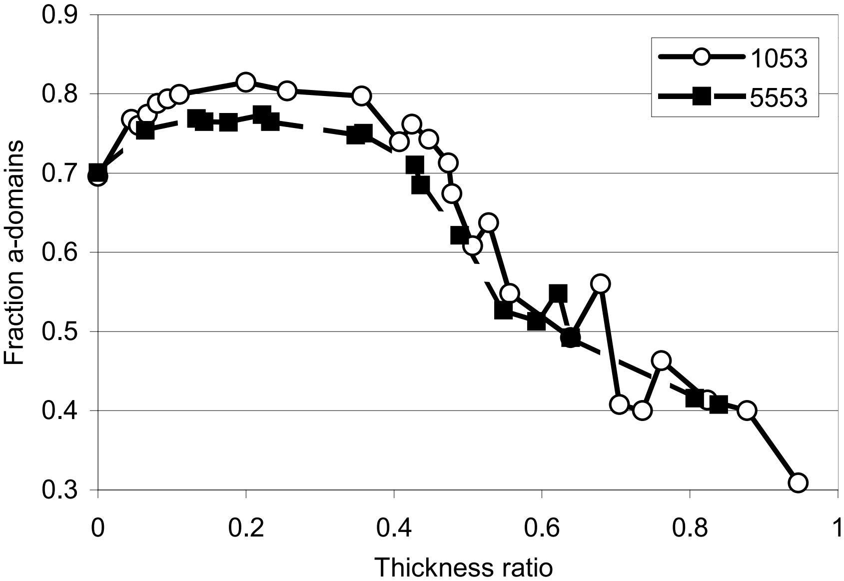

Fig. 1. Domain populations for Rainbow actuators fabricated with different reduced/piezoelectric layer thickness ratios. 1053 refers to actuators fabricated from PLZT 1/53/47; 5553 refers to PLZT 5.5/53/47 compositions. After Ref. 7.

Fig. 1 presents an analysis of the (200)/(002) peak intensity ratio data of Li[7] for Rainbows fabricated with different thickness ratios, and thus, different stress states. Thermoelastic and finite element analyses[7-10,22] suggest that the maximum tensile stress levels at the surface of the actuators are obtained for a thickness layer ratio of ~ 0.35. Analysis of Li's x-ray diffraction results support this conclusion, with the highest a-domain population devices forming under the highest lateral tensile stress. The formation of a-domains occurs because orientation of the polar axis in the plane of the structure can partially offset the high tensile stresses that are present. Using Eqn. 3 and 4, it may be determined that for the PLZT 1/53/47 samples, the domain configuration is characterized by ~ 80% a-domains and ~ 20% c-domains for thickness ratios of ~ 0.3. These values confirm that the material is mechanically (and extensively) de-poled in the as-fabricated condition since a higher percentage of a-domains than expected for the random material (67%) is observed. As the thickness ratio is changed to yield a device where compressive stresses are present at the surface (thickness ratios of greater than 0.5) a lower a-domain population than anticipated for a randomly oriented piezoelectric ceramic prior to poling is observed. For devices with the thickest reduced layers, and the highest compressive stress levels, an a-domain population of only 40% is obtained. Because this value is much less than that expected for a randomly oriented material, under these conditions, in the as-fabricated state, the device is partially poled by only mechanical effects (i.e., the compressive stresses present).

The PLZT 5.5/53/47 samples display similar behavior to the PLZT 1/53/47 devices when the device thickness layer ratio is such that compressive stresses are produced throughout the piezoelectric layer. However, lower c-domain populations are observed for this composition for actuator geometries that result in tensile stresses at the sample surface. At the present time, this difference in behavior is not fully understood. Potentially, it is related to the slight differences in the elastic moduli of the two different materials. The Young's modulus of PLZT 5.5/53/47 is 7.79×10^{10} N/m^2 whereas the modulus of PLZT 1/53/47 is only 7.42×10^{10} N/m^2. Thus, the higher lanthanum-doped material may be more resistant to stress effects. Another contributing factor to this behavior may be the different anisotropies of the two materials. The anisotropy of PLZT 1/53/47 is ~ 1.9% whereas the anisotropy of PLZT 5.5/53/47 is only ~ 1.4%.[20] The lower anisotropy may reduce the importance of ferroelastic softening (90˚ domain switching) effects during processing, resulting in a device that has a domain configuration more like the conventional un-poled ceramic.

3.2 Domain configurations and switching behavior under electric field

As with conventional piezoelectrics, prior to use, stress-biased actuators are subjected to electric fields that exceed the coercive field of the material for poling. As expected, this process results in a significant reduction in the percentage of a-domains. Reports in the literature[8] of (200)/(002) x-ray peak intensities following poling indicate that standard ceramic bodies and Rainbow devices possess poled configurations that are not greatly dissimilar, since nearly identical peak intensity ratios were observed. Our analysis of these results indicates that a standard polycrystalline PLZT 5.5/53/47 ceramic disc possesses a domain configuration characterized by 67% c-domains and 33% a-domains. The analogous Rainbow devices possess 65% c-domains and 35% a-domains. Thus, the stress-biased device is only slightly less poled.

Other evidence also suggests that conventional and stress-biased piezoelectric devices possess similar domain configurations. For example, our own studies of standard PLZT 1/53/47 ceramics and Rainbow devices yield results similar to those of Li, Furman, and Haertling:[8] the stress-biased devices possess c-domain populations that vary from 69 to 75% while the conventional ceramic is 78%. Again, differences in the domain configuration appear surprisingly small. However, as will be shown, even such apparently minor differences in initial domain configuration have significant implications for the performance of the devices.

To gain further insight into the importance of stress on the performance of Rainbow devices, the domain configuration of the poled devices must be considered together with the configuration following (during) the application of an electric field. The results of these investigations are presented in Fig. 2 for several actuators characterized by different stress levels. First, we will consider the poled nature of these devices and the effects of stress on the state of poling. For all devices studied, the x-ray diffraction results indicate that the devices are better poled than the conventional piezoelectric ceramic discs reported by Li, Furman, and Haertling.[8] Values of c-domain percentages range from nearly 78%, for the standard (stress free) ceramic, to ~ 70% for the actuator prepared with the highest lateral tensile stress level. The observed differences between these results and those previously reported are most likely due to differences in the poling procedures. The key result, though, is that fairly large lateral tensile stresses do not significantly inhibit the ability of the piezoelectric layer within the Rainbow device to attain a well-poled configuration.

Also shown in Fig. 2 are the domain configurations of the devices following the application of a 10 kV/cm electric field. Again, these results are obtained in-situ in the x-ray diffractometer during the application of the electric field. All devices, irrespective of stress state, demonstrate an increase in c-domain population with applied field; however, the effect is greatest for the Rainbow device with the highest (~ 50 MPa) lateral tensile stress. For example, while the conventional disc only shows an approximate 1% increase in c-domain population under field, the high stress device demonstrates almost a 7% increase in c-domain population. Thus, following the application of the electric field, nearly equivalent domain configurations are obtained for all devices.

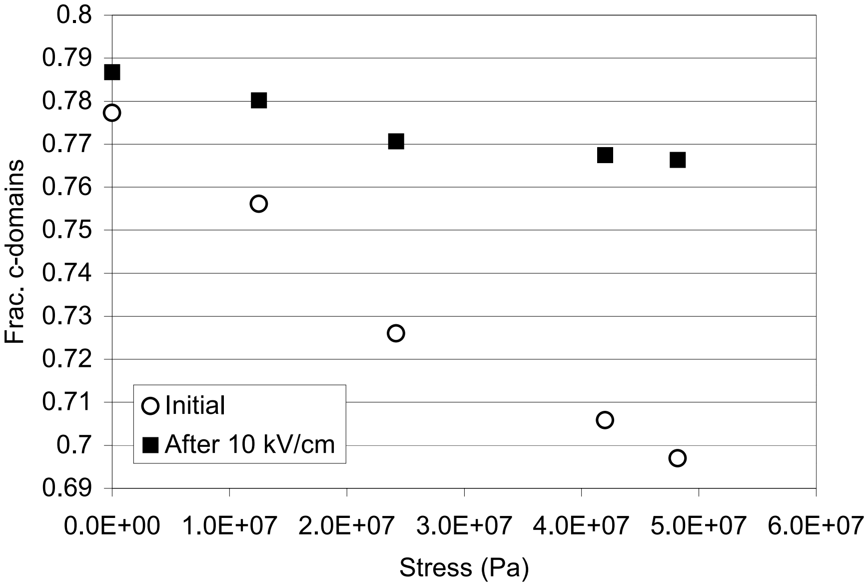

Fig. 2. Domain configurations of standard and Rainbow ceramic devices after poling and during the application of a 10 kV/cm electric field. Results obtained by in-situ XRD measurements of (200) and (002) peak areas. The actuator composition was PLZT 1/53/47 and the grain size was 7.4 μm.

Considering both data sets in Fig. 2, the role of lateral tensile stress in these devices is to alter the initial domain configuration and to only slightly inhibit 90˚ domain switching (a- to c-domains) under an applied electric field. Thus, from one perspective, tensile stress does enhance domain switching in these devices. However, a more complete, and more accurate, description of the extrinsic, 90˚ domain switching response in these devices includes consideration of the domain configuration before and after the application of the electric field.

We have also studied the effect of grain size on domain configuration and switching and the results are presented in Fig. 3. Grain size impacts the nature of the domain configuration in the poled devices, as well as the domain configuration following the application of the electric field. Actuators fabricated from materials with larger grain sizes are better poled, and under field, demonstrate a domain configuration with greater c-domain alignment. These results would be expected based on the ease of domain wall motion that is know to occur in larger grain size materials. However, it appears that there is little influence of grain size on the relationship between 90˚ domain switching and stress magnitude. An analysis of domain switching behavior as a function of grain size is shown in Fig. 4. To first approximation, this figure indicatesthat stress level, and not grain size, dictates 90˚ switching behavior.

3.3 Calculation of effective piezoelectric coefficients

The results presented in Fig. 2 – 4 for domain switching may also be used to calculate effective (extrinsic) d_{31} coefficients for the surface region of the device. If we assume that the extrinsic response is dictated by the strain associated with 90˚ domain switching, we may write the following expression:

$$S_1 = 0.019 * (\text{fraction of domains switched}) \qquad (5)$$

where S_1 is calculated strain, 0.019 represents the crystalline anisotropy between the c and a axes in PLZT 1/53/47 ($c/a = 1.019$),[20] and the fraction of domains switched is obtained from Fig. 4. To describe the strain response of the device in terms of the effective piezoelectric coefficient and the applied field, we may write the following simplified constitutive law:

$$S_1 = d_{31}E_3 \qquad (6)$$

where d_{31} is the piezoelectric coefficient in pm/V. Rearrangement of Eqn. 6 allows for straightforward estimation of the "effective" d_{31} coefficient due to extrinsic effects associated with 90˚ domain switching.

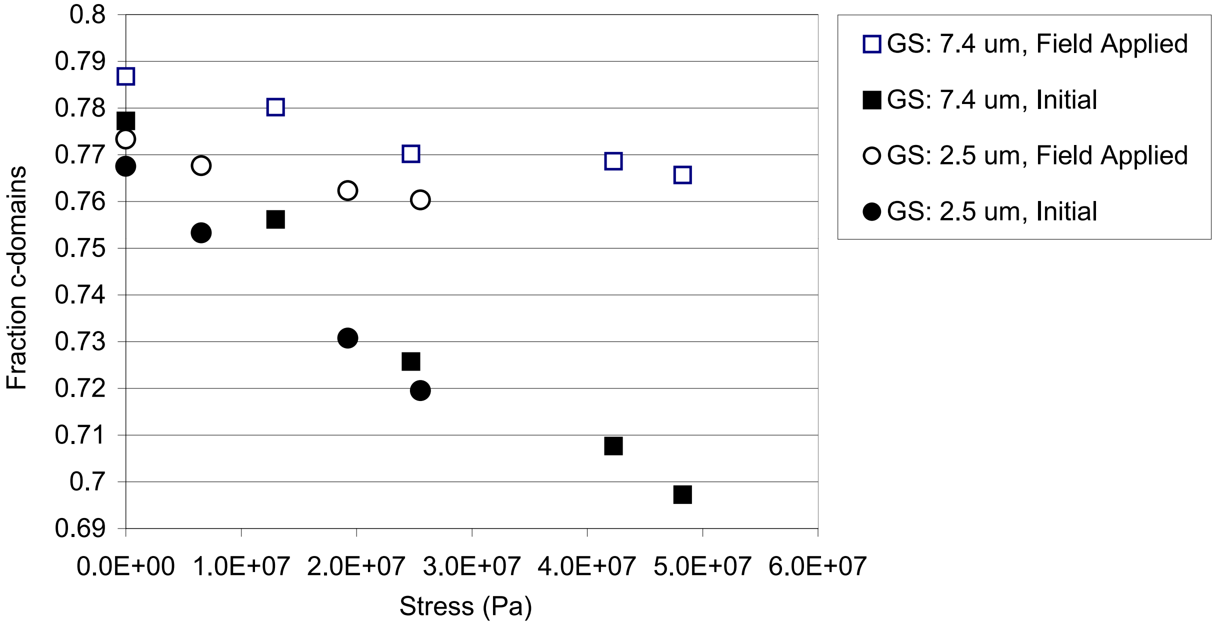

Fig. 3. Grain size effects on domain configuration and switching behavior in PLZT 1/53/47 Rainbow actuators; results shown for poled (initial) devices and devices subjected to a 10 kV/cm applied electric field.

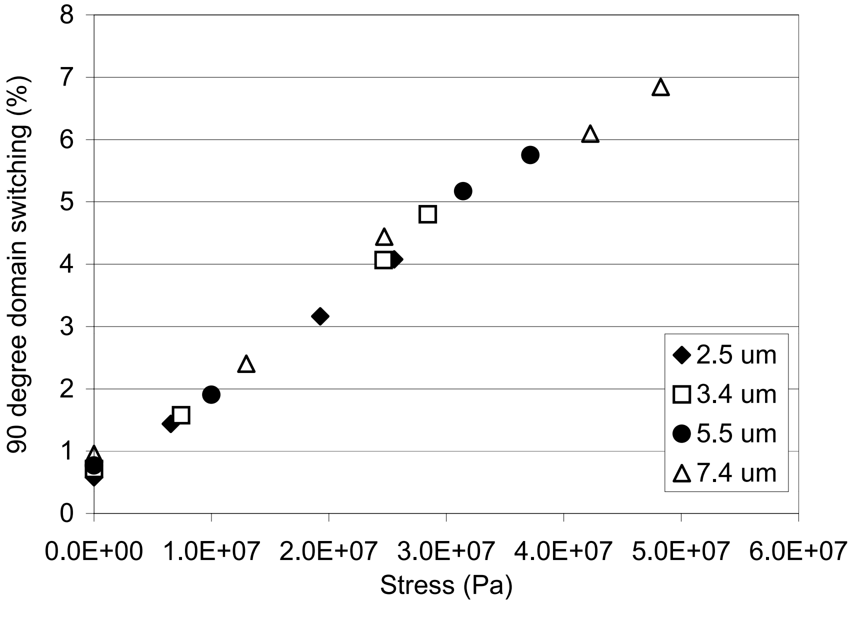

Fig. 4. 90° domain switching (a- to c-domain) as a function of stress in Rainbow actuators fabricated with grain sizes from 2.5 to 7.4 μm.

The results of these calculations are shown in Fig. 5 for Rainbow actuators prepared with a grain size of 7.4 μm. Although these devices show minimal 90° domain switching (only up to ~ 7% for the highest stress level), the impact on the effective d_{31} coefficient is pronounced. Under normal operational conditions (low field, poled polycrystalline ceramic), it is frequently assumed that the intrinsic and extrinsic contributions to electromechanical response are of similar magnitude. Since the reported value of d_{31} for PLZT 1/53/47 is – 271 pm/V, the expected extrinsic contribution would be approximately – 135 pm/V. The measured d_{31} value of approximately – 190 pm/V for the conventional ceramic actuator is close to the value expected. Further, when allowance is made for the large applied electric field, the measured value seems quite reasonable. With increased stress levels, the extrinsic contribution to electromechanical response becomes more important. Although 90˚ domain switching only occurs for 7% of the a-domains, because of the large anisotropy associated with switching, d_{31} coefficients that approach – 1400 pm/V are obtained.

Since these measurements only represent what is occurring in the surface region of the devices, more modest "average" d_{31} values would be expected for the piezoelectric layer overall. However, the effective piezoelectric coefficient values that were determined appear to be in agreement with previous estimates.[15] Further, the results confirm the key role of stress on the electromechanical response of these devices and begin to quantify the magnitude of the non-linearity in the piezoelectric coefficients.

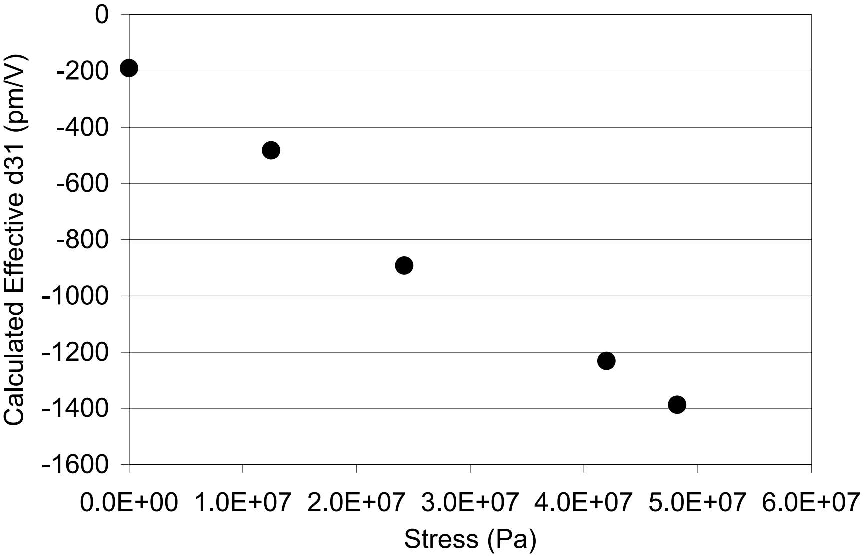

Fig. 5. Estimated effective d_{31} coefficients of Rainbow ceramics prepared with different surface stress levels; extrinsic (90˚ domain switching) response only.

4. CONCLUSIONS

An x-ray diffraction method was used to characterize domain configuration and switching effects in stress-biased Rainbow actuators. The focus of these investigations was the surface region of the devices due to the limited penetration of the x-ray beam in the lead-based perovskite studied. One objective was to begin to quantify the effects of stress on extrinsic electromechanical response. A second objective was to determine whether domain configuration effects, or more simply, enhanced domain switching, was responsible for the improved performance of stress-biased Rainbow and Thunder™ devices. By characterizing domain configuration in poled devices and devices subjected to externally applied electric fields, we have shown that the stress contribution to the improved performance of these devices is due to an altered initial domain configuration in the poled device coupled with minimal suppression of the 90˚ switching response. While stress contributions to performance have previously been referred to as "stress-enhanced domain switching," this definition inadequately describes, as well as oversimplifies, the actual response mechanism. By measuring the domain configuration and switching behavior in devices prepared with different stress levels, it was possible to quantify the resulting effective piezoelectric coefficients. Extrinsic electromechanical response that is more than seven times greater than that observed for conventional piezoelectric ceramics was observed. By studying devices with different stress levels, the electromechanical response of underlying regions within the piezoelectric layer of Rainbow devices fabricated for maximum displacement response (i.e., devices with the highest tensile stress levels at the surface) may be inferred. Studies of the response of piezoelectric layers under lateral compressive stresses remain to be completed for a more thorough understanding, and prediction, of device performance. Studies are also in progress to quantify the intrinsic electromechanical response of the devices under these different stress levels and to elucidate polarity effects.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. Gene H. Haertling for enlightening technical discussions. This research was sponsored by the South Carolina NASA EPSCoR office through award # NCC5-413.

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