Ultrahigh superelastic and actuation strains in BaTiO3 crystals by reversible electromechanical domain switching

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Abstract

Reversible non-180^0 domain switching in ferroelectrics, although could generate large strains, is difficult to realize under electric fields and has never been accomplished by stresses. We show in a specially poled BaTiO3 crystal cube, large and electric-field-tunable superelastic strains up to 0.85% can be realized via compression with a bias field, which is promising for advanced damping applications. When keeping the compression and making the electric field cycling, an actuation strain of 0.93% has been obtained at 800V/mm. The large superelastic/actuation strains are both caused by reversible 90^0 domain switching which can be depicted by an incremental switching criterion.

Key words: Domain switching, barium titanate, superelasticity, acutation.

It is well known that in shape memory alloys (SMA), reversible martensitic phase transformations can be realized via stress loading/unloading or heating/cooling, which will lead to very large superelastic or actuation strains [1]. Theoretically, superelasticity (SE) via reversible ferroelastic domain switching may also appear in ferroelectrics by stress loading/unloading but should be under a bias electric field because in that case the energy profiles for different domains can be changed and then the driving force for reverse switching could be provided. However, such behavior has never been observed so far. Ferroelectrics would get much more wide applications if it could also exhibit large SE.

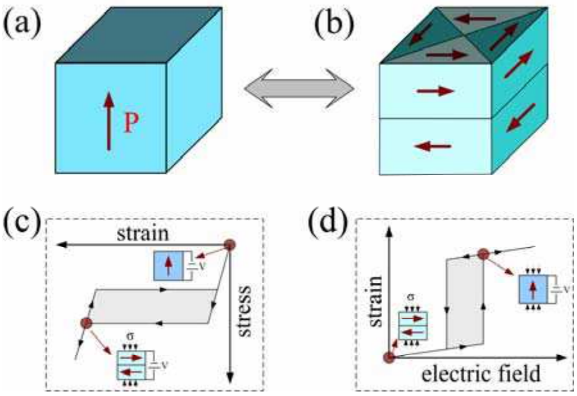

Fig 1. The principle of realization of large superelasticity and actuation in a poled tetragonal ferroelectric crystal via reversible 90^o domain switching under electromechanical loading. (a) Single domain state of a completely poled crystal; (b) Multiple domain configurations after complete compression depolarization; (c) Realization of large superelasticity during compression loading/unloading with a positive dc bias electric field; (d) Realization of large actuation under uni-polar electric field with a pre-compression.

The principle of realization of large superelasticity (SE) and actuation in ferroelectrics is illustrated in Fig.1, where the reversible 90^0 domain switching in a completely poled tetragonal crystal is accomplished by uni-polar electric field loading and compression loading. To realize the domain states in Fig.1a and Fig.1b, we use a [001] oriented BaTiO3 crystal cube with the dimension of 5*5*5mm3 and the two opposite 5*5mm2 faces spread with silver electrodes for electric loading. We then conduct compression depolarization of the poled BaTiO3 crystal to reach the multiple "a" domain state as in Fig.1b. During testing, the maximum compressive stress is limited to 15MPa as a higher stress is apt to break the sample frequently. After compression depolarization, the specimen is re-poled by a uni-polar electric field of 800V/mm.

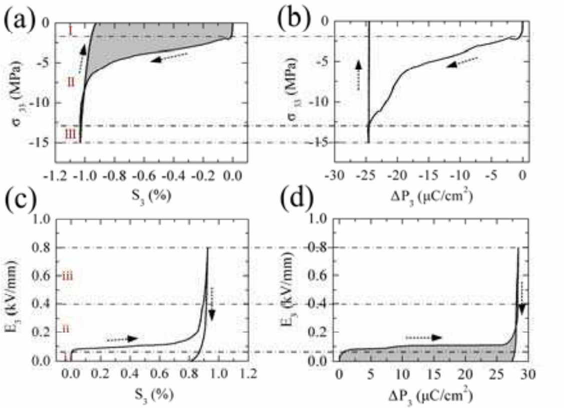

Fig.2 90^0 domain switching curves under compression loading/unloading and subsequent electric loading/unloading. (a) stress-strain curves; (b) stress-depolarization curve; (c) electric field induced strain curve; (d) electric field induced polarization curve

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The stress-strain curve and stress-depolarization curve of the poled BaTiO3 crystal are shown in Fig.2a and Fig.2b where the loading process can be divided into three stages. During one stress loading/unloading cycle, the dissipated energy density is measured to be 36 kJ/m^3. The strain and polarization responses during electric re-poling after compression are shown in Fig.2c and Fig.2d. The dissipated energy density during the electric loading/unloading cycle is about 28 kJ/m^3, among which about 26 kJ/m^3 is associated with 90^0 domain switching, obviously lower than that of 36 kJ/m^3 during compression loading/unloading. This may indicate that considerable amount of strain energies were stored in the 90^0 domain walls after compression depolarization and it will be released to assist the 90^0 domain switching during electric re-poling.

Based on the compression depolarization and electric re-poling testing, we then proposed a quasi-static incremental switching criterion for 90^0 domain switching as:

$$\pm\left[(\sigma_{33}S_0 - E_3P_s)\cdot\Delta f - \Delta W_{sto}\right] = U_{90}^{D}(f)\cdot\Delta f \qquad (1)$$

Where the “+” and “-“ in front of the parentheses are for the 90^0 domain switching from Fig.1a to Fig.1b and its reverse, respectively; W_{sto} is the strain energy stored in the 90^0 domain walls and ΔW_{sto} is its increment; Δf is the volume fraction increment of 90^0 domain switching; $U_{90}^{D}(f)$ means that the energy barrier (per unit volume) for 90^0 domain switching depends on the volume fraction (f) of switched domains and then the hardening effect can be taken into account.

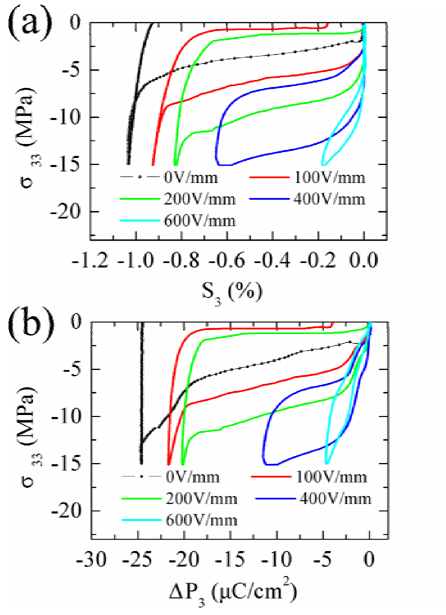

Fig 3. Stress-strain curves (a) and stress-depolarization curves (b) of poled BaTiO3 crystals with different levels of positive dc bias electrical fields

We then conduct compression depolarization testing with a series of dc bias fields (Edc=100, 200, 400 and 600 V/mm) along the poling direction. The obtained stress-strain curves and stress-depolarization curves are shown in Fig.3. When the Edc reaches at or above 200V/mm, both the strain and polarization during the stress loading/unloading circle is completely recoverable, i.e., the crystal shows SE in this case. As expected, the recoverable strain and polarization decrease as Edc increases, with the maximum values (at Edc=200V/mm) of 0.85% and 20μC/cm^2, respectively. When Edc reaches 600V/mm, the maximum recoverable strain drops to only about 0.2% and the recoverable polarization 5μC/cm^2.

We finally conducted the actuation testing of the poled BaTiO3 crystals under a cyclic uni-polar electric field of 800V/mm at 0.1Hz with the pre-stresses of 0, 1, 2, 4, 6, 8 and 10MPa, respectively, and the results were shown in Fig.4. When the pre-stress is very low (<1MPa), little domain switching occurs by the compression depolarization and thus little actuation strain can be obtained. The achievable actuation strain under 800V/mm is 0.33% with the pre-stress of 2MPa, 0.53% at 4MPa and reach its maximum of 0.93% when the pre-stress is 6MPa, which is larger than all previously reported reversible strains in BaTiO3 [2,3] and may also be the largest actuation strain in existing ferroelectric crystals under the same level of electric field [4]. Referring to Fig.2a and 2b, it can be seen that 6MPa can depole the crystal nearly completely and it is just near the inflection point between the first and second hardening stages (see more clearly in Fig.2b). When the pre-stresses increases to be 8MPa and 10MPa, the achievable actuation strains at 800V/mm drop to 0.82% and 0.68%, respectively, which may indicate that some of the twinned domains became more stabilized under higher compression and are more difficult to switch during the re-poling process. Furthermore, the obtained ultrahigh actuation strain in this way has a quick response and is quite stable [5], which would be very attractive in actuation areas.

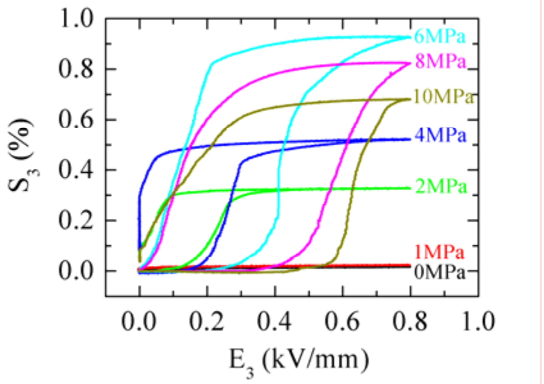

Fig.4 The actuation strain curves of BaTiO3 crystals under a uni-polar electric field with different levels of pre-stresses

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