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Coercive fields in ferroelectrics: A case study in lithium niobate and lithium tantalate

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The experimentally measured coercive electric fields for domain reversal in ferroelectrics are typically many orders of magnitude lower than the estimates from phenomenological free-energy theory. This letter specifically investigates the influence of polarization gradients at pre-existing 180° domain walls in ferroelectrics on coercive fields for domain wall motion. It is shown that the ratio of theoretical coercive field without and with a preexisting domain wall is directly proportional to the ratio x_o/a , where a is the lattice parameter and $2x_o$ is the polarization wall width. This factor is 7.5–45 for a 20–120 nm wall width, the latter width determined here as the experimental upper limit for polarization wall width in lithium tantalate. © 2002 American Institute of Physics. [DOI: 10.1063/1.1470247]

Why are the experimentally measured coercive fields for domain reversal in ferroelectrics many orders of magnitude smaller than theoretical estimates? The question mirrors a similar one asked with regard to mechanical strength of materials, namely, why is, for example, the measured critical resolved shear stress in materials (e.g., $\sim 10^{10}$ N/m² in metals) many orders of magnitude lower than experimentally observed deformation shear stresses (e.g., $\sim 10^6$ N/m² in metals).¹ This discrepancy in mechanical strength is explained by the presence of dislocations in materials. The discrepancy in ferroelectrics has primarily been discussed through the recognition that while the simple estimate of intrinsic coercive fields from the Landau–Ginzburg (LG) theory does not account for the presence of domain walls or other defects, *real* single domain crystals nonetheless possess defect sites where it is easier to nucleate domains.^{2,3} Once a domain nuclei exists, the Miller and Weinreich theory⁴ explains the effective lateral motion of pre-existing, *atomically sharp* domain walls, in terms of the probability of overcoming an energy barrier, U , to preferentially nucleate small wedge-shaped domains *adjoining* the wall. Though not uniquely defined, one can consider the maximum electric field, $E = dU/dP$ required to completely overcome the steepest climb out of the energy well, U versus P (polarization), as an estimate of the intrinsic coercive field. Domain wall pinning at physical defects can also contribute to the experimental coercive fields, which manifests as the threshold field for wall depinning.⁵

In this letter, we explore the theoretical estimate of coercive field from the LG theory *in* the presence of pre-existing 180° domain walls with *finite* wall widths. Specifically, we wish to show that a finite polarization gradient at the domain wall can *lower* the *local* intrinsic coercive fields adjacent to the wall, thereby facilitating *local* wall motion.

The problem is treated generally for any ferroelectric with a second-order phase transition, and two possible antiparallel domain states. As specific examples, we consider ferroelectric lithium niobate (LiNbO₃) and lithium tantalate (LiTaO₃), which are technologically important,^{6,7} and typically contain pre-existing domain nuclei in nominally single-crystal, single-domain crystals.^{8,9}

Let us first calculate the theoretical coercive field for 180° domain reversal in these materials. The Ginzburg–Landau–Devonshire free energy per unit volume, G , of a ferroelectric with a second order phase transition is given by²

$$G = -\frac{\alpha_1}{2}P^2 + \frac{\alpha_2}{4}P^4, \quad (1)$$

where the order parameter is the polarization, P . One can calculate the effective α_1 and α_2 coefficients from the dielectric constant ϵ_{33} and the homogeneous spontaneous polarization, P_s as $\alpha_1 = 1/(2\epsilon_{33})$ and $\alpha_2 \sim \alpha_1/P_s^2$. These values at room temperature are $\epsilon_{33} = 43.5\epsilon_o$ and $P_s = 0.55$ C/m² for LiTaO₃, $\epsilon_{33} = 30\epsilon_o$, $P_s = 0.75$ C/m², for LiNbO₃. The equation of state, $E = dG/dP$ defines the theoretical P versus E hysteresis loop. The coercive field $E = E_c$ is defined as the turning point $(dE/dP)_{E=E_c} = 0$, which determines the polarization P_c at the coercive field as $P_c = \pm \sqrt{\alpha_1/(3\alpha_2)}$. Substituting this value back in the equation of state yields the coercive field E_c as

$$E_c = \pm \frac{2}{3\sqrt{3}} \sqrt{\frac{\alpha_1^3}{\alpha_2}} \sim \pm 0.385\alpha_1 P_s. \quad (2)$$

Substituting for the values of α_1 and α_2 in Eq. (2), the intrinsic coercive fields are $E_c \sim 2750$ kV/cm (LiTaO₃) and $E_c \sim 5420$ kV/cm (LiNbO₃). In contrast, the coercive fields reported in literature for near-stoichiometric LiTaO₃ is

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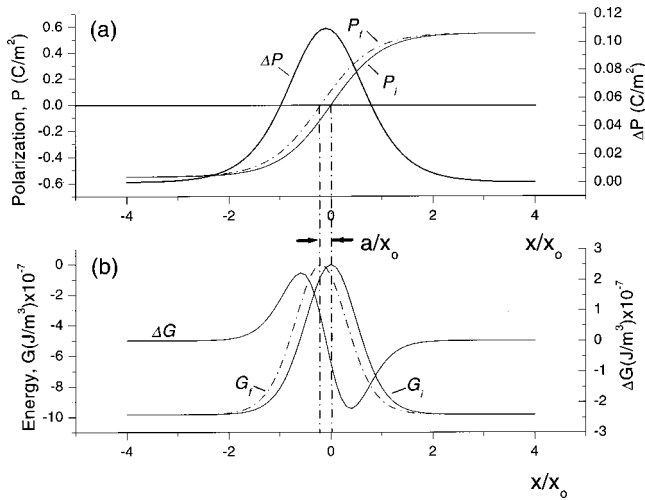


FIG. 1. (a) A plot of the polarization gradients [Eq. (3)], P_i (initial), P_f (final), and $\Delta P = P_f - P_i$, of a 180° domain wall in LiTaO_3 after movement of the wall by an amount a under the influence of an external field E in the $+x$ direction. (b) The corresponding polarization energies [Eq. (1)], G_i , and G_f , and $\Delta G = G_f - G_i$ are also shown. The normalization term x_0 is the domain half width according to Eq. (3).

$\sim 17 \text{ kV/cm}$,¹⁰ for near-stoichiometric LiNbO_3 is $\sim 40 \text{ kV/cm}$,¹¹ and for congruent compositions of both materials is $\sim 210 \text{ kV/cm}$.^{10,11}

In the following analysis, we now consider the presence of pre-existing 180° domain walls with a *finite* wall width of polarization gradient, $P(x)$ defined as²

$$P = P_s \tanh(x/x_0), \quad (3)$$

where P_s is the spontaneous polarization, x is coordinate normal to the wall and $2x_0$ is the characteristic wall width. This polarization, P and the associated free energy, G [from Eq. (1)] is plotted in Fig. 1(a) for LiTaO_3 . Now we ask the following question: What is the free energy change ΔG when such a domain wall moves by one lattice parameter, $\Delta x = a$, resulting in a change of polarization and energy at *every* location x by amounts $\Delta P = P_f - P_i$ and $\Delta G = G_f - G_i$? (Subscripts i and f stand for initial and final states, respectively, as shown in Fig. 1). One can numerically calculate these quantities. On the other hand, if one assumed that a/x_0 is small, then, one can analytically evaluate $\Delta P = (dP/dx)\Delta x$ from Eq. (3). The corresponding free energy change is calculated as $\Delta G = (\partial G/\partial P)\Delta P$, using Eq. (1) and ΔP . For example, from Fig. 1, it is clear that for the wall to move in the $-x$ direction, there is a positive energy barrier, ΔG that the external field, $+E$ has to overcome, which is less than the original energy barrier, G for a graded wall. The minimum external field required to overcome this barrier is therefore, the steepest slope of the energy well ΔG versus P , i.e., $E'_c = (-d(\Delta G)/dP)_{\text{max}}$. This occurs at the wall center ($x=0$). The negative sign reflects the negative slope of ΔG versus P at the wall center under a positive field $+E$ (see Fig. 1). The coercive field for domain motion can therefore be simplified at the wall center as

$$E'_c \sim P_s \alpha_1 a/x_0, \quad (4)$$

where $K = P_s \alpha_1 a$ was determined as 0.368 V for LiTaO_3 and 0.726 volts for LiNbO_3 . Clearly, the coercive field contribution for this type of domain wall motion is inversely

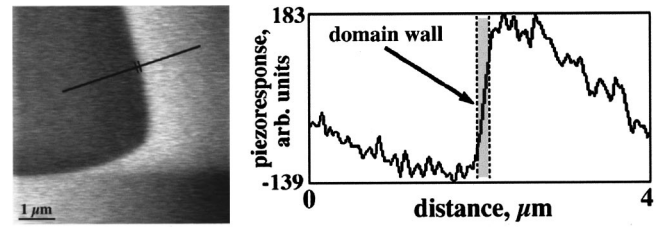


FIG. 2. First harmonic piezoresponse signal image (left-hand side) of one vertex of a triangular 180° domain in a congruent LiTaO_3 crystal using a scanning probe microscope. Polarization is normal to the image plane. The cross section profile of the piezoresponse signal across the domain wall (i.e., along the black line in the image) is shown on the right-hand side. The imaging voltage of 5 V , 10 kHz was applied using a standard Au-coated Si_3N_4 cantilever with a spring constant of 0.1 N/m and a resonant frequency of 34 kHz . The probing tip with an apex curvature radius of about 20 nm was in mechanical contact with the sample surface during the measurements (repulsive force regime). The image scan rate was 0.5 Hz .

proportional to the wall width, $2x_0$. Out of curiosity, if we presently ignore other mechanisms, and calculate the values of the equivalent domain wall widths, x_0 required to account for experimentally measured coercive fields in near-stoichiometric lithium niobate¹¹ and lithium tantalate,¹⁰ we arrive at the *upper limits* of domain wall widths of $x_0 \sim 216 \text{ nm}$ for near-stoichiometric LiTaO_3 and $x_0 \sim 181 \text{ nm}$ for near-stoichiometric LiNbO_3 . For congruent compositions, these widths would be 17.5 nm (LiTaO_3) and 34.5 nm (LiNbO_3).

Are these *polarization* widths at all reasonable? On the one hand, first-principle calculations on 180° domain walls suggest that they may be just a unit cell ($\sim 0.4 \text{ nm}$) wide.¹² On the other hand, recent work on domain walls in LiNbO_3 and LiTaO_3 show unexpectedly wide regions of strain¹³ and optical birefringence (extending over micrometers) around individual domain walls, which are strongly correlated with the presence of nonstoichiometry in the crystal.⁵ Further, we have recently conducted *in situ* x-ray synchrotron experiments of individual domain wall strains under external fields in lithium niobate single crystals, which clearly show that extended domain wall strains develop over $10\text{--}50 \mu\text{m}$ around the wall at fields an order of magnitude below experimental coercive fields. One naturally enquires if the corresponding polarization gradient at the domain walls might be broadened as well in these materials due to nonstoichiometry or in the presence of an external field. A piezoelectric scanning probe microscopy image of domain walls in congruent LiTaO_3 is shown in Fig. 2. The principle of domain imaging in the piezoresponse mode is described in detail elsewhere.¹⁴ Figure 2 also shows a cross section profile of the piezoresponse signal across the domain wall (i.e., along the black line in the image). Due to possible artifacts related to sample leveling, we refer not just to the distance between maximum and minimum values of the piezoresponse signal (which is $\sim 400 \text{ nm}$ wide) but also to the actual image of the wall, which was found to be about 120 nm . The best resolution that could be expected can be as small as the radius of the tip-sample contact area, i.e., of the order of several nanometers. However, the observed widths should be treated as upper limits until a detailed modeling of the image is performed.

In addition to wall broadening, other factors can contrib-

ute to coercive fields. Taking some these into account, we can therefore write the net experimentally observed coercive fields as,

$$E_c = E'_c - E_{sc} + E_{\text{defect}}, \quad (5)$$

where E_{sc} is the space-charge field, and E_{defect} is the bulk dipolar defect field. Surface polarization relaxation¹⁵ can give rise to a polarization gradient and hence a space-charge layer near the crystal surface as recently observed in LiNbO_3 .^{16,17} Even if the space-charge density (charge/area) in this layer is $\sigma \sim 10^{-2} - 10^{-3} P_s$, the space-charge field, $E_{sc} \sim \sigma/\epsilon$ would be of the *same* order of magnitude as the experimental coercive fields in lithium niobate and tantalate, and will aid in domain wall motion. The dipolar defects, which stabilize domains, such as defect complexes of Ta or Nb antisites and lithium vacancies proposed in recent literature,¹⁰ will give rise to *equivalent* defect fields, E_{defect} ,¹⁸ which tend to increase the coercive fields. As noted in Refs. 10 and 18, the defect field E_{defect} is not an existing electric field in the material. Rather, it is a formal equivalent to the energetic difference between the two domain states $+P_s$ and $-P_s$, one stabilized by the dipolar defects by an amount of energy $-E_{\text{defect}} \cdot P_s$ and another raised in energy by the same amount. Therefore, a very likely scenario for near-stoichiometric crystals, ($E_{\text{defects}} \sim 0$) is that the experimentally measured coercive field, E_c , may be equal to the net sum of the first two terms in Eq. (5) (and perhaps further contributions arising from other types of defects). Since the stoichiometric composition of LiTaO_3 has a coercive field of ≤ 17 kV/cm, the defect field in the congruent composition would be $\geq 210 - 17 = 193$ kV/cm, which clearly dominates the experimentally observed coercive fields (210 kV/cm) in congruent compositions.

The important conclusion of this letter is that, compared with theoretical estimates, the *local* coercive field in the presence of a polarization gradient at a 180° domain wall is

reduced by a factor of $\sim 0.385 x_o/a$, where a is the lattice parameter and $2x_o$ is the wall width. More generally, one could expect that any significant polarization fluctuation in a ferroelectric crystal, not just limited to a domain wall, would potentially reduce the coercive field for domain reversal in that region. The precise experimental determination of *polarization* wall width (particularly in the presence of small amounts of nonstoichiometry and under external fields) is central to resolving the issue of theoretical coercive fields in ferroelectric crystals.

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