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DYNAMICS OF INCOHERENT DOMAIN WALLS IN GADOLINIUM MOLYBDATE

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By optical method with stroboscopic illumination the arising, dynamics and interaction of incoherent domain walls under electric field in gadolinium molybdate are investigated. The difference of start fields for plane domain walls and tops of spike domains are explained by the dependence of internal field on the wall upon the domain shape. The influence of geometrical parameters of zigzag domain walls on its start field value is considered.

INTRODUCTION

It is known that in improper ferroelectric-ferroelastics exists a strong anisotropy of surface energy of uncharged 180° domain walls. Due to this fact the orientation of coherent domain walls coincides with twinning planes.1 Switching of polarization under weak field is accompanied by sidewise motion of planar domain walls. However, in GMO during the switching it can arise and even be stable the nonplanar walls of another orientations, the so-called incoherent domain walls.2 These walls limit the lense and blade-like domain3,4 and also form domain walls having a zigzag configuration (ZDW).5,6 It was shown that polarization reversal in strong field is accompanied not only by the motion of existing planar and incoherent walls but also by the mutual transformation of domain walls.4,7

EXPERIMENTAL METHOD

The rectangular plates of GMO samples with carefully polished surfaces covered by the transparent electrodes of Sn and In oxides were used.

The polarization in the samples was switched by applying of square alternating-sign pulses of electric field (front duration 0.2 μs). In order to observe the domain structure during polarization reversal pulse enlightenment was used (light pulse duration was less than 1 μs). At temperature less than 380 K in whole range of using fields (up to 2 × 10⁶ V/m) the momentary domain patterns reproduced from cycle to cycle, so it was possible to use stroboscopic method.

The spike domains were created in the samples by electrical or mechanical methods before measurements. In the first case previously the stripe domain of 20–30 μm width had been formed in the sample and mechanically fixed at one edge by glue. Under the constant electric field stripe domain transformed into spike one and after being in this state during 30–60 min it became stable even without
field. In the other case spike domain was created in single-domain sample by local mechanical affect, which stopped only after spike foot fixing.

EVOLUTION OF DOMAIN STRUCTURE IN ELECTRIC FIELD

The behaviour of domain structure evolution in GMO is qualitatively changed with increasing of temperature and field strength. One can distinguish four steps in observed changing of domain structure during complete switching from single-domain state:

1. Arising of spike domains with nonplanar walls.
2. Enlargement of spike domains and forming of stripe domains.
3. Growth of stripe domains as a result of sidewise motion of planar walls.
4. Coalescence of domains and disappearance of remanent domains with disadvantageable orientation.

At room temperature in the fields up to $2 \cdot 10^5$ V/m the reciprocal switching time linearly depends upon the field strength:

$$t_s^{-1} \sim E_{ex} - E_{st}$$  \hspace{1cm} (1)

where $E_{st}$ — start field.

On the exceeding some critical field $E_{cr}$ the field dependence of switching time qualitatively changes and can be described in this field range by the following expression:

$$t_s^{-1}(E) = t_s^{-1}(E) \exp(-\alpha/E)$$  \hspace{1cm} (2)

where $\alpha$ — activation field.

The change of field dependences is accompanied by the essential change of the character of domain kinetics. Under the fields close to $E_{cr}$ during switching a lot of planar domain walls have been formed due to arising of spike domains near the edge and their growth to the opposite side of the sample. Simultaneously, spike and lense domains oriented in orthogonal directions are arised. It has been observed anomalously strong deviation from coherent directions, achieving 90 degrees.

DYNAMICS OF THE SPIKE DOMAINS

Detailed investigation of domain dynamics in electric field showed that character of motion of spike domain top was qualitatively similar to the motion of planar domain wall. One could observe the slowing of the top motion after its shift from initial state (Figure 1) and spontaneous backward switching after the field was turned off.

The field dependence of spike domain top motion is as follows:

$$V_{sp}(E) = \mu_{sp}(E - E_{st})$$  \hspace{1cm} (3)

It must be noted that mobility $\mu_{sp}$ and start field $E_{st}$ of spike top essentially depends on sample sizes, prehistory and methods of fixing. Usually they are equal to $(0.7-1.2) \times 10^{-4}$ m$^2$/V·s and $(3.0-4.4) \times 10^5$ V/m respectively.
The velocity of the spike top for $E = 5 \cdot 10^5$ V/m is equal to 40–50 m/s, which is more than 30–50 times higher than velocity of planar wall in the same sample.

Comparison of field dependences of velocity for planar wall and spike domain top (Figure 2) shows that start field for spike domain is on $(8–9) \cdot 10^4$ V/m lower than for planar wall and mobility is 30 times higher.

To explain these peculiarities it must be taken into account the fact that motion of spike domain top is similar to the motion of planar walls limiting stripe domains considered in [10]. We assume that in fully screening sample for very narrow domain internal field on domain wall is equal to external one: $E_{ib} = E_{ex}$. In the case of
moving spike domain it's true for the regions closed to the spike top. Thus, the field dependence of spike top velocity has to define by following expression:
\[ V_{sp}(E) = \mu_{sp}(E - E_{th}) \] (4)

where \( E_{th} \) - threshold field for planar wall.

At the same time in the case of planar wall for large shifts from initial state:
\[ V(E) = E_{sc} - (E_{ex} + E_{th}) \] (5)

where \( E_{sc} \), the screening field.\(^9,\(^10\)

So, in an agreement with experiment the start field for planar wall must be larger than for top of spike domain on the value of \( E_{sc} \).

FORMAND OF ZIGZAG DOMAIN WALLS IN ELECTRIC FIELD

The investigation of domain dynamics in GMO showed that ZDW may arise during switching under electric field. Such types of walls were observed in many crystals with ferroelastic properties\(^11\)\textsuperscript{-14} and even GMO,\(^5,\(^6\) but usually they were created by lending mechanical stress.

In our case ZDW arised under the action of nonuniform electric field or during the interaction of spike domains with orthogonal planar walls.

For obtaining of ZDW in nonuniform electric field the half of rectangular sample was covered by electrode and then the ensemble of spike domains orientated perpendicularly to the electrode boundary was formed. The foots of spikes were mechanically fixed at incovered edge of sample.

After applying of electric field spike domains had grew to the opposite side of the sample and transformed into stripe domains (Figure 3a). Further domain walls near the edge of electrode had bent (Figure 3b). When deviation from coherent direction achieved a critical value (near 20° at \( T = 300 \) K) at that place arised the

FIGURE 3 Formation of ZDW in nonuniform electric field. a) photos of momentary patterns (delay time from the front of switching pulse: A, 20 \( \mu s \); B, 50 \( \mu s \); C, 75 \( \mu s \)); b) schematic drawing.
spike and wall deviation decreased. This process repeated over and over again up to full switching under the electrode (Figure 3c). ZDW arising as a result of this process was stable and had an aperture $A_0 = 90-150 \, \mu m$ and period $p = 15-20 \, \mu m$. Relation between parameters of such ZDW are in good agreement with expression, obtaining in References 15-17: $A_0 \sim p^{3/2}$

DYNAMICS OF ZIGZAG DOMAIN WALLS

For ZDW the same peculiarities of the motion as for planar walls and spike domains were observed. In weak field its motion was quite nonuniform up to stop in a new position. After the field pulse was switched off ZDW spontaneously returned to initial position. It must be noted that behaviour of ZDW also essentially depended on the prehistory of the sample.

For terminal motion of ZDW teeth tops the field dependence of velocity is described by usual law:

$$V_z(E) = \mu_z(E - E_{st})$$

Mobility of ZDW teeth tops is quite high but a little less than for spike top. Its start field depends on ZDW sizes but in any case is more than for planar domain wall and less than for spike top (Table I).

Recently\textsuperscript{18} it was mentioned that start field depends on geometrical parameters of ZDW. For ZDW of 1 mm aperture the value of $E_{st}$ is closed to the value for single spike. The decreasing of ZDW aperture leads to the increasing of $E_{st}$, which aspires to the value for planar domain wall.

This feature can be explained by the following way. In the case of large aperture ($A_0 >> L_{sc}$) it's possible to consider the teeth of ZDW as separate spikes, so the field dependence of its top velocity have to be the next:

$$V_z(E) = \mu_z(E_{ex} - E_{th} - E_{fr})$$

In another limit case of small aperture ($A_0 << L_{sc}$) ZDW is similar to planar wall, therefore $V_z(E)$ will describe by the following way:

$$V_z(E) = \mu_z(E - E_{sc} - E_{th} - E_{fr})$$

Thus, with decreasing of aperture and period of ZDW the value of $E_{st}$ have to increase, as we experimentally observe.

On the base of ZDW investigations it was concluded that really ZDW is an ensemble of spike domains, and consequently, a special type of domain structure but not a domain wall. Its stability is determined by the energy advantage of its shape.\textsuperscript{17}

| TABLE I |

<table>
<thead>
<tr>
<th>START FIELD $E_s$ (mT)</th>
<th>MOBILITY $\mu_z$ ($10^{-5} , \text{m}^2 \cdot \text{V} \cdot \text{s}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLANAR DOMAIN WALL</td>
<td>4.71</td>
</tr>
<tr>
<td>SPIKE DOMAIN TOP</td>
<td>3.54</td>
</tr>
<tr>
<td>ZIGZAG DOMAIN WALL</td>
<td>4.17</td>
</tr>
</tbody>
</table>
CONCLUSION

On the base of obtained results we can state the following conclusions:

1. The difference between value of start fields for spike domain tops and planar domain walls is determined by dependence of internal field value from domain shape.

2. It was shown that ZDW can arise during switching in electric field when the deviation of domain wall from the coherent plane became more than some limiting value. In room temperature the limiting angle for incoherent wall is equal to 20 degrees.

3. It was concluded that ZDW really is not a domain wall but a special type of domain structure.

4. Dependence of start field of ZDW teeth tops on parameters of ZDW is qualitatively explained by decreasing of internal field on the teeth tops under decreasing of ZDW aperture.

Finally it’s necessary to draw attention that in any case incoherent (nonplanar) domain walls without external influence are metastable ones. But as a result of screening and pinning effects it can be stable enough at the temperatures far from transition point. So the shape of real stable domain structure depends on its kinetics and usually its energy value is rather far from absolute minimum.

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