Fast reversal process in real ferroelectrics

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FAST REVERSAL PROCESS IN REAL FERROELECTRICS

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Abstract On the base of comparison of domain dynamics and
transient current the applicability of Kolmogorov's model for the
description of current shape in real ferroelectrics is considered. The
influence of electrode edges and inhomogeneity of real samples are
taken into account. The computer modeling of switching process is
carried out. The obtained results can be applied for the
improvement of the description the change of parameters in
Ferroelectric memory devices.

INTRODUCTION
It is known that switching of polarization in ferroelectrics is a result of
arising and growing of domains with preferable polarization direction [1].
Usually this complicated process of domain structure evolution is
investigated through the measuring of some indirect integral parameters
[2]. The most informative method is a registration of transient current
[3] from which one can calculate some parameters of domain dynamics
[4]. However, the theoretical analysis of transient current shape is based
on Kolmogorov's model, which was developed from infinite homogeneous
medium [5]. The present paper is devoted to the clarification of
applicability of this model for real ferroelectric samples. To solve this
problem we have carried out the direct observation of domain dynamics
and also the measurement of transient current in model crystal.

EXPERIMENT
It is known that fast polarization reversal with switching time less than
100 nsec is the base for creation of modern ferroelectric memory.
Unfortunately, it is impossible to observe directly the fast domain
dynamics in thin films, which is why we have studied as a model the
single crystal plate of uniaxial ferroelectric lead germanate $\text{Pb}_5\text{Ge}_3\text{O}_{11}$. Domain structure of this ferroelectric is quite simple and consists of 180° optically distinguished domains. With the help of pulse polarized light we observed the momentary domain configurations with high space and time resolution.

The investigated samples were plates of few hundreds microns thickness cut perpendicular to polar axis and coated by transparent electrodes after fine mechanical working.

The pulse nitrogen laser was used as a light source. Its ultraviolet emission had been transformed into green light by rodamin 6G. Pulse light duration was less than 10 nsec.

The polarization was switched under the action of alternating—sign square voltage pulses. It was found that under this condition domain structure changed repeatedly in every cycle of switching, so we had the opportunity to use stroboscopic method. Besides the registration of momentary domain patterns we measured the transient currents.

DOMA IN STRUCTURE DYNAMICS
It is known that domain dynamics in lead germanate — essentially depends on electric field strength [6]. In weak fields (less than $2\times10^5\text{V/m}$) after applying the voltage only few domains then grew by the sidewise motion of domain walls (Fig. 1). In strong fields (more than $3\times10^5\text{V/m}$) the switching is achieved by arising a lot of through domains and forming shapeless domains after its coalescence (Fig. 2) All these peculiarities can be explained supposing that the nuclei (in thermodynamic sense [7] of various dimensions take part in switching process [8]. In weak fields one—dimensional nuclei occur on the steps of domain walls. This mechanism leads to the layer after layer growth of domains. In strong fields there are both two—dimensional nucleation on domain walls which provides isotropic growth of domains and three—dimensional nucleation which leads to the formation of new domains.

One would think that further increasing the field must lead only to the increase of concentration of new domains, but as we have found, it is not so. In fact, in superstrong fields (more than $1.5\times10^6\text{V/m}$) we have observed qualitatively different character of switching (Fig. 3).
FIGURE 1  Evolution of domain structure during polarization reversal in weak field ($E = 1.8 \times 10^5$ V/m); Delay time from the front of switching voltage pulse: a - 2.5 ms; b - 4 ms; C - 6 ms; d - 9 ms.

FIGURE 2  Evolution of domain structure during polarization reversal in strong field ($E = 1.1 \times 10^6$ V/m); Delay time from the front of switching voltage pulse: a - 0.5 ms; b - 0.7 ms; c - 0.9 (ms); d - 1.1 ms.
FIGURE 3 Evolution of domain structure during polarization reversal in superstrong field \( (E = 1.9 \times 10^6 \text{ V/m}) \); Delay time from the front of switching voltage pulse: a – 10 mcs; b – 15 mcs; c – 30 mcs; d – 49 mcs.

In this field region as in weak fields prevails the sidewise motion of the walls, but detailed investigations show that mechanism of this motion qualitatively differs from the one observed in weak fields (Fig. 4).

FIGURE 4 Chain-like domain structure arising as a result of correlated nucleation near the moving domain wall in superstrong field.
Near the wall appears a lot of new small domains which organize a specific chain-like structure. As a result of correlated nucleation these arising domains are growing and coalescing with parent domain. Then a new chain appears and this process repeats once again.

It is necessary to draw attention to some more peculiarities of domain structure evolution during switching. Firstly, the behavior of domain structure essentially depends on the quantity and space distribution of nucleation sites and residual nonthrow domains because they determine the number of newly arising domains. Secondly, the switching always starts at the electrode edges. This boundary effect is very important in real samples of small surface area when switching is achieved through the sidewise wall motion (in weak or superstrong field). Thirdly, the interaction of walls of growing domains when they are reproaching each other is observed. In weak fields (Fig. 5) this interaction reveals itself through the slowing of wall motion before the coalescence.

FIGURE 5 Interaction of domain walls during polarization reversal in weak field \( (E = 1.8 \times 10^5 \text{ V/m}) \); Delay time from the front of switching voltage pulse: \( a - 1.5 \text{ ms}; b - 2.5 \text{ ms}; c - 5.5 \text{ ms}; d - 7.5 \text{ ms}. \)
In strong fields (Fig. 6) it leads to the formation of raster-type structure of newly arising domains.

FIGURE 6 Raster-type domain structure arising in strong field.

THE QUALITATIVE EXPLANATION
In order to explain the observed peculiarities we use the fact that in broad sense, the formation and evolution of domain structure is nothing but the kinetics of new phase growth during phase transition. It is clear that nucleation probability at the given place and consequently the rate of domain growth depends on the local value of internal field. For ferroelectric capacitor this value is determined not only by the electric potential difference between electrodes but also by the sum of depolarization field of bound charges and screening fields produced by electrode charges (external screening) and bulk charges (internal screening). Due to the existence near the crystal surface of so-called dielectric gap [9] the effect of internal screening is very important and the magnitude of bound internal field produced by localized bulk charges can be up to $10^6$ V/m. It was shown by us earlier that domain dynamics during switching strongly depends on the screening effects [10].
The existence of dielectric gap leads to the incomplete screening of the depolarization field in the vicinity of domain wall. The calculated space distribution of summarized internal field for staying domain wall is plotted on (Fig. 7, curve 1).

![Diagram showing the calculated space distribution of internal electric field in the vicinity of moving domain wall. Velocity of the wall: 1 - 0; 2 - 3 m/s; 3 - 10 m/s.]

**FIGURE 7** The calculated space distribution of internal electric field in the vicinity of moving domain wall: Velocity of the wall: 1 - 0; 2 - 3 m/s; 3 - 10 m/s.

It is seen that nearby domain wall electric field strength reaches its maximum value. In the case of moving wall behind it appears the so-called train of depolarization field which decreases the field on the wall and slows its motion. The length of this train is determined by the domain wall velocity and the time constant of external screening. The space distribution of summarized internal field becomes asymmetrical but even in this case (Fig. 7, curves 2, 3) in front of the wall remains the maximum of internal field. Such behavior makes it possible to explain the arising of chain-like domain structure in superstrong field.
The estimations of internal field with taking into account depolarization effects shows that it is decreasing on the walls of narrow domains. This fact permits to explain the domain interaction just before the coalescence.

The suppression of the arising of new domains in super–strong field can be explained if we take into account the delay time — the interval between the moment of voltage applying and the moment when the nuclei start to form. It is known mention that this delay time increases with increasing of nuclei dimension. The rate between delay time and time of external field action (switching time in our case) is very important. If switching time becomes less than delay time for three–dimensional nuclei the polarization reversal will be achieved through the sidewise motion of existing domain walls and arising the chains of new domains near it. It is clear that in this case the already existing domain walls in the vicinity of electrode boundary and existing residual domains will play the main role.

COMPUTER MODELING

To clarify the influence of observed phenomena on the transient current the computer modeling of domain structure evolution was carried out using matrix comprising 80*80 elements. The space distribution of newly arising domains (switching elements) was defined by Monte–Carlo method. The next stage of its evolution involved the switching of nearest elements (sidewise motion of domain walls). The edge effect was taken into account by the existence from the very beginning of already switched elements along the matrix boundary (existence of domain walls near electrode edges). This modeling permits nevertheless to explain some peculiarities observed in experiment. It was shown that the edge effect produces the initial jump in transient current in accordance with experimental results (Fig. 8 & 9). The appearance of the observed bends on transient current curve (Fig. 9) while passing from strong to superstrong fields can be explained within this model by the diminishing of the number of newly arising domains.
FIGURE 8 The transient currents in strong field and results of computer modeling for high density of nuclei.
FIGURE 9  The transient currents in superstrong field and results of computer modeling for low density of nuclei.
CONCLUSIONS

We must conclude that direct observation of domain dynamics during the switching in real ferroelectrics reveals the influence of boundary effects and inhomogeneities of internal field distribution on the shape of switching current. These peculiarities cannot be accounted for within the Kolmogorov's model. This can lead consequently to the misinterpretation of observed experimental results. The obtained results can be applied for the improvement of the description the change of parameters in ferroelectric memory devices due to fatigue and affect of external influences.

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REFERENCES