Investigation of the dielectric fatigue on the example of lead titanate films PbTiO$_3$

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Abstract. The phenomenon of dielectric fatigue of active dielectrics, which consists in a decrease in the residual polarization depending on the number of switching cycles, is researched. A model of the dependence of the residual polarization of ferroelectric materials on the number of switching cycles is proposed. The model is based on piecewise - linear approximation of the results of measurements of the hysteresis loops of thin films PbTiO$_3$ at a temperature T = 470 (°C), the electric field strength $E = 100$ (kV/cm). The developed model was used in the development of a technique for studying dielectric fatigue, depending on different modes of material switching.

1. Introduction
Piezoelectrics are characterized by the appearance of electric polarization at certain elastic deformations even in the absence of an electric field (direct piezoelectric effect). A consequence of the direct piezoelectric effect is the inverse piezoelectric effect - the appearance of mechanical deformations under the action of an electric field. In general, we are talking about a linear relationship between mechanical deformation (mechanical stress) and electrical parameters (polarization $P$, electric field $E$, electric induction $D$). This feature allows the use of piezoelectric materials in the sensitive elements of products of sensor equipment, detectors, transducers [1, 2].

Piezoelectric instrumentation is a narrowly focused specific field in which the most important aspect is the study of the parameters of materials, on which the characteristics and modes of operation of elements based on them depend [3].

When operating elements and devices based on piezoelectric materials, it is necessary to take into account the phenomenon of material degradation, which affects the reliability and service life of the device as a whole [4]. The operation of a product that does not take into account such an important factor contributes to obtaining unreliable experimental data.

Thus, the development of the direction for the formation of thin-film sensitive structures of sensors is conditioned not only by the expansion of the technical characteristics of devices in general, but also by the increase in the reliability of such elements. It is important to note the simplest way to improve the quality of measurements in a long time interval by introducing corrections in the measurement results.

2. Basic principles of dielectric fatigue of active dielectrics
The class of active dielectrics is massively used in various products of functional electronics, such as small-sized capacitors, non-volatile memory chips and others, since in the ferroelectric phase at certain values of the external electric field strength, these materials have high values of anisotropic relative permittivity.
Exposure to an external electric field of polarization promotes switching of subminiature domains - memory cells in which information is recorded at this moment. Therefore, an important qualitative characteristic of ferroelectric films is the number of polarization switching cycles (more than $10^{10}$ times) [5].

From a metrological point of view, the task is to develop the following methods:

- measurement of hysteresis loops of polarization dependences on the electric field strength $P(E)$, determination of characteristic parameters (saturation polarization $P_s$, residual polarization $P_r$, coercive field $E_c$);
- study of the dynamics of changes in the characteristic parameters of the hysteresis loop (their temporal instability) depending on time; depending on the number of switching cycles.

In works [6–8], the basic principles of degradation of thin ferroelectric films are considered.

3. Modeling of the mechanism of dielectric fatigue of films $PbTiO_3$

According to the developed measurement technique, using an automated setup [9], during interval switching of the polarization cycle $N$, a set of hysteresis loops $P(E)$ is measured, on the basis of which the dependence of the residual polarization on the number of polarization switching cycles is formed.

The graph of the residual polarization dependence on the number of polarization switching cycles $P_r(lgN)$ for thin films of lead titanate $PbTiO_3$ at a temperature $T = 470^\circ C$, an electric field strength $E = 100$ (kV / cm) is shown in Figure 1.

![Figure 1](image)

**Figure 1.** Dependence of the residual polarization of thin films of lead titanate on the number of switches.

The $P_r(lgN)$ dependence shown in Figure 1 can be represented as linear sections, which is shown in Figure 2.
Figure 2. Linear approximation of the dependence of the residual polarization of thin films of lead titanate on the number of switchings.

The approximated three straight lines, obtained in accordance with Figure 2, can be represented in the form of the following expressions:

\[
P_r = \begin{cases} 
  c, & \text{if } 0 < N \leq N_1, \\
  a + b \cdot \lg N, & \text{if } N_1 < N \leq N_2, \\
  e + v \cdot \lg N, & \text{if } N_2 < N \leq N_3,
\end{cases}
\]  

(1)

where the values of the coefficients \((c, a, b, e, v)\) in the approximating equations of the straight lines, as well as the intervals themselves, bounded by the values \(N_1, N_2, \) are selected in accordance with the least squares method.

Relations (1) make it possible to determine the relative deviation of the residual polarization for the continuous switching mode in the time intervals \(\left[\frac{N_1}{f}, \frac{N_2}{f}\right]\) at the switching frequency \(f\) according to the formula (2):

\[
\delta_P(t_s) = 1 - \frac{c}{a + b \cdot \lg (ft_s)}
\]

(2)

The maximum permissible value of the number of switchings is related to the distribution of measurement results that do not go beyond the interval of the standard deviation \(\sigma\). This maximum amount is determined by the formula (3):

\[
N_{\text{max}} = 10 \frac{P_r (1 - \delta_P) - a - \Delta_P - 3\sigma_{\text{max}}}{b},
\]

(3)

where \(\Delta_P\) is the maximum absolute deviation.

With an idea of the maximum number of operations, the maximum permissible deviation can be compared with the calculated absolute value. The excess of the calculated values relative to the limiting value indicates the need for relaxation of the dielectric material parameters.

The method described above for modeling the \(P_r(\lg N)\) dependences of active dielectrics was used to develop a technique for investigating dielectric fatigue in three modes of material switching.
(continuous polarization switching mode, polarization switching mode with alternating long waiting times, and a mode with an uneven polarization switching frequency).

Thus, on the basis of this model, one can calculate the dielectric fatigue of the lead titanate film PbTiO$_3$ and correct the operation of this component of the piezoelectric device. It is important to note that this technique can serve as a basis for determining the dielectric fatigue parameter for other active dielectrics.

4. Conclusion
The presented model allows for a more in-depth presentation of the design of sensitive elements formed by lead titanate films or similar active dielectrics from the composition of various products of functional electronics. The presented technique makes it possible to take into account the degradation of the piezoelectric material, which affects the service life of the sensor as a whole.

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