

## Software - Hardware Complex for Measurement and Control of Ferroelectrics Parameters

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**Abstract:** The structure of a measuring unit as a part of hardware and software complex for measurement and control of the parameters of ferroelectrics and products based on them is examined. This complex allows to measure automatically dielectric parameters depending on the electric field tensity and the temperature, to control the temporary instability of the residual polarization.

**Keywords:** automation of measurements, ferroelectric, measurement technique, the temporary instability.

### 1. INTRODUCTION

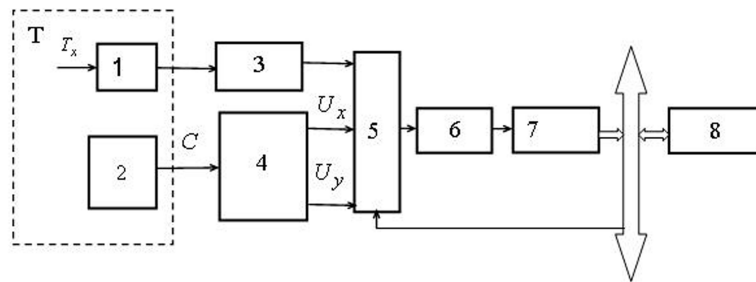
In the past decade increased interest in thin film ferroelectrics is due to the perfection of technologies of their production which results in a high reproducibility of parameters and the ability to control the properties. In the study of materials in technological processes of manufacturing of products based on them the task of measuring and monitoring the parameters specific to the active dielectrics is actual now. We propose an software - hardware complex to solve it in this paper.

### 2. EXPERIMENTAL

#### *2.1 Structure and Function Of Hardware And Software For Measurement And Control Of Ferroelectrics*

Hardware-software complex consists of a measuring unit, a computer, an intelligent application. The structure of the measuring unit and its connection with the computer through the interface is shown in Fig. 1. The structure of the measuring unit includes three measuring channels, which are respectively designed to measure the polarization  $P$  and the dielectric parameters (capacitance  $C$ , the dielectric loss tangent  $\tan\delta$ ); the temperature inside the heat chamber with the test material; the electric field strength  $E$ . This allows you to measure the temperature and field dependences of ferroelectrics dielectric parameters, the time dependences of the switching current and to control the temporary instability of parameters.

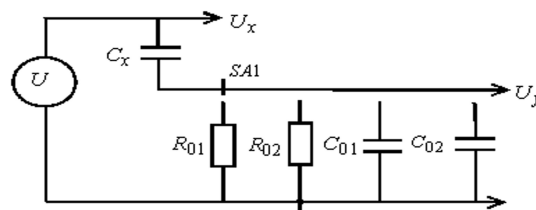




**Fig. 1** - The structure of the measuring unit:

T - heat camera;  $T_x$  - measuring temperature; 1 - the primary temperature sensor; 2 - material; C - the capacity of the measured material; 3 - transducer of electrical resistance into strain; 4 - Sawyer - Tower circuit; 5 - measuring signals switch; 6 - booster; 7 - analog-digital converter; 8 - computer.

Intelligent application contains a set of compatible software tools for processing of information coming from the output of the measurement unit channels, a multi-purpose bank of knowledge. The main functions of intelligent applications are to adopt a number of decisions in time the following processes: measurement planning based on an analysis of apriori information about the material properties; measurement and control using automated measuring methods which are suitable for use depending on the type of material, phase transition type; timely correction of managed material properties and products based on them, in accordance with specified requirements on the analysis of measurement data, such as the control of



**Fig. 2** - The modified Sawyer - Tower scheme

dielectric parameters time instability. In addition to the above described functions of decision-making the software content makes the modeling of dielectric parameters depending on the influencing factors, the processing of the experimental data, the estimation of measurement results errors.

## 2.2 Measurement Of Dielectric Parameters Depending On The Electric Field Intensity And The Time Dependence Of The Switching Current

The variant of experimental setup for poling of polyvinylidene fluoride (PVDF) and switching of polarization described in the article [1]. The original version of the Sawyer - Tower scheme was proposed in the 30s of XX century by Sawyer and Tower to observe on the oscilloscope screen hysteresis loops. Its modifications to automate measurements and metrological analysis are presented in [2], [3]. This paper proposes a connection of the capacitor with the test material into the modified Sawyer - Tower scheme (Fig. 2). To measure dielectric parameters depending on the electric field intensity the generator of sinusoidal signal is used. The voltage  $U_x$  is proportional to the electric field. During switching in the divider lower arm of one of capacitors capacitance  $C_0$ , voltage  $U_y$  is proportional to  $P$ , if  $C_0 \gg C_x$ :

$$U_y = \frac{PS_x}{C_0} = \frac{UC_x}{C_0 + C_x} \approx \frac{UC_x}{C_0}. \quad (1)$$

Connecting a resistor with  $R_0$  in the lower arm of a divider under the influence of voltage from the generator of rectangular pulses as a function of time  $t$  described by the expression (2) the measurement of switching current  $i_s$  is made:

$$i_s(t) = \frac{U_m}{R_{eq}} e^{-\frac{t}{\tau}}, \quad (2)$$

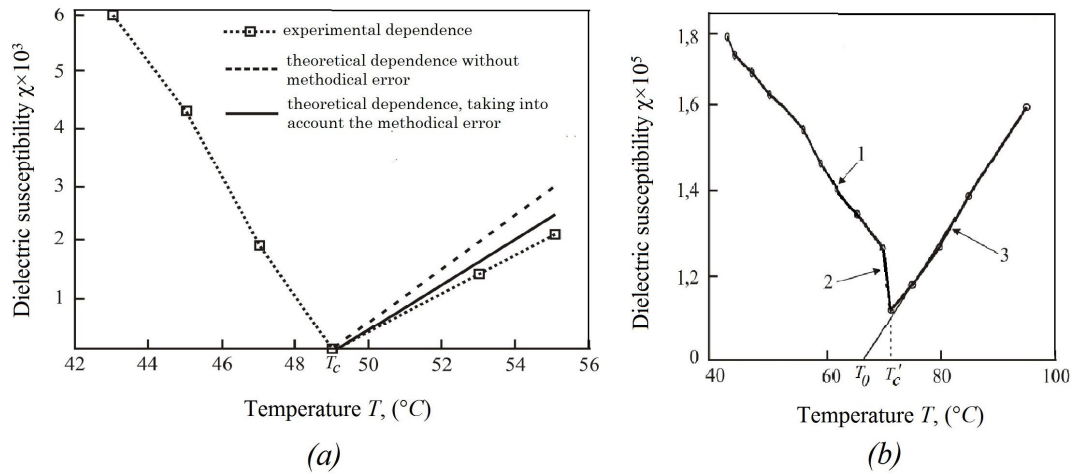
where  $U_m$  - peak voltage of the generator of rectangular pulses,  $\tau$  - the circuit time constant,  $R_{eq} = R_x + R_0$  - the equivalent resistance of divider,  $R_x$  - comprises the resistance characterized loss of energy in spontaneous polarization and the resistance of the ferroelectric to current of through conductivity, connected in parallel according to the electrical pattern of the ferroelectric.

### 2.3 Dielectric Parameters Measurement Depending On The Temperature

On the basis of the phenomenological theory of Landau - Ginzburg -Devonshir, the Curie – Weiss law the identified principle of measuring the temperature dependence of the dielectric parameters of ferroelectric with the phase change of the second kind is based on the following relationships:

$$\begin{cases} \frac{\partial E}{\partial P} = -\frac{2\chi(T)}{\varepsilon_0}, \text{ if } T < T_c, \\ \frac{\partial E}{\partial P} = \frac{\chi(T)}{\varepsilon_0}, \text{ if } T > T_c, \end{cases} \quad (3)$$

meaning that inverse dielectric susceptibility dependences from the temperature  $\chi(T)$  in ferroelectric and paraelectric phases can be approximated by straight lines. Thus steepness in the ferroelectric phase is twice higher than in the paraelectric one. At the same time, the temperature dependences of capacitance, relative permittivity, dielectric loss tangent are nonlinear. Therefore, in order to optimize the measurement process by criterion of not exceeding the maximum permissible error for the minimum amount of measurement procedures it was suggested to indirectly measure precisely the inverse dielectric susceptibility depending on temperature. For the measurement of the inverse dielectric susceptibility uniquely interconnected with the capacity and the relative dielectric penetrability the measurement channel on the basis of Sawyer - Tower circuitry



**Fig. 3** - The temperature dependences of the inverse dielectric susceptibility of triglycinesulfat with a second kind phase transition (a); ceramics based on barium titanate with a phase transition of the first one (b)

consisting the measuring unit of an intelligent system is used. To measure the temperature the measuring channel, which comprises a primary temperature sensor, a converter of electrical resistance into the voltage, a measuring signals switch, a booster, an analog-to-digital converter is used. The functional diagram of the temperature measurement channel and the results of its metrological analysis is presented in [4].

The technique is to measure the adequacy of the inverse dielectric susceptibility  $\chi$  at least at three temperatures in the temperature range limited by available means of measurements. For other values of temperature, the function  $\chi(T)$  is modeled on the basis of expressions (3), shown in Fig. 3.

In this example, measurements refer to the ferroelectric phase and the simulation is performed in the paraelectric phase.

The measurement results can satisfy one of three situations: all results are consistent with the ferroelectric phase; all results are consistent with the paraelectric phase; results of measurements are consistent with both phases including the transition phase. Described situations (after the elimination of misses and provided that the parameters of the ferroelectric obey the Curie-Weiss law) are formalized by the following system

$$\begin{cases} \text{if } \chi_{i+1} < \chi_i \text{ and } T_{i+1} > T_i, \text{ferroelectric phase,} \\ \text{if } \chi_{i+1} > \chi_i \text{ and } T_{i+1} > T_i, \text{paraelectric phase,} \\ \text{if } \chi_{i+1} < \chi_i \text{ and } T_{i+1} > T_i, T_i \leq T_c; \text{if } \chi_{i+1} > \chi_i \text{ and} \\ T_{i+1} > T_i, T_i > T_c, \text{measurements are made in both phases,} \end{cases} \quad (4)$$

where the temperature  $T_c$  corresponds to the minimum inverse dielectric susceptibility.

For materials with the first kind transition the Curie temperature  $T'_c$  and the phase transition temperature  $T_0$  are not matched (Fig. 3b). Up to the error consisting of the approximation error and the measurement results errors in the section 2 of the function  $\chi(T)$ , the value  $T'_c$  may be defined as the abscissa of the intersection of the line 2 with the horizontal axis. Similarly, the phase transition temperature  $T_0$  is defined as the abscissa of the intersection with the horizontal axis of the straight line approximating the section 3 of the function  $\chi(T)$  in Fig. 3b. If because

of the multiplicative errors of measurements results the approximating line 3 is flatter, it leads to the overestimation of  $T'_C$  and it can be argued at the true Curie temperature belongs to the interval  $[T_0 - \Delta T_0; T'_C + \Delta T'_C]$ .

These techniques should be used not only for the measurement of the dielectric parameters of ferroelectrics temperature dependences with the first kind phase transition, but also in the study of materials with the diffuse phase transition. The selection of measurement procedure is carried by the proposed intelligent system.

#### *2.4 Measurement Of Dielectric Parameters Depending On The Electric Field Intensity And The Time Dependence Of The Switching Current*

The effect of aging and dielectric fatigue on active dielectrics parameters used in memory devices is described in [5], for example. The experimental part of the study process of active dielectrics dielectric fatigue is based on the polarization measurements depending on the electric field intensity at a different number of switching cycles of polarization [6]. It allows to calculate the values of the residual polarization  $P_r$  and the coercive field  $E_C$  depending on the number of polarization  $N$  switching cycles (Fig. 4).

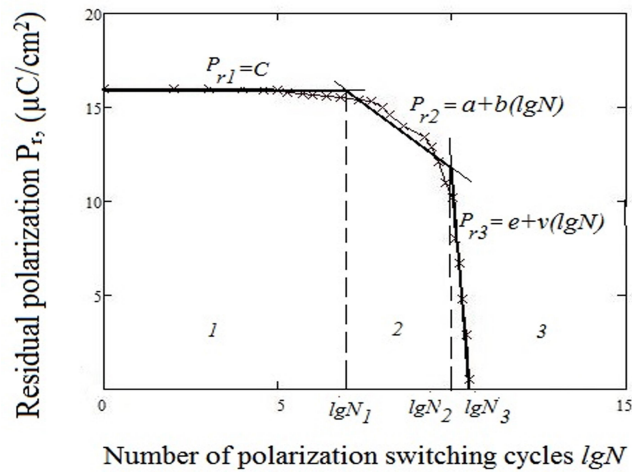
The dependence  $P$  is approximated by straight lines in three sections marked in Fig. 4 in accordance with the following expressions:

$$P_r = \begin{cases} c, & \text{if } 0 < N \leq N_1, \\ a + b \cdot \lg N, & \text{if } N_1 < N \leq N_2, \\ e + v \cdot \lg N, & \text{if } N_2 < N \leq N_3, \end{cases} \quad (5)$$

where the coefficients  $a, b, c, e, v$  in approximate equations of the lines and intervals limited by values  $N_1, N_2, N_3$  are selected in accordance with the method of least squares. The intelligent system implements control techniques of the field dependences time instability of active dielectrics dielectric parameters due to their fatigue which are implemented by various algorithms, depending on the operating modes of the elements on the basis of these materials (in continuous switching, switching with alternating long waiting, in which possible partial or complete recovery of values of dielectric parameters, mode switching with a non-uniform frequency of exposure signal leading to a temporary instability of dielectric parameters of the random nature).

For example, in the continuous switching mode the relative deviation of the residual polarization  $\delta_p(t_x)$  at the time range  $N_1 / f < t_x \leq N_2 / f$  in which  $f$  - switching frequency is determined by the expression

$$\delta_p(t_x) = 1 - \frac{c}{a + b \cdot \lg(f \cdot t_x)}. \quad (6)$$



**Fig. 4** - Experimental dependence  $P_r(\lg N)$  and its piece-linear approximation for thin films PbTiO (at  $T = 470^\circ\text{C}$ , electric field density  $E = 100\text{kV/cm}$ )

The evaluation of the critical number of switching cycles  $t_k \cdot f = N_k$ , which corresponds to the maximum permissible absolute deviation  $\Delta_{pm}$  in this area is calculated using the formula:

$$N_k = 10^{\frac{P_r(t_0)[1-\delta_p] - a - \Delta_{pm} - 3\sigma_{\max}}{b}}, \quad (7)$$

where  $\delta_p$  - maximum relative error of polarisation measurement;  $\sigma_{\max}$  - the largest standard deviation of the residual polarization measurement results in the interval. Methods of the residual polarization time instability control function according to polarization switching modes specificity.

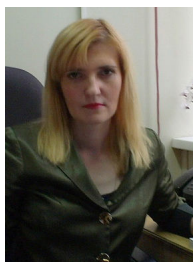
### 3 CONCLUSION

Due to the intelligent application the software-hardware complex allows to make decisions on the choice of measurement techniques in the planning phase of an experiment; processing of measurement results including the evaluation of methodological and instrumental components of their errors; automated control of the time instability of the residual polarization depending on the polarization switching mode and a decision to correct material properties. Methods of the temperature dependences measuring of ferroelectrics dielectric parameters depending on the kind of phase transition allowed to increase the effectiveness of measurements in 3 times due to the number of measurement procedures reducing and measurement in a narrow temperature range followed by the modeling of dielectric parameters functional dependences in the desired temperature range. Control methods of the time instability of ferroelectrics dielectric parameters (their applications areas are dictated by different modes of polarization switching) are directed to the timely establishment of a critical number of switching cycle which helps to prevent a metrological rejection of products on the basis of the studying materials.

The software - hardware complex can be used for the controlled synthesis of materials with desired properties for the measurement of their dielectric parameters as well as in manufacturing processes of functional electronics components based on them.

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